APPENDIX L

Marine Mammals and Sound Sources in the Flemish Pass
(Maxner et al. 2019)

equinor

Marine Mammals and Sound Sources in the Flemish Pass

Analysis from 2014 to 2017 Acoustic Recordings

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Executive Summary

This report provides results from the analysis of long-term passive acoustic data gathered in or near the Flemish Pass. AMEC, on behalf of Statoil, deployed an acoustic recorder in the Flemish Pass from June to October 2014 and from May to September 2015. A separate recorder was deployed in Orphan Basin from August 2015 to July 2016, then redeployed at the northern opening of the Flemish Pass from July 2016 to July 2017. These data were analyzed to characterize the baseline soundscape, the presence of marine mammals, and characterize to the effects on the soundscape of Statoil's 2014–2016 drilling program.

Two anthropogenic sound sources affected the soundscape over extended periods of time. First, drilling operations by the semi-submersible drill rig *West Hercules* generated sound levels similar to those previously reported for the *Stena IceMAX* off Nova Scotia. Second, seismic surveys increased baseline sound levels by 10–35 dB throughout the summers. An analysis of seismic reverberation in the project area showed that our understanding of the listening space of mysticete whales is reduced by 90% for at least half of the 12-second inter-pulse period when the vessel is within 15 km of a whale. Beyond 15 km the listening space is reduced by 90% for 1-2 seconds in most cases, but up to 6 seconds in others. Relative to mysticetes, the analysis indicated that masking of odontocete clicks and whistles did not occur during the seismic survey.

Five confirmed species of marine mammals, plus an unknown number of dolphin species (up to six), were detected acoustically within the Flemish Pass in 2014–2015. Baleen whale detections were sparse and occurred predominantly in the late summer and early fall, showing pronounced seasonal variations as a result of changes in vocal behaviour, migratory movements, or both. Blue whales were detected once in early August and once in early October 2014, and three times in early September 2015. Fin whale vocalizations were only detected once at the beginning of the study period in 2014, but detections increased in early fall 2015. The occurrence of northern bottlenose whale clicks was sporadic throughout the study period in 2014–2015 and were acoustically active during seismic surveys. In both 2014 and 2015, sperm whale calls occurred continuously throughout the recording. Delphinids, which include pilot whales as well as several species of dolphins, were the most broadly detected species group. Noise associated with anthropogenic activities (namely seismic surveys, vessel traffic, and oil and gas activities) at times restricted or prevented our ability to detect some species.

Marine mammal acoustic detections were much greater across all species in the 2016–2017 recordings, which were collected on the shelf edge at the mouth of the Flemish Pass. These results included three addition species not recorded in 2014–2015 or 2015–2016: Cuvier's beaked whales, Sowerby's beaked whales, and humpback whales. It is difficult to determine whether the differing results are attributable to the different locations, different years, or differences in the anthropogenic contributions to the soundscape that could lead to area avoidance, acoustic masking, and/or reduced vocalization rates.

1. Introduction

The Canadian Atlantic seaboard is home to a wealth of marine life and the site of diverse human activities, including fishing, shipping, and oil and gas activities. To varying degrees, these anthropogenic activities all contribute to the soundscape of the surrounding waters. In 2014 and 2015, Statoil Canada Limited employed a JASCO Applied Sciences (JASCO) acoustic recorder owned by AMEC for opportunistic acoustic recordings at Statoil's 2014–2016 drilling areas in the Flemish Pass. From 2015 to 2017, JASCO collected acoustic data near the Flemish Pass as part of a larger monitoring project sponsored by the Environmental Studies Research Fund (ESRF). Here we present an analysis of these recordings, focusing on biological (marine mammal) and anthropogenic (seismic surveys, and oil and gas production activities) sound sources.

1.1. Soniferous Marine Life and Acoustic Monitoring

Passive acoustic monitoring of marine life relies on the monitored species to produce detectable sound. Several marine taxa produce sounds, including all marine mammals as well as some crustaceans (e.g., snapping shrimp; see Au and Banks 1998) and fish (e.g. Nordeide and Kjellsby 1999, Hawkins et al. 2002, Amorim 2006, Erbe et al. 2015). Neither crustaceans, fish spawning aggregations, nor fish choruses were present in the acoustic data.

The biological focus of this study was on marine mammals. Twenty-five cetacean and six pinniped species may be found in the study area (Table 1). The presence of pygmy sperm whales is known only from strandings (Measures et al. 2004). Blainville's beaked whales have stranded in Nova Scotia (Mead 1989) and were observed live once near the Gully Canyon ([DFO] Fisheries and Oceans Canada 2016). Gervais' and True's beaked whales may occur in the study area based on habitat characteristics, but have not been sighted or recorded. A bowhead whale sighted in the Bay of Fundy in 2012 is believed to have been a vagrant individual (http://rightwhales.neaq.org/2012/08/11-bowhead-whale-in-bay-of-fundy.html), so detections of this species, if any, would be rare.

Marine mammals are the main biological contributors to the underwater soundscape. For instance, fin whale songs can raise noise levels in the 18–25 Hz band by 5–10 dB over extended time periods (Delarue et al. 2016, Delarue et al. 2018b). Marine mammals, cetaceans in particular, rely almost exclusively on sound for navigating, foraging, breeding, and communicating (Clark 1990, Edds-Walton 1997, Tyack and Clark 2000). Although species differ widely in their vocal behaviour, most can be reasonably expected to produce sounds on a regular basis, and passive acoustic monitoring is therefore increasingly preferred as a cost-effective and efficient survey method. Seasonal and sex- or age-biased differences in sound production, as well as signal frequency, source level, and directionality, influence the applicability and success rate of acoustic monitoring to some extent and should therefore be considered for each species.

The acoustic signals of some species are poorly known or unknown, which prevents or complicates the acoustic assessment of their occurrence. This is the case for hooded seals, pygmy sperm whales, and True's beaked whales. While the vocal repertoire of most odontocetes in the area is fairly well known, similarities in the spectral features of their signals generally preclude resolving species identity for most detection events. Exceptions include the tonal signals of killer whales and pilot whales and the clicks of sperm whales, beaked whales, and harbour porpoise. In most cases, baleen whale signals can be reliably identified by species.

Table 1. Cetacean and pinniped species known to occur (or possibly occurring) in the study area and their Committee on the Status of Endangered Wildlife in Canada (COSEWIC) and Species at Risk Act (SARA) status.

Species name	Scientific name	COSEWIC status	SARA status
Baleen whales			
Minke whale	*Balaenoptera acutorostrata*	Not at risk	Not listed
Sei whale	*Balaenoptera borealis*	Data deficient	Not listed
Blue whale	*Balaenoptera musculus*	Endangered	Endangered
Fin whale	*Balaenoptera physalus*	Special concern	Special concern
Humpback whale	*Megaptera novaeangliae*	Not at risk	Special concern
North Atlantic right whale	*Eubalaena glacialis*	Endangered	Endangered
Bowhead whale	*Balaena mysticetus*	Special concern	Endangered
Toothed whales			
Short-beaked common dolphin	*Delphinus delphis*	Not at risk	Not listed
Striped dolphin	*Stenella coeruleoalba*	Not at risk	Not listed
White-beaked dolphin	*Lagenorhynchus albirostris*	Not at risk	Not listed
White-sided dolphin	*Lagenorhynchus acutus*	Not at risk	Not listed
Bottlenose dolphin	*Tursiops truncatus*	Not at risk	Not listed
Risso's dolphin	*Grampus griseus*	Not at risk	Not listed
Killer whale	*Orcinus orca*	Special concern	Not listed
Beluga whale	*Delphinapterus leucas*	Endangered[1]	Threatened[1]
Long-finned pilot whale	*Globicephala melas*	Not at risk	Not listed
Harbour porpoise	*Phocoena*	Special concern	Threatened
Pygmy sperm whale	*Kogia breviceps*	Not at risk	Not listed
Sperm whale	*Physeter macrocephalus*	Not at risk	Not listed
Cuvier's beaked whale	*Ziphius cavirostris*	Not at risk	Not listed
Sowerby's beaked whale	*Mesoplodon bidens*	Special concern	Special concern
Northern bottlenose whale	*Hyperoodon ampullatus*	Endangered[2]	Endangered[2]
Blainville's beaked whale	*Mesoplodon densirostris*	Not at risk	Not listed
Gervais beaked whale	*Mesoplodon europaeus*	Not assessed	Not listed
True's beaked whale	*Mesoplodon mirus*	Not at risk	Not listed
Pinnipeds			
Grey seal	*Halichoerus grypus*	Not at risk	Not listed
Ringed seal	*Phoca hispida*	Not at risk	Not listed
Hooded seal	*Cystophora cristata*	Not at risk	Not listed
Bearded seal	*Erignathus barbatus*	Not assessed	Not listed
Harp seal	*Phoca groenlandica*	Not at risk	Not listed
Harbour seal	*Phoca vitulina*	Not at risk	Not listed
Atlantic walrus	*Odobenus rosmarus*	Special concern	Not listed

[1] Status of the Gulf of St. Lawrence population
[2] Status of the Scotian shelf population

1.2. Ambient Sound Levels

The ambient, or background, sound levels that create the ocean soundscape are comprised of many natural and anthropogenic sources (Figure 1). The main environmental sources of sound are wind, precipitation, and sea ice. Wind-generated noise in the ocean is well-described (e.g., Wenz 1962, Ross 1976), and surf noise is known to be an important contributor to near-shore soundscapes (Deane 2000). In polar regions, sea ice can produce loud sounds that are often the main contributor of acoustic energy in the local soundscape, particularly during ice formation and break up. Precipitation is a frequent noise source, with contributions typically concentrated at frequencies above 500 Hz. At low frequencies (<100 Hz), earthquakes and other geological events contribute to the soundscape.

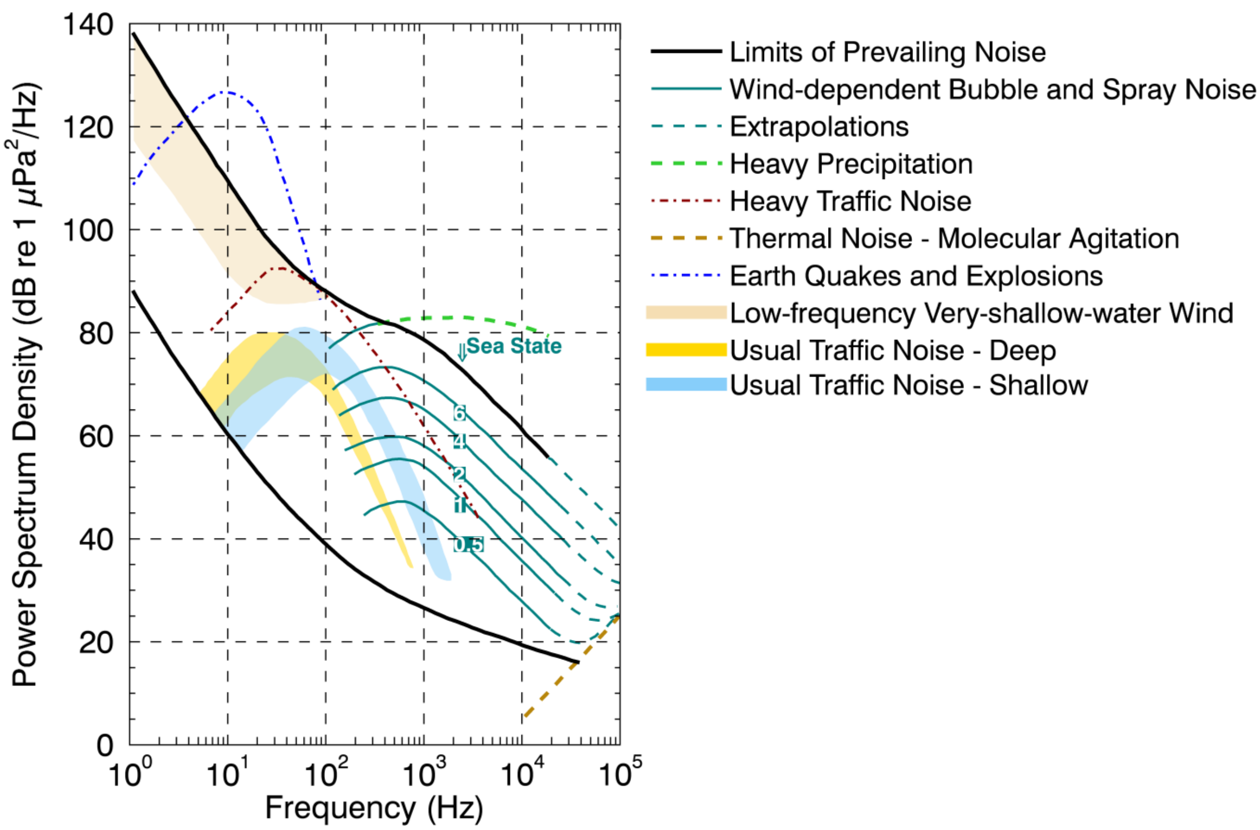

Figure 1. Wenz curves (NRC 2003), describing pressure spectral density levels of marine ambient noise from weather, wind, geologic activity, and commercial shipping, adapted from Wenz (1962).

1.3. Anthropogenic Contributors to the Soundscape

Anthropogenic (human-generated) sound can be a by-product of vessel operations, such as engine noise radiating through vessel hulls and cavitating propulsion systems, or a product of active acoustic data collection with sonar, depth sounding, and seismic surveys. The contribution of anthropogenic sources to the ocean soundscape has increased steadily over the past several decades. The anthropogenic increase is largely driven by greater worldwide amounts of shipping and oil and gas exploration (Hildebrand 2009). Seismic survey sounds have increased significantly following their expansion into deep water, and they can now be detected across ocean basins (Nieukirk et al. 2004). The main anthropogenic contributors to ambient noise in the study area are dynamic positioning vessels and seismic surveys.

1.3.1. Vessel Traffic

There are several major shipping lanes south of the study area. Vessel tracks fan out after leaving the Gulf of St. Lawrence, resulting in constant traffic on the Scotian shelf and in areas south of Newfoundland. A few isolated areas of denser vessel traffic off the coast indicate the location of oil and natural gas extraction platforms and the associated transit of support vessels, as well as areas targeted by seismic surveys and potential fishing hotspots (Figure 2).

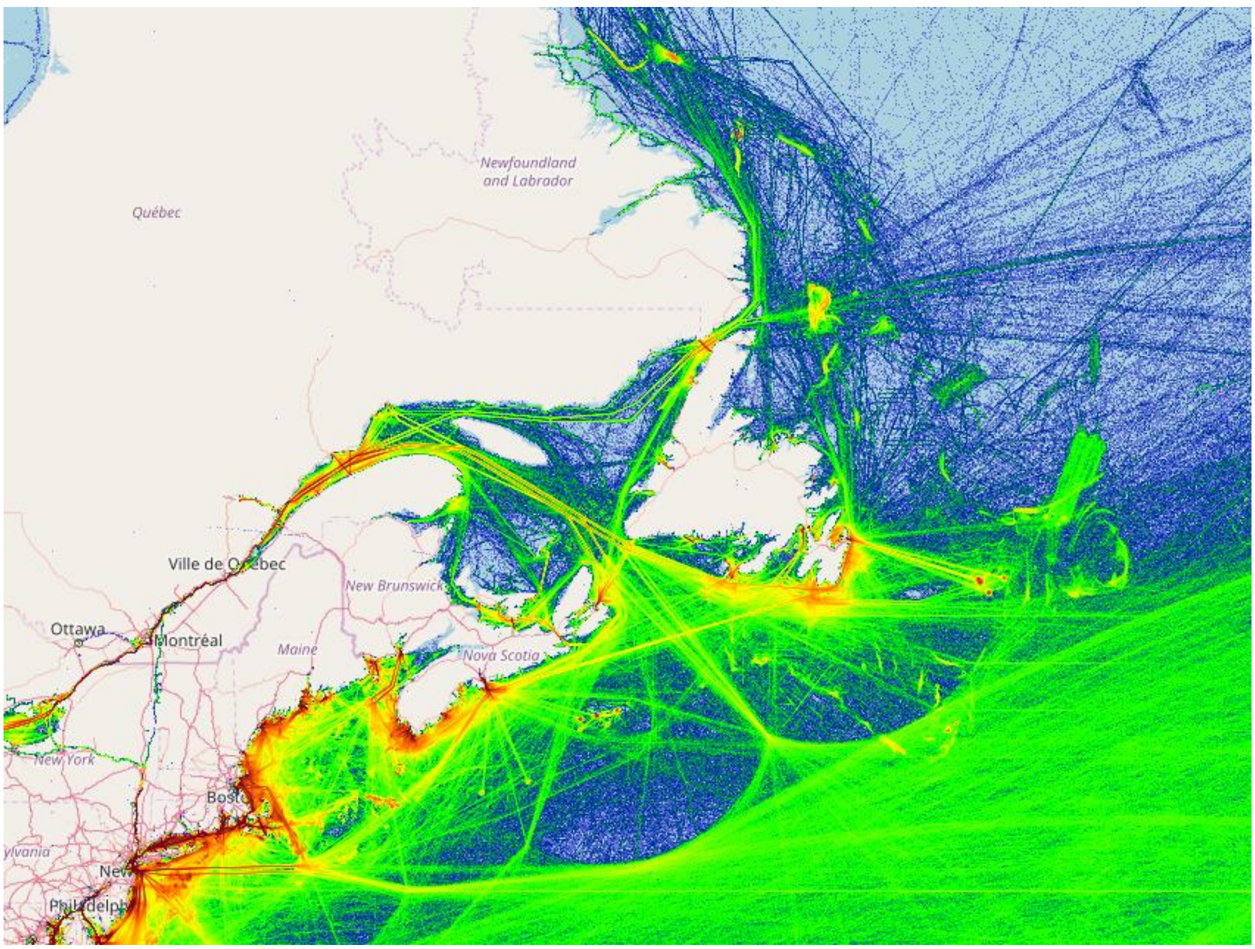

Figure 2. Shipping traffic off the US and Canadian east coast (source: marinetraffic.com; accessed 30 Aug 2017).

1.3.2. Seismic Surveys and Oil and Gas Extraction

Seismic exploration has a long history on Canada's east coast. Increasing in the 1960s, success in both Nova Scotia and Newfoundland in the 1970s and 1980s resulted in an exploration peak in 1983. The next wave of seismic exploration began in 1995 and continued into the 2000s, as 3-D work focused on the Scotian Shelf. In recent years TGS, Petroleum Geo-Services (PGS), Nalcor Energy, and to a lesser extent Shell and BP have undertaken extensive surveys from Nova Scotia to Labrador. Nearly 500,000 km were surveyed across areas under the jurisdiction of the Canada Newfoundland Labrador Offshore Petroleum Board (CNLOPB) during the 2015–2016 fiscal year (Table 2). Figure 3 shows the extent of the surveys conducted by MKI, a joint venture between Nalcor, TGP, and PGS in 2015–2016. There were no seismic surveys conducted in 2015–2016 in areas under the jurisdiction of the Canada Nova Scotia Offshore Petroleum Board (CNSOPB).

In addition to the seismic exploration programs, the Statoil 2014–2016 drilling program in the Flemish pass contributed to the soundscape from 4 Nov 2014 to 22 May 2016. The Seadrill *West Hercules* semi-submersible drill rig equipped with 8 Rolls-Royce 3,500 kW azimuthing dynamic positioning thrusters was employed for the drilling operations (Figure 4).

Table 2. Geoscientific programs with fieldwork authorized during 2015–2016 fiscal year.(Source: CNLOPB 2016).

Operator	Program	Region	Distance surveyed (km)
Hibernia Management and Development Company Ltd.	4-D Seismic	Jeanne d'Arc Basin	90,818
Multi Klient Invest	2-D Seismic	Northern Labrador and Northeastern Newfoundland	9,951
Multi Klient Invest	3-D Seismic	Eastern Newfoundland	166,219
Multi Klient Invest	3-D Seismic	Eastern Newfoundland	211,734
Multi Klient Invest	2-D Seismic	Eastern and northeastern Newfoundland	2,483
Multi Klient Invest	2-D Seismic	Southern and southeastern Newfoundland	14,403

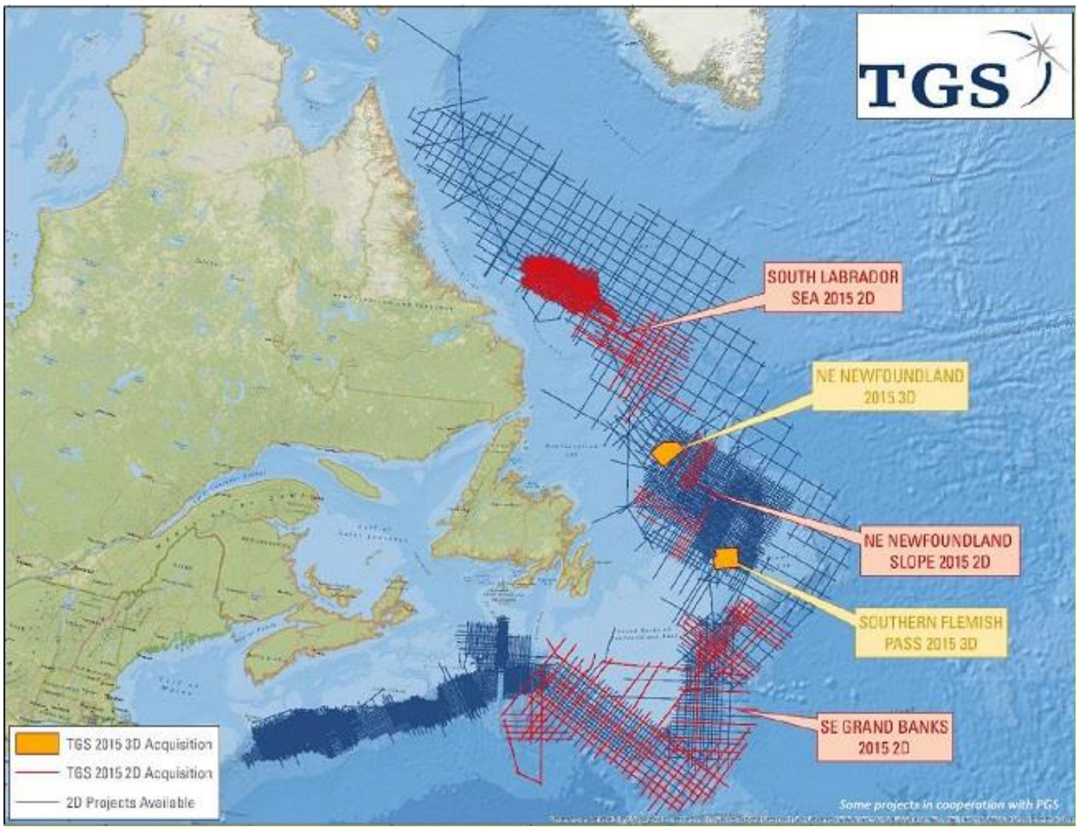

Figure 3. 2015 seismic surveys completed by TGS and PGS and previously available 2-D seismic data in eastern Canadian waters. (Source: Larsen and Ashby 2015; accessed 14 Nov 2016).

Figure 4. Seadrill *West Hercules* semisubmersible drill rig.

2. Methods

2.1. Data Collection

An acoustic recorder (AMAR172) was purchased by AMEC for the Statoil program in 2014, and it was included in the CM2 current meter mooring. JASCO performed a data download and refurbishment for AMEC prior to the redeployment in 2015.

In August 2015, JASCO deployed an AMAR at Stn 19 (Stn 19 2015–2016), ~230 km northeast of the Statoil 2014–2016 drilling area, as part of a project sponsored by ESRF. The AMAR recorded until its retrieval in July 2016 when ESRF Stn 19 2016–2017 was deployed at the mouth of the Flemish Pass. The AMAR recorded until July 2017. These data are included in this report because sounds from the Statoil 2014–2016 drilling program were detected at Stn 19 2015–2016, which serves as a baseline for comparison to the CM2 data. Stn 19 2016–2017 provides acoustic information of the Flemish Pass region after completion of the Statoil project.

2.1.1. Mooring Design and Deployment Location

AMEC designed the mooring configuration for a suspended AMAR (Figure 5). The recorded drilling operations was 13.4 km distance to the mooring CM2 (Table 3). The AMAR was deployed twice in the Flemish Pass (CM2 Recorder; Figures 7 and 8) from 2 Jun to 9 Oct 2014 and 9 May to 11 Sep 2015 (Table 4). The CM2 deployment recorded the drilling operations of BdN4 L-76 from 2 May to 11 Sep 2015 (Table 3, Figure 8). The AMAR recorded for an average duration of four months each year and was successfully retrieved using an acoustic release.

Stn 19 mooring (Figures 6 and 7) was deployed twice. The first deployment (Stn 19 2015–2016) was on 25 Aug 2015, and it was retrieved 17 Jul 2016 in 1280 m of water. The recorder was 209–246 km from the drilling operations until drill ceased on 22 May 2016 (Table 3). For the second deployment (Stn 19 2016–2017), Stn 19 was moved 213 km southeast where it was deployed on 17 Jul 2016, and it was retrieved 19 July 2017 in 1547 m of water. Stn 19 was moved to the 2016–2017 position to study the presence of northern bottlenose whales after a cruise by the Whitehead Laboratory team from Dalhousie university found a concentration of the whales in that area.

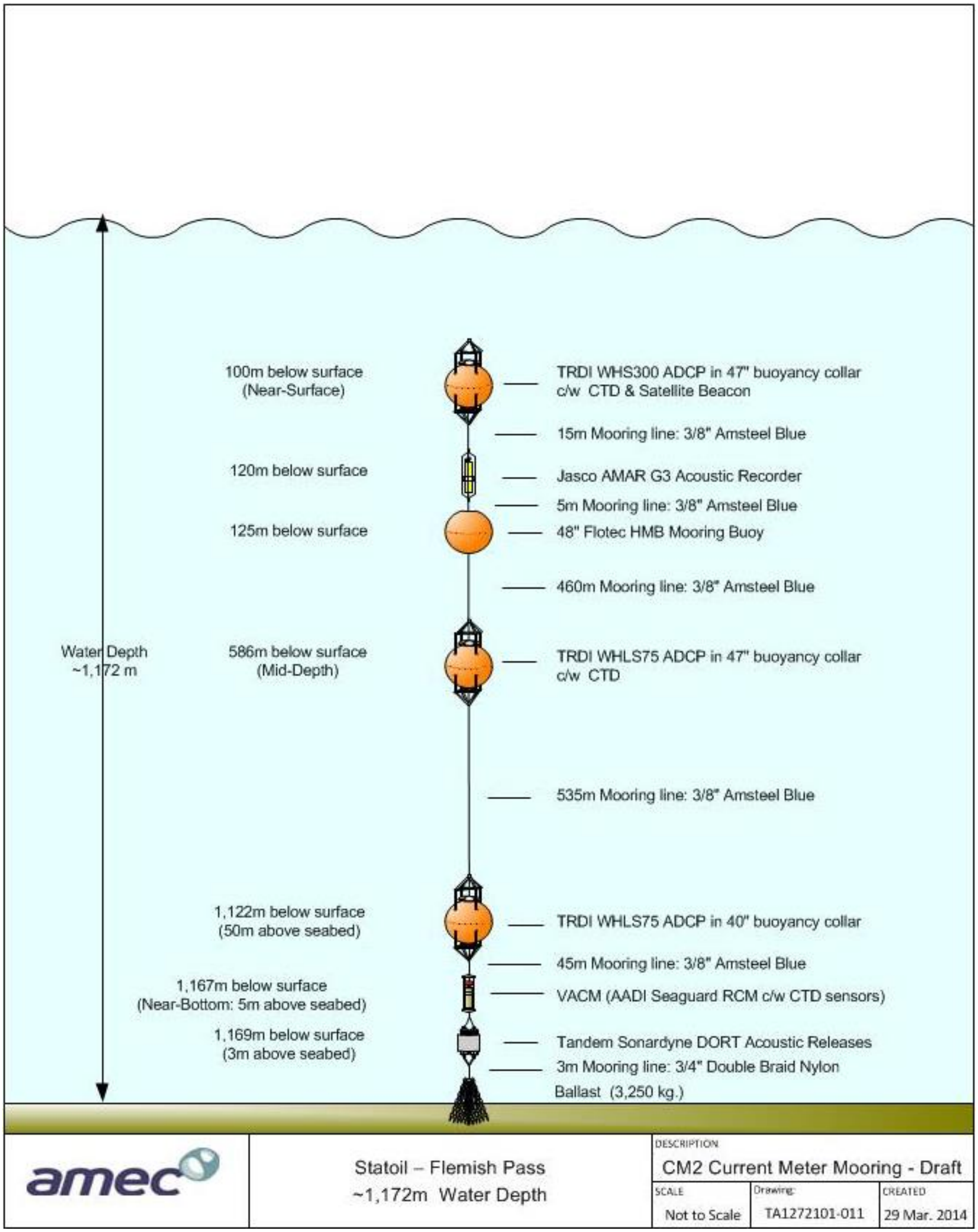

Figure 5. The mooring design used by AMEC.

