Vocalisations of Antarctic blue whales, *Balaenoptera musculus intermedia*, recorded during the 2001/2002 and 2002/2003 IWC/SOWER circumpolar cruises, Area V, Antarctica

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ABSTRACT

Blue whale vocalisations recorded during the 2001/2002 and 2002/2003 International Whaling Commission-Southern Ocean Whale and Ecosystem Research (IWC/SOWER) cruises were analysed to determine the feasibility of using acoustic recordings for sub-species identification of the Antarctic blue whale (*Balaenoptera musculus intermedia*) and the pygmy blue whale (*B.m. brevicauda*). The research was conducted in IWC Area V, from latitude 60°S to the ice edge and between longitudes 130°E and 150°E on the *Shonan Maru* (2001/2002), and between 150°E and 170°W on the *Shonan Maru No.2* (2002/2003). Data including 15 groups consisting of 42 animals, as well as opportunistic recordings of an unknown number of animals during evening sonobuoy stations were examined for this study. Vocalisations included long-duration 28Hz tonal sounds and relatively short-duration frequency-modulated sounds. The short-duration calls were similar to vocalisations recorded in the presence of blue whales in other locations worldwide. Not all recordings contained the long-duration 28Hz call, considered to be a species-specific vocalisation of Antarctic blue whales. None of the sounds that have previously been attributed to pygmy blue whales were detected. The long-duration 28Hz tonal vocalisations included 3-unit calls, considered to be song phrases, as well as simple 28Hz sounds and 28Hz sounds followed by a downsweep. The centre and peak frequencies of the 28Hz tone for these three sound types were stable regardless of signal strength; however, for the 3-unit vocalisation, the presence and characteristics of their 2nd and 3rd units were variable. Examination of two distinct groups of simultaneously vocalising blue whales showed no evidence of temporally repeated patterns of vocalisations (song phrases). The results of this study suggest that the peak frequency of the 28Hz vocalisations may be used as a diagnostic feature to aid in discriminating between Antarctic blue whales and pygmy blue whales in the field; however, examination of vocalisations in relation to group size and behaviour are necessary to understand the circumstances in which the 28Hz vocalisations are produced.

KEYWORDS: BLUE WHALE; COMMUNICATION; VOCALISATION; ANTARCTIC; MANAGEMENT PROCEDURE; SURVEY-ACOUSTIC; POPULATION ASSESSMENT; ACOUSTICS; DISTRIBUTION; SOWER

INTRODUCTION

Two sub-species of blue whale are found in the Southern Ocean, the Antarctic blue whale, *Balaenoptera musculus intermedia*, and the pygmy blue whale, *B.m. brevicauda*. There appears to be a general geographic segregation of the sub-species in the austral mid-summer, with pygmy blue whales occurring primarily north of 60°S and Antarctic blue whales south of this latitude (Kato *et al.*, 1995). Sub-species discrimination in the field is problematic because it relies on experienced observers noting relative body proportions and details of the head shape. Population research related to the conservation of large baleen whales requires accurate species identification (IWC, 1995). Recent studies indicate that monitoring of blue whale vocalisations may provide a means of determining sub-species in the field (Ljungblad *et al.*, 1997; 1998; Stafford *et al.*, 1999; 2001).

Sounds recorded in the presence of blue whales can be divided into two categories: short-duration or long-duration (Thompson and Cummings, 1996; Norris and Barlow, 2000). The short-duration vocalisations consist of individual pulses and frequency-modulated (FM, typically downswept) sounds of less than five seconds duration. These vocalisations vary in frequency and duration and have been recorded in the presence of blue whales in many locations (Thompson and Cummings, 1996; Ljungblad *et al.*, 1997; Stafford *et al.*, 2001). Short-duration sounds appear to be common; however, they are underrepresented in the literature.

Long-duration vocalisations are composed of one or more units that are FM or amplitude-modulated (AM) sounds and longer than five seconds (McDonald *et al.*, Submitted). An individual unit is defined as a continuous sound having consistent characteristics; these vocalisation units are often repeated in patterned sequences, or songs (Payne and McVay, 1971; McDonald *et al.*, Submitted). These song units have been shown to vary geographically (Cummings and Thompson, 1971; Edds, 1982; Thompson and Friedl, 1982; Alling *et al.*, 1991; Thompson and Cummings, 1996; Stafford *et al.*, 1999; 2001). Preliminary examination of sounds recorded in the presence of Antarctic blue whales and pygmy blue whales in the Southern Hemisphere indicate a similar geographic distribution of long-duration, low-frequency song units (Clark and Fowler, 2001; Ljungblad *et al.*, 1997).

