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Blue whale continuous frequentations of St. Lawrence habitats from multi-year PAM series

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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 endangered northwest Atlantic blue whale is a regular visitor of the Gulf of St. Lawrence where they feed upon aggregated krill. As part of the population recovery plan, a passive acoustic monitoring (PAM) observatory was set up to track the space-time patterns of blue whale use of this northwest Atlantic marginal sea from their species-specific calls from 2010 to 2015. The PAM network included 4 regular multi-year stations and 2 1-year stations covering the two Gulf entrances and the expected excursion routes. The most frequent “A-type” infrasonic call was tracked with a dedicated algorithm while the rarer and less energetic low frequency D-call was manually detected from the spectrograms, aided by an energy detector.

During the monitoring period, the blue whale was present year-round in the southern Gulf of St. Lawrence, and almost year-round in the Lower Estuary. They were not detected at the northeastern station near Belle Isle Strait. No clear lag between the appearance and disappearance at the stations along the inland route from the Atlantic was observed, which does not plea in favour of a seasonal synchronous migration. The co-occurrence of detections at all sites during a large part of the annual cycle indicate a dispersed population over numerous sites of interest in the studied area, which includes periods of arrival and departures as indicated by fluctuations in call occurrence. Results clearly show that blue whales occupy the whole region, not only during summer and fall, but year-round.

Fréquentation continue de la baleine bleue des habitats du Saint-Laurent à partir de la série pluriannuelle de monitorage par acoustique passive

RÉSUMÉ

Le rorqual bleu de l'Atlantique Nord-Ouest, en voie de disparition, est un visiteur régulier du golfe du Saint-Laurent où des agrégations de krill font partie de son aire d'alimentation. Dans le cadre du plan de rétablissement de cette population, un observatoire de monitorage par acoustique passive (PAM) a été mis en place pour suivre les patrons spatio-temporels de fréquentation de cette mer marginale de l'Atlantique Nord-Ouest par ces baleines, grâce à la détection de leurs sons spécifiques entre 2010 et 2015. L'observatoire PAM était constitué d'un réseau de 4 stations pluriannuelles et de 2 stations annuelles couvrant les 2 entrées du golfe du Saint-Laurent, ainsi que les principales routes de passage. Les plus fréquentes vocalises infrasoniques de type A ont été suivies au moyen d'un algorithme dédié. Les vocalises D, plus rares et d'énergie moindre, furent détectées visuellement sur les spectrogrammes à haute-résolution avec l'assistance d'un détecteur d'énergie.

Pendant la période d'écoute, la baleine fut détectée à l'année longue dans la partie méridionale du golfe du Saint-Laurent, et quasiment toute l'année dans l'estuaire maritime. Aucune détection n'a été recensée à la station située près du détroit de Belle Isle. Les débuts et fins des périodes de détection annuelles aux stations ne présentèrent pas de délais nets qui soutiendraient l'hypothèse d'une migration saisonnière synchrone des individus le long de la route menant de l'Atlantique à l'estuaire. La détection simultanée de vocalises aux différentes stations pendant une grande partie de l'année indique une population dispersée, répartie sur les différents sites d'intérêts dans la zone d'étude, dont les fluctuations d'occurrence montrent des périodes d'arrivée et de départ. Les résultats indiquent clairement que le rorqual bleu est présent dans toute la région, non seulement l'été et l'automne, mais à l'année longue.

INTRODUCTION

The Northwest Atlantic blue whale (*Balaenoptera musculus*) population of a few hundreds individuals (Sears and Calambokidis 2002) has been designated as endangered on the Species at Risk Act of Canada since May 2002 (Beauchamp et al. 2009). The Canadian recovery strategy developed as a result of this listing aims to increase the population size to 1000 adult individuals (Beauchamp et al. 2009). Besides evaluating the actual number of individuals, one of the primary objectives of the recovery plan is to determine the home range and critical habitats in Canadian waters. This includes both the spatial and temporal components of the habitats, over a range of scales, notably covering the annual cycle.

The Lower Estuary and Gulf of St. Lawrence are considered important feeding grounds for this population (Beauchamp et al. 2009). Information on spatial and temporal distribution of the blue whale in this ~240000 km^2 marginal sea of Northwestern Atlantic is partial due to limited, uneven or systematic, observations from aircraft or boats over this large area (Kingsley and Reeves 1998, Sears and Calambokidis 2002, Lawson and Gosselin 2009, Ramp and Sears 2012). Systematic aircraft surveys can cover large areas but the observation effort at a given location is generally limited to a few minutes. They may provide the large-scale picture at a given time, but they do not account for the dynamic redistribution and migration of the animals, unless they are repeated at a high rate. On the contrary, observations on small areas can be easily repeated but their spatial coverage is often limited for free-ranging animals with large life domain. Observations outside summer and fall months for this population are also very scarce.

This paper is an effort to fill this knowledge gap on blue whale time-space frequentation of the St. Lawrence system throughout the annual cycle, using long-term recordings of their specific calls from a passive acoustic monitoring (PAM) observatory.

