The following supplement accompanies the article

Temporal patterns in the acoustic presence of baleen whale species in a presumed breeding area off Namibia

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SUPPLEMENT

Modelling the propagation range of Antarctic blue whale Z-calls off Namibia

In the present study, the robustness of conclusions on the importance of the eastern South Atlantic Ocean as baleen whale habitat strongly depends on the range over which vocalizing animals can be detected by the acoustic recorder. Particularly large propagation ranges of low-frequency vocalizations may occur when both the vocalizing individual and the acoustic receiver are located within the SOFAR channel (Urick 1983, Richardson et al. 1995). In the present study, propagation ranges of thousands of kilometers for baleen whale vocalizations (as reported by e.g. Clark & Gagnon 2002, Miller et al. 2015) are unlikely, given the mismatch between the cetacean calling depths and the depth of the SOFAR channel where the receiver was moored (see also Urick 1983, Richardson et al. 1995). However, the depth of the SOFAR channel axis decreases with increasing latitudes and reaches the sea surface at around 50°S in the Atlantic Ocean (Northrop & Colborn 1974), potentially enabling long-range propagation of low-frequency vocalizations produced near-surface in a longitudinal direction. To estimate the range over which vocalizing whale individuals were detected in the present study, site-and time-specific sound propagation of Antarctic blue whale Z-calls in the eastern South Atlantic Ocean was modeled for our study area and for different seasons.

Methods

Sound propagation modelling

The acoustic propagation of Antarctic blue whale Z-call vocalizations was modeled using the BELLHOP ray tracing program (Porter 2011) to obtain an estimate of the detection range of Antarctic blue whales (and other baleen whales) recorded in this study. Antarctic blue whale were selected as case species for this purpose, given that their Z-call vocalizations (and in particular the Z-call unit A) are among the baleen whale vocalizations propagating furthest in the worlds' oceans, due to their high source level (189±3 dB re:1 µPa 1 m over the 25–29 Hz frequency range), the low frequency (ca. 27 Hz), and the long duration (ca. 8–12 s, (Ljungblad et al. 1998, Širovi□ et al. 2007)). Previous studies estimated Antarctic blue whale Z-call detection ranges of about 200 km or less (Širović et al. 2007, Samaran et al. 2010, Thomisch et al. 2016), but sound propagation strongly depends on the prevailing environmental (acoustic) characteristics of a study area and season, highlighting the need for a site- and time-specific detection range estimation (e.g. Helble et al. 2013, Širović et al. 2015).

Three north-south directed transects along 6°E between the actual receiver position (i.e. the acoustic recorder moored at 20° 58' S, 5° 59' E at 740 m depth) and a fictive sender position were chosen for sound propagation modeling. For this purpose, a vocalizing individual was assumed to be located 200, 500 and 3229 km south of the recording device, with 3229 km representing the distance between the actual recording position and an assumed sender position at 50°S, i.e. where the SOFAR channel reaches the surface in the South Atlantic Ocean (Northrop & Colborn 1974). The source was assumed to signal omnidirectional (i.e. at angles between -90 and +90°) and with a frequency of 27 Hz at 20 m depth, which is in accordance with previous studies stating that baleen whales are likely to vocalize at depths < 40 m (Aroyan et al. 2000, Thode et al. 2000). Although the BELLHOP beam tracing model exhibits a useful frequency range lower than standard ray trace programs, ray tracing models in general should be applied only for scenarios with water depths substantially lower than the wave length of the sound of interest (Jensen et al. 2000). Although a frequency of 27 Hz is comparatively low for ray-tracing models (with a resulting wavelength of 56 m, when an average sound speed of 1500 m s^{-1} is assumed), water depths exceed 700 m for the entire transect. Therefore, the BELLHOP ray-tracing model is considered suitable for assessing the maximum propagation range of baleen whale calls off Namibia in the present study.

Environmental data

Hydrography data, i.e. temperature and salinity profiles between surface and sea floor were extracted from the World Ocean Atlas 2013 (Boyer et al. 2013), using the climatological mean data of the years 2005-2012 with a quarter degree resolution for different seasons. Seasonal data are provided for periods from January to March (hereinafter referred to as 'austral summer'), April to June ('austral autumn'), July to September ('austral winter') and October to December ('austral spring'). From these temperature and salinity data, sound velocity profiles were calculated using the 'sea water library' for MATLAB. For the BELLHOP model runs assuming 200 and 500 km distance between sender and receiver, a mean sound velocity profile (obtained by averaging 7 and 18 single sound velocity profiles, respectively) was used as model input. For the model assuming a 3229 km sender-receiver distance, a sound speed field containing of 116 single sound speed profiles evenly distributed along the north-south transect was implemented in the BELLHOP model, in order to represent range-dependent differences in the sound velocity profiles and hence, SOFAR channel depths.

Bathymetry data for the three transects were obtained from the ETOPO1 1 Arc-Minute Global Relief Model (Amante & Eakins 2009) to take into account range-dependent differences in water depths in the BELLHOP model.

