ELSEVIER

Deep-Sea Research II 51 (2004) 2327–2344

DEEP-SEA RESEARCH
PART II

www.elsevier.com/locate/dsr2

Seasonality of blue and fin whale calls and the influence of sea ice in the Western Antarctic Peninsula

Ana Širović[a,*], John A. Hildebrand[a], Sean M. Wiggins[a], Mark A. McDonald[b], Sue E. Moore[c], Deborah Thiele[d]

[a]*Scripps Institution of Oceanography, UCSD, La Jolla, CA 92093-0205, USA*
[b]*Whale Acoustics, Bellvue, CO, USA*
[c]*NOAA/AFSC/National Marine Mammal Laboratory, Seattle, WA, USA*
[d]*Deakin University, School of Ecology and Environment, Warrnambool, VIC, Australia*

Accepted 8 July 2004

Abstract

The calling seasonality of blue (*Balaenoptera musculus*) and fin (*B. physalus*) whales was assessed using acoustic data recorded on seven autonomous acoustic recording packages (ARPs) deployed from March 2001 to February 2003 in the Western Antarctic Peninsula. Automatic detection and acoustic power analysis methods were used for determining presence and absence of whale calls. Blue whale calls were detected year round, on average 177 days per year, with peak calling in March and April, and a secondary peak in October and November. Lowest calling rates occurred between June and September, and in December. Fin whale calling rates were seasonal with calls detected between February and June (on average 51 days/year), and peak calling in May. Sea ice formed a month later and retreated a month earlier in 2001 than in 2002 over all recording sites. During the entire deployment period, detected calls of both species of whales showed negative correlation with sea ice concentrations at all sites, suggesting an absence of blue and fin whales in areas covered with sea ice. A conservative density estimate of calling whales from the acoustic data yields 0.43 calling blue whales per 1000 n mi^2 and 1.30 calling fin whales per 1000 n mi^2, which is about one-third higher than the density of blue whales and approximately equal to the density of fin whales estimated from the visual surveys.

1. Introduction

Baleen whales were severely depleted throughout Antarctic waters by intense commercial whaling in the first half of the 20th century. Large species such as blue (*Balaenoptera musculus*) and fin (*B. physalus*) whales were the most sought after. It has been estimated that over 360,000 blue whales and 725,000 fin whales were removed from the southern hemisphere by whaling during the 20th century (Clapham and Baker, 2001). Efforts

*Corresponding author. Fax: + 1-858-534-6849
E-mail address: ana@mpl.ucsd.edu (A. Širović).

0967-0645/$ - see front matter
doi:10.1016/j.dsr2.2004.08.005

to document the status of whale populations in the Western Antarctic Peninsula region have been limited to three cruises simultaneously conducted by up to four vessels under the auspices of the International Whaling Commission during 1982/83, 1989/90, and 1993/94 in Area I (longitude 60°–120°W). These cruises yielded only nine blue whale sightings and 14 fin whale sightings (Branch and Butterworth, 2001). Such alarmingly low sightings suggest either a population in jeopardy, inadequate population assessment methods, or both (Horwood, 1986; IWC, 2001). The need to develop alternative methods of assessing whale populations, such as passive acoustics, has already been established (Clark and Ellison, 1988, 1989; Clark and Fristrup, 1997), but this need is even more important for the Southern Ocean given the considerable expense and logistical constraints of working there (Costa and Crocker, 1996).

Seasonal migrations have been documented, both visually and acoustically, for several baleen whale species (Mackintosh and Wheeler, 1929; Dawbin, 1966; Mackintosh, 1966; Clapham and Mattila, 1990; Katona and Beard, 1990; Mate et al., 1999; Norris et al., 1999; Stafford et al., 1999b). In general, many baleen whales spend summers feeding in productive waters at high latitudes and over-winter in warmer waters at lower latitudes (Mackintosh and Wheeler, 1929; Mackintosh, 1965; Bowen and Siniff, 1999). Whaling records suggest that blue and fin whales migrate seasonally to and from the Southern Ocean (Kellogg, 1929; Brown, 1962; Mackintosh, 1966). Although blue whales have been found close to the ice edge in the austral summer (Kasamatsu et al., 1988), there is little information on their wintering areas (Mackintosh, 1965; Mizroch et al., 1984) and some high latitude areas, such as South Georgia and the North Pacific, may be continuously occupied by blue whales (Kellogg, 1929; Hart, 1935; Curtis et al., 1999; Watkins et al., 2000; Stafford et al., 2001). Fin whales are rarely sighted at the ice edge during the summer and in the winter they appear to calf and breed at low latitudes (Laws, 1961; Brown, 1962).

