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Annual, seasonal, and diel patterns in blue whale call occurrence off eastern Canada

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ABSTRACT: Little is known about the year-round occurrence of blue whales in Atlantic Canadian waters. We used passive acoustic monitoring to investigate blue whale call presence and increase our understanding of year-round blue whale occurrence along the eastern edge of the Scotian Shelf, Nova Scotia, Canada. Blue whale calls were recorded at 3 deep water sites within and near the Gully Marine Protected Area from October 2012 to September 2014 using bottom-mounted passive acoustic recorders. Calls were categorized as either tonal or downsweeping. At all 3 sites, tonal calls occurred most often from November through January in both years and in August 2014, while the majority of downsweeping calls occurred during May through September 2014. There was no discernible diel pattern in the occurrence of tonal calls. Downsweeping calls occurred most often during evening twilight, with a dramatic peak in occurrence during the hour of 19:00 Atlantic Standard Time at all 3 sites. The peak in downsweeping call occurrence during evening twilight may have been related to blue whale foraging ecology. This study sheds light on the poorly understood year-round occurrence of blue whales off Atlantic Canada. Understanding when and where blue whales occur will help to inform management decisions for the protection and conservation of this endangered population.

KEY WORDS: Blue whale · Diel and seasonal occurrence · Passive acoustic monitoring · Northwest Atlantic Ocean · Conservation

1. INTRODUCTION

Blue whales *Balaenoptera musculus* are found throughout the world's oceans, but at greatly reduced population sizes following the commercial whaling of the twentieth century. During the time of modern whaling (1900–1979), an estimated 379 185 blue whales were killed worldwide (Rocha et al. 2014). As a direct result of this mass mortality, blue whales are currently listed as endangered on the International Union for Conservation of Nature (IUCN) Red List, with approximately only 5000 to 15 000 mature individuals remaining globally (Cooke 2018). In the North Atlantic, an estimated 6699 blue whales were killed during modern whaling (Rocha et al. 2014). The northwest Atlantic population of blue whales mainly inhabits the Gulf of St. Lawrence and St. Lawrence Estuary, and waters off Newfoundland, Nova Scotia, west Greenland, and New England (Sears & Perrin 2018). The current size of this population is unknown, but experts believe it is unlikely that the number of mature individuals exceeds 250 (Sears & Calambokidis 2002, Beauchamp et al. 2009). The Northwest Atlantic blue whale population was assessed as endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) (COSEWIC 2002, 2012) and is listed as endangered under the Canadian Species at Risk Act (SARA)

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(Beauchamp et al. 2009). Given this population's status, it is critical to understand where these whales occur throughout the year to implement effective management strategies.

The majority of the research effort on this population of blue whales has taken place within the St. Lawrence Estuary and northern Gulf of St. Lawrence (Comtois et al. 2010, Sears & Perrin 2018). Within these areas, blue whales have been sighted almost year-round, except during months with extensive sea ice coverage (Sears et al. 1990, Comtois et al. 2010). Many known individuals have been sighted in the area across multiple years (Sears et al. 1990, Ramp et al. 2006). Blue whales have also been detected acoustically throughout the St. Lawrence Estuary and Gulf of St. Lawrence year-round (Simard et al. 2016). Satellite tag data suggest individual movement patterns out of the area during the fall are highly variable (Lesage et al. 2017). In the western North Atlantic Ocean, blue whales have been detected acoustically north of the West Indies and east of the US exclusive economic zone (Clark 1995, Nieukirk et al. 2004), and tracked via satellite tags to North Carolina, USA (Lesage et al. 2017). Historical strandings in the Gulf of Mexico (Baughman 1946) and in the Caribbean Sea near Panama (Harmer 1923) suggest their range extends at least that far south, although their true southern range limit remains unknown (Davis et al. 2020). In the north, their range reaches Davis Strait and Baffin Bay (Sears & Perrin 2018). In Canadian waters outside of the Gulf of St. Lawrence and St. Lawrence Estuary, blue whales have been sighted and acoustically detected off Nova Scotia, Newfoundland, and Labrador (Clark 1995, Lawson & Gosselin 2009, Gomez et al. 2017, Delarue et al. 2018, Lesage et al. 2018).

On the eastern Scotian Shelf edge specifically, blue whales have been sighted during summer months and detected acoustically nearly year-round (Whitehead 2013, Marotte & Moors-Murphy 2015, Moors-Murphy et al. 2019, Davis et al. 2020). The Whitehead Lab of Dalhousie University photographed and identified individuals in this area that had been previously identified in the Gulf of St. Lawrence (Moors-Murphy et al. 2019). These studies broadly summarize blue whale occurrence, but we know very little about how blue whales use the eastern Scotian Shelf and shelf edge throughout the year, despite habitat suitability models identifying this area as important and highly suitable blue whale habitat (Gomez et al. 2017, Lesage et al. 2018).

Visual surveys for blue whales can only be undertaken during daylight hours and when weather is favourable (e.g. low winds and calm sea state), which is typically during summer months in the Northwest Atlantic. To overcome these limitations, passive acoustic monitoring (PAM) has been used worldwide to investigate seasonal and diel trends in occurrence of marine mammals (e.g. Norris et al. 1999, Stafford et al. 2005, Munger et al. 2008, Thompson et al. 2015, Kowarski et al. 2018). PAM allows for the continuous (or near-continuous) collection of data during day and night, and in any weather conditions. However, for PAM to be effective, the target species must produce audible and distinct calls.

Blue whale vocalizations in the Northwest Atlantic were first described in detail by Edds (1982) for 1 individual in the St. Lawrence Estuary. Seven tonal calls were 18 to 20 Hz in frequency and 15 to 18 s in length (Edds 1982). Since then, a variety of call types have been attributed to blue whales in the North Atlantic (Mellinger & Clark 2003, Nieukirk et al. 2004, Berchok et al. 2006, McDonald et al. 2006). The 2 main categories of blue whale calls in the existing literature are tonal, consisting of 'A', 'B' or 'AB' calls, and higher-frequency downsweeping calls. 'A' calls are of constant or very nearly constant frequency of approximately 18 Hz lasting approximately 8 s, while 'B' calls sweep down in frequency from approximately 18 to 15 Hz and last approximately 11 s (Mellinger & Clark 2003). These 2 call types often occur together as 'AB' calls, where the 'A' call occurs first, followed by a short silent period or continuous transition into the 'B' call (Mellinger & Clark 2003). Tonal calls are often emitted in patterned sequences, called songs (Mellinger & Clark 2003, Berchok et al. 2006, McDonald et al. 2006), but can also be produced as single calls at irregular intervals (Oleson et al. 2007b). While the function of blue whale song is not completely understood, it is believed to be a mating display produced by males (McDonald et al. 2001, 2006, Oleson et al. 2007b), as is the case with fin whale *Balaenoptera physalus* song (Croll et al. 2002). Lewis et al. (2018) recorded a few singular tonal calls on tags attached to 3 female blue whales; however, it was possible these calls were actually produced by nearby untagged whales of unknown sex.