Recordings of pygmy blue whales off Madagascar show repetitive sequences of 10-20s tonal sounds in the 25-45Hz band (Ljungblad *et al.*, 1998). Pygmy blue whale vocalisations recorded off Australia consist of three separate long tonal units in the 18-26Hz band (McCauley *et al.*, 2000). The long-duration sounds recorded in the presence of Antarctic blue whales in the Antarctic consist of patterned sequences of tonal sounds composed of three distinct units. The first tone is centred at 28-29Hz with a duration of 8-12s. A short 2s downsweep from 28-20Hz connects the first tonal unit to the third, a slightly modulated tone (20-18Hz), that is approximately 8-12s in duration (Ljungblad *et al.*, 1998). The three-unit vocalisation, or phrase, is usually repeated

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every 70-80s, at intervals between 40-50s (Ljungblad *et al.*, 1998). There is a high degree of variability in the presence and intensity of the three individual units, and therefore we use the terms '3-unit vocalisation' to describe vocalisations with all three units intact, '28Hz downsweep' to describe vocalisations with the first two units intact, and '28Hz tone' to describe vocalisations where only the first unit is intact.

In addition to studying the distinct variation in vocalisations of the two sub-species of blue whale for accurate species identification in the field, knowledge of the behavioural contexts of these sounds is needed for long-term vocal and population studies. The blue whale component of the International Whaling Commission's SOWER (Southern Ocean Whale and Ecosystem Research) programme obtains videos, photographs, biopsies and acoustic recordings of blue whales in the field. This study examines recordings and behavioural information obtained in the presence of blue whales during two seasons of SOWER cruises to provide a preliminary examination of the variability associated with the 3-unit vocalisation, and its effect on blue whale population studies in the Southern Ocean.

METHODS

Data collected by the authors during the 2001/2002 SOWER cruise from the vessel *Shonan Maru* and the 2002/2003 SOWER cruise from the vessel *Shonan Maru No.2* were used for this study. The research area surveyed was in IWC Area V[1] between 130°E-150°E (2001/2002) and 150°E-170°W (2002/2003), and extending from 60°S to the ice edge (Fig. 1). Line-transect visual observations of cetaceans were conducted between 06:00 and 18:00 local time, weather permitting, using a visual observation team consisting of three tiers of experienced observers (Anonymous, 2002b). Summaries of the methods are given in Ensor *et al.* (2002 and 2003). Briefly, the visual observation team was responsible for sighting and positively identifying whales, estimating group sizes and obtaining biopsy samples, video tapes, and photo-identification photographs. An acoustician was responsible for obtaining recordings in the vicinity of blue whales and collecting opportunistic evening recordings.

The primary acoustic recording method used expendable DIFAR (Direction Finding and Ranging) AN/SSQ 53B sonobuoys. These were deployed in close proximity to sighted blue whales and monitored for as long as time permitted for a minimum of 30 minutes. Opportunistic recordings were also made while drifting in the evenings. The sonobuoy radio signal was received *via* the ship antenna, which was coupled to an *ICOM* IC-R100 single channel receiver. This output was connected to a *Sony* DAT TCD-D7 recorder (flat frequency response from 5Hz to 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) and analysis was performed using Spectra-Plus software. All vocalisations attributed to blue whales with a strong signal-to-noise ratio (SNR) from the 2001/2002 season were measured (44.1kHz sample rate, 32768 point FFT size, 90% overlap, Hamming window). Only long-duration calls with a strong SNR from the 2002/2003 season were measured (5512Hz sample rate, 8192 point FFT size, 90% overlap, Hanning window).

All high-quality vocalisations attributed to blue whales were categorised according to their frequency and duration characteristics. The short-duration FM calls included amplitude-modulated downsweeps, high-frequency downsweeps, low-frequency downsweeps, high-frequency upsweeps, low-frequency upsweeps and complex calls. The long-duration sounds included the 3-unit vocalisations, 28Hz downsweeps and 28Hz tonal vocalisations. Measurements were made of lowest frequency, highest frequency, centre frequency (for tonal sounds), start frequency, end frequency, frequency shift, peak frequency, and duration for all vocalisations and vocalisation units. Measurement of the time between the deployment of the sonobuoy and detection of the first 3-unit vocalisation was made to examine feasibility of using these vocalisations for *in situ* species identification.

Temporal patterns of vocalisations were examined for a series of recordings (10.5 hours total) associated with blue whale sightings on 23 January 2003. All times are given as local times at sea. Bearings to each vocalisation were obtained using DIFAR signal processing. This was performed using an automatic *MATLAB* function within Ishmael that executes a series of commands for de-multiplexing the DIFAR signal (software developed by Greenridge Sciences, Inc.), and determines the bearing to a sound source (software designed by M. McDonald). Bearings of individual vocalisations allowed the detection of distinct groups of vocalising whales, so that patterns of vocalisations could be examined within and between groups. It was not possible to use DIFAR to distinguish individuals within groups due to the close association and variable movement patterns of animals. The paucity of recording tapes available during the 2001/2002 season 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 and so bearings could not be obtained for these data.

RESULTS

Recordings were made in the vicinity of 12 blue whale groups (31 animals total) during the 2001/2002 season and in the vicinity of three blue whale groups (11 animals total) for the 2002/2003 season (Table 1). Blue whale sounds were detected during 14 of these 15 groups.

Blue whale encounters

2001/2002

Between 6 and 8 January 2002, a total of nine sightings of blue whales were observed within an area bounded by 64°18'S and 64°29'S and 136°29'E and 137°24'E, near the northern margin of belts of the pack ice. Seven of the groups (totalling 14 animals) were determined to be Antarctic blue whales; photo and/or video and biopsy attempts were made for these groups (Table 1). The eighth was a group of three animals observed at night that was not approached and was classified as undetermined blue whales. A distant group of two animals determined to be 'like' blue whales were sighted outside of a larger congregation of blue whales, but these animals were not approached. During all encounters, sounds attributed to Antarctic blue whales were recorded, although for most encounters these sounds were not detected within the first hour of recording (Table 1).

From 21-31 January 2002, three groups of Antarctic blue whales (totalling 12 animals) and three groups of unidentified blue whales (six animals total) were sighted.

[1] For a description of IWC Areas, see Donovan (1991).

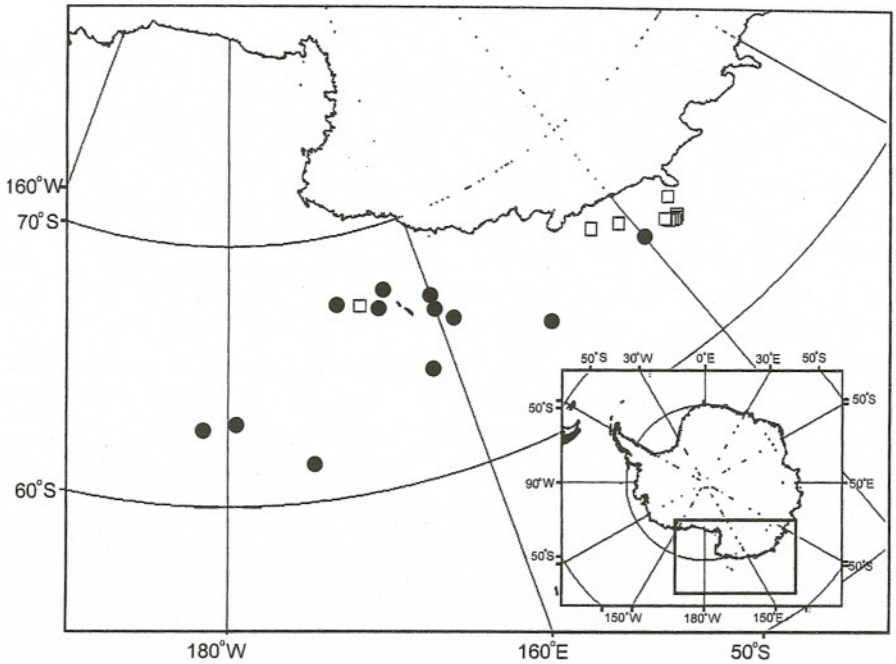

Fig. 1. Locations of acoustic detections of blue whales within the study area. The open squares represent recordings from blue whale sightings; the closed circles represent opportunistic evening sonobuoy stations with blue whale acoustic detections.

Table 1

Blue whale sightings with habitat, presence of vocalisation types and acoustic identification (ID) time. DIFAR confirmation of the location of the sound source was performed for 23/01/03 only; all others are speculative based on sound intensity and presence of other cetaceans. Detection of 'faint' vocalisations suggests that vocalisations were not produced from the sighted blue whales. Operations conducted for each sighting include: P = photo-identification; B = biopsy attempt; V = video; A = acoustic recording. Whale identification includes: True = Antarctic or true blue whale; Und = undetermined blue whale; Like = like-blue whale. Acoustic ID time is the time necessary for acoustic identification of species and is based on the time delay between the deployment of the sonobuoy and the first recorded 3-unit vocalisation.

Date	Sighting number	Group size	Habitat	Operations	3-unit vocalisations	Long tonal vocalisations	Short FM vocalisations	Whale ID	Acoustic ID time
06/01/02	1	2	Pack ice	P, B, V, A	Yes	Yes	Yes	True	>1hr
06/01/02	2	2	Pack ice	P, B, V, A	Yes	Yes	Yes	True	>1hr
06/01/02	3	1	Pack ice	P, B, V, A	Yes	Yes	Yes	True	>1hr
06/01/02	4	2	Pack ice	P, B, V, A	Yes	Yes	Yes	True	>1hr
06/01/02	5	1	Pack ice	P, B, V, A	Yes	Yes	Yes	True	>1hr
07/01/02	2	1	Pack ice	B, V, A	Yes	Yes	Yes	True	50min.
07/01/02	4	3	Pack ice	A	Yes	Yes	Yes	Und	45min.
08/01/02	2	5	Pack ice	P, B, A	None	Faint	Faint	True	-
08/01/02	5	2	Pack ice	A	Faint	Faint	Faint	Like	-
21/01/02	9	3	Ice edge	P, A	None	Yes	None	True	-
29/01/02	1	5	Open water	P, B, V, A	Yes	Faint	Faint	True	50min.
31/01/02	14	4	Open water	P, B, V, A	None	None	None	True	-
23/01/03	11	3	Pack ice	P, B, A	Yes	Yes	Yes	True	30min.
23/01/03	12	5	Pack ice	A	Yes	Yes	Yes	True	30min.
24/01/03	1	3	Pack ice	A	None	None	Yes	True	-

Photos and/or video and acoustic recordings were obtained for all but the undetermined groups of whales, and biopsy attempts were made for the groups identified on 29 and 31 January (Table 1). Very few vocalisations were recorded during these encounters.

2002/2003

On 23 January 2003, two groups of Antarctic blue whales (totalling 8 animals) were sighted in the outer margin of the pack ice, in the vicinity of 67°07'S and 166°54'E (Table 1). All animals appeared to be feeding on krill patches. Photography, biopsy attempts and acoustic recordings were undertaken during this sighting. Acoustic recordings began at 17:10 and continued throughout the night in the location of the scattered blue whale sightings. An additional sighting of three animals was detected in the middle of the night (24 January) and confirmed the continued presence of blue whales in the area. A detailed examination of DIFAR processing of the acoustic behaviour of these groups is described below.

Characteristics of blue whale vocalisations

A total of 85 hours of recordings were made from the *Shonan Maru* during the 2001/2002 cruise, with over 33 hours of recordings in areas of blue whale sightings. All recordings were monitored for the presence of sounds that could be attributed to blue whales, and over 42 hours of recordings contained blue whale vocalisations. A total of 193 short FM vocalisations and 261 long-duration tonal vocalisations (including 3-unit, 28Hz downsweep and 28Hz tonal vocalisations) were measured from the recordings for this survey.

A total of 38.7 hours of recordings were made from the *Shonan Maru No.2* during the 2002/2003 survey, including 11 hours in the vicinity of blue whale sightings. Sounds that could be attributed to blue whales were detected in nearly 26 hours of recordings, however only recordings associated with sightings were examined. A total of 92 long-duration tonal vocalisations with high SNRs were measured from this survey; short FM vocalisations were recorded, but not measured.

The most common short-duration FM vocalisation was the simple high-frequency downsweep from 76.3-40.0Hz, with a mean signal duration of 2.7 seconds (*n*=132, Table 2, Fig. 2(a)). The amplitude-modulation found in the pulsed downsweep appeared to be caused by propagation, and the basic frequency and duration characteristics closely resemble those of the high-frequency downsweep (Fig. 2(b)). The low-frequency downsweep (*n*=4), low-frequency upsweep (*n*=7) and high-frequency upsweep sounds (*n*=4) were relatively uncommon compared to the high-frequency downsweep vocalisations (Table 2).

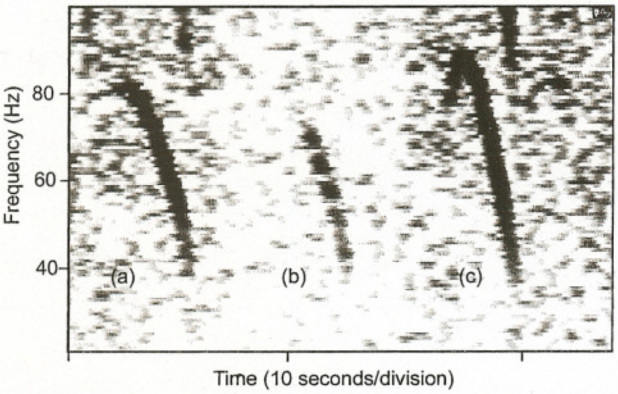

Fig. 2. Spectrogram of the most common short-duration FM vocalisations (5kHz sample rate, 2048 point FFT): (a) high-frequency downsweep; (b) amplitude-modulated downsweep; and (c) a complex variation of the high-frequency downsweep.

Although the complex sounds were variable in nature, several similar types were frequently observed. The most common complex vocalisations were variations on the high-frequency downsweep, with one or more inflection points (Fig. 2(c)). Other less common complex vocalisations are short, high-frequency downsweeps, variable FM sounds and 'concave' sounds (Fig. 3).

The long-duration calls were divided into three categories as described in the Introduction: the 3-unit vocalisation; the 28Hz downsweep; and the 28Hz tone (Fig. 4). The 3-unit

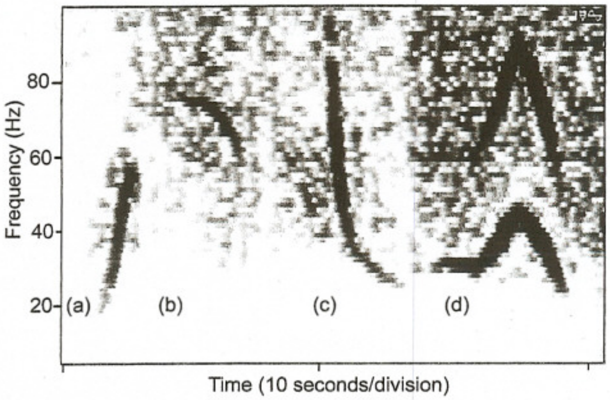

Fig. 3. Spectrogram of uncommon short-duration FM vocalisations (5kHz sample rate, 2048 point FFT): (a) high frequency upsweep; (b) short high frequency downsweep; (c) variable high frequency downsweep; and (d) concave vocalisation.

vocalisation consisted of a tone at 27.7Hz lasting an average of 8.3 seconds, occasionally followed by a brief downsweep of variable duration, to a typically FM moan from 19.5-19.1Hz with an average duration of 6.9 seconds (Table 3). The 28Hz downsweep consisted of a moan at 27.7Hz of a variable duration followed by a downsweep to approximately 19.1Hz. Measurements of the entire sample of vocalisations ('All') were compared with a sub-sample of high-quality vocalisations ('Best'); the centre and peak frequency of the 28Hz tone varied little, regardless of the vocalisation type or signal quality. For vocal animals, at least 30 minutes elapsed between sonobuoy deployment and initial detection of vocalisations associated with the Antarctic blue whales (defined as the acoustic identification time) (Table 1).

DIFAR analyses of vocalisations

DIFAR analyses of recordings from 23 January 2003 allowed differentiation between the calls from several groups of blue whales (sightings 11 and 12; Fig. 5). Determination of the bearing angles to the sound source using DIFAR analysis was performed on 1,069 vocalisations (208 long-duration, 861 short-duration) during the 11 hours of recordings. Close association of several animals within a group prevented identification of the vocalising animal in most cases; sound source for all sightings is for the group and not an individual animal (where group size >1). The similar DIFAR bearing angles of the blue whales (160°) and the ship (167°) at 17:45 indicate that animals biopsied at this time were vocalising (Fig. 5(a)). The discontinuity in the ship's course at 18:15 (Fig. 5(b)) occurred as the ship returned to course and speed after biopsy sampling;

Table 2

Summary of frequency measurements and signal duration of simple short-duration FM vocalisations measured in the presence of blue whales during the 2001-2002 season (48kHz sample rate, 32,768 point FFT). Due to the variation inherent in the complex FM vocalisations, frequency characteristics and signal duration where not measured. AM downsweep calls are considered here for comparison with the high-frequency downsweep calls.

	Start frequency (Hz)			End frequency (Hz)			Frequency change (Hz)			Signal duration (s)		
Sound type (sample size)	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
High-frequency downsweep (132)	76.3	11.5	48.5-106.9	40.0	7.5	22.1-58.4	36.2	10.6	11.7-65.6	2.7	0.9	0.8-7.5
AM downsweep (46)	73.7	5.9	60.1-85.4	41.0	6.0	23.3-52	32.7	6.5	22.1-48.6	2.5	0.7	1.1-5.9
Low-frequency downsweep (4)	29.8	0.6	28.9-30.3	19.1	0.6	18.1-19.5	10.7	1.1	9.4-12.2	3.0	0.8	2.4-4.3
High-frequency upsweep (4)	23.2	9.4	16.7-36.9	57.4	6.5	49-64.9	34.2	5.2	28-40.1	1.6	0.2	1.4-1.9
Low-frequency upsweep (7)	14.7	1.0	12.9-15.4	24.5	2.0	20.8-27.6	9.7	1.9	7.9-13.5	3.8	1.2	1.6-5.5

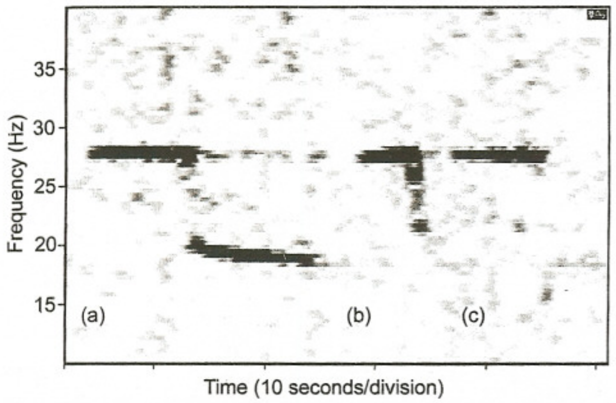

Fig. 4. Spectrogram of three long-duration blue whale vocalisations associated with different Antarctic blue whales (48kHz sample rate, decimation ratio 4:1, 32768 point FFT): (a) 3-unit vocalisation including 28Hz tone followed by an inter-tone interval and a 19Hz tone; (b) 28Hz tone plus downsweep; and (c) a 28Hz tone. All were sufficiently intense to suggest detection of the entire signal.

excessive noise during this manoeuvre temporarily precluded DIFAR processing. At 18:15 the ship's true course of 5° closely matched that determined by the sonobuoy. At 18:45 the ship's course crossed 0° in front of the sonobuoy.

Movement of the ship and the subsequent loss of the sonobuoy signal led to a gap in the recordings from 19:00 until 23:00. Recordings continued while the vessel was drifting for the remainder of the night, and DIFAR bearing angles suggest that a large congregation of vocalising blue whales separated into two distinct groups at about 00:30 (Fig. 6(a)). At 01:20 on 24 January a group of three blue whales (Fig. 6(b), 350°) were seen feeding next to the ship. DIFAR angles show that this group may have produced occasional short-duration FM vocalisations, but was not a part of either consistently vocalising group (40° and 150°).

Between 00:39 and 02:49 the sounds from the two simultaneously vocalising blue whale groups (denoted A and B) had a high SNR and well-defined DIFAR bearing angles. Both short-duration FM and long-duration tonal vocalisations from the two groups were plotted over time to identify patterns in temporal variation (Fig. 7). However, there was no apparent temporal pattern for the short-duration or long-duration 28Hz vocalisations. An expanded view of the common high-frequency downsweeps (HFDN) does not suggest countercalling between groups A and B.

DISCUSSION

This study shows that the 3-unit vocalisation is a geographically distinct call associated with Antarctic blue whales in the Southern Ocean south of 60°S. The 3-unit vocalisations recorded during 2001/2002 are consistent with previous results for sounds attributed to Antarctic blue whales in the Antarctic (Anonymous, 2002a; Clark and Fowler, 2001; Ljungblad *et al.*, 1998). The dataset presented here represents the largest analysis to date of these calls. None of the characteristic sounds attributed to pygmy blue whales in Madagascar (Ljungblad *et al.*, 1998) or Chile (Cummings and Thompson, 1971) were detected in the 247 hours of recordings. During the two cruises, all whales visually identified at the sub-species level were considered to be Antarctic blue whales. Genetic analysis of biopsies obtained on these cruises is underway and will hopefully confirm that these sounds were indeed produced by Antarctic blue whales. The association of specific calls exclusively to Antarctic blue whales provides a step towards *in situ* acoustic sub-species identification. As noted earlier, real-time identification currently relies on visual inspection by experienced observers. However, whales do not vocalise continuously, which limits the value of the technique. In addition, should time be limited, identifications in real-time may not be feasible due to the processing time required for a single identification. Nonetheless, the technique is a valuable tool, particularly when used in conjunction with genetic analysis and visual identification methods.

To use vocalisation for species identification one must be able to positively detect the call. There appears to be variability in the presence and characteristics of the 2nd (inter-tone downsweep) and 3rd (19Hz tone) unit of this vocalisation (Table 3). It is clear that blue whales produce both 28Hz tonal and 28Hz downsweep vocalisations, in addition to the 3-unit calls previously examined. Even with a high SNR, an overlap of the multi-path signals of long-

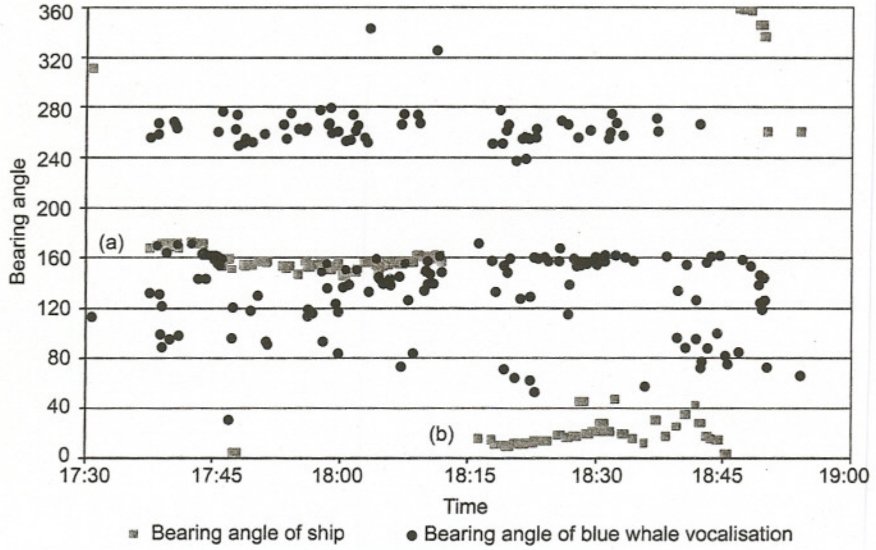

Fig. 5. DIFAR bearings for blue whales during biopsy attempts for sighting number 11 on 23 January 2003. Two distinct groups could be identified, one at 260° and the other at 160°. All magnetic bearing angles were converted to true angles for comparison.

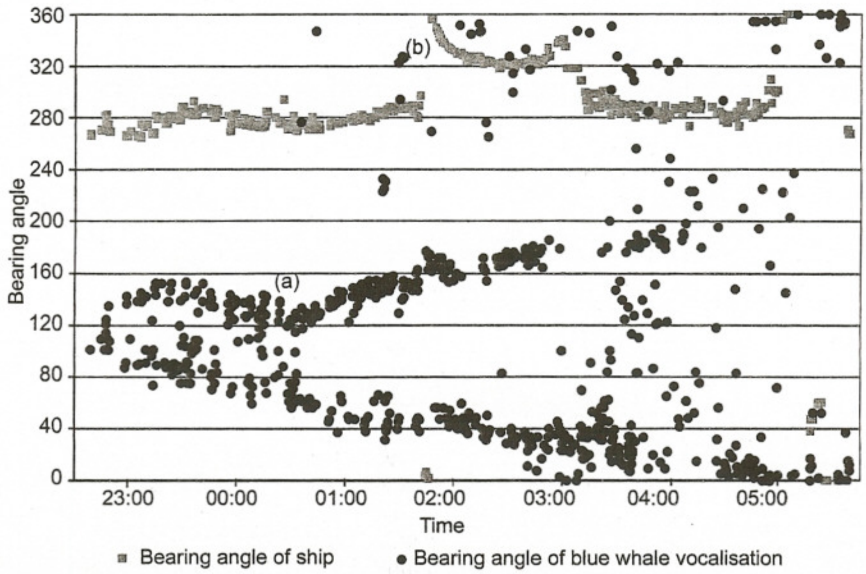

Fig. 6. DIFAR bearings for blue whales during evening recording in location of sighting numbers 11 and 12 for 23 January 2003 and sighting number 1 on 24 January 2003. All magnetic bearing angles were converted to true angles for comparison. The discontinuities in the ships' bearing angle are associated with repositioning.

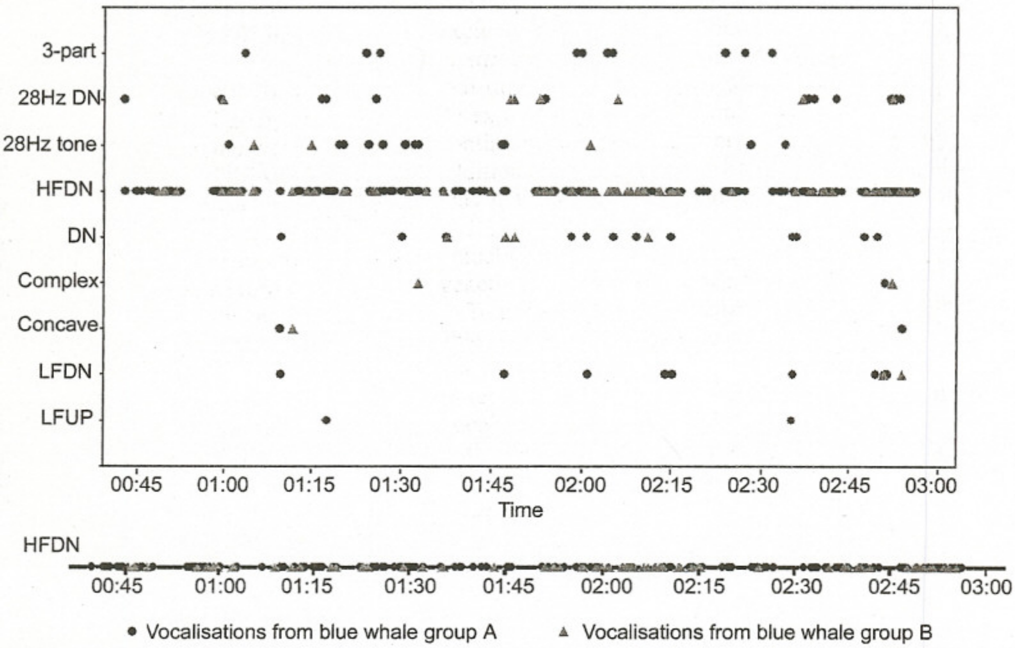

Fig. 7. Temporal variation of vocalisation types for the two blue whale groups from 00:30 until 3:00, 24 January 2003. An expanded view of HF DN vocalisations is provided for clarity. HF=high frequency; LF=low frequency; DN=downsweep; UP=upsweep.

duration calls can make it difficult to determine the characteristics of individual sounds. With increasingly faint vocalisations, it may be difficult to distinguish the 3-unit vocalisations from the 28Hz tonal and 28Hz downsweeps. The primary consistent feature is the tone centred at 27.7Hz; peak frequency varies little among these three vocalisations regardless of the signal intensity. If all three long-duration 28Hz vocalisations can be positively, and exclusively, linked to Antarctic blue whales, then this research suggests that it may be possible to attribute any long (6-12s) 28Hz tonal vocalisation south of 60°S to Antarctic blue whales. Research to date suggests this to be the case. Sub-species identification based on detection of the 28Hz tonal vocalisation is feasible for most groups of Antarctic blue whales, assuming a minimum one hour recording time. Future efforts should include deployment of sonobuoy arrays to localise calling animals so that comparisons with visual detection and genetic sampling of individual calling animals can be conducted.

Previous studies suggested that the long-duration, low-frequency sounds produced by blue whales are songs (Anonymous, 2002a), or patterned series of repeated vocalisations. The 2.5 hour sample of two vocalising groups within the larger congregation of scattered blue whales, recorded on 23 January 2003, does not suggest that the vocalisations were repeated in patterned series within a given group, or between the two groups (Fig. 7). The comparisons of vocalisations with the various blue whale

Table 3

Summary statistics of frequency measurements and signal duration for long-duration low-frequency vocalisations (5,512Hz sample rate, 8,192 point FFT). For each vocalisation type, all measured vocalisations are presented in the left column, while a sub-sample of the clearest vocalisations are presented for comparison in the column on the right. The sample sizes for all vocalisation types are given in parentheses.

		3-unit		28Hz down		28Hz tone	
		All (66)	Best (22)	All (70)	Best (19)	All (217)	Best (16)
First unit							
Centre frequency (Hz)	Mean	27.7	27.7	27.7	27.8	27.6	27.8
	SD	0.3	0.2	0.3	0.3	0.2	0.3
	Range	25.5-28.3	27.2-28.3	27.2-29.2	27.2-28.8	26.7-28.6	27.5-28.6
Signal duration (s)	Mean	8.7	8.3	5.9	6.3	7.9	7.2
	SD	1.7	1.5	1.9	1.9	2.2	2.2
	Range	4.1-13	5.3-11.2	2.2-10.2	3.1-9.7	2.7-18.8	3.6-11.5
Spectral peak (Hz)	Mean	27.9	27.8	28.0	28.0	28.0	27.8
	SD	0.4	0.2	0.4	0.2	0.3	0.4
	Range	26.8-29.2	27.4-28.3	26.8-29.5	27.7-28.3	26.8-28.3	26.8-28.3
Downsweep							
Low frequency (Hz)	Mean	19.8	20.0	20.0	19.1	-	-
	SD	0.9	0.8	1.7	1.6	-	-
	Range	18.1-22.5	18.3-21.8	16.9-23.8	16.9-23.5	-	-
Frequency shift (Hz)	Mean	7.3	6.9	7.5	8.4	-	-
	SD	1.3	1.3	1.7	1.5	-	-
	Range	4.4-9.5	4.4-8.8	4.0-11.5	4.5-11.5	-	-
Signal duration (s)	Mean	0.7	0.5	1.2	1.3	-	-
	SD	0.3	0.1	0.4	0.5	-	-
	Range	0.2-1.5	0.2-0.9	0.3-2.2	0.3-2.1	-	-
Third unit							
Start frequency (Hz)	Mean	19.4	19.5	-	-	-	-
	SD	0.4	0.5	-	-	-	-
	Range	18.6-21.2	18.8-21.2	-	-	-	-
End frequency (Hz)	Mean	19.1	19.1	-	-	-	-
	SD	0.5	0.6	-	-	-	-
	Range	17.9-21.2	18.2-21.2	-	-	-	-
Frequency shift (Hz)	Mean	0.3	0.4	-	-	-	-
	SD	0.5	0.5	-	-	-	-
	Range	0-2.0	0-2.0	-	-	-	-
Signal duration (s)	Mean	7.3	6.9	-	-	-	-
	SD	3.4	3.9	-	-	-	-
	Range	1.2-13.5	1.2-12.3	-	-	-	-
Spectral peak (Hz)	Mean	19.1	19.1	-	-	-	-
	SD	0.4	0.4	-	-	-	-
	Range	18.7-20.5	18.7-20.5	-	-	-	-

sightings (Table 3) suggest that there is considerable variation in the vocal behaviour of different groups. The sightings in the 2001/2002 study differed in group size, behaviour and habitat. Unfortunately, the locations of vocalising animals in relation to the sonobuoy could not be determined due to problems in recording the DIFAR signal. This severely limited our ability to examine temporal patterns, or the presence of song during the 2001/2002 cruise. Further research combining visual and acoustic studies (with functional DIFAR) on different blue whale groups is necessary to understand the circumstances in which the temporal patterns considered to be 'song' are produced.

Successful use of bottom-mounted hydrophones to monitor whale song in the Pacific (McDonald *et al.*, 1995; Stafford *et al.*, 1999) and Atlantic Oceans (Clark, 1995) led to deployment of similar hydrophones in the Southern Ocean to monitor the blue whale population year-round (Sirovic *et al.*, 2004). Minimum abundance can be estimated through noting the ranges of individual singing whales; however, our results suggest that only a small proportion of the blue whale population may be singing. The ability to relate geographically distinct vocalisations (song units) to an index of abundance relies heavily on their behavioural contexts. These concerns are essentially the same as those for using acoustics as a method for species identification.

The short FM vocalisations recorded here are similar to sounds associated with blue whales in other regions. With the exception of the high-frequency downsweep, most short FM vocalisations are uncommon. Groups of vocalising whales were noted to produce both short-duration FM and long-duration 28Hz vocalisations. During extended biopsy attempts during the 2001/2002 survey there was an apparent overall increase in vocalisations. The inability to confirm the vocalising group using DIFAR software limits this to a simple speculation. This should be examined for other close approaches, as this may influence the ability of acoustics to determine species identification.

Clearly there is great variation in the vocal behaviour of different blue whale groups; however, we cannot yet explain these differences. The structure of the 3-unit vocalisation appears to be highly variable, but 27.7Hz peak frequency is stable even over great distances. The 3-unit vocalisations, and the other 28Hz vocalisations do not always occur in patterned series or 'songs', and some whale groups are not vocal. More information must be gathered on the variations in vocalisations by age, sex, season, time of day, group composition and behaviour. These data can only be obtained by integrated *in situ* studies of blue whales.

The IWC has stated that there is a need for a dedicated blue whale study in the Southern Ocean to combine visual and acoustics surveys with biopsy, photo-identification and satellite tagging of individuals in order to determine the winter breeding grounds. Blue whales have been known to frequent the ice edge between 150°E and 165°E (Kato *et al.*, 1995). The relatively high populations of blue whales in this area during the 2001/2002 and 2002/2003 confirm that this is an ideal location for deployment of a series of bottom-mounted hydrophones for recording of vocalisations, coinciding with future shipboard populations surveys.

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