Aggregations of blue and fin whales have been observed in association with dense patches of euphausiids during the summer and fall in regions with high biological productivity (Croll et al., 1998; Fiedler et al., 1998; Reid et al., 2000; Murase et al., 2002). These regions often have distinguishing characteristics such as complex bathymetry, presence of sharp oceanographic fronts, eddies, and upwelling that can support high phytoplankton and zooplankton biomass (Beklemishev, 1960; Whitehead and Glass, 1985; Reilly and Thayer, 1990; Fiedler et al., 1998; Tynan, 1998). In the highly productive Southern Ocean, sea ice is an additional factor that affects the ecosystem, generally increasing krill productivity in areas of large sea ice fluctuation, thereby also affecting higher trophic predators (Smith and Nelson, 1985; Fraser et al., 1992; Loeb et al., 1997; Nicol et al., 2000; Croxall et al., 2002). The Western Antarctic Peninsula has a distinct, fluctuating sea ice pattern (Stammerjohn and Smith, 1996), which could support high primary productivity, concentrations of Antarctic krill, and higher predators.

Blue and fin whales produce low frequency (<1 kHz), high intensity (above 180 dB re: 1 μPa at 1 m) calls and are good subjects for acoustic monitoring (Clark, 1990). Whale call detections have been applied to studies of seasonal occurrence and migration since the 1980s (e.g., Clark and Ellison, 1988, 1989; Stafford et al., 1999a; Watkins et al., 2000). Blue whale calls can be distinguished by their relatively long duration (10–20 s) and very low frequency (20–100 Hz) (Cummings and Thompson, 1971; Edds, 1982; McDonald et al., 1995; Stafford et al., 1998). Typically, the calls consist of two to four units that can be either pulsed or tonal in character. Blue whales produce a single call-type with uniform acoustic characteristics around the Antarctic (Ljungblad et al., 1998; Matsuoka et al., 2000; Clark and Fowler, 2001). Fin whale calls have been well documented in the northern hemisphere (Watkins, 1981; Edds, 1988; McDonald et al., 1995). They typically consist of short (1 s duration), repetitive downsweeps, but they show some variation among different geographic locations in the frequency range of the sweep and the intercall interval (Thompson et al., 1992). We are not aware of any previous reports of fin whale call recordings from the Antarctic.

Recent advances in computer technologies have enabled the development of instruments capable of long-term autonomous acoustic sampling (McDonald et al., 1995; Stafford et al., 1999a; Fox et al., 2001; Wiggins, 2003). We took advantage of this developing technology and deployed seven acoustic recording packages (ARPs) near the SO GLOBEC study site in the Western Antarctic Peninsula from March 2001 until February 2003 to monitor for baleen whale calls (Wiggins, 2003). They provided a record of seasonal occurrence of these large euphausiid predators that can be integrated further with the studies of other biotic and abiotic parameters within the SO GLOBEC framework. In this paper we report the first results on the seasonality of blue and fin whale calls from this acoustic monitoring effort.

2. Methods

Seven ARPs were deployed in the Western Antarctic Peninsula from March 2001 to February 2003 (Fig. 1). ARPs are bottom-moored instruments that consist of a data logging system with a 16-bit A/D converter and 36 GB of storage capacity, a hydrophone tethered 10 m above the seafloor-mounted package (sensitivity −198 dB re: 1 Vrms/μPa and a −3 dB low-end roll-off at around 5 Hz), an acoustic release, two ballast weights, batteries, and flotation (Wiggins, 2003). The acoustic data were collected at 500 samples/s with a –6 dB roll-off at 250 Hz, so the effective bandwidth sampled was 5–250 Hz. At this sampling rate, the instruments were capable of recording data for 400 days. The instruments were retrieved in February 2002 for data recovery and battery replacement, then redeployed with final recovery in February 2003. In this paper we refer to the period between March 2001 and February 2002 as the 'first year of deployment', while the 'second year of deployment' refers to February 2002–February 2003.

