Baleen whales in the Scotia Sea during January and February 2003

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ABSTRACT

Different species of baleen whales display distinct spatial distribution patterns in the Scotia Sea during the austral summer. Passive acoustic and visual surveys for baleen whales were conducted aboard the RRS *James Clark Ross* in the Scotia Sea and around South Georgia in January and February 2003. Identified calls from four species were recorded during the acoustic survey including southern right (*Eubalaena australis*), blue (*Balaenoptera musculus*), fin (*B. physalus*) and humpback whales (*Megaptera novaeangliae*). These acoustic data included up calls made by southern right whales, downswept D and tonal calls by blue whales, two possible types of fin whale downswept calls and humpback whale moans and grunts. Visual detections included southern right, fin, humpback and Antarctic minke whales (*B. bonaerensis* sp.). Most acoustic and visual detections occurred either around South Georgia (southern right and humpback whales) or south of the southern boundary of the Antarctic Circumpolar Current (ACC) and along the outer edge of the ice pack (southern right, blue, humpback and Antarctic minke whales). Fin whales were the exception, being the only species acoustically and visually detected primarily in the central Scotia Sea, along the southern ACC front. In addition to identifiable calls from these species, two types of probable baleen whale calls were detected: 50Hz upswept and pulsing calls. It is proposed that minke whales may produce the pulsing calls, based on their similarities with minke whale calls recorded in the North Atlantic Ocean. There was an overlap between locations of fin whale sightings and recordings and locations of 50Hz upswept calls in the central Scotia Sea, but these calls were most similar to calls attributed to blue whales in other parts of Antarctica. More study is required to determine if baleen whales produce these two call types, and if so, which species. The efficiency of acoustics and visual surveys varied by species, with blue whales being easier to detect using acoustics, Antarctic minke whales being best detected during visual surveys and other species falling in between these two extremes.

KEYWORDS: BALEEN WHALES; SURVEY-ACOUSTIC; SURVEY-VESSEL; ANTARCTIC; SOUTHERN RIGHT WHALE; BLUE WHALE; FIN WHALE; HUMPBACK WHALE; ANTARCTIC MINKE WHALE; OCEANOGRAPHY

INTRODUCTION

South Georgia was one of the prime commercial whaling grounds in the early 20th century and during this time most stocks of baleen whales were depleted from the area (Moore *et al.*, 1999). According to International Whaling Commission (IWC) records, the total numbers of baleen whales taken from Area II (which encompasses the area from 0 to 60°W south of 40°S, including South Georgia and the Scotia Sea; see Fig. 1a) since 1931 were 518 southern right (*Eubalaena australis*), 32,810 blue (*Balaenoptera musculus*), 149,678 fin (*B. physalus*) and 1,305 humpback whales (*Megaptera novaeangliae*). These data, however, do not include Soviet catches since World War II, which were often falsely reported until the 1990s, slightly overestimating blue and fin whale and grossly underestimating humpback whale catches (Yablokov, 1994). While there are no current population estimates for Area II, the total whale sightings during four summer-season IWC cruises in Area II in the 1980s and 1990s (Branch and Butterworth, 2001a) were 14 southern right, 18 blue, 31 fin, 38 humpback and 1,621 Antarctic minke whales (*B. bonaerensis* sp.).

The focus of the JR82 cruise aboard the RRS *James Clark Ross* was to study the large scale distribution and transport of Antarctic krill (*Euphausia superba*), as well as ecosystem dynamics of the Scotia Sea (Anon., 2003). The study area links two well studied and krill-rich regions of the Southern Ocean, the Antarctic Peninsula and South Georgia, that have been the focus of ecosystem research since the Discovery expeditions of the 1930s (e.g. Mackintosh, 1936). In the Scotia Sea, the Antarctic current system loops north, steered away from the winter pack ice zone by the bathymetry and the Antarctic Peninsula land mass projection (Orsi *et al.*, 1995). This region features both high rates of primary productivity and high densities of krill in spring and summer (El-Sayed and Weber, 1982; Priddle *et al.*, 1988; Hewitt *et al.*, 2004; Holm-Hansen *et al.*, 2004). In addition to the work in the Scotia Sea, the cruise included a fine-scale sampling section near South Georgia, in the Western Core Box (WCB), part of the British Antarctic Survey's (BAS) long-term fine-scale ecological monitoring program (Reid *et al.*, 2000).

The goal of the marine mammal acoustic monitoring programme during JR82 was to conduct an along-track passive acoustic survey for cetaceans using opportunistic deployments of sonobuoys. These recordings can provide insight into the acoustic repertoire as well as the spatial distribution of various species of cetaceans. The acoustic survey was focused on southern right, blue, fin, humpback and minke whales, since calls from these species have not previously been reported in this area. In other locations, each species produces distinctive low-frequency (<1kHz) calls, which are the only calls that have been analysed in this study. During daylight hours there was concurrent visual survey for cetaceans conducted by a team of two experienced IWC observers.

The majority of previous cetacean visual surveys in the Scotia Sea have been conducted under the auspices of the IWC in collaboration with German, US and UK polar and multidisciplinary research programmes, e.g. as part of Commission for the Convention on Antarctic Marine Living Resources (CCAMLR) and Southern Ocean Global Ocean Ecosystem Dynamics (SO-GLOBEC) studies (Kasamatsu *et al.*, 1988; 1996; Pankow and Kock, 2000; Reid *et al.*, 2000; Secchi *et al.*, 2001; Reilly *et al.*, 2004). Generally, blue and

