The following supplement accompanies the article

Spatio-temporal patterns in acoustic presence and distribution of Antarctic blue whales *Balaenoptera musculus intermedia* in the Weddell Sea

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INDEPENDENCE OF ACOUSTIC RECORDINGS

Interpretation of acoustic data in terms of distribution and migratory behavior requires an understanding whether signatures detected at neighboring recording sites are independent of each other or if the same signatures are recorded on both sensors. Here we tested for acoustic independence of recorders by employing two different approaches:

A. compare the distance between recorder pairs with estimates of detection range of Antarctic blue whale calls and

B. look for unique sequences of ABW Z-calls that are coherently detectable in recordings from neighboring sensors by cross-correlation and supporting manual analyses.

In summary, the results of approach A indicated that detected individuals were in most cases closer than 200 km to at least one of the recorders, while results from approach B indicated that sequences were rarely detected simultaneously by even the closest neighboring recorders. Both findings consistently imply independence of our acoustic recorders, permitting interpretation of possible temporal differences in acoustic presence as migratory movements.

APPROACH A: DISTANCE ESTIMATIONS

Methods

Estimates of the distance of the vocalizing individuals from the respective recording site were obtained from received levels of detected ABW Z-calls. Prior to analysis, SonoVault recorders deployed from 2012 to 2014 were calibrated using a Brüel & Kjaer pistonphone calibrator (type 4229) with a custom-made adapter (by Develogic GmbH, Hamburg Germany), applying the same SonoVault configuration settings as during the recording period (Table S1). Sound pressure level calculations for the remaining recorder deployments are based on manufacturer information according to chosen amplifier settings.

Upper components (12 s duration) of auto-detected Z-calls were extracted from band-pass filtered audio files (Butterworth filter, pass band 25–29 Hz) and the sound pressure level SPL_{RMS} [dB re: 1µPa] within the 25–29 Hz band of each Z-call event was determined. The 25-29 Hz frequency band represents the peak (i.e., loudest) frequency range of an ABW Z-call, and matches the approach taken in the analysis by Širović et al. (2004). Approximate distances between vocalizing ABWs and the respective recorder location were calculated assuming a source level of 189 dB re: 1 µPa at 1m over 25–29 Hz and a transmission loss

TL[dB] = 17.8 $\log_{10}(r)$ as reported by Širović et al. (2007). However, as this transmission loss law was calculated based on data from bottom-moored recorders in waters off the Western Antarctic Peninsula (Širović et al. 2004), it might not necessarily be applicable for our study area and our study setup, with recorders moored at typically 1000 m depth in most cases. Hence, additional distance estimates were calculated applying TL[dB] = 20.0 $\log_{10}(r)$ and TL[dB] = 20.9 $\log_{10}(r)$ to assess the potential uncertainty in the range of the estimated distances. The former represents a spherical spreading loss modeled for the propagation of seismic signals, which comprise most energy at frequencies below 100 Hz, in the Weddell Sea (Breitzke & Bohlen 2010). The transmission loss law of TL[dB] = 20.9 $\log_{10}(r)$ represents almost spherical spreading plus some attenuation and was empirically determined for RAFOS sound source sweeps of approx. 260 Hz in a coastal Antarctic environment neighboring our study area (Van Opzeeland et al. 2013).

The MARU recorder was excluded from all amplitude related analyses due to unresolved strong fluctuations in the received levels in all frequency bands of interest, potentially caused by broad-band electronic noise. Additionally, the record of device AWI230-07 SV1001 exhibited an unexpected decrease in the received levels, probably caused by a flawed internal resistor (Develogic GmbH, pers. comm.). Over a period of seven days (22 to 28 March 2011) the received levels decreased slowly but steadily. While this period was excluded from further analyses, the period after 28 March 2011 was corrected for this offset by adding a frequency band-specific correction value (equaling 9.25 dB for the 25–29 Hz frequency range) to account for the amplitude drop.

