Overview of the SOWER cruise circumpolar acoustic survey data and analyses of Antarctic blue whale calls

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ABSTRACT

The International Whaling Commission (IWC) carried out blue whale research within its annual Southern Ocean Whale and Ecosystem Research (SOWER) cruises between 1996 and 2010. Over 700 sonobuoys were deployed to record blue whale vocalisations during 11 Antarctic and three low-latitude blue whale cruises off Australia, Madagascar and Chile. The recorded acoustic files from Antarctic deployments were collated and reviewed to develop a database of digital acoustic files and the associated deployment station metadata of 7,486 acoustic files from 484 stations. Acoustic files were analysed using the automated detection template and visual verification method. We found a significant difference between the total number of acoustic recording hours (2,481) reported in the associated cruise reports and the currently available number of acoustic recording hours (1,541). Antarctic blue whale vocalisations (9,315 D-calls and 24,902 Z-calls) were detected on 4,183 out of the total 7,486 acoustic files. December had the lowest call rates; January and February yielded high call rates. While most sonobuoys (63%) were deployed between 1800hrs and 0600hrs, the majority of calls (62%) were detected during observation periods between 0600hrs and 1800hrs. The difference between the available and reported data is a significant concern. Reconciliation of these and any future IWC acoustic data is strongly recommended.

KEYWORDS: ACOUSTICS; ANTARCTIC; BLUE WHALE; COMMUNICATION; DISTRIBUTION; HABITAT; MONITORING

INTRODUCTION

There are two recognised subspecies of Southern Hemisphere blue whale: the 'Antarctic' blue whale (*Balaenoptera musculus intermedia*; Burmeister, 1871) and 'pygmy' blue whale (*B. m. brevicauda;* Ichihara, 1966). The Indian Ocean blue whale (*B. m. indica*; Blyth, 1859) is considered to be an approximate synonym of *B. m. brevicauda*

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(Reeves *et al*., 1998; Rice, 1998). Differentiation between these subspecies at sea is difficult and the IWC therefore initiated a programme of passive acoustic monitoring and recording in the presence of blue whales to determine whether the subspecies might produce distinctly different sounds.

Blue whales were whaled to near extinction by modern whaling (1904–73), with catches of some 360,000 individuals in the Southern Hemisphere. The 1996 estimate of population size 1,700 (860–2,900) remains at less than 1% of their pre-exploitation abundance of 239,000, despite protected status in the Southern Hemisphere since 1964 (Branch *et al*., 2004). The recovery and population status since protection has remained challenging to estimate from visual sighting surveys due to low abundance (Branch *et al*., 2007) and wide winter dispersal (Branch *et al.*, 2023), but the population is increasing at an average rate of 8.2% per annum (Branch *et al*., 2004; Thomas *et al*., 2016).

The recovery status of pygmy blue whale populations is unknown. Population assessments must consider subspecies to allow for different recovery rates, but field identification of subspecies based on visual observation is unreliable (Kato *et al*., 1996). Within the SOWER programme, the IWC considered alternative methodologies for blue whale subspecies identification, including surface expression of dive, relative body proportion, blow-hole morphology (Ichihara, 1966; Donovan, 1984) and passive acoustic monitoring (Ljungblad *et al*., 1998).

Some of the earliest acoustic studies of blue whales suggest that blue whale sounds – in particular their various songs as recorded in different regions and ocean basins – were distinctly different from each other (Cummings and Thompson, 1971; Thompson *et al*., 1996; McDonald *et al*., 2006). Acoustic monitoring of blue whale sounds might therefore provide a means of determining subspecies in the field (Ljungblad *et al*., 1997; Ljungblad *et al*., 1998; Stafford *et al*., 1999; 2001; Branch *et al*., 2023) in much the same way that humpback whale songs (*Megaptera novaeangliae*) can be used to identify and distinguish between populations (Payne and Guinee, 1983).

Sounds recorded in the presence of blue whales are basically of two forms: calls and songs. Blue whale D-calls typically occur as single or short sequences of frequency-modulated (FM) sounds in the 22–106Hz frequency band, last c.2–6s. These are always downswept but sometimes start with an up-down frequency inflection (Thompson *et al*., 1996; Mellinger and Clark, 2003; Rankin *et al*., 2005; Ljungblad and Stafford, 2005; Oleson *et al*., 2007). In contrast, songs are composed of c.1–4 stereotyped sounds (i.e., notes) that have been reported as 1–2s amplitude-modulated (AM), 1–2s pulses or long-duration (5–25s) FMs with and without harmonics. Song notes are organised into phrases that are repeated in a patterned sequence lasting c.10–20 mins (i.e., a song) which is sung repeatedly (i.e., song bout) over periods of hours to many days (Cummings and Thompson, 1971; Edds, 1982; Thompson and Friedl, 1982; Thompson *et al*., 1996; Alling *et al*., 1991; Stafford *et al*., 1999; 2001; Clark and Gagnon, 2002; Mellinger and Clark, 2003; Rankin *et al*., 2005; McDonald *et al*., 2006). D-calls have been reported for both males and females whereas all identified singers to date have been male (McDonald *et al*., 2001; Oleson *et al*., 2007).

Antarctic blue whales and pygmy blue whales in the Southern Hemisphere exhibit geographic variation in their songs (Ljungblad *et al*., 1997; Clark and Fowler, 2001; McDonald *et al*., 2006; Samaran *et al*., 2010a; Stafford *et al*., 2011). The songs recorded from Antarctic blue whales consist of patterned sequences of tonal sounds composed of three distinct parts: an 8–12s tone centred at 28Hz (28–Hz component); a 2s FM downsweep; a 3–6s tone centred at 18Hz (Ljungblad *et al*., 1998). Following SOWER studies, there has been a documented decrease in the tonal frequency of the first part of the song to between 25–26Hz (Leroy *et al*., 2018). This contrasts with the song of Southern Hemisphere pygmy blue whales, for which at least eight different songs have been described to date, consisting of 2–4 units, including both frequency- and amplitude-modulated notes (Ljungblad *et al*., 1998; Samaran *et al*., 2010a; Stafford *et al*., 1999; 2011; Buchan *et al*., 2014; Miller *et al*., 2014; Cerchio *et al.*, 2020; Leroy *et al.*, 2021).

Dedicated research directed at Antarctic blue whales in the Southern Ocean was carried out by the SOWER programme between 1996 and 2010. The SOWER programme was preceded by the IWC International Decade of Cetacean Research (IDCR) programme which ran from 1978–95. The SOWER programme included a blue whale research component that centred on the evaluation of acoustic techniques and identifying criteria to distinguish between Antarctic and pygmy blue whales in the field (IWC, 1996). SOWER research was conducted in all six IWC Management Areas in the Southern Ocean (Donovan, 1991): Area I (120°W–60°W), Area II (60°W–0°), Area III

(0°–70°E), Area IV (70°E–130°E), Area V (130°E–170°W) and Area VI (170°W–120°W). Much of the blue whale research centred on Area III.

The blue whale component of the SOWER cruises included video recording, behavioural notes, photographs, biopsy samples and acoustic recordings that can be integrated to learn more about the behavioural ecology of blue whales. This included determining the sex of vocal whales by combining biopsy results with recordings of localised whales, estimating the proportion of calling whales in a region by comparing the number of whales seen with the number heard, and comparing the types of sounds recorded in association with observed behaviour. Finally, while blue whales were the primary targets of acoustic monitoring, the gathered data included acoustic detections from other species, including killer whales (*Orcinus orca*), sperm whales (*Physeter macrocephalus*), crabeater (*Lobodon carcinophaga*) and leopard (*Hydrurga leptonyx*) seals.

The South African Blue Whale Project (SABWP) was aimed at estimating the relative abundance, distribution and seasonal movements of Antarctic blue whales within the southeastern Atlantic Ocean, including through investigation of seasonal call rates (Findlay *et al*., 2012; Shabangu and Findlay, 2014). In 2013, the SABWP received permission to analyse the SOWER Antarctic and low-latitude blue whale cruise acoustic data from 1996/97 to 2008/09. This paper summarises the acoustic data collected during the circumpolar SOWER Antarctic cruises and the compilation of resultant data from these cruises.

MATERIALS AND METHODS

Field recordings

Acoustic data were collected on board two research vessels, *Shonan Maru* (SM) and *Shonan Maru No. 2* (SM2), during nine out of 14 SOWER cruises which took place in the austral summer between 1996 and 2010, with opportunistic recordings obtained during an additional three cruises in the Southern Ocean in 1996/97, 1997/98 and 2000/01 (Figure 1, Table 1).

These cruises have been fully described by Branch *et al*. (2007) and Kelly *et al*. (2012). Detailed descriptions of survey methodology are provided in the annual cruise reports (Ensor *et al*., 1997; 1998; 1999; 2000; 2001; 2002; 2003; 2004; 2005; 2006; 2007; 2008; 2009; Kato *et al.,* 1996; Ljungblad *et al*., 1998; Findlay *et al*., 1998;