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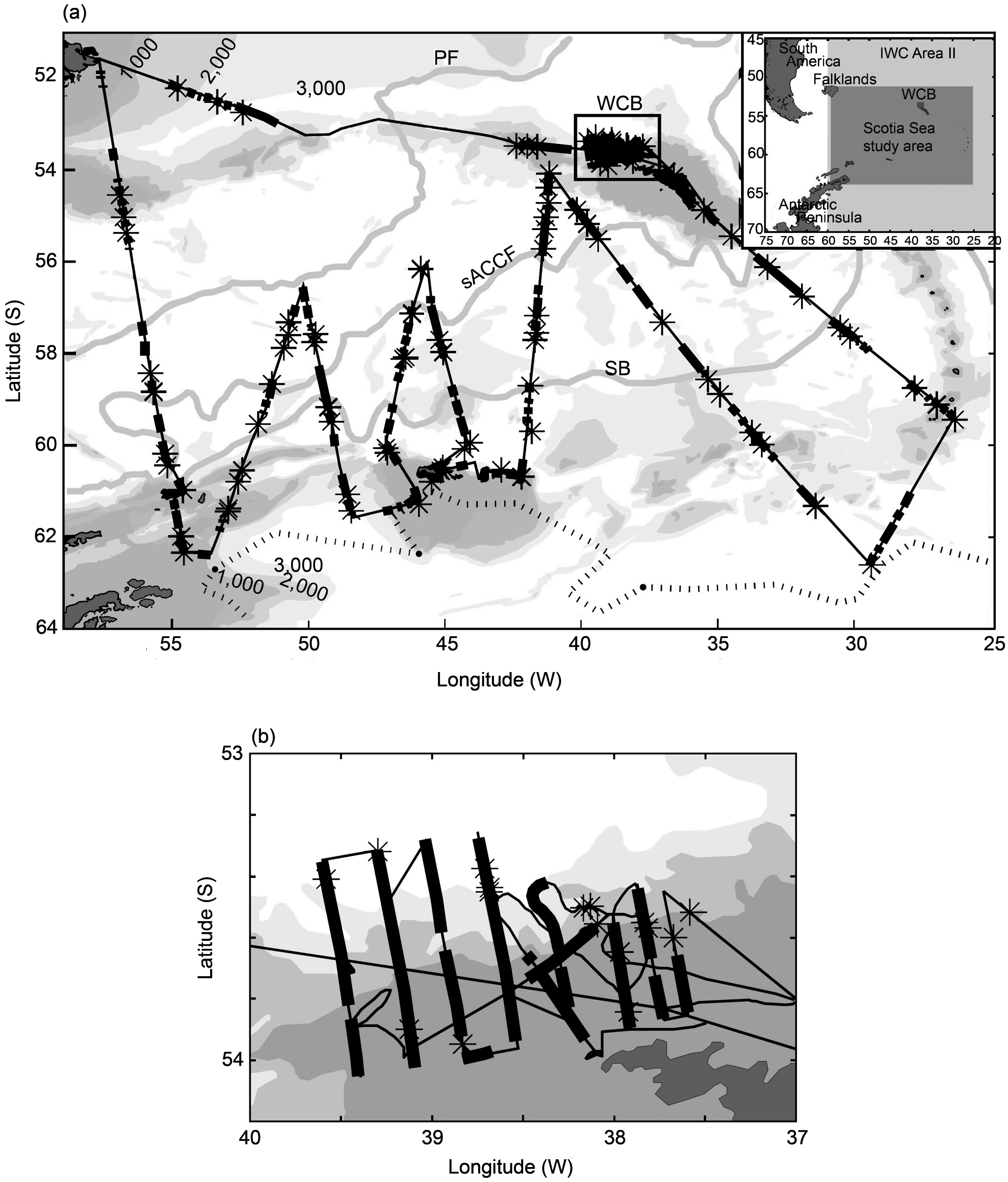

Fig. 1. Cruise track across (a) the Scotia Sea and (b) the Western Core Box (WCB), with locations of sonobuoy deployments (stars) and tracks of visual survey effort (thick line segments). Bathymetry is shaded in 1,000m isobath increments and land is the darkest shading. Thick grey lines represent major fronts in the area, after Orsi *et al.* (1995): PF = polar front; sACCf = southern Antarctic Circumpolar Current front; SB = southern boundary of the ACC. The broken black line is the inferred ice edge (15% cover) on 1 February 2003 from the NSIDC satellite image. Inset image shows a larger area including nearby continents and indicating locations of surveys, as well as IWC Area II.

Antarctic minke whales are known to occur further south than fin whales, which are not commonly associated with sea ice; humpback whales can occur over a range of latitudes and southern right whales occur near island groups (Kellogg, 1929; Kasamatsu *et al.*, 1988; 1996; Moore *et al.*, 1999). Whaling records also indicate that blue, fin and humpback whales associate with the southern boundary of the Antarctic Circumpolar Current (ACC; Tynan, 1998). All of these species have been sighted previously in the Scotia Sea. Fin whale sightings occurred further to the north of humpback whales in the vicinity of Elephant Island in December 1996 (Pankow and Kock, 2000). Minke whale sightings were common east of the Antarctic Peninsula, while humpback whale sightings were common around South Shetlands and South Georgia in surveys conducted from 1997 to 2000 (Secchi *et al.*, 2001; Reilly *et al.*, 2004).

Call characteristics

Calls of some baleen whale species have been studied extensively (reviewed in Richardson *et al.*, 1995). Calls from southern right whales off Argentina have been described by many authors (e.g. Cummings *et al.*, 1971; 1972; Payne and Payne, 1971; Clark, 1982; 1983). The most commonly described southern right whale call is the up call, sweeping in frequency from 50 to 200Hz and lasting 0.5-1.5s. This call has been associated with swimming animals and appears to be a contact call (Clark, 1983). Blue whales make low frequency (below 100Hz), long duration (10-20s), repetitive calls that vary between regions (Kibblewhite *et al.*, 1967; Edds, 1982; Alling *et al.*, 1991; Stafford *et al.*, 1998; McDonald *et al.*, 2006) and they also produce a shorter and less stereotyped call (D call) whose general characteristics are consistent between regions (Thompson *et* *al.*, 1996; Thode *et al.*, 2000; McDonald *et al.*, 2001; Mellinger and Clark, 2003; Rankin *et al.*, 2005). There are no blue whale recordings from the South Atlantic Ocean, but blue whale calls have been recorded south of 60°S in the region between 0-30°W and at 38°W in the Weddell Sea (Ljungblad *et al.*, 1998; Clark and Fowler, 2001). These calls consist of three segments: a 28Hz tone that lasts approximately 8s, immediately followed by a short (1s) downsweep to 19Hz and a slightly downswept tonal from 19 to 18Hz, lasting about 8s. The same type of call has been reported at other locations around Antarctica (Matsuoka *et al.*, 2000; Širović *et al.*, 2004; Rankin *et al.*, 2005), although all three components may not always be present. Rankin *et al.* (2005) suggested the '28Hz tonal' is the identifying feature. Fin whales produce regular, short (1s duration) downsweeps ranging in frequency from approximately 40 to 15Hz, the exact frequency range and repetition rate dependant on the geographic location (Thompson *et al.*, 1992). These calls occur throughout the Northern Hemisphere (Watkins, 1981; Edds, 1988; McDonald *et al.*, 1995), but the only report from the Southern Hemisphere is from the Western Antarctic Peninsula (Širović *et al.*, 2004). Stafford *et al.* (1999) recorded pulse series similar to calls produced by fin whales south of the equator in the eastern tropical Pacific, however fin whale sightings are rare in this area (Wade and Gerrodette, 1993). There have also been reports of higher frequency (75-40Hz) calls produced by fin whales from the North Atlantic (Watkins, 1981).

