Applied Acoustics 71 (2010) 1099–1106

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Detection range modeling of blue whale calls in Southwestern Indian Ocean

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ARTICLE INFO

Article history:
Available online 23 June 2010

Keywords:
Detection distance
Parabolic equation
Blue whale calls
Ambient noise

ABSTRACT

In the Southwestern Indian Ocean, one year of continuous acoustic data from calibrated hydrophones maintained by the International Monitoring System provided data on blue whale calls from two subspecies Antarctic and pygmy blue whales. Using an automatic detection method with a fixed threshold, both call types were detected and received levels were measured for each detected call. By using a parabolic equation loss model configured with the precise characteristics of the biological source, hydroacoustic station, and environment in the study area, distances at which calls could be detected were estimated. These methods were used to define the maximum detection range around each array of hydrophones and the influence of the seasonal variation of the ambient noise and sound velocity on the detection ranges. Results showed that detection ranges were critically dependent on the choice of the biological source's input parameters, including frequency bandwidth and source level. Over the course of the year, detection distances were different for both subspecies; the pygmy blue whale seemed to be consistently closer to the station than the Antarctic blue whale. The distribution of the estimated distances confirmed the presence of both subspecies of blue whales near the Crozet Islands showing the importance of this sub-Antarctic area for these endangered species, especially during the austral summer feeding season.

1. Introduction

In the Southern Hemisphere, overexploitation during the 20th century by commercial whaling reduced blue whale populations (*Balaenoptera musculus spp.*) to the brink of biological extinction [1]. Despite gaining complete international legal protection several decades ago, blue whale populations remain at low levels and their recovery seems to be slow [2,3], particularly in the face of the unknown impacts of global climate change on their critical habitats. Little is known about the abundance and distribution of blue whales off the Southwestern part of the Indian Ocean [4]. These populations were largely exploited by whalers during legal and illegal whaling program in the 1950s, 60s and early 70s [5–7]. Waters around sub-Antarctic islands are known to be primary pygmy blue whale (*Bm. brevicauda*) habitat during summer [4,8]. Antarctic blue whales (*Bm. intermedia*) seem inhabit the area year-round and the two subspecies are probably mixing during the austral summer feeding season [8].

Monitoring blue whales to assess their distribution, movement, habitat preference, and the recovery of their populations remains difficult, especially in high-latitude regions where standard visual surveys are costly and difficult. However, blue whale emit almost year-round, redundant, stereotyped long and low frequency calls (10–100 Hz) with high intensity [9,10]. Blue whale calls can be detected for ranges of many hundreds of kilometers by other individuals or by passive acoustic monitoring systems [10–14]. Long-term deployment of passive acoustic recorders are well adapted to collect blue whale data continuously for years on end, under ice cover, and in any weather conditions or sea-states. This method allows the monitoring of seasonal distribution and acoustic behaviour of blue whale populations over ocean basins and remote areas as in the Pacific Ocean [15–17], Atlantic Ocean [18–20], Indian Ocean [20], Southern Ocean, and off the Antarctic Peninsula [21,22].

Acoustic surveys of several species of balaenopterid whales have been largely enhanced by acoustic data available from a wide variety of instruments that were originally designed to monitor the seismicity of the earth [19,23,24] or for defense purposes [12,18,20]. In the Southwestern part of the Indian Ocean, hydroacoustic stations maintained by the International Monitoring System (IMS) provided one year of valuable records of a large variety of specific low frequency sounds. Among them, calls produced by different blue whale subspecies including Antarctic blue whales and 'acoustic populations' of pygmy blue whales including 'Madagascar', 'Australia' and 'Sri Lanka' [8] were detected. Antarctic (BMi) and pygmy blue whale 'Madagascar' type (BMb) calls were predominant in the dataset. An automatic detection method was created [25] to detect both call types and to establish the

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0003-682X/$ - see front matter
doi:10.1016/j.apacoust.2010.05.014

seasonal occurrence of each blue whale subspecies [8]. The average call source level of both subspecies were also estimated [26].

The aim of this paper is to determine the distribution range over which Antarctic and pygmy blue whale 'Madagascar' type calls can be detected by the IMS hydroacoustic station. We report the estimated detection distances of calling animals using a parabolic equation propagation loss model performed with the Range dependent Acoustic Model (RAM). This model allows evaluation of the range over which each low frequency whale sound can be expected to propagate by taking into account the monthly received level, frequency, and source level of whale call with the seasonal ambient noise levels received at the station and the seasonal propagation conditions along the transmission path from source to receiver. We also report on the analysis of the ambient noise level received at each hydrophone's array over the recorded period.