Downsweeping calls include 'arch' and 'D' calls. 'Arch' calls initially sweep up in frequency from approximately 65 to 70 Hz before dropping to approximately 30 Hz and are typically 5 to 7 s in duration (Mellinger & Clark 2003). 'D' calls are shorter, approximately 1 to 4 s, and descend from 90 to 25 Hz (Thompson et al. 1996). However, there can be a large amount of variability between individual downsweeping calls, as demonstrated by Mellinger &

Clark (2003) and Berchok et al. (2006). Downsweeping calls are produced by both males and females, often in pairs or groups, and have been recorded between deep foraging dives (Mellinger & Clark 2003, Berchok et al. 2006, Oleson et al. 2007b). The function of downsweeping calls is therefore thought to relate to social interaction rather than reproduction (Oleson et al. 2007b). McDonald et al. (2001) hypothesized that 'D' calls may be used as a counter-call between individuals.

In this study, we used PAM to characterize diel, monthly, and annual patterns in the occurrence of blue whale tonal and downsweeping calls at 3 sites just off the eastern Scotian Shelf, 2 adjacent to and one within the Gully Marine Protected Area (MPA), over a 2 yr period. We used the occurrence of calls as a proxy for blue whale presence and analyzed tonal and downsweeping calls separately given the evidence that these call types are associated with different behaviours. Because 'arch' and 'D' calls can be difficult to tell apart, they were considered together under the downsweeping call category. We have expanded upon the preliminary analyses of this dataset presented by Moors-Murphy et al. (2019) and upon the results presented by Davis et al. (2020) by analyzing the occurrence of the 2 call categories separately and at a finer-resolution time scale for all 3 sites.

2. MATERIALS AND METHODS

2.1. Data collection

Acoustic data were recorded near-continuously on autonomous multichannel acoustic recorders (AMARs; JASCO Applied Sciences) at 3 sites along the edge of the Scotian Shelf from October 2012 to September 2014. MidGul was located at the mouth of the Gully Canyon, GulSho was located on the slope between the Gully and Shortland canyons, and ShoHald was located on the slope between Shortland and Haldimand canyons (Fig. 1). The recorders were deployed and recovered approximately every 6 mo, resulting in 4 deployment periods for each site (Table 1). Recordings from the first 2 deployments at MidGul contained high flow and strumming noise, which was particularly evident at lower frequencies. The mooring setup was adjusted for the last 2 deployments to overcome these issues (Cochrane & Moors-Murphy 2017). For all sites, the duty cycles differed slightly between the first 2 and last 2 deployments. The AMARs were set to sample at a rate of 16 kHz for 13 of every 15 min during the first 2 deployments and for 18 of every 20 min during the last 2 deployments, resulting in datasets consisting of either 4 or 3 files per hour, respectively. The recorders were sus-

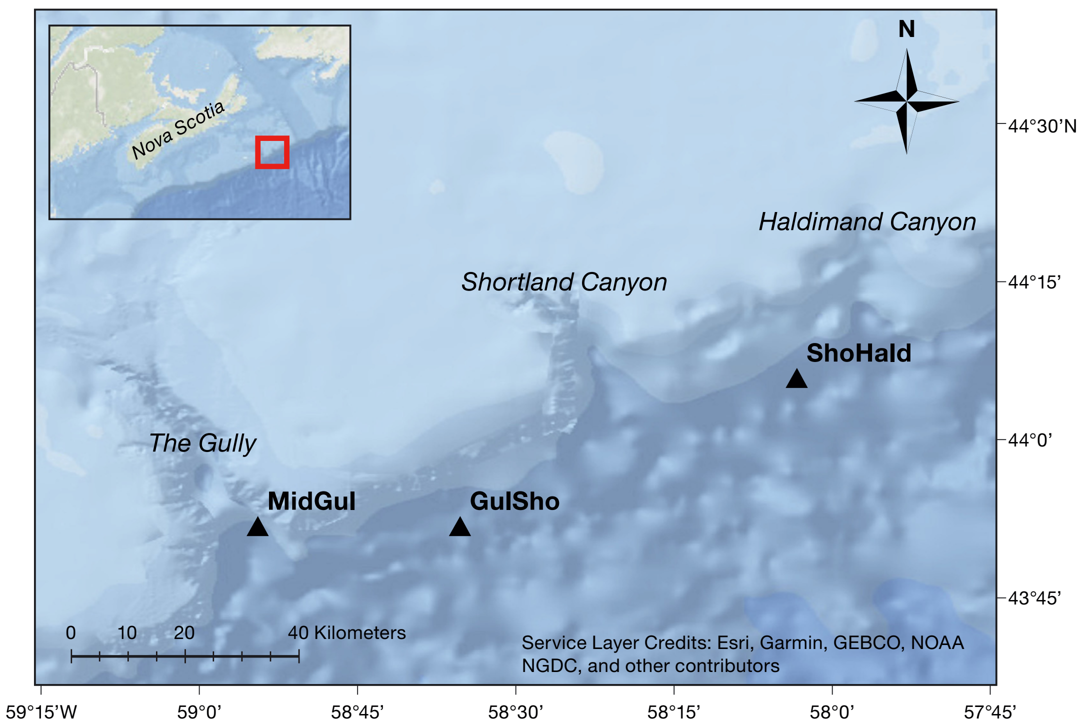

Fig. 1. Locations of the 3 recording sites, MidGul, GulSho, and ShoHald (black triangles), and adjacent canyons along the eastern Scotian Shelf, offshore Nova Scotia

Table 1. Deployment and retrieval dates, position, bottom depth, and number of days and hours with recordings (full days only) for each deployment period at each site. See Fig. 1 for location of sites

Site	Deployed	Retrieved	Latitude (° N)	Longitude (° W)	Bottom depth (m)	No. of days (h) with recordings
MidGul	Oct 12 2012	Apr 10 2013	43.851	58.919	1780	179 (4296)
	May 07 2013	Sep 25 2013	43.862	58.910	1580	140 (3360)
	Nov 15 2013	Apr 06 2014	43.862	58.910	1525	141 (3384)
	May 03 2014	Sep 26 2014	43.864	58.908	1614	145 (3480)
GulSho	Oct 12 2012	Apr 10 2013	43.868	58.596	1516	179 (4296)
	May 08 2013	Sep 26 2013	43.864	58.588	1583	141 (3384)
	Nov 15 2013	Apr 06 2014	43.861	58.588	1530	141 (3384)
	May 03 2014	Sep 26 2014	43.864	58.355	1573	145 (3480)
ShoHald	Oct 12 2012	Apr 10 2013	44.089	58.065	1700	179 (4296)
	May 08 2013	Sep 26 2013	44.098	58.056	1545	140 (3360)
	Nov 15 2013	Apr 07 2014	44.097	58.056	1550	142 (3408)
	May 03 2014	Sep 26 2014	44.163	58.104	1559	145 (3480)

pended approximately 55 m off the seafloor, where moorings sat at bottom depths ranging from 1516 to 1780 m (Table 1). The recording systems were equipped with 24 bit analog-to-digital converters (ADC) with a hydrophone sensitivity of approximately −165 dB re 1µPa V^{-1}.