Two ARPs were located on the continental shelf (sites 7 and 9) at depths of 450 and 870 m. Six ARPs were located on the shelf break; the northernmost (site 1) was at a depth of approximately 1600 m, while the depths of the remaining five

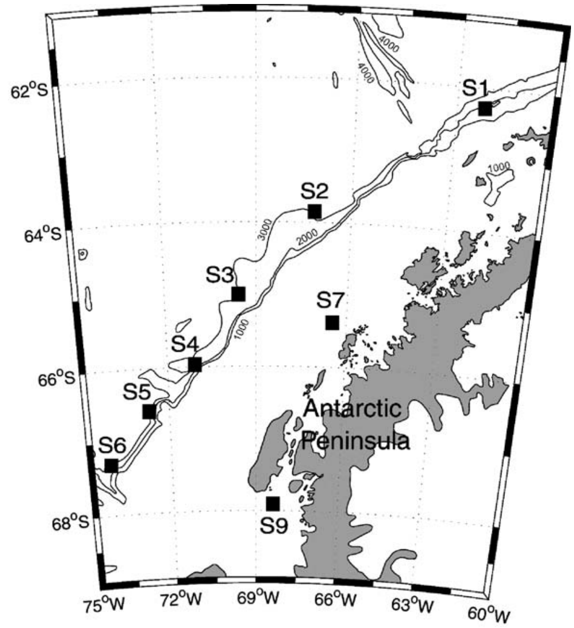

Fig. 1. ARP deployment locations west of the Antarctic Peninsula. The actual locations for ARPs were as follows: S1–62° 16.44' S 62° 10.02' W; S2–63° 50.63' S 67° 08.33' W; S3–64° 59.41' S 69° 28.79' W; S4–65° 58.40' S 71° 04.10' W; S5–66° 34.99' S 72° 41.43' W; S6–67° 18.25' S 74° 10.15' W; S7–65° 22.62' S 66° 28.21' W; S9–67° 54.50' S 68° 23.00' W.

ARPs ranged between 2500 and 3500 m. In this paper, we refer to sites 1 and 2 as 'northern sites', sites 3 and 4 are 'central sites', 5 and 6 are 'southern sites', and 7 and 9 are 'shelf sites.' Distances between neighboring ARPs ranged from 110 to 260 km. Acoustic data for the two northern sites were available for the entire deployment period, data for site 3 were available from July 2001 to February 2002, data for site 4 were available only for the first year of deployment and those for sites 5, 6, 7, and 9 were available only for the second year of deployment.

In order to describe the acoustic characteristics of blue and fin whale calls, we measured beginning and ending frequencies, durations, intercall and intersequence intervals (time between successive call sequences that is shorter than 100 s and is presumably too short to be a surfacing event; only applicable for fin whales), and long intervals (time between successive call series longer than 100 s, when the calling animal is presumably at the surface) of calls of both species. We used spectrograms of calls with high signal-to-noise ratios from several different times and various sites. We reported the mean and the standard deviation of each property.

We used these measurements to conduct automatic detection of blue and fin whale calls from this large data set using spectrogram correlation (Mellinger and Clark, 2000; Mellinger, 2001). This method cross-correlates the data set spectrogram with an artificial kernel that represents a whale call. The values for two kernels that represented blue and fin whale calls were obtained from the ARP data set as described above. For blue whales, we used a kernel that started with a 9 s flat tone at 27.7 Hz, followed by a 1 s downsweep to 19.5 Hz and another 7 s downsweep to 18.8 Hz. The fin whale call kernel was made to last 1 s and sweep down in frequency from 28 to 15 Hz.

