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Fin whale continuous frequentation of St. Lawrence habitats detected from multi-year passive acoustic monitoring (PAM)

Nathalie Roy[a], Yvan Simard[a,b], Florian Aulanier[a], and Samuel Giard[a]

[a]Fisheries and Oceans Canada
Maurice Lamontagne Institute,
850 route de la Mer,
Mont-Joli, QC, Canada G5H-3Z4

[b)] Fisheries and Oceans Canada Chair in underwater acoustics applied to marine mammals and their ecosystem,
Marine Science Institute, University of Québec at Rimouski
310 Allée des Ursulines,
Rimouski, QC, Canada G5L-3A1

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Canada

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

The Atlantic fin whale is a regular visitor to the Lower Estuary and Gulf of St. Lawrence. From 2010 to 2017, their frequentation of this feeding habitat was monitored with a passive acoustic monitoring (PAM) observatory composed of four multi-year stations and four one-year stations that covered the two Gulf entrances and the expected incursion routes. The typical pulsed 20 Hz infrasonic call of fin whales was monitored with a dedicated algorithm.

Fin whale calls were detected year-round although only sporadically in June and July. In the southeastern Gulf, the intense call period extended from August to May. In the northwestern Gulf, it generally ended earlier in January. Calls were detected in both entrances of the Gulf, but occurred much more frequently in Cabot Strait. The occurrence time series does not support a slow synchronous annual migration of the individuals from the Atlantic to the Estuary and vice versa. The co-occurrence of detections at all sites during a large part of the annual cycle indicates a dispersed population over numerous sites of interest in the studied area.

INTRODUCTION

The Atlantic fin whale (*Balaenoptera physalus*) population has been designated as 'special concern' by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2005), and has the same designation under the Canadian Species at Risk Act (SARA). One objective of the fin whale management plan (DFO 2016) is to monitor population size and trends in Canadian waters.

Information on spatial and temporal distribution of the fin whale in the Estuary and Gulf of St. Lawrence is fragmentary due to limited survey effort, which is highly localized and coastal (reviewed in Lesage et al. 2007; but see (Kingsley and Reeves 1998, Lawson and Gosselin 2009). Observations outside summer and fall months are scarce.

Fin whales emit a unique sound that can be used to monitor their presence. This is the 20 Hz pulse (Edds 1988, Watkins et al. 1987), a frequency-modulated (FM) downsweep between ~25-17 Hz, with a duration of ~1 s. This sound is generally produced in long sequences, called "bouts", which may last many hours. Inter-pulse interval (IPI) patterns vary between oceans and are possibly indicative of different stocks. In the Northwest Atlantic, the IPI ranges between 10 and 15 s (Delarue et al. 2014, Delarue et al. 2009, Hatch and Clark 2004, Morano et al. 2012, Oleson et al. 2014). The powerful call has a source level (SL) of ~189 dB re 1 µPa @ 1 m (Širović et al. 2007, Weirathmueller et al. 2013).

In this study, our objective is to fill the knowledge gap on fin whale seasonal frequentation of the St. Lawrence by using long-term recordings of their specific calls from a passive acoustic monitoring (PAM) observatory.

MATERIAL AND METHODS

DATA ACQUISITION

The PAM observatory included eight stations located in the Lower Estuary and Gulf of St. Lawrence (Fig. 1). Two were located at the entrances of the Gulf, in Cabot and Belle Isle Straits. One station was in the most upstream baleen whale feeding ground (Simard 2009, Simard and Lavoie 1999), at 'Les Escoumins' in the Estuary, with another station about 75 km further downstream near Baie-Comeau and called the 'Lower Estuary' station. Two stations were positioned around the whale feeding area east of the Gaspé peninsula called 'Cap d'Espoir' and 'Percé', and one station was north-east of New Brunswick called 'Shediac'. The last station, named 'Old Harry', was along an expected two-way migration path between the western Gulf feeding areas and the Cabot Strait entrance. At each station, an AURAL autonomous underwater recorder (AURAL-M2, Multi-Electronique Inc., Rimouski, Qc, Canada) was deployed ~5-50 m from the bottom using a typical I-type oceanographic mooring, comprised of an anchor, an acoustic release, the instrument and low-drag streamlined sub-surface floats (cf. Simard and Roy 2008). The AURALs sampled the 16-dB pre-amplified acoustic signal with 16-bit resolution and sampling rates between 8192 and 32768 Hz, for 15 or 30 min per hour depending on the year. The receiving sensitivity of the HTI 96-MIN (High Tech Inc., Gulfport, MS) hydrophone equipping the AURAL is -164 ± 1 dB re 1V µPa-1 over the < 4-kHz bandwidth used here, as confirmed by calibrations made at the calibration facility at Defense Research and Development of Canada – Atlantic (Dartmouth, NS). The recordings covered an eight year period from 2010 to 2017 with series lengths varying between stations from one year to eight years (Fig. 2).