The transmission loss laws used for our study were obtained for acoustic environments other than our study area (Širović et al. 2007) and for signals other than ABW calls (Breitzke & Bohlen 2010, Van Opzeeland et al. 2013). To take this to some extent into account, we employed all three different transmission loss laws to calculate the detection range of ABW Z-calls.

Results

Mean distance estimates (as based on a transmission loss of TL = 17.8 $\log_{10}(r)$) ranged between 87 and 144 km and were generally larger for AURAL recorders than for SonoVault devices (Fig. S1, Table S2). Although the maximum detection ranges of Z-calls may extend up to 700 km or more for some recorders, the bulk of estimated distances nevertheless ranged below 200 km for all recorders (Fig. S1, Table S2). As data were recorded concurrently at locations of at least 222 km apart, this indicates that a rather small percentage of Z-calls may have been audible at more than one recording site, whereas most recorded vocalizations will have been audible at only one recorder.

The range of distance estimates varied considerably depending on the transmission loss coefficient applied. Using a transmission loss of TL= 20.0 $\log_{10}(r)$ yielded mean distance estimates ranging between 25 and 36 km, with the majority of vocalizations (95th percentile) emitted within 100 km of the respective recorders (Table S2). Applying a transmission loss of TL= 20.9 $\log_{10}(r)$ yielded mean distance estimates ranging between 16 and 25 km, with the majority of vocalizations (95th percentile) produced in a range of up to 60 km (Table S2).

Previous studies reported detection ranges of ABW vocalizations of up to 600 nm (>1100 km) at maximum (Širović et al. 2007, Miller et al. 2015), similar to the maximum range estimates obtained in our study and hence supporting the plausibility of the distances estimated in our study. Calculations employing each of the three transmission laws, however, indicated that by far the most Z-calls were produced by animals that were closer than 200 km from the recorder. Our recorders are can therefore be considered independent from each other with respect to ABW Z-calls.

APPROACH B: CROSS-CORRELATION OF Z-CALL SEQUENCES

Methods

Three data sets (recorded at 64°S (G64, SV1010), 66°S (G66, SV1009) and at 69°S (G69, SV1011)) were selected for this test based on their close proximity (227 km between G64 and G66 and 330 km between G66 and G69, respectively) and hence, their potential acoustic dependence in terms of ABW Z-calls.

Assuming a constant sound propagation speed of 1500 m s^{-1}, the maximal travel time difference of sound between adjacent sites was expected to be about ±151 s (G64-G66) and ±220 s (G66-G69), respectively (source in-line with recorder pair). The internal clock drifts of the selected recorders were calculated to account for -26.5 seconds (G64, SV1010), -14 seconds (G66, SV1009) and -46 seconds (G69, SV1011) per year (Table S3). In turn, the maximal expected time lag of the same sound recorded at neighboring sites was 164 s and 252 s, respectively.

Z-call detection times were mapped onto binary (time) vectors of 5 s resolution, i.e., each 5-second-bin was assigned a logical “1” if a Z-call occurred within the interval, and a logical “0” otherwise. Binary vectors from G66 were cross-correlated with those from G64 and G69, respectively (Fig. S2). To allow for potential time lags between recordings of sequences, clock drifts and different travel times, a 10 minute long segment (template from -5 min to +5 min) from the binary vector of recorder A was cross-correlated with a 30 minute period (-15 min to +15 min) from the binary vector of recorder B, for each pair of data sets (Fig. S2: Step 1). The template’s duration of 10 min is assumed to capture a significant portion of ABW song (Ljungblad et al. 1998, Širović et al. 2004). The cross-correlation procedure resulted in time series of correlation coefficients of 30-minutes length at 5 s resolution (Fig. S2: Step 2). Times at which the correlation coefficient exceeded 0.9 were stored (Fig. S2: Step 3).