Furthermore, the following sea floor properties were used for the BELLHOP models based on literature data, with the selected properties representing sea floor characteristics of Walvis Ridge: p-velocity of 1550 m s^{-1} (Bolli et al. 1978, Chave 1979, Fromm et al. 2017), s-velocity of 0.0 m s^{-1} (Chave 1979), bottom density of 1.03 g m^{-3} (Fromm et al. 2017), bottom attenuation is neglected.

Antarctic blue whale Z-call received levels

Transmission loss results obtained by the BELLHOP model for different sender-receiver distances were compared to the actual received levels of detected Antarctic blue whale Z-calls. Sound pressure level calculations are based on manufacturer information according to pre-defined amplifier settings for the SonoVault recorders, i.e. a set gain of 48 and 30 dB for recorder SV1008 and SV1019, respectively, and a sensitivity level of -193 dB at 250 Hz for both devices.

The upper components (12 s duration, frequency range 25–29 Hz) of auto-detected Z-calls were extracted from band-pass filtered audio files (Butterworth filter, pass band 25–29 Hz). In accordance to the approach taken in previous studies (e.g., Širović et al. 2004), the 25-29 Hz frequency band was chosen as it represents the peak (i.e., loudest) frequency range of an Antarctic blue whale Z-call. The sound pressure level SPLRMS [dB re: 1µPa] within the 25–29 Hz band of each Z-call detection was determined. Statistic means of the received levels were calculated for different seasons, i.e. austral summer (January – March), austral autumn (April – June), austral winter (July-September) and austral spring (October – December), to ensure direct comparability to the transmission loss results. Due to the premature recording stop of both devices, no acoustic data were available for September and October.

Results & Discussion

Off Namibia, actual received Z-call levels varied both between seasons and between different recording periods (Table S1). From January to March, mean sound pressure levels (SPLRMS) were 89 ± 2 dB for SV1008 and 96 ± 2 dB for SV1019. From April to June, mean received Z-call levels were 92 ± 2 dB for SV1008 and 97 ± 2 dB for SV1019. From July to September, data were only available from SV1008 with mean received levels of 91 ± 2 dB. From October to December, Z-calls with mean levels of 88 ± 3 dB and 95 ± 2 dB were recorded at SV1008 and SV1019, respectively. For SV1008, maximum received Z-call levels were 105 dB in austral summer, 102 dB in austral autumn, 104 dB in austral winter and 111 dB in austral spring. For SV1019, maximum Z-call levels of 118 dB (austral summer), 107 dB (austral autumn) and 103 dB (austral spring) were recorded (Table S1).

The impulse response of a 27 Hz signal was dependent on the distance between sender and receiver and also showed some seasonal variation for all transect lengths modeled (Table S2). For the propagation scenarios representing 200 km and 500 km long transects, the transmission loss model results showed intra-seasonal variability for both recorders (as shown by the 5th, 10th, 90th and 95th percentiles in Table S2). Nevertheless, for the purpose of this study, only the minimum transmission loss calculated by the BELLHOP ray tracing model is of interest, as it represents a signals' propagation 'route' with least energy loss, enabling the longest propagation ranges. Over a distance of 200 km, minimum transmission losses were 109 dB (austral summer), 115 dB (austral autumn), 107 dB (austral winter) and 98 dB (austral spring). Along the 500 km transect, the model yielded minimum transmission loss values of 116 dB (austral summer), 116 dB (austral autumn), 122 dB (austral winter) and 114 dB (austral spring, Table S2).

Assuming a source level of 189 dB re:1 µPa 1 m over the 25–29 Hz for an Antarctic blue whale Z-call (Širović et al. 2007), this minimum transmission loss values were used to calculate the theoretically expected maximum received Z-call levels (hereinafter referred to as '$SPLmax_{expected}$'), which were then compared to the actual minimum received Z-call levels ('$SPLmin_{recorded}$', Table S3). For the 200 km propagation scenario, $SPLmin_{recorded}$ was larger than $SPLmax_{expected}$ in almost all seasons in both recording periods, indicating that most of the recorded Z-calls were produced within a distance of less than 200 km of the recording site (Table S3). Only in austral spring (November and December) 2011, $SPLmax_{expected}$ (91 dB) was larger than $SPLmin_{recorded}$ (69 dB in SV1008) over a 200 km distance. Given that the majority of Z-call received levels in spring 2011 ranged between 84 dB and 94 dB (5th and 95th percentile, respectively; see Table S1), we consider the $SPLmin_{recorded}$ of 69 dB in SV1008 an outlier which is not representative for the majority of Z-calls recorded off Namibia during this season. Nevertheless, part of the recorded Z-call received levels recorded between in November and December 2011 may have been produced farther than 200 km away from the recording location. Over a distance of 500 km however, $SPLmin_{recorded}$ exceeded $SPLmax_{expected}$ in all seasons, implying that all Z-calls recorded off Namibia during our study were produced within a radius of 500 km of the recording site (Table S3).

For the propagation scenarios representing of the transect of 3229 km length, none of the modeled rays was found to arrive at the recording position. This indicates that the decreasing depth of the SOFAR channel towards the south does not seem to favor particular long-range propagation of more than 3000 km along the modeled transect. Hence, our results point out that it is highly unlikely to detect Antarctic blue whale calls originating from individuals vocalizing at 50°S at the recording position.