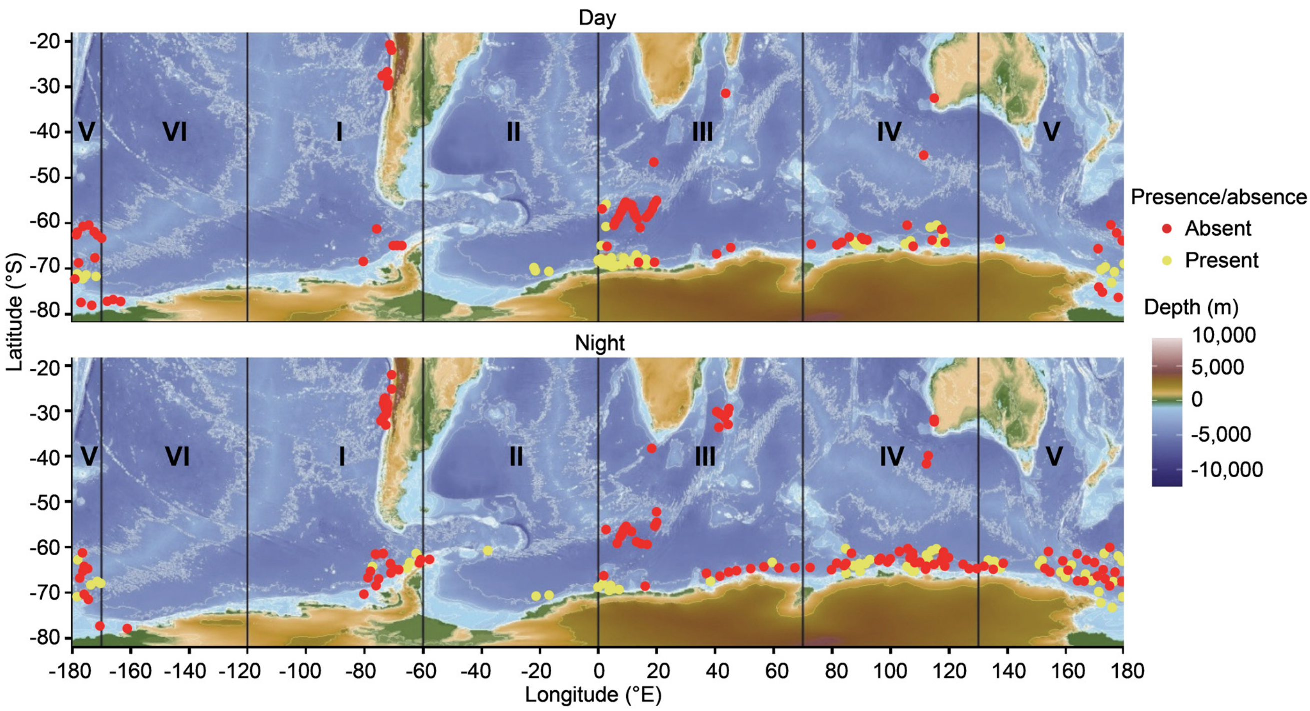

Fig. 1. Distribution of SOWER sonobuoy deployments showing the presence/absence of Antarctic blue whale calls over various water depths of the Antarctic Peninsula and the low latitudes. The six 'outlying' sonobuoys in Area VI are from three stations of the 2003/04 *SM2* cruise deployed in Area V.

Table 1

Summary and comparison of available and reported acoustic data associated with Antarctic blue whale vocalisation from the SOWER cruises. Values in brackets refer to those reported in the cruise reports. RVs used: *Shonan Maru* (SM), *Shonan Maru No. 2* (SM2) and *Kaiko Maru* (KM). Only the acoustic recording data are presented here. The species detected include BL = blue whales (*Balaenoptera musculus*), PBL = pygmy blue whales (*Balaenoptera musculus brevicauda*), FW = fin whales (*Balaenoptera physalus*), RW = southern right whale (*Eubalaena australis*), HW = humpback whales (*Megaptera novaeangliae*), KW = killer whale (*Orcinus orca*), SW = sperm whale (*Physeter macrocephalus*) and SE = seals (Pinniped). There was no acoustic component during the 2000/01, 2004/05 and 2009/10 cruises.

Cruise	RV	Recording dates	Total hours recorded	Number of sonobuoys	Hydro–phones	IWC Area	Species reported	Reference
1996/97	SM	15 Jan.–04 Feb. 1997	42.85 (59.73)	3 (6)	9 (10)	II	BL, PBL	Ensor *et al.* (1997)
	SM2	08–12 Feb. 1997	12.42 (12.00)	4 (3)	0 (0)	II		
1997/98	SM	–	0 (17.32)	0 (2)	0 (13)	II	BL	Ensor *et al.* (1998)
	SM2	29 Jan. 1998	5.00 (26.40)	2 (12)	0 (1)	II		
1998/99	SM	08 Jan.–23 Feb. 1999	190.10 (241.96)	98 (50)	0 (7)	III and IV	BL, SP, KW, FW, HW,	Ensor *et al.* (1999)
	SM2	13 Jan.–21 Feb. 1999	30.53 (235.84)	11 (35)	0 (11)	III and IV	SE, BN, HG	
1999/00	SM	14 Jan.–12 Feb. 2000	33.62 (151.5)	10 (30)	0 (0)	I and II	BL, SP, KW, FW, HW,	Ensor *et al.* (2000)
	SM2	14 Jan.–13 Feb. 2000	164.70 (177.8)	50 (51)	0 (0)	I and II	SE, UN	
2000/01	SM	12 Jan. 2001	0 (2.63)	0 (0)	0 (1)	V, VI and I	None	Ensor *et al.* (2001)
	SM2	–	0 (0)	0 (0)	0 (0)	V, VI and I		
2001/02	SM	31 Dec. 2001–23 Jan. 2002	64.30 (117)	17 (26)	3 (8)	V	BL, SP, KW, HW, SE	Ensor *et al.* (2002)
	SM2	–	0 (118.5)	0 (7)	0 (20)	V		
2002/03	SM	23 Dec. 2002–24 Feb. 2003	120.17 (271.1)	26 (39)	7 (16)	V	BL, SP, KW, FW, HW,	Ensor *et al.* (2003)
	SM2	22 Dec. 2002–24 Feb. 2003	44.95 (162.25)	23 (42)	0 (2)	V	SE, UN	
2003/04	SM	26 Dec. 2003–26 Feb. 2004	68.00 (106)	18 (26)	5 (18)	V	BL, SP, KW, HW, SE	Ensor *et al.* (2004)
	SM2	26 Dec. 2003–28 Feb. 2004	142.23 (136)	28 (28)	12 (12)	V		
2004/05	SM and SM2	–	0 (0)	0 (0)	0 (0)	III	None	Ensor *et al.* (2005)
2005/06	SM2	23 Dec.–15 Feb. 2006	231.40 (264)	127 (127)	0 (0)	III	BL, SP, KW, FW, SE, UN	Ensor *et al.* (2006)
2006/07	SM2	29 Dec. 2006–08 Feb. 2007	76.32 (87)	51 (55)	0 (0)	III	BL, SP, FW, SE	Ensor *et al.* (2007)
2007/08	SM2	26 Dec. 2007–13 Feb. 2008	251.77 (251)	59 (71)	0 (0)	IV	BL, SP, FW, RW, KW, SE, UN	Ensor *et al.* (2008)
2008/09	SM2	21 Jan.–09 Feb. 2009	40.00 (43.38)	23 (25)	0 (0)	IV	BL, SP, FW	Ensor *et al.* (2009)
2009/10	KM	–	0 (0)	0 (0)	0 (0)	IV	None	Sekiguchi *et al.* (2010)
Total			**1,518 (2,481)**	**550 (635)**	**36 (119)**			

Sekiguchi *et al*., 2010). Sonobuoys were deployed on acoustic stations in close proximity to sighted blue whales and fin whales (*B. physalus*) during directed research. They were otherwise deployed while drifting at night. The primary acoustic recording method used expendable DiFAR (Direction Finding and Ranging) sonobuoys (Spartan Electronics Model AN/SSQ53D DIFAR). A modified reusable AN/SSQ 57A Sonobuoy (fixed 27.4m hydrophone cable) and a fixed hydrophone with a preamp and 305m cable were also available. These instruments could be retrieved and recharged for redeployment. No calibrations were conducted between different listening systems. Individual units were not calibrated before surveys.

The sonobuoy radio signal was received via the ship antenna, coupled to an ICOM IC-R100 single channel receiver modified to extend its audio bandwidth. This output was connected to a Sony DAT TCD-D7 recorder (flat frequency response from 5Hz–24kHz) or a Sony mini-disk MZ-R700 recorder (frequency response 20Hz–20kHz ± 3dB). Recordings were later digitised to a Sony PCG-FX120 computer (sample rate 48kHz) using the software program Ishmael (Mellinger, 2001). As opportunity allowed, recordings were monitored visually using a scrolling spectrographic display in Ishmael or Raven Pro software (Bioacoustics Research Program, 2013) from 2003 onward and aurally using headphones. The spectrographic display characteristics varied by user but in general were selected to allow for detection of very low frequency sounds associated with blue or fin whales (< 200Hz). Not all recordings were monitored to detect sounds from other species (e.g., sounds > 200Hz). There may therefore be additional acoustic recordings of other species in existing unreviewed data (e.g., Ross seals (*Ommatophoca rossii*) in Shabangu and Rogers (2021)).

When possible, DiFAR processing provided bearings to sounds. DiFAR signal processing was performed using an automatic MATLAB function within Ishmael that executes a series of commands for de-multiplexing the DiFAR signal and determines the bearing to a sound source (McDonald, 2004). DiFAR was not always available in real time for surveys, but on occasion it was used to obtain bearings to animals in real time, and extensive post-cruise analysis was performed on a subset of these DiFAR data (Rankin *et al*., 2005). During the 2001/02 cruise, the lack of recording media necessitated recording at the lowest possible sampling rate to maximise the recording time (with a sample rate of 32kHz, the frequency response of the Sony TCD-D7 was 20–14,500Hz ± 1dB). This eliminated the multiplexed DiFAR signal which meant bearings could not be obtained for these data.

Acoustic monitoring and recording durations at stations ranged between five minutes and 17 hours. For our purposes, acoustic monitoring is defined as when the underwater environment was acoustically monitored, i.e., listened to using headphones or viewed on a spectrogram without recording in Ishmael or Raven. Acoustic recording is defined as when blue whale sounds were recorded and archived for future use.

All acoustic stations were described by an acoustic record form which included the monitoring and/or recording times. Acoustic recordings were made over short intervals, but animal calls were monitored for a longer time period (Ensor *et al*., 1997; 1998; 1999; 2000; 2001; 2002; 2003; 2004; 2005; 2006; 2007; 2008; 2009; Kato *et al.*, 1996; Findlay *et al*., 1998; Ljungblad *et al*., 1998). In a few cases, marine mammal vocalisations were recorded but not documented on the acoustic record form. Prior to 2005, recorded acoustic files were logged at hourly intervals and were saved in an Audio Interchange File Format (AIFF) at a 16-bit encoding with the majority of the files having two channels. From 2005 onwards, the sampling interval decreased to 10 minutes and sound file type was changed from AIFF to Waveform Audio File format (WAV) at a 16-bit signed encoding.