2. Materials and method

2.1. Dataset

Acoustic data from May 2003 to April 2004 used for this study were recorded at a station of the IMS moored in the Southwestern Indian Ocean (Crozet Islands - 46°51′S-51°53′E) in support of the Comprehensive Nuclear Test-Ban Treaty (CTBT) (Fig. 1). The station was composed of two arrays of three instruments located in the Northern (HA4N: AHA4N1, HA4N2, HA4N3) and Southern (HA4S: HA4S1, HA4S2, HA4S3) coasts of Possession Island. In an array, instruments were deployed in a triangular configuration (triad) with approximately 2 km spacing. The two arrays were located on opposite sides of the island and spaced 60 km apart. Instruments were moored to the seafloor between depths of 1100 and 1500 m and hydrophones were suspended near the sound channel axis (SOFAR) at a depth of approximately 300 m. The hydrophones monitored sound continuously at a sampling rate of 250 Hz, encoded by 24 bits (S/N: 126.5 dB), with a flat (±3 dB) frequency response from 1.2 to 102.5 Hz. The hydrophones had a calibration of -56.6 dB re:counts^2/μPa^2 in the 10–50 Hz band. Acoustic data for HA4N2, HA4N3, HA4S1 and HA4S3 were available for the entire recording period. Data for HA4S2 were available only from May 2003 to December 2003. No data were available for HA4N1 due to instrument failures. Due to the close hydrophone spacing, data were analyzed from only one instrument in each array.

2.2. Blue whale calls

Recordings from the hydrophones included a large variety of sounds including Antarctic and pygmy blue whale 'Madagascar' type calls. Antarctic blue whale calls (Fig. 2a) consist of three tonal units lasting approximately 26 s, that repeat in patterned sequences every 40–50 s over a period extending from a few minutes to hours [21,20,25,27,28]. The first component (Part 1) is a constant frequency tone centered on 28 Hz followed by a short frequency-modulated (FM) down-sweep from 28 Hz to 20 Hz (Part 2) ending with the third component (Part 3), a slightly modulated tone (20–18 Hz). Pygmy blue whale 'Madagascar' type calls (Fig. 3a) consist of two long units repeated in patterned sequences every 90–100 s over a period extending from a few minutes to hours [25,27]. The first component (Part 1) is primarily a constant frequency tone at 35 Hz lasting 15–20 s. A silence (approximately 20 s) separates the two-part phrase. The second component (Part 2) starts with a 1–2 s 15–28 Hz FM down-sweep that ends with a long (20–25 s) slightly modulated tone. Each component has strong associated harmonics.

The acoustic data from each hydrophone on both triads were analyzed to check for the presence of calls typically associated with Antarctic and pygmy blue whales. An automatic detection method for both call types was employed. The detector used a matched filter process which cross-correlated the acoustic data with synthetic