The blue whale vocal repertoire in North Atlantic and St. Lawrence is composed of three main call types: the 'A' and 'B' infrasounds, and the audible low-frequency 'D' call (Mellinger and Clark 2003, Berchok et al. 2006). The infrasound source level (SL) is estimated to ~190 dB re 1 μPa @ 1 m (McDonald et al. 2001, Širović et al. 2007), while the D-call SL is ~30 dB lower (Berchok et al. 2006). The A and B infrasounds generally occur in song sequences where the A and B, or A (alone) phrases are repeated at ~70 s intervals (Mellinger and Clark 2003). B infrasounds rarely occur alone without A-calls. The D-calls are less stereotyped, less frequent and they rarely occur in long sequences or songs (Mellinger and Clark 2003, Berchok et al. 2006). Their time frequency pattern is also highly variable (Berchok et al. 2006, Mouy et al. 2009). Other baleen whales, namely minke (Schevill and Watkins 1972, Edds-Walton 2000) and sei whales (Baumgartner et al. 2008), produce downsweep calls that overlap with blue whale D-calls low-frequency band (~[30-100 Hz]), their frequency sweeping rate, and duration. This may confound automatic detectors as well as experienced observers when the D-calls come from distant sources and only the most energetic time-frequency fraction of the call is received at the recorder. Tissue samples of Pacific blue whales tagged with acoustic recording tags indicated that the AB-calls were produced by 6 males and D-calls were produced by 1 female and 2 males (Oleson et al. 2007).

In this paper we focus on A-calls recorded over a network of 6 PAM stations distributed over the study area to examine the blue whale frequentation of this ecosystem over the annual cycle. D-calls are used as a secondary cue of blue whale presence. The next sections present the material and methods and the relevant results for the specific objective of documenting the blue whale habitat in the study area as a contribution to define its critical habitat in Canadian waters.

MATERIAL AND METHODS

DATA ACQUISITION

The PAM observatory included 6 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 in the most upstream baleen whale feeding ground at Les Escoumins (Simard and Lavoie 1999, Simard 2009), another one about 75 km further downstream in Lower St. Lawrence Estuary, one positioned around the whale feeding ground east of the Gaspé peninsula off Cap d'Espoir, and a last one, named Old Harry, 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 off bottom following a typical I-type oceanographic mooring, comprising 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 h 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 of the Defense Research and Development of Canada – Atlantic (Dartmouth, NS). The recordings covered a 5-y period from June 2010 to June 2015 with series lengths varying from 1 y to 5 y (Fig. 2).

DATA ANALYSIS

For the detection of blue whale presence using a dedicated algorithm, we focused on A-calls, ignoring the B-calls, which seldom occur without A calls (Fig. 3). The presences of the D-calls were also counted from manual examination of the high-resolution spectrograms in the relevant frequency band by an experienced observer assisted by an energy-based call-event detector. The A-call automatic detection algorithm used time-frequency matching of the signal with synthetic A-call templates (Mouy et al. 2009) (Fig. 4). Briefly, the acoustic signal is downsampled to 200 Hz and a high-resolution spectrogram is computed and cleaned of noise to enhance signal to noise ratio (SNR) (Fig. 4, section 1). The match with the synthetic A-call templates is examined in a time-frequency window whose length includes the call and noise portions before and after it. Detection is triggered when the match index exceeds a threshold manually determined from a subset of the recordings (Fig. 4, section 2). The threshold is set to minimize the missed detection rate, with the risk of inflating the false alarms. These latter are then filtered out in a following step by validation by an experienced observer (Fig. 4, section 3). When the number of detections at a station is very large a regular subsampling of the detection time-series is performed to estimate the actual false alarm rate, *Fdetr*. This latter is interpolated through the time-series and used to estimate the number of true A-call detections by its multiplication by the number of detections (*Ndet*). Overall, the recall index (i.e. percentage of detected true detections) of this algorithm is 88%, from manual examination of a regularly distributed subsample of the recordings at 4 stations representing 1,223 true A-calls. The algorithm precision index (i.e. percentage of properly classified true detections) varies from a maximum of 100%, when all detections were validated, to a mean of 82%.

Examination of the performance of the above algorithm with the SNR (from rms sound pressure level (SPL, in dB re 1 μPa) in the call band) for 5,213 manually validated detections from 2 stations for two annual time series indicates that detection probability starts at 0-dB SNR and reaches a maximum at 5-dB SNR. For the purpose of the present work, this means that the targeted calls cannot be detected when noise level (NL) exceeds their expected received levels (RL_{call}). In these cases, the PAM system can be considered as inactive. To assess the importance of inactive A-call PAM occurrences through the recordings, the NL time series and the cumulative probability 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. the chance to detect an A-call is less than 5%) were considered as not sampled for further analyses if no calls were detected. The proportion of time when A-call PAM was active, P_{det}, is obtained by the complement of the inactive proportion. The lowest estimate obtained for P_{det} was 84.6%.

The call detection capacity of a PAM system depends on its location in the three-dimensional basin, the call SL, transmission loss (TL), and NL. 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 computed for the recording periods at the PAM stations using a parabolic equation (PE) propagation model to propagate 190-dB re 1 µPa @ 1 m A-call SL (Širović et al. 2007) and 160-dB re 1 µPa @ 1 m D-call SL (Berchok et al. 2006), and the resulting RL_{call} at the stations were compared to the median NL in the same frequency bands. The PE model (Collins 1993, OALIB 2016) was configured with 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 bottom geoacoustic properties from Loring and Nota (1973) and Jensen *et al.* (2011) (details in Aulanier et al. 2016). The 15-m deep source (Oleson et al. 2007) was radially positioned in steps of 1 km along 360 200-km radii centered at the PAM station. Interpolation was used to fill the 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 for both A and D calls separately.