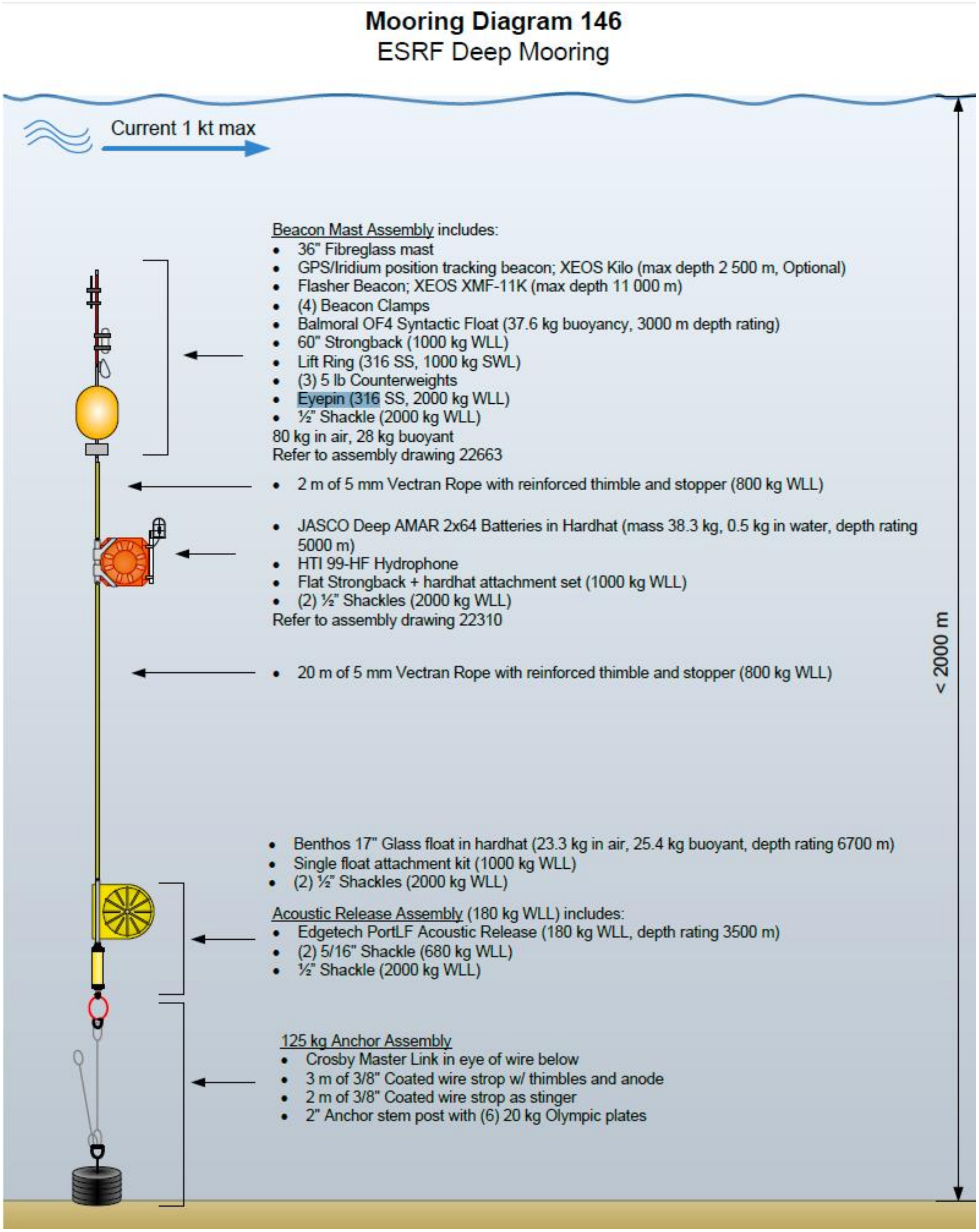

Figure 6. JASCO Mooring 146 employed at Stn 19.

Table 3. The drill rig operation period, location, and distance to the CM2 and Stn 19 recorders. Only BdN4 L-76 was recorded at CM2.

Well drilling operation	Rig coordinates (Lat, Long)	Approx. distance to CM2 (km)	Approx. distance to Stn 19 (km)	Operation date
BdN4 L-76	47° 55' 43.9403 N 46° 26' 42.6303 W	13.4	234	2 May to 12 Sep 2015
BdE, B-09	47° 58' 09.8601 N 46° 30' 19.8867 W	Not deployed	230	13–28 Sep 2015 1–31 Dec 2015
Cupids, A-33	49° 02' 08.2606 N 46° 04' 43.9385 W	Not deployed	246	29 Sep to 23 Nov 2015
Fitzroya, A-12	48° 01' 00.1739 N 46° 46' 43.1924 W	Not deployed	209	24–30 Nov 2015
M-62	47° 51' 48.6828 N 46° 25' 19.5067 W	Not deployed	240	31 Mar to 22 May 2016

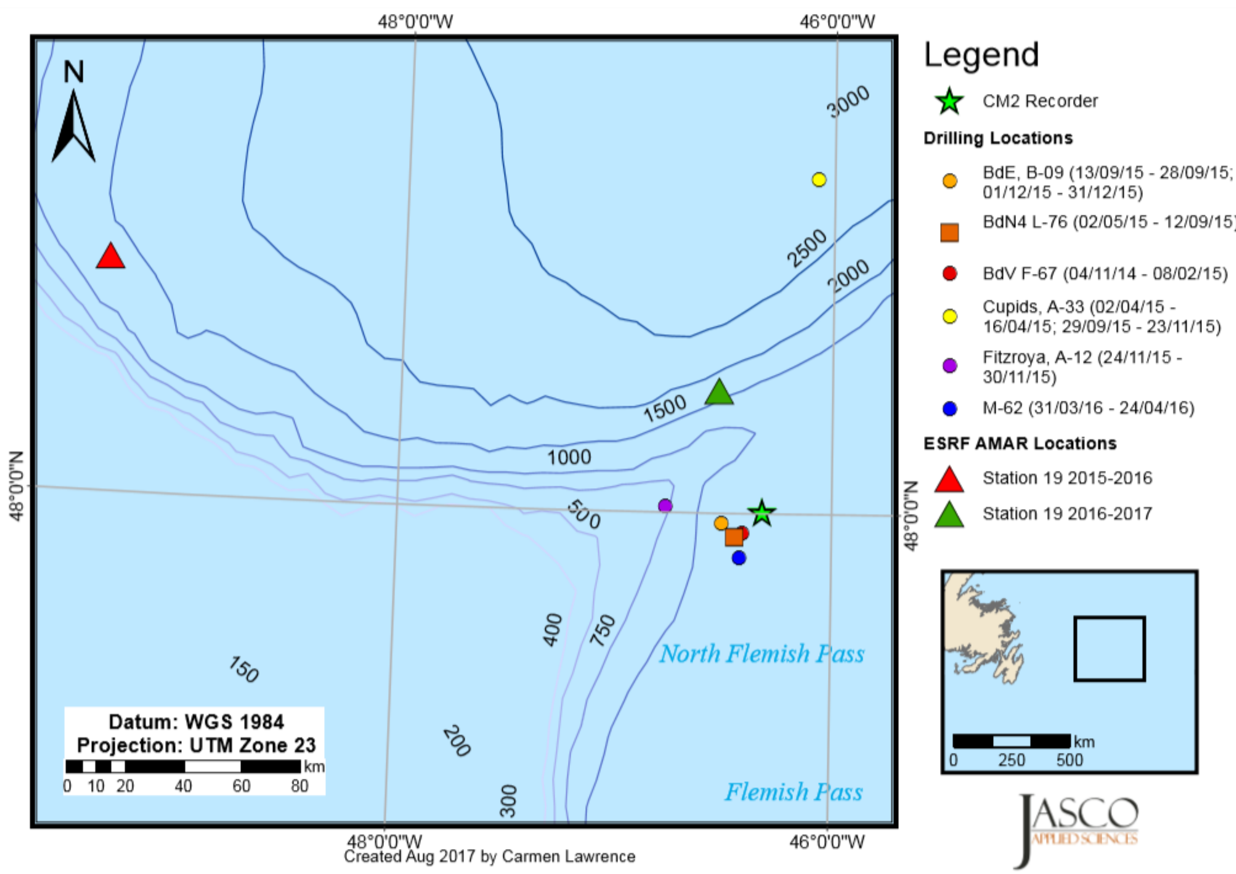

Figure 7. CM2 recorder, Stn 19 recorders, and Statoil 2015–2016 drilling locations off the east coast of Newfoundland.

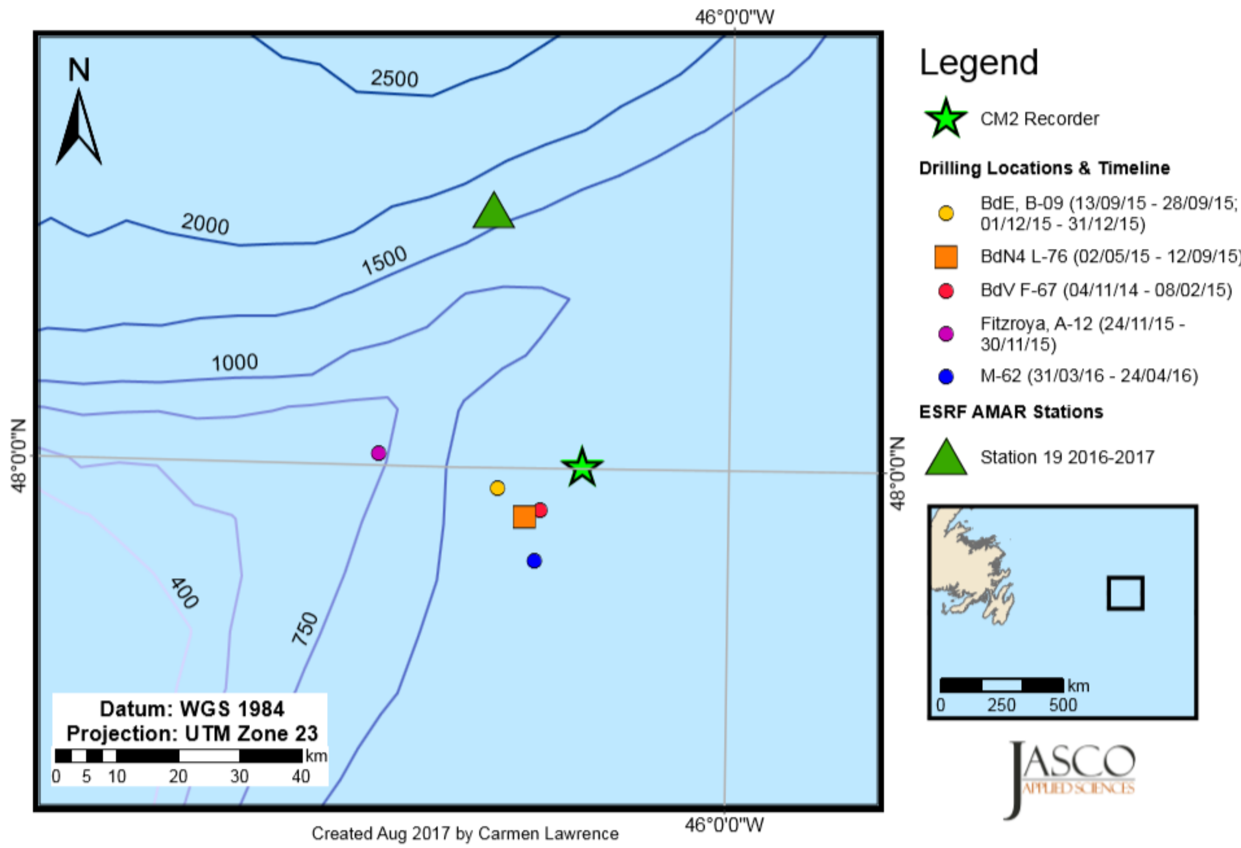

Figure 8. Statoil 2014–2016 drilling sites and CM2 recorder location. The BdN4 L-76 site is highlighted as a square.

Table 4. Operation period, location, and depth of the AMAR deployed in 2014 and 2015 for the Statoil study.

Year	Latitude	Longitude	Depth (m)	Deployment	Retrieval	Duration (days)
2014	44.71155	−63.5874	~1,170	2 Jun 2014	9 Oct 2014	129
2015	49.89104	−47.6597	~1,170	9 May 2015	11 Sep 2015	125

2.1.2. Acoustic Recorders

Underwater sound was recorded with Autonomous Multichannel Acoustic Recorders (AMARs, JASCO). The AMAR G3 on CM2 was fitted with a M8E-35dB omnidirectional hydrophone (GeoSpectrum Technologies Inc.; −164 dB re 1 V/µPa sensitivity). The AMAR hydrophone was protected by a hydrophone cage, which was covered with a cloth shroud to minimize noise artifacts due to water flow. The AMAR sampled on a 15 min duty cycle: 680 s at 16 ksps, then 170 s at 128 ksps, and then 50 s of sleep. The 16 ksps recording channel had a 24-bit resolution with no gain, resulting in a spectral noise floor of 24 dB re 1 µPa^2/Hz and could resolve a maximum sound pressure level (SPL) of 171 dB re 1 µPa. The 128 ksps data were recorded at 24-bit resolution with no gain, resulting in a spectral noise floor of 18 dB re 1 µPa^2/Hz and could resolve a maximum SPL of 171 dB re 1 µPa. The spectral noise floor represents the quietest sounds that can be recorded, and is directly comparable to the Wenz ocean noise spectra (Figure 1). Acoustic data were stored on internal solid-state flash memory.

The AMAR deployed at Stn 19 had an HTI-99 hydrophone (Hi-tech Industries; −165 dB re 1 V/µPa sensitivity). This AMAR hydrophone was also protected by a hydrophone cage to minimize noise artifacts.

The AMAR sampled on a 20 min duty cycle: 680 s at 8 ksps, then 65 s at 250 ksps, and then 455 s of sleep. The 8 ksps recording channel had a 24-bit resolution with 6 dB gain, resulting in a spectral noise floor of 32 dB re 1 µPa^2/Hz and could resolve a maximum SPL of 165 dB re 1 µPa. The 250 ksps data were recorded at 16-bit resolution with no gain, resulting in a spectral noise floor of 32 dB re 1 µPa^2/Hz and could resolve a maximum SPL of 171 dB re 1 µPa

2.1.3. Recorder Calibrations

A 42AC pistonphone calibrator (G.R.A.S. Sound & Vibration A/S; Figure 9) was used to verify the sensitivity of the whole recording apparatus—the hydrophone, pre-amplifier, and AMAR. The pressure response of the recording system was verified by placing the pistonphone and its adapter over the hydrophone while the pistonphone produced a known pressure signal on the hydrophone element (a 250 Hz sinusoid at 152.2 dB re 1 µPa). The system sensitivity was measured independently of the software that performed the data analysis. This independently calibrated the analysis software. Calibrations were performed in JASCO's facility before the recorders were shipped. The reading was verified for consistency before data analysis was performed.

Figure 9. Split view of a G.R.A.S. 42AC pistonphone calibrator with an M15B hydrophone.

2.2. Automated Data Analysis

Automated and manual analysis methods were employed to determine when vessels, seismic surveys and marine mammals were present in the data sets. These methods, along with information on acoustic metrics are contains in Appendix A.

3. Results

3.1. Total Soundscapes

The objective of this analysis was to identify the sound sources contributing to the recordings at CM2 in 2014 before the start of the Statoil 2014–2016 drilling program and in 2015 during the drilling program. Recordings made at Stn 19 2015–2016 provide contextual information, both during and after the drilling program. Stn 19 2016–2017 could not be analyzed for ambient sound levels as flow-induced noise at lower frequencies was near-constant. The flow-induced noise was caused by higher than anticipated currents speeds near the seabed.

The main sound contributors in the 2014–2016 data were seismic survey airgun pulses, fin whales and the *West Hercules* semi-submersible drill rig. This section provides an overview of the measured sound levels. Section 3.2 provides a summary of when vessels were detectable at CM2. Section 3.3 discusses the nature and occurrence of the seismic sounds detected at CM2, and Section 3.4 documents the detections of marine mammals.

Long-term spectral averages along with median band-level time series (Figure 10) provide an overview of the time and frequency evolution in the soundscape. In 2014, the soundscape at CM2 was dominated by a relatively close seismic survey. In 2015 CM2, recorded both the *West Hercules* drilling operations and a distant seismic survey. Stn 19 2015–2016 recorded seismic survey sounds until November 2015, and beginning again in June 2016. The winter period of 15 Nov 2015 to 1 Jun 2016 was representative of a normal ambient soundscape for this region, with the *West Hercules* being faintly detectable (Figure 10). Fin whale mating choruses were a dominant sound source in the band of 18–25 Hz from November to March, and they were detectable in September and October (Figure 10).

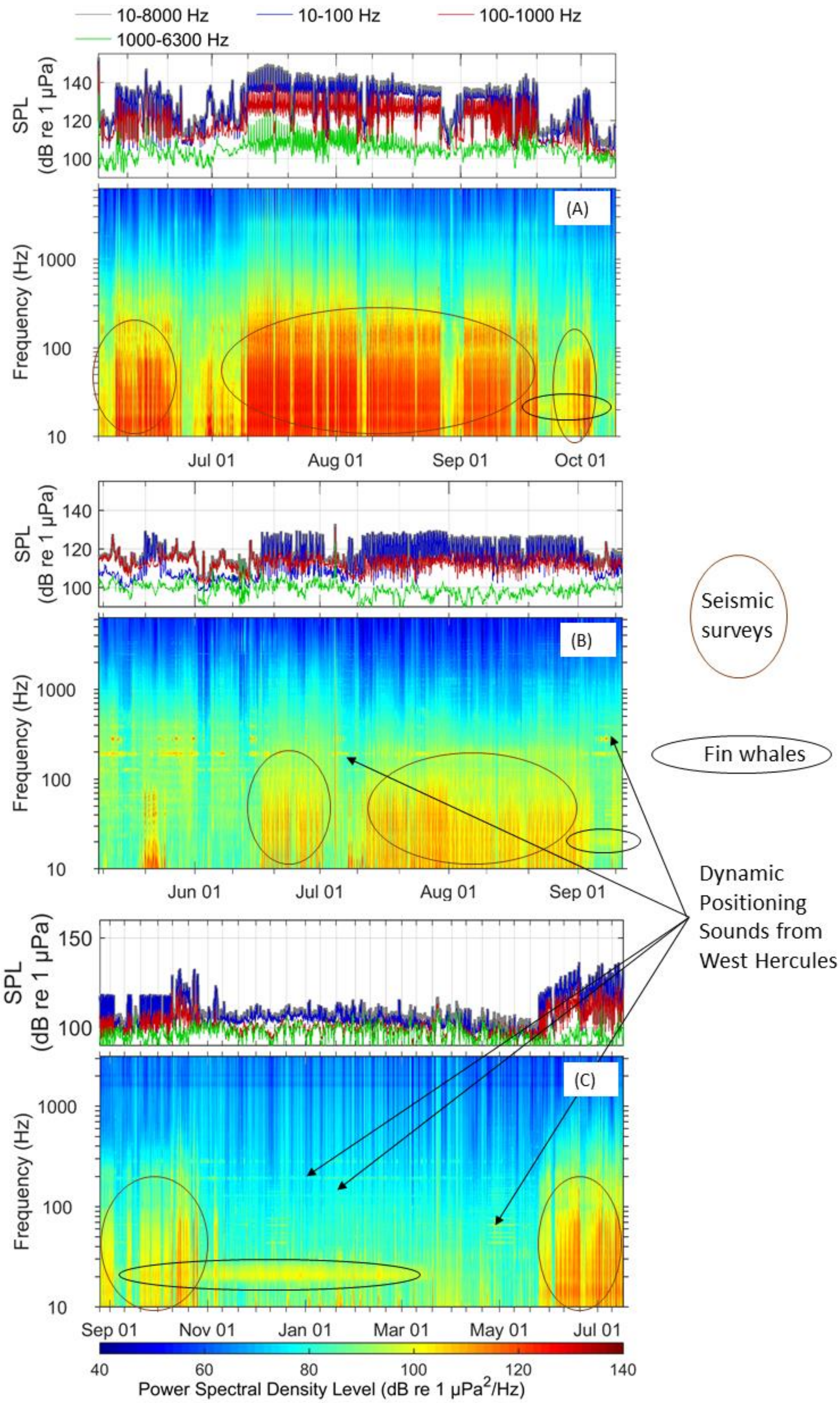

Figure 10. Summary of each recorder's acoustic data: (A) CM2 2014, (B) CM2 2015, and (C) Stn 19 2015–2016. For each station the top figure is the median hourly in-band SPL and bottom is the long-term spectral average of the measured sound. On the long-term spectral averages the sounds from seismic surveys, fin whales and the *West Hercules* are annotated.

Band-level box and whisker plots provide a statistical representation of the magnitude of the sound levels recorded (Figure 11). The maximum and minimum broadband SPL measured in 2014 were 165.8 and 104.9 dB re 1 µPa, respectively, and 148.3 and 102.4 dB re 1 µPa in 2015. At Stn 19 2015–2016 the values were 139.5 and 90.5 (Figure 11). The median SPL at Stn 19 2015–2016 of 107.5 dB re 1 µPa is representative of the level measured in most northern deep water ocean locations far from shipping lanes and industrial activity. The seismic survey increased the median levels measured at CM2 to 130 dB re 1 µPa in 2014 and 117 dB re 1 µPa in 2015 (a 10 dB increase in SPL is 10 times louder). In all cases the 10–100 Hz band contained the most energy. This is the band associated with seismic surveys and large shipping. In the winter, it is also associated with fin whale mating choruses.

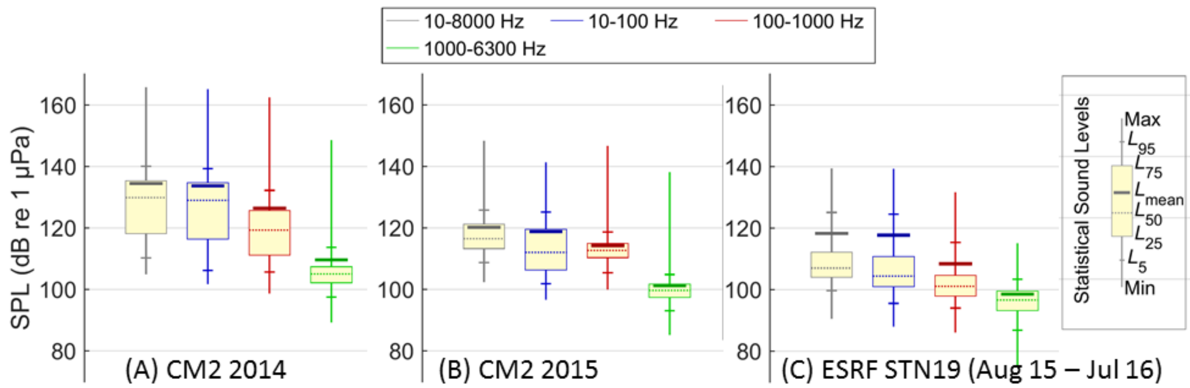

Figure 11. Comparison of the broadband and decade band 1-minute sound pressure levels for (A) CM2 2014, (B) CM2 2015, and (C) Stn 19 2015–2016.

Power spectral density and 1/3-octave-band distribution plots (Figure 12) can be directly compared to the Wenz plots (Figure 1) and provide more detailed spectral distribution information than the long-term spectral averages and box-and-whisker plots. In 2014, noise from seismic activity caused the noise between 30 to 250 Hz to exceed the expected limits of prevailing noise for the L_{75} percentile curve, or for 75% of the time (Figure 12). The maximum sound levels were measured during a period of seismic activity. Similarly in 2015, anthropogenic noise between 40–250 Hz L_{50} exceeded expected limits of prevailing noise (Figure 12) (Wenz 1962). These noise levels were likely caused by the thrusters of the drill rig *West Hercules* (see Section 4.1).

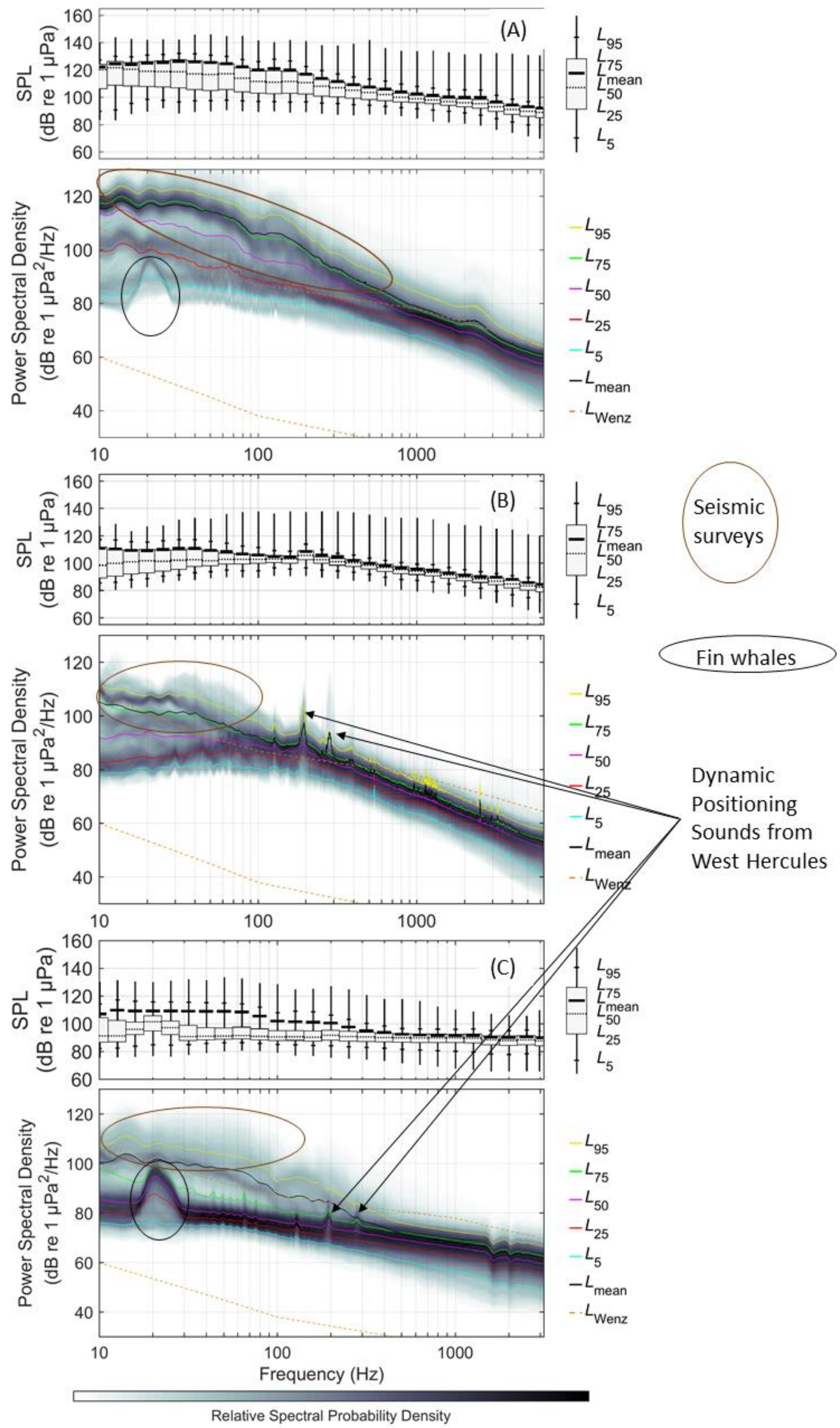

Figure 12. Summary of spectral content of each recorder's acoustic data. (A) CM2 2014, (B) CM2 2015, and (C) Stn 19 2015–2016. For each station the top figure shows a box-and-whisker plot for the 1/3-octave-band SPLs, and bottom shows the power spectral density percentiles and probability density (grayscale) of 1-min PSD levels compared to the limits of prevailing noise (Wenz 1962). The signatures of seismic surveys, fin whales and the *West Hercules* are annotated.