2.2. Blue whale call detection and validation

Following the retrieval of the data, a Spectro Correlator (SC; JASCO Applied Sciences) detector, written in MATLAB version 7.10 (MathWorks), was modified and applied to each of the recording files to detect blue whale calls. This spectrogram correlation technique was based on methods described in detail in Mouy et al. (2009) and Martin et al. (2014), and was configured to detect either blue whale tonal or downsweeping calls. Data were processed into spectrograms with a frame size of 1 s, a Blackman window, a fast Fourier transform (FFT) size of 2 s, and a step size of 0.1 s. The spectrogram was normalized in each frequency using a median filter with a window size of 20 s. The spectrogram was then binarized by calculating the variance of energy values around each spectrogram bin using a kernel size of 0.1 s by 10 Hz. Bins of the spectrogram with a local variance of less than 0.4 and a normalized energy value less than 1.9 were set to zero, and remaining bins were set to 1. Seven binary time–frequency templates, or masks, were created: 2 for 'A' calls, 1 for 'B' calls, and 4 for 'D' calls. To create a detection function, correlation indices that measured how well the masks matched the binarized spectrogram were defined for each time step. A correlation index of 1 indicated a perfect match. Detections were identified when the correlation index exceeded an empirically chosen minimum detection threshold. See Table A1 in the Appendix for these thresholds and all other detector parameters.

Each of the 15 057 files the detectors identified as having a blue whale tonal and/or downsweeping call were inspected aurally and visually by a trained analyst using PAMlab-Lite (JASCO Applied Sciences) or Raven Pro (K Lisa Yang Center for Conservation Bioacoustics 2014) acoustic analysis software. Only the files confirmed to contain an actual blue whale call (true positive, TP), were used in further analyses. Pseudo-random subsamples of 6280 files with no tonal detections and 6442 files with no downsweeping detections were chosen for review, ensuring that sampled files were distributed across all months within the dataset. False negative (FN) rates were calculated for each call type separately based on these subsamples, by dividing the number of FN files by the total number of files in the subsample. The total number of FN files for the entire dataset was estimated by multiplying the FN rate of the subsampled data by the total number of files with no detections for each site and call type, in order to calculate an estimated overall recall value. Estimated recall was calculated for each site and each call type separately as follows: TP/(TP+FN).

Validated call data were condensed into hourly presence and absence for each call type and site, with presence defined as an hour containing at least 1 file with at least 1 validated call, and absence being the lack of any validated calls on all files within the hour. Only complete recording days with data available for the full 24 h were included in analyses. All analyses of blue whale call occurrence data and associated figures were completed in R version 4.0.4 (R Core Team 2021) using the packages lubridate (Grolemund & Wickham 2011), ggplot2 (Wickham 2016), scales (Wickham 2018), egg (Auguie 2019), padr (Thoen 2019), suncalc (Agafonkin & Thieurmel 2019), and stringr (Wickham 2019).

2.3. Estimated detection range

To investigate the likelihood that the calls we recorded came from within our study area, a 'best case scenario' detection range model for tonal calls was created for MidGul. Blue whale tonal calls have the potential to travel several hundred km (Stafford et al. 1998), so this call type was an ideal candidate for modelling. The detection range calculations were based on the passive SONAR equation with a linear regression model (SL − TL − (NL − DI) = DT), where SL is source level, TL is transmission loss, NL is the noise level, DI is the directivity index, and DT is the detection threshold. The SL for blue whale calls used in this simulation was 185 dB re 1μPa at a frequency of 16 Hz, chosen based on previously published values for blue whale calls of similar frequencies (Cummings & Thompson 1971, Thode et al. 2000, McDonald et al. 2001, Širović et al. 2007, Bouffaut et al. 2021). TL was computed using a range-dependent acoustic model (RAM) based on the parabolic equation approach. The geoacoustic properties for the Gully and Scotian Slope used in the RAM are shown in Table A2. TL was estimated along every 10° azimuth direction using an integrated ocean acoustic modelling approach (Lermusiaux et al. 2010). Monthly averaged ocean background sound speed profiles were extracted for January to March and June to September 2014 from the GLobal Ocean ReanalYsis product (GLORY; Lellouche et al. 2013), produced by the COPERNICUS Marine Environment Monitoring Service program (CMEMS). The product was defined on a standard grid at 1/12° (approx. 8 km) and on 50 standard vertical levels. The resulting TL used in the model was the average of the propagation loss from the surface to 60 m depth, based on the assumption that blue whales were calling from within this depth range (Thode et al. 2000, Oleson et al. 2007b, Lewis et al. 2018, Bouffaut et al. 2021). The bathymetry data used in the model were obtained from an updated global bathymetry and topography grid presented using a spatial sampling interval of 15 arc s (Tozer et al. 2019). The daily averaged root mean square (RMS) ambient NLs in the 10 to 24 Hz frequency band were estimated based on *in situ* measurements at the mooring depth and location. The DI of the omnidirectional hydrophone was 0. The DT was assumed to be 0 dB. Blue whale tonal call detection range was mapped for January through March and June through September 2014 by combining both the ambient noise variation and TL introduced by changes in the monthly averaged sound speed. Additionally, daily averaged RMS NLs (dB) in the 10 to 24 Hz frequency band for the entire study period were calculated for MidGul to further inform seasonal patterns in the estimated detection range.

2.4. Seasonal and diel trends in call occurrence

For each site and call type, we determined the total number of hours and days during which at least 1 validated call was present. The number of hours during which validated calls occurred at 1, 2, or all 3 recording sites was calculated as a measure of independence between the recording sites. We calculated the proportion of days per month during which each call type occurred, as not all months had a complete set of recording days. These proportions were calculated for each of the sites separately and together, by pooling the data from all 3 sites. We additionally determined the duration of each calling period, defined as the number of consecutive hours with calls present, and plotted the results as a frequency plot for each call type.

For diel analyses, we used the package suncalc (Agafonkin & Thieurmel 2019) in R version 4.0.4 (R Core Team 2021) to extract sunrise, nautical dawn, sunset, and nautical dusk times for each full recording day. These times were rounded to the nearest hour to match the scale of the hourly call presence/absence data and used to assign the hours of each day to 4 diel periods: morning twilight (nautical dawn hour to hour before sunrise), day (sunrise hour to hour before sunset), evening twilight (sunset hour to hour before nautical dusk), and night (nautical dusk hour to hour before nautical dawn). To assess diel patterns in call presence, we used quasibinomial generalized linear models (GLMs) to model hourly call presence as a function of diel period. We ran a GLM for each call type using data pooled across sites. To examine differences between diel periods, we used the emmeans package (Lenth 2021) in R to perform pairwise Tukey contrasts based on estimated marginal means. Downsweeping call presence was also visualized across hours of the day for each site individually and for all sites combined.