Database compilation

All available SOWER acoustic recording files (including duplicates) amounting to 286GB were sourced from archives held by the Cornell University Laboratory of Ornithology or from individual cruise participants. The acoustic recording files from low latitudes (i.e., the Australia, Madagascar and Chile blue whale cruises) amounted to 3.31GB. The remainder were largely from south of 40°S. Spatial and temporal metadata of the observed stations were extracted from the cruise reports (Ensor *et al*., 1997; 1998; 1999; 2000; 2001; 2002; 2003; 2004; 2005; 2006; 2007; 2008; 2009; Kato *et al*., 1996; Findlay *et al*., 1998; Ljungblad *et al*., 1998; Sekiguchi *et al*., 2010). Acoustic data forms and associated sightings forms were sourced from the IWC Secretariat. The reconciled acoustic database and all metadata are currently held by the Mammal Research Institute Whale Unit at the University of Pretoria.

Acoustic data files were archived in the following format: folder (cruise year and region), sub-folder (vessel), sub-folder (tape or hard-drive) and file (acoustic file). A corresponding Microsoft Excel database was designed to include these fields for each acoustic file. For example, database entries for an acoustic file from the 2000 Antarctic *Shonan Maru* cruise include: 2000 Antarctic (cruise year and region), SM1 (vessel), Tape 01 (tape or hard Drive number) and SM1_000114-000000.aif (acoustic file). Once these data were captured, duplicates and empty folders were identified and deleted from the working database. Thereafter, the date, time and location (latitude and longitude) data of each station were derived from cruise reports and acoustic record forms before being merged with the acoustic file database to complete the properties of each acoustic station. File duration, visual presence or absence of blue whales and total recording time (which comprised a number of files at each station) were then entered into the database.

Records were categorised as daytime or nighttime based on recording times depicted on each file name, with daytime designated as 06h00–18h00 and night-time as 18h00–06h00, though this does not correspond to natural light regimes. The visual survey operations during daytime hours meant that acoustic stations were biased towards the night period, while daytime acoustic stations were biased towards deployments in association with whale groups. Acoustic data were further grouped by IWC Management Area. Data fields were later added to the dataset to include numbers and rates of D- and Z-calls detected at each station once the data analyses had been completed. The final spreadsheet dataset contains: cruise year, IWC Management Area, research vessel, date, tape/sonobuoy number, station number, file name, acoustic file type, time of day, file duration, blue whale presence/absence, station total recording duration, station position (latitude, longitude) and a comments field (Table 2).

Database analyses

Acoustic data were investigated and characterised using the Raven Pro. Antarctic blue whale call detection templates were created and applied to all acoustic files in eXtensible Bio-Acoustic Tool (XBAT; Figueroa, 2006) software operated on the MATLAB R2014a platform (MathWorks, 2014) (Figure 2). The non-decimated acoustic

Table 2

Example of the final database content.

Field	Example
Cruise (year and region)	2007/08 Antarctic cruise
Research vessel	SM2
Date	12 February 2008
Tape/sonobuoy number	SB 59
IWC Management Area	IV
Station number	46
File name	SOWERD-080212-000000
Acoustic file type	WAV
Time of the day	Night
File duration (hr)	8.08
Blue whale presence/absence	Present
Station total recording duration (hr)	8.08
Station position (latitude, longitude)	–64.27, 105.59
Comments	Faint calls

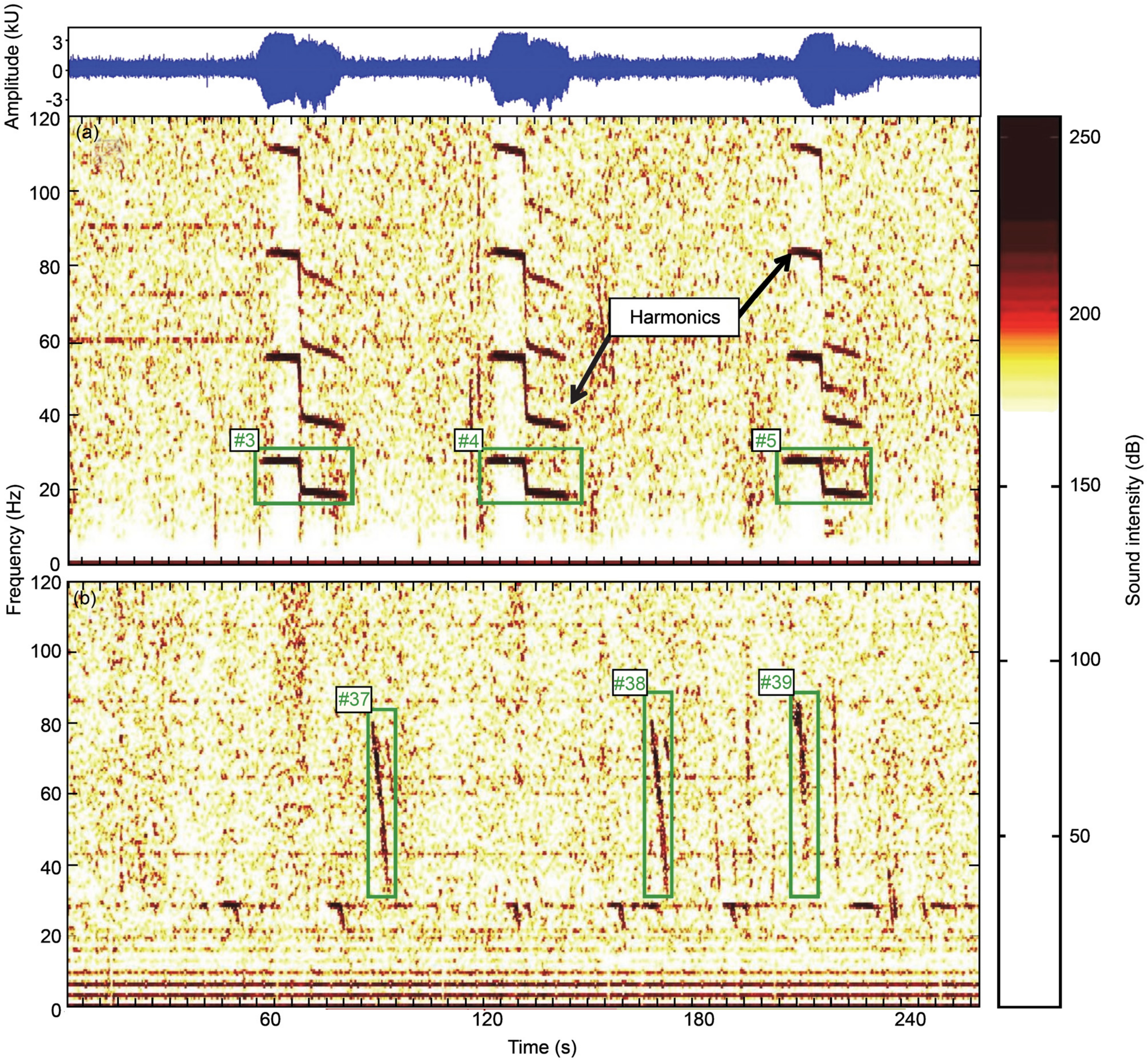

Fig. 2. Spectrograms of three auto-detected Antarctic blue whale: (a) Z-calls; (b) D-calls. Z-calls and amplitudes were recorded during the 2001/02 cruise at –64.57°S and 137.68°E. D-calls were recorded during the 1996/97 cruise at 68°48'S and 00°06'E. The hash (#) number on the top left corner of each box refers to the call-type auto count number for that particular acoustic file. Spectrogram parameters: frame size 1.28s, 50% overlap, FFT size 1650 points, Hanning window.

files from 2003/04 to 2008/09 sampled at 48,000Hz were decimated/downsampled to 1,000Hz using custom-written MATLAB script to improve the frequency resolution and the Fast Fourier Transform (FFT) length. All call detections were verified by a manual visual verification method and visually checked for pygmy blue whale calls (Figure 3). More details about the detector performance are given in Shabangu *et al*. (2017). Sonobuoy deployments from Australia, Chile and Madagascar are not considered in our analyses as they do not contain Antarctic blue whale calls.

Statistical data analyses and plotting of call data were performed in the R statistical software package (R Development Core Team, 2015), using script editor RStudio version 0.99.473 (RStudio Team, 2015). Call data were standardised by survey effort (recording duration) to calls per hour, which defines call rates. Pearson's correlation coefficients (r) were estimated to measure the linear correlation (dependence) between variables, while a two-sample Kolmogorov-Smirnov test (KS test) was used to determine significant differences between datasets.

RESULTS

Based on information extracted from the cruise reports, acoustic data were collected at a total of 716 acoustic stations during the SOWER cruises between 1996/97 and 2009/10 (Figure 1). Sampling at acoustic stations was conducted in all IWC Areas except Area VI. Most effort occurred in Areas III, IV and V. A total of 635 sonobuoys were deployed during nine cruises (Table 1). Not all sonobuoys were functional; the overall failure rate of sonobuoys ranged from 0–40% per cruise. Overall, a total of 2,600hrs of acoustic monitoring were conducted in real time where acousticians actively listened to sounds and monitored spectrograms (Table 1). Recording acoustic data to media occurred for 24 hours of the day.

Detections included Antarctic blue whales (Figure 2), Madagascan pygmy blue whales (Figure 3), fin whales, humpback whales, killer whales, southern right whales (*Eubalaena australis*), sperm whales, small odontocetes and seals (Figures 4–8, Table 1). Assignment of a species to recorded call types was based on a combination of: (1) acoustician experience with visual spectrogram and real-time listening; (2) comparison of signals with the literature; and (3) post-processing attribution, as was the case for leopard seal sounds previously attributed to humpback whales based on presence of humpback whales and humpback whale-like low-frequency vocalisations reported in the literature.