The daily sound exposure level integrates the total sound energy at a receiver location and is believed to be a good predictor of possible temporary threshold shifts in marine life hearing if it is high enough (NMFS 2016). Noise associated with a seismic survey was the main contributor to the daily SEL in 2014, which was up to 35 dB higher than daily SEL recorded at Stn 19 2015–2016 in the absence of seismic surveys (Figure 13). At CM2 in 2015, seismic surveys and vessel noise were the main contributors to the daily SEL, which was 10–15 dB higher than the levels measured at Stn 19 2015–2016 without seismic surveys (Figure 13). The daily SEL associated with seismic surveys in 2015 and 2016 were higher at Stn 19 than what was recorded at CM2. The daily SEL at Stn 19 2015–2016 rose in winter due to both fin whale songs and increased wind and wave activity (Figures 13 and 12).

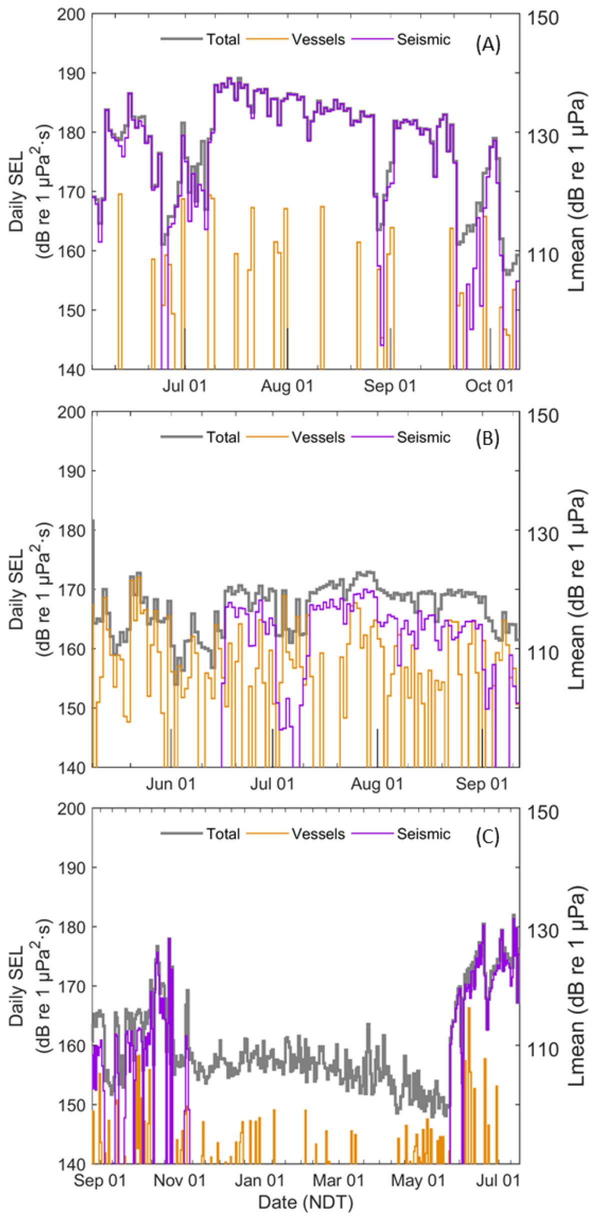

Figure 13. Total, vessel, and seismic-associated daily SEL and equivalent continuous noise levels (L_{mean}). (A) CM2 2014, (B) CM2 2015 and (C) Stn 19 2015–2016. The detectors described in Appendices A.2 and A.3 were used to identify the periods when seismic surveys and vessel were the dominant sound sources. In 2015, there were multiple simultaneous surveys which are difficult for the detector to properly distinguish, leading to less energy assigned to the seismic source than was actually in the water.

3.2. Vessel Detections

Vessels were detected using the automated detection algorithm described in Appendix A.2. Vessel detections denote closest points of approach (CPA) to the recorder, by hour (Figures 14 and 15). The second year of the study had the most vessel detections, which agrees with the known presence of the vessels supporting the Statoil 2014–2016 drilling program (Figure 15). Note that the shipping detector does not detect the constant energy from the drill rig thrusters.

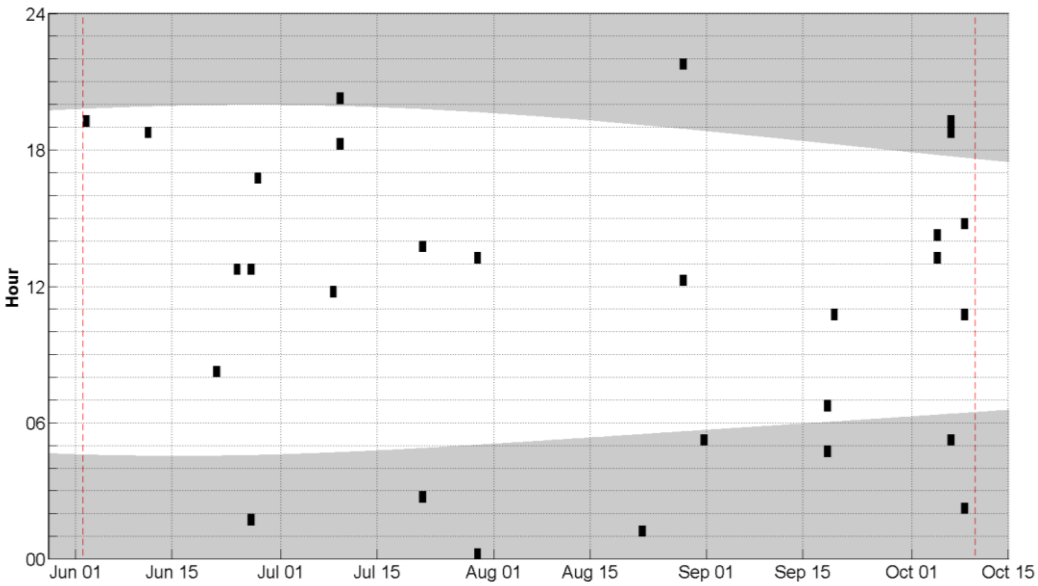

Figure 14. Vessel detections each hour (vertical axis) compared to date (horizontal axis) in the Flemish Pass from 2 Jun to 9 Oct 2014 on CM2. Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates.

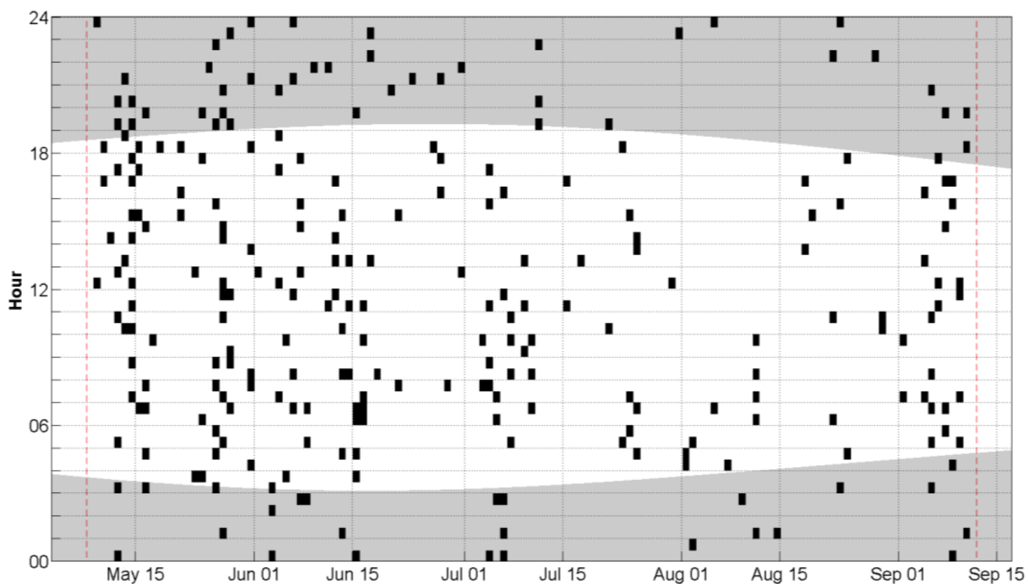

Figure 15. Vessel detections each hour (vertical axis) compared to date (horizontal axis) in the Flemish Pass from 9 May to 11 Sep 2015 on CM2. Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates.

3.3. Seismic Survey Sounds

Seismic survey sounds were detected using the automated detection algorithm described in Appendix A.3. In 2014, seismic noise was the main contributor to the total SEL, and this year had more hours with seismic detections (Figure 16) compared to the distant seismic detected in 2015 (Figure 17). At Stn 19 seismic detections occurred from the start of recording in July to November 2015, May to October 2016, and June 2017 to the end of recording (Figure 18). Figures 12 and 13 show the effects of the seismic surveys on the mean daily SPL and power spectral densities. Seismic surveys contributed the most energy to the soundscape from June to October in both of the Stn 19 data sets.

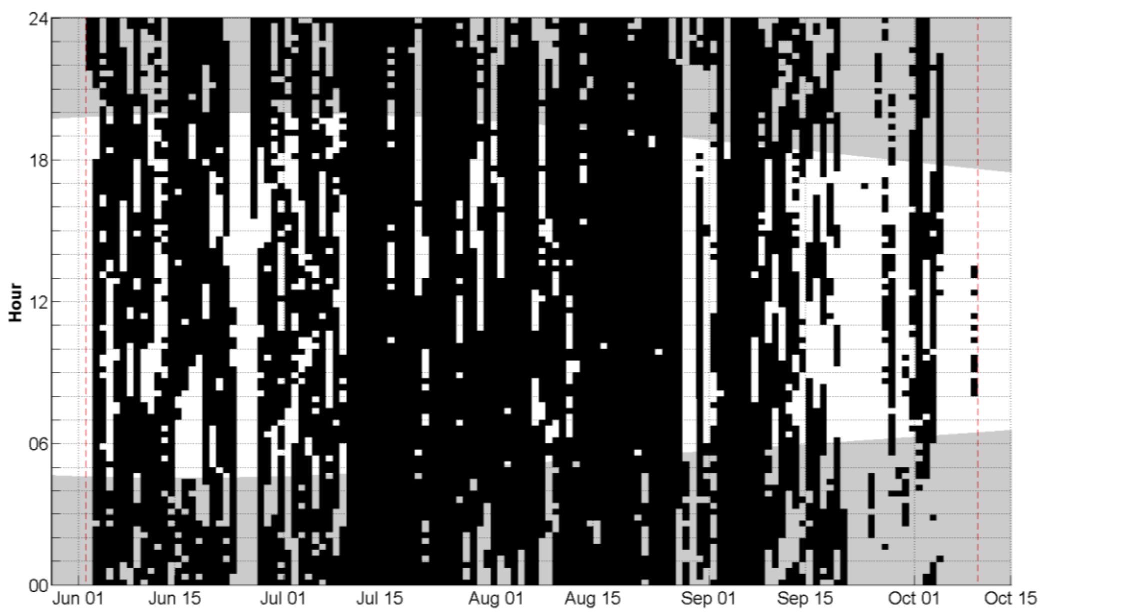

Figure 16. Seismic detections each hour (vertical axis) versus date (horizontal axis) in the Flemish Pass from 2 Jun to 9 Oct 2014. Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates.

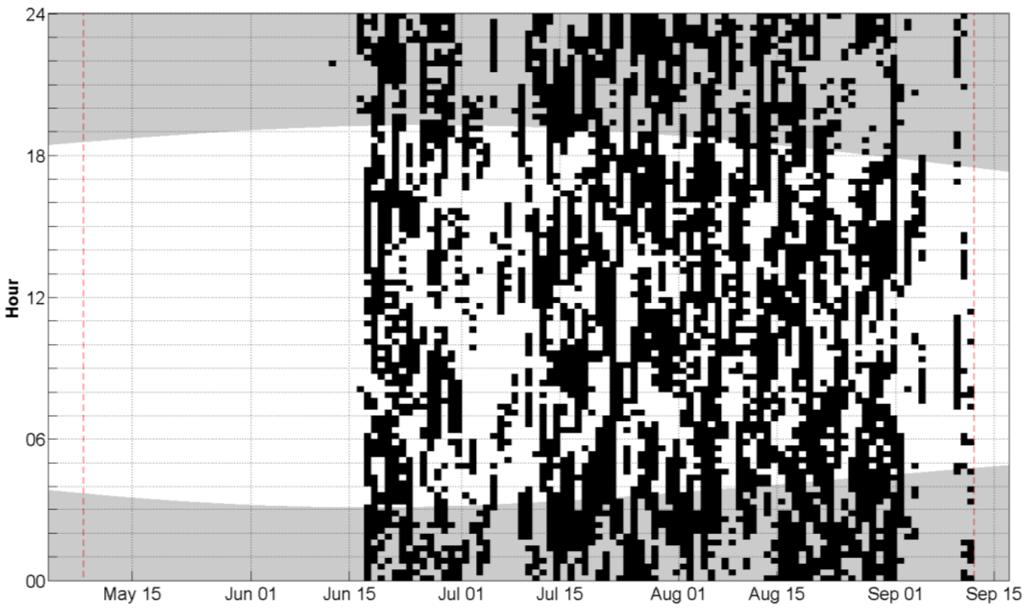

Figure 17. Seismic detections each hour (vertical axis) versus date (horizontal axis) in the Flemish Pass from 9 May to 11 Sep 2015. Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates.

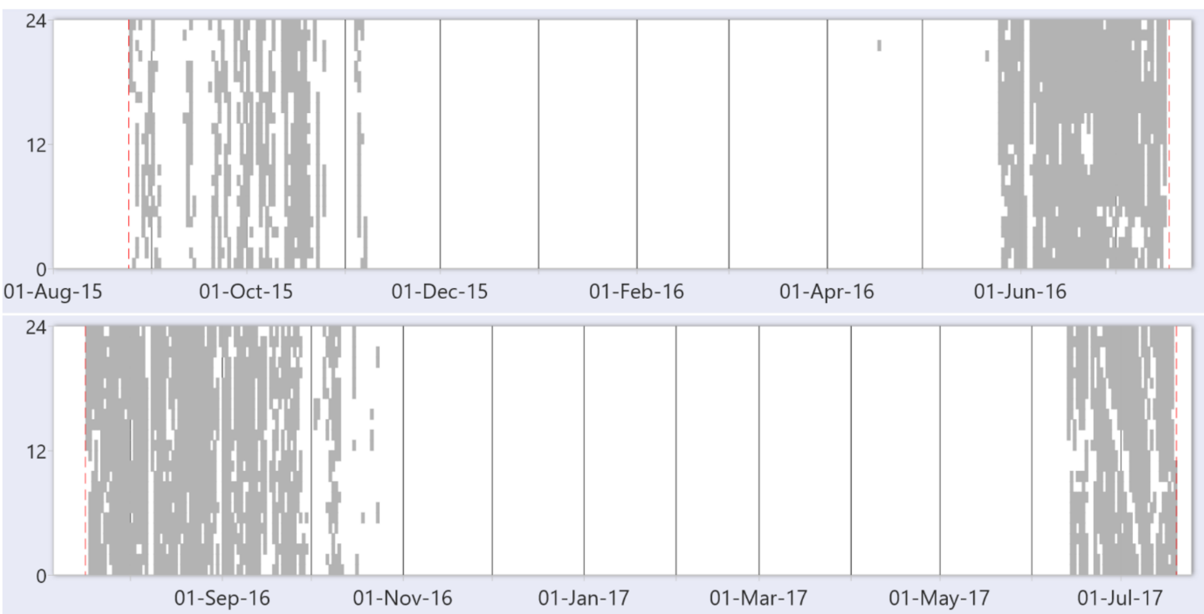

Figure 18 Seismic detections each hour (vertical axis) versus date (horizontal axis) at Stn 19 in 2015-2016 (top) and 2016-2017 (bottom). Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates.

Propagation of airgun signals in deep waters is highly complex, with different frequencies contributing to the received energy at different ranges and depths. Small changes in the range of the source, the sound speed profile, or the source or receiver depth significantly change the sound levels (Figures 19 and 20). Typical 2-D and 3-D seismic survey generate one impulse every 10–12 seconds. The multiple impulsive arrivals shown in Figures 19 and 20 are the result of the sound reflecting off the seabed and sea surface multiple times in deeper waters. This number of multipath arrivals increases with distance between the source and receiver. In the case of Figure 20, the arrivals continue for 8 seconds, a pattern JASCO has previously observed in waters 800 m deep off Greenland (Martin et al. 2017). The multipath arrivals tend to have lower amplitudes in deeper waters and for environments with softer bottoms.

Notably in 2015, seismic noise was distant, and an example of multiple seismic surveys displaying close and distant seismic noise source is shown in Figure 21.

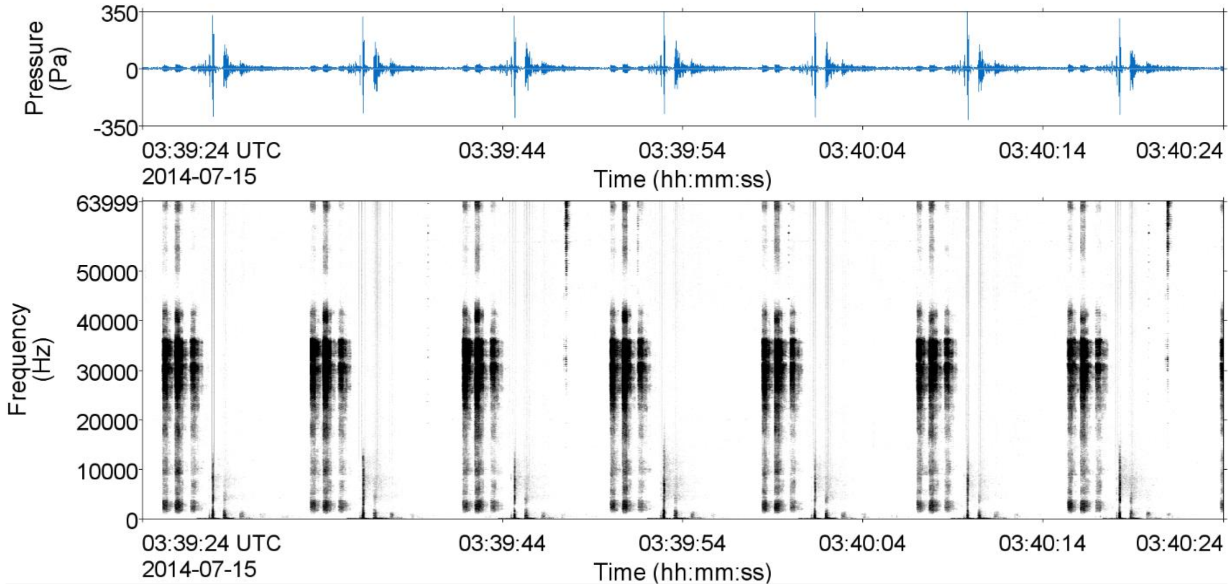

Figure 19. (Top) Pressure signature and (bottom) spectrogram of multibeam seismic pulses from an airgun array on 15 Jul 2014 (2 Hz frequency resolution, 0.128 s frame size, 0.032 s time step, and Hamming window).

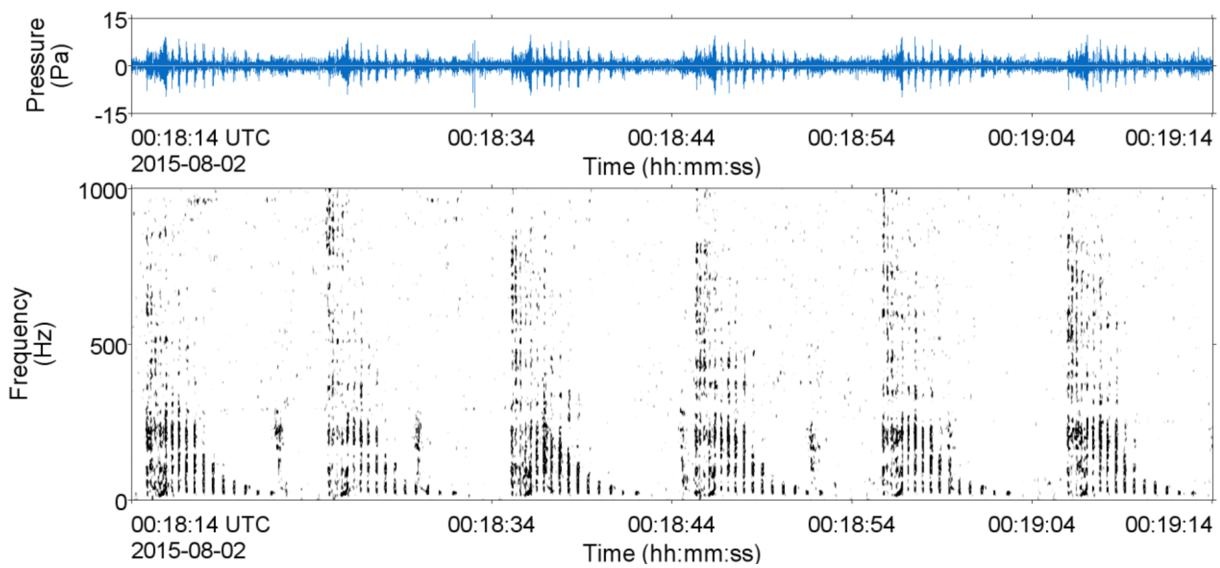

Figure 20. (Top) Pressure signature and (bottom) spectrogram of seismic pulses from an airgun array on 2 Aug 2015 (2 Hz frequency resolution, 0.128 s frame size, 0.032 s time step, and Hamming window).

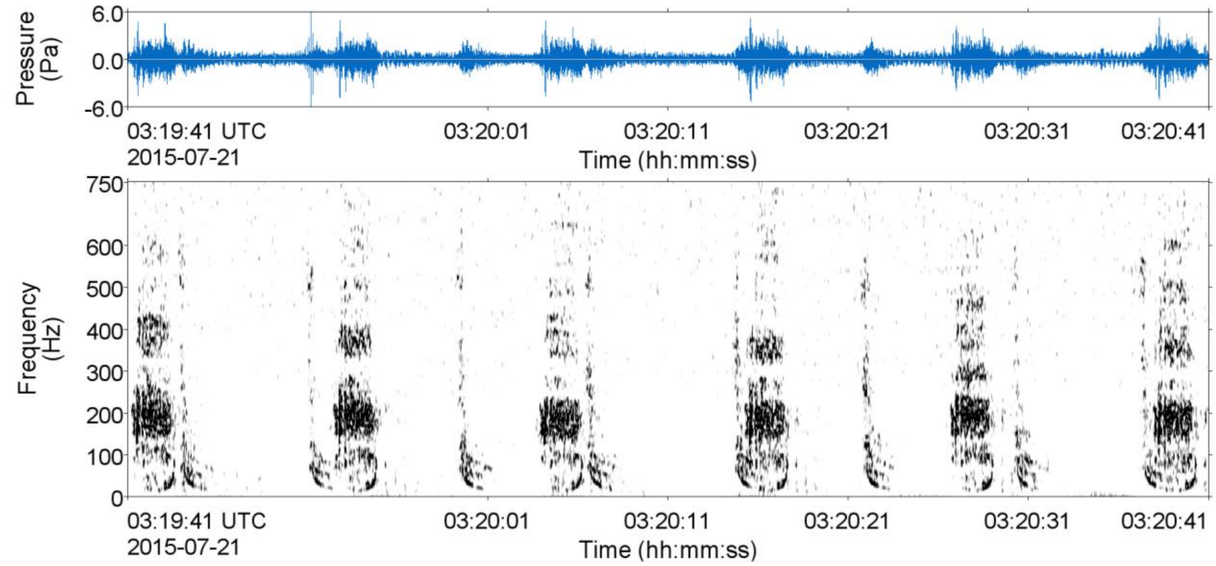

Figure 21. (Top) Pressure signature and (bottom) spectrogram of two seismic surveys on 21 Jul 2015 (2 Hz frequency resolution, 0.128 s frame size, 0.032 s time step, and Hamming window).

3.4. Marine Mammals

3.4.1. CM2 Flemish Pass 2014–2015

The acoustic presence of marine mammals in the Flemish pass in 2014 and 2015 (CM2 recorder) was identified automatically by JASCO's detectors (Appenidx A.4.3), and 5% of the acoustic data was verified by the manual analysis. Detectors and analysts found the 63 kHz acoustic recordings contained sounds from blue, fin, long-finned pilot, northern bottlenose, and sperm whales, as well as dolphins.

3.4.1.1. Detector Performance

Detector performance varied across species and call types. Except for northern bottlenose whale clicks, pilot whale whistles, and blue whale moans, the detector precision was generally high. It ranged from 0.80 (for sperm whales) to 1 (for fin whales), indicating that 80 to 100% of files containing calls were correctly detected and classified (Table 5). The lower the precision value, the higher the proportion of non-target signals included in the results. The poor precision for the blue whale moan, pilot whale whistle, and northern bottlenose whale click detectors can be attributed to interfering noises consistently falsely triggering the detectors. For pilot whales, false detections were triggered by airgun sounds, vessel noise, and other delphinid whistles. For sperm and northern bottlenose whales, false detections were triggered by airgun sounds, vessel noise (particularly echosounders), and loud delphinid clicks.

Manual validation indicated that detection thresholds were needed for all species identified, except for unknown dolphin/pilot whale clicks (Table 5). These thresholds raised the precision, but lowered the recall values of the detectors. Except for the moderately high-performing dolphin whistle (R = 0.69) and click (R = 0.68) detectors, detector recall values were low to moderate, ranging from 0.13 for fin whales to 0.54 for sperm whales (Table 5). The consistently lower R than P in our detectors reflects the bias of our analysis protocol in favour of precision over recall. A low recall may translate into missing detection events, defined as a string of consecutive files (one or more) with detections of a given species, completely, or missing some files within a detection event. The ultimate effect of a low recall is likely a combination of both scenarios, although the relative contribution of each will depend on species, season, and interfering sound sources at a location. When the primary measure of interest is daily presence of a species, detectors with high precision and lower recall generally provide accurate results with low false alarms.

To compare results across years, the detection count thresholds were calculated using validated detections from both 2014 and 2015. For northern bottlenose, pilot, fin, and blue whales, the manual (rather than the automated) detections are presented in the following sections.

Table 5. Classification thresholds determined from validating the automated detector outputs. The classification thresholds are the minimum number of detected calls/file required to be confident in that detections are not false alarms. The precision (P), recall (R), and F-score (F) before the threshold is applied (original) and after (threshold) is shown.