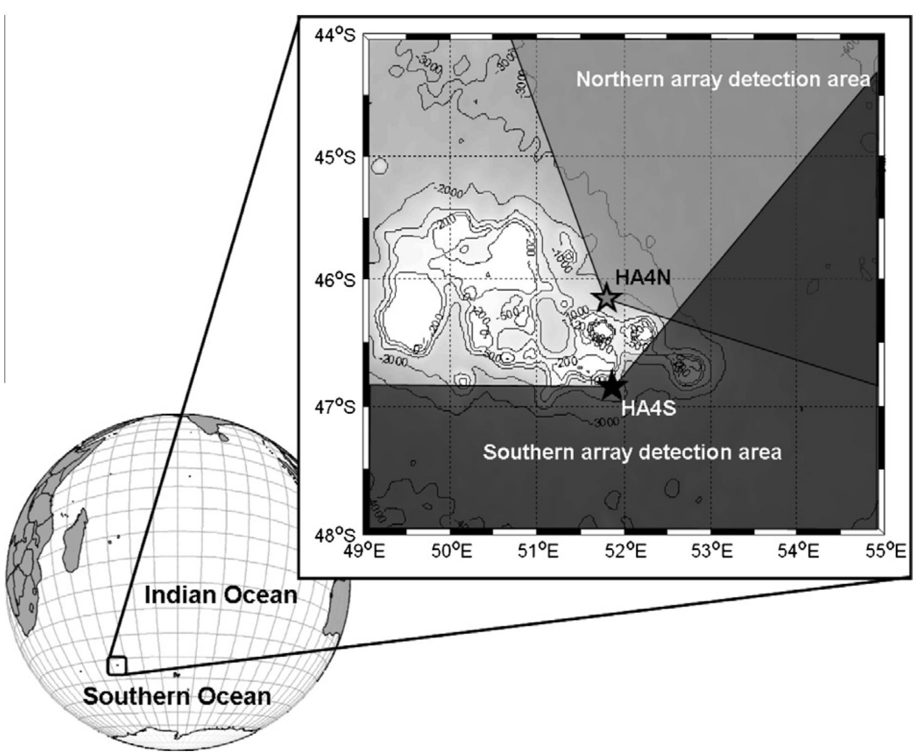

Fig. 1. Location of the two arrays (grey stars: Northern array and black star: Southern array) of the hydroacoustic station of the International Monitoring System moored in the Southwestern Indian Ocean near Crozet Islands. The potential call detection area for the both arrays (grey area: Northern array and black area: Southern array) is delimited from the detection range modeling using the Range-dependant Acoustic Model.

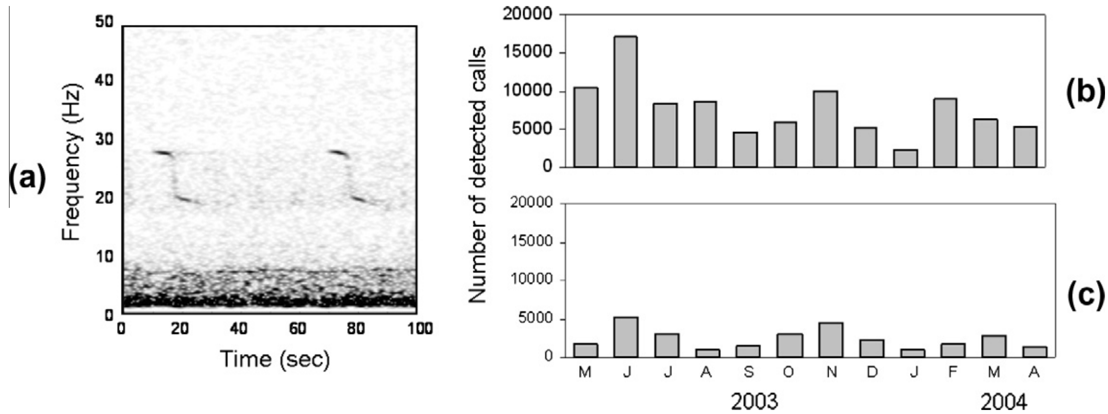

Fig. 2. Antarctic blue whale calls detected on hydroacoustic station of the International Monitoring System moored in the Southwestern Indian Ocean. (a) Spectrogram of two Antarctic blue whale calls (FFT 1024 points, 93.75% overlap, Hanning window), seasonal pattern of calls detected on the Northern array (a) and on the Southern array (b).

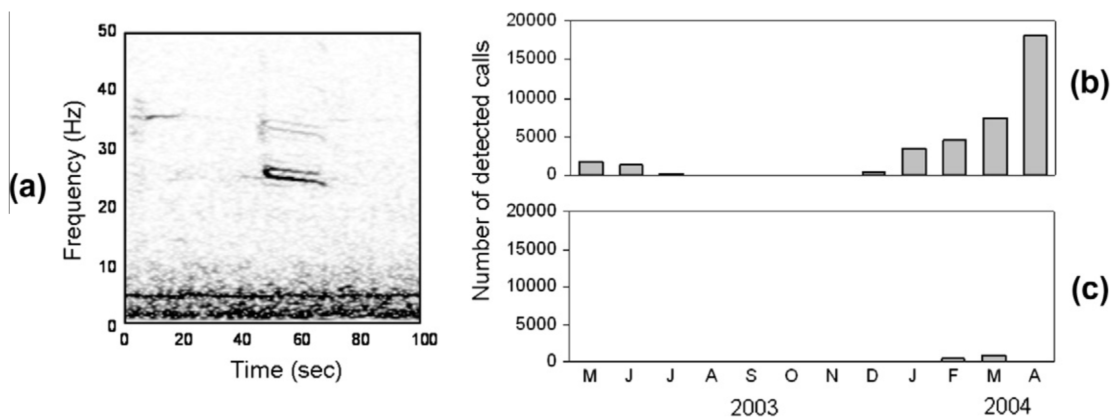

Fig. 3. Pygmy blue whale 'Madagascar' type calls detected on the hydroacoustic station of the International Monitoring System moored in the Southwestern Indian Ocean. (a) Spectrogram of one pygmy blue whale 'Madagascar' type call (FFT 1024 points, 93.75% overlap, Hanning window), seasonal pattern of calls detected on the Northern array (a) and on the Southern array (b).

waveforms (templates) defined for both blue whale subspecies' calls (based on the limited range of variability in the blue whale calls, see details in [25]). This method was used to detect both blue whale calls with a Signal-to-Noise Ratio (SNR) up to −15 dB in the 17–30 Hz bandwidth for BMi calls and 17–50 Hz for BMb calls.