Humpback whales are acoustically among the best studied baleen whale species (e.g. Payne and McVay, 1971; Winn and Winn, 1978; McSweeny *et al.*, 1989; Clapham and Mattila, 1990; Helweg *et al.*, 1998; Cerchio *et al.*, 2001). Even though songs from low-latitude breeding grounds have been the focus of most research, there is evidence of singing from high-latitude feeding grounds (Mattila *et al.*, 1987; McSweeny *et al.*, 1989; Clark and Clapham, 2004). In the Southern Hemisphere, recent acoustic work on humpback whales has included Atlantic, Indian and Pacific waters (Helweg *et al.*, 1998; Noad *et al.*, 2000; Cato *et al.*, 2001; Razafindrakoto *et al.*, 2001; Darling and Sousa-lima, 2005). Leaper *et al.* (2000) reported 'moan' type calls from humpback whales off South Georgia, but otherwise humpback whale calls in the Antarctic are under-sampled. Antarctic minke whales in the Ross Sea produce very short downsweeps (~0.3s) that have variable starting and ending frequencies, generally between 130 and 60Hz (Schevill and Watkins, 1972; Leatherwood *et al.*, 1981). Other minke whale recordings from the Southern Hemisphere are not of the Antarctic minke, but of the dwarf minke whale (*B. acutorostrata*) from lower latitudes and generally include more complex and higher frequency calls (Gedamke *et al.*, 2001). No calls from any of these species have been reported previously from the Scotia Sea since past acoustic surveys in the area focused on frequencies higher than 300Hz and did not focus on baleen whales (Leaper and Scheidat, 1998; Leaper *et al.*, 2000). Although knowledge of baleen whale calling in this area is scant, whaling data indicate that it was once a very productive whaling ground and that it was historically abundant in baleen whales (Kellogg, 1929; Mackintosh, 1966; Horwood, 1986).

METHODS

The JR82 cruise departed Stanley, Falkland Islands, on 7 January 2003. Eight long transects across the Scotia Sea from north of the southern Antarctic Circumpolar Current front (sACCf) to approximately 63°S were completed during the first part of the cruise along 4,300 miles of transect (Anon., 2003). During the second stage of the cruise, four pairs of 80km transects were conducted in the WCB (Fig. 1b). Data collected during the cruise included: conductivity-temperature-depth profiles, expendable bathythermograph profiles, acoustic Doppler current profiler data, nutrient analyses, phytoplankton biomass, primary production, krill abundance and growth. Sonobuoys were deployed when marine mammals were visually detected, prior to arrival to oceanographic stations, as well as occasionally throughout the cruise. The visual survey was conducted during daylight hours when weather conditions were favourable. The JR82 cruise ended on 23 February 2003 in Stanley, Falkland Islands.

Acoustic survey

Two types of sonobuoys were used during this cruise due to their differences in direction-finding capabilities and frequency response characteristics. Omnidirectional sonobuoys (AN/SSQ-57B) have a broadband frequency response of 10-20,000Hz, but it is not possible to determine the direction of the sound source using individual omnidirectional sonobuoys. DIFAR (directional frequency analysis and recording; AN/SSQ-53D) sonobuoys, in contrast, have directional detection capabilities within individual sonobuoys and a frequency response of 10-2,400Hz. Sound bearing relative to the sonobuoy can be determined from direction sensors and an internal compass located within the sensor package of the DIFAR sonobuoys (McDonald, 2004). Sonobuoy specifications require the bearing error to be less than 10°. Using these bearings, acoustic data can be correlated to visual observations of marine mammals.

Custom electronics and software were used to record and analyse the sonobuoy data. The antenna used for the reception of the sonobuoy radio signal during the cruise was a 160MHz omnidirectional *Cushcraft Ringo Ranger* ARX-2B. The maximum range for the radio transmission during the cruise was approximately 8 n.miles, but was variable dependant on weather conditions. A software controlled *ICOM* IC-PCR1000 scanner radio receiver, modified to provide improved low frequency response, for reception of sonobuoy signal (frequency response from 10-1,000Hz ±1dB) was used. Data were recorded continuously on digital audiotapes while receiving the signal using a *Sony* PCM-M1 digital audio recorder (frequency response from 20-22,000Hz ±1.0dB at 48kHz sample rate) and reviewed in real-time using the *SpectraPlus* software package. When DIFAR sonobuoys were deployed, bearings to interesting sounds were calculated in real-time using Greeneridge Sciences DIFAR demultiplexing software and beam forming code developed by M. McDonald. Upon each deployment the following were recorded: time, latitude, longitude and depth at deployment; sonobuoy type, channel, time and depth settings; speed of the ship; and the reason for deployment. After deployment, the sonobuoys transmitted their radio signal to the underway ship for a maximum of 8h before scuttling and sinking.

During the post-processing analyses, recordings of interest were reviewed using *SpectraPlus* with 32,768-point Fast Fourier Transform (FFT), 90% overlap and a Hanning window. Periods that were not monitored in real-time during the cruise were reviewed. Frequency and temporal characteristics were measured for calls with a good signal-to-noise ratio (SNR) using the above spectral parameters. For southern right whale up calls, both types of fin whale calls, blue whale D calls and 50Hz upswept calls, the starting and ending frequency and the duration of the calls were measured. The middle point of the tonal frequency was measured for blue whale calls along with the duration of the call and it was also noted if the downswept part of the call was present. Intercall interval was measured for blue whale 28Hz tonal, fin whale low and high frequency and 50Hz upswept calls. For pulsing calls, the energy band over which pulsing occurred was measured and the pulse duration and rate were calculated. The averages and standard deviations for all call characteristics were reported. Due to the variability in the duration of blue whale D calls, the duration range was also reported and the locations at which different call types occurred were plotted. *Ishmael* software (Mellinger, 2001) was used for verification of bearing calculations, as well as the calculation of bearings to additional calls. All reported bearings are in true degrees. Data were decimated before making spectrograms of representative calls.