DATA ANALYSIS

To detect fin whale 20 Hz calls (Fig. 3), an automatic detection algorithm used time-frequency matching of the signal with six representative synthetic 20 Hz call templates. These templates represent the different time-frequency patterns of the 20 Hz calls found in the study area. They were obtained from a k-means cluster analysis (Legendre and Legendre 1998) of the 20 Hz call spectrogram patterns of a subset of 1077 validated 20 Hz pulses from two different stations.

Briefly, the acoustic signal was downsampled to 200 Hz and a high-resolution spectrogram was computed and cleaned of noise to enhance signal to noise ratio (SNR) (Fig. 4, step 1). The match with any one of the synthetic call templates was examined in a time-frequency window whose length included both the call and noise portions before and after the call (Fig. 4, step 2). Detection was triggered when the match index exceeded a threshold set to minimize both missed detections and false alarms. The latter mostly occurred at low SNRs and were filtered out and validated by an experienced observer (Fig. 4, step 3). In this paper, the metric used to report call occurrence (i.e. fin whale frequentation index) is the number of hours-with-calls per day, *Nhd.* Only one detection is needed for this metric to be non-zero. Because of the high calling rate per hour and the resulting high number of calls detected (> 200,000 detections/year in some cases), the validation step ignored detections with SNRs below 0 dB. This approach made validation more manageable by removing a large number of false detections, but generally did not affect the number of hours where calls were detected (only 1% of the total hourly presence were lost at a test station - Old Harry during June-Sept 2012, N=21,802 call detections).

The call detection recall index (i.e. percentage of detected true calls) of this algorithm is 77%, which was determined from manual examination of a subsample of the recordings at two stations (Old Harry and Belle-Isle) representing 1119 true calls. Given this high recall index and the high recurrence of these 20 Hz calls in one hour, the percentage of missed hours-with-calls is likely to be nearly nil, since one call is sufficient to validate an hour-with-calls. Therefore the fin whale call occurrence series presented hereafter can be considered as likely exempt of false alarms and missed events when the PAM was active.

The PAM system was considered inactive when noise levels (NL) exceeded the expected received level (RL_{call}) of targeted calls. To assess the importance of inactive call occurrences through the recordings, the NL time series in the call frequency band and the cumulative distribution function (cdf) of the corresponding RL_{call} were computed for a few annual series. Times when NL > [cdf(RL_{call}) = 0.95] (i.e. chances of detecting a call was less than 5%) were considered as periods of inactivity. The proportion of time when PAM was active, P_{det}, was obtained by the complement of the inactive proportion. The lowest estimate obtained for P_{det} was 85%.

The call detection capacity of a PAM system depends on its location in the three-dimensional basin, the call source level (SL), transmission loss (TL), and noise level (NL) (Simard et al. 2008). For comparing detection series at different locations in a non-homogeneous basin, such as continental shelves, the local detection areas must be taken into account (Helble et al. 2013, Širovic et al. 2015). Detection areas were calculated for the recording periods at the PAM stations using a parabolic equation (PE) propagation model propagating a 20 Hz call with 189 dB re 1 µPa @ 1 m SL (Širović et al. 2007); the resulting RL_{call} at the stations were compared to the median NL in the same frequency band. The parabolic equation model (Collins 1993, OALIB 2016) was configured with: (1) typical summer water mass characteristics from the outputs of an operational three-dimensional circulation model of the Estuary and Gulf of St. Lawrence for the month of July 2013 (Senneville and Lefaivre 2015); and (2) bottom geoacoustic properties from Loring and Nota (1973) and Jensen *et al.* (2011) (Aulanier *et al.* 2016a, Aulanier *et al.* 2016b).

The 15-m deep source (Stimpert *et al.* 2015) was radially positioned in steps of 1 km along multiple evenly spaced 200-km long radii centered at the PAM station. Interpolation was used to fill 360 1°-pie slices delimited by the radii. Call detection was assumed to stop when SNR ≤ 0 dB. The detection area was the sum of all 1-km^2 source pixels that produced a SNR > 0 dB. The relative detection areas, RA_{det} (i.e. the ratio of detection area at the station to the smallest detection area of all stations) were computed for each PAM station.