A receive level *RL* (RMS, in dB re 1 $\mu Pa^2/Hz$) was measured for each call detected as follows:

$$RL_{dB} = 10\log_{10}\left(\frac{1}{T}\int_0^T x^2(t)\mathrm{d}t\right)$$

where *T* is the signal duration of the filtered signal *x* (after using two successive Butterworth filters). Antarctic blue whale call received levels were measured over 17–30 Hz and pygmy blue whale call received levels were measured over 17–50 Hz. When whales were present near the Southern array, a combination of time difference of arrival and a least squares hyperbolic approach was used to localize the call and measure the distance of the source to the receiver. The call source levels of both subspecies (see details in [26]) were then estimated.

2.3. Ambient noise level

The ambient acoustic noise level received at each array was measured for each available hour from May 2003 to April 2004. As described above, frequency bandwidths vary for the two blue whale subspecies calls. Ambient noise levels were also measured over the two different bandwidths (i.e. 13–30 Hz corresponding to the BMi calls bandwidth and 17–50 Hz corresponding to the BMb calls bandwidth). The ambient noise level *AN* at frequency bandwidths (in dB re 1 $\mu Pa^2/Hz$), was measured as follows:

$$AN_{dB} = 10\log_{10}\left(\frac{1}{T}\int_0^T x^2(t)\mathrm{d}t\right)$$

T is the signal duration of the filtered signal *x* where the energy is calculated (with non-overlapping sliding window of 30 s). Per hour, we retained the minimum energy value as the hourly ambient noise level by assuming that this value represents the acoustic signal energy when any whale calls are present or when whale call received levels are lower than the ambient noise level. Resulting data were pooled by month and a Student's *t*-test was used to determine whether ambient noise levels measured were significantly different between the two arrays of hydrophones.

2.4. Detection distance modeling

To evaluate the acoustic detection ranges over which Antarctic and pygmy blue whale calls can be detected (above the chosen threshold) by the hydrophones in the background noise off Crozet Islands, we used the received level of the call combined with a reliable sound transmission loss model. This approach assumes that the source level of calling whales is constant. Given these assumptions, the received call level measured at the hydrophone can be used to estimate range by applying a transmission loss equation. Transmission loss *TL* was also estimated as follows:

$$TL_{dB} = SL_{dB} - RL_{dB}$$

where *SL* is the source level value of each blue whale subspecies and *RL* is the received level measured for each detected call.

Different models could be used to estimate the acoustic propagation loss. These main methods are obtained from the resolving of the Helmholtz equation and are based on (1) ray theory [29], (2) the normal mode equation [30], or (3) the parabolic equation [31]. The drawback of the ray theory is that it does not consider interaction between the rays. Moreover, the calculation time increases with the number of rays. However, this approach could be efficient for low distances or under certain conditions.

Models based on the normal mode equation are range-independent, but in the region off Crozet Islands, bathymetry is highly variable over long-distance due to the presence of islands, seamounts and deep water. Likewise, the sound velocity is variable over the propagation range and during the season.

For the specific context of this study, propagation loss estimates were performed with parabolic equation methods using the RAM model [31]. The method provides an effective model for transmission loss especially for low frequency signals with limited bandwidths where the acoustic sources are far from the receivers and the acoustic parameters vary with range. Using this method, transmission loss curves along the range-depth plane from source to receiver for characteristic frequencies of each blue whale call type were obtained, taking into account environmental, receiver, and source parameters.

Environmental parameters were specifically configured for the Crozet region along the transmission path from source to receiver. Parameters include the bathymetric profile obtained from ETOPO 2 (http://www.ngdc.noaa.gov), monthly sound speed profiles within the water column obtained from the climatic (average) U.S. Naval Oceanographic Office's General Digital Environmental Model – GDEM (which provide monthly averages at 0.5° intervals), ocean bottom composition (i.e. silicic limestone), and monthly ambient noise level received at each array and measured as described above.

For each subspecies, the primary *receiver parameter* was the received level (*RL*). RL was calculated, as described above, for each automatically detected call. In addition, receiver parameters such as hydrophone depth and geographic position were required.