When analyzing data by automatic spectrogram correlation, a detection threshold must be set. Exceeding this threshold for a set period of time (6 s for blues and 0.5 s for fins) triggered a detection event. We initially chose high thresholds to minimize false detections. The detection threshold was iteratively adjusted until the false detection rate was less than 1%. The consequence of a high detection threshold, however, is the omission of calls with low signal-to-noise ratios, which results in an underestimate of the total number of calls. Detected calls were saved as individual WAV files, along with the information on the day and time when the call occurred. Files from days with low call counts (<50) were additionally screened to verify the detections. Of the remaining files, we randomly chose for verification approximately 1000 files for each species' calls to confirm that the false detection rate was $<1\%$. Calling statistics and seasonality were reported for the automatic detection results. We define seasonality (or seasonal calling) as a pattern by which whale calls were present during one part of the year and absent during another continuous period longer than 1 month. Intermittent calling is used to describe a pattern of calling in which there are no periods longer than 1 month during which there are no detected calls. Detection totals for each species and site were combined into 8-day bins for qualitative comparison with sea ice concentrations.

Sound velocity profiles were calculated from XBTs (expendable bathythermographs) deployed in the region. They indicated that the Western Antarctic Peninsula was an upward refracting environment for sound propagation with a relatively shallow (50–150 m) sound channel axis in the summer. Most of the ARPs were in deep water, therefore minimizing reception of very distant (>1000 km) calls. The manual detection range for blue whale calls was determined to be up to 250 km by observing calling sequences produced by the same animal and recorded on multiple instruments. It was then possible to localize on the animal using differences in arrival times of the same call to multiple instruments. Comparison of those calls to automatic detections yielded an automatic detection range of up to 60 km for blue whales, and somewhat less for fin whale calls. It should be noted, however, that the spectrogram correlation method is signal-to-noise dependent and the automatic detection range changes depending on ambient acoustic conditions. During times of high ambient noise the detection range will be diminished. Since the instruments were fairly deep, sea ice formation and melting did not increase the ambient noise in the detected bands and the noise was generally lowered during the periods of ice cover. Therefore the presence of sea ice did not decrease our capability to detect calling whales.

Recordings were also analyzed by comparing the acoustic power in frequency bands characteristic for whale calls, to the power levels of adjacent frequencies. We calculated power spectral density (500-point FFT, 50% overlap, Hanning window) of the entire data set and averaged it over 15 min samples. We determined the ratio of the power in the whale call frequency band to the average power in two adjacent bands where no whale sounds were expected. We assumed linear noise at frequencies around the whale call. For blue whales, we used power at 28 Hz as the calling band and compared it to powers at 15 and 41 Hz as the noise bands. For fin whales, we compared the power at 89 Hz (see Fig. 2B) as the calling band to powers at 80 and 98 Hz as the noise bands. We

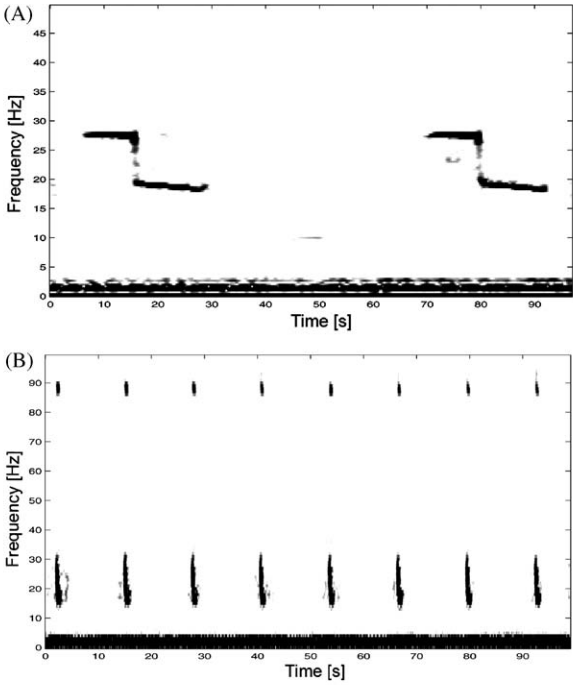

Fig. 2. Spectrograms of (A) Antarctic blue (1500-point FFT, 90% overlap, Hanning window) and (B) fin whale (500-point FFT, 90% overlap, Hanning window) calls recorded in the Western Antarctic Peninsula.

used the higher frequency component of fin whale call to avoid overlap with blue whale calls and because of lower ambient noise at higher frequencies. The range of detection using this method is probably larger than for automatic detections, but it is also a signal-to-noise dependant method. We calculated one-day averages of the signal-to-noise ratios and cross-correlated the results to one-day total automatic detections, and we used a t-test to determine whether the two methods yielded significantly different results.