Finally, the metric used here to express blue whale daily frequentation of the different areas from A-call monitoring, $BWF_{A\text{-}call}$, is the number of hours with A-call detections per day, $Nhd_{A\text{-}all.}$

$$BWF_{A-call} = Nhd_{A-call}\ , in\ calling\ h \cdot d^{-1}$$

Similarly, a second blue whale presence index was computed from D-call detections, $BWF_{D\text{-}call}$. P_{det} is considered close to 1.0 for this frequency band where interference from mooring strum, vibrations and flow noise is smaller and less frequent than for the A-call band.

$$BWF_{D-call} = Nhd_{D-call}\ , in\ calling\ h \cdot d^{-1}$$

RESULTS

The size of the A-call detection areas within a 200 km radius at the PAM stations largely depends on the local bathymetry and water mass characteristics (Fig. 5). They ranged from 2.5 thousand km^2 at the Belle Isle station to 58.0 thousand 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 detection time series among stations. The proportion of recording time A-calls were detectable according to the Pdet criterion was greater than 84.6%.

The D-call detection areas were orders of magnitude smaller than the A-call areas (Table 1), as expected from the 30 dB lower SL of D-calls and higher shipping noise in their frequency band (Aulanier et al. 2016). The smallest detection area was from the PAM station located on the shipping route in the Lower Estuary. The largest detection area was from Cap d'Espoir station, which is located in a basin away from the main shipping route in the Laurentian Channel (Simard et al. 2014).

No blue whale calls were detected during the 1-y recording period at Belle-Isle Strait PAM station in 2010-2011. Blue whale calls were detected at all other stations (Fig. 6). A-calls were present at all stations with a clear seasonal recurrence pattern from year to year (e.g. Fig. 7) while D-call presence was more dispersed over the annual cycle. For a large part of the recordings, blue whales were simultaneously present in all detection areas from Les Escoumins to Cabot Strait. The two PAM stations in the southern part of the Gulf were detecting blue whale calls for a longer proportion of the year than those of the head of the Laurentian Channel in the Estuary and of the basin east of the Gaspé peninsula (Figs. 1, 6; Table 2). The annual period of A-call occurrence at the PAM stations varied from 43 days in Cap d'Espoir area to 265 days in Old Harry area (Table 2). Based on D-call occurrence, the corresponding time range was 129 and 364 days. Daily index of A-call presence time series indicate more continuous occurrence at Old Harry and Cabot stations, with notable semi-monthly to monthly fluctuations, than Les Escoumins and Cap d'Espoir stations, where monthly intermittence is noticeable (Fig. 6).

The A-call annual occurrence at Les Escoumins station started between the first week of August and September and ended between mid-November and the end of January (Table 2, Fig. 7a). For D-calls the start date was as early as the beginning of March and the end date varied from mid-October to the end of January. Both calls combined, the no-call period was in winter, from the end of January to the beginning of March (Fig. 7a).

In Cap d'Espoir detection area, A-calls tended to appear later in fall, between mid-October to mid-November, and disappear about the same time as for Les Escoumins, between the ends of November and January. This occurrence is extended to March and June from D-call appearance and to mid-February for their disappearance, leaving only the period from mid-February to the first week of March for call absence.

In the southern Gulf stations, A-call tended to start between mid-June and the beginning of August and to stop between the beginning of February and the end of April (Fig. 7b). D-calls were detected year-round. The similarity between the time occurrence pattern at these stations possibly indicate call recruitment from the same group of whales roaming in the area, and possible double detections although the proportion of overlap between the 2 detection areas is relatively limited (Figs. 5,6).

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 blue whales from the detection of their specific sounds over the complete annual cycle. This contribution establishes the present baseline of blue whale frequentation of this part of their home range in Northwest Atlantic. Results clearly show that blue whales occupy the whole region, not only during summer and fall but year-round, except for a ~2-month winter leave of the most upstream area in the Lower St. Lawrence Estuary. Blue whales are present from the south to the most upstream sites at the same time, which indicates numerous sites of interest within the basin by a dispersed population and not a synchronized seasonal migration of a unique coordinated group migrating to and from the Atlantic waters. Belle Isle Strait does not appear to be on the in-and-out excursion route, at least for the 2011-12 season when the area was monitored. Fluctuations in A-call occurrence with monthly or semi-monthly periods at all stations, is likely more indicative of movements of callers within the region rather than calling rate changes. This latter, however, is clearly seasonally patterned for A-calls, which occurred between ~ mid-summer to spring. Seasonal pattern for D-calls was less evident since they were encountered year-round. D-calls variability and possible interferences from calls from other species in the same frequency band make it less reliable, especially in the southern Gulf, although we are confident that possible confusion with other species calls concerns only a small percentage of the detected calls.