Source parameters included, for each subspecies, depth of the calling whale, a single frequency that highly describes the whale call and the source level of the call. We assumed that sounds are emitted omni-directionally for a calling blue whale located at 50 m below the surface [32]. Because each blue whale call type is composed of different frequencies [25], a single highly characteristic frequency was chosen as input to the RAM model. Calls with high SNR with no interfering sounds were selected for measurement of time, frequency and received level characteristics for each call unit (Table 1). Finally, the frequency value corresponding to the longest unit of each call with the highest intensity was chosen; i.e. 28 Hz for the Antarctic blue whale call and 25 Hz for the pygmy blue whale call. The source level values for each blue whale subspecies were previously estimated in the study area [26]. The source levels used for the propagation loss modeling were 179 dB_{rms} re 1 μPa at 1 m for Antarctic blue whale and 174 dB_{rms} re 1 μPa at 1 m for pygmy blue whale. Previously, the average call source level of the blue whale has been estimated in different locations using different methodologies e.g. [14,33,34]. These varied slightly as compared to estimates reported in the study area. This could be due to differences between individuals, subspecies and/or calculation method [26]. Consequently, to test the effect of source level on the model, estimated distances were also obtained with different source level values, as reported in the literature (189 dB re 1 μPa at 1 m for the BMi [14] and 183 dB re 1 μPa at 1 m for the BMb [34]).

To explore horizontal range independence and to define probable shadow areas due to the bathymetry of Crozet area, propagation loss at each array was modeled for the two subspecies-specific frequencies along 36 transects at 10° intervals to a distance of 400 km for a given month. A fixed *RL* value corresponding to the lower ambient noise value measured at each array (Northern array BMi and BMb Bandwidths: RL = 82 dB re 1 $\mu Pa^2/Hz$; Southern array BMi Bandwidth: RL = 94 dB re 1 $\mu Pa^2/Hz$) was used.

To explore the influence of the seasonal variation of the environmental conditions (i.e. sound speed, ambient noise) on the transmission loss, we modeled propagation loss for the two specific frequencies at each array by using *RL* values corresponding to the lower ambient noise level received at the instruments for each month.

Finally, the detection distances over which each of the Antarctic and pygmy blue whale calls can be detected at each array were estimated by using loss measurements iterated for each month along a single transect for the Northern array (i.e. 10°) and a single transect for the Southern array (i.e. 180°).

3. Results

3.1. Ambient noise level

For each frequency bandwidth where the ambient noise level was calculated, there was a significant difference between the monthly ambient noise levels measured on each array (BMi bandwidth and BMb bandwidth on HA4N ($n = 7352$) and HA4S ($n = 6071$); Student's t-test: $p < 0.05$). For each frequency bandwidth the ambient acoustic noise was time-variant for the recording period (Fig. 4a and b). On the Northern array, ambient noise level presented variation over the course of the year and increased in wintertime. On the Southern array, ambient noise level was higher by approximately 14 dB irrespective of months with a seasonal variation slightly less marked.

3.2. Shadow area

To estimate the area in the shade for the two chosen frequencies due to the bathymetry of the study area, transmission loss

Table 1
Summary of frequency measurements, signal duration and received level of Antarctic (BMi) and pygmy 'Madagascar' type (BMb) blue whales calls measured on selected calls with high SNR with no interfering sounds and recorded at the hydroacoustic station of the International Monitoring System moored in the Southwestern Indian Ocean near Crozet Islands.

		Main frequency (Hz)		Signal duration (s)		Received level (dB re 1 $\mu Pa^2/Hz$)	
		Mean	SD	Mean	SD	Mean	SD
BMi ($n = 318$)	Part 1	27.9	0.1	7.2	1.3	88.4	3.2
	Part 2	19.5	0.3	7.1	2	87.7	3.2
BMb ($n = 105$)	Part 1	35.2	0.2	16.9	1.8	95.7	2.1
	Part 2	25.0	0.1	20.2	1.8	98.7	2.8

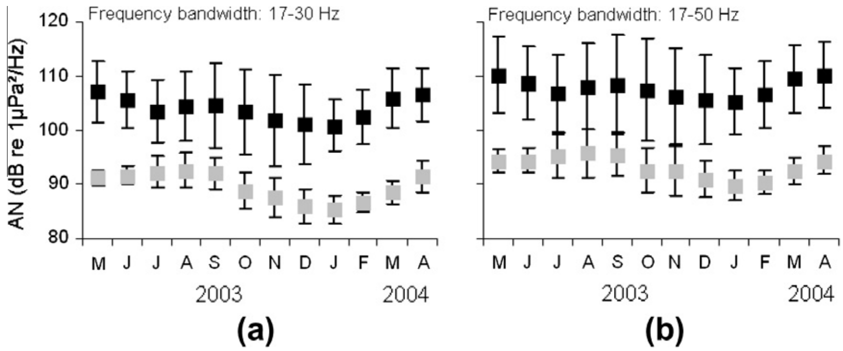

Fig. 4. One year of ambient noise level received at the Northern array (grey) and at the Southern array (black) in the frequency bandwidth of Antarctic blue whale calls (a) and pygmy blue whale calls (b) in the Southwestern Indian Ocean.