RESULTS

The size of the detection areas within a 200 km radius at the PAM stations depends on water mass characteristics, but also largely on the local bathymetry (Fig. 5). Detection areas ranged from 2,485 km^2 at the Belle Isle station to 58,044 km^2 at Old Harry in the larger basin of the Gulf (Table 1). This represents a relative factor of 23.4. The Cabot Strait and the Cap d'Espoir detection areas were respectively 8.0 and 5.3 times that of Les Escoumins station. These relative detection areas must be kept in mind when comparing the call detection time series among stations, and are illustrated in Figure 5. However, the hours-with-call metric is less sensitive to the variation in detection areas since a single call detection is enough to indicate presence for a given hour. Detection area for the Percé station has not been evaluated, but is expected to be similar to the Cap d'Espoir station nearby. Because of their proximity, the call results for these two stations are combined (Fig 6).

The 20 Hz calls were detected year-round in the surveyed area, notably throughout the winter (Fig. 6, Table 2). The calls were present at all stations (Fig. 6) with a clear seasonal recurrence pattern from year to year (e.g. Fig. 7). Their occurrences were low in June and July at all stations. For a large part of the recordings, fin whales were simultaneously present in all detection areas from Les Escoumins to Cabot Strait. The two PAM stations in the southeastern part of the Gulf detected fin whale calls for a longer proportion of the year than those of the head of the Laurentian Channel in the Estuary and the basin east of the Gaspé Peninsula (Figs. 1, 6; Table 2). The annual period of call occurrence at the PAM stations varied from 183 days in the Percé area to year round in the Old Harry area (Table 2).

At Les Escoumins, the call occurrence typically picked up in August and ended in late December or January (Table 2, Fig. 7a), with a no-call period from the end of January to the end of March (Fig. 7a). In the southern Gulf stations, the calls picked up in August and dropped in April (Fig. 7b).

DISCUSSION

The present PAM work is the first attempt to systematically monitor the frequentation of the whole Estuary and Gulf of St. Lawrence inland sea by fin whales from the detection of their specific sounds over the complete annual cycle. This contribution establishes a baseline of fin whale frequentation of this part of their home range in the Northwest Atlantic. Results clearly show that fin whales occupy the whole region year-round, except for a ~2-month winter departure from the most upstream area in the Lower St. Lawrence Estuary. Fin whales were present from the south to the most upstream sites at the same time, which indicates simultaneous use of numerous sites by fin whales within the basin. These results also do not support the idea of a synchronized slow seasonal migration of a unique coordinated group gradually migrating to and from the Atlantic waters. The calling occurrence is clearly seasonally patterned and is occurring between ~ mid-summer and spring. How much of this pattern reflects true seasonal changes in abundance vs. changes in individual calling rate is unknown.

The daily occurrence metric index used to express the call detections is less sensitive to the difference in detection area between the stations than the alternative metrics of call numbers per units of time. The hour-with-calls metric is positive when a single call is detected and does not change if more than one call is detected in the same hour, either in response to increased detection area or number of callers. Assuming similar whale distributions and calling rate, the call detections likely increase with the detection area, as well as the probability to detect a call. This latter effect might affect the estimated daily occurrence for low-occurrence periods but not for high-occurrence ones. To further minimize possible effects of different detection areas by PAM stations in a surveyed region, a larger number of stations, whale tracking, and call count areal density estimation would be needed.

The identification of active PAM times, P_{det}, used the 95th percentile of the call energy cumulative distribution function to decide when noise was too high for detection. The use of another less permissive centile may produce a slightly different call occurrence time series, but possible effects are limited since the effective duty time was higher than 85% when recording was on. For further monitoring, PAM station locations could be improved by examining the detection area for different locations in the basin with the modeled probability of shipping noise (Aulanier *et al.* 2016b), to better cover the whole region with a limited number of stations.

ACKNOWLEDGEMENTS

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TABLES

Table 1. Relative median detection areas at the PAM stations.

PAM station	**Call detection area (km^2)**	**Relative call detection area (RA_{det})**
Les Escoumins	4768	1.9
Lower Estuary	8098	3.3
Belle-Isle	2485	1.0
Cap d'Espoir	25183	10.1
Shediac	15107	6.1
Old Harry	58044	23.4
Cabot	38098	15.3

Table 2. Earliest and latest dates and durations of 20 Hz fin whale seasonal call occurrences at the PAM stations. Underlined italics indicate a seasonal call occurrence period which possibly began before recording started or continued after end of recording. Periods are cut when no calls occurred for more than 30 days.