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 hourly calling activity 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, the call detection probability likely increases with the detection area. However, this would mostly affect the occurrence metric used for the cases where calling activity is low. The main difference in A-call detection area was between the Lower Estuary and the Gulf, and it was due to the limitation by the basin size. We believe that the calling activity series are representative of the actual relative activity at the PAM stations, possibly with lower values than shown for the lowest activities at Old Harry and Cabot stations. A larger number of stations, whale tracking and call count areal density estimation would be needed to remove this effect of different detection areas of PAM stations.

The identification of inactive PAM times for A-call, Pdet, used the 95th percentile of the A-call energy cumulative distribution function to decide when noise was too high for detection. The use of another less permissive centile may produce slightly different A-call occurrence time series, but possible effects are limited since the effective duty time was higher than 84 % 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 (cf. Aulanier et al. 2016), in order to better cover the whole region with a limited number of stations or setup tracking arrays by favouring overlapping detection areas.

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TABLES

Table 1. A- and D-call median detection areas at the PAM stations.

PAM station	**A-call detection area (km^2)**	**Relative A-call detection area ($RA_{det\text{-}Acall}$)**	**D-call detection area (km^2)**	**Relative D-call detection area ($RA_{det\text{-}Dcall}$)**
Les Escoumins	4,768	1.9	29	1.4
Lower Estuary	8,098	3.3	21	1.0
Belle-Isle	2,485	1.0	111	5.3
Cap d'Espoir	25,183	10.1	4,120	196.2
Old Harry	58,044	23.4	504	24.0
Cabot	38,098	15.3	62	3.0

Table 2. Earliest and latest dates and durations of blue whale seasonal call occurrences at the PAM stations. Italics indicate seasonal call occurrence period possibly began before recording started or was still going when the recording ended.

	$BWF_{A\text{-}call}$ **index**			$BWF_{D\text{-}call}$ **index**			**All**
PAM station	**Start date**	**End date**	**days**	**Start date**	**End date**	**days**	**days**
Les Escoumins	2010-08-02	2010-12-20	140	*2010-07-14*	2010-11-23	*>132*	*>159*
	2011-08-19	2011-11-19	92	2011-03-09	2011-11-01	*237*	255
	2012-09-05	2012-12-23	109	*2012-06-19*	2012-11-10	*>144*	*>187*
	2013-09-20	2013-12-20	91	*2013-05-23*	2013-10-17	*>147*	*>211*
	2014-09-01	2014-12-06	96	*2014-07-01*	2015-01-17	*>200*	*>200*
Lower Estuary	*2012-11-04*	2013-02-19	*>107*	*2012-11-22*	2013-03-14	*>112*	*>112*
	2013-07-15	*2013-10-31*	>108	2013-03-26	*2013-10-31*	*>219*	*>219*
Cap d'Espoir	2011-11-22	2012-01-26	65	2011-06-13	2012-02-10	242	242
				2012-03-07	-		
	2013-10-26	2013-12-29	65	2013-08-06	2013-12-15	129	130
	2014-04-24		-				
	2014-10-15	2014-11-27	43	2014-06-27	2014-11-11	137	153
Old Harry	*2010-11-16*	2011-04-11	*>146*	*2010-11-16*	2011-04-06	*>141*	*>146*
	2011-08-01	2012-04-09	252	2011-04-27	2012-04-25	364	364
	2012-06-10	2013-02-15	250	2012-04-29	2013-02-23	300	300
	2013-08-14	2014-02-23	193	*2013-07-13*	2014-03-18	*>248*	*>216*
	2014-07-19	2015-02-06	202	2014-05-02	2014-11-18	200	280
Cabot	*2010-11-09*	2011-03-23	*>134*	*2010-11-09*	2011-04-24	*>166*	*>166*
	2011-08-03	2012-03-23	233	2011-04-28	2012-03-28	335	335
	2012-07-20	2013-03-06	229	2012-04-05	2012-12-04	243	335