was modeled for each array of hydrophones using fixed parameters. Results revealed two important shadow areas for detection of Antarctic and pygmy blue whale calls. The theoretical call detection areas were delimited for the Northern array between 110° and 340° and for the Southern array between 40° and 270° (Fig. 1).

3.3. Seasonal differences of the transmission loss

Because of ambient noise and sound speed variation present over the course of the year in the study area, transmission loss was modeled on both hydrophones array for 28 Hz and 25 Hz bandwidths and on Southern array only for 28 Hz bandwidth (because very few BMb was detected on Southern array) with monthly fixed parameters corresponding to the minimum level of ambient noise measured. For each frequency and for each array, transmission loss paths showed a marked seasonal difference with detection ranges reduced during austral fall-winter months (Fig. 5).

3.4. Detected blue whale calls

The detection method takes into account of the chosen threshold [25]. Then the number of detections of Antarctic and pygmy blue whale 'Madagascar' type calls were lower on the Southern than on the Northern array (Fig. 2b and c and Fig. 3b and c). On both arrays, Antarctic blue whale calls were detected year-round with less detection during austral summer months. On the Northern array, pygmy blue whale calls were only detected from the beginning of austral summer to the beginning of winter. Very few pygmy blue whale calls have been detected on the Southern array to allow estimation of their detection ranges.

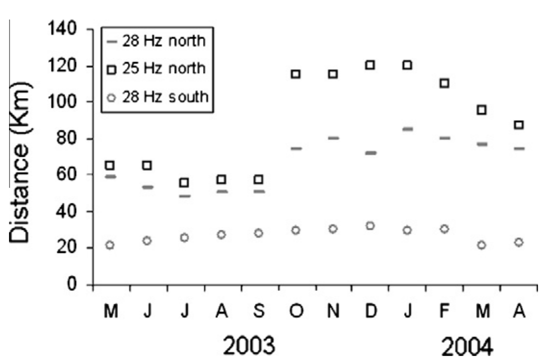

Fig. 5. Monthly maximum detection range estimated for frequency characteristics of the Antarctic (28 Hz) and pygmy (25 Hz) blue whale using the Range-dependant Acoustic Model performed for fixed received value corresponding to the minimum ambient noise level measured at each array (Northern and Southern) of the hydroacoustic station of the International Monitoring System moored in the Southwestern Indian Ocean.

3.5. Estimates of detection distances and detection ranges

3.5.1. For low frequency signal attributed to the Antarctic blue whale calls characteristics i.e. 28 Hz

In the Northern array, estimates of maximum detection range for the Antarctic blue whale calls characteristics (28 Hz bandwidth) were different over the course of the year (Fig. 6a). Roughly the maximum detection range was greater during the middle of spring and summer months (around 70 km and up to 180 km) than during the fall, winter and the beginning of spring months (around 50 km and up to 140–150 km). The majority of detection distances were located over 20 km from the hydrophones but every month some Antarctic blue whale calls were detected very close to the Northern array. In the Southern array, estimates of maximum detection range were different over the course of the year (Fig. 6b). The estimated maximum detection range was greater during the spring and summer months (around 30–40 km and up to 80 km) than during the fall and winter months (under 20 km and up to 55 km). By changing the source level parameters based on values reported in the literature [14], the detection distances increased by a factor of 1.89 on both arrays.

3.5.2. For low frequency signal attributed to the pygmy blue whale calls characteristics i.e. 25 Hz

In the Northern array, estimates of detection distances for characteristics of pygmy blue whale calls (25 Hz bandwidth) were approximately 40–50 km for the months in which calling whales were detected (Fig. 6c). Estimates of maximum detection range were around 150 km but a majority of the detection distances were around 30–40 km and were closer to the instruments especially in April. By changing the source level parameters based on values reported in the literature [33], the detection distances increased by a factor of 2.40.

4. Discussion

Detection distances for low frequencies characteristic of Antarctic and pygmy blue whale calls were modeled in order to estimate how far each call might be detected by the Northern and Southern arrays of the hydroacoustic station on which they were detected using our automated detection method [25]. These results are only applicable to the parameters used in the experiment in particular the depths of both the animals and the receiving instruments, and the transmission path between them in the study area of the Crozet Islands.