File analyzed	Species/call	$P_{original}$	$R_{original}$	Classification threshold	$P_{threshold}$	$R_{threshold}$	$F_{threshold}$
353 files at 2 min 128 ksps	Dolphin whistle	0.90	0.69	1	0.90	0.69	0.85
	Delphinid click	0.79	0.92	40	0.98	0.68	0.90
	Sperm whales	0.55	0.85	17	0.80	0.54	0.73

3.4.1.2. Odontocetes

3.4.1.2.1. Beaked Whales

The northern bottlenose whale detector was unreliable, as it was falsely triggered by dolphin clicks and high-frequency sperm whale clicks. Therefore, results from manual analysis are presented here and represent a minimum estimate of acoustic occurrence. Clicks classified as northern bottlenose whales had a centroid frequency between 25 and 30 kHz and a smooth upswept contour, ranging in frequency from 20–50 kHz (Figures 22 and 23) (Hooker and Whitehead 2002, Wahlberg et al. 2012).

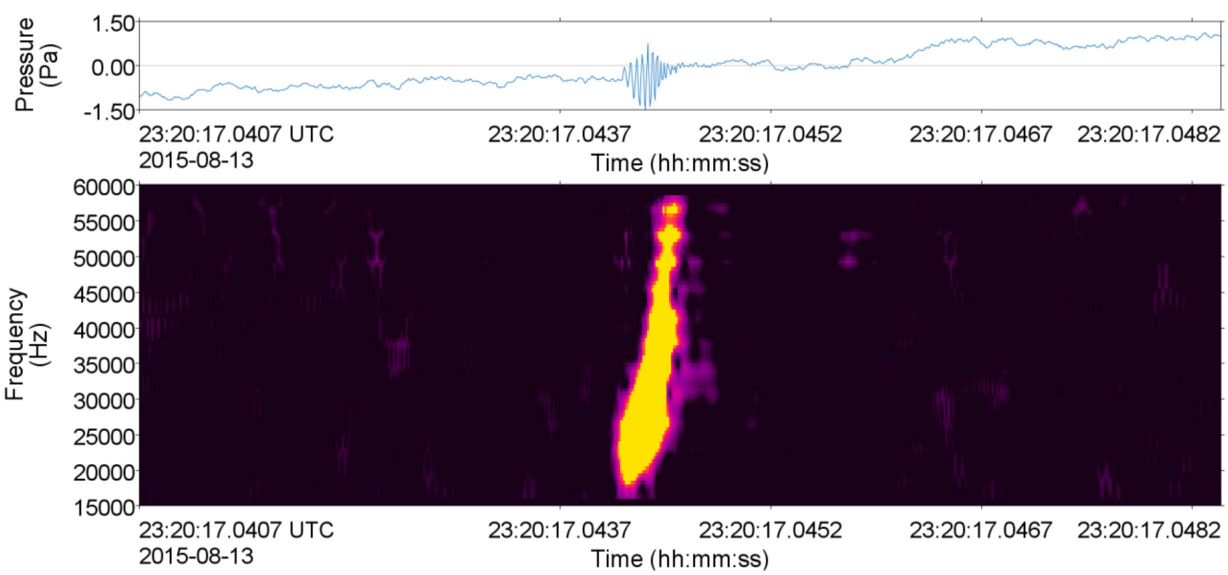

Figure 22. Spectrogram of a northern bottlenose whale click recorded on 13 Aug 2015 (512 Hz frequency resolution, 0.26 ms time window, 0.02 ms time step, Hamming window).

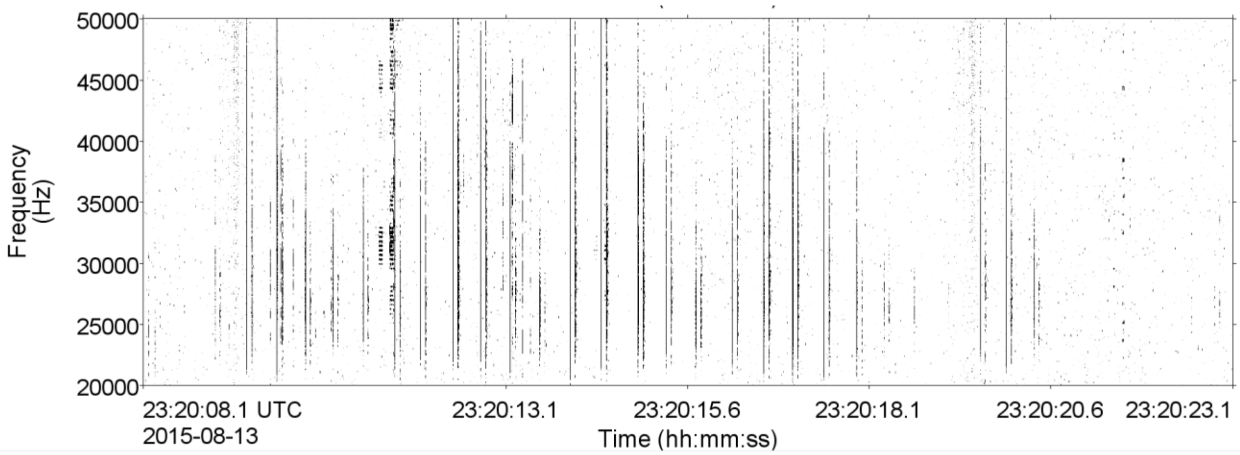

Figure 23. Spectrogram of northern bottlenose whale click trains recorded at 13 Aug 2015 (64 Hz frequency resolution, 0.01 s time window, 0.005 s time step, Hamming window). The window length is 15 s.

Northern bottlenose whale clicks were sporadic throughout the recording period in each year. In 2014, detections occurred from mid-June to mid-July. Additionally, there were detections on one day in mid-August and one in late September (Figure 24, Table 6). In 2015, Two detections occurred in June, while 9 days in July contained northern. Detections also occurred on 4–5 days in August and September (Figure 25, Table 6).

Table 6. Northern bottlenose whales: Summary of manually validated acoustic detections.

Year	Deployment	First detection	Last detection	Record end	Number of days with manual detections
2014	2 Jun	12 Jun	26 Sep	9 Oct	9
2015	9 May	9 Jun	8 Sep	11 Sep	19

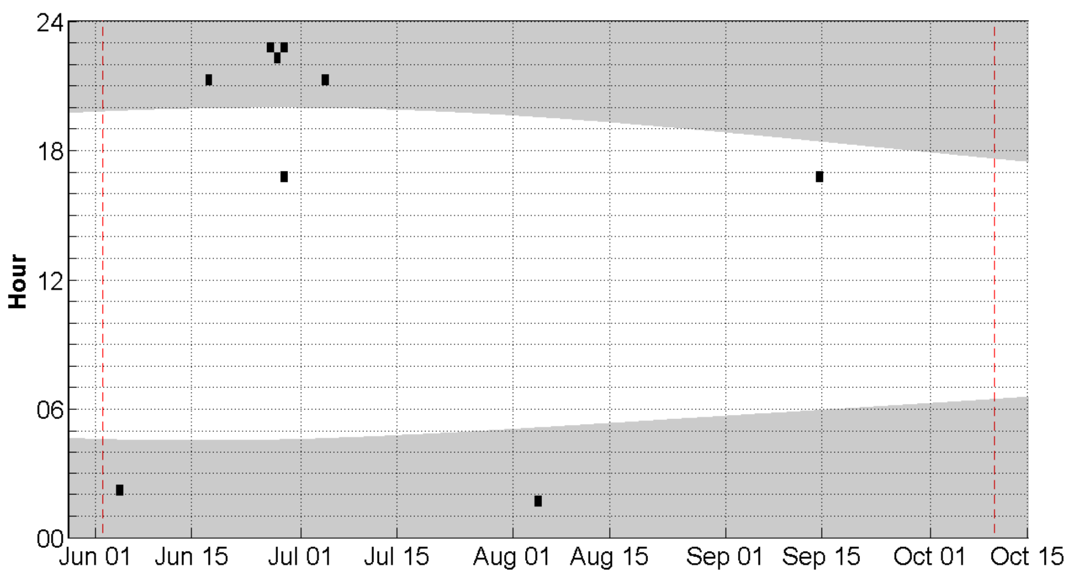

Figure 24. Manual validation of daily and hourly occurrence of northern bottlenose whale clicks recorded in the Flemish Pass from 2 Jun to 9 Oct 2014. Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates.

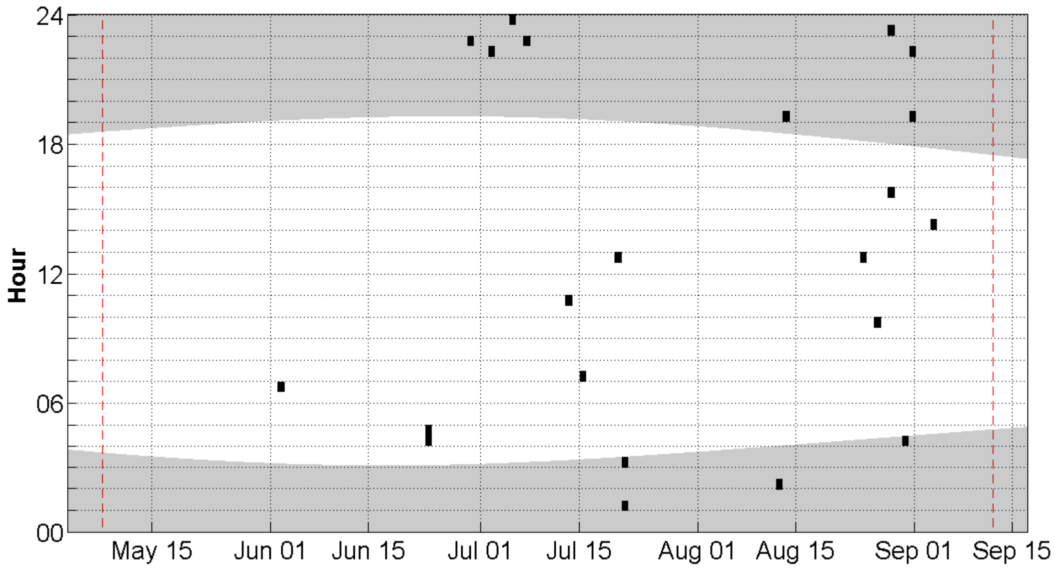

Figure 25. Manual validation of daily and hourly occurrence of northern bottlenose whale clicks recorded in the Flemish Pass from 9 May to 11 Sep 2015. Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates.

3.4.1.2.2. Delphinids

Unlike most odontocetes that are only known to produce clicks, delphinids produce both impulsive (click) and tonal (whistle) sounds that show less species-level specificity than other marine mammal signals and are therefore more difficult to distinguish acoustically. Here, we present results for pilot whales and unidentified dolphins, species groups that can be confidently distinguished based on their tonal signals (Steiner 1981, Rendell et al. 1999). The tonal calls of pilot whales have energy at frequencies as low as 1.0 kHz and whistles with acoustic energy concentrated below 5–6 kHz. The main energy in tonal calls of unidentified dolphins is greater than 6 kHz. Because of the overlap in spectral features of tonal signals from the different dolphin species expected in the study area (Steiner 1981) and the expected but unquantified variability of these signals around the few described call types, we were unable to distinguish dolphin calls by species in most cases.

Delphinid clicks show even less species-uniqueness than tonal signals, partially because of their directionality and the associated degradation of their spectral features when recorded at increasing angles away from the longitudinal axis of the calling animal. The following subsections present pilot whale and dolphin whistle detections, as well as delphinid click detections.

3.4.1.2.3. Pilot Whales

Pilot whale whistles (Figure 26) were distinguished from dolphin whistles based frequency. Detections generally occurred during summer, June to September (Figures 27 and 28). Pilot whale calls were sparsely detected on 10% of the recording days in 2014, and increased to 15% in 2015 (Table 7). The pilot whale detector had a low recall of 32%, reflecting the ability of manual analysts to identify whistles too faint for the automated detector (Table 5). Thus, the results presented here are the manually validated pilot whale whistles.

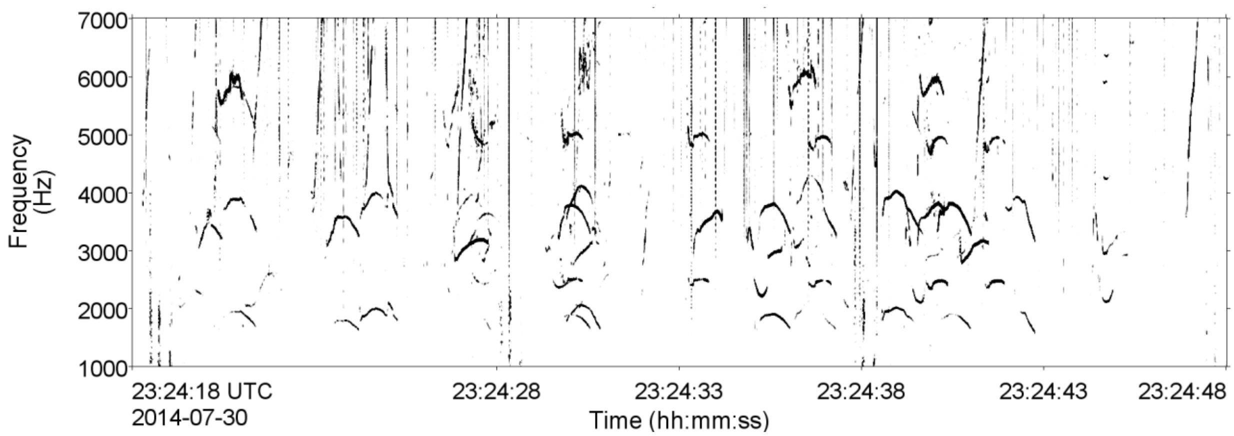

Figure 26. Spectrogram of pilot whale whistles recorded on 30 Jul 2014 (4 Hz frequency resolution, 0.05 s time window, 0.01 s time step, Hamming window). The window length is 30 s.

Table 7. Pilot whales: Summary of manually validated acoustic detections.

Year	Deployment	First detection	Last detection	Record end	Number of days with manual detections
2014	2 Jun	3 Jun	7 Oct	9 Oct	13
2015	9 May	14 May	3 Sep	11 Sep	19

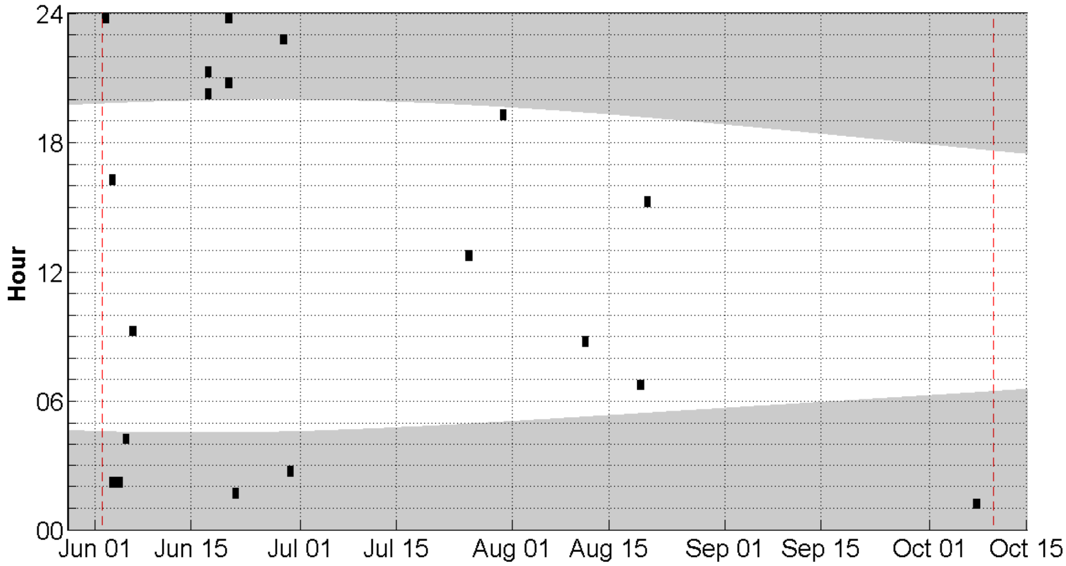

Figure 27. Manual validation of daily and hourly occurrence of pilot whale whistles recorded in the Flemish Pass from 2 Jun to 9 Oct 2014. Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates.

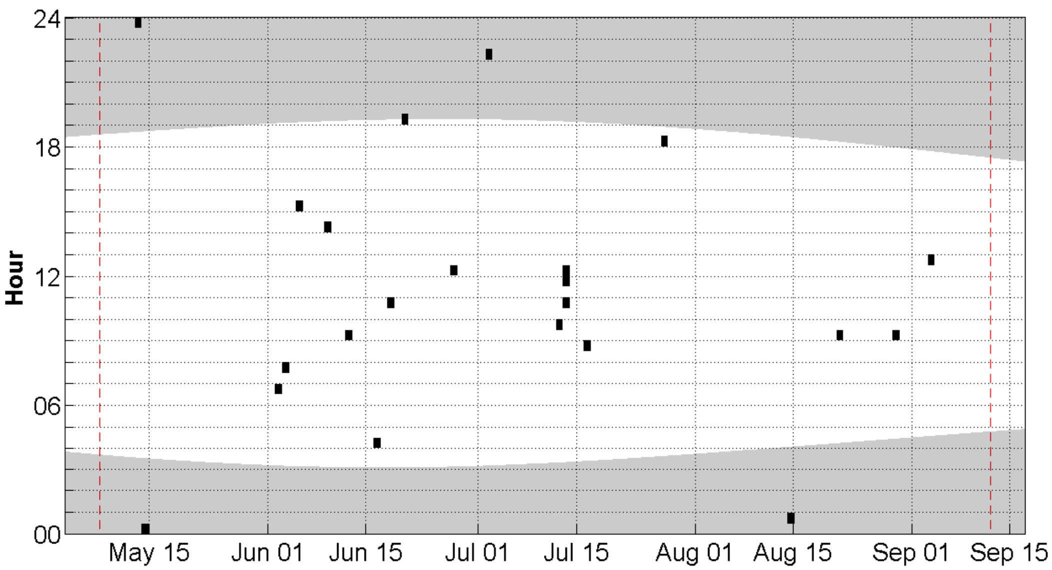

Figure 28. Manual validation of daily and hourly occurrence of pilot whale whistles recorded in the Flemish Pass from 9 May to 11 Sep 2015. Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates.

Small Dolphins

The detector performed well for small dolphin whistles (Figure 29) and delphinid clicks (Figures 30 and 31, Table 5). Ninety percent of whistle detections and almost 100% of click detections presented here are accurately classified. The whistle results likely include other acoustic signals, such a high-frequency components of pilot whale whistles.

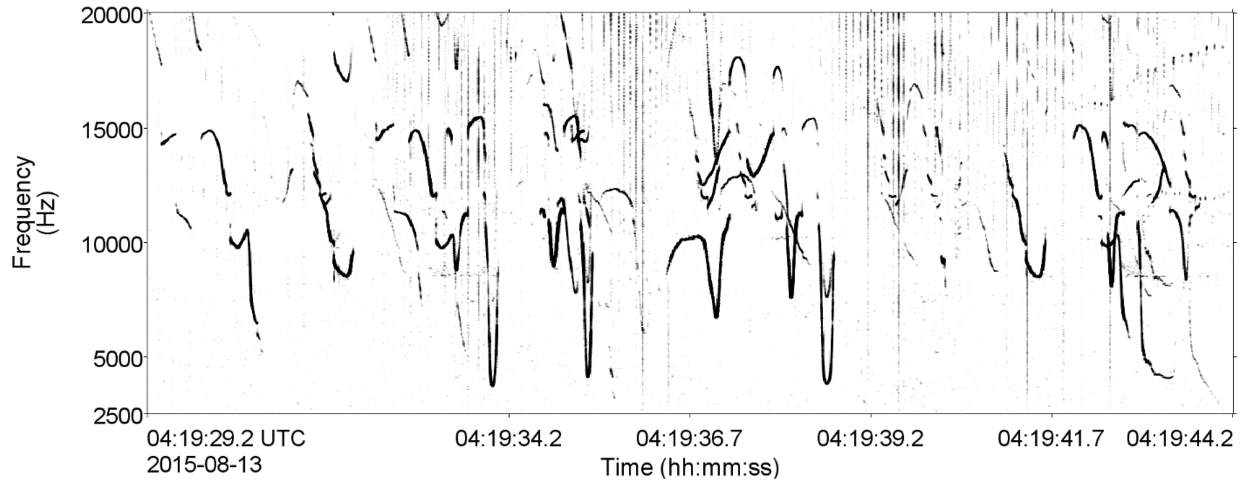

Figure 29. Spectrogram of unidentified dolphin whistles recorded on 13 Aug 2015 (4 Hz frequency resolution, 0.05 s time window, 0.01 s time step, Hamming window). The window length is 15 s.

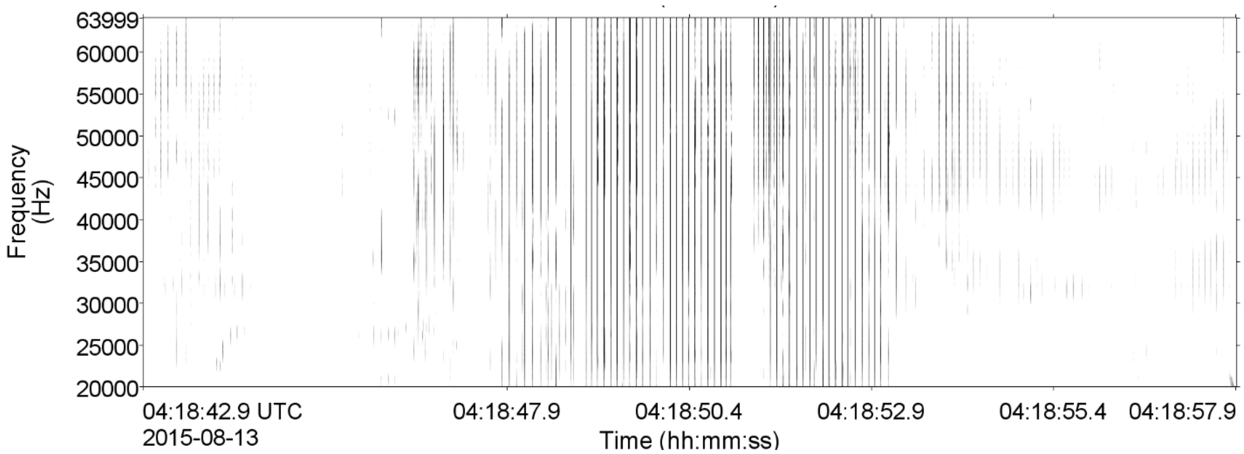

Figure 30. Spectrogram of unidentified dolphin click trains recorded on 13 Aug 2016 (128 Hz frequency resolution, 0.001 s time window, 0.0005 s time step, Hamming window). The window length is 15 s.

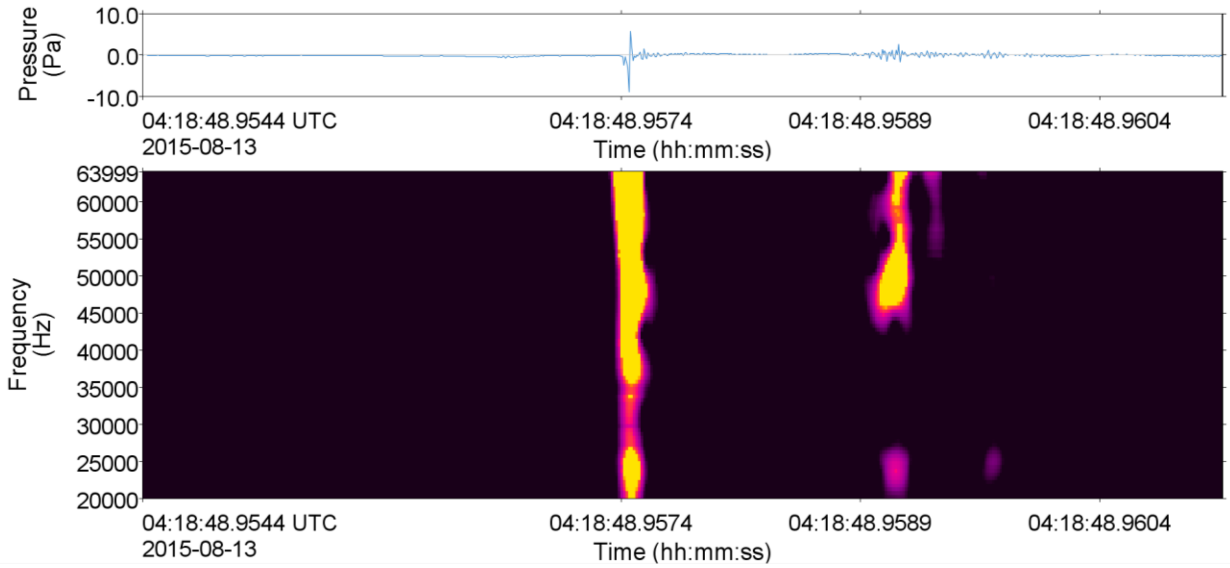

Figure 31. Spectrogram of unidentified dolphin click recorded on 29 Jun 2014 (512 Hz frequency resolution, 0.26 ms time window, 0.02 ms time step, Hamming window).

Clicks and whistles produced by delphinids occurred on ~30% of the recording days (Tables 8 and 9). The number of click detections in 2014 was almost double that of 2015 (Table 8). The opposite is true for whistles detected, as the number of detections in 2015 almost doubles those detected in 2014 (Table 9). Unlike dolphin whistles that were detected evenly throughout the 24-hour day (Figures 32 and33), delphinid clicks showed a diel pattern, occurring more often during hours of darkness than during hours of daylight (Figures 34 and 35).

Table 8. Delphinid clicks: Summary of automated acoustic detections.

Year	Deployment	First detection	Last detection	Record end	Number of days with manual detections	Number of detections
2014	2 Jun	12 Jun	9 Oct	9 Oct	50	40,852
2015	9 May	9 Jun	10 Sep	11 Sep	36	26,268

Table 9. Dolphin whistles: Summary of automated acoustic detections.

Year	Deployment	First detection	Last detection	Record end	Number of days with manual detections	Number of detections
2014	2 Jun	3 Jun	9 Oct	9 Oct	50	1,598
2015	9 May	14 May	10 Sep	11 Sep	40	2,460

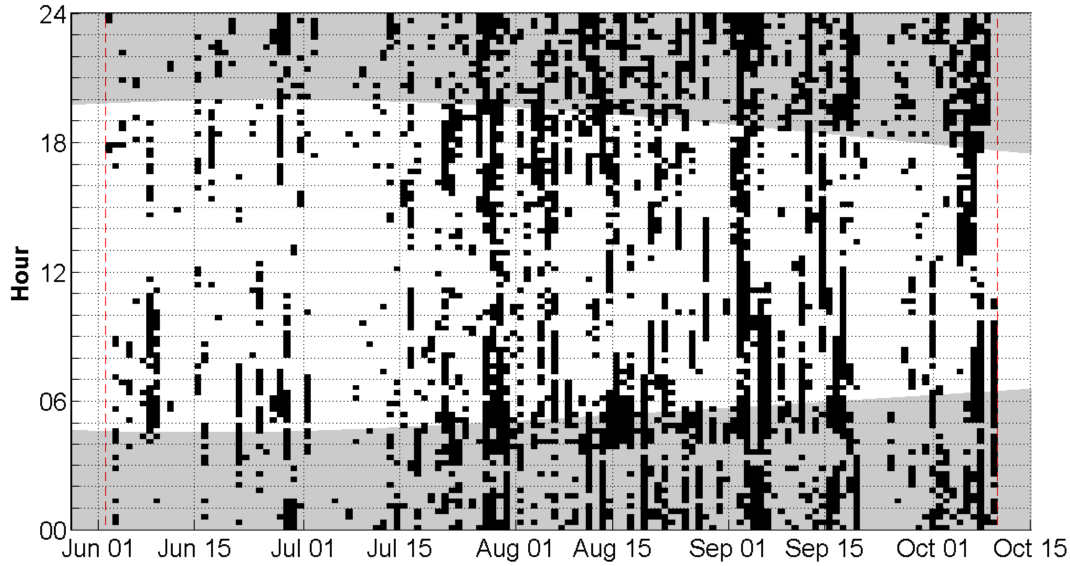

Figure 32. Daily and hourly occurrence of dolphin whistles recorded in the Flemish Pass from 2 Jun to 9 Oct 2014. Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates.