FIGURES

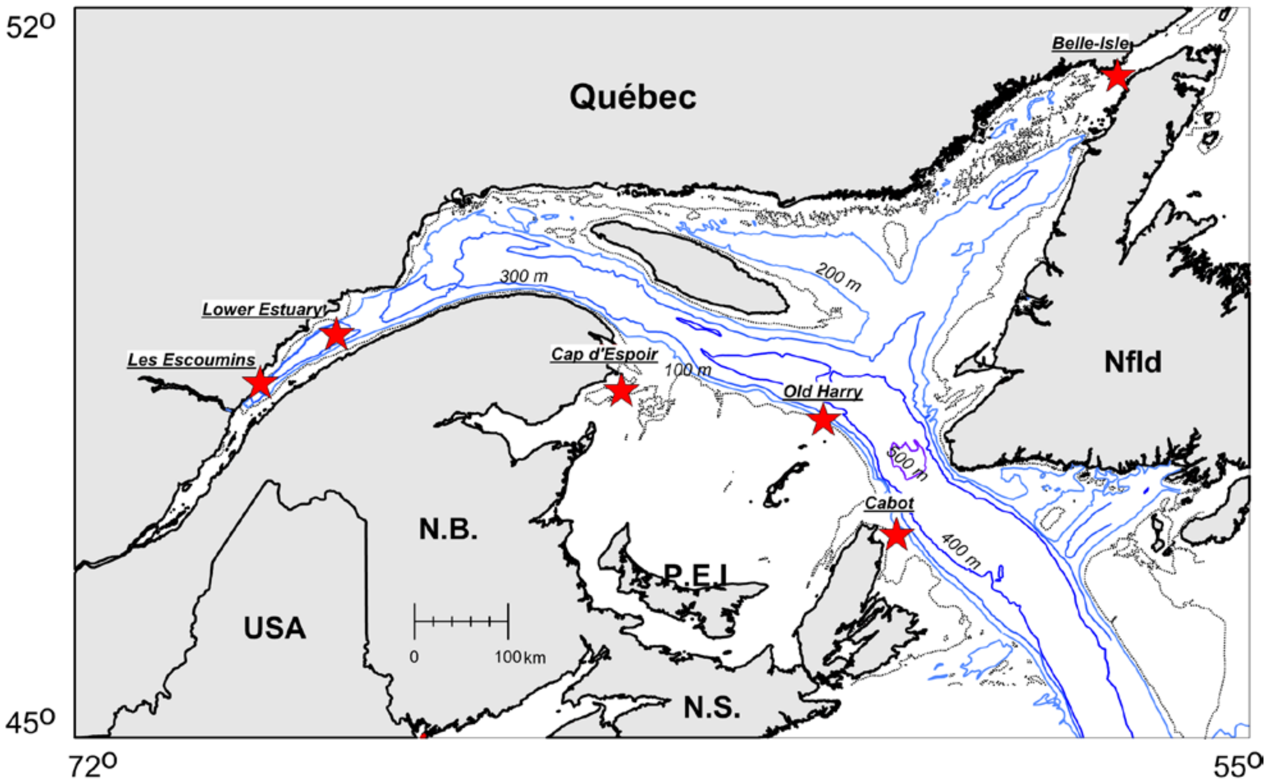

Figure 1. Map of the Estuary and Gulf of St. Lawrence showing the location of the 6 stations of the PAM observatory and 100-m bathymetric contours.

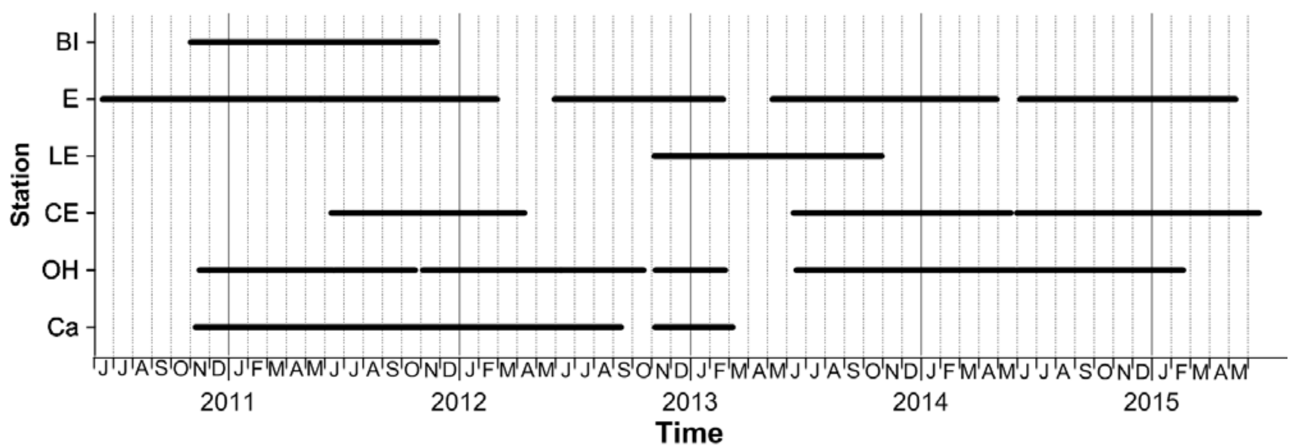

Figure 2. Recording schedule at the 6 stations shown in Fig. 1, sorted from northwest to southeast. BI: Belle Isle strait; E: Les Escoumins; LE: Lower Estuary; CE: Cap d'Espoir; OH: Old Harry; Ca: Cabot strait.