PAM station	***$BWF_{A\text{-}call}$* index**		
	Start date	**End date**	**days**
Belle-Isle	*2010-11-02*	2010-11-09	>8
	2011-08-26	*2011-10-25*	>61
Les Escoumins	*2007-10-29*	2007-12-10	>43
	2008-04-27	2008-04-29	3
	2008-06-12	*2008-06-12*	>1
	2008-08-06	2009-01-02	>150
	2009-04-19	2009-04-19	1
	2009-06-19	2009-06-23	5
	2009-08-01	*2009-10-26*	>87
	2010-07-08	2010-12-29	>175
	2011-03-27	2011-04-23	28
	2011-05-30	2012-01-06	222
	2012-08-22	2012-12-31	132
	2013-06-09	2013-06-09	1
	2013-07-11	2013-07-17	7
	2013-09-10	2013-12-08	90
	2014-10-30	2014-12-16	48
	2015-08-11	2015-08-12	2
	2015-09-28	2016-01-12	107
	2016-03-28	2016-04-19	23
	2016-07-11	2017-01-24	198
Lower Estuary	*2012-11-05*	2013-01-20	>77
	2013-03-06	2013-04-19	45
	2013-05-31	2013-05-31	1
	2013-07-05	2013-07-05	1
	2013-09-05	*2013-10-29*	>55
Cap d'Espoir/Percé	2011-09-04	2012-01-08	127
	2012-02-25	2012-03-24	29
	2013-08-30	2014-01-01	125
	2014-08-30	2015-01-12	136
	2015-09-03	2016-02-06	157
	2016-08-05	2017-02-03	183
Shediac	2015-07-18	2015-07-18	1
	2015-09-20	*2015-10-20*	>31
	2015-11-01	2016-01-14	>75
	2016-08-31	*2016-10-20*	>51

PAM station	$BWF_{A\text{-}call}$ index		
	Start date	**End date**	**days**
Old Harry	*2010-11-16*	*2011-10-24*	>343
	2011-11-04	*2012-10-19*	>351
	2012-11-06	*2013-02-24*	>111
	2013-06-18	2013-06-21	>4
	2013-08-11	*2014-05-30*	>293
	2014-06-03	*2015-02-17*	>260
	2015-07-06	*2016-04-30*	>300
	2016-06-11	2016-06-17	>7
	2016-07-18	*2017-06-04*	>322
Cabot	*2010-11-09*	*2012-09-12*	>674
	2012-11-07	*2013-03-07*	>121

FIGURES

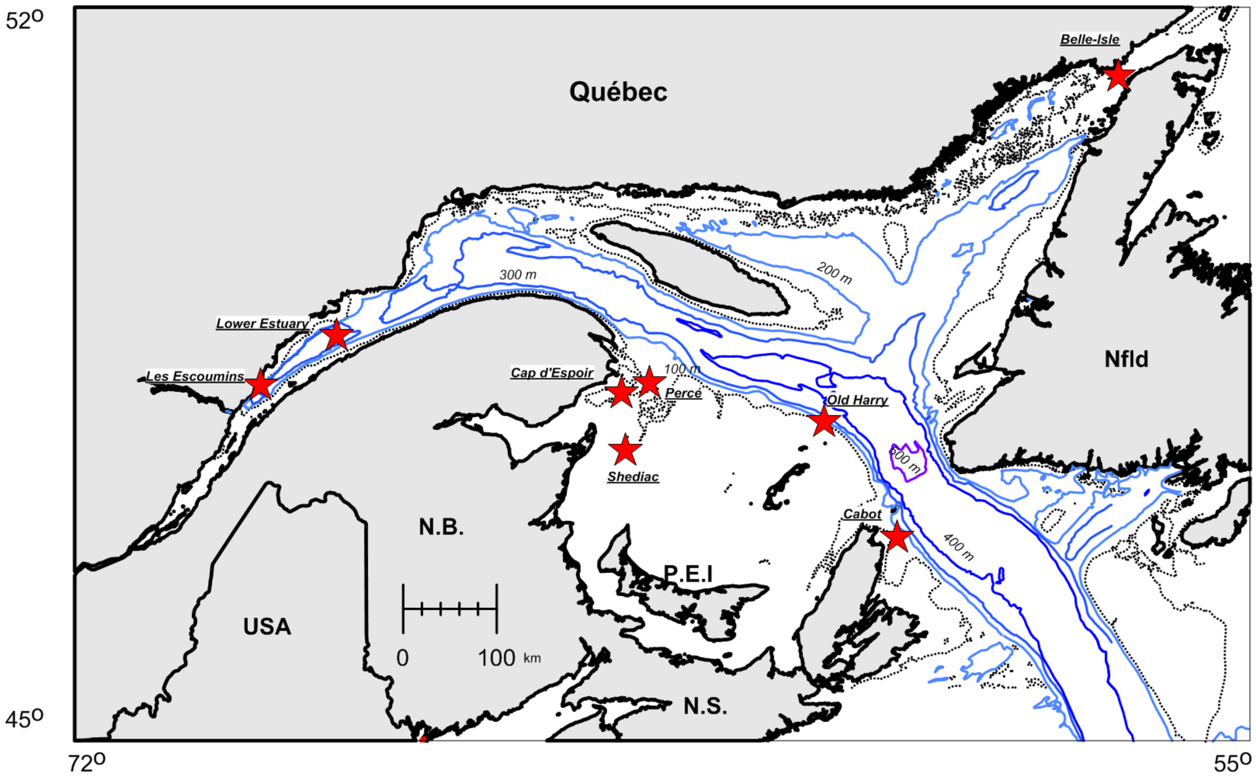

Figure 1. Map of the Estuary and Gulf of St. Lawrence showing the location of the eight stations of the PAM observatory and 100-m bathymetric contours.