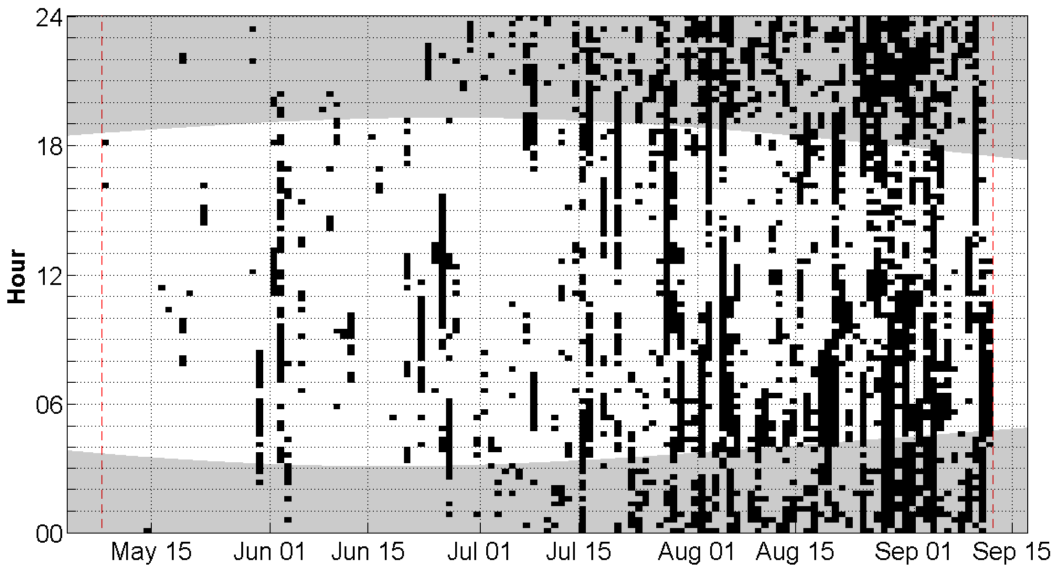

Figure 33. Daily and hourly occurrence of dolphin whistles recorded in the Flemish Pass from 9 May to 11 Sep 2015. Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates.

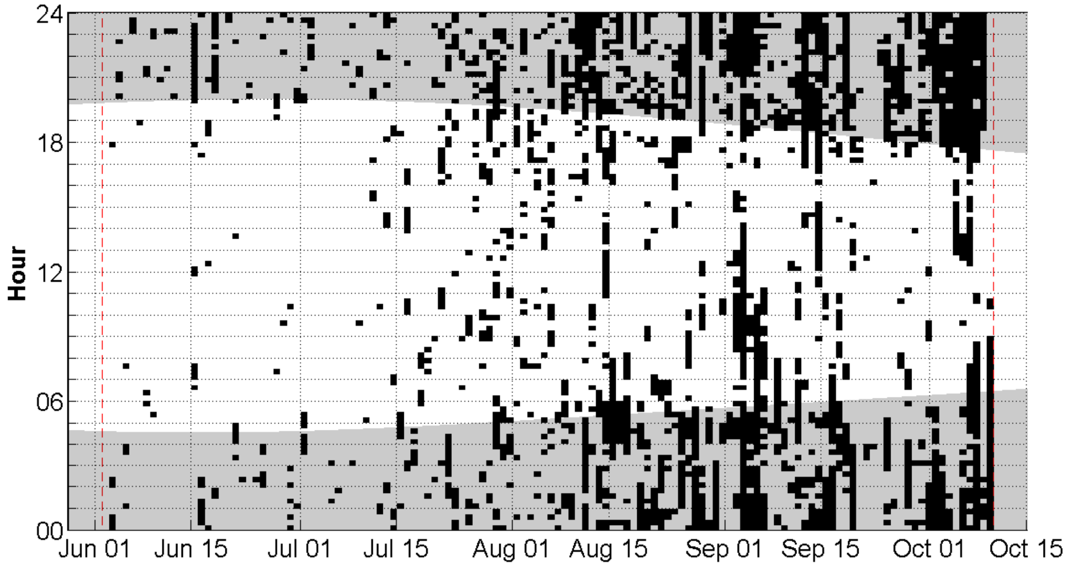

Figure 34. Daily and hourly occurrence of dolphin clicks recorded in the Flemish Pass from 2 Jun to 9 Oct 2014. Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates.

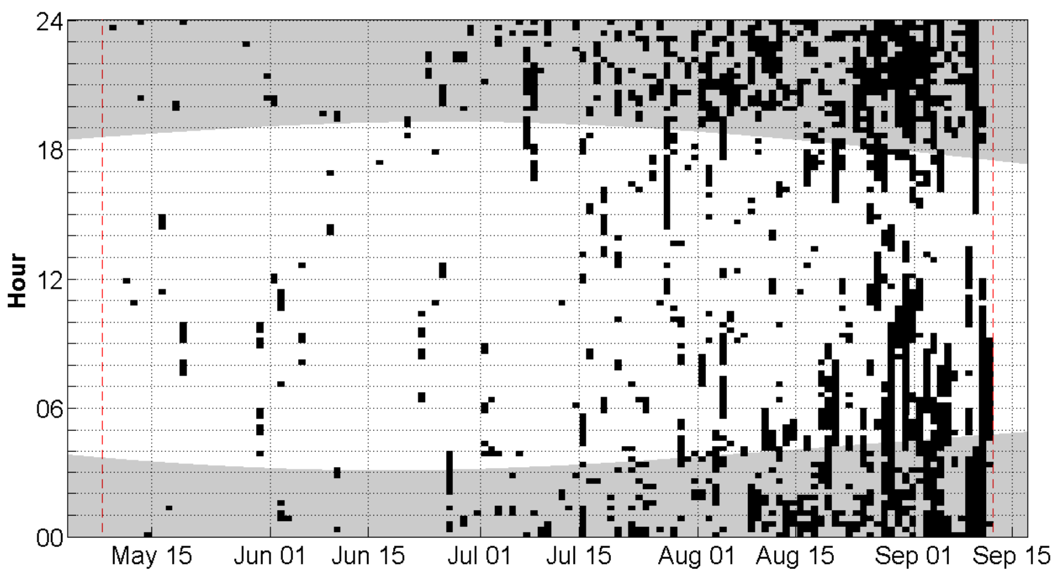

Figure 35. Daily and hourly occurrence of dolphin clicks recorded in the Flemish Pass from 9 May to 11 Sep 2015. Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates.

3.4.1.2.4. Sperm Whales

Sperm whale clicks (Figure 36) were detected consistently throughout the study period in both years (Table 10, Figures 37 and 38). Sperm whale detections were expected in the deep waters of the Flemish Pass along the shelf break. Sperm whale clicks were accurately classified (P = 80%), but the results underestimate the true presence of the species, as the detector missed over 50% of clicks. This could be the result of the high-frequency targeted by the detector (centre frequency ≥8 kHz), whereas most clicks were faint (<8 kHz) or masked by anthropogenic noise.

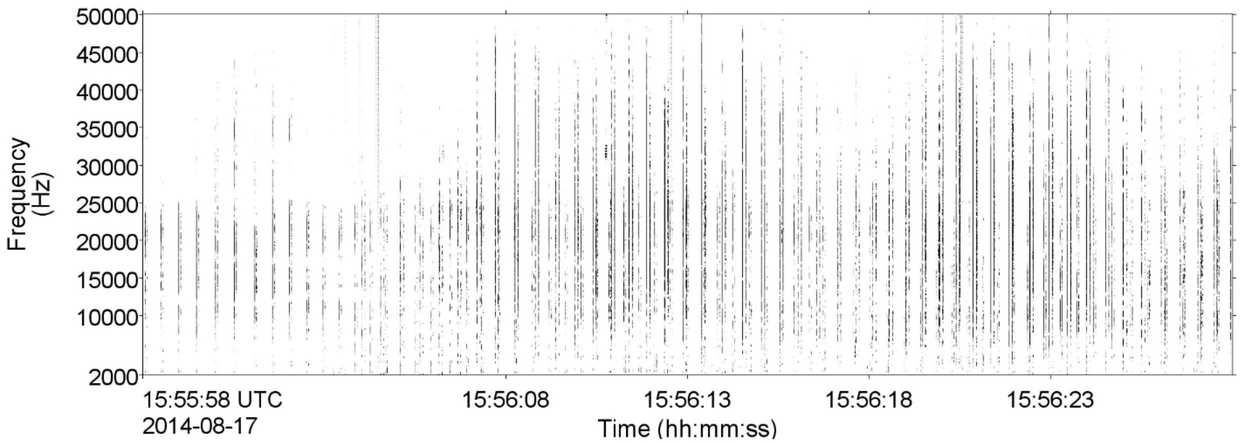

Figure 36. Spectrogram of sperm whale clicks recorded on 17 Aug 2014 (64 Hz frequency resolution, 0.01 s time window, 0.005 s time step, Hamming window). The window length is 30 s.

Table 10. Sperm whales: Summary of automated acoustic detections.

Year	Deployment	First detection	Last detection	Record end	Number of days with manual detections	Number of detections
2014	2 Jun	3 Jun	6 Oct	9 Oct	37	6,517
2015	9 May	9 May	10 Sep	11 Sep	37	6,089

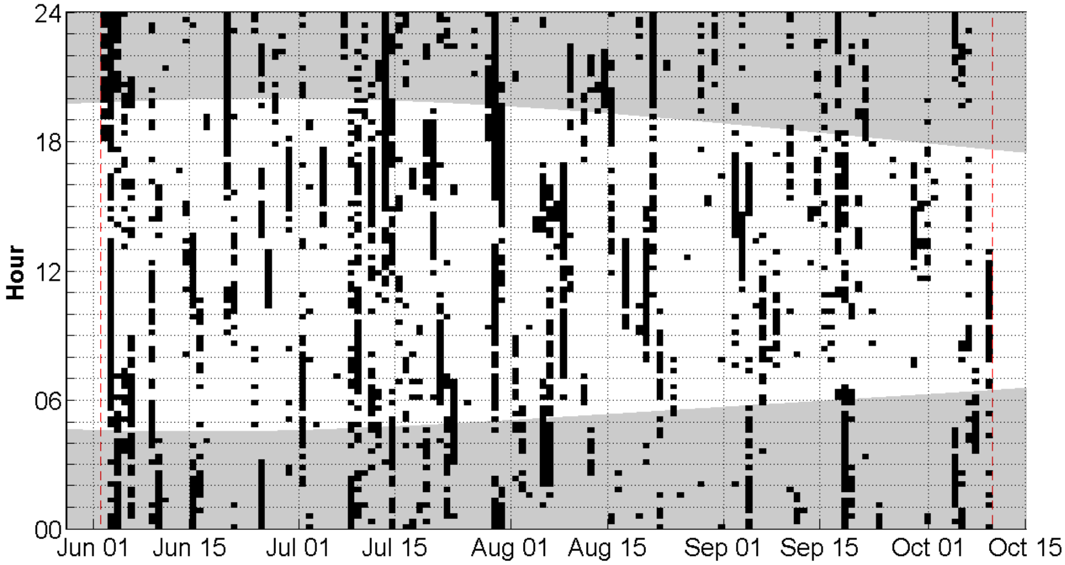

Figure 37. Daily and hourly occurrence of sperm whale clicks recorded in the Flemish Pass from 2 Jun to 9 Oct 2014. Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates.

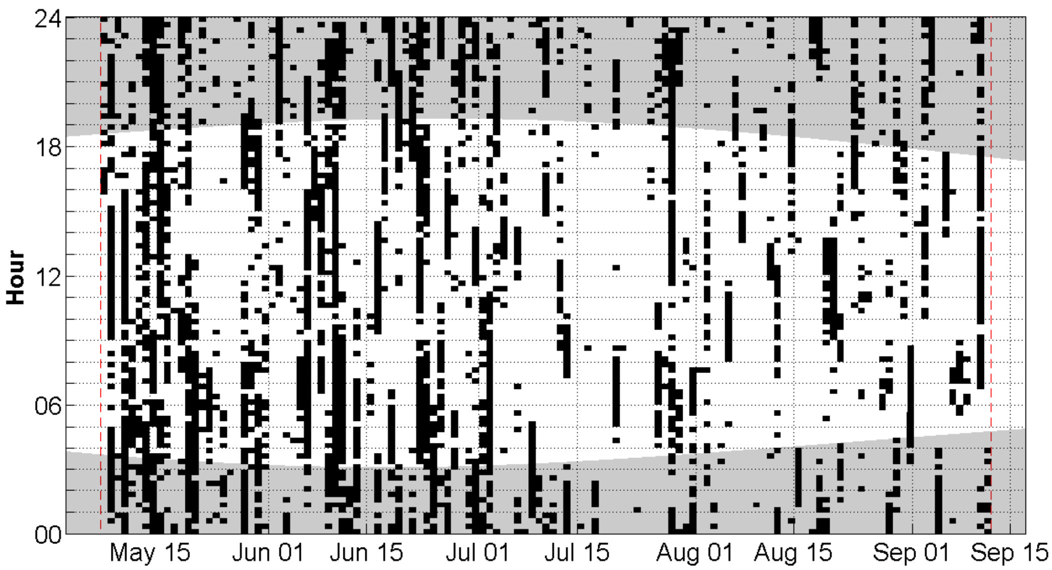

Figure 38. Daily and hourly occurrence of sperm wale clicks recorded in the Flemish Pass from 9 May to 11 Sep 2015. Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates.

3.4.1.3. Mysticetes

3.4.1.3.1. Blue Whales

Infrasonic blue whale calls were manually detected in the Flemish Pass in both years of the CM2 recordings (Figure 39) (Mellinger and Clark 2003). This call type is produced in late summer, fall, and winter. Calls were detected on 7 Aug and 2 Oct 2014 (Table 11). While most automated detections occurred in mid-May through mid-June during the 2015 deployment, none of these calls were validated as truly produced by blue whales. Seismic and vessel noise triggered the detector; thus, only manual validated results are presented here. Validated detections occurred on 2 Sep and ended 10 Sep 2015 (Table 11).

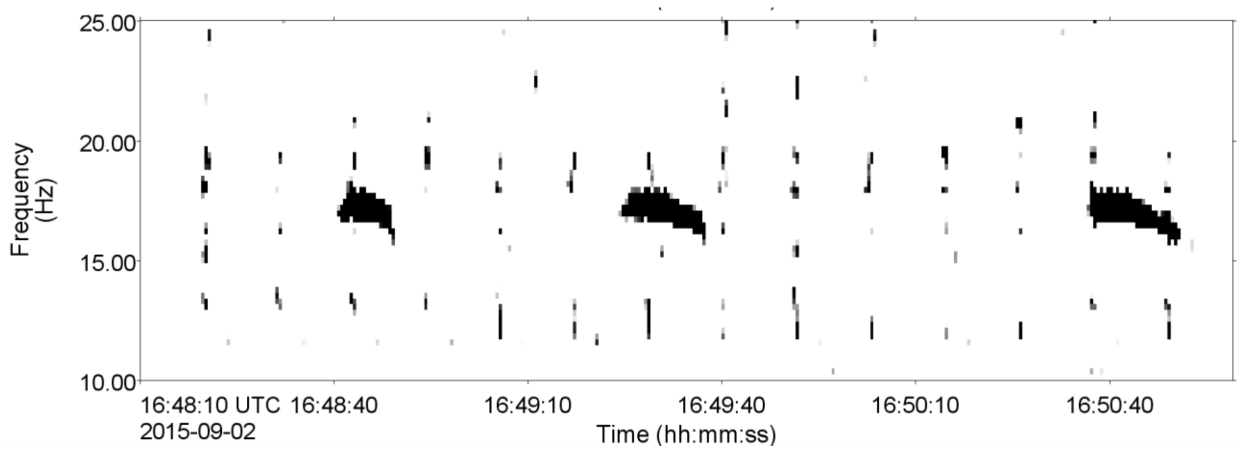

Figure 39. Spectrogram of blue whale infrasonic moans recorded on 2 Sep 2015 (0.4 Hz frequency resolution, 2 s time window, 0.5 s time step, Hamming window).

Table 11. Blue whales: Summary of manually validated acoustic detections.

Year	Deployment	First detection	Last detection	Record end	Number of days with manual detections
2014	2 Jun	7 Aug	2 Oct	9 Oct	2
2015	9 May	2 Sep	10 Sep	11 Sep	3

3.4.1.3.2. Fin Whales

A low number of fin whale calls were manually detected, as the detector was falsely triggered by seismic noise during the study period and some calls were likely masked by these same noises. Fin whale calls were detected on 3 Jun 2014 and occurred sporadically in August (on 22 Aug) and September (5–8 Sep) 2015 (Table 12). The 20-Hz notes detected in late summer to early fall coincided with the beginning of the period associated with song production (Figure 40) (Watkins et al. 1987).

Table 12. Fin whales: Summary of manually validated acoustic detections.

Year	Deployment	First detection	Last detection	Record end	Number of days with manual detections
2014	2 Jun	3 Jun	3 Jun	9 Oct	1
2015	9 May	22 Aug	8 Sep	11 Sep	5

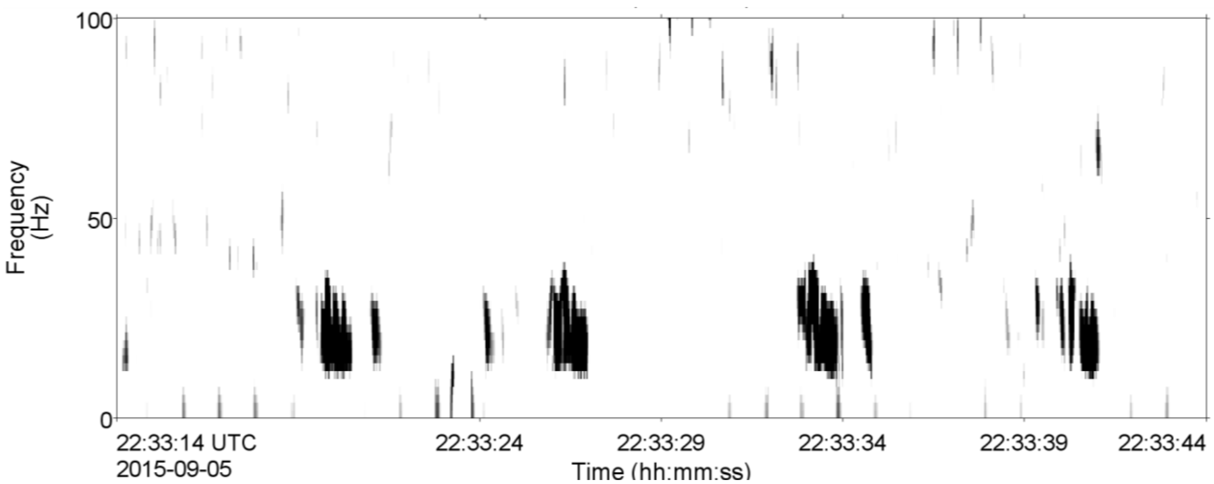

Figure 40. Spectrogram of fin whale 20 Hz notes recorded on 5 Sep 2015 (2 Hz frequency resolution, 0.128 s frame size, 0.032 s time step, and Hamming window).

3.4.2. Stn 19 2016–2017

The acoustic presence of marine mammals at the mouth of the Flemish pass in 2016 and 2017 (Stn 19 2016–2017) was identified automatically by JASCO's detectors (Appendix A.4.3), and 0.5% of the acoustic data was verified by manual analysis. In the high sampling rate recordings (250 ksps), beaked whales, sperm whales, and dolphins were identified. In the low sampling rate recordings (8 ksps), baleen whales and pilot whales were identified. The Stn 19 2016–2017 data set contained all species identified in the CM2 data sets from 2014 and 2015 (Section 3.4.1), with the addition of Cuvier's beaked whales, Sowerby's beaked whales, and humpback whales.

3.4.2.1. Detector Performance

Detector performance varied across species and call types with some detectors proving ineffective. The Cuvier's beaked whale click detector was found to be ineffective, with only 40% of files containing clicks that were correctly identified. The detector was likely challenged by the occurrence of other similarly clicking species, including dolphins and northern bottlenose whales. The manually observed humpback whale vocalizations were too few to validate detector performance. Therefore, only manual results are presented for Cuvier's beaked whales and humpback whales.

The precision of the remaining detectors was high. It ranged from 0.76 (dolphin clicks) to 1 (fin, blue, and Sowerby's beaked whales), indicating that 76 to 100% of files containing calls were correctly detected and classified (Table 13).

Except for the high-performing Sowerby's beaked whale (R = 1) and northern bottlenose whale (R = 0.92) detectors, detector recall values were low to moderate, ranging from 0.15 for fin whales to 0.62 for dolphin clicks (Table 13). Low recall indicates that the automated detectors found fewer calls than the manual analysts. For blue and fin whales, the low detector recall values reflect the inability of our detectors to identify the vocalizations of these species through the strum noise that occurred throughout Stn 19 2016–2017.

Table 13 Detection thresholds determined from validating the automated detector outputs. The thresholds are the minimum number of detected calls/file required to be confident in detections. The precision (P), recall (R) after the threshold is applied are shown.

Species	Threshold	Precision	Recall
Cuvier's beaked whale	5	0.40	0.67
Northern bottlenose whale	1	0.94	0.92
Sowerby's beaked whale	1	1.00	1.00
Dolphin clicks	1	0.76	0.62
Dolphin whistles	1	0.94	0.50
Pilot whale whistles	1	0.89	0.18
Sperm whale	4	0.95	0.56
Blue whale	2	1.00	0.20
Fin whale	1	1.00	0.15
Humpback whale	NA*	NA	NA

*Insufficient occurrence of humpback whales to calculate detector threshold and performance.

3.4.2.2. Odontocetes

3.4.2.2.1. Beaked Whales

Three beaked whales species were acoustically identified at Stn 19 2016–2017, which contrasts with CM2 in the Flemish Pass in 2014–2015, where only northern bottlenose whales were present. The Cuvier's beaked whale clicks recorded in this study were identified on the basis of descriptions by researchers in different areas of the world (Zimmer et al. 2005, Baumann-Pickering et al. 2013). The detected clicks had a centroid frequency of ~40 kHz (Figures 41 and 42). Sowerby's beaked whale clicks were identified as those labelled "high clicks" in Cholewiack et al. (2013). These clicks had a frequency-modulated slope that peaked in frequency near 67 kHz, which placed them above the frequency bands of other species' clicks (Figures 43 and 44).

Northern bottlenose whales occurred regularly throughout the recording period at Stn 19 2016–2017, while Cuvier's and Sowerby's beaked whale clicks were rarer (Figure 45). Sowerby's beaked whale clicks occurred sporadically throughout the recording, with the lowest occurrence in February and March 2017. Limited to manually validated data only, it is difficult to ascertain patterns in Cuvier's beaked whale occurrence, but the species was present in December, March, and April.

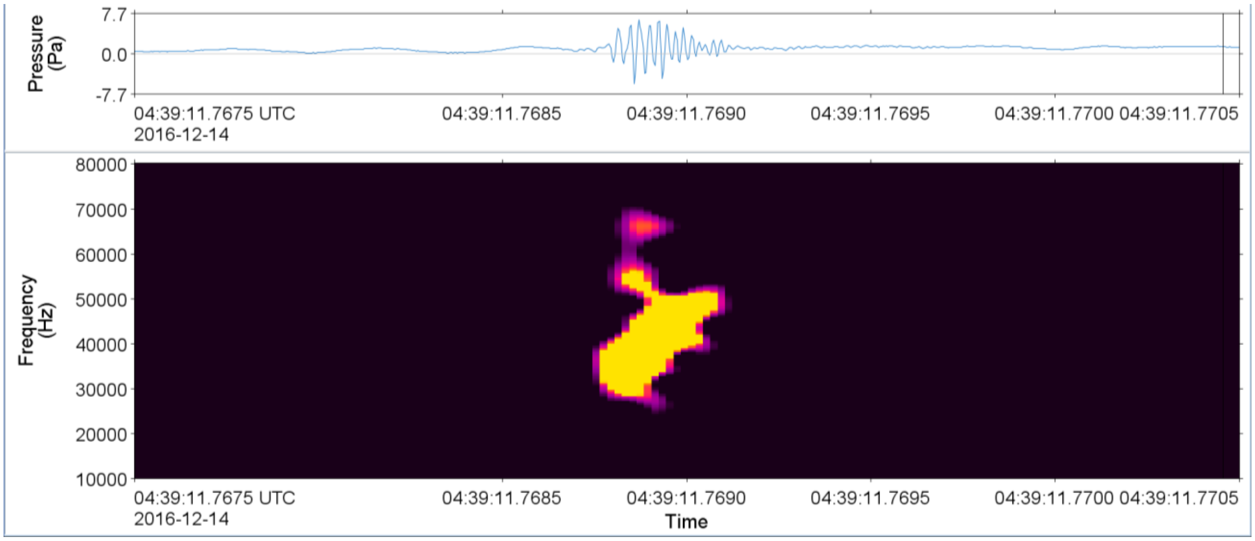

Figure 41 Spectrogram of a Cuvier's beaked whale click recorded on 14 Dec 2016 (512 Hz frequency resolution, 0.26 ms time window, 0.02 ms time step, Hamming window).

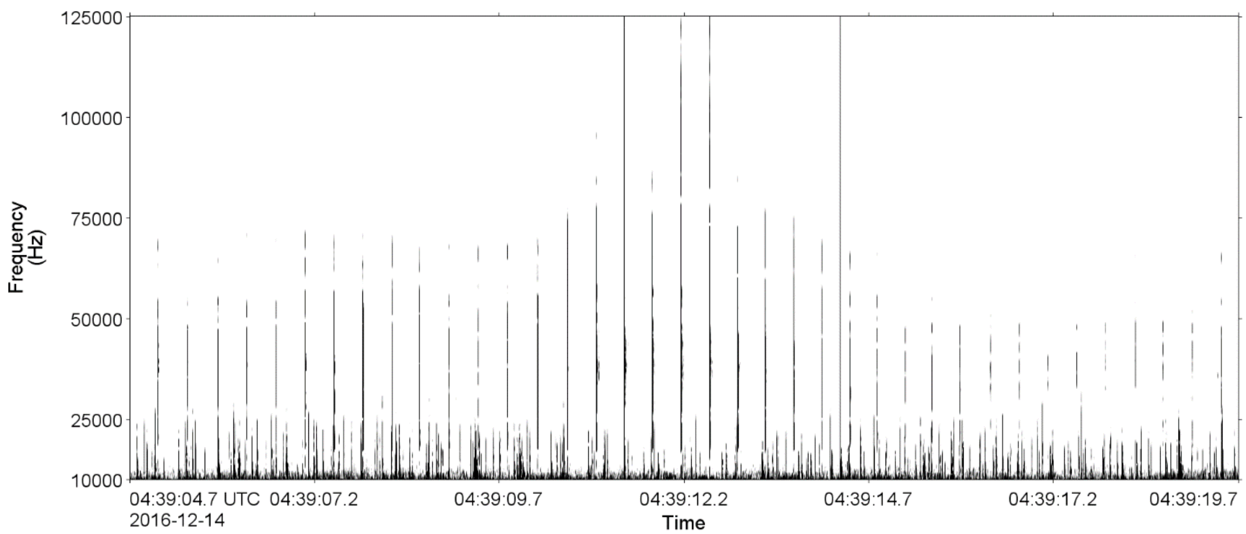

Figure 42 Spectrogram of Cuvier's beaked whale click trains recorded on 14 Dec 2016 (64 Hz frequency resolution, 0.01 s time window, 0.005 s time step, Hamming window). The window length is 15 s.