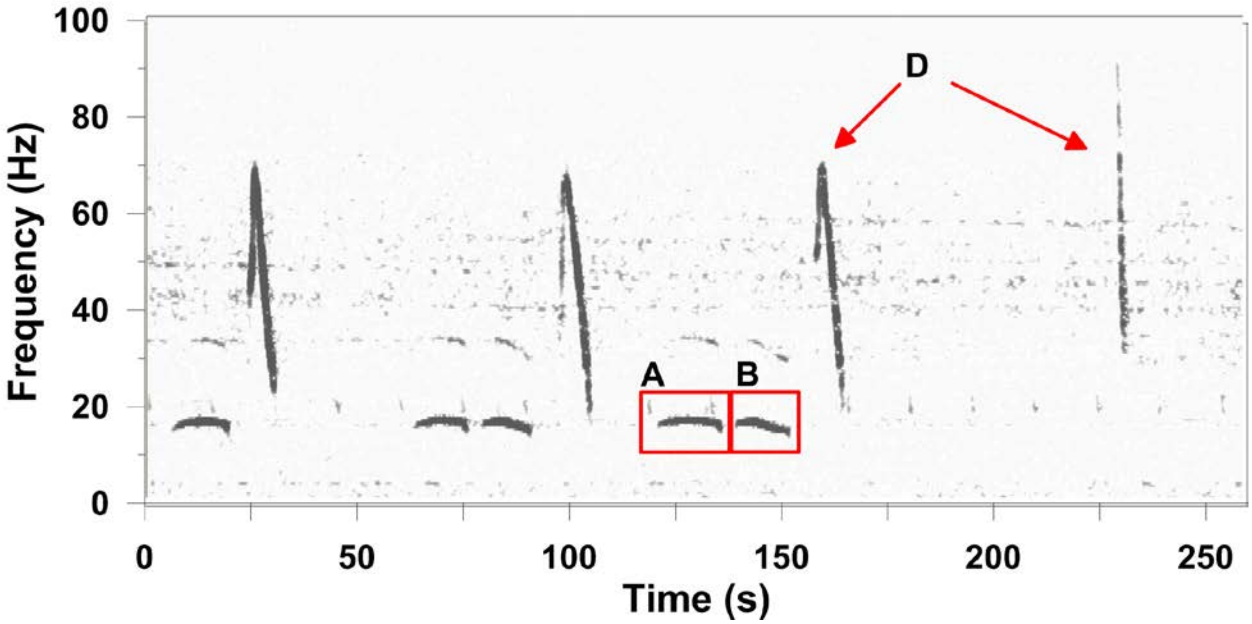

Figure 3. Spectrogram example of North Atlantic blue whale A, B and D calls.

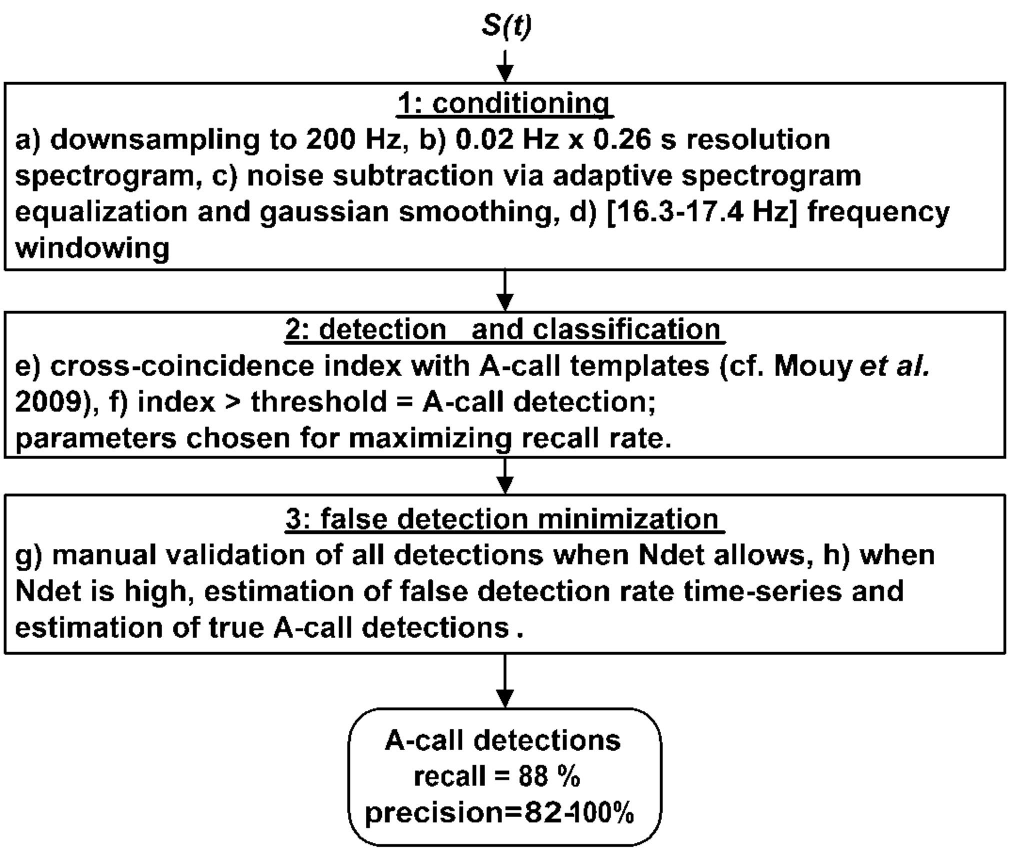

Figure 4. Scheme of the A-call detection algorithm.