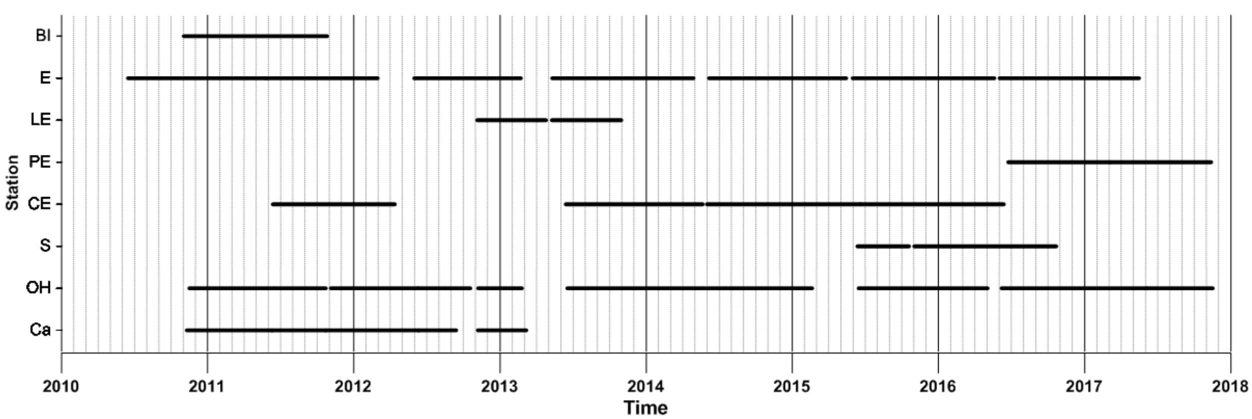

Figure 2. Recording schedule at the eight stations shown in Fig. 1, sorted from north to south. BI: Belle Isle strait; E: Les Escoumins; LE: Lower Estuary; PE: Percé; CE: Cap d'Espoir; S: Shediac; OH: Old Harry; Ca: Cabot Strait.

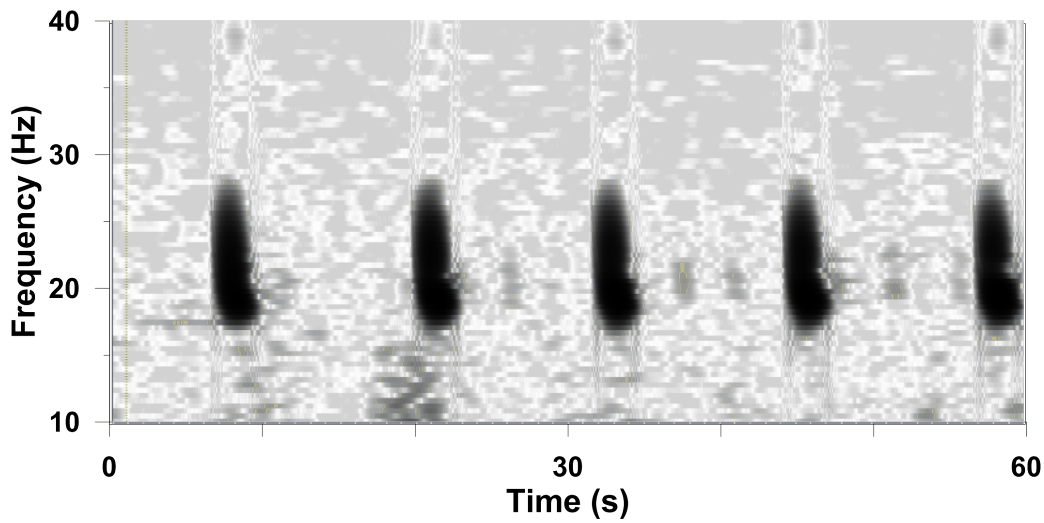

Figure 3. Spectrogram example of a series of fin whale 20-Hz calls.