The nature of the acoustic data enables us to determine only when calling animals are present in the detection area. During periods when no calls are detected, whales may be absent or silent (Stafford et al., 1999b). In this paper, we use call abundance as a proxy for whale abundance. The relationship between the number of calls detected and the number of animals present is not currently understood. We assume that higher calling rates in automatic detection and higher signal-to-noise ratios in acoustic power analysis reflect a greater number of animals present, although seasonal variation in the tendency to call may also be reflected in these data.

In calculations of the average number of days/site that whales were detected during the year, we did not include site 3 (because it did not have a full deployment year of data) nor site 9 (because no blue or fin whale calls were detected). We reported the average number of calls at all sites, normalized by the number of sites recording that month and the number of days with recordings per month for each site, as well as the total number of blue and fin whale call detections for each deployment year. We compared the differences between the 2 years as well as the differences among sites. Also, we cross-correlated in time daily detections at different sites, for indication of blue and fin whale movement between the sites. These time lag analyses were conducted for periods when data were available at all sites (April 2, 2001–February 9, 2002 during the first deployment year and March 1, 2002–February 17, 2003 during the second) and we report the ones that showed clear trends. We did not perform time lag calculations for site 7 because of the low call detection numbers at that site.

Sea ice concentration estimates were made using Special Sensor Microwave/Imager (SSM/I) passive microwave data obtained from the National Snow and Ice Data Center. Derived daily gridded sea ice concentration data sets were generated using the Bootstrap algorithm (Comiso, 1991, updated 2002) and are archived from 1995. Ice concentrations are binned to 25 km square cells in a polar stereographic projection. We extracted daily mean values for $75\,\text{km} \times 75\,\text{km}$ areas centered around each ARP using the imaging software *WIM* (Kahru, 2000). Since sites 7 and 9 were less than 75 km from coastline that has snow and ice cover year round, it is likely that the sea ice coverage on these sites is overestimated. We calculated 8-day averages for qualitative comparison to whale call detections. Since daily or weekly samples are not necessarily independent, to determine the number of independent sea ice and whale call samples at each site we calculated the integral time scales from autocorrelations of the sea ice and whale call detection data. We calculated Pearson's coefficient of correlation between blue and fin whale call detections and sea ice concentrations binned in periods corresponding to the integral time scale. The number of deployment days was divided with the calculated integral time scale to determine the number of independent samples, N, at each site. We used a t-test for testing a null hypothesis that sea ice concentration and the number of blue and fin whale call detections are not related, using significance level $\alpha = 0.05$.

We made minimum density estimates of calling whales. We assumed detection radius of 60 km (32.4 n mi) for both species. Since we know blue whales make calls at regular 62 s intervals, we assumed there were two calling whales present when two calls were detected in less than a minute and we inspected the automatic detection results at each of the sites for sequences of calls with the intercall interval shorter than one minute. For fin whales, we estimated the number of calls that occurred in a 13 s interval. We report the values in number of calling animals/n mi^2 so that they are comparable to the results of visual surveys.

3. Results

The call of the Antarctic blue whale (Ljungblad et al., 1998; Clark and Fowler, 2001) consists of three components and lasts about 18.6 s (Fig. 2A). For our data, on average, the call starts with a tone at 27.7 ± 0.4 Hz that lasts 9.5 ± 1.4 s. The second component is a short, 1.1 ± 0.5 s duration downsweep in frequency from 27.7 ± 0.4 Hz to 19.5 ± 0.4 Hz, and the third component is a slightly downswept 18.9 ± 0.5 Hz tone lasting 8.0 ± 3.0 s (for all measurements, $n = 241$). The calls are produced in sequences and repeated with intercall intervals of 62.3 ± 5.2 s ($n = 316$) and long intervals of 172 ± 48 s ($n = 44$), presumably for breathing.

Fin whales in the Antarctic produce short, 0.7 ± 0.3 s average duration pulsed calls (Fig. 2B). They sweep down from 27.6 ± 2.2 Hz to 14.9 ± 1.3 Hz ($n = 277$). There is an additional, simultaneous pulse centered at 89.2 ± 0.7 Hz with an average bandwidth of 4.5 ± 0.9 Hz ($n = 90$). The calls are repeated at 12.9 ± 0.5 s intercall intervals ($n = 238$) and 29.7 ± 6.5 s intersequence intervals ($n = 32$) over long periods, with long intervals of 140 ± 64 s ($n = 8$), again presumably for breathing.