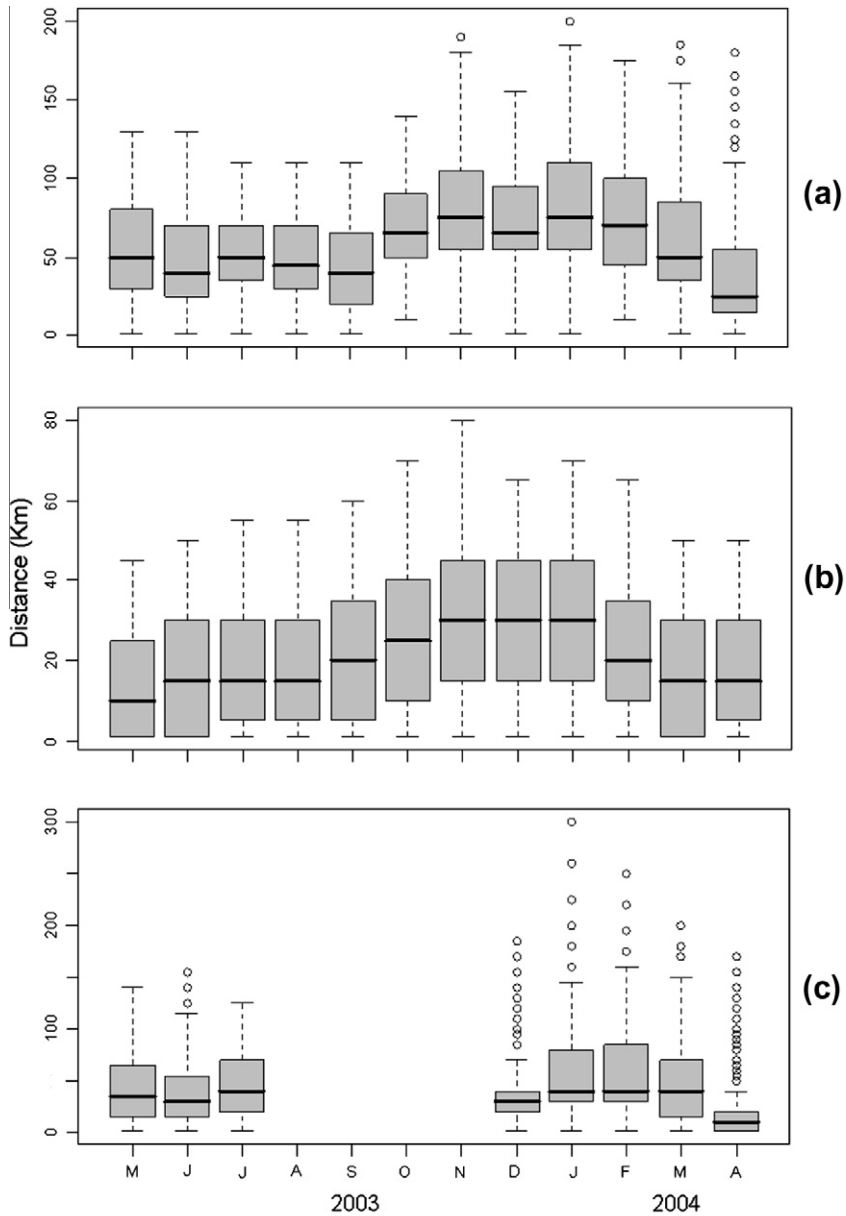

Fig. 6. Annual distance distribution for frequency characteristics of the Antarctic (28 Hz-a,b) and pygmy (25 Hz-b) blue whale using the Range-dependant Acoustic Model performed on each blue whale call detected on the Northern array (a, c) and on the Southern array (b) of the hydroacoustic station of the International Monitoring System moored in the Southwestern Indian Ocean.