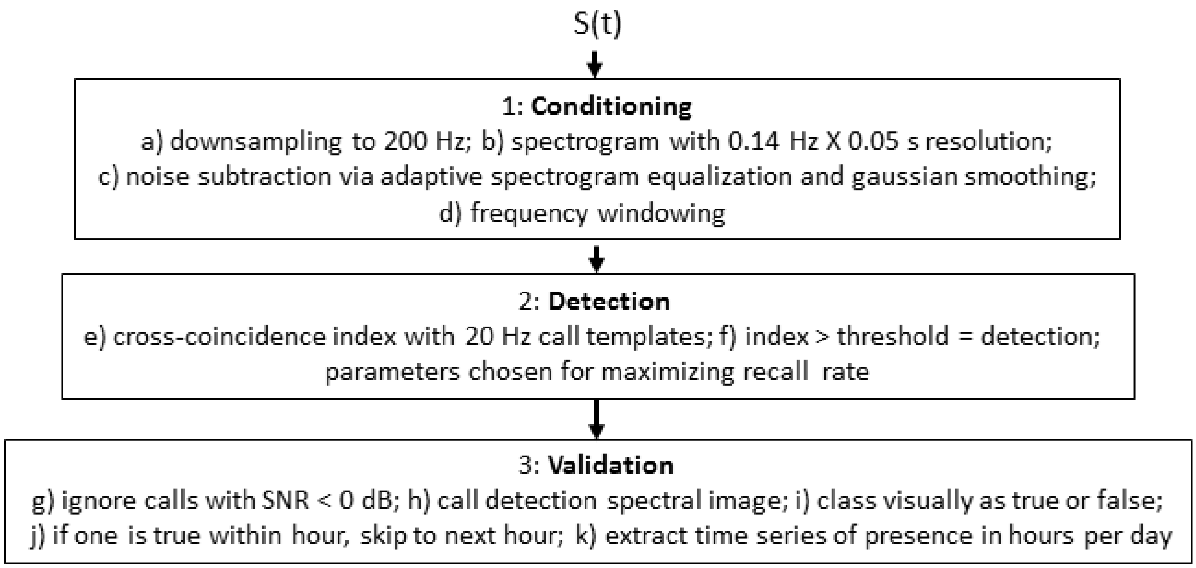

Figure 4. Scheme of the 20-Hz call detection algorithm.