3. RESULTS

3.1. Detector performance

The automated tonal and downsweeping detectors identified calls on a combined 15 057 of 153 812 files generated throughout the 2 yr recording period across all 3 sites. Of those 15 057 files, only the 4580 files confirmed to be TP detections following manual review were considered for subsequent analyses. We reviewed 6280 of 144 771 (~4 %) and 6442 of 145 026 (~4 %) files with no tonal or downsweeping detections, respectively. There were relatively few FN detections, which resulted in moderate to high estimated recall values for each of the detectors (Table 2). However, recall values were lower for the downsweeping detector compared to the tonal detector for each site, indicating that a higher proportion of downsweeping calls were missed, particularly at GulSho (Table 2). Missed calls were found primarily during months with higher overall numbers of calls. If estimated at the hourly level, recall values would have been at least as high, and likely higher, than our file-level estimates. Therefore, the values we present are conservative estimates of hourly recall.

3.2. Spatial call occurrence and detection range

Tonal calls were detected during more hours and days than downsweeping calls at GulSho and ShoHald (Table 3). At MidGul, tonal and downsweeping calls occurred during a similar number of hours and days, with downsweeping call occurrence being slightly higher (Table 3). Tonal calls were detected during the greatest number of hours and days at ShoHald and during the fewest number of hours and days at MidGul (Table 3). Tonal calls were recorded during nearly 25 % of all recording days at ShoHald (Table 3). Conversely, downsweeping calls were detected during the greatest number of hours at MidGul and during the fewest number of hours at ShoHald (Table 3). Downsweeping calls occurred during a very similar number of days at all 3 sites (Table 3). Tonal and downsweeping calls rarely occurred within the same hour (Table 3).

The results of the detection range modelling for tonal calls at MidGul showed that regardless of the season, the calls we recorded were most likely produced by whales on the eastern Scotian Shelf (Fig. 2). The estimated detection ranges were larger

Table 2. The detector performance variables used to calculate estimated recall, and resulting estimated recall values, for each site and call type. The columns are as follows: the number of files with no detections (negative files), the number of negative files reviewed by an analyst, the number of true positive (TP) files, the number of false negative files within the reviewed subsample ($FN_{reviewed}$), the estimated overall number of false negative files ($FN_{overall}$, $FN_{reviewed}$/Negative files reviewed * Total files with no detections), and the resulting estimated recall ($TP/(TP+FN_{overall})$) values

Site	Call type	Negative files	Negative files reviewed	TP	$FN_{reviewed}$	$FN_{overall}$	Estimated recall
MidGul	Tonal	48027	3079	598	12	187	0.76
	Downsweeping	47116	2056	540	11	252	0.68
GulSho	Tonal	48951	1411	1202	1	35	0.97
	Downsweeping	49199	1673	294	8	235	0.55
ShoHald	Tonal	47793	1790	1696	4	107	0.94
	Downsweeping	48711	2713	318	8	144	0.69

Table 3. Number and percentage of all recording hours and days during which only tonal, only downsweeping, and both tonal and downsweeping calls were detected at each recording site

Site	Only tonal		Only downsweeping		Tonal and downsweeping		Total	
	Hours (% of total)	Days (% of total)	Hours (% of total)	Days (% of total)	Hours (% of total)	Days (% of total)	Hours	Days
MidGul	306 (2.1)	55 (9.1)	309 (2.1)	57 (9.4)	38 (0.3)	25 (4.1)	14520	605
GulSho	548 (3.8)	92 (15.2)	188 (1.3)	63 (10.4)	31 (0.2)	20 (3.3)	14544	606
ShoHald	789 (5.4)	115 (19.0)	173 (1.2)	50 (8.2)	38 (0.3)	30 (4.9)	14544	606