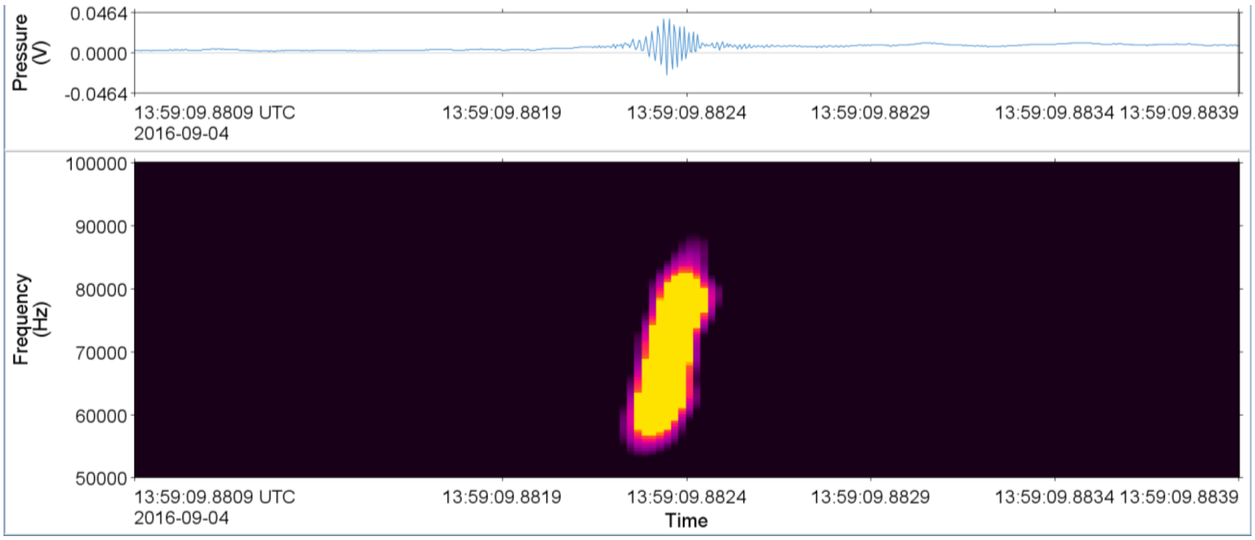

Figure 43 Spectrogram of a Sowerby's beaked whale click recorded on 4 Sep 2016 (512 Hz frequency resolution, 0.26 ms time window, 0.02 ms time step, Hamming window).

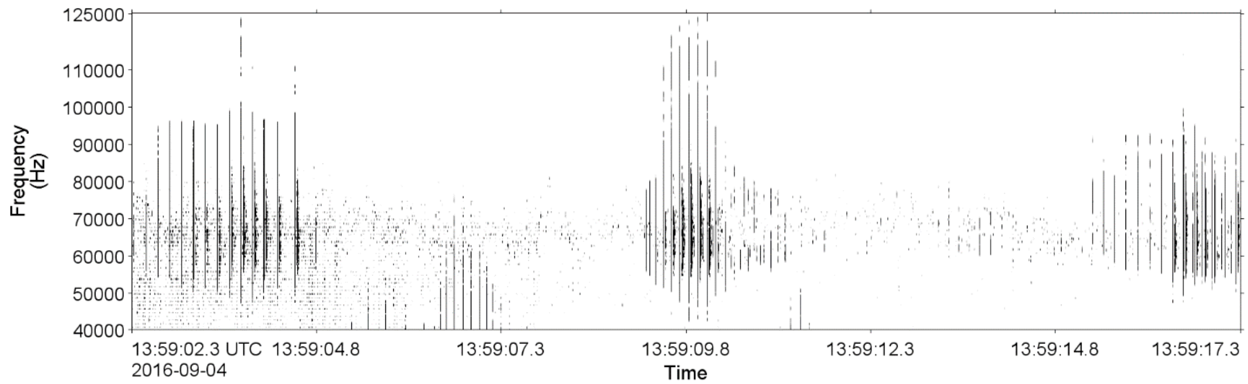

Figure 44 Spectrogram of Sowerby's beaked whale click trains recorded on 4 Sep 2016 (64 Hz frequency resolution, 0.01 s time window, 0.005 s time step, Hamming window). The window length is 15 s.

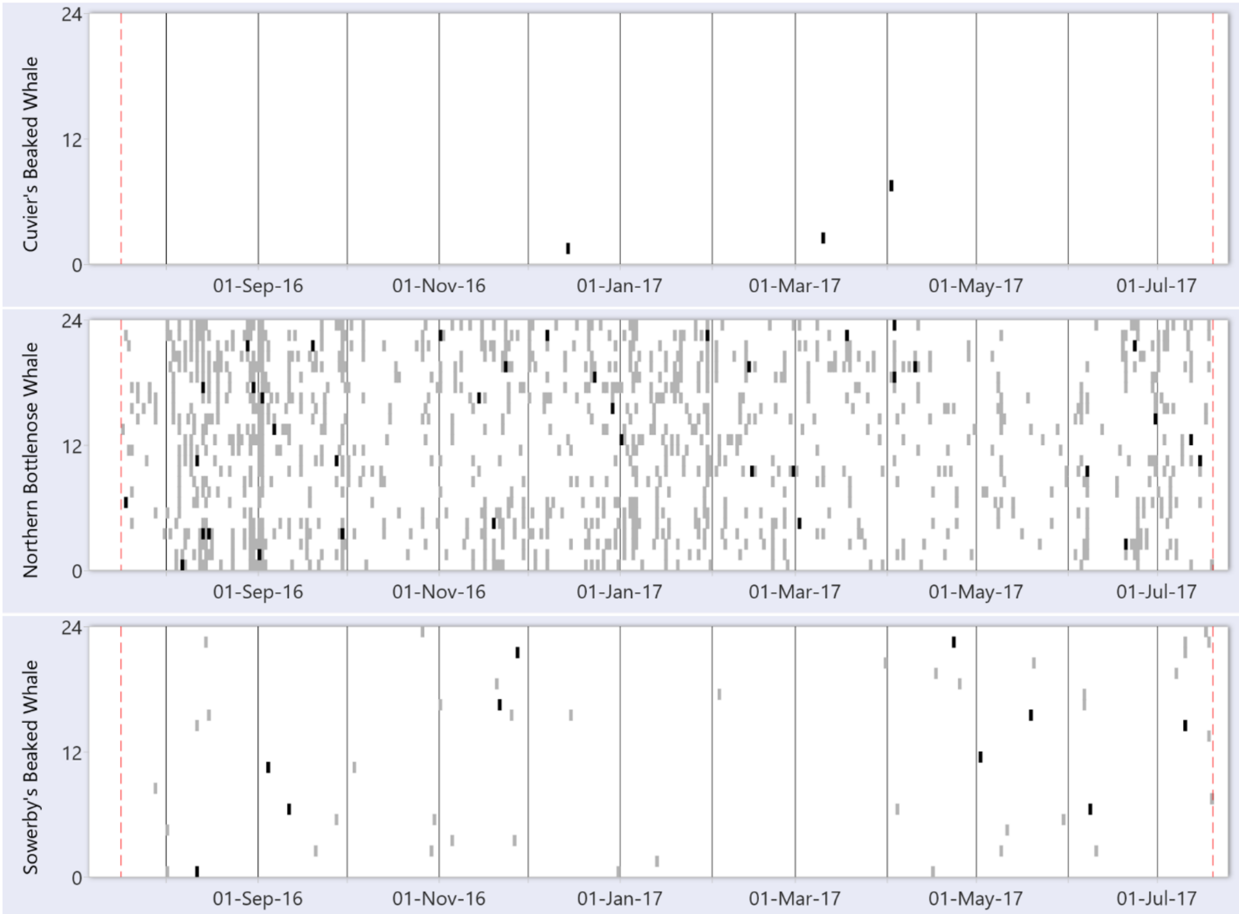

Figure 45 Automated detection (grey) and manual validation (black) of daily and hourly occurrence of beaked whale clicks recorded at Stn 19 2016–2017. Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates. The Cuvier's beaked whale automated detector was deemed ineffective, thus only validated results are presented.

3.4.2.2.2. Delphinids

Compared to findings from CM2 in the Flemish Pass in 2014–2015, dolphins and pilot whales occurred more frequently at Stn 19 2016–2017. Dolphin occurrence in particular was nearly constant with a slight decrease in April and May (Figure 46). Dolphin click diel call behaviour was apparent, particularly from July through May, with dolphins clicking more during periods of darkness than during daylight (Figure 46). Pilot whale whistles were present almost daily, except for December to March when their vocalizations were less frequent (Figure 46).

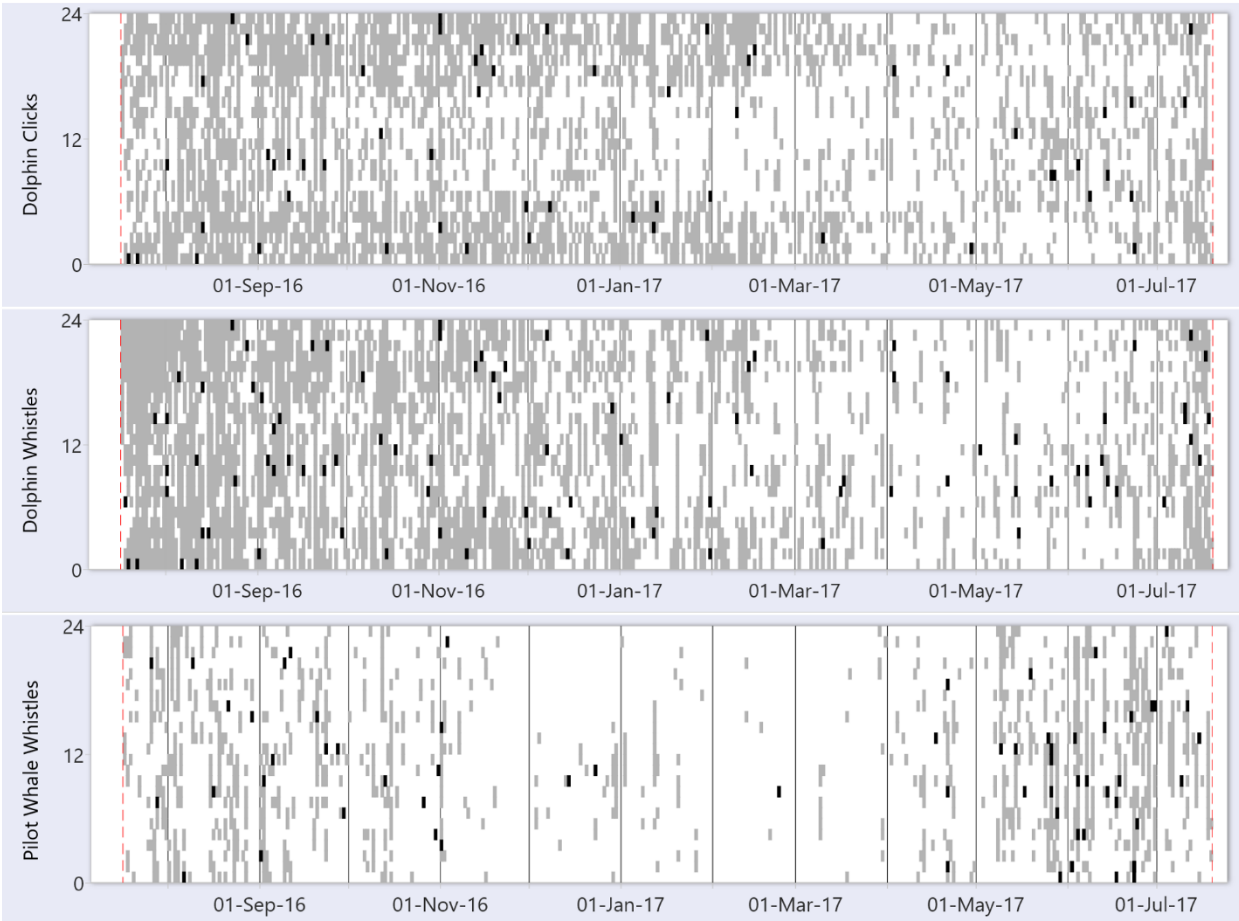

Figure 46 Automated detection (grey) and manual validation (black) of daily and hourly occurrence of dolphin clicks (that also include pilot whale clicks), dolphin whistles, and pilot whale whistles recorded at Stn 19 2016–2017. Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates.

3.4.2.2.3. Sperm Whales

As was observed at CM2 in the Flemish Pass in 2014–2015, sperm whales were detected consistently throughout the study period at Stn 19 2016–2017 (Figure 47).

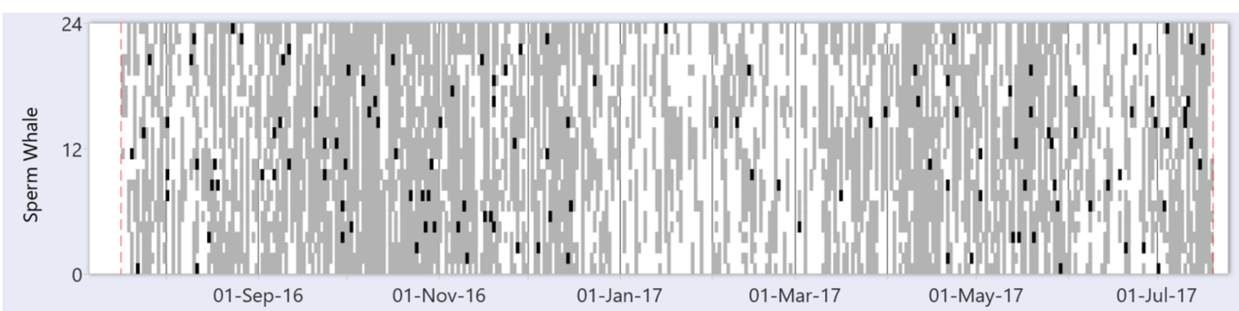

Figure 47 Automated detection (grey) and manual validation (black) of daily and hourly occurrence of sperm whale clicks recorded at Stn 19 2016–2017. Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates.

3.4.2.3. Mysticetes

The occurrence of baleen whales differed greatly between the CM2 recordings in the Flemish Pass in 2014–2015 and those from Stn 19 2016–2017. Blue whales were only manually identified twice at CM2, but they occurred regularly at Stn 19 2016–2017 from mid-July to late January (Figure 48). Fin whales were identified on five days at CM2 but were constantly presence at Stn 19 2016–2017 from October to early June (Figure 48). It is important to note that our fin and blue whale detectors identified the infrasonic calls of these species that are known to occur seasonally. Therefore, blue and fin whales may have occurred outside of the timeframes present in Figure 48, but their vocalizations simply went undetected. Indeed, higher frequency blue whale vocalizations were manually confirmed in May and June 2017 (Figure 48). Humpback whales were never identified in CM2 recordings, but they were manually confirmed on five days in January and two days in February 2017 of the Stn 19 2016–2017 recordings (Figure 48). The humpback whale vocalizations occurred in sequences characteristic of song (Figure 49) (Payne and McVay 1971).

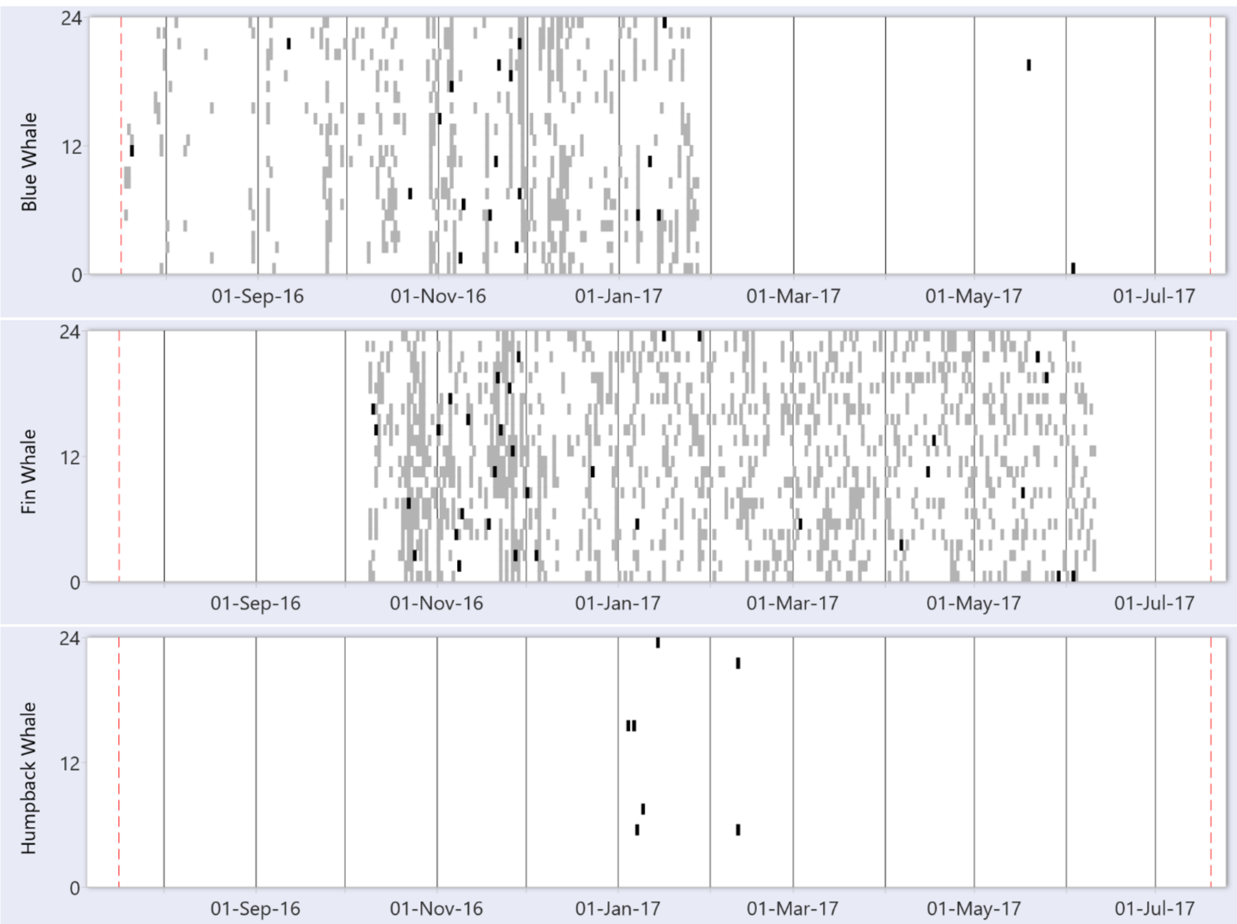

Figure 48 Automated detection (grey) and manual validation (black) of daily and hourly occurrence of mysticete vocalizations recorded at Stn 19 2016–2017. Shaded areas indicate periods of darkness. The red dashed lines indicate AMAR deployment and retrieval dates. The humpback whale automated detector was deemed ineffective, thus only validated results are presented.

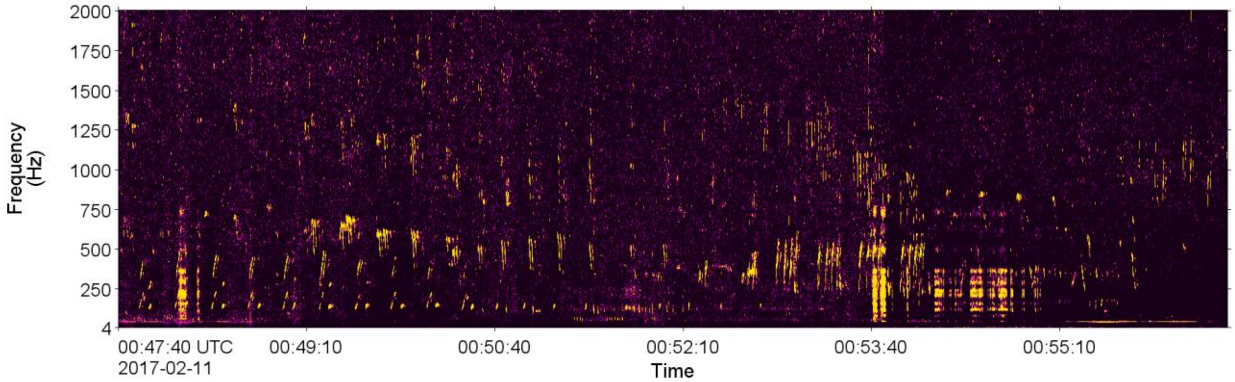

Figure 49 Spectrogram of humpback whale song recorded on 11 Feb 2017 (2 Hz frequency resolution, 0.128 s frame size, 0.032 s time step, and Hamming window). Window is 9 minutes in duration. Vibrating ropes from current flow caused the vertical bands of noise starting at 00:53:40.

4. Discussion and Conclusion

4.1. Identifying the Effects of Drilling Operations and Seismic Surveys on the Measured Sound Levels

The data collected at CM2 provide an opportunity to analyze the sounds generated by a semi-submersible drilling operation and seismic surveys. In Figure 50, the mean power spectral density for ESRF Stn 19 from 15 Nov 2015 to 1 Jun 2016 is provided as a baseline for deep water sound levels in the general area of the Flemish Pass. The seismic signature from CM2 in 2014 was 30–35 dB above this baseline up to 100 Hz, and remained 10 dB above the baseline even at 4 kHz. This result is typical for an area within 10–100 km from a seismic survey. A single day's mean power spectral density from 7 Oct 2014 during which there was no seismic surveys or close passes of vessels is also provided. This curve closely follows the baseline, which indicates that Stn 19 was a good proxy for the conditions in the Statoil 2014–2016 drilling area and that differences in recording depth did not affect our ability to compare the measurements.

The period of 25 May–17 June 2015 was selected as representative of the sounds from the semi-submersible drilling operation in the absence of seismic surveys (see Figure 10). The mean power spectral density for this period exceeded the baseline in the frequency range of 30–2000 Hz, with two notable tones at 200 Hz and 290 Hz that were also barely detectable in the baseline (see Figures 10, 12, and 50). A third tone at 120 Hz may be associated with the power generation systems on the semi-submersible drill rig. To further compare the sound levels, a box-and-whisker plot of the decade band SPL from 100–1000 Hz is provided (Figure 51). The mean sound levels from the semi-submersible drill rig were 13 dB above the baseline, while the seismic was 25 dB above baseline in this band.

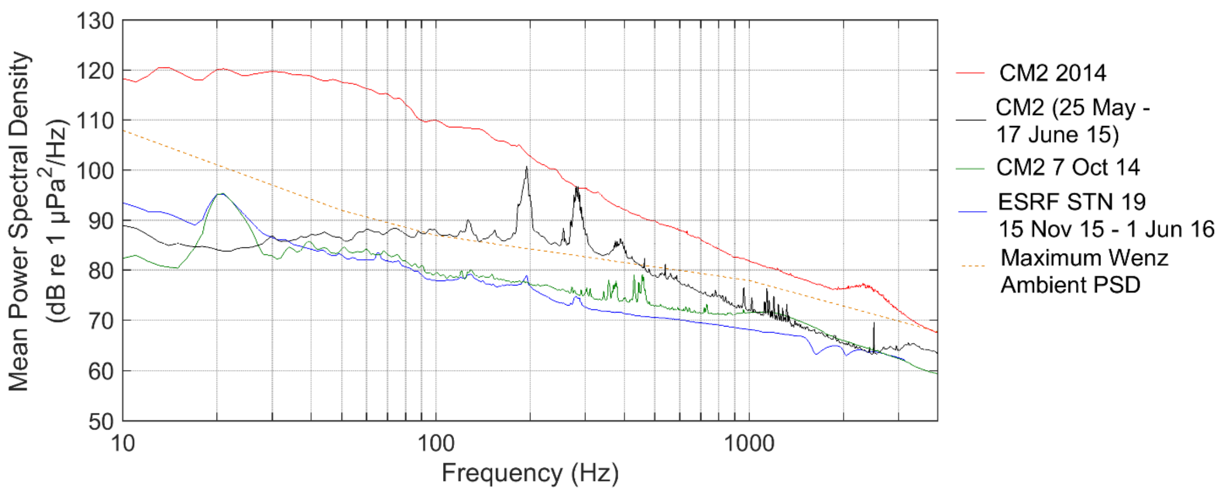

Figure 50. Mean power spectral densities for the complete CM2 2014 data set and three data sets without seismic: CM2 on 7 Oct 14, CM2 2015 for the period of 25 May–17 Jun 15 and Stn 19 for 15 Nov 15–1 Jun 16.

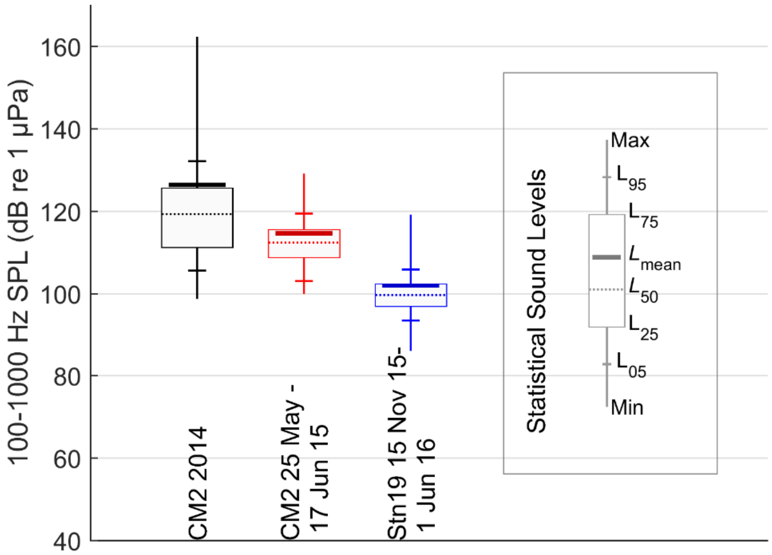

Figure 51. Comparison of the 100–1000 Hz SPLs for all of the CM2 2014 data, CM2 2015 for three weeks without seismic, and Stn 19 without seismic.

JASCO previously measured the sound levels from the Stena IceMAX drill ship during Shell Canada's drilling at the Monterey Jack well site (MacDonnell 2017). This rig had six Rolls-Royce UUC-505 5,500 kW dynamic positioning thrusters. This rig has a similar shape to it's power spectral density signature, but without the distinct tones at 200 and 290 Hz (Figure 52). The broadband source level of the Stena IceMAX was computed to be 187.7 dB re 1 µPa. Based on the current results and a conservative estimate of the propagation loss differences between the Stena IceMAX measurement and the CM2 location, the *West Hercules* likely has a similar source level. Detailed acoustic modelling could be performed in the future to estimate a more accurate source level if required.

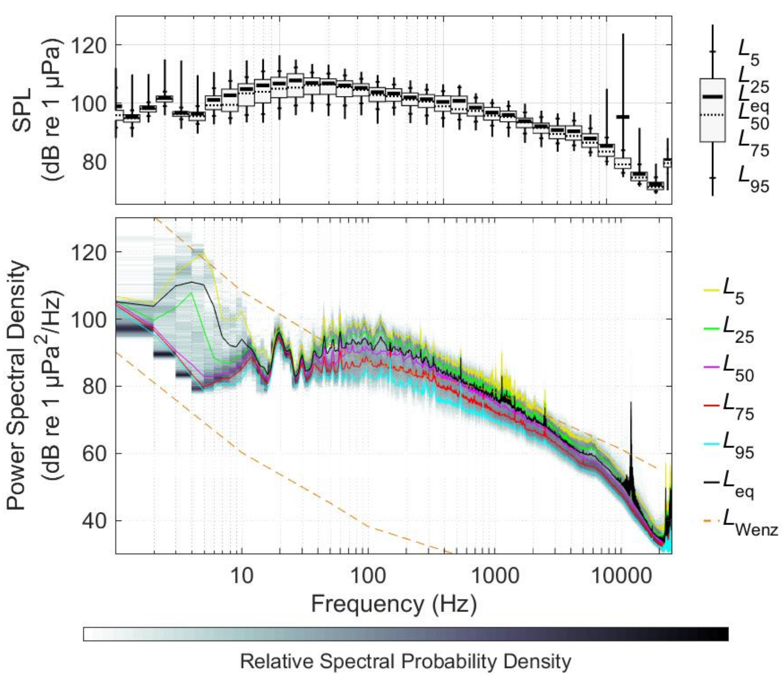

Figure 52 . Power Spectral density plot from 1 day of data collected 2800 m slant range from the Stena IceMAX (MacDonnell 2017).