The noise levels from the RRS *James Clark Ross* were generally low and decreased as the ship moved away from the sonobuoy. The noise did not affect the quality of recordings, except when using the bow thrusters at stations. As most of the cruise took place in ice-free waters, there was no ice breaking noise to decrease the SNR. The data from periods when the noise of the ship was too loud to distinguish possible calls were not used for analyses.

Comparison with visual survey

Acoustic data were compared to the visual sightings data (the two data sets, however, were not collected independently). Two experienced observers conducted the visual survey during all daylight hours according to a standard line transect methodology for cetaceans (Buckland *et al.*, 2001). Each observer's search area included a 90° arc from the trackline to abeam of the ship and extending all the way to the horizon. Search was conducted in passing mode with *Fujinon* 7×50 binoculars from the bridge roof (eye height 18.3m). *Nikon* 10×50 binoculars were available for species identification and group size estimation. Sightings data were entered into a laptop computer running the *WinCruz* software program, recording casual-effort and off-effort sightings separately. Sightings data reported here were collected while observers were on full-effort, unless otherwise stated. For fin and southern right whales the sightings of 'like fin' and 'like right whale' were pooled together with the confirmed sightings of their respective species. For minke whales, sightings of the following categories were pooled: 'minke (ordinary)'; 'like minke'; 'like ordinary minke'; 'undetermined minke'.

Acoustic and visual data were compared to oceanographic and sea ice data. The positions of mean locations of three main oceanographic fronts (Polar Front, PF; sACCf; and the southern boundary of the ACC, SB) were obtained from Orsi *et al.* (1995). The location of the ice edge (defined as 15% or less sea ice cover) on 1 February 2003 was determined from the National Snow and Ice Data Centre (NSIDC) daily sea ice concentration satellite image with 25km resolution (Comiso *et al.*, 1991). Locations of these features were plotted on the same maps as the locations of visual and acoustic whale detections for qualitative comparison.

RESULTS

A total of 107 sonobuoys (80 omnidirectional and 27 DIFAR) were deployed during the JR82 cruise and there were 167 hours total of acoustic effort (Figs 1a and 1b). Of the deployed sonobuoys, four DIFARs and 12 omnidirectionals failed (15% failure rate for each type). Baleen whale calls detected during the cruise included: southern right whale up calls (Fig. 2a); blue whale 28Hz tonal and D calls (Figs 2b and c); low and high frequency fin whale calls (Figs 2d and 2e); and humpback whale calls (Fig. 2f). Two types of calls were acoustically detected that cannot be attributed to a particular species, but, since we propose they are likely to come from baleen whales, their characteristics are described and locations of occurrence are also shown. These calls were referred to as 50Hz upswept and pulsing calls (Figs 2g and 2h). Calls from sperm whales, as well as some other unidentified odontocetes were recorded during the cruise, but were not analysed for this paper. The visual survey resulted in 220 hours of survey effort and a total of 217 sightings of groups or individuals. Baleen whales sighted were: southern right, fin, sei (*B. borealis*), humpback and minke whales.

Southern right whales

Southern right whales were detected visually and acoustically at three locations: in the vicinity of the South Orkneys; in the vicinity of South Georgia; and in the southeastern Scotia Sea (Fig. 3a). There was a total of 20 sightings of 33 southern right whales while the only call type recognised as a southern right whale call was the up call (Fig. 2a). Southern right whales were detected twice visually and acoustically during the same time, but during every southern right whale occurrence other species of whales were sighted in the vicinity as well. During one such visual encounter, on 13 February 2003, a deployment of a directional sonobuoy made it possible to calculate bearings to calling whales. They were compared to locations of the two groups of southern right whales detected by the visual observers (who were off-effort at the time) and it was found that the bearing of one group of three calls at 165±8° corresponded to the bearing of one of the two visually detected groups, which were observed at 176° and 260°. A group of 14 sei whales was detected by the observers during the same time period at 235°.

A total of 31 up calls from three different days of recordings were measured to determine their temporal and frequency characteristics. The average starting frequency of the calls was 92±11Hz, the ending frequency was 173±11Hz and the average duration was 0.7±0.1s. The average sweep rate of the up calls was 125±24Hz s^{-1}.

Blue whales

Most blue whale acoustic detections occurred along the southern edges of the survey area in the Scotia Sea, with two detections in the northern area closer to South Georgia (Fig. 3b). There were no blue whale sightings throughout the cruise, so it was not possible to relate any of these acoustic detections to visual ones. Two different call types detected during the JR82 cruise were from blue whales, the 28Hz tonal call and the D call. Blue whale 28Hz tonal calls were detected on seven sonobuoys and temporal and frequency characteristics were analysed from 29 calls. Generally, only the flat, 27.7±0.1Hz tonal component was visible, lasting an average of 8±1s (Fig. 2b) and the average intercall interval was 65s. The downswept part ('28Hz downsweep' in Rankin *et al.*, 2005) was visible in 14 analysed calls. D calls occurred on five sonobuoys and four of these also had 28Hz tonal detections (Fig. 3b). Fifty D calls from four sonobuoys were analysed. These calls varied in duration from 1.0-3.7s (with average 2.1±0.8s) and their frequency changed from 80±8Hz to 38±7Hz (Fig. 2c). The average sweep rate was