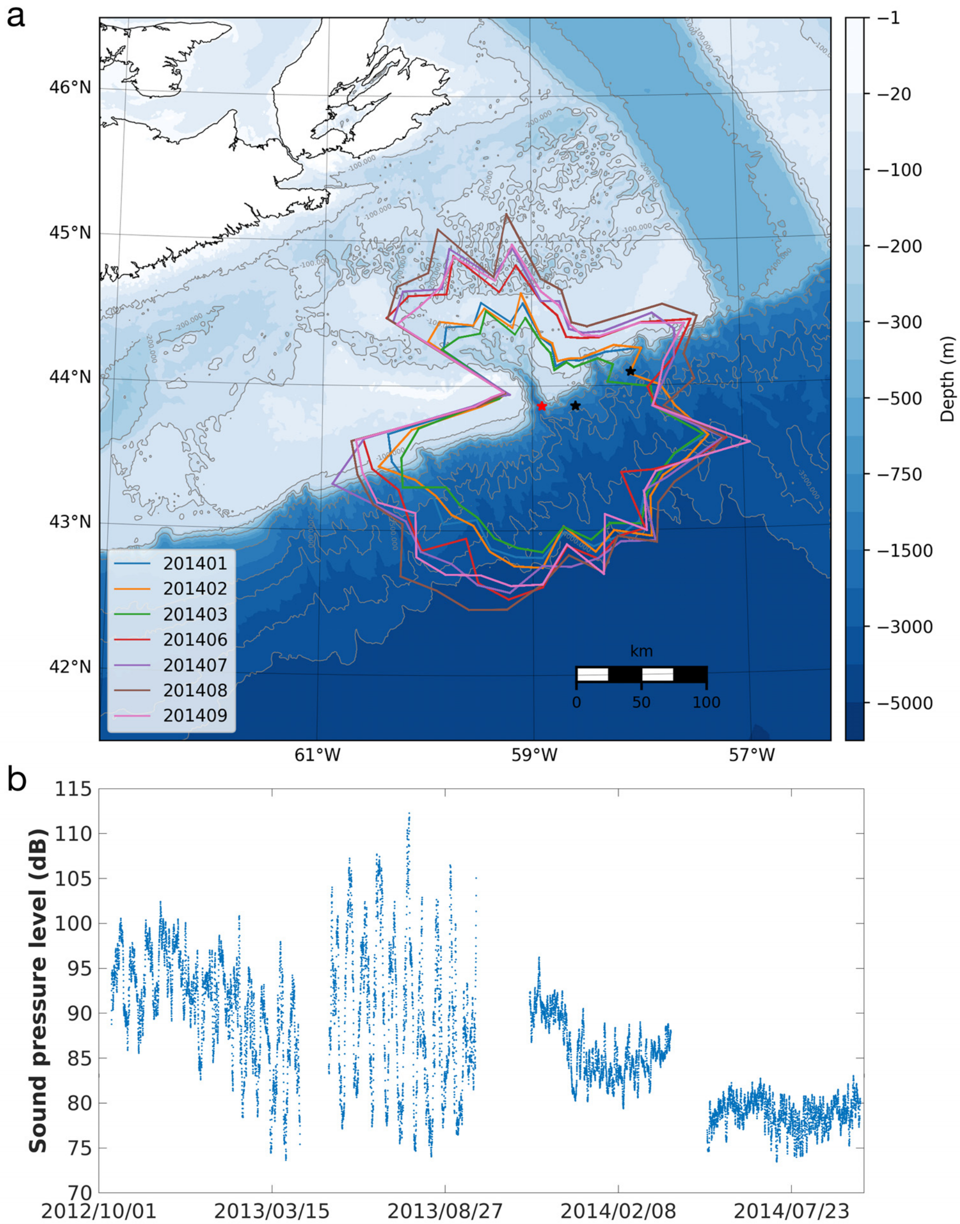

Fig. 2. (a) Estimated monthly detection ranges for blue whale tonal calls (frequency: 16 Hz, source level: 185 dB re 1µPa) at the MidGul recording site (red star) for January through March (201401–201403) and June through September 2014 (201406–201409). The locations of GulSho and ShoHald are indicated by black stars. (b) Averaged daily sound pressure levels (dB) in the 10 to 24 Hz frequency band for each of the 4 deployments at MidGul (dates provided as yyyy/mm/dd)

during summer months (June, July, August, September) than winter months (January, February, March) (Fig. 2). The daily averaged NLs in the 10 to 24 Hz frequency band were highest during the first 2 deployments (Fig. 2). In the second year, noise levels were slightly higher in the winter and spring months of the third deployment than in the summer months of the final deployment (Fig. 2).

Throughout the entire study period and at all 3 sites combined, tonal calls occurred during 1299 h and downsweeping calls occurred during 635 h. Tonal calls were recorded at only 1 site during 70% of tonal call hours, while downsweeping calls were recorded at only 1 site during 80% of downsweeping call hours (Table 4). When tonal calls occurred within the same hour at 2 sites, the majority (74%) were recorded at GulSho and ShoHald. When downsweeping calls occurred in the same hour at 2 sites, the majority (53%) were recorded at MidGul and GulSho.

Table 4. Number (#) and percentage (%) of hours containing calls during which a tonal or downsweeping call occurred at 1, 2, or all 3 of the recording sites

# of sites	Tonal Hours (#)	Tonal Hours (%)	Downsweeping Hours (#)	Downsweeping Hours (%)
1	907	69.8	511	80.5
2	338	26.0	106	16.7
3 (all)	54	4.2	18	2.8
Total	1299		635	

3.3. Seasonal and diel trends in call occurrence

Tonal calls occurred most often in September and November through January in both years, and in August 2014 (Fig. 3). Downsweeping calls occurred most often in July and August 2014 at MidGul and GulSho and in August 2014 at ShoHald (Fig. 3). Smaller peaks in the daily presence of downsweeping calls occurred in December 2012 and November 2013 at GulSho and ShoHald (Fig. 3). When the data from all 3 sites were pooled, the seasonal trends in occurrence of both call types were enhanced (Fig. 3). Downsweeping calls occurred within the general area during almost every day in August 2014 (Fig. 3).

We found no significant effect of diel period on the presence of tonal calls (Fig. 4). For downsweeping calls, there was a clear diel pattern (Fig. 4), and pairwise Tukey contrasts indicated significantly higher call presence during evening twilight than during morning twilight ($p = 0.0007$), day ($p < 0.0001$), or night ($p < 0.0001$). Fig. 5 further illustrates this result, revealing a dramatic peak in downsweeping call occurrence in the hour of 19:00 AST at each of the 3 sites, which was enhanced when the data were pooled. This hour coincided with evening twilight during July and August, the months during which downsweeping calls occurred most frequently.

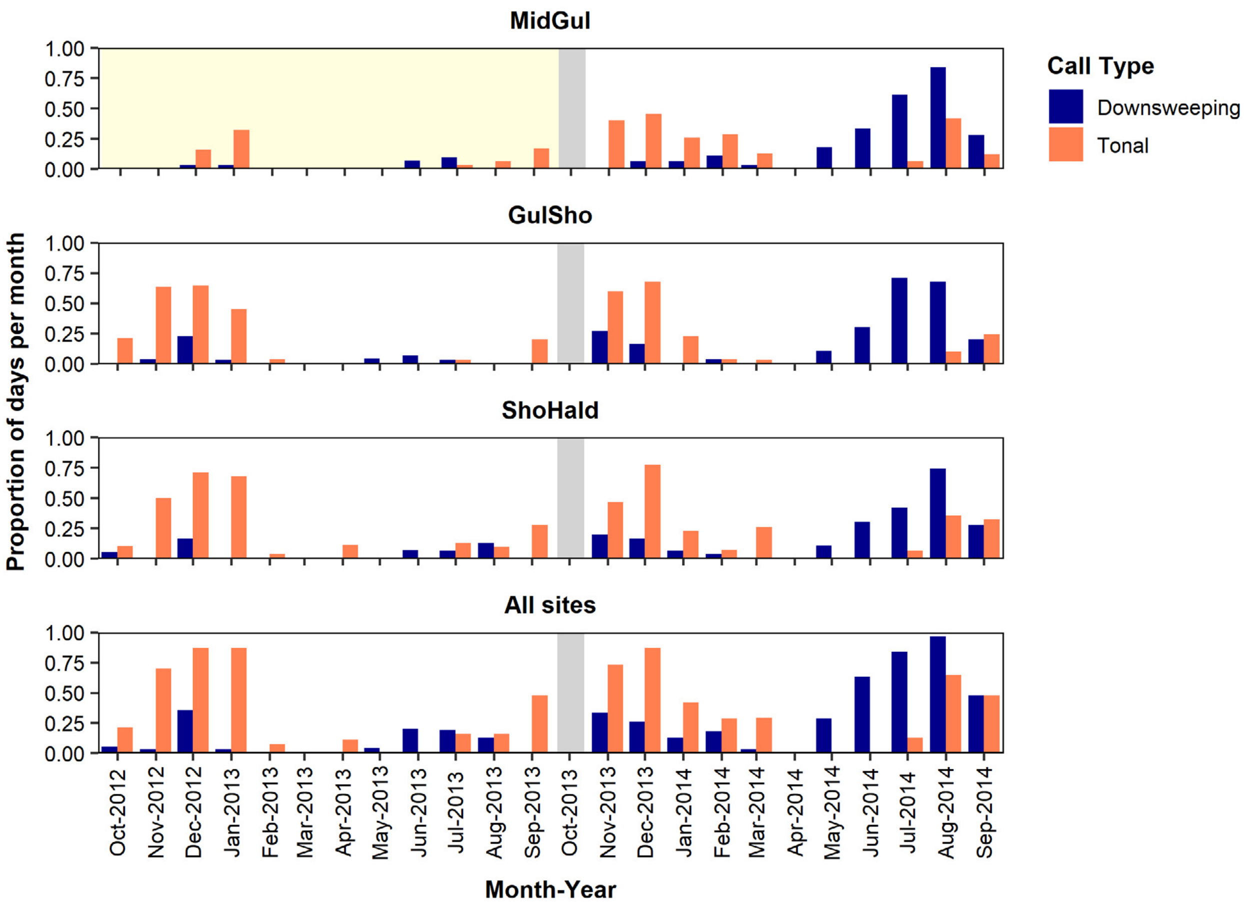

Fig. 3. Proportion of days per month that tonal or downsweeping calls were detected throughout the study period at each site, and for all sites pooled. There were no recordings made during October 2013, as shown by the gray shaded bars. The yellow shading in the MidGul panel indicates the period during which detection ranges may have been reduced due to higher noise levels in the recordings