Distinct Antarctic blue whale sounds were detected at 179 stations (Figure 1, Table 1). Except for the 1996/97 cruise, all blue whale songs detected were D-calls or 28Hz tonals attributed to Antarctic blue whales (Figure 2),

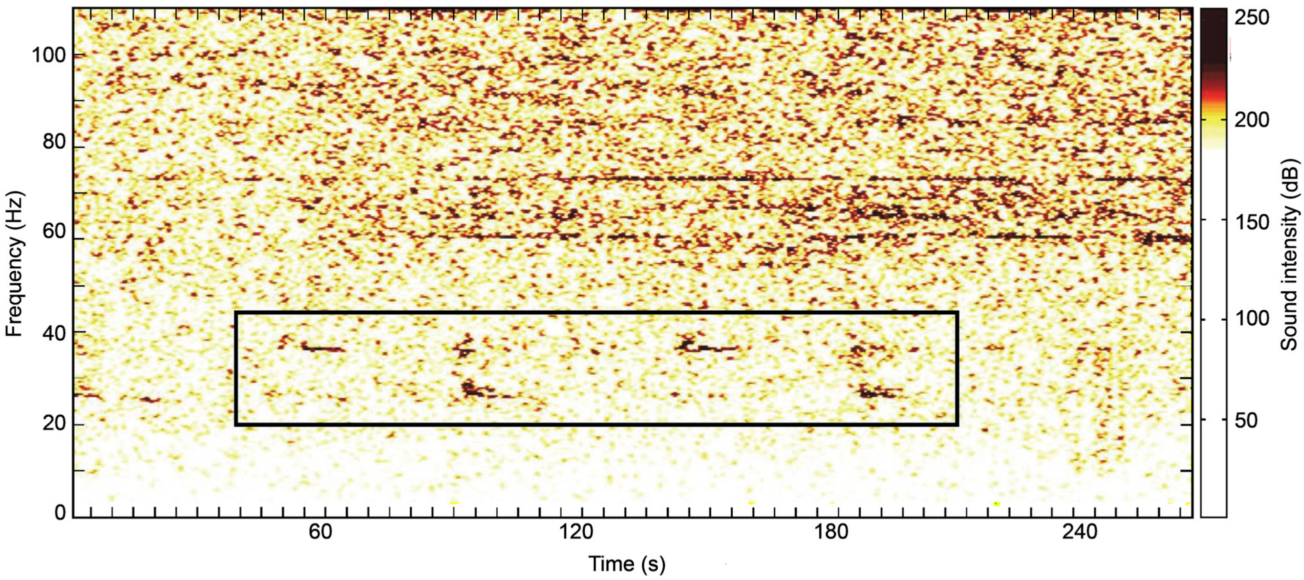

Fig. 3. Spectrogram showing calls of pygmy blue whales (rectangle) recorded in Madagascar during the 1996/97 cruise. Spectrogram parameters: frame size 1.28s, 50% overlap, FFT size 1650 points, Hanning window.

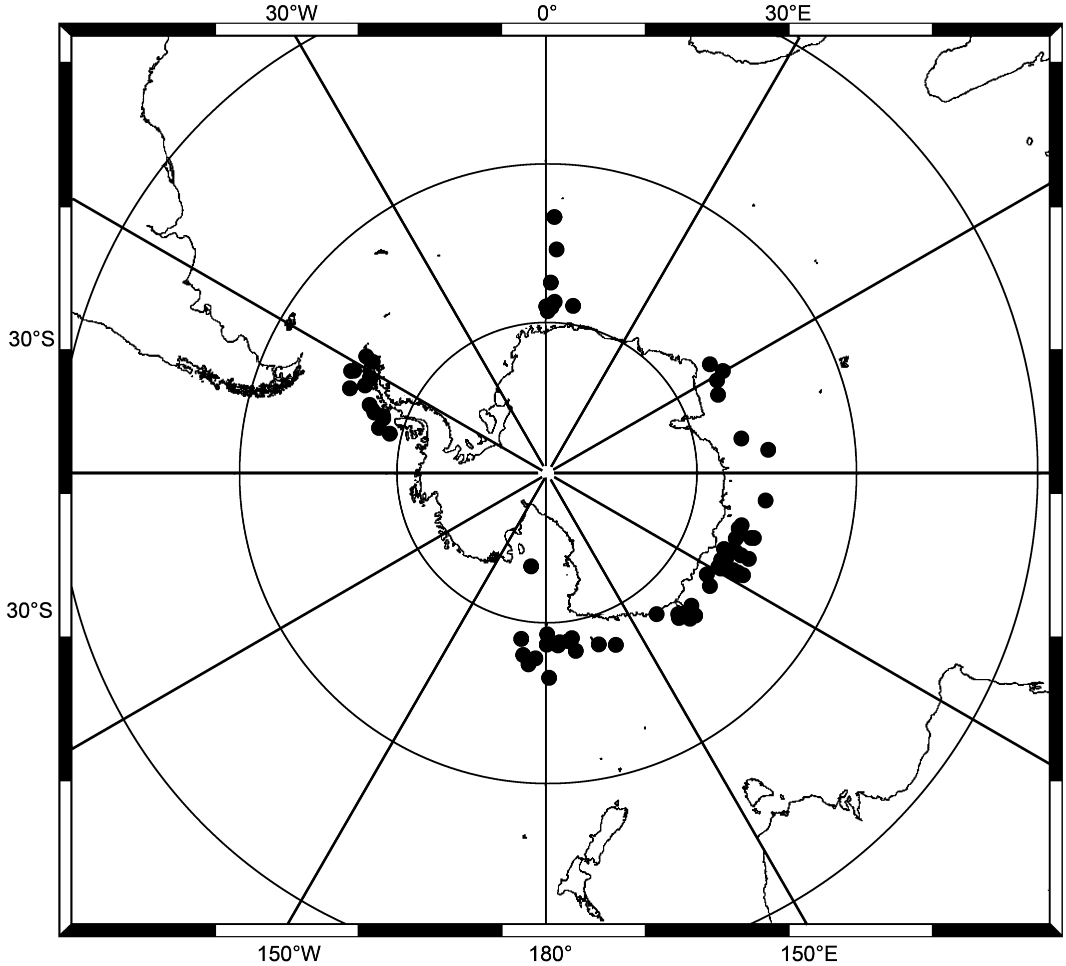

Fig. 4. Locations of all sonobuoy recordings with identified acoustic detections of humpback whales (●) from 1996–2009.

while songs associated with other Southern Hemisphere blue whales were recorded near Madagascar and Chile (Ljungblad *et al*., 1998; Clark and Fowler, 2001) and not during the Antarctic cruises. Not all Antarctic blue whale songs comprised all three note types, but the songs always contained the first 28Hz component (see Rankin *et al*. (2005) for a full description). In addition to these stereotyped long-duration songs, shorter duration FM D-calls were also detected at some stations. Ljungblad *et al*. (1998) compared data from recordings south of 60°S with those made off the Madagascar Plateau (25°–35°S and 40°–45°E) and described differences in the sounds produced by blue whales in these areas. These recordings amounted to the first descriptions of each of the two song types and supported the idea that acoustic monitoring was a robust means of distinguishing between Antarctic and pygmy blue whales.

Available recordings: new analyses of the compiled database

After database compilation, approximately 7,485 recorded acoustic files were available from 484 stations of the Antarctic cruises, comprising a total of 1,518hrs of acoustic recordings from the analysed 586 deployed acoustic recorders (i.e., 550 sonobuoys and 36 towed or deployed hydrophones). Antarctic blue whale calls were detected on 4,183 out of the 7,485 recorded files. The available hours of recordings and number of sonobuoys represent only 63% and 80% respectively of the effort documented in the cruise reports as significant numbers of acoustic data files from the SOWER cruises could not be sourced (Table 1). The 2003/04 and 2005/06 *SM2* cruises were the only two years where the available data match the documented data in the cruise reports. It is also apparent that some of the acoustic data collected using cabled hydrophones from earlier years are missing (Table 1). The longitudinal acoustic survey coverage of the Southern Ocean is fairly sporadic between IWC Management Areas during the SOWER programme (Figure 1). Areas III, IV and V had the highest acoustic survey coverage (Tables 1

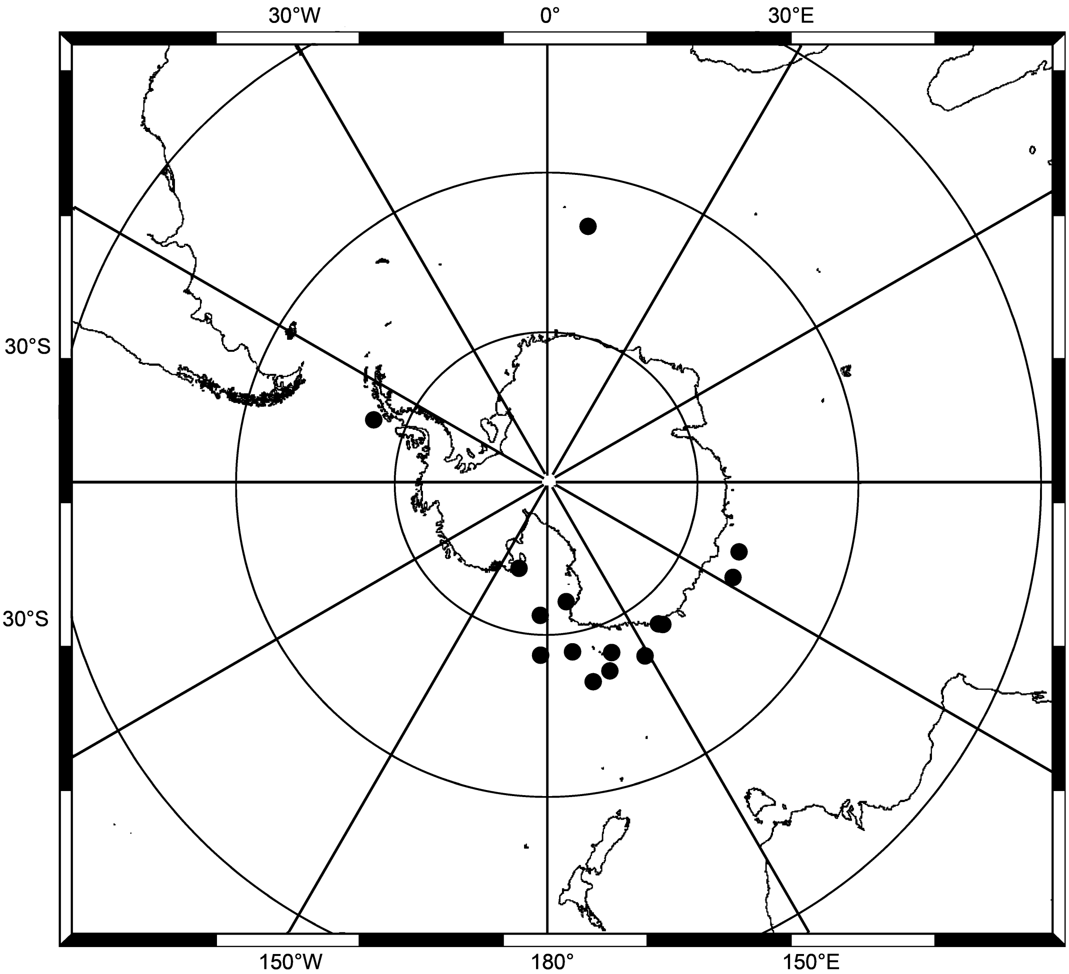

Fig. 5. Locations of all sonobuoy recordings with identified acoustic detections of killer whales (●) from 1996–2009.

and 3). Most sonobuoy deployments were conducted between the ice edge and 60°S but most blue whale calls were detected close to the ice edge.