4.1. Study area, ambient noise and blue whale calls

With the RAM model, the transmission loss paths for the low frequency sounds chosen showed horizontal variation around both arrays of instruments and revealed shadow areas that greatly reduced the detection range. Likewise, when all parameters (*RL*, *SL*, and bearing) were held constant, the transmission loss paths showed seasonal differences in detection ranges due to the seasonal variation in sound velocity that occurred at this latitude. It was assumed that all blue whale calls were detected within restricted areas that vary in distance during the season. However, while detection ranges in the wintertime were reduced many acoustic detections were recorded. The number of blue whale calls detected during the year was first a function of the number of calling whales present in the area and second dependent on the seasonal changes in the propagation characteristics. In the study area, the seasonal variation of ambient noise received at the Northern array was probably due to storms that occurred in this sub-Antarctic region during wintertime. However, the seasonal effect of storms on the ambient noise measured on the Southern array seemed to be less clear because the instruments were more exposed to the current, ice movements and tidal effects year-round. These factors potentially increased the ambient noise level on the recorded signals [35]. The number of detections were highly dependent on the ambient noise level because of the automated detection methods utilized a fixed threshold [25]. The performance of the detection method probably explained the lower number of calls detected on the Southern array as compared to the Northern array. However, there were a larger number of detected calls during the wintertime for both subspecies. It was assumed that the number of calling whales or the vocal activity of whales was likely more pronounced within the detection range during this specific period [8].

4.2. Estimates of detection distances and detection ranges

For the characteristic frequency of the Antarctic blue whale, the estimate of the maximum detection range of calling whale was 200 km in the Northern restricted area and 80 km in the Southern restricted area. However, the detection distances over which the majority of the calls were detected were around 100 km for the Northern array and 50 km for the Southern array. Pygmy blue whales were present closer to the Northern array than were Antarctic blue whales. The maximum detection range of pygmy blue whale calls was 300 km, but the majority of calls were estimated at less than 70 km and very close to the instruments during given months. These detection ranges were much smaller than expected and are largely lower than long range acoustic localization previously reported in the North Pacific and in the Atlantic oceans [11,12]. However, ranges are comparable to recent results. Stafford et al. [11] detected blue whales in the Gulf of Alaska over ranges of 10–190 km using a parabolic equation loss model. Širović et al. [14] reported detecting Antarctic blue whales in the Southern Ocean to a range of 200 km using hyperbolic localization and time difference of arrival. In our study case, it was not possible to apply this localization method due to the configuration of the station, the presence of large shadow areas, and the ambient noise difference measured between both arrays.

We chose to use of a high threshold value for our automatic detection method to minimize the false alarm rate. However, this choice reduced the maximum detection range. Here, we focus our analysis on the occurrence of blue whales in this sub-Antarctic area using their specific calls as cue of whale species presence or absence. We have avoided detecting potential calling whale far from our instruments. By using another threshold or another detection method, the maximum detection ranges could be increased or decreased. Estimates of maximum detection range and detection distances of each detected call are critically dependent on assumptions such as a fixed frequency or source level. The two chosen low frequency values that characterize both biological sources were slightly different (4 Hz), but the transmission loss paths have revealed different attenuation profiles. The lower frequencies could be detected at a non-negligible larger distance from the instruments. In the same vein, results obtained by using previously reported source level values showed a large difference in detection range; as much as a factor of 2. More measurements of source characteristics, both frequency and source level, are required to better determine detection ranges. We did not vary the depth of the source in this experiment, although changing this value, which must certainly vary in nature, can result in large differences in detection range [13]. To improve estimates of maximum detection range and detection distances of the detected calls, a distribution of source levels and all others quantities that go into estimating distance could be taken into account in order to quantify uncertainty in the estimates. Finally, detection ranges were largely determined by the performance of the instruments and the acquisition process. Hydroacoustic stations deployed for the IMS can provide valuable data with regard to whale monitoring [20].

5. Conclusion

The RAM model is efficient under range-dependent conditions such as sloping bottom and seasonal variation of sound speed that occurred in our study area. In further work, additional continuous acoustic recordings from hydrophone arrays dedicated to localizing calling whales will be conducted in the Southwestern Indian Ocean to combine hyperbolic localization and an acoustic propagation model. Quantifying the range of calling animals allows us to evaluate the efficiency of the passive acoustic monitoring method and could be included in the estimation of the density of calling whales [36]. Moreover, variation in the number of detected calls on a well known restricted area could be compared with physical and biotic habitat parameters that occur in the study area (e.g. physics, temperature, fronts, chlorophyll concentration) in order to better understand the ecology of the animals.

Acknowledgements

We thank Y. Cansi and G. Ruzié who provided access to the data; P.-F. Piserchia for access and helping with IHM RAM for the detection distance range modeling, C. Cotté and M. Viviant for helping in data analysis. This work was supported by the French Ministry of Ecology, the Association DIRAC (France) and the Commissariat à l'Energie Atomique. The IMS hydrophone data have been available through the CEA under contract (CEA n°169-C-BEFI & CNRS n°781513). The information released in this paper conforms to the conditions set forth in this contract. L. Thomas, D. Moretti and N. DiMarzio provided comments that greatly improved earlier versions of this manuscript. This work represents a portion of F.S.'s PhD.

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