For those events (i.e., times at which the cross-correlation coefficient exceeded 0.9), time lags between the detection time in recorder A and in recorder B were calculated. Taking into account a potential time delay between signal detections in recordings from different sites, only those events were considered that exhibited less than 10 minutes time delay between the detection times in different devices. Consecutive 10 minute templates (progressively shifted by 5 min) and 30 minute periods (shifted accordingly, Fig. S2: Step 4) were correlated for the entire duration of each record. Cross-correlation was performed in both directions for each pair of data sets, i.e., first, 10 minute templates of recorder A were correlated with 30 minute periods of recorder B and second, 10 minute templates of recorder B were correlated with 30 minute periods of recorder A. To assess the acoustic independence of data sets, only those events based on sequences of 3 or more Z-calls per 10 minute template were used, as they are unlikely to be caused by coincidence given that at least 2 intervals between consecutive vocalizations are required to match in both data sets.

To substantiate the results of the cross-correlation approach, manual checks were performed to determine whether a set of selected sequences of Z-calls from the recordings of one recorder was also detectable in the recordings of the adjacent recorder(s). A total of 12 sequences was selected from the recorders SV1009, SV1010 and SV1011, with the sequences comprising Z-calls consisting of one (unit A), two (units A + B) or all three units (A + B + C), respectively. This approach aimed to take into account song sequences of individuals vocalizing close to the respective recorder (i.e., with all three units being discriminable), and those of more distant individuals potentially sojourning between two recording sites (i.e., not all three units being detectable at the recording sites, see also Miller et al. (2015)). The corresponding period during which Z-call sequences were observed at one recording site was visually scanned in the recordings of the respective adjacent recorder(s), while allowing for potential time delays due to time lag between recordings of sequences, potential clock drifts and different travel times of the signals.

Results

For the cross-correlation of data sets recorded at G64 and G66 (distance 227 km), no events were detectable in both data sets, hence implying that data sets recorded at G64 and G66 can be assumed independent (Table S4). For cross-correlation of data sets recorded at G66 and G69 (distance 330 km), 6 events were based on 3 or more Z-calls and exhibited a time lag of <10 minutes between the two data sets, i.e., were detected in both data sets (Table S4). Hence, the data sets recorded at G66 and G69 are not completely independent from each other. However, although some overlap is likely to occur in the recorded signals from these two adjacent recording sites, the very limited number of interdependent sequences found is unlikely to bias the results substantially.

Similarly, manual analyses indicated that none of the Z-call sequences selected was discriminable in two recorders at the same time. Although this approach does not represent a quantitative analysis, it further supports the results of the distance estimation and cross-correlation approach, indicating that recorders can be considered acoustically independent from each other.