Calls attributed to blue and fin whales were recorded at seven out of eight sites in the Western Antarctic Peninsula, with no calls from either blue or fin whales detected at site 9 in Marguerite Bay. A total of 258,706 blue whale calls were automatically detected from March 2001 to February 2003 by use of spectrogram correlation. Likewise, 72,194 fin whale calls were detected by spectrogram correlation during this period, although poor performance of the automatic call detection method during periods of intense calling suggests that the total number of fin whale calls in our data was actually higher. On average, blue whale calls were detected on 177 days during a year and fin whale calls were detected on 51 days. There was a significant increase in the number of blue whale call detections at the northern sites (1 and 2) from the first deployment year to the second ($\chi^2 = 432$, df = 2, $p < 0.001$; $\chi^2 = 1128$, df = 2, $p < 0.001$, respectively). There was also a significant increase in fin whale call detections at the same sites during that period ($\chi^2 = 88$, df = 2, $p < 0.001$ at site 1; $\chi^2 = 1295$, df = 2, $p < 0.001$ at site 2).

On average for all sites and both years, blue whale calls were detected intermittently year round in the Western Antarctic Peninsula (Fig. 3A). The highest blue whale calling rates were in March and April. Calling decreased in May and was minimal between June and August. There was a secondary peak in calling in October and November. Typically, few calls were detected in December. Fin whale calls showed a strong seasonal presence (Fig. 3B). They were detected from February until June, with the peak in call detections in May. No calls were detected between July and January.

Blue whale calling varied among sites and between deployment years (Fig. 4). Northern sites had intermittent calling during the austral winter of the first deployment year and seasonal calling during the second year. Other sites had a seasonal pattern of blue whale calls throughout their deployment periods. Fewer calls were detected on the shelf sites than on the shelf break sites. The detections at the two northern sites occurred

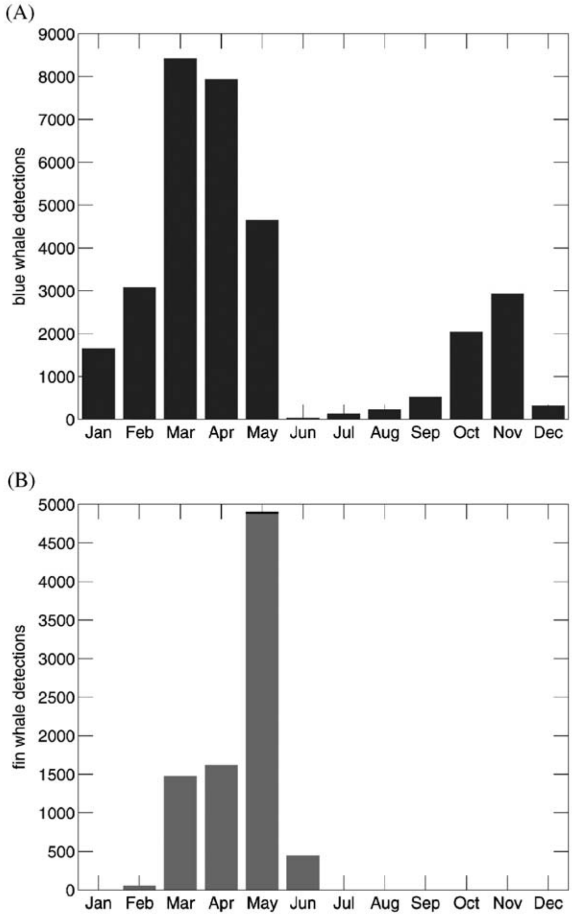

Fig. 3. Monthly averages of the number of blue (A) and fin (B) whale call automatic detections over the whole deployment period, normalized by the number of sites with recordings in a month and the number of days with recordings at each site.

simultaneously during the second year of deployment (Fig. 5). Calls on the two southern sites occurred simultaneously as well, but they lagged the northern sites by 3–4 weeks during the summer, and preceded them by about a month in