4.2. Seismic Reverberation

The duration of a seismic impulse at the airgun array is approximately 50 ms (Caldwell and Dragoset 2000). As the sound propagates and interacts with the surface and seabed the energy spreads in time for up to the full period between pulses, as shown in Figure 19, Figure 20 and Figure 21. The slow decay in sound levels is known as reverberation and will mask communications by marine life (Guan et al. 2015). If the masking occurs through too much of the inter-pulse period then exposed animals will have limited opportunities for communication. Quantifying the extent of the reverberant masking is useful for understanding the possible effects on marine mammals.

To quantify the degree of masking in the project area, data from another ESRF recording in the project area was analyzed (ESRF Station 17 at the southern end of the Flemish Pass). The seismic source vessel Atlantic Explorer passed within 5,500 meters of this recorder on May 24th 2017. To assess masking effects the Listening Space Reduction (LSR, (Pine et al. 2018)) was computed for ranges of 5.5 – 60 km from the source. The LSR metric determines the percent reduction in the area that a marine mammal can hear calls in specific critical hearing bands (Equation 1, Equation 7 from Pine et al. (2018)). In Equation 1, NL_2 is the sound pressure level with the masking noise present, NL_1 is the sound pressure level without the masking present, and N is the geometric spreading coefficient for the acoustic propagation environment. The sound pressure levels are computed for 1/3 octave bands that are representative of the important listening frequencies for animals of interest.

$$LSR = 100 * (1 - 10^{2\frac{NL_2 - NL_1}{N}}) \qquad \text{Equation 1}$$

For this analysis we used the representative third-octave bands at 20 Hz for fin and blue whale calls, 400 Hz for humpbacks, 8000 Hz for delphinid whistles, and 31.5 kHz for echolocation clicks. In Pine et al. (2018) the LSR method was applied to continuous sounds using a modeling approach. Here we adapt the method to look at the reverberation between the seismic pulses in real data. The analysis was performed for each 0.5 second time window after the first arrival (Figure 53). The time window of 0.5 seconds was selected in consultation with one of the authors of Pine et al. (2018) as a compromise between being long enough to be typical for the calls of the species of interest, but not too long whereby too much variation in the seismic reverberation would occur. For each time window the power spectral density of the signal was computed, then summed over the frequencies in the third octave bands of interest to obtain the sound pressure level in the band (NL_2). A nominal geometric spreading coefficient of 15 was assumed to simplify the analysis. The reference sound pressure level NL_1 was found using a 1-minute during an ambient noise period prior to the start of the seismic line. When NL_1 was less than the animal's hearing threshold at the analysis frequency, the hearing threshold was used at NL_1 rather than the ambient noise. For this analysis we used the composite audiogram functions from Finneran (2016) to estimate the hearing threshold at the third-octave-band center frequency. The fin and humpback whale as well dolphin whistle audiogram thresholds were within 3 dB of the ambient noise levels. The dolphin click audiogram thresholds were ~15 dB below the ambient noise levels.

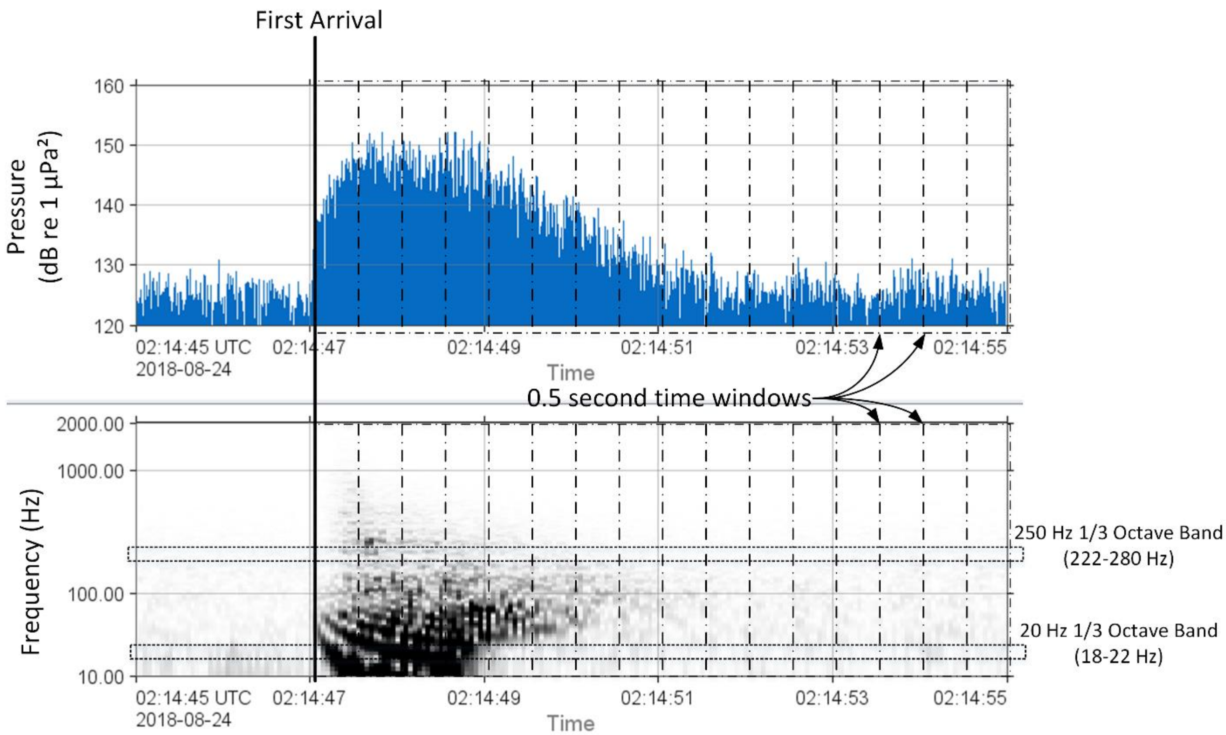

Figure 53. Listening Space Reduction concept for determining reverberation between seismic pulses. Note that when viewed on a log-frequency scale, 1/3-octave-bands all appear to have the same size.

Figure 54 shows that the different types of calls are affected differently by seismic reverberation masking. Fin whale listening space at 20 Hz between seismic pulse arrivals is reduced by 90% for 1-6 seconds after the first arrival when the vessel is 30-60 km away. As the vessel gets closer the percentage of the inter-pulse interval where the fin whale listening space is reduced by 90% increases until almost the entire inter-pulse period is unavailable, but then decreases to about half the inter-pulse period at closer ranges. Similarly humpback whale calls around 400 Hz are masked for much of the inter-pulse period when the source is ~10 km away, but the percentage decreases again closer to the source when there is less scattering, multipath arrivals and hence less overall reverberation. Beyond 15 km the humpback calls are masked for 1-2 seconds after the first arrival, although the duration varies. As expected odontocete whistles and clicks were not substantially affected by masking for ranges from the array longer than 5.5 km. It should be noted that the analysis does not take into consideration that marine mammals have mechanisms that enhance the detectability of signals in the presence of noise including spatial release, comodulation masking release, as well as the within valley (or “dip”) listening strategy that was analyzed here (see Erbe et al. 2016 for a review). Also, marine mammals may change the characteristics of their vocalizations in the presence of noise as an anti-masking strategy.

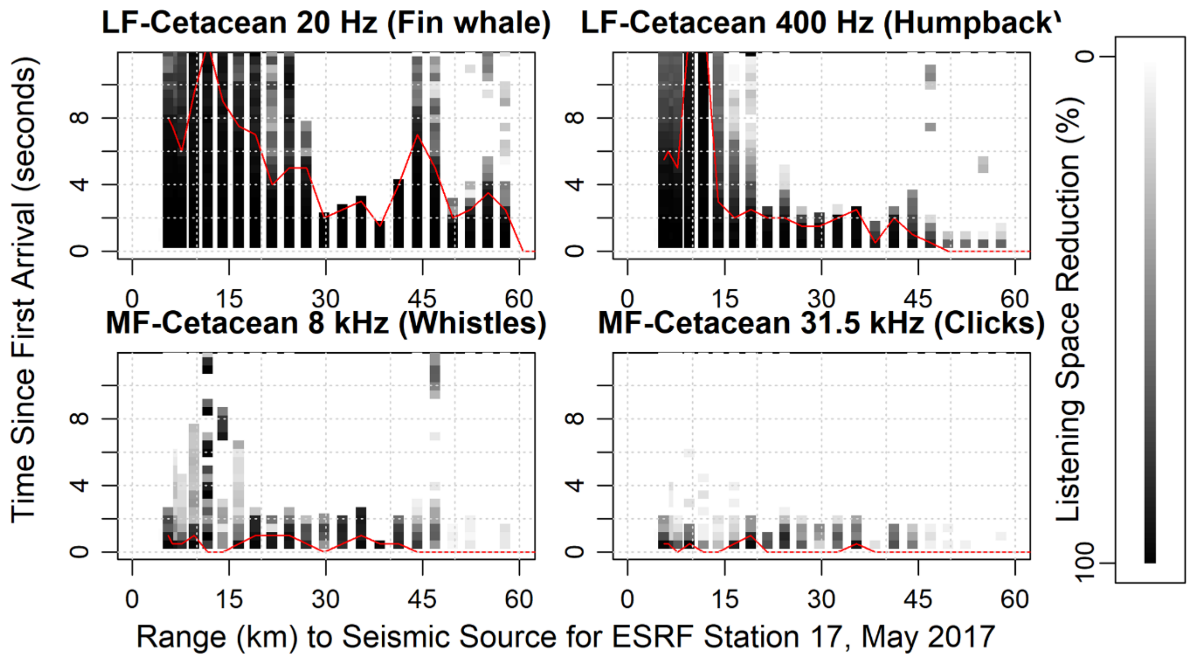

Figure 54. Listening Space Reduction during a seismic line on 24 May 2017 that passed 5.5 km from ESRF Station 17 at the southern end of the Flemish Pass. The red line marks the time after the first arrival where our understanding of the listening space is reduced by 90%.

4.3. Marine Mammals

The acoustic detections of marine mammals presented in this report provide an index of acoustic occurrence for each species. They do not represent the number of individuals present at the time of detections. An absence of detections could be the result of an absence of animals, individuals near the acoustic recorders not vocalizing, masking of calls by environmental or anthropogenic noise sources, or a combination of these factors. We compare the acoustic occurrence of each species in the context of noise conditions and their effect on the detectability or masking of calls. Seasonal variations in marine mammal calling behaviour, which may falsely suggest changes in occurrence, are also discussed.

The range at which marine mammals can be detected by acoustic recorders is dependent on a number of parameters. The frequency of the vocalization impacts sound propagation with low frequency signals (typical of mysticetes) travelling further than high frequency signals (typical of odontocetes) that attenuate quickly. For example, high frequency porpoise clicks are only expected to travel 1.1 km in favourable conditions (DeRuiter et al. 2010) while low frequency blue and fin whale vocalizations can travel 200 to 56 km, respectively (Širović et al. 2007). The source level of the signal will also impact the range the signal can be detected. For example, humpback whale social calls have a median source level of 158 dB re 1µPa (Dunlop et al. 2013) while humpback whale songs propagate further on average with source levels from 171-189 dB re 1µPa (Au et al. 2001). Ambient sound levels greatly impact the detection range of an acoustic signal. Such was shown in humpback whale vocalizations on the Scotian Shelf where signals were detectable only 1 km from the recorders in the noisiest conditions, but up to 100 km from the recorders in the quietest conditions (Kowarski et al. 2018). Therefore, there is variability in the expected marine mammal detection range of the recorders in the present study, and such should be taken into consideration in the below discussion.

4.3.1. Odontocetes

4.3.1.1. Beaked Whales

Based on the measured source levels of two Ziphiid species, the estimated detection range of Ziphiids is between 2 and 7 km, depending on the species and season (JASCO, unpublished data). Therefore, the beaked whale clicks recorded at here reflect the occurrence of species in the immediate vicinity of the recorders. Beaked whales are deep diving species that feed at depth where they produce their foraging clicks (Johnson et al. 2004), making them detectable by the deep-water recorders utilized in the present study.

4.3.1.1.1. Northern Bottlenose Whales

Two northern bottlenose whale populations occur off eastern Canada (Dalebout et al. 2001): an endangered, well-studied population in the Gully and adjacent canyons (Whitehead et al. 1997, Gowans et al. 2000, Wimmer and Whitehead 2004) and a larger, predominantly unstudied population off the northeast Grand Banks, Labrador, and in the Davis Strait. The boundary between these two populations is unclear (Dalebout et al. 2001). A recent study (ESRF unpublished data) confirmed that northern bottlenose whales are present year-round along the shelf break, particularly north of the Flemish Cape and off the southern Labrador coast.

Detections in 2014–2015 were infrequent, but they do confirm that northern bottlenose whales are in the Flemish Pass throughout the summer and early fall. Northern bottlenose whale detections occurred simultaneously with seismic surveys in 2014–2015. In 2016–2017, at the mouth of the Flemish Pass, northern bottlenose whales were present regularly throughout the year, a contrast to sparseness of the 2014–2015 findings. Based solely on acoustics, it seems beaked whales were more abundant in 2016–2017 in the Flemish Pass region, though one cannot make any confident conclusions, as the data were collected in different years at different locations.

4.3.1.1.2. Cuvier's Beaked Whales

Cuvier's beaked whales were acoustically absent from the 2014–2015 Flemish Pass data set, but were identified sporadically in late winter of the 2016–2017 data. Sightings and strandings of Cuvier's beaked whales in eastern Canadian waters are scarce (Whitehead 2013, NOAA Fisheries 2018) though the acoustic occurrence of the species has been documented along the Scotian Shelf and southern Grand Banks and seasonally around the Flemish Pass and farther north (ESRF unpublished data). Nova Scotia is believed to be at the northern edge of the range of Cuvier's beaked whales (Macleod et al. 2005). An eastern seaboard-wide study showed acoustic detections to be most common off Cape Hatteras and decreasing in regularity farther north (Stanistreet et al. 2017). Therefore, the paucity of Cuvier's beaked whale detections in our study are expected.

4.3.1.1.3. Sowerby's Beaked Whales

The occurrence of Sowerby's beaked whales in the study region was expected, as they are known as the most northerly of the *Mesoplodon* in the North Atlantic, they have been reported off Labrador in the past, occur as far north as the Norwegian Sea in the eastern Atlantic (Macleod 2000), and they are regularly sighted in summer on the Scotian Slope (Hooker and Baird 1999, Whitehead 2013). The species was not detected in the 2014–2015 data, as they were (though in low numbers) throughout 2016–2017, either representing a variability in occurrence across years or locations. An additional factor that may have limited the detectability of Sowerby's in the 2014-2015 data is that the recorder was positioned several hundred meters below the surface rather at the seabed, where the 2016-2017 recorder was located. The seabed is believed to be the foraging area of these deep diving animals and it is believed the clicks recorded in 2016-2017 are associated with foraging.

4.3.1.2. *Dolphins*

Dolphin whistles were the most prevalent tonal acoustic signals in both the 2014–2015 and 2016–2017 data, being more abundant in the latter data set. We could not determine the species due to the limited manual validation performed and the lack of detailed whistle descriptions for the species potentially involved. Based on the results from previous aerial surveys (Lawson and Gosselin 2011), the species likely responsible for most of the detections are white-beaked, white-sided, and short-beaked common dolphins.

The white-beaked dolphin is the northernmost species included in this group (Mercer 1973). Their habitat is characterized by shallow depth and low water temperatures (MacLeod et al. 2007). In eastern Canadian waters they have been observed in winter and spring off Newfoundland and in summer off Labrador (Mercer 1973, Reeves et al. 1998). They are regularly observed in summer in the Strait of Belle Isle (Kingsley and Reeves 1998). White-beaked dolphins were the most abundant dolphin species recorded in the Newfoundland-Labrador strata during the 2007 TNASS aerial surveys (Lawson and Gosselin 2011).

Atlantic white-sided dolphins are known to occur in the study region (Mercer 1973). The northern limit of these species is presumably linked to that of white-beaked dolphins. As white-beaked dolphins retract to the more northern part of the east coast waters, tracking the movement of colder waters, white-sided dolphin likely expand their range to the north in summer. Their abundance was second to that of white-beaked dolphins and common dolphins in the Newfoundland-Labrador and Scotian shelf-Gulf of St. Lawrence strata of the 2007 TNASS surveys, respectively (Lawson and Gosselin 2011).

Short-beaked common dolphins prefer warmer, more saline waters than Atlantic white-sided dolphins, and they tend to inhabit the edge of the continental shelf (Selzer and Payne 1988, Gowans and Whitehead 1995). However, these species often inhabit the same area when an abundance of prey is present. Off eastern Canada, they occur mostly in summer and fall in slope waters of the Scotian Shelf and southern Newfoundland, as well as near prominent bathymetric features such as the Flemish Cape (Jefferson et al. 2009). Common dolphins were by far the most common dolphins sighted in the Scotian Shelf-Gulf of St. Lawrence strata during the 2007 TNASS surveys (Lawson and Gosselin 2011).

It is unlikely, but possible, that Risso's, striped, and bottlenose dolphins are present the study area. Their relative contribution to the dolphin acoustic detections is unlikely or very limited.

Click detections followed a strong diel pattern. Detections occurred almost exclusively at night, which reflects the night-time foraging of dolphins that takes advantage of the diel vertical migration of their prey species (Au et al. 2013). Species-unique identification using clicks remains challenging due to the overlap in click characteristics and lack of published description, especially for dolphins.

4.3.1.3. *Pilot Whales*

The range of pilot whales extends in the western North Atlantic from the United States to Greenland (Abend and Smith 1999). Gowans and Whitehead (1995) reported them on the Scotian Slope, and (Sergeant 1962) reported them in Newfoundland waters. The 2007 TNASS surveys estimated the population size for the Scotian Shelf-Gulf of St. Lawrence strata at ~16,000 individuals (Lawson and Gosselin 2011). In a previous study (ESRF unpublished data), acoustic detections were more focused at stations along the continental slope, a known preferred habitat where pilot whales (Payne and Heinemann 1993) forage on long-finned squid (*Lollgo pealei*), among other species (Gannon et al. 1997, Aguilar Soto et al. 2009). In the current study, pilot whales were detected infrequently in 2014–2015, but were present almost every day in 2016–2017, except in winter when they were detected less frequently. Because pilot whale calls have tonal components (pulsed calls and whistles) that can be reliably distinguished from dolphin whistles on the basis of frequency, the results presented here are believed to accurately represent the occurrence of this species. It is difficult to attribute reasons for the differences in findings between data sets as they are from different years and different locations.

4.3.1.4. *Sperm Whales*

Sperm whales are widely distributed in the Atlantic Ocean, including the present study region. In eastern Canada, they prefer areas near the continental slope, although they are occasionally encountered in shallow areas of the Scotian Shelf (Whitehead et al. 1992). Sperm whales in eastern Canadian waters appear to be exclusively males, with the possible exceptions of areas near the US-Canada border (Reeves and Whitehead 1997). Females remain at lower latitudes year-round, while males migrate between higher latitudes feeding grounds in summer and lower latitude to breed in winter (Whitehead 2002). In the current study, sperm whales were acoustically detected throughout summer and early fall, in 2014 and 2015, and occurred year round in 2016–2017. The almost continuous detections presented here confirm the importance of the Flemish Pass and continental slope area for this species.

4.3.2. Mysticetes

4.3.2.1. *Blue Whales*

Blue whale calls were infrequent in 2014–2015, occurring only on two days in the late summer to early fall of 2014 and three days during the beginning of September in 2015. In contrast, blue whale infrasonic vocalizations occurred regularly from July to January in 2016–2017. The difference in results across data sets could reflect increased masking of these low-frequency vocalizations at the drilling site in 2014–2015, though similar challenges occurred in 2016–2017 where a combination of strum noise coupled with the high anthropogenic sounds associated with the region posed similar challenges. Another explanation of the contrast in results could be the different detectability ranges between the 2014–2015 data recorded within the shallow, enclosed, Flemish Pass and the 2016–2017 data recorded on the shelf edge where blue whales may be detectable at greater distances. Indeed, blue whale vocalizations are known to travel great distances and, thus, variation in detection radius between sites could greatly influence results.

Besides localized, well-studied, summer concentrations, such as in the Gulf of St. Lawrence (Sears and Calambokidis 2002), the distribution and movements of endangered blue whales off Atlantic Canada and in the north Atlantic in general remain poorly understood (Reeves et al. 2004). Some of these detections may be from individuals foraging in the Davis Strait in summer and migrating south in fall (Sears and Calambokidis 2002). In most areas of the North Atlantic, peak song detections occur in December and January, with a sharp decline in February and March (Charif and Clark 2000, Clark and Gagnon 2002, Nieukirk et al. 2004).

4.3.2.2. *Fin Whales*

Previous results (Delarue et al. 2018b) indicate that the Grand Banks is an important area for fin whales, particularly in fall and winter. In 2014–2015, we observed sparse fin whale detections in early fall. While in 2016–2017, fin whale vocalizations were near-constant from October to early June. These findings are consistent with the fin whales' known preference for shelf break and deep water habitats that are characteristic of our 2016–2017 recorder location. Fin whale vocalization results would similarly be impacted by processes effecting blue whale detection, including masking effects of drilling activities and the varying detectability of the species from within the Flemish Pass and on the shelf edge.

Fin whales produce loud sequences of low-frequency notes (~20 Hz) repeated every 9–15 s for hours at a time (Watkins et al. 1987). An ongoing analysis of fin whale songs suggest that at least three acoustic populations, characterized by different song structure (Hatch and Clark 2004, Delarue et al. 2009), occur in Canadian waters. One occurs in the Gulf of St. Lawrence, eastern Scotian Shelf and southern Newfoundland; a second is found in the Bay of Fundy, western Scotian Shelf and farther south; the third one prefers areas on the Grand Banks and off Labrador (Delarue et al. 2009, Delarue et al. 2018a).

4.3.2.3. Humpback Whales

The lack of humpback whale vocalizations in 2014–2015 and few winter manual detections in 2016–2017 suggests that the species does not use the Flemish Pass region to a great extent. Rather, some individuals of the North Atlantic population may traverse the area on route to other areas. In winter and early spring, most humpback whales leave their northern summer feeding grounds (Katona and Beard 1990, Smith et al. 1999) and migrate to their breeding grounds in the West Indies (Whitehead and Moore 1982, Martin et al. 1984, Palsbøll et al. 1997). Though evidence suggests that not all individuals undertake the large-scale migration, which may explain the late occurrence of humpback songs, we observed here (Clapham et al. 1993, Vu et al. 2012, Stanistreet et al. 2013, Kowarski et al. 2018). The animals may have been undertaking a late migration south or moving between more regionally suitable habitats.

Humpback whales are typically described as having two predominant calling behaviours. The first is the song (Payne and McVay 1971) produced by males (Herman et al. 2013) on southern breeding grounds. Here, we observed songs, which supports emerging literature that humpbacks sing not only on the breeding grounds, but also on feeding grounds before and during migration (Clapham and Mattila 1990, Charif et al. 2001, Clark and Clapham 2004). Whether this is indicative of mating behaviour in Canadian waters is yet unknown (Stimpert et al. 2012).

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Appendix A. Automated Data Analysis Methods

We employed a specialized computing platform for processing acoustic data hundreds of times faster than real-time. The system performs automated analysis of total ocean noise and sounds from vessels, seismic surveys, and (possible) marine mammal calls. Figure A-1 outlines the stages of the automated analysis.

We also classify the dominant sound source in each minute of data as “Vessel”, “Seismic”, or “Ambient”. To minimize the influence of anthropogenic sources on ambient sound level estimates, we define ambient levels from individual minutes of data that did not have an anthropogenic detection within one hour on either side of that minute. This results in more accurate estimates of daily sound exposure levels from each source class, cumulative distribution functions of sound pressure levels, and exceedance spectra.

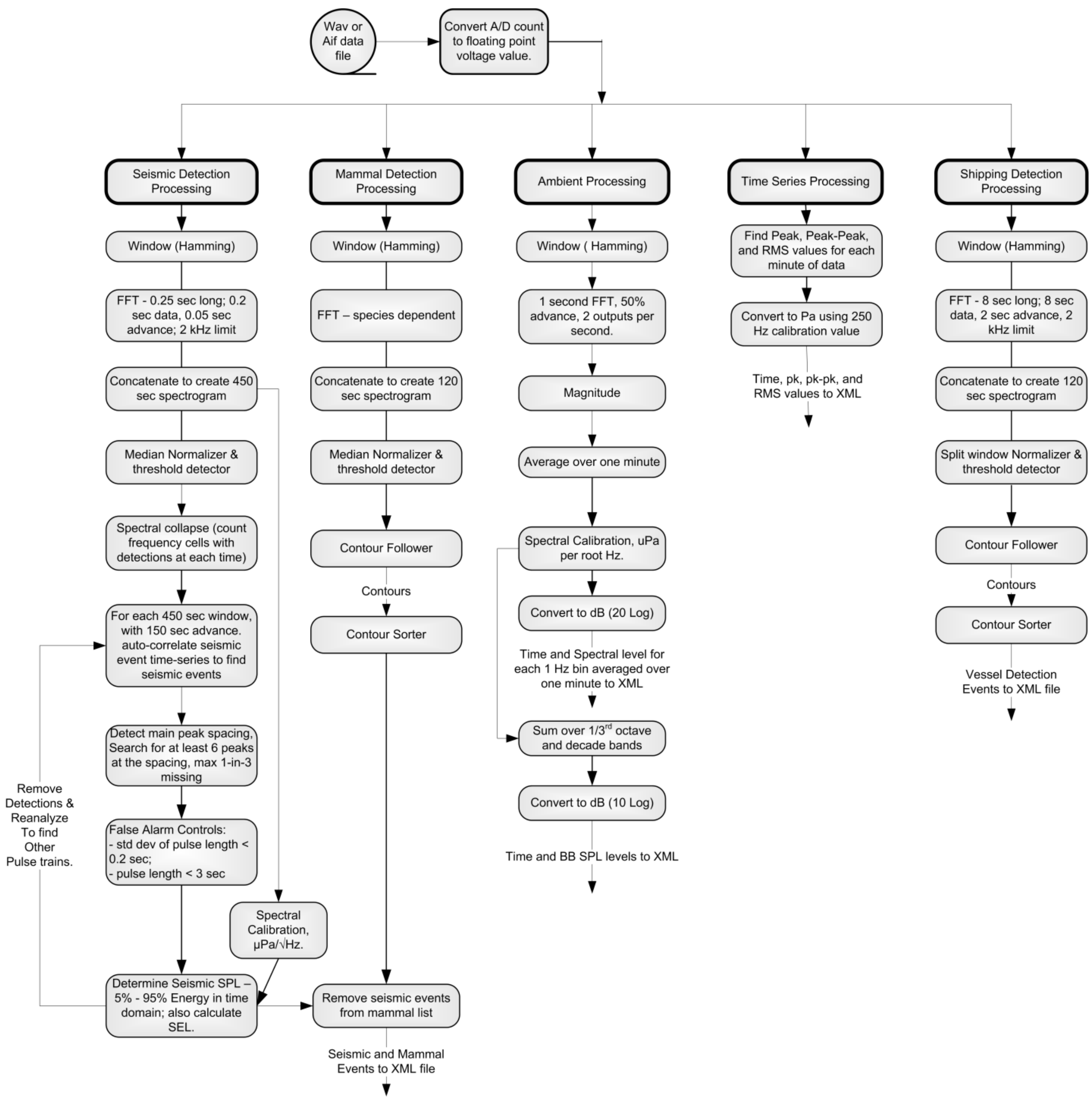

Figure A-1. Major stages of the automated acoustic analysis software suite.