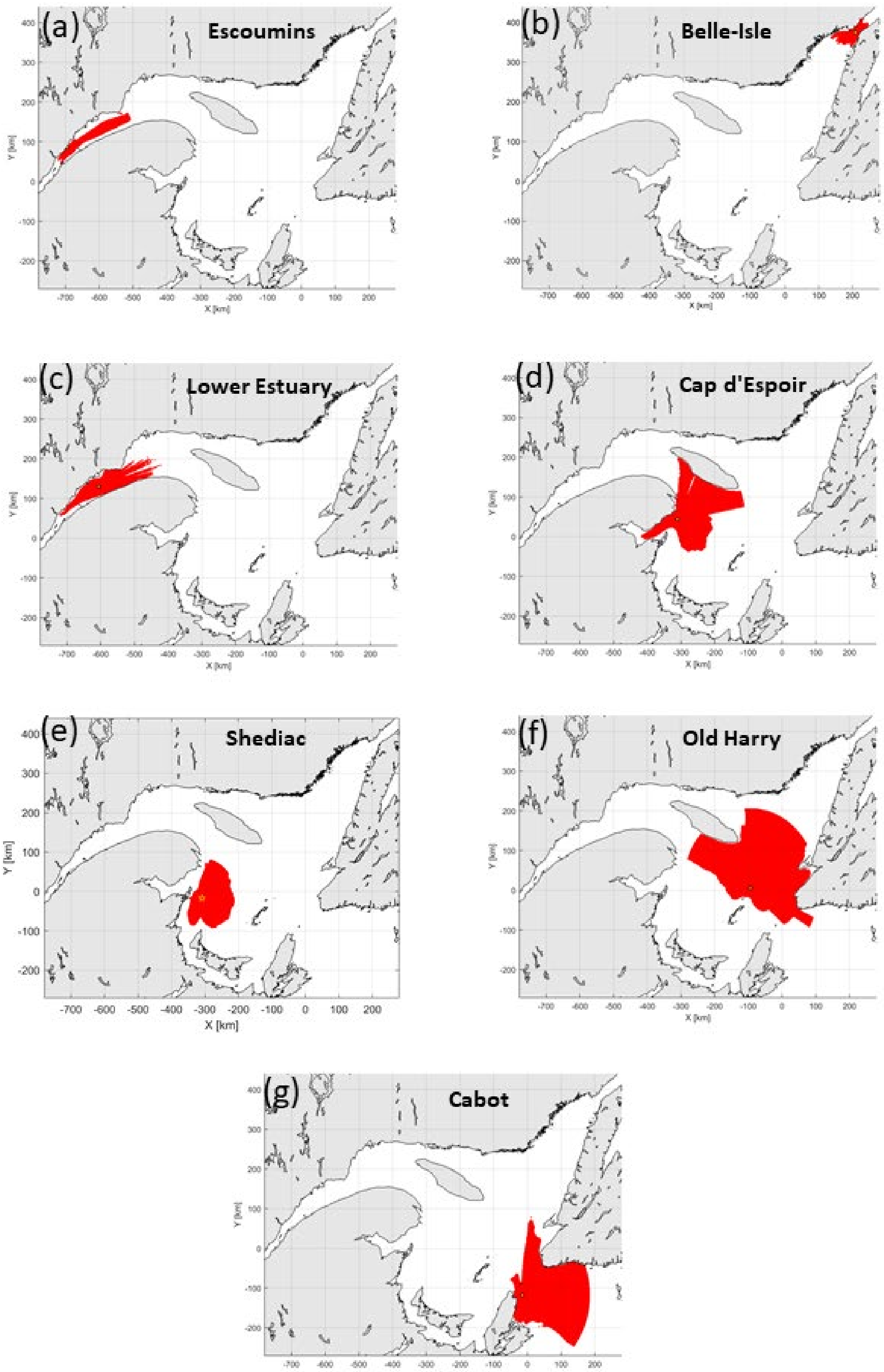

Figure 5. Maps of the median detection areas for 20 Hz calls at the PAM stations.