The acoustic survey effort in terms of the number of acoustic stations and duration of the recordings varied significantly (two-sample KS test, $p < 0.05$) between years and areas (Tables 1 and 3). The duration of recordings at each station varied considerably as some acoustic stations had two or more sonobuoy deployments where others had just one. Acoustic recordings were made in 11 out of 14 years of the SOWER programme. Only one acoustic recording was listed for Area VI from *Shonan Maru* for 2.38 hours on 12 January 2001 in the presence of four blue whales (Ensor *et al*., 2001), but this acoustic recording file could not be sourced for analyses. Details of the available acoustic data from the SOWER blue whale cruises conducted in low latitudes are given in Table 4. Acoustic data files from the 1997/98 Antarctic cruise have not yet been sourced, but data files from the preceding Chile blue whale cruise have been reviewed, including identification of files grouped with the Chile cruise data which were dated within the Antarctic cruise time period.

Antarctic blue whale call detections

The characteristic Antarctic blue whale Z-calls were successfully detected using the template method (Figure 2a); 24,902 calls were counted. The blue whale D-call was also detected using the template method (Figure 1); 9,315 calls were counted. The acoustic presence of Antarctic blue whales from the sonobuoy deployments shows patchy distribution over the surveyed area (Figure 1). Not all deployed sonobuoys yielded blue whale vocalisations (Figures 1 and 9) but there was a good correlation between blue whale Z-call detections and number of sonobuoys deployed ($r = 0.66$, $n = 586$, $p > 0.05$). A weak correlation was found between D-calls and the number of sonobuoys deployed ($r = 0.49$, $n = 586$, $p > 0.05$). Only 241 of the 586 available sonobuoy/

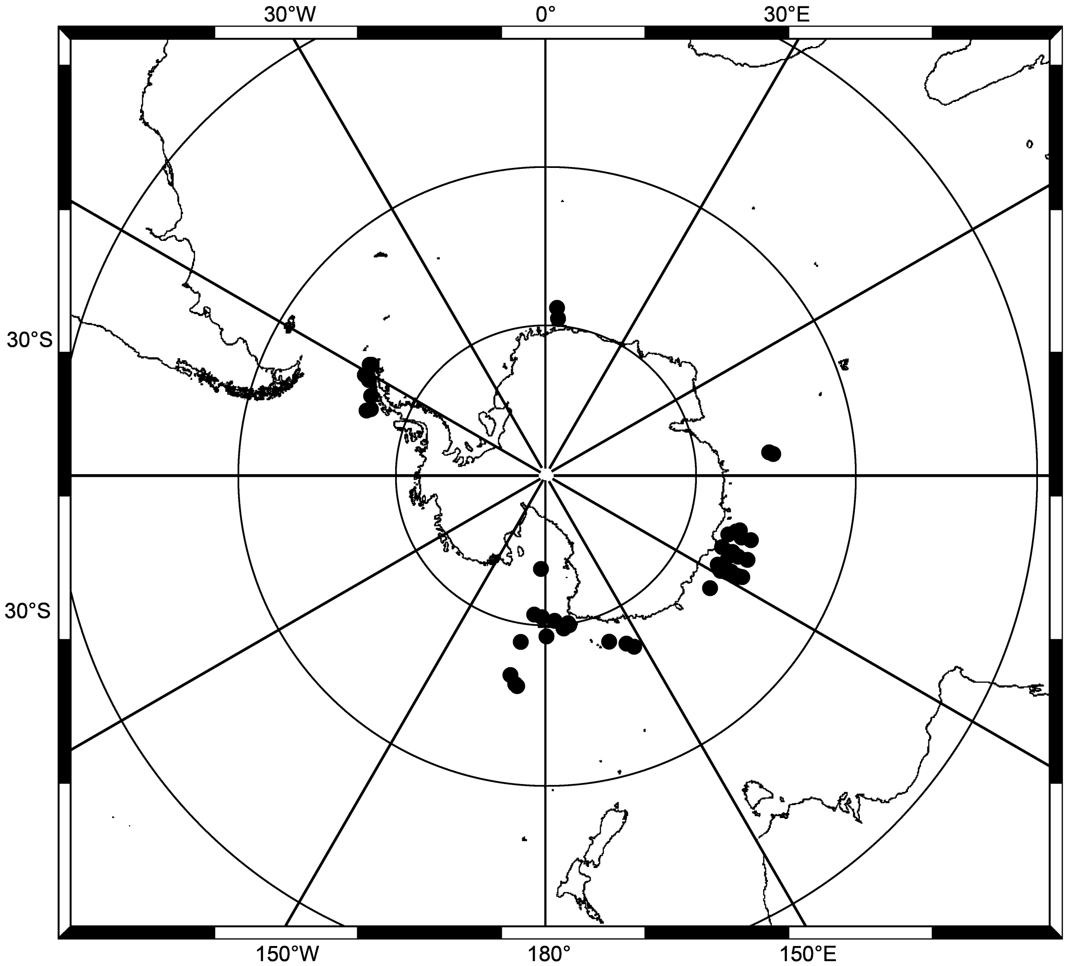

Fig. 6. Locations of all sonobuoy recordings with identified acoustic detections of unidentified and other marine mammal species including southern right whales (⬤) from 1996–2009.

hydrophone deployments contained either or both types of the Antarctic blue whale calls. Area III had the highest call rates of both D- and Z-calls (Figures 10 and 11). No call detections were made in Area VI due to lack of acoustic survey effort.

A total of 214 sonobuoys were deployed during daytime and 372 deployed at night. More Z-calls were detected during daytime (14,724) than at night (10,178; two-sample KS test, $p < 0.05$). This was also the case for D-calls with more calls being detected in the daytime (6,492) than at night (2,823; two-sample KS test, $p < 0.05$). Weak correlations were found between acoustic station duration and the number of calls detected for both call types ($r = 0.33$ and 0.49 for D- and Z-calls respectively).

Data comparison

Comparisons of mean number of hours recorded in all cruises indicated a significant difference between the available recorded hours from the dataset and documented recorded hours from cruise reports (two-sample KS test, $p < 0.05$). A significant difference was observed between the number of sonobuoys available in the dataset and the sonobuoy numbers documented in cruise reports (two-sample KS test, $p = 0.05$). There was good agreement between analysed blue whale call detection results and blue whale calls observed and documented in cruise reports ($r = 0.62$).

Other sounds and vocalisations detected

While no calls of either Antarctic or pygmy blue whales were detected from the 1995/96 Australia low latitude cruise, calls of pygmy blue whales and fin whales were found in the 1996/97 Madagascar acoustic data

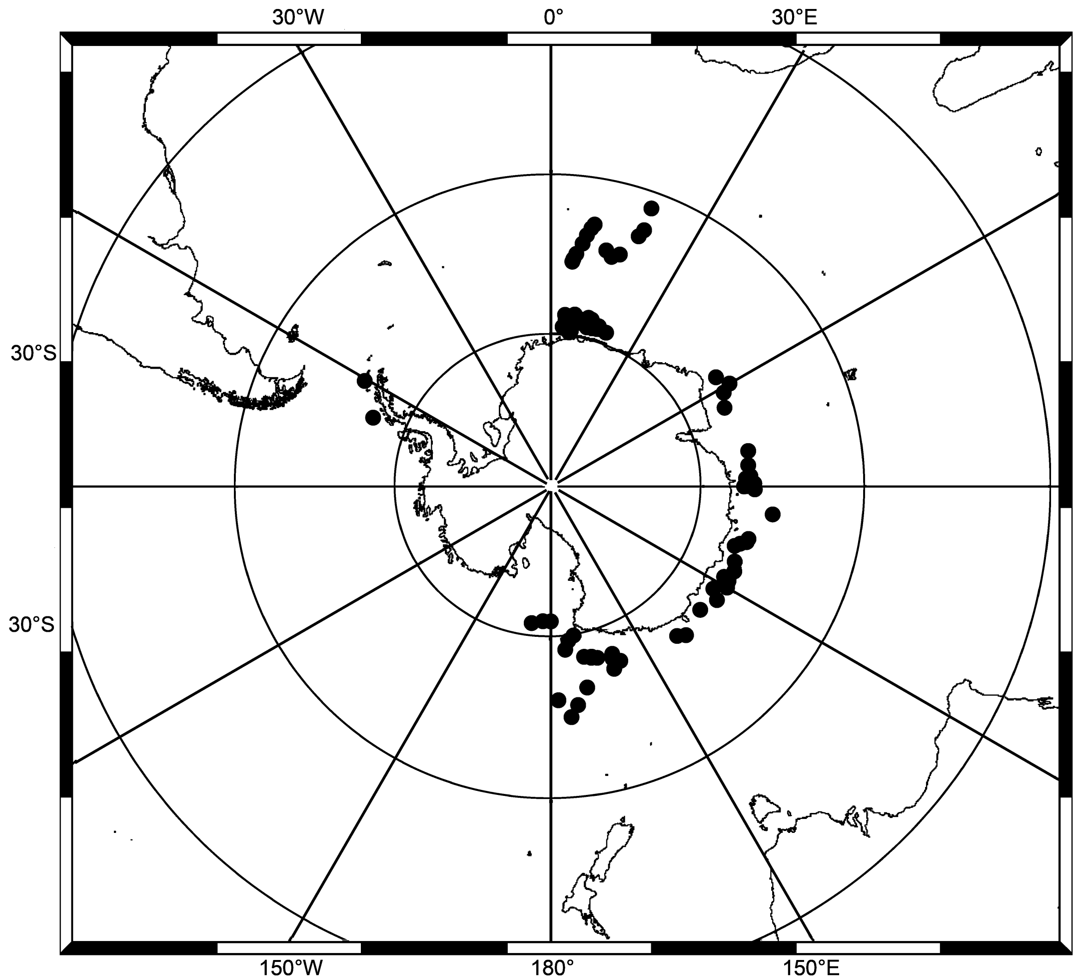

Fig. 7. Locations of all sonobuoy recordings with identified acoustic detections of sperm whales (●) from 1996–2009.