Figures & Tables

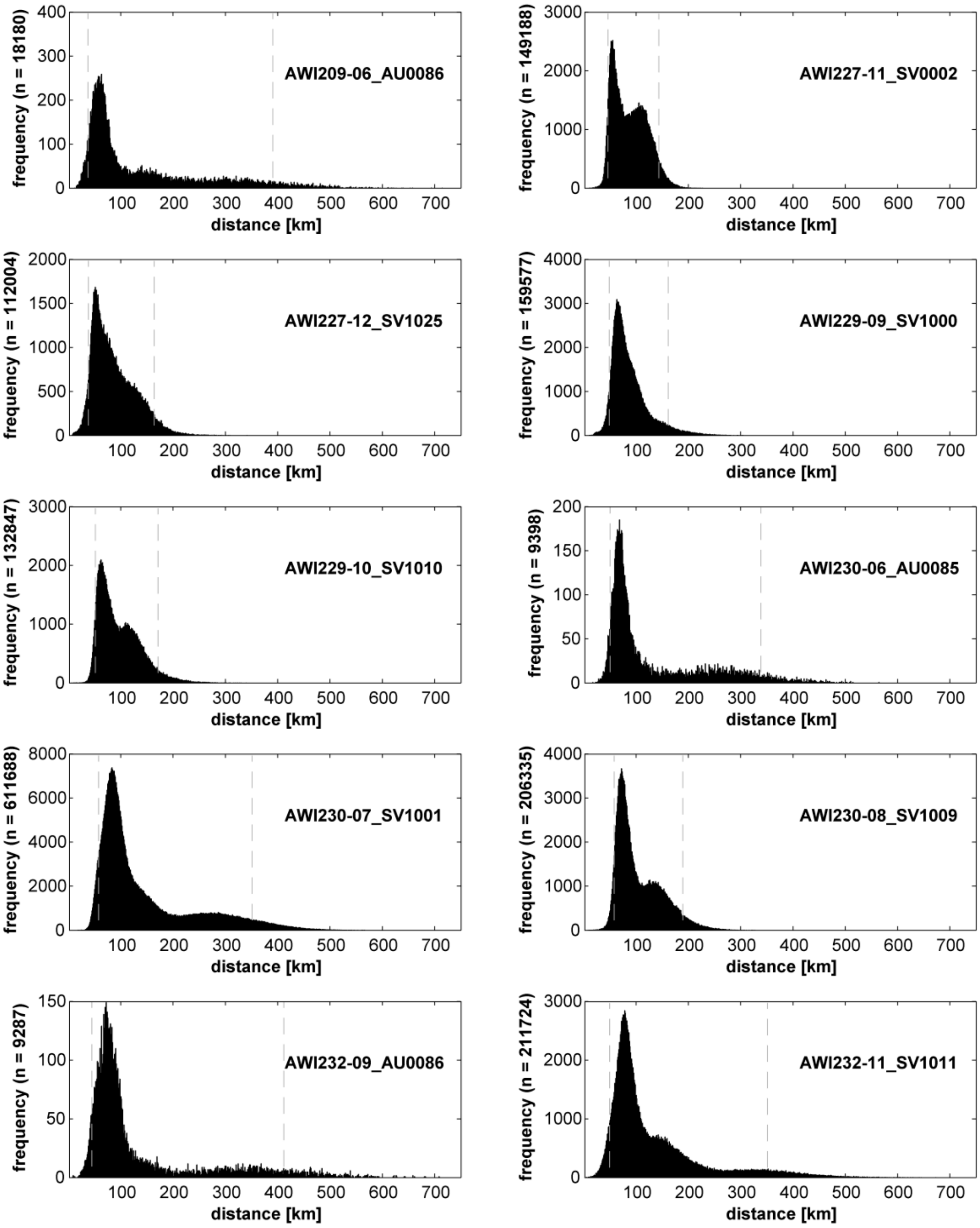

Fig. S1: Distribution (absolute frequency) of estimated distances [km] of the vocalizing ABW individuals from the respective recording site; distance calculations based on received levels in the 25-29 Hz frequency band of all Z-calls detected at a false alert rate of 1%, assuming a source level of 189 dB and a transmission loss TL[dB] = 17.8 $\log_{10}(r)$ (Širović et al. 2007); vertical dashed lines indicate the 5th and 95th percentile of estimated distances, respectively; subplots ordered by location as given by recorder ID in Table 1 (main article); note that y-axes are differently scaled due to the varying number of Z-call detections per recorder.