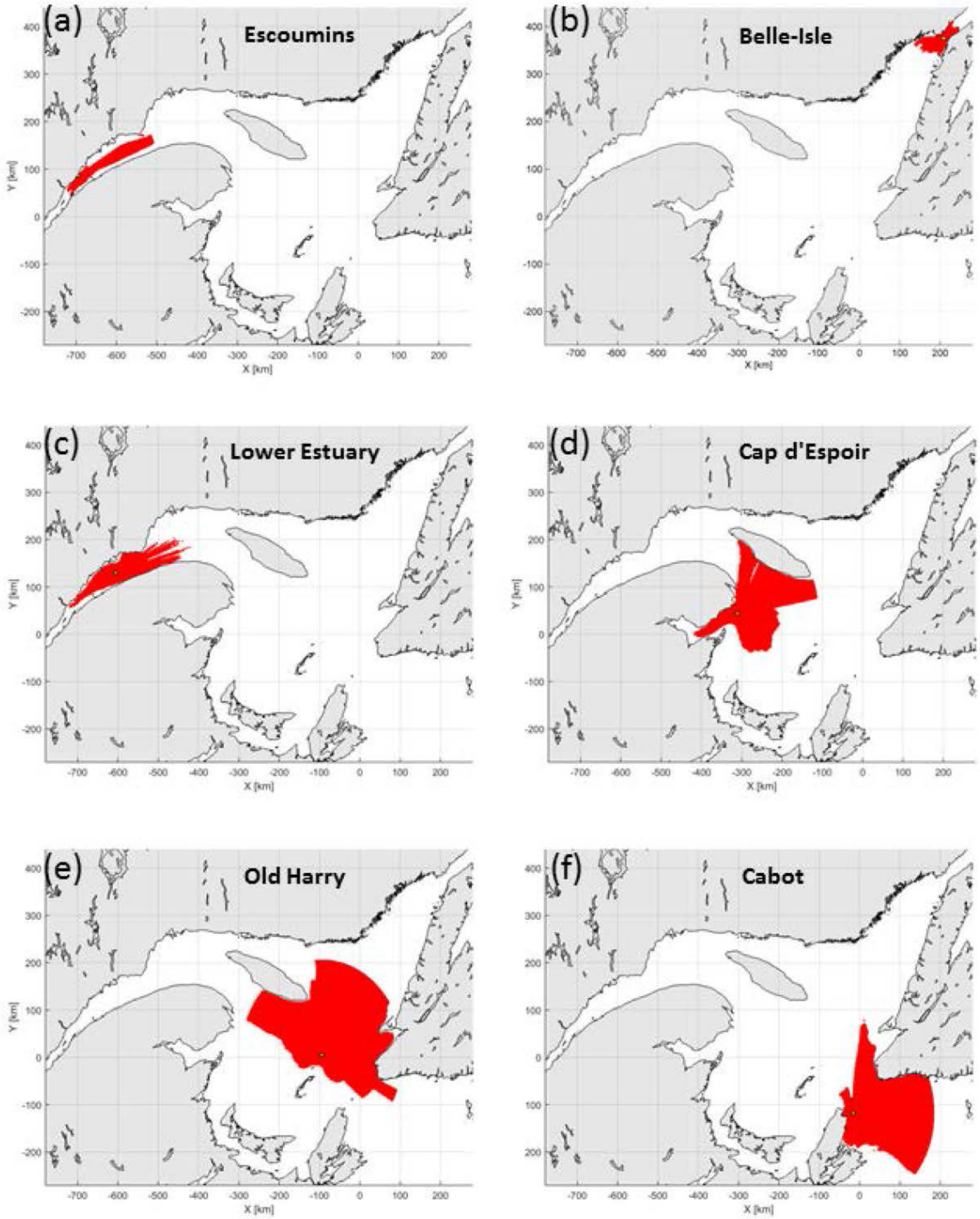

Figure 5. Maps of the median detection areas for blue whale A calls at the 6 PAM stations.