(Figure 3) (Ljungblad *et al*., 1998). No Z-calls were found in the 1997/98 Chile cruise, but D-calls and numerous southeastern Pacific 2 (SEP2) calls of the Chilean pygmy blue whale were found (Figure 12). These call detections confirm observations from previous studies in the southeastern Pacific Ocean (Cummings and Thompson, 1971; Stafford *et al*., 1999; Buchan *et al*., 2010; 2014). The SEP2 call has a C2 unit which is 5s long (Figure 12) followed by an inter-unit gap of 3s, then a 9s-long D2 unit. The overall duration is approximately 17s (Buchan *et al*., 2014). The D-calls observed from the southeastern Pacific Ocean were not considered for analysis since we concentrated on the Southern Hemisphere Antarctic blue whale population.

Detections of other marine mammal species included fin whales, humpback whales, killer whales, southern right whales, sperm whales, small odontocetes and seals (Figures 4–8, Table 1). In addition, ice noise, seismic air guns and other unidentified sounds were detected on numerous occasions.

DISCUSSION

The original goal of the acoustics component of the SOWER cruises was to determine if passive acoustics could be used as a tool to help identify the subspecies of sighted blue whales. In 2006/07 and 2007/08, the passive acoustic method was also assessed for the purpose of monitoring fin whales, but numerous limitations prevented this during the cruises, including limited resources (sonobuoys and recording tapes). Most of the sonobuoys used were surplus instruments whose expiration dates had long passed, which resulted in some high failure rates. Nevertheless, the electronics expertise of the ships' radiomen and one of the co-authors (DL) enabled the acousticians to modify some of the sonobuoys while at sea.

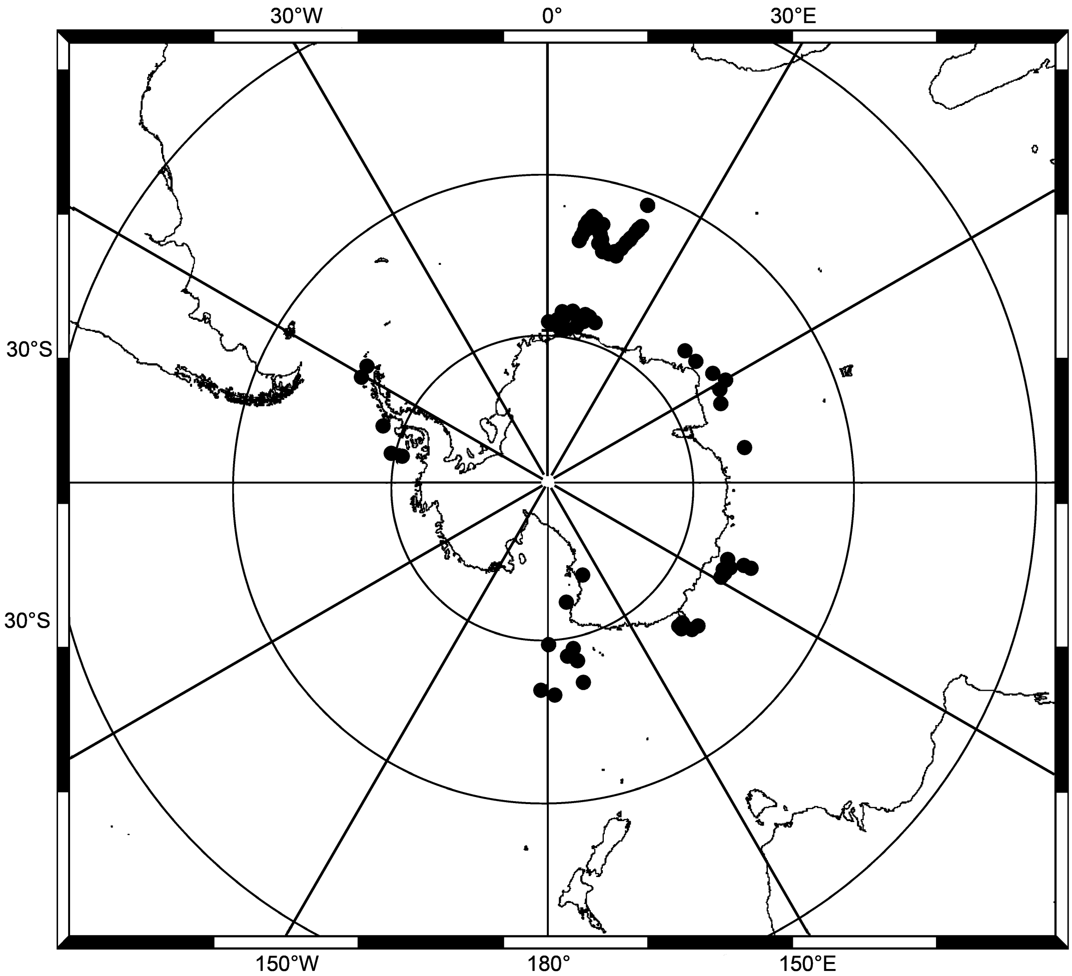

Fig. 8. Locations of all sonobuoy recordings with identified acoustic detections of all seal species (leopard, crabeater, Weddell (*Leptonychotes weddellii*)) (●) from 1996–2009.

Table 3

The total number of available acoustic stations recorded on SOWER cruises grouped by IWC Management Area.

Area	Total number of stations
Area I	31
Area II	19
Area III	193
Area IV	119
Area V	122
Area VI	0
Total	**484**

Table 4

Details of the available acoustic data recorded from other IWC blue whale cruises conducted in the low latitudes. Values in brackets refer to records in the cruise reports.

Cruise year	RV	Recording dates	Total hours recorded	Number of sonobuoys	Cruise Area	Positions (longitude)	Reference
1995/96	SM	–	0 (18.06)	0 (12)	Australia	114°–115°E	Kato *et al.* (1996)
	SM2	07–26 Dec. 1995	17.60 (78.04)	10 (43)	Australia	114°–115°E	Kato *et al.* (1996)
1996/97	SM	10–24 Dec. 1996	39.93 (182.12)	12 (52)	Madagascar	40°–44°E	Ljungblad *et al.* (1998)
	SM2	–	0 (81.18)	0 (45)	Madagascar	40°–44°E	Ljungblad *et al.* (1998)
1997/98	SM	09 Dec. 1997–02 Jan. 1998	43.32 (72.50)	16 (29)	Chile	72°–74°W	Findlay *et al.* (1998)
	SM2	17 Dec. 1997–02 Jan. 1998	100.97 (106.21)	23 (30)	Chile	70°–74°W	Findlay *et al.* (1998)
Total			**201.82 (538)**	**61 (211)**			

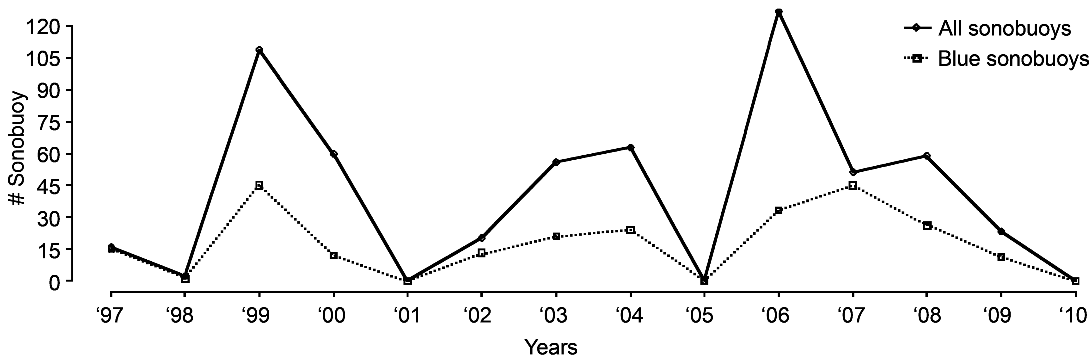

Fig. 9. Total number of sonobuoys deployed per year (all sonobuoys) and the resultant sonobuoys containing Antarctic blue whale calls (blue sonobuoys) from all cruises.