Based on the comparison of modeled transmission losses for the 200 and the 500 km propagation scenarios and the actual received levels of Antarctic blue whale Z-calls, we conclude that most vocalizing Antarctic blue whale individuals were located within a radius of 200 km of the recording site during our study period. The detection range of Antarctic blue whale Z-calls was larger only in austral spring (November and December) 2011, with vocalizing individuals ranging within a distance of 500 km from the recording site at maximum. Ignoring the possibility of misclassifying (faint) Antarctic blue whale chorus as single Z-calls, the low number of Z-call detections in November and December 2011 (Fig. 3) indicates that only a small portion of the Antarctic blue whale Z-calls recorded in this study has been produced at distances greater than 200 km of the recording site. Our results further indicate that long-range propagation of Z-calls over thousands of kilometers facilitated by the depth pattern of the SOFAR channel is unlikely in our study period and area.

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Table S1: Received Antarctic blue whale Z-call levels SPLRMS [dB re 1 µPa] in different seasons and recording periods at the recording position at 20° 58’ S, 5° 59’ E in the South Atlantic Ocean off Namibia.

recorder	**recording period**	**season**	**mean**	**standard deviation**	**median**	**maximum**	**minimum**	**5th percentile**	**10th percentile**	**90th percentile**	**95th percentile**
SV1008	Nov 2011 – Aug 2012	summer (Jan-Mar)	88.88	2.20	88.83	104.79	82.71	85.37	86.06	91.71	92.61
		autumn (Apr-Jun)	92.22	1.91	92.08	102.49	87.02	89.38	89.94	94.73	95.64
		winter (Jul-Aug)	90.62	2.21	90.23	103.62	85.80	87.51	88.07	93.89	94.82
		spring (Nov-Dec)	88.45	3.45	88.49	110.83	69.13	83.60	84.23	92.44	93.48
SV1019	Nov 2012 – May 2013	summer (Jan-Mar)	95.55	2.35	95.26	117.62	89.23	92.34	93.07	98.36	99.51
		autumn (Apr-May)	97.37	1.86	97.18	106.71	92.56	94.76	95.23	99.66	100.67
		winter					*no data*				
		spring (Nov-Dec)	94.53	2.41	94.47	103.23	86.12	90.51	91.45	97.68	98.56

Table S2: Intra- and inter-seasonal variability in impulse response for different arrivals of a 27 Hz signal emitted at 20 m depth in a distance of 200 km and 500 km from the recording site at 20° 58' S, 5° 59' E as obtained by BELLHOP ray tracing model with a pre-defined step size of 100m.

scenario	season	months	mean	median	standard deviation	maximum	minimum	5th percentile	10th percentile	90th percentile	95th percentile
200km transect	summer	Jan-Mar	152.29	152.05	30.85	231.87	108.49	108.93	111.08	189.47	200.77
	autumn	Apr-Jun	155.26	152.36	30.46	216.25	115.42	115.79	118.44	205.96	212.31
	winter	Jul-Sep	139.33	131.06	24.14	209.33	107.36	111.85	114.47	175.37	179.47
	spring	Oct-Dec	137.77	131.42	26.12	215.00	98.16	109.87	111.81	171.83	185.80
500 km transect	summer	Jan-Mar	153.50	150.13	21.54	237.06	116.23	123.51	128.91	181.26	194.66
	autumn	Apr-Jun	152.34	147.35	21.75	217.58	115.54	124.22	127.64	182.16	198.11
	winter	Jul-Sep	153.14	148.28	21.26	203.09	122.05	125.57	128.15	183.51	191.13
	spring	Oct-Dec	156.15	152.67	21.53	219.83	113.66	123.11	127.70	182.39	193.25

Table S3: Expected maximum Antarctic blue whale Z-call received levels $SPLmax_{expected}$ and actually recorded minimum received Z-call levels $SPLmin_{recorded}$ for different seasons, propagation scenarios and recording devices at the recording position at 20° 58’ S, 5° 59’ E in the South Atlantic Ocean off Namibia. A source level of 189 dB re 1 µPa was assumed. Minimum transmission losses as given in Table S2 and $SPLmin_{recorded}$ as given in Table S1. No passive acoustic data were available from September and October. * SV1019 stopped recording in May 2013.

season	months	*minimum transmission loss at 200km [dB]*	*minimum transmission loss at 500km [dB]*	*$SPLmax_{expected}$ at 200 km [dB]*	*$SPLmax_{expected}$ at 500 km [dB]*	*$SPLmin_{recorded}$ at SV1008 [dB]*	*$SPLmin_{recorded}$ at SV1019 [dB]*
summer	Jan-Mar	108.49	116.23	80.51	72.77	82.71	89.23
autumn	Apr-May/Jun*	115.42	115.54	73.58	73.46	87.02	92.56
winter	Jul-Aug	107.36	122.05	81.64	66.95	85.80	no data
spring	Nov-Dec	98.16	113.66	90.84	75.34	69.13	86.12