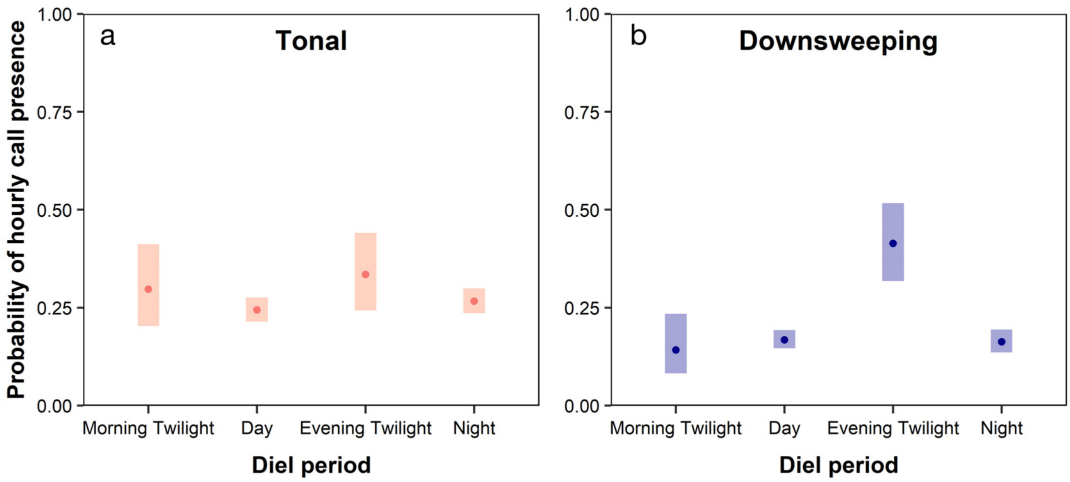

Fig. 4. Probability of hourly call presence in each diel period for (a) tonal and (b) downsweeping calls. Points represent the estimated marginal means; error bars (shaded areas) indicate 95 % confidence intervals

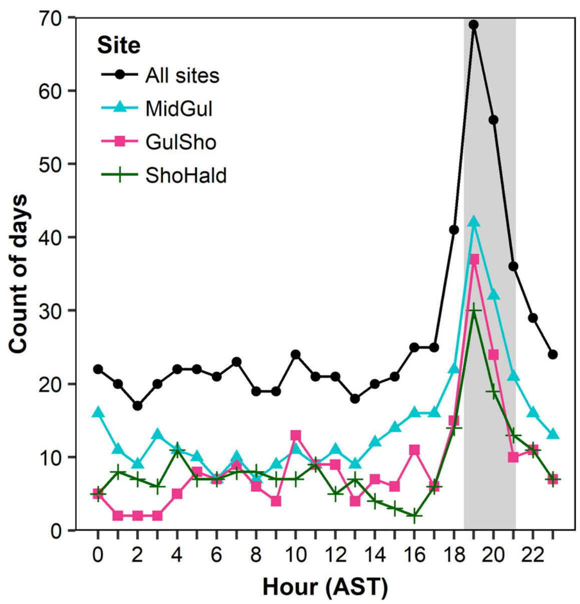

Fig. 5. Number of days with downsweeping calls detected during each hour (Atlantic Standard Time, AST) at each site separately and for all sites pooled. The grey shaded area indicates the times between the earliest onset (18:34 AST) and the latest ending (21:04 AST) of evening twilight from July through August 2014, the months during which downsweeping calls occurred most often

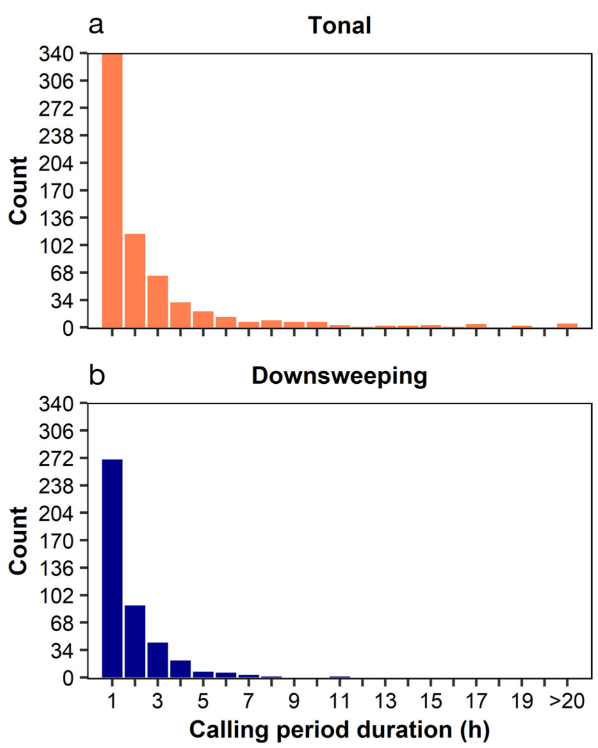

Fig. 6. Duration and frequency of occurrence of (a) tonal and (b) downsweeping calling periods. Data from all sites were combined

Trends in calling period duration were similar across sites, and so the counts of each duration for each site were added together and only these combined totals are shown in Fig. 6. Tonal calling period durations ranged from 1 to 48 h, with 1 h being the most common (Fig. 6). Longer tonal calling periods, including the 48 h maximum, typically occurred from November to late December or early January. Downsweeping calling period durations ranged from 1 to 11 h, with 1 h being the most common (Fig. 6). Longer downsweeping calling periods, including the 11 h maximum, occurred in July and August.

4. DISCUSSION

Blue whales were detected year-round at each of our 3 study sites off the eastern Scotian Shelf. The year-round presence of blue whales in the region is consistent with previously reported year-round sightings (McDonald et al. 2006, Sears & Perrin 2018, Moors-Murphy et al. 2019) and call occurrence (Marotte & Moors-Murphy 2015, Delarue et al. 2018, Moors-Murphy et al. 2019, Davis et al. 2020) within the Northwest Atlantic. Whitehead (2013) reported frequent sightings of blue whales in the Gully, Shortland, and Haldimand Canyons over several summers, and suggested cetaceans may favour canyon environments for their ability to concentrate prey. Moors-Murphy (2014) described several oceanographic processes occurring within canyons that would cause the aggregation of cetacean prey, including zooplankton, the preferred prey of blue whales.