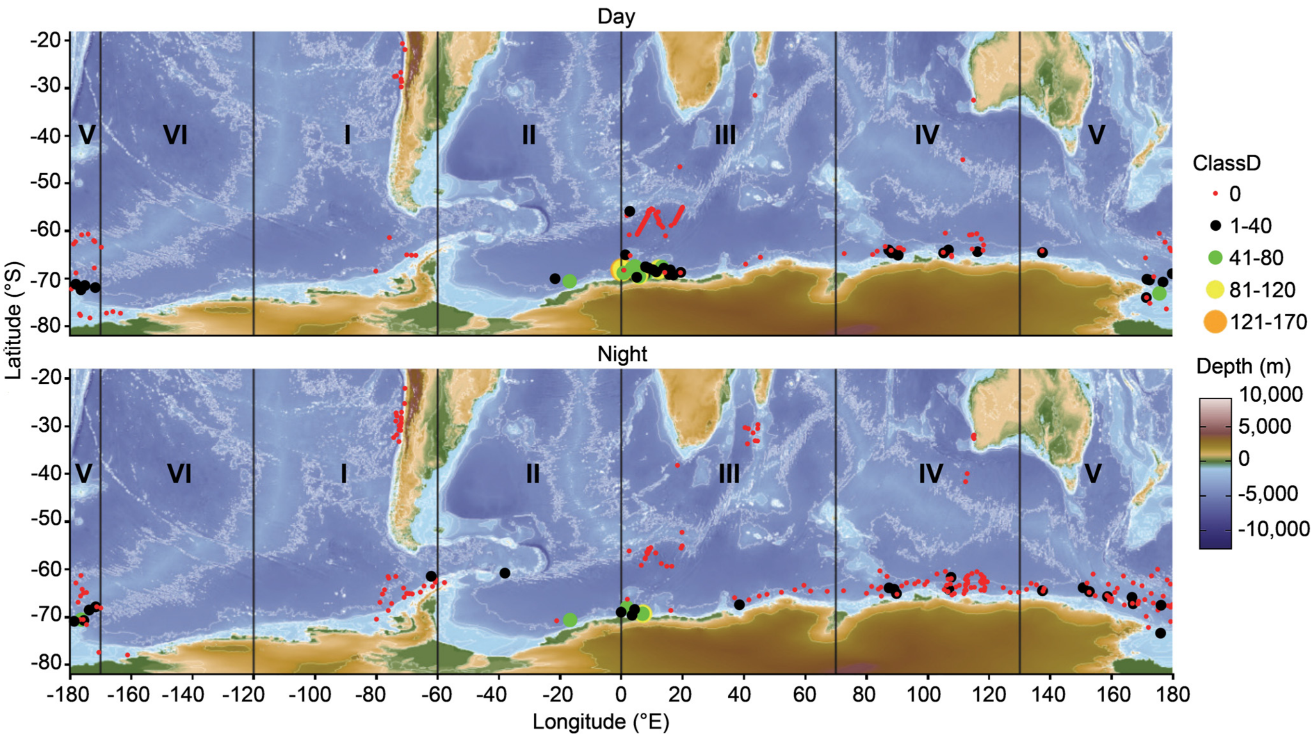

Fig. 10. Day and night distribution of D-call numbers in the Southern Ocean. Class D is the class of D-call rates.

These cruises were moderately successful and laid the foundation for future work using acoustics to study blue whales in the Southern Ocean. For instance, Ljungblad *et al*. (1998) compared data from recordings made south of 60°S with those made off the Madagascar Plateau (25°–35°S and 40°–45°E) and described differences in the sounds produced by blue whales in these areas. These recordings provided the first descriptions of each of these two song types and supported the idea that acoustic monitoring was a robust means of distinguishing between Antarctic and pygmy blue whales. Acoustic data collected on both Antarctic and pygmy blue whale vocalisations (Ljungblad *et al*., 1998; Clark and Fowler, 2001; Rankin *et al*., 2005) paved the way for numerous studies delineating occurrence and habitat usage of blue whales based on passive acoustic monitoring and further strengthened the concept of 'acoustic populations' of blue whales (Stafford *et al*., 2004; 2011; McDonald *et al*., 2006; Samaran *et al*., 2010a; 2010b; 2013). Recent surveys that actively used passive acoustics to detect, identify, track and approach blue whales in the Southern Ocean for photo-ID and biopsy also used SOWER reports and publications to select a target research area, develop methods and train field personnel (Clark and Fowler, 2001; Rankin *et al*., 2005; Gedamke and Robinson, 2010; Miller *et al*., 2015). The success of the Australian Antarctic Division's Southern Ocean Research Partnership (SORP) 2013 survey was based on foundations laid by the SOWER cruises (Double *et al*., 2013; Miller *et al*., 2013a).

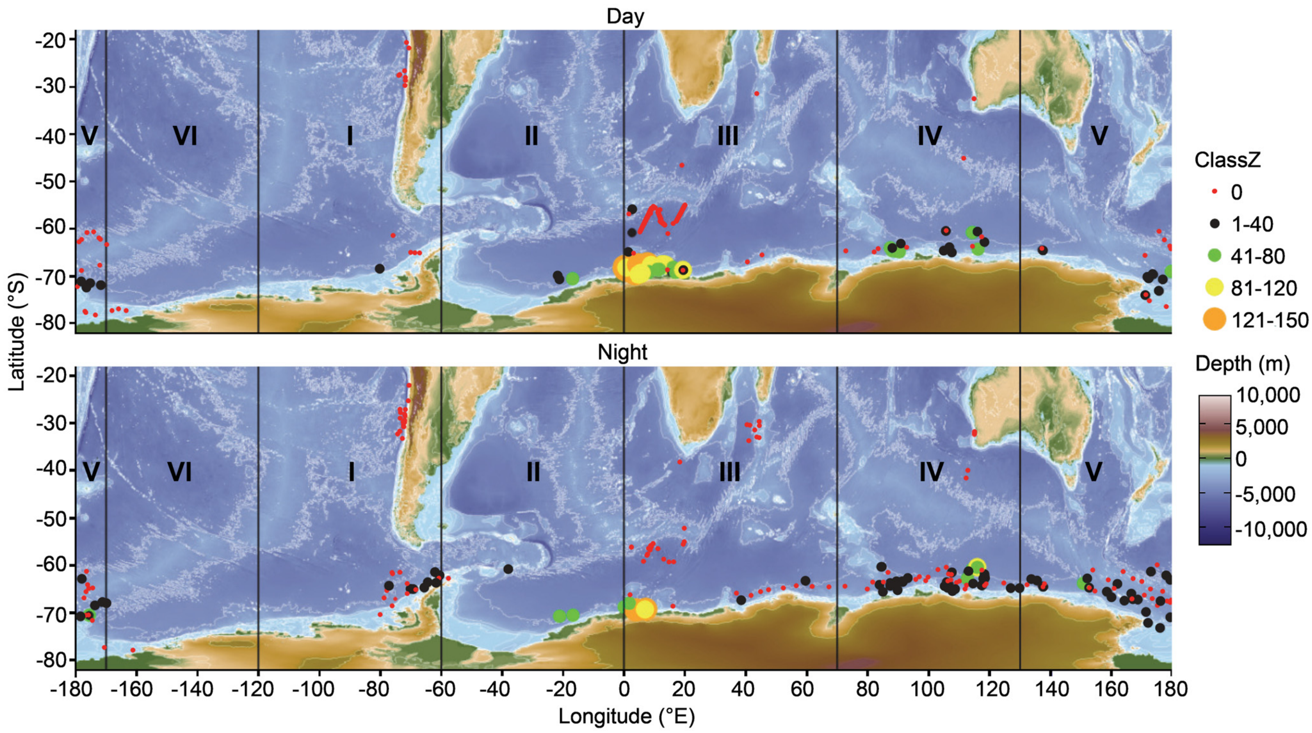

Fig. 11. Day and night distribution of Z-call rates in the Southern Ocean. Class Z is the groups of Z-call rates. Deployments from Australia, Chile and Madagascar are shown in maps for completion's sake but not considered in our analyses.

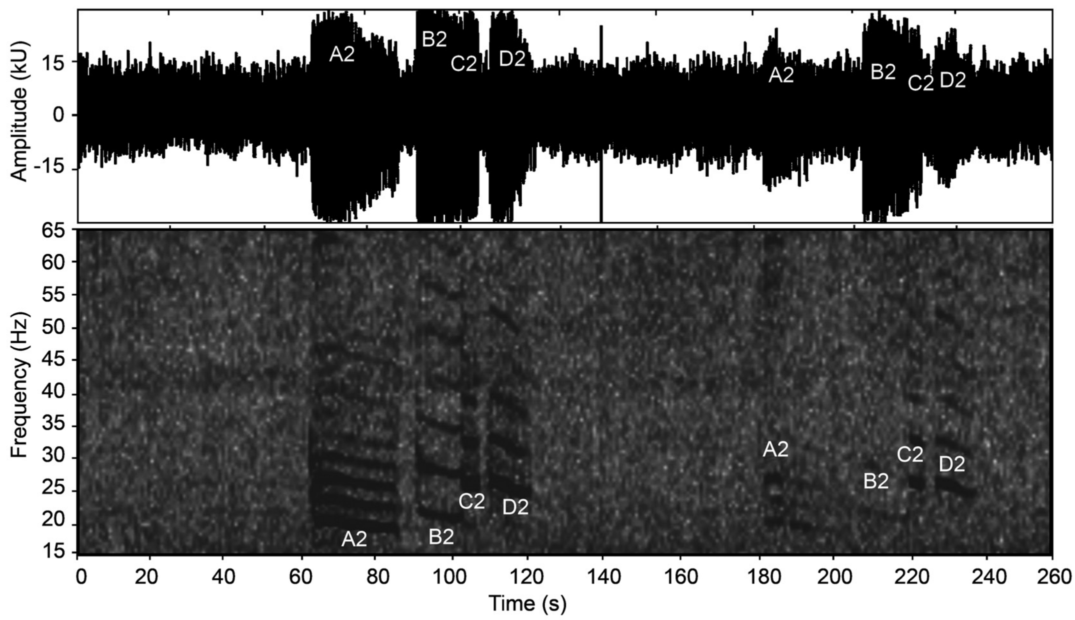

Fig. 12. Pressure waveform (top panel) and spectrogram (bottom panel) of the Chilean blue whale SEP2 song phrases (A2, B2, C2 and D2). This sonobouoy was deployed on 31 December 1997 off the southeastern Pacific Ocean at 28°39'N, 71°47'W during the 1997/98 cruise. Spectrogram parameters: frame size 1.39s, 50% overlap, FFT size 2048s, Hanning window.