A.1. Total Ocean Noise and Time Series Analysis

Ambient noise levels at the recording station were examined to document the local baseline underwater sound conditions. In Section 3, ambient noise levels are presented as:

- Statistical distribution of SPL in each 1/3-octave-band. The boxes of the statistical distributions indicate the first (L_{25}), second (L_{50}), and third (L_{75}) quartiles. The whiskers indicate the maximum and minimum range of the data. The solid line indicates the mean SPL, or L_{mean}, in each 1/3-octave.
- Spectral density level percentiles: Histograms of each frequency bin per 1 min of data. The L_{eq}, L_5, L_{25}, L_{50}, L_{75}, and L_{95} percentiles are plotted. The L_5 percentile curve is the frequency-dependent level exceeded by 5% of the 1 min averages. Equivalently, 95% of the 1 min spectral levels are above the 95th percentile curve.
- Broadband and approximate-decade-band SPL over time for these frequency bands: 10 Hz to 8 kHz, 10–100 Hz, 100 Hz to 1 kHz, and 1–63 kHz.
- Spectrograms: Ambient noise at each station was analyzed by Hamming-windowed fast Fourier transforms (FFTs), with 1 Hz resolution and 50% window overlap. The 120 FFTs performed with these settings are averaged to yield 1 min average spectra.
- Daily sound exposure levels (SEL): Computed for the total received sound energy and the detected shipping energy. The SEL is the linear sum of the 1 min SEL. For shipping, the 1 min SEL values are the linear 1 min squared SPL values multiplied by the duration, 60 s. For seismic survey pulses, the 1 min SEL is the linear sum of the per-pulse SEL.

The 50th percentile (median of 1 min spectral averages) can be compared to the well-known Wenz ambient noise curves (Figure 1), which show the variability of ambient spectral levels off the east coast of Canada as a function of frequency of measurements for a range of weather, vessel traffic, and geologic conditions. The Wenz curve levels are generalized and are used for approximate comparisons only (see Appendix A.1.2).

A.1.1. Sound Levels

Underwater sound pressure amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 μPa. Because the perceived loudness of sound, especially impulsive noise such as from seismic airguns, pile driving, and sonar, is not generally proportional to the instantaneous acoustic pressure, several sound level metrics are commonly used to evaluate noise and its effects on marine life. We provide specific definitions of relevant metrics used in the accompanying report. Where possible we follow the ANSI and ISO standard definitions and symbols for sound metrics, but these standards are not always consistent.

The zero-to-peak pressure level, or peak pressure level (PK; dB re 1 µPa), is the maximum instantaneous sound pressure level in a stated frequency band attained by an acoustic pressure signal, $p(t)$:

$$PK = 10\log_{10}\left[\frac{\max\left(\left|p^2(t)\right|\right)}{p_0^2}\right] . \qquad \text{(A–2)}$$

$L_{p,pk}$ is often included as criterion for assessing whether a sound is potentially injurious; however, because it does not account for the duration of a noise event, it is generally a poor indicator of perceived loudness.

The sound pressure level (SPL or L_p; dB re 1 µPa) is the root-mean-square (rms) pressure level in a stated frequency band over a specified time window (T, s) containing the acoustic event of interest. It is important to note that SPL always refers to an rms pressure level and therefore not instantaneous pressure:

$$\mathrm{SPL} = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)dt \Big/ p_0^2\right) . \tag{A–3}$$

The SPL represents a nominal effective continuous sound over the duration of an acoustic event, such as the emission of one acoustic pulse, a marine mammal vocalization, the passage of a vessel, or over a fixed duration. Because the window length, T, is the divisor, events with similar SEL, but more spread out in time have a lower SPL.

The SEL (dB re 1 µPa^2·s) is a measure related to the acoustic energy contained in one or more acoustic events (N). The SEL for a single event is computed from the time-integral of the squared pressure over the full event duration (T):

$$\mathrm{SEL} = 10\log_{10}\left(\int_T p^2(t)dt \Big/ T_0 p_0^2\right) \tag{A–4}$$

where T_0 is a reference time interval of 1 s. The SEL continues to increase with time when non-zero pressure signals are present. It therefore can be construed as a dose-type measurement, so the integration time used must be carefully considered in terms of relevance for impact to the exposed recipients.

SEL can be calculated over periods with multiple events or over a fixed duration. For a fixed duration, the square pressure is integrated over the duration of interest. For multiple events, the SEL can be computed by summing (in linear units) the SEL of the N individual events:

$$L_{\mathrm{E,N}} = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\frac{L_{E,i}}{10}}\right) . \tag{A–5}$$

To compute the SPL(T_{90}) and SEL of acoustic events in the presence of high levels of background noise, equations A–4 and A–5 are modified to subtract the background noise contribution:

$$L_{\mathrm{p90}} = 10\log_{10}\left(\frac{1}{T_{90}}\int_{T_{90}} (p^2(t) - \overline{n^2})dt \Big/ p_0^2\right) \tag{A–6}$$

$$L_{\mathrm{E}} = 10\log_{10}\left(\int_T (p^2(t) - \overline{n^2})dt \Big/ T_0 p_0^2\right) , \tag{A–7}$$

where $\overline{n^2}$ is the mean square pressure of the background noise, generally computed by averaging the squared pressure of a temporally-proximal segment of the acoustic recording during which acoustic events are absent (e.g., between pulses).

Because the SPL(T_{90}) and SEL are both computed from the integral of square pressure, these metrics are related by the following expression, which depends only on the duration of the time window T:

$$L_p = L_E - 10\log_{10}(T) \quad \text{(A–8)}$$

$$L_{p90} = L_E - 10\log_{10}(T_{90}) - 0.458\ , \quad \text{(A–9)}$$

where the 0.458 dB factor accounts for the 10% of SEL missing from the SPL(T_{90}) integration time window.

Energy equivalent SPL (dB re 1 µPa) denotes the SPL of a stationary (constant amplitude) sound that generates the same SEL as the signal being examined, $p(t)$, over the same period of time, T:

$$L_{eq} = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)dt \bigg/ p_0^2\right)\ . \quad \text{(A–10)}$$

The equations for SPL and the energy-equivalent SPL are numerically identical; conceptually, the difference between the two metrics is that the former is typically computed over short periods (typically of one second or less) and tracks the fluctuations of a non-steady acoustic signal, whereas the latter reflects the average SPL of an acoustic signal over times typically of one minute to several hours.

A.1.2. One-Third-Octave-Band Analysis

The distribution of a sound's power with frequency is described by the sound's spectrum. The sound spectrum can be split into a series of adjacent frequency bands. Splitting a spectrum into 1 Hz wide bands, called passbands, yields the power spectral density of the sound. These values directly compare to the Wenz curves, which represent typical deep ocean sound levels (Figure 1) (Wenz 1962). This splitting of the spectrum into passbands of a constant width of 1 Hz, however, does not represent how animals perceive sound.

Because animals perceive exponential increases in frequency rather than linear increases, analyzing a sound spectrum with passbands that increase exponentially in size better approximates real-world scenarios. In underwater acoustics, a spectrum is commonly split into 1/3-octave-bands, which are one-third of an octave wide; each octave represents a doubling in sound frequency. A very similar measure is to logarithmically divide each frequency decade into 10 passbands, which are commonly misnamed the 1/3-octave-bands rather than deci-decades; we use this naming in the report. The centre frequency of the ith 1/3-octave-band, $f_c(i)$, is defined as:

$$f_c(i) = 10^{i/10}\ , \quad \text{(A–11)}$$

and the low (f_{lo}) and high (f_{hi}) frequency limits of the ith 1/3-octave-band are defined as:

$$f_{lo} = 10^{-1/20} f_c(i) \quad \text{and} \quad f_{hi} = 10^{1/20} f_c(i)\ . \quad \text{(A–12)}$$

The 1/3-octave-bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure A-2).

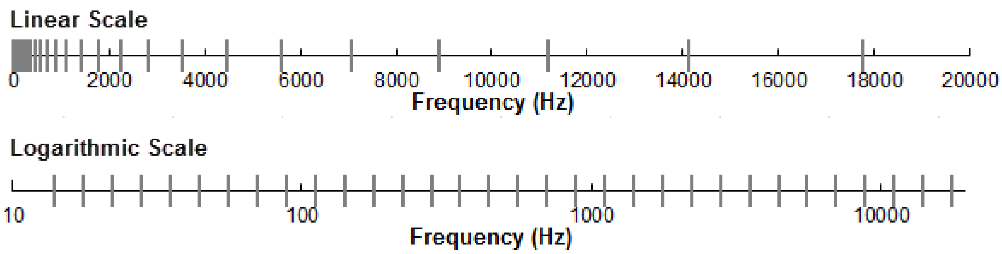

Figure A-2. One-third-octave-bands shown on a linear frequency scale and on a logarithmic scale.

The sound pressure level in the *i*th 1/3-octave-band $(L_b^{(i)})$ is computed from the power spectrum $S(f)$ between f_{lo} and f_{hi}:

$$L_b^{(i)} = 10\log_{10}\left(\int_{f_{lo}}^{f_{hi}} S(f)df\right). \quad \text{(A–13)}$$

Summing the sound pressure level of all the 1/3-octave-bands yields the broadband sound pressure level:

$$\text{Broadband SPL} = 10\log_{10}\sum_i 10^{L_b^{(i)}/10}. \quad \text{(A–14)}$$

Figure A-3 shows an example of how the 1/3-octave-band sound pressure levels compare to the power spectrum of an ambient noise signal. Because the 1/3-octave-bands are wider with increasing frequency, the 1/3-octave-band SPL is higher than the power spectrum, especially at higher frequencies. 1/3-octave-band analysis is applied to both continuous and impulsive noise sources. For impulsive sources, the 1/3-octave-band SEL is typically reported.

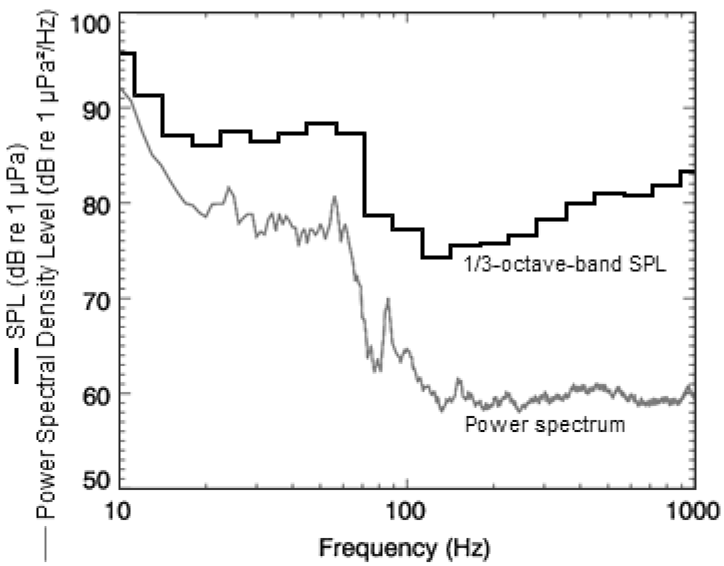

Figure A-3. A power spectrum and the corresponding 1/3-octave-band sound pressure levels of example ambient noise shown on a logarithmic frequency scale. Because the 1/3-octave-bands are wider with increasing frequency, the 1/3-octave-band SPL is higher than the power spectrum.

A.2. Vessel Noise Detection

Vessels are detected in two steps:

1. Detect constant, narrowband tones produced by a vessel's propulsion system and other rotating machinery (Arveson and Vendittis 2000). These sounds are also referred to as tonals. We detect the tonals as lines in a 0.125 Hz resolution spectrogram of the data.
2. Assess the rms SPL for each minute in the 100–315 Hz frequency band. Figure A-4 shows an example with a bandwidth of 40–315 Hz, which commonly contains most sound energy produced by mid-sized to large vessels; however, for this study, most of the energy below 100 Hz is likely due to seismic noise. Background estimates of the shipping band SPL and broadband SPL are then compared to their median values over the 12 h window, centred on the current time.

Vessel detections are defined by three criteria:

- The SPL in the shipping band is at least 3 dB above the median.
- At least 3 shipping tonals (0.125 Hz bandwidth) are present.
- The SPL in the shipping band is within 12 dB of the broadband SPL (Figure A-4).

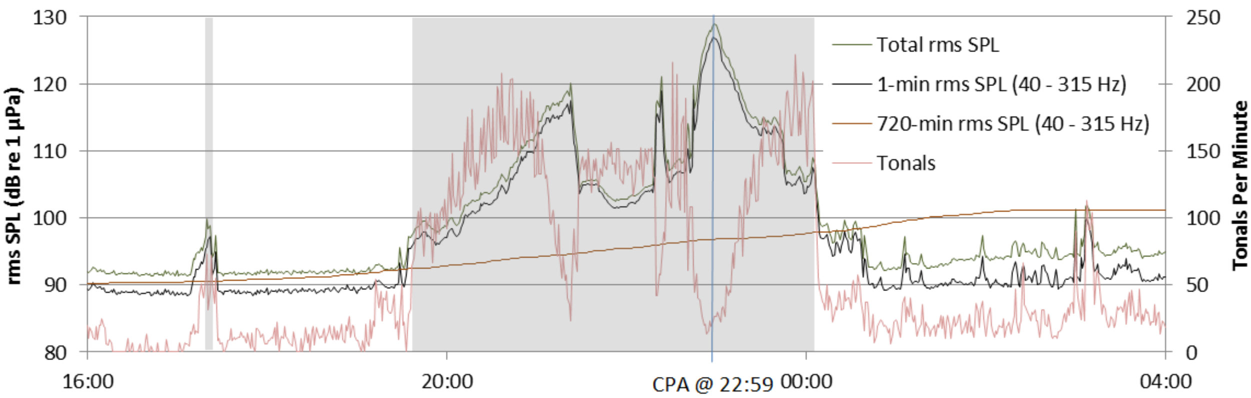

Figure A-4. Example of broadband and 40–315 Hz band SPL, as well as the number of tonals detected per minute as a ship approached a recorder, stopped, and then departed. The shaded area is the period of shipping detection. Fewer tonals are detected at the ship's closest point of approach (CPA) at 22:59 because of masking by broadband cavitation noise and due to Doppler shift, that affects the tone frequencies.

A.3. Seismic Survey Event Detection

Seismic pulse sequences are detected using correlated spectrogram contours. We calculate spectrograms using a 300 s long window with 4 Hz frequency resolution and a 0.05 s time resolution (Reisz window). All frequency bins are normalized by their medians over window the 300 s window. The detection threshold is three times the median value at each frequency. Contours are created by joining the time-frequency bins above threshold in the 7–1000 Hz band using a 5 × 5 bin kernel. Contours 0.2–6 s in duration with a bandwidth of at least 60 Hz are retained for further analysis.

An "event" time series is created by summing the normalized value of the frequency bins in each time step that contained detected contours. The event time series is auto-correlated to look for repeated events. The correlated data space is normalized by its median and a detection threshold of 3 is applied. Peaks larger than their two nearest neighbours are identified, and the peaks list is searched for entries with a set repetition interval. The allowed spacing between the minimum and maximum time peaks is 4.8 to 65 s, which captures the normal range of seismic pulse periods. Where at least six regularly spaced peaks occur, the original event time series is searched for all peaks that match the repetition period within a tolerance of 0.25 s. The duration of the 90% SPL window of each peak is determined from the originally sampled time series, and pulses more than 3 s long are rejected.

A.4. Marine Mammal Detection

We apply automated analysis techniques to detect sounds from odontocetes, mysticetes, and pinnipeds in the acoustic data. Targeted signals for odontocetes are echolocation clicks and tonal whistles. Echolocation clicks are high-frequency with impulses ranging from 5 to over 150 kHz (Au et al. 1999, Møhl et al. 2000), while the whistles are commonly between 1 and 20 kHz (Steiner 1981, Rendell et al. 1999). Baleen whale and pinniped calls are lower in frequency and range predominantly between 15 Hz and 4 kHz (Berchok et al. 2006, Risch et al. 2007). The detectors are applied to the 128 ksps data (audio bandwidth up to 65 kHz for ~2 min of every 15 min).

A.4.1. Click Detection

We apply an automated click detector/classifier to the high-frequency data to detect clicks from sperm whales, beaked whales, porpoise, and delphinids (Figure A-5). This detector/classifier is based on the zero-crossings in the acoustic time series. Zero-crossings are the rapid oscillations of a click's pressure waveform above and below the signal's normal level (e.g., Figure A-5). Clicks are detected by the following steps (Figure A-5):

1. The raw data is high-pass filtered to remove all energy below 8 kHz. This removes most energy from other sources such as shrimp, vessels, wind, and cetacean tonal calls, while allowing the energy from all marine mammal click types to pass.
2. The filtered samples are summed to create a 0.5 ms rms time series. Most marine mammal clicks have a 0.1–1 ms duration.
3. Possible click events are identified with a Teager-Kaiser energy detector.
4. The maximum peak signal within 1 ms of the detected peak is found in the high-pass filtered data.
5. The high-pass filtered data is searched backwards and forwards to find the time span where the local data maxima are within 12 dB of the maximum peak. The algorithm allows for two zero-crossings to occur where the local peak is not within 12 dB of the maximum before stopping the search. This defines the time window of the detected click.
6. The classification parameters are extracted. The number of zero crossings within the click, the median time separation between zero crossings, and the slope of the change in time separation between zero crossings are computed. The slope parameter helps to identify beaked whale clicks, as beaked whale clicks increase in frequency (upsweep).
7. The Mahalanobis distance between the extracted classification parameters and the templates of known click types is computed. The covariance matrices for the known click types, computed from thousands of manually identified clicks for each species, are stored in an external file. Each click is classified as a type with the minimum Mahalanobis distance, unless none of them are less than the specified distance threshold.

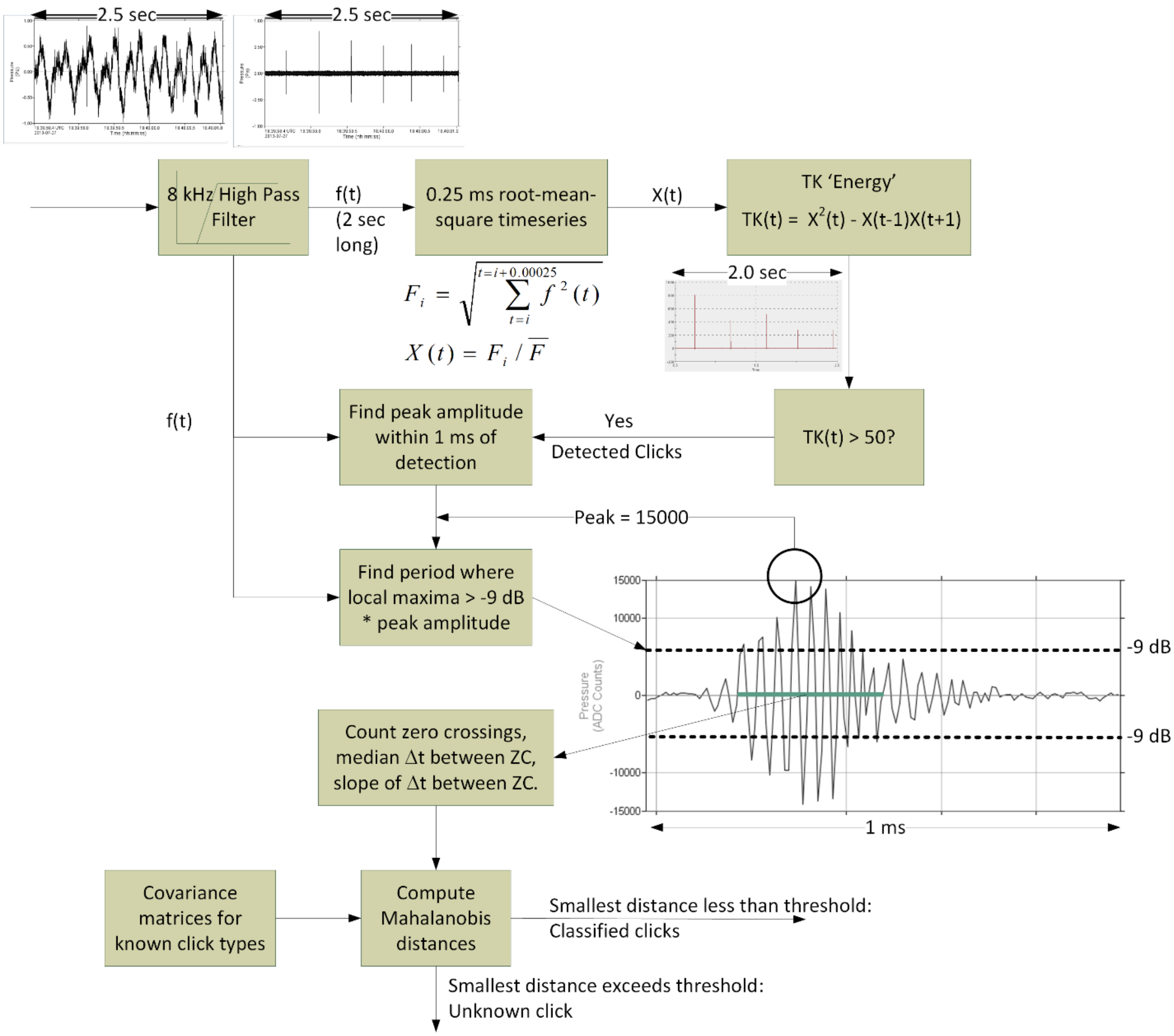

Figure A-5. The click detector/classifier and a 1-ms time-series of four click types.

A.4.2. Tonal Call Detection

The tonal call detector identifies data likely to contain marine mammal moans, songs, and whistles. Tonal calls are detected by the following steps:

1. Spectrograms of the appropriate resolution for each mammal call type that are normalized by the median value in each frequency bin for each detection window (Table A-1) are created.
2. Adjacent bins are joined and contours are created via a contour-following algorithm (Figure A-6).
3. A call sorting algorithm determines if the contours match the definition of a mammal call type (Table A-2).

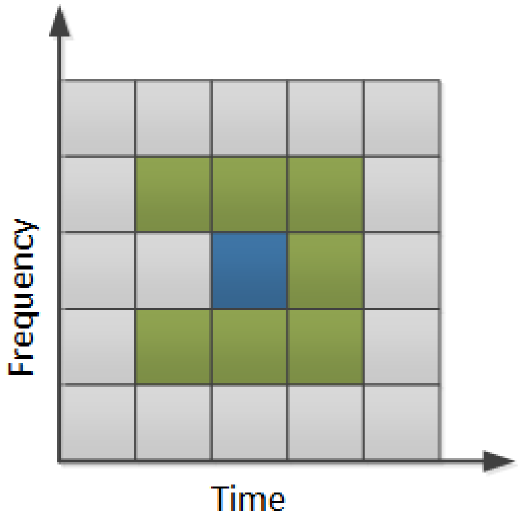

Figure A-6. Illustration of the search area used to connect spectrogram bins. The blue square represents a bin of the binary spectrogram equalling 1 and the green squares represent the potential bins it could be connected to. The algorithm advances from left to right so grey cells left of the test cell need not be checked.

Table A-1. Fast Fourier Transform and detection window settings used to detect tonal calls of marine mammal species expected in the data. Values are based on JASCO's experience and empirical evaluation on a variety of data sets.

Possible species	Call type	FFT			Detection window (s)	Detection threshold
		Resolution (Hz)	Frame length (s)	Timestep (s)		
Pilot whales	Whistle	16	0.03	0.015	5	3
Dolphin	Whistle	64	0.015	0.005	5	3
Humpback whales	Moan	4	0.2	0.05	5	3
Blue whales	Infrasonic moan	0.125	2	0.5	120	4
Fin whales	20-Hz note	1	0.2	0.05	5	4
Sei whales	Downsweep	3.25	0.2	0.035	5	3.5

Table A-2. Call sorter definitions for the tonal calls of cetacean species expected in the area.

Possible species	Call type	Frequency (Hz)	Duration (s)	Bandwidth (Hz)	Other detection parameters
Pilot whales	Whistle	1,000–10,000	0.5–5	>300	Minimum frequency <5,000 Hz
Dolphin	Whistle	4,000–20,000	0.3–3	>700	Maximum instantaneous bandwidth = 5,000 Hz
Humpback whales	Moan	100–700	0.5–5	>50	Maximum instantaneous bandwidth = 200 Hz
Blue whales	Infrasonic moan	15–22	8–30	1–5	Minimum frequency <18 Hz
Sei whales	Downsweep	20–150	0.5–1.7	19–120	Maximum instantaneous bandwidth = 100 Hz Sweep rate = −100 to −6 Hz/s
Fin whales	20 Hz downsweep	8–40	0.3–3	>6	Minimum frequency <17 Hz Sweep rate = −100 to 0 Hz/s

A.4.3. Validation of Automated Detectors

Automated detectors are often developed and tested with example data files that contain a range of vocalisation types and representative background noise conditions. However, test files normally cannot cover the full range of possible conditions. Therefore, a selection of files must be manually validated to check the detector performance in the specific conditions of each recorder. For each recorder and for each species or call type, a sample of files containing low, medium, and high numbers of detections was reviewed. Files that contained early or late automated detections were primarily selected to help bound the period of occurrence of a species/call type. The automated detector results were checked to evaluate the true presence or absence of each species, as well as vessels and other anthropogenic signals. These validated results were fed to a maximum likelihood estimation (grid search) algorithm that maximized the probability of detection and minimized the number of false alarms using the 'F-score':

$$F = \frac{(1+\beta^2)P * R}{(\beta^2)P + R}; P = \frac{TP}{TP+FP}; R = \frac{TP}{TP+FN}$$

where *TP* (true positive) is the number of correctly detected files, *FP* (false positive) is the number of files that are false detections, and *FN* (false negatives) is the number of files with missed detections. *P* is the classifier's precision, representing the proportion of detected calls that are true positives. A *P* value of 0.9 means that 90% of the detections are correctly classified, but says nothing about whether all calls in the dataset were identified. *R* is the classifier's recall, representing the proportion of calls in the dataset that are detected by the detector. An *R* value of 0.8 means that 80% of all calls in the dataset were detected, but says nothing about how many classifications were wrong. Thus, a perfect detector/classifier would have *P* and *R* values equal to 1. An F-score is a combined measure of *P* and *R* where an F-score of 1 indicates perfect performance–all events are detected with no false alarms. The algorithm determines a classification threshold for each species that maximizes the F-score. Table A-3 shows the dependence of the classification threshold on the β-parameter and its effect on the precision and recall of the detector and classifier system. β is the relative weight between the recall and precision. Here, we have made precision more important than recall as a β of 0.5 means the recall has half the weight of the precision.

Table A-3. Effects of changing the F-score β-parameter on the classification threshold, precision, and recall for the odontocete clicks.

β	Classification threshold	Precision $P = \frac{TP}{TP+FP}$	Recall $R = \frac{TP}{TP+FN}$	F-score
2	25	0.87	0.95	0.93
0.5	50	0.91	0.91	0.91

Detection time series based on the restrictions above are plotted using JASCO's ADPT software and critically reviewed. Questionable detections based on time of year and location or overlap with the detection period of other species are manually reviewed and removed from the plots if they are found to be false. The detector performance metrics presented in Section 3.4.1.1 are based on the fully revised and edited results as shown in the detection time series. Detections are also presented as spatial plots showing the number of detections at each station over selected periods.