Our estimated recall values provided assurance that, although we did not detect every call, we likely did not miss a high number of files containing calls. Therefore, the seasonal and diel trends in call occurrence we observed likely reflect actual trends in blue whale call occurrence on the eastern Scotian Shelf. Seasonal and diel patterns in call occurrence were similar across our 3 study sites. Tonal calls were detected most often from September through March, particularly from November through January, in both years, and in August 2014. Given that estimated detection ranges were larger in summer months than winter months, it is possible that there was a seasonal bias in the detectability of tonal calls. However, increased occurrence of these calls during the winter months demonstrates that we were quite capable of detecting these calls, regardless of the season.

Tonal calls are produced mostly by male blue whales (McDonald et al. 2001, 2006, Oleson et al. 2007b, Lewis et al. 2018), and only males have been observed emitting tonal calls in repetitive phrases, or songs (Oleson et al. 2007b, Lewis et al. 2018). Due to this sex bias, tonal calls are thought to relate to reproduction and mate attraction. Humpback whales *Megaptera novaeangliae* have been found to sing in northern foraging areas (e.g. Vu et al. 2012, Stanistreet et al. 2013, Kowarski et al. 2018). It is thought that humpbacks may sing on foraging grounds to advertise to potential mates prior to the breeding season or to court females who did not conceive in the previous winter (Clark & Clapham 2004). The songs may also be produced in these more northern areas by younger males who do not migrate south but remain in foraging areas to feed and practice singing (Vu et al. 2012, Stanistreet et al. 2013). These explanations may also apply to blue whales, but much less is known about the function of blue whale song or the location of their breeding grounds. However, winter is the typical breeding period for blue whales in the western North Atlantic (Sears & Perrin 2018). Tonal calls were rare or absent from March through July at all sites, which may suggest that singing males potentially move further south during this time to mate. A late migration south has been hypothesized for male humpbacks (Vu et al. 2012). However, it could also be that blue whales remain in the area throughout these months, but foraging becomes their primary focus. The absence of deep diving behaviour while male blue whales are singing suggests that singing and foraging are mutually exclusive activities (Oleson et al. 2007b, Lewis et al. 2018). Szesciorka et al. (2020) found that the onset and cessation of downsweeping calls and the onset of tonal calls in recordings of blue whales off Southern California were correlated with fluctuations in krill abundance.

In this study, we analyzed call occurrence at the level of hourly presence or absence to capture general temporal trends, but did not investigate the timing of tonal calls to identify song sequences. It is possible that blue whales produced tonal calls sporadically outside of song sequences (Oleson et al. 2007b). Sporadic 'A' and 'B' calls have been recorded on tags attached to both male and female blue whales (Oleson et al. 2007b, Lewis et al. 2018); however, some evidence suggests that calls recorded on tags attached to female whales may have been produced by nearby untagged whales of unknown sex (Lewis et al. 2018). It is possible that these sporadic calls account for most of the instances where we observed only 1 consecutive tonal call hour, while song sequences accounted for the longer calling periods, some of which lasted as long as 2 d. However, male blue whales sing while traveling (Oleson et al. 2007b), and therefore it is also possible that the recorders detected only fragments of songs as whales passed by our study sites. Regardless of whether the production of tonal calls during winter months was related to mating, it is clear that at least some males occur in waters off the Scotian Shelf into the winter and spring months. These results are consistent with those observed by Davis et al. (2020), who detected blue whale tonal calls year-round in the western North Atlantic. Further investigation into the sequences of tonal calls may provide a better understanding of blue whale behaviour during the winter months. Noise levels were much higher at MidGul during the first 2 deployments, prior to the modification of the mooring design. This may explain why there were fewer tonal calls detected at MidGul in the first year compared to the second, and why the estimated recall value for tonal calls at this site was lower than those for ShoHald and GulSho.

While downsweeping calls were detected in some winter months and during the summer in 2013, the majority of these calls were detected in summer 2014. 'D' calls, which we included in our downsweeping call category, have been recorded at shallow depths between deep foraging dives (Oleson et al. 2007b) and during shallow non-lunging dives and periods of surface behaviour (Lewis et al. 2018). Given that downsweeping calls are produced by both males and females, and often in groups of 2 or more individuals, these calls are believed to be social calls used to maintain acoustic contact between individuals (McDonald et al. 2001, Oleson et al. 2007b). If downsweeping calls coincide with the occurrence of foraging, as Oleson et al. (2007b) observed, the increase in this call type during the spring and summer when blue whales are feeding on northern foraging grounds was expected. However, we did not expect that the occurrence of these calls would be so much greater in 2014 than in 2013. Blue whales feed almost exclusively on euphausiid krill, and therefore krill distribution and swarm characteristics are likely to be strong predictors for blue whale occurrence (Kawamura 1980, Gavrilchuk et al. 2014, McQuinn et al. 2016, Miller et al. 2019). Zooplankton biomass typically peaks in the spring and summer months on the Scotian Shelf (Johnson et al. 2016), and was greater during the summer of 2014 than in 2013, particularly in the Bay of Fundy and on the central Scotian Shelf, southwest of our study sites (Johnson et al. 2016). There was also an increase in biomass around our sites in 2014 compared to 2013, although less dramatic than for the areas previously mentioned (Johnson et al. 2016). We were unable to estimate blue whale abundance based on our acoustic data, but it is possible that the increase in productivity attracted more individuals to the area, and thus the increased call occurrence observed in summer 2014 was the result of more calling whales rather than an increase in individual call production. McQuinn et al. (2016) found that blue whale density was greatest in slope areas where krill aggregated. As previously mentioned, the Gully MPA is a highly productive habitat and is thought to be an attractive foraging ground for several species of cetaceans (Moors-Murphy 2014).

Alternatively, individual blue whales may have increased their call production. Di Iorio & Clark (2010) reported that blue whales in the St. Lawrence Estuary increased call production during seismic airgun activity. The Tangier 3D WATS Seismic Survey was conducted near our study area from mid-May through mid-September 2014 (RPS Energy Canada 2014) and may have led to increased downsweeping call production in response. It has been hypothesized that downsweeping calls may be a counter-call to maintain acoustic contact between individuals (McDonald et al. 2001), and so perhaps blue whales were attempting to connect with one another amidst the noise emitted by the seismic air guns. The seismic survey did not noticeably increase daily averaged noise levels in the 10 to 24 Hz frequency band at MidGul, but it is possible that calling blue whales were closer to the survey and experienced elevated noise levels. The estimated recall value for downsweeping calls was lower at GulSho than at MidGul and ShoHald, which suggests we may have disproportionately underestimated downsweeping call occurrence at this site. The reason for this decreased detectability is unknown; however, trends in downsweeping call occurrence at GulSho were similar to those at the other 2 sites.