Distribution and occurrence of Antarctic blue whale call types

The higher number of Antarctic blue whale calls found during daytime (31% and 56% more Z- and D-calls respectively), despite more sonobuoys being deployed at night, might be an indication that Antarctic blue whales are most vocally active during daytime and less vocal at night. A similar observation has been made from autonomous acoustic recorders off the Maud Rise and Benguela ecosystem off South Africa (Shabangu *et al.*, 2019; 2020). Alternatively, the higher daytime call numbers might arise because daytime acoustic recordings were often conducted in the presence of visually sighted blue whales whereas night-time acoustic recordings were made without knowledge of blue whale presence or absence. Low numbers and rates of Antarctic blue whale calls observed in December could be due to the fact that most of the SOWER cruises usually started in late December when the majority of the Antarctic blue whales may have been in transit from the low-latitude overwintering grounds to the Southern Ocean feeding grounds (Mackintosh and Wheeler, 1929).

Sea ice extent in December could also have affected the number of vocally active Antarctic blue whales, as suggested by Širović *et al*. (2004), since recordings from stationary autonomous Acoustic Recording Packages (ARPs) in Area II found low call numbers in December. These SOWER data showed that Antarctic blue whale call rates peaked in February (Shabangu *et al*., 2017), which is closer to the blue whale call peak period of March and April observed by Širović *et al*. (2004). Despite most acoustic recordings being conducted before mid-February, a considerable number of calls were detected in this month, showing the high numbers of Antarctic blue whales in the Southern Ocean at this time when sea ice retreat is strongest (e.g., Shabangu *et al.*, 2020). The increased call rates of Antarctic blue whales observed in the later years of the SOWER programme (Shabangu *et al*., 2017) may support the initial population recovery of 8.2% estimated by Branch *et al*. (2004). The increase in blue whale call rates in later years is not due to more dedicated ship-time as there was no increase in the number of hours dedicated to acoustic research (Table 1). The high correlation between blue whale call detections and number of sonobuoys deployed demonstrates that greater coverage effort in particular areas of interest improved the precision of distribution and occurrence estimates (Aglen, 1989). It is worth noting that a special effort was dedicated to certain IWC Management Areas with suspected high blue whale prevalence.

Antarctic blue whale calls have previously been detected as far north as the equator in the Atlantic Ocean (Samaran *et al.*, 2019) and 08°S in the Indian Ocean (Stafford *et al*., 2004). During these analyses, no Antarctic blue whale calls were found off Australia, in the southeastern Pacific or South of Madagascar in the low latitude cruises, presumably reflecting the summer periods during which they were carried out. The SOWER low-latitude acoustic data were collected within a single summer month each year when the majority of Antarctic blue whales were expected to be further south than the region surveyed, whereas the data analysed by Stafford *et al*. (2004) were collected over 24 months. Calls of pygmy blue and fin whales were found during our analyses of the incomplete acoustic data from Madagascar, confirming the observation by Ljungblad *et al*. (1998). The 1995/96 Australia blue whale cruise reported pygmy blue whale calls (Kato *et al*., 1996), but no such calls were found from the incomplete acoustic dataset analysed here.

Ljungblad *et al*. (1998) and Rankin *et al*. (2005) analysed a subset of the SOWER acoustic data from 1996/97, 2001/02 and 2002/03. This study is the first of its kind to review and analyse a more complete SOWER acoustic dataset for Antarctic blue whale vocalisations. The difference between available and reported acoustic datasets from the cruise reports is a significant concern such that a fuller reconciliation of the SOWER cruises acoustic dataset is recommended if possible. This SOWER acoustic dataset is a valuable acoustic time series of Antarctic blue whale vocalisations. It is further recommended that the archiving and management of these data are centralised to ensure these circum-Antarctic data are readily available for future studies. The Acoustic Trends Working Group (ATWG) of the Southern Ocean Research Partnership (SORP) is adopting a similar approach for ongoing acoustic data collection (van Opzeeland *et al*., 2014).

While reconciliation of the full circumpolar SOWER acoustic dataset could not be completed, the compilation of this dataset has allowed for the merging of both acoustic data from the recordings and associated metadata, including spatial and temporal data, from the station and acoustic record forms. Further analyses of these data (and particularly call rates) by location (position, depth and distance from the ice edge), timing (both across the summer season and by time of day), and in association with observed groups of blue whales and broader blue whale densities obtained from line-transect visual observations, will provide important information on Antarctic blue whale call behaviour, migrations and distribution. Shabangu *et al*. (2017) used the SOWER blue whale recordings to examine the occurrence of Antarctic blue whale call types in the context of oceanographic variability in the region over the 14-year span of data collection. They found that the number of both D- and Z-calls recorded positively related to the number of animals seen during visual observations. Call rates for both types were dictated by region and the location of the southern boundary of the Antarctic Circumpolar Current (ACC). This is important for the analysis and understanding of autonomous acoustic recordings and other long-term acoustic recordings from the Southern Ocean region.

SOWER datamining potential

Compiling the SOWER acoustic dataset and analysing it for different types of blue whale calls recorded over more than a decade of survey effort was a first step towards expanding the utility of these data. In-depth studies can now be undertaken to improve our understanding of the role that sound production plays in blue whale ecology. Further studies using these SOWER recordings would be valuable and deserve serious consideration. While the acoustic equipment was not calibrated, these recordings could provide important baseline data regarding ambient noise, vocal repertoire and seasonal calling behaviours of other species. The combination of photo-ID, biopsy and behavioural data can provide valuable insights that are otherwise difficult and expensive to obtain. Currently, there are no data on what proportion of blue whales produce downsweeps or what proportion of males sing. Analysis of SOWER acoustic data in conjunction with sighting survey and behavioural data (for which there were at least 120 instances over the years – see Table 1) may be used to develop distribution curves for acoustically active blue whales: i.e., when sighted blue whales appeared to be feeding, what types of sound were recorded; which of these could be attributed to the observed animal; what was the behavioural context? What was the whale doing when no sounds were recorded? Was acoustic behaviour different when females with calves were present? Understanding the variability of acoustic behaviour and associated behavioural context will lead to a better understanding of acoustic function. Vocal rates in different contexts will inform efforts to determine absolute or relative population sizes from remote passive acoustic monitoring, as suggested by the IWC SORP blue and fin whale acoustics working group (Samaran *et al*., 2012).

In cases where two DiFAR sonobuoys were deployed at the same time, processing the same blue whale sound on each buoy can help localise calling whales. While the SOWER cruises did not take advantage of these opportunities, this type of post-cruise analysis is readily feasible (Rankin *et al*., 2005). Where a biopsy sample was obtained, acoustic localisation can be used to compare vocal behaviours between females and males (Rankin *et al*., 2005). This information is critical for the application of passive acoustic monitoring to population estimation. Based on data from the eastern North Pacific population of blue whales, there is evidence that only male blue whales sing (McDonald *et al*., 2006; Oleson *et al*., 2007), while both males and females appear to produce D-calls (Oleson *et al*., 2007). If this is the case, the use of 28-Hz song notes to determine acoustic occurrence only accounts for males in a population. Assuming that the present-day sex ratio for blue whales is similar to that during commercial whaling (47:53 female: male, Branch *et al*., 2004), then correction factors could be made to account for non-singing females.

One requirement for estimating abundance from passive acoustic monitoring is knowledge of the range at which sounds of interest can be detected. The source level of a signal (how loud it is) is needed to estimate detection range and therefore detection probability. Presently there are few source level estimates for Antarctic blue whales (Širović *et al*., 2007; Samaran *et al*., 2010b). For Antarctic blue whales, there are estimates of detection range based on known sighting locations and calls attributed to these sightings based on DiFAR processing. While our hydrophones were uncalibrated, these data can be used to calculate relatively robust measures of received level to estimate source levels, which, when combined with estimating distances of whales from a hydrophone, can be used to estimate source levels. Data from the SOWER cruises might be used to obtain statistical data, including detection ranges, from Antarctic blue whale source levels, particularly where the animals are a known distance from a sonobuoy. Factors such as call detection range, probability of call detection, cue rate per individual and group sizes can therefore be evaluated. These parameters are crucial to successful estimates of animal densities and relative abundance of vocalising whales in an area (Marques *et al*., 2013). What complicates this analysis is that the frequency response of the recording systems and the gain settings used over the years were not generally reported and the age of the sonobuoys may have influenced the received levels of signals. Our observed high agreement between sightings and acoustic detections are encouraging for whale abundance estimation using passive acoustic monitoring as it indicates that passive acoustic monitoring can successfully capture the number of animals in an area.

There is recent evidence that the fundamental frequency of the Antarctic blue whale 28-Hz song note is changing both within a season and over years on a wintering ground (Gavrilov *et al*., 2012; Ward *et al*., 2017). The SOWER acoustic database has data from over a decade that could be used to determine if this decrease exists on the feeding grounds. The data could be used to examine variability between individual tonal frequencies and if/how these change within a season and across regions. In addition, analysis of some very low frequency sounds (9–11Hz) in relation to behaviour could be examined to identify any vocal response to direct vessel approach (Ljungblad *et al*., 2001).

Other species

These data have a wide range of potential relevance. For example, since the initiation of the SOWER programme, four distinct morpho-types of killer whale (A, B, C and D) have been identified from Antarctic waters (Pitman and Ensor, 2003; Pitman *et al*., 2010). Each form is readily distinguishable in the field and believed to occupy a different ecological niche based on prey and habitat preferences (Pitman and Ensor, 2003). The SOWER dataset contains at least 18 recordings of killer whale vocalisations. A database of call types from each of these forms based on photo-ID could contribute to acoustic identification, as has been done for killer whales in other parts of the world (Ford, 1989; Deecke *et al*., 2011; Riesch and Deecke, 2011; Shabangu *et al*., 2024).

For at least one Southern Hemisphere sperm whale population, there is no evidence of recovery following the end of whaling (Carroll *et al*., 2014). It may be feasible to investigate the SOWER recordings to see if there has been a change in relative occurrence of sperm whale sounds on a circumpolar basis or if there has been low recruitment and therefore a change in age structure which might be investigated by looking at inter-click interval to determine animal size (Adler-Fenchel, 1980; Miller *et al*., 2013b). Seal vocalisations recorded around the Antarctic could also be used to determine whether individuals might be identified or if pan-Antarctic geographic variation exists (Rogers and Cato, 2002; Van Parijs and Clark, 2006; Terhune *et al*., 2008).

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