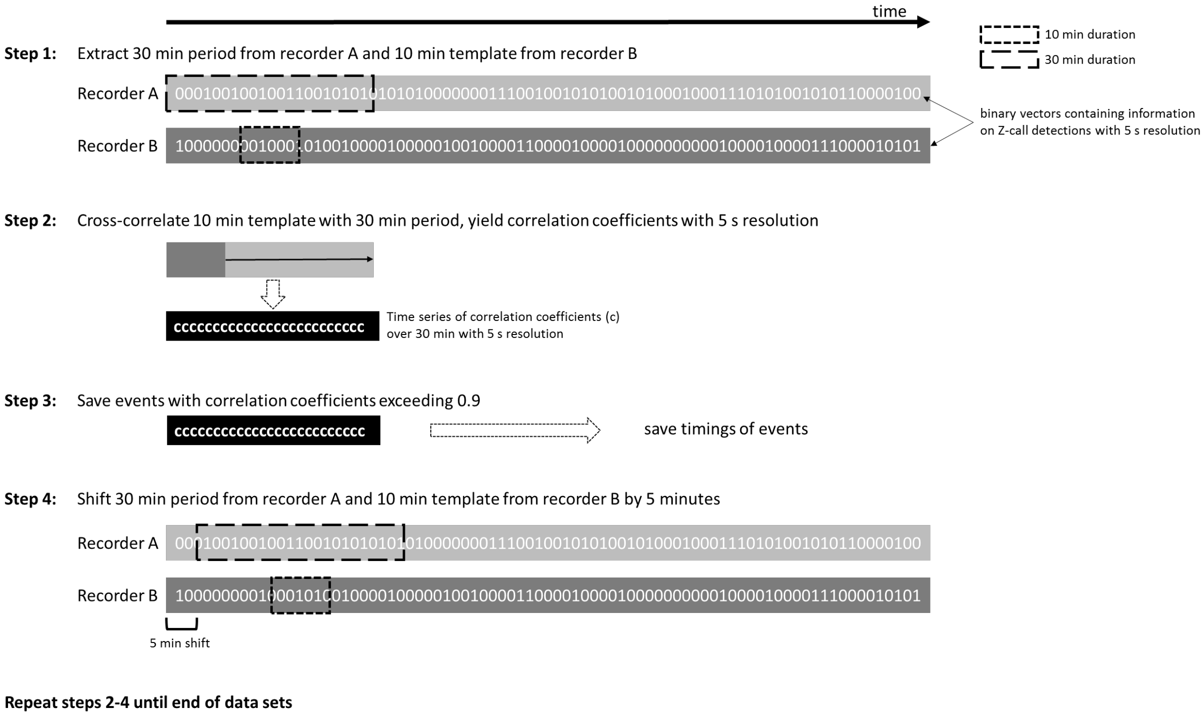

Fig. S2: Scheme of cross-correlation procedure to test independence of acoustic recordings.

Table S1: Post-calibration of SonoVault recorders deployed from 2012 to 2014 (after battery replacement) was conducted with a Brüel & Kjaer pistonphone calibrator (type 4229) with a custom-made adapter (by Develogic GmbH, Hamburg Germany). Actual gain G_{cal} (i.e., set gain + digitization gain) was calculated by $\boldsymbol{G_{cal}[dB] = 20 \cdot log_{10}(signal_{out}) - S - SPL_{in}}$ with $signal_{out}$ being the recorded sound pressure level [dB_{rms}] of the calibration signal SPL_{in}. Normalized signal values from .wav files were corrected for ADC input voltage of 2.5 V. Hydrophone sensitivity S and sound pressure level of the calibration signal are given for a frequency of 250 Hz and 251.2 Hz ± 0.1%, respectively.

recorder ID	**hydrophone sensitivity S [dB]**	**set gain G_{set} [dB]**	**ADC input U_{in} [V]**	**Sound pressure level of calibration signal SPL_{in} [dB]**	**calculated gain G_{cal} [dB]**
AWI227-12 SV1025	-192.50	24.00	2.5	153.85	24.89
AWI229-10 SV1010	-192.30	24.00	2.5	153.85	24.52
AWI230-08 SV1009	-193.00	24.00	2.5	153.85	25.32
AWI232-11 SV1011	-192.60	30.00	2.5	153.85	27.94

Table S2: Potential range of distance estimations [km] of vocalizing individuals from the recording site using TL[dB] = 17.8 log_{10}(r) as estimated for Antarctic blue whale Z-calls in the Western Antarctic Peninsula area (Širović et al. 2007), TL[dB] = 20 log_{10}(r) as calculated for seismic signals in the Weddell Sea (Breitzke & Bohlen 2010) and TL[dB] = 20.9 log_{10}(r) as determined for sounds at approx. 260 Hz in coastal Antarctic waters near our study area (Van Opzeeland et al. 2013).