There was a significant peak in the occurrence of downsweeping calls during evening twilight. There are mixed results in the existing literature regarding diel patterns in blue whale call occurrence. Some studies, such as Oleson et al. (2007a) and Leroy et al. (2016), report increased calling rates during the day, while others, such as Wiggins et al. (2005), Stafford et al. (2005), and Lewis et al. (2018) observed increased call rates during twilight and night hours. Baumgartner & Fratantoni (2008) found that sei whales *Balaenoptera borealis* in the Gulf of Maine called more often during the day. Diel patterns in the calling behaviour of cetaceans are often linked to the vertical migration of their prey. Zooplankton, including krill, migrate from depth to surface waters at night to feed on phytoplankton, and migrate back to depth during daylight hours to avoid predation (Dodson 1988, Lampert 1989, Bollens et al. 1992, Kaartvedt 2010). Lewis et al. (2018) observed an increase in 'D' call occurrence during dusk and hypothesized that blue whales fed on aggregated krill at depth during the day, and were then free to call at dusk as their prey began to scatter.

Alternatively, blue whales may continue to forage into the evening, but are able to call while doing so because their prey is at shallower depths where the whales are capable of producing calls (Stafford et al. 2005). Due to physiological constraints, blue whales produce calls at shallow depths, generally less than

60 m, with an average calling depth of 20 to 30 m (Thode et al. 2000, Oleson et al. 2007b, Lewis et al. 2018). Foraging and calling are mutually exclusive during the day when the whale must choose between diving to depths of concentrated prey abundance or remaining shallow enough to emit calls (Wiggins et al. 2005). Doniol-Valcroze et al. (2011) and McQuinn et al. (2016) argued that diving predators should forage as close to the surface as possible for maximum efficiency, and found that the position and accessibility of krill in the water column were important drivers of blue whale foraging. Similarly, Miller et al. (2019) found that blue whales in the Antarctic were more likely to be detected near krill swarms that were taller, in shallower waters, and had a higher density of krill. Given that we observed tonal calls mostly in the fall and winter, it could be that during that time the main focus was mate attraction rather than foraging, and thus whales were free to call during all hours of the day. Downsweeping calls occurred across consecutive hours much less often than tonal calls, likely because downsweeping calls are more sporadic and are not produced in patterned sequences.

The estimated detection ranges for tonal calls at MidGul included GulSho and ShoHald, but tonal calls were typically detected at only 1 site within an hour. Kowarski et al. (2018) found humpback whale calls were recorded at only 1 site for the majority of call hours in the same dataset, despite estimated detection ranges encompassing more than 1 site. Our estimated detection range model was intended to demonstrate that the calls we recorded came from within the eastern Scotian Shelf study area, regardless of the season. Given that the majority of call hours (~70% for tonal and ~80% for downsweeping) occurred at only 1 site, our detection range model is likely an overestimation. There are several possible reasons for this. First, blue whales may emit tonal calls at lower source levels than the estimate used in our detection range model. Second, noise levels at each of the sites may have varied, with louder noise levels leading to lower probability of call detection. This was demonstrated for humpback whale detection range at the same 3 recording sites by Kowarski et al. (2018). Daily averaged noise levels at MidGul were higher in the winter months than the summer months in 2014, and thus detection ranges were smaller in winter. Third, the model operated under the best-case scenario that a tonal call would be detected as long as the call was louder than the background noise, but it is more likely that detection would require the call to be at least 3 dB greater than the background noise. Finally, calls detected at GulSho and/or ShoHald that were not detected at MidGul could have originated from areas to the east, outside of the estimated detection range for MidGul.

While PAM has allowed us to investigate year-round blue whale call occurrence on the Scotian Shelf, this method is not without its limitations. Our duty-cycled recording schedules varied slightly over the course of the study, resulting in 52 min of data per hour in the earlier deployments and 54 min of data per hour in the later deployments. However, this difference is not likely to have had a significant effect on our estimation of blue whale presence at the hourly level (Thomisch et al. 2015). The time of year and noise levels can affect call detectability, as demonstrated by our detection range model for tonal calls at MidGul. Noise, whether it be from vessels, seismic air guns, or even biological sources, can mask blue whale calls. This may have been the case during the first 2 deployments at MidGul, as elevated noise levels occurred in the same frequency band in which blue whales produce calls. The results of this study therefore represent minimum blue whale call occurrence over space and time.

To our knowledge, this is the first published study to characterize the year-round occurrence of both blue whale tonal and downsweeping calls off the eastern Scotian Shelf and within the Gully MPA. By including downsweeping calls and analyzing calls on an hourly scale, we were able to expand upon the results of Davis et al. (2020) to provide a more detailed understanding of year-round blue whale occurrence off the eastern Scotian Shelf. Including both tonal and downsweeping call categories is important, as it provides insight into both mating and foraging behaviours, and into the presence of both sexes. Better understanding of blue whale occurrence in this region will enhance efforts to better protect this endangered population, which currently faces threats such as anthropogenic noise, pollution, human-induced changes in food availability, ship strikes, and entanglement (Sears & Calambokidis 2002, Beauchamp et al. 2009, Aulanier et al. 2016, Sears & Perrin 2018, Ramp et al. 2021). PAM efforts in the Scotian Shelf area have been expanding (e.g. Fisheries and Oceans Canada is now monitoring a minimum of 10 sites off Nova Scotia throughout the year) and analysis of blue whale calls on both old and new datasets continues. We recommend that analyses of these data include both call types (tonal and downsweeping) to fully capture long-term seasonal and annual changes in blue whale call occurrence.

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Appendix.

Table A1. Parameters for each of the masks used to detect 'A', 'B', and 'D' calls. If the time between several detections was shorter than the value given in the 'Minimum duration between detections' column, only the detection with the highest correlation index was kept (the others were ignored). One of the 'D' call mask templates contained 2 line segments; the values in square brackets describe the second segment

Call type	Start time (s)	Stop time (s)	Start frequency (Hz)	Stop frequency (Hz)	Width (Hz)	Minimum frequency (Hz)	Maximum frequency (Hz)	Duration (s)	Minimum duration between detections (s)	Minimum detection threshold
A	1	11	17	17	2	12	21	12	9	0.3
A	1	6	17	17	2	12	21	7	9	0.3
B	0.1	9.1	17	15	2	10	21	10.1	9	0.3
D	0.1 [2.1]	2.1 [9.1]	65 [64]	64 [30]	2	25	70	9.5	6	0.2
D	0.1	6.1	60	30	2	28	62	6.2	6	0.4
D	0.1	3.1	60	40	10	28	70	3.2	6	0.4
D	0.5	2	75	50	15	39	89	2.3	6	0.3

Table A2. Geoacoustic properties for the Gully and shelf break slope used in the range-dependent acoustic model (RAM) to estimate detection range of blue whale tonal calls with an assumed source level of 185 dB re 1µPa at 16 Hz; pressure-wave is abbreviated to 'P-wave'

Depth (m)	Material	Density (g cm^{-3})	P-wave speed (m s^{-1})	P-wave attenuation (dB λ^{-1})
0–30	Pelite	1.52–1.61	1505–1740	0.44–1.2
30–120	Glacial till	2.0–2.1	2000–2400	1.5–2.2
120–1000	Sandstone	2.2–2.6	3000–4000	0.05
>1000	Sandstone	2.6	4000	0.05

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