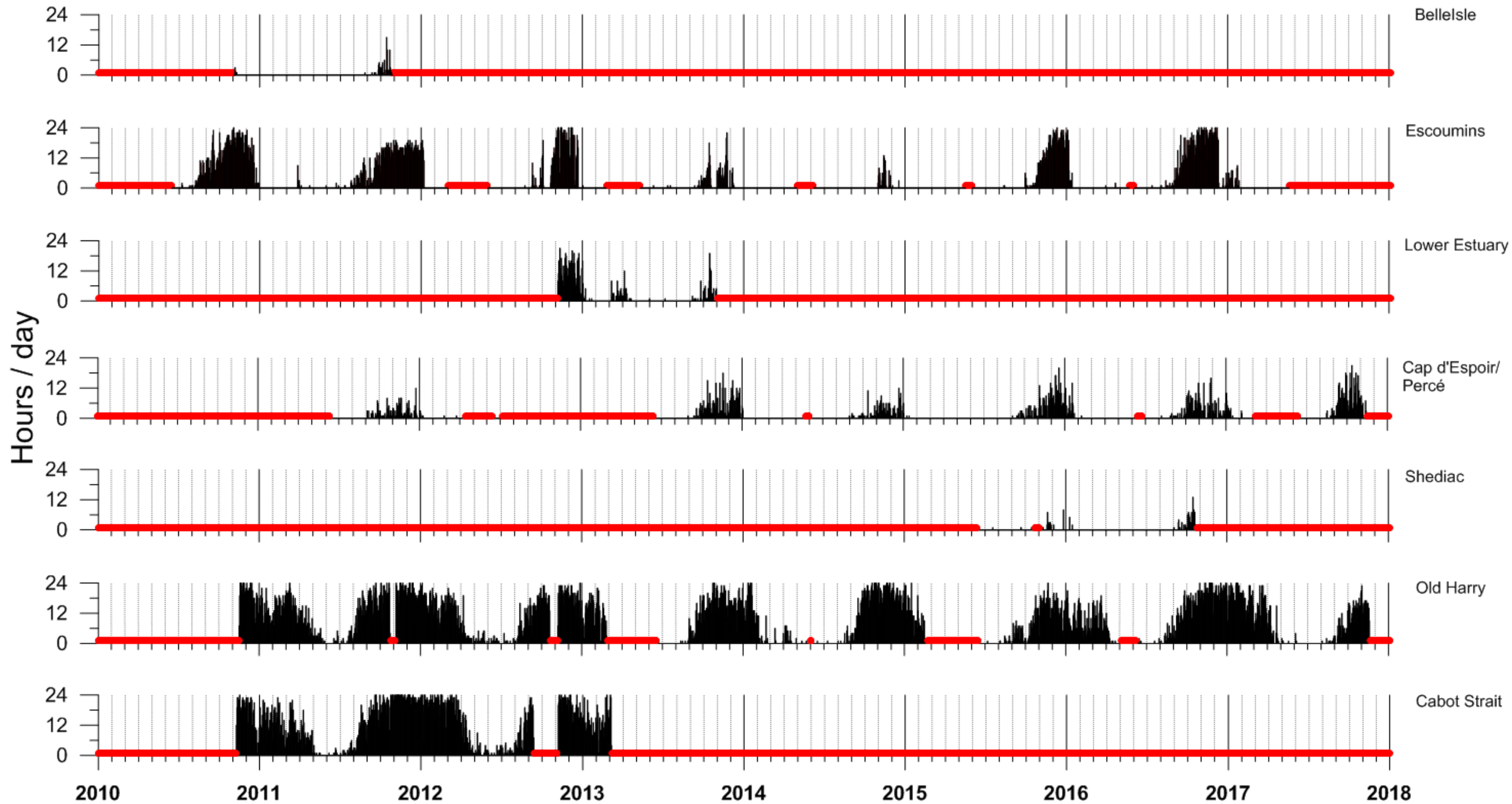

Figure 6. Time series of number of hours with fin whale calls per day at the PAM station in the Estuary and Gulf of St. Lawrence from 2010 to 2018. Bold red lines indicate periods without recordings. Cap d'Espoir is joined with Percé (which starts in 2016) for concision.

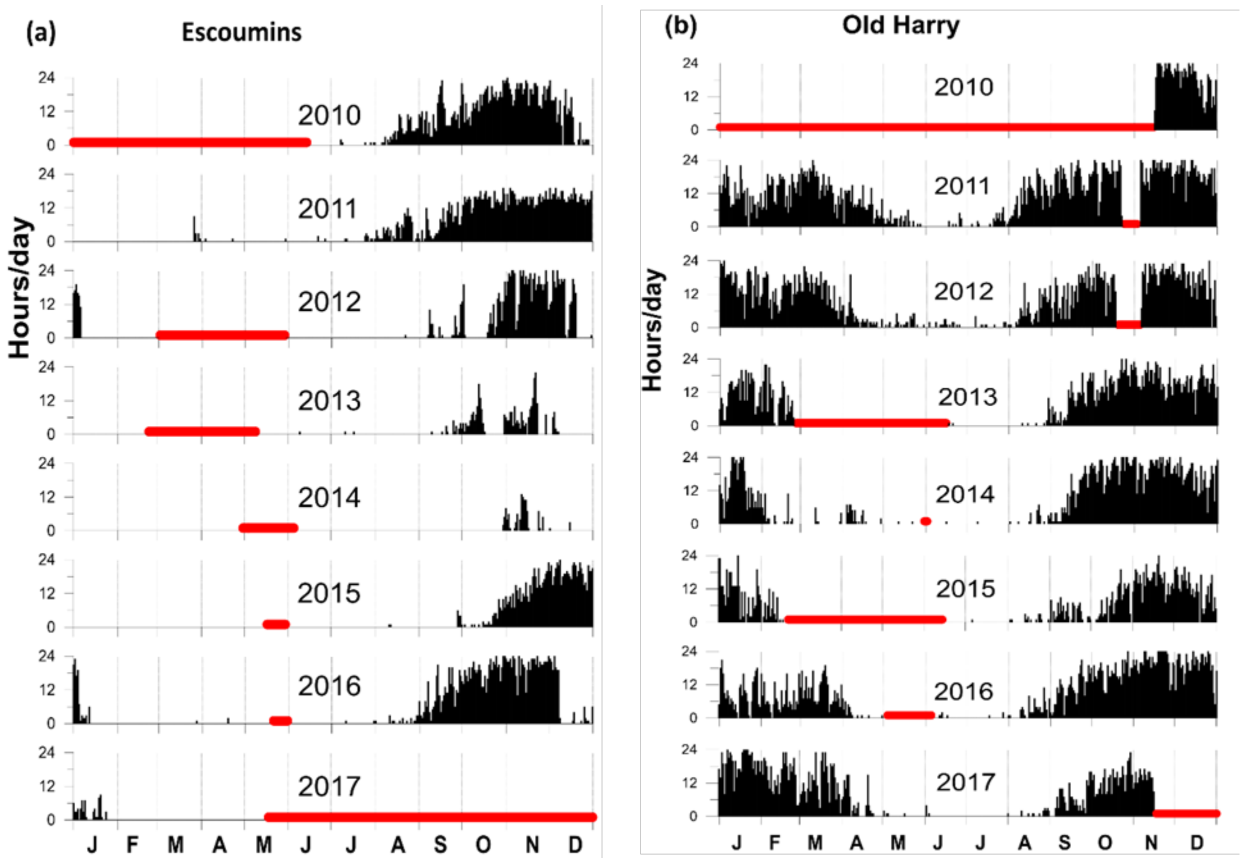

Figure 7. Annual time series of number of hours with fin whale calls per day at Les Escoumins (a) and Old Harry (b) PAM stations. Bold red lines indicate periods without recordings.