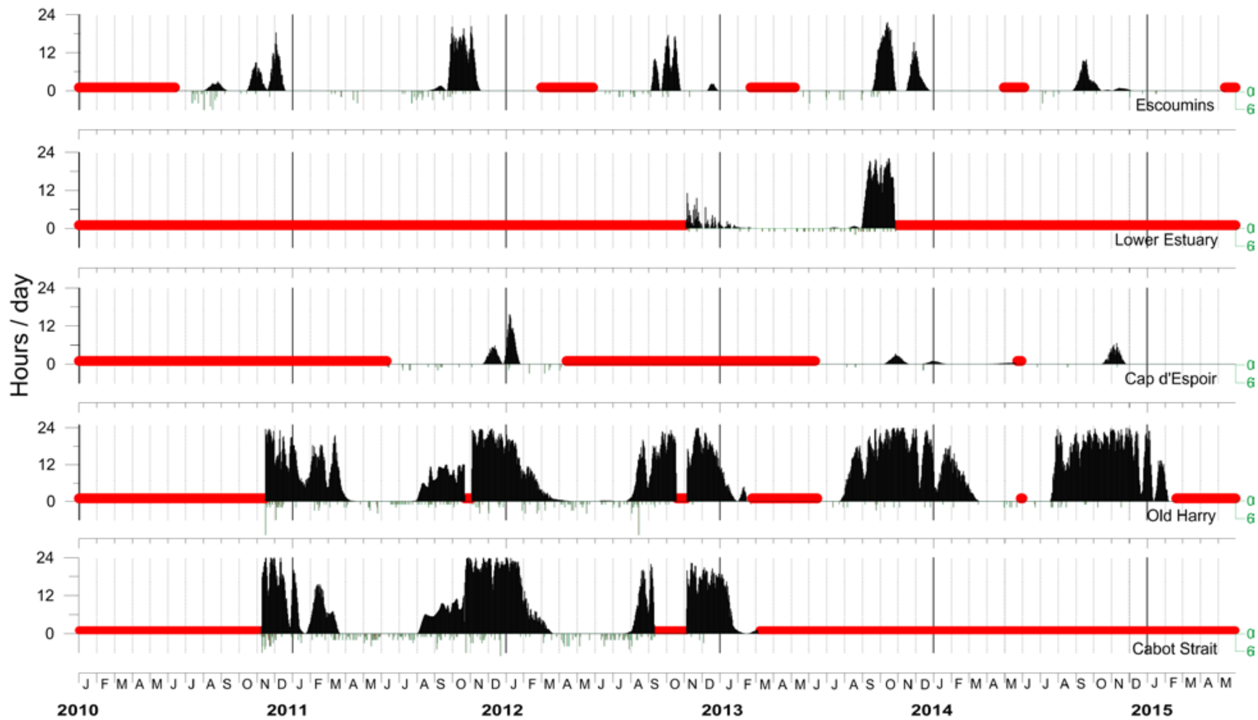

Figure 6. Time series of blue whale daily frequentation indices of the PAM station detection areas in Estuary and Gulf of St. Lawrence during 2010 to 2015. Bold red lines indicate periods without recordings. Upward bars are for frequentation index from A-call detections and downward bars are for that of D-call detections. No blue whale calls were detected at Belle-Isle station visited in 2010-2011 (Fig. 2) and is therefore omitted here.

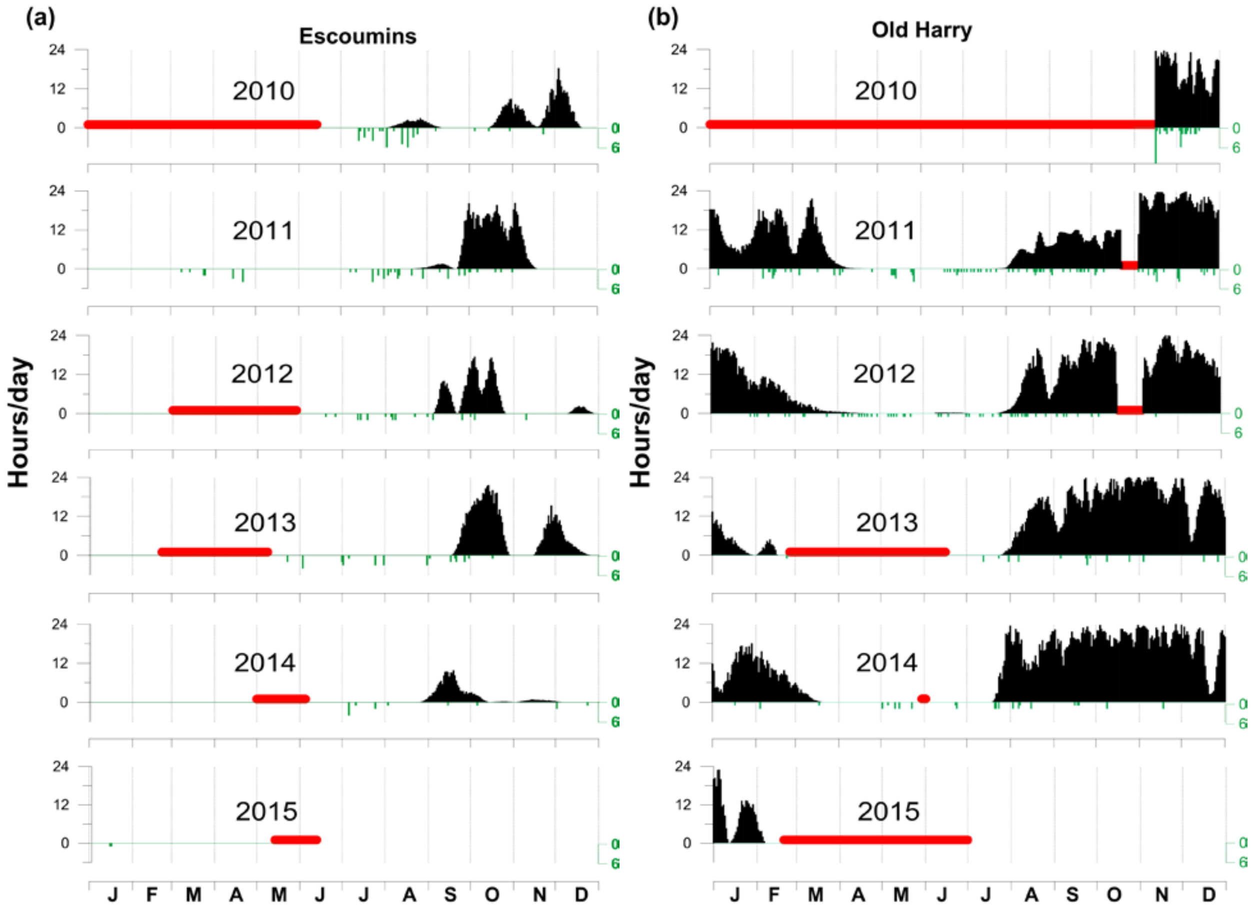

Figure 7. Annual time series of blue whale daily frequentation indices of the Les Escoumins and Old Harry PAM station detection areas during 2010 to 2015. Bold red lines indicate periods without recordings. Upward bars are for frequentation index from A-call detections and downward bars are for that of D-call detections.