recorder ID	**range of distance estimates [km] at TL = 17.8 log_{10}(r)**			**range of distance estimates [km] at TL = 20.0 log_{10}(r)**			**range of distance estimates [km] at TL = 20.9 log_{10}(r)**		
	5th %ile	**mean**	**95th %ile**	**5th %ile**	**mean**	**95th %ile**	**5th %ile**	**mean**	**95th %ile**
AWI209-06 AU0086	37.07	136.53	390.04	11.65	36.08	94.64	7.79	23.63	57.78
AWI227-11 SV0002	46.15	87.91	143.30	14.16	24.97	38.82	9.38	16.25	24.63
AWI227-12 SV1025	37.92	86.89	163.29	11.89	24.62	43.60	7.94	16.08	27.53
AWI229-09 SV1000	48.38	87.13	161.03	14.77	24.75	43.07	9.77	16.12	27.20
AWI229-10 SV1010	50.95	97.07	171.08	15.46	27.24	45.45	10.21	17.68	28.64
AWI230-06 AU0085	49.97	130.71	338.12	15.20	34.96	83.34	10.04	22.77	51.16
AWI230-07 SV1001	57.23	144.15	350.51	17.15	38.22	86.06	11.27	24.75	52.76
AWI230-08 SV1009	57.71	105.15	188.98	17.28	29.25	49.66	11.35	18.92	31.17
AWI232-09 AU0086	44.60	132.50	411.43	13.74	35.18	99.25	9.11	23.04	60.47
AWI232-11 SV1011	49.36	131.82	350.84	15.04	35.34	86.13	9.94	22.94	52.80

Table S3: Calculation of time drift in SonoVault (SV) recorders from recorded RAFOS (Ranging And Fixing Of Sound) sound source signals. While a RAFOS source was hosted by the same mooring as the respective SonoVault (SV1010) for mooring AWI229, for mooring AWI230 (with recorder SV1009) time drift calculations were based on recorded signals from RAFOS sources at 227 km and 53 km distance, for mooring AWI232 (with recorder SV1011) time drift calculations were based on recorded signals from a RAFOS source at 276 km distance. Columns 3-4 and 5-6 indicate the time of reception of a RAFOS signal at the beginning and end of the recording period, respectively.

recorder ID	**RAFOS ID**	**date d_1**	**time t_1**	**date d_2**	**time t_2**	**period covered $D = d_2 - d_1$ [d]**	**$\Delta t = t_2 - t_1$ over D [s]**	**time drift RAFOS per day [$s\ d^{-1}$]**	**time drift RAFOS over D [s]**	**time drift SV over D [s]**	**time drift SV [$s\ a^{-1}$]**
AWI229-10 SV1010	AWI229-10_D0026	15.12.2012	12:29:59.1	01.08.2013	12:29:43.2	229	-15.9	-0.0027	-0.6183	-16.5183	-26.3283
AWI230-08 SV1009	AWI229-10_D0026	07.01.2013	12:32:23.7	26.09.2013	13:32:15.0	262	-8.7	-0.0027	-0.7074	-9.4074	-13.1057
	AWI231-10_D0024	07.01.2013	13:00:09.2	26.09.2013	12:59:59.0	262	-10.2	0	0.0000	-10.2000	-14.2099
AWI232-11 SV1011	AWI231-10_D0024	20.12.2012	13:02:53.9	12.11.2013	13:02:13.0	327	-40.9	0	0.0000	-40.9000	-45.6529

Table S4: Cross-correlation of Z-call detection results from data sets collected by SonoVault (SV) recorders at neighboring recording sites (G64: SV1010, G66: SV1009, G69: SV1011) to assess independence of recordings. Only events (i.e., times at which the cross-correlation coefficient exceeded 0.9) based on sequences of ≥ 3 Z-calls per 10 minute template, that exhibited less than 10 minutes delay between the detection time in different devices, were considered for assessing the independence of data sets.

Z-call number (per 10 min template)	**Number of events with correlation coefficients ≥ 0.9**	
	SV1009 & SV1010	SV1009 & SV1011
3	0	5
4	0	0
5	0	0
6	0	1
Σ of events detectable at both recorders	**0**	**6**

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