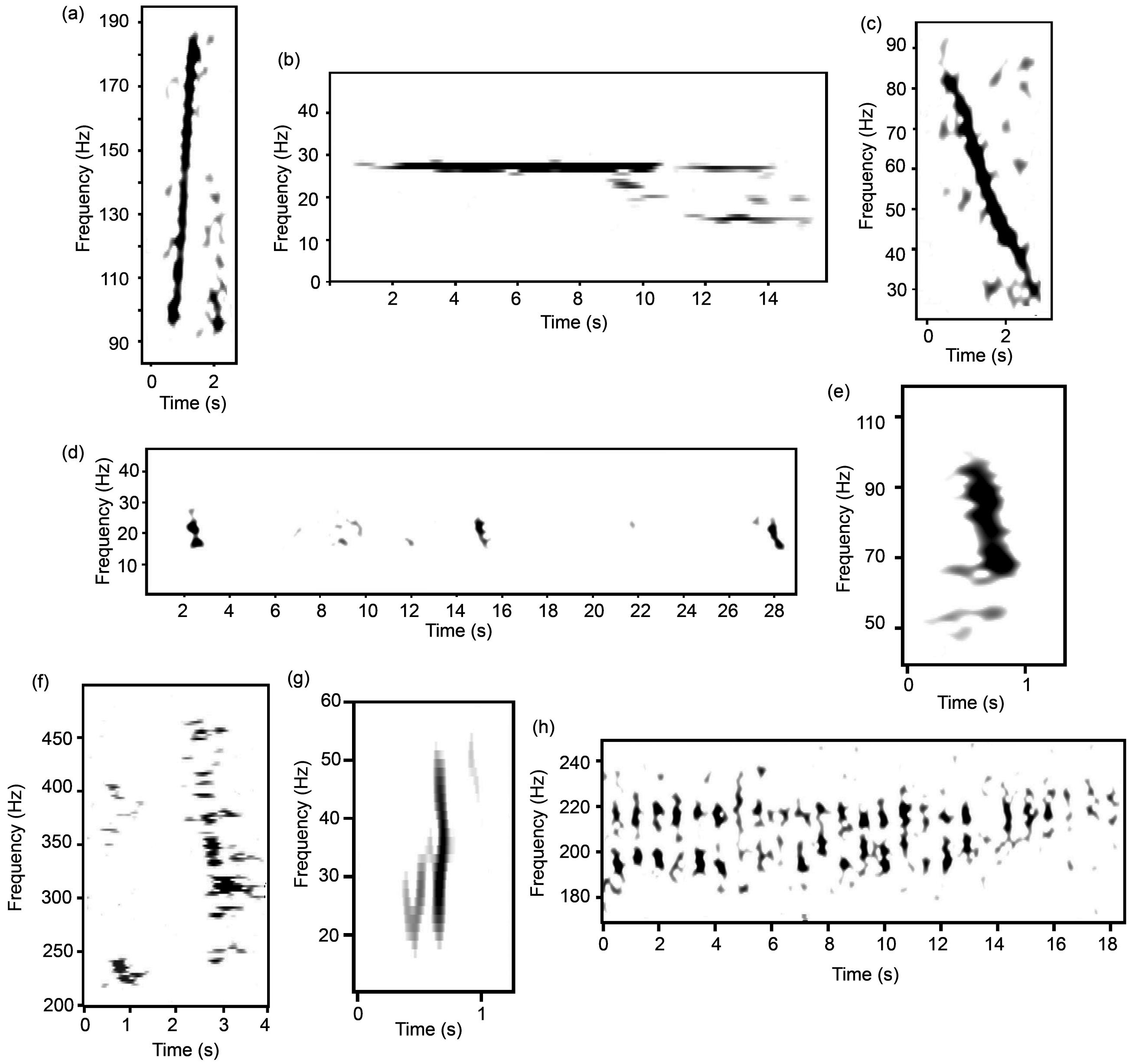

Fig. 2. Spectrograms of calls recorded during JR82 cruise: (a) southern right whale up call (600-point FFT, 99% overlap, Hanning window); (b) blue whale 28Hz tonal call (parts of the downsweep and the second tonal are also visible; 2,400-point FFT, 95% overlap, Hanning window); (c) blue whale D call (1,200-point FFT, 99% overlap, Hanning window); (d) fin whale low frequency call (900-point FFT, 95% overlap, Hanning window); (e) fin whale high frequency call (300-point FFT, 99% overlap, Hanning window); (f) sample of humpback whale calls (600-point FFT, 95% overlap, Hanning window); (g) unidentified 50Hz upswept call (100-point FFT, 99% overlap, Hanning window); (h) unidentified pulsed calls (600-point FFT, 99% overlap, Hanning window).

23±10 Hz s^{-1}. Five out of 50 analysed D calls started with a short upsweep in frequency and one started with a flat tone before the main, downswept part. The flat tone was at the same frequency as the beginning of the downsweep and the upsweeps were variable in their duration and frequency range. These calls did not have regular intercall intervals.

Blue whale calls were detected on two occasions on directional sonobuoys, on 26 and 30 January 2003. Bearings to both 28Hz tonal and D calls were calculated on 26 January. Bearings to seven 28Hz tonals were calculated around 19:30 GMT, while the ship was on the 110° heading, and were found to belong to at least two different animals with bearings 10±18° (calculated from 3 calls) and 335±10° (from 4 calls). There were no D calls at this time. Bearings to four 28Hz tonal calls around 21:00 GMT were found to be 319±7°, while bearings to four D calls during that period were 313±5°. The ship's bearing during this time was 90°. On 30 January it was possible to determine the bearings to four 28Hz tonal calls over a one-hour period and they changed between 147° and 128°. The ship's bearing during this period was steady at around 270°.

Fin whales

In general, sightings of fin whales occurred in the central Scotia Sea and correspond well to areas where two types of fin whale calls were detected on 10 sonobuoys (Fig. 3c). Low frequency fin whale calls were detected on eight of these sonobuoys, all of them deployed in the central Scotia Sea. A total of 49 low frequency fin whale calls were measured to determine their frequency characteristics. The calls were repetitive downsweeps in frequency from 31±2Hz to 15±1Hz (Fig. 2d). Downsweeps lasted on average 0.7±0.1s and had a sweep rate of 25±4Hz s^{-1} and intercall intervals of 13.0±0.9s. On five occasions fin whale sightings were made within an hour of call recordings and once other identified species of cetaceans (pilot whales,

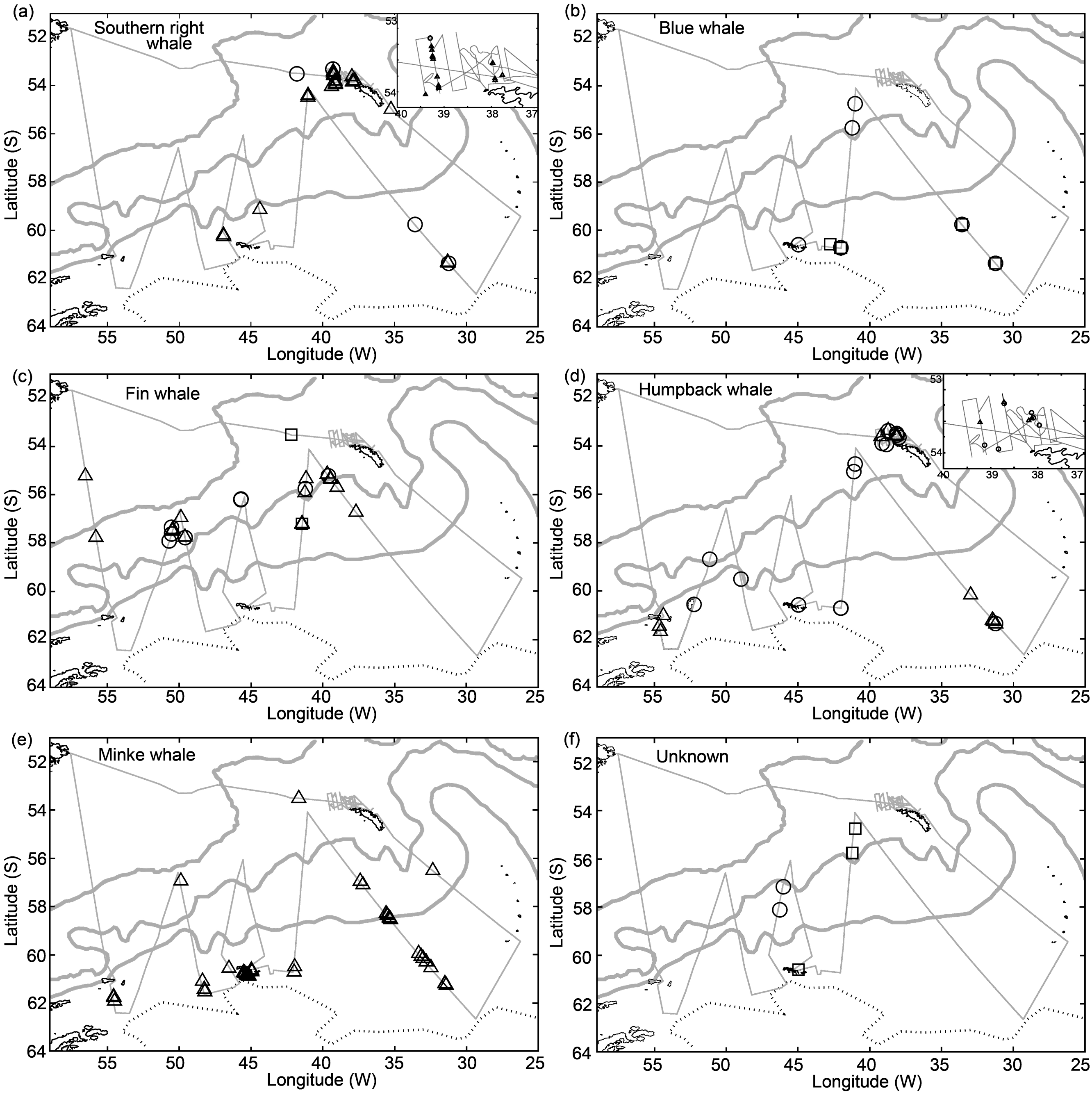

Fig. 3. Locations of acoustic (circles and squares) and visual (triangle) sightings: (a) southern right; (b) blue (circles are tonal call and squares D call locations); (c) fin (circles are low frequency and squares high frequency call locations); (d) humpback; (e) minke whales; (f) locations of 50Hz up (circles) and pulsing calls (squares). Insets on (a) and (d) show sightings in the WCB. Thin grey line is the cruise track, thick grey lines represent major fronts in the area: PF; sACCf; SB and the broken black line is the inferred ice edge on 1 February 2003 from the NSIDC satellite image (same as Fig. 1).

Globicephala melas and hourglass dolphins, *Lagenorhynchus cruciger*) were sighted. Fin whale calls were recorded twice by directional sonobuoys, but the visual observers sighted no fin whales at those times.

Higher frequency fin whale calls were detected by two additional sonobuoys (Fig. 3c). For both occurrences of these calls there were no lower frequency fin whale calls, but only fin whales were visually detected within an hour before or after the acoustic detection. One of these sightings was during a period when the visual observers were not on full-effort. Only 14 calls of this type were available for analysis. They were regularly repeated downswept calls that ranged on average from 102±15Hz to 51±3Hz over 0.6±0.1s, with the average sweep rate of 80±17Hz s^{-1} (Fig. 2e). Their intercall interval was 4.6±0.9s. Unfortunately, both recordings of the high frequency calls were made on omnidirectional sonobuoys so it was impossible to relate them to the visual fin whale detections. During the cruise, visual observers sighted 15 groups of fin whales, for a total of 36 animals.

Humpback whales

The areas where humpback whale calls were detected acoustically generally corresponded to areas of humpback sightings: around South Georgia, near the South Shetland Islands in the southwest, as well as in the southeast corners of the surveyed area (Fig. 3d). The calls attributed to humpback whales during this cruise were a variety of grunts and moans ranging approximately 100-600Hz (Fig. 2f). Grunts and moans that were detected repetitively in the above frequency range and lasted longer than 1s and that could not be attributed to any other species were subjectively assigned as humpback whale calls. Humpback whale calls were detected on 15 sonobuoys deployed during the cruise (Fig. 3d). A total of 12 groups and 38 humpback whales were visually detected during the JR82 cruise.

Minke whales

A total of 43 groups (76 total animals) of minke whales were visually detected during the JR82 cruise, most of them along the southern edge of the survey area close to the ice edge. No confirmed Antarctic minke whale calls were detected (Fig. 3e). In the southeastern section of the survey area, minke whales were seen further away from the ice edge, in the central sector of the Scotia Sea.

Other calls

Two other call types were heard on sonobuoys on multiple occasions, 50Hz upswept and pulsing calls. They cannot be linked positively to a particular baleen whale species, but it is likely that baleen whales produced these calls, as they contain typical baleen whale call characteristics: low-frequency and repetitiveness.

The 50Hz upswept calls were recorded by two sonobuoys deployed in the central Scotia Sea (Fig. 3f). There were no visual sightings of whales near the sonobuoys on which these calls were heard and there were higher frequency odontocete calls on one of the sonobuoys deployed nearby. The 50Hz upswept calls did not coincide with any other baleen whale calls. It was possible to determine frequency and temporal characteristics of 12 of these calls and they generally started at 26±4Hz, ended at 52±4Hz and lasted 0.5±0.1s (Fig. 2g). They were repeated at intervals ranging 62-78s, with usually 2-3 calls in a sequence.

Pulsing sounds were detected on three occasions (Fig. 3f). The pulsing was concentrated mainly in the 140-240Hz energy band, but it was highly variable within a pulsing bout (Fig. 2h). The average pulse duration and rate were calculated using 44 individual pulses and the duration was 0.31±0.04s while the pulse rate was 1.8±0.2pulses s^{-1}. The pulses were equally spaced throughout a call series and there was no evidence of slowing down or speeding up through the series. All three times these calls were detected by the same sonobuoys as blue whale 28Hz tonal calls and twice they were acoustically detected on the same sonobuoys as humpback whale calls.

DISCUSSION

This acoustic survey for baleen whales was the first of its type to be conducted in the Scotia Sea. In addition to multiple recordings of known baleen whale calls, two call types from unknown sources were recorded. The acoustic survey, in conjunction with the visual survey, enabled assessment of the spatial distributions of southern right, blue, fin, humpback and Antarctic minke whales in the area and comparison of the differences among the species. More work on call rates, gender bias and seasonal variation in calling is needed, however, to determine whether acoustics can be used to obtain reliable abundance estimates.

Sources of calls

Acoustic surveys offer an opportunity to study baleen whales even when whales are not available for observation by more traditional visual survey methods (e.g. due to darkness, high sea-state, low visibility). One of the problems acoustic surveys face is that calls cannot always be linked reliably to a particular species of whale since the animals often are not simultaneously seen and heard. Sometimes, however, it is possible to link the bearing of a calling animal and a visual sighting of a known species.

Up calls are well documented to be produced by southern right whales at other locations in the Southern Hemisphere (Cummings *et al.*, 1971; Payne and Payne, 1971; Clark, 1982; 1983). Southern right whales were also heard using directional sonobuoy and seen concurrently on one occasion during the cruise. Even though a group of sei whales was visually detected in the vicinity at the same time, they were at a different bearing to the detected calls. While little is known about sei whale calls, McDonald *et al.* (2005) reported sei whale calls off the Antarctic Peninsula to be of a higher frequency (around 200Hz) and have different characteristics to the up call reported here. The similarity of the calls detected during this survey to calls attributed to southern right whales in other reports and the evidence from the bearing measurements taken from acoustic and visual detection of these animals during this cruise, are strong evidence that southern right whales produced these up calls.

Since no blue whales were sighted during this cruise, previous reports of their calls in the Antarctic were relied upon to link the sounds heard to blue whales. Rankin *et al.* (2005) suggest that the 28Hz tonal call, similar to ones heard on multiple sonobuoys during this cruise, are a diagnostic feature in detecting blue whales. Given the flat tonal nature of the call, one possible mistake would be to confuse the ship's noise for a blue whale tonal, since the ship produced a tone at 27Hz while the bow thrusters were on at sampling stations. In this study additional identifying features were used, such as predictable repetitiveness of the call (Širović *et al.*, 2004), duration of the tonal being less than 10s or the presence of the downswept part of the call (28Hz downsweep, after Rankin *et al.*, 2005). Also, when possible, bearings were calculated to the 28Hz tonal calls and compared to the ship's bearing. Even though it is possible a calling blue whale and the ship could be on the same bearing, in instances when this happened we erred on the side of caution and did not report a blue whale call. From calls recorded while at sampling station with bow thrusters on, only ones that satisfied at least two of the above conditions were reported. The presence of 28Hz tonal calls was analysed independently of the presence of D calls and it was found that the two types of calls coincided at four sonobuoys. Downsweeps similar to these D calls have been reported as coming from blue whales at other locations worldwide (Thompson *et al.*, 1996; McDonald *et al.*, 2001; Mellinger and Clark, 2003; Rankin *et al.*, 2005). Confusion of blue whale D calls with calls from other species is more likely than for 28Hz tonals. Southern right whales, for example, are known to produce some low frequency downswept calls (e.g. Cummings *et al.*, 1972; Clark, 1983), but these are generally in the 200-100Hz frequency range and last less than 1.5s. Thus though there is some overlap with the location of right whale calls and blue whale D calls, it is not likely that the 1.0-3.7s duration calls heard in the frequency range below 100Hz can be attributed to southern right whales, but are indeed blue whale D calls. Confusion with high frequency fin whale calls is avoided because D calls are of a longer duration and are not repeated at regular intervals.

The fin whale calls recorded could not be linked to visual sightings of these animals, but the low frequency calls are similar to those reported for fin whales at other worldwide locations (Walker, 1963; Edds, 1988; Thompson *et al.*, 1992), although they differ from calls reported off the Western Antarctic Peninsula in their absence of the 89Hz component (Širović *et al.*, 2004). The high frequency calls are similar to the fin whale calls reported by Watkins (1981) but the frequencies are higher here (downsweep from 105 to 50Hz compared to 75 to 40Hz) and the duration is longer (0.6s compared to 0.3s). Two incidental sightings of fin whales around the time of these calls strengthens the case that fin whales produced these calls and their distribution followed the general pattern of fin whale distribution in the central Scotia Sea.

Calls similar to both 50Hz upswept and pulsing calls have been reported previously as having been produced by baleen whales (Winn and Perkins, 1976; Mellinger *et al.*, 2000; Rankin *et al.*, 2005) and their frequency and temporal characteristics are consistent with those generally reported for baleen whales. Pulsing calls were recorded using the same sonobuoys as blue whale calls, but it is not thought that blue whales produced these calls. Pulsing has previously been reported as being produced by common minke whales, but in those instances the pulsing rate was 2.2 pulses s^{-1} (Winn and Perkins, 1976), slightly higher than that reported here. Also, it has been implied that similar pulsing calls, with pulsing rates between 1.5 and 4.5 pulses s^{-1}, could be minke whale songs, as they have been recorded mostly in lower latitudes (Mellinger *et al.*, 2000; Gedamke *et al.*, 2001). If these pulses are from a minke whale, then this is the first recording of this species producing a song-like call at a high latitude. Even though similar pulsing sounds appear to be rather ubiquitous, they are not usually associated with visual sightings of common minke whales (Folkow and Blix, 1991; Mellinger *et al.*, 2000) and during this cruise they were recorded mostly in an area with no Antarctic minke whale sightings. It would be helpful to determine the source of this pulsing call, as well as the sources of pulsing sounds recorded elsewhere.

There were no baleen whale sightings in the vicinity of the sonobuoys on which 50Hz upswept calls were heard, but Rankin *et al.* (2005) reported similar upswept calls, from 23 to 57Hz with 1.6s duration, as coming from blue whales in the Antarctic. While the frequency range of the calls is similar, calls reported here are three times shorter. The frequency range of this call is lower than previously reported for minke or southern right whales. Although minke whales are not known to make upsweeps, the short duration of the calls means they resemble minke whale downsweep calls (Schevill and Watkins, 1972; Edds-Walton, 2000). Antarctic minke whale acoustics are very poorly understood and it is possible that they could be making these calls. Southern right whales also produce upsweeps, but their upsweeps tend to be higher in frequency and longer in duration, so it is unlikely the 50Hz upswept calls were produced by them. Edds (1988) reported upsweeps from fin whales in the St. Lawrence estuary and Thompson *et al.* (1992) reported that 17% of calls heard from fin whales in the Gulf of California were upsweeps. The much shorter duration of these calls than those of the blue whale reported in Rankin *et al.* (2005), the short intercall interval and their occurrence in the areas where fin whales mostly occurred during this survey make it possible that these calls were produced by fin whales. A more focused study, with dedicated ship time for visual observations and acoustic work with DIFAR sonobuoys, would be required to determine whether both the pulsing and 50Hz upswept calls are made by a species of baleen whale.

Whale distributions and environmental parameters

The locations of baleen whale calls and sightings provide a comparison of differences in spatial distribution among species. Comparison of these locations with major environmental parameters, such as the oceanographic fronts, the location of the ice edge and bathymetry, can offer insight into habitat use differences between the species. There was a difference in the distribution of fin whales in comparison with all other species of baleen whales. Fin whales were prevalent in the central part of the Scotia Sea, in deeper waters along the sACCf. This is in contrast to Tynan's (1998) observations from whaling data indicating that blue, fin and humpback whales are associated with the southern boundary of the ACC. All other species were found south of the southern boundary, around the South Orkneys and in areas of the Scotia Sea close to the ice edge. Humpback and southern right whales were found also in shallow areas around South Georgia, between the polar front and the sACCf, consistent with previous findings (Kellogg, 1929; Kasamatsu *et al.*, 1996).

During this survey no fin whales were detected near the ice edge, where all other baleen whale species were commonly located. This is consistent with the knowledge that fin whales are more pelagic in comparison with other baleen whales and generally are not associated with sea ice (Kellogg, 1929; Mackintosh, 1965). The association of fin whales with the sACCf average location in this survey is not surprising, but it is worthy of further investigation. The marginal ice zone along the retreating ice edge is known to be a biologically productive zone and this area is further enriched by the shallow upwelling of the Upper Circumpolar Deep Water (UCDW) associated with the southern boundary (Laws, 1985; Smith and Nelson, 1985; Tynan, 1998). Such a rich area has the potential to sustain a large animal biomass and diversity. The sACCf, on the other hand, is characterised by a deeper UCDW upwelling. Before reaching the central Scotia Sea this front passes along the continental shelf of the Antarctic Peninsula, where it is enriched with iron and other limiting micronutrients (Holm-Hansen *et al.*, 2004). While the productivity in the central Scotia Sea may be less than in the marginal ice zone, the combination of deep UCDW upwelling and micronutrient enrichment gives this deep water region potential for sustaining baleen whales. Fin whales, with their ability to make relatively deep dives (Panigada *et al.*, 1999), could potentially exploit the productivity brought by the deep upwelling and in turn avoid competition with other species that prefer the area near the southern boundary (Laws, 1977; Costa and Crocker, 1996).

Acoustic methods for population estimation are still under development, since parameters such as the whale calling rates and daily and seasonal calling patterns are not well understood (Barlow and Taylor, 2005). Direct comparison of acoustic and visual surveys is further complicated by a difference in range over which the two operate. While visual surveys cover a range of several km, a more typical range for acoustic survey of baleen whales with sonobuoys is several tens of km (McDonald, 2004). There are also differences in the availability of animals for either type of survey due to their diving preferences and differences in the frequency of calling. However, a simple comparison of the numbers of groups detected by each method can be done if we assume a single detection of a species by one sonobuoy represents one acoustic group. This introduces a low bias to the acoustic survey, and this bias could be reduced by using only DIFAR sonobuoys. Blue whales, for example, appear to be a better subject for acoustic surveys, as eight groups were detected acoustically and none visually. Minke and southern right whales, with zero and four acoustic and 43 and 20 visual groups, respectively, seem to be better suited for visual surveys. Humpback and fin whales fall in the middle, with 15 and 10 acoustic and 12 and 15 visual groups, respectively. There was a bias in this acoustic survey, however, since it was not independent of the visual survey and sonobuoys often were deployed deliberately after a visual sighting.

The efficiency of acoustic and visual surveys varies between species, as exemplified by blue and minke whales. While blue whales were heard on a number of occasions during the cruise, they were never seen. Due to the sound speed profile characteristics in polar regions, making the area an upward refracting environment (Richardson *et al.*, 1995), the area that was monitored acoustically was likely 1-2 orders of magnitude larger than the area surveyed visually. This could explain why blue whales were heard acoustically but were never seen by the visual observers as their low frequency calls propagate better than calls from other species. Also, a low density of blue whales in the Antarctic (Branch and Butterworth, 2001a) would give a low likelihood of a visual encounter with this species. Antarctic minke whales, on the other hand, were commonly seen during the survey, but were not heard. While they are the most abundant of the baleen whales in the Antarctic (Branch and Butterworth, 2001b), their known Antarctic calls are short and occur irregularly (Schevill and Watkins, 1972) and therefore can be difficult to detect with sonobuoys.

Acoustic surveys from ships complement visual surveys for cetaceans, since they provide larger scale coverage and can be conducted when the conditions are not appropriate for visual survey (e.g. darkness, rough seas, poor visibility). Sonobuoys are better suited for surveys of baleen whales than towed arrays, since ship noise interferes with low frequency whale calls and this noise diminishes as ships steam away from a sonobuoy. Concurrent visual and acoustic efforts are necessary, however, to investigate the sources of different call types, as well as to devise methods for population estimation using acoustics. Even though there are currently no means to estimate population sizes from a sonobuoy survey, it is possible to determine areas where certain call types are heard commonly and to estimate the spatial distribution of various baleen whale species if a consistent acoustic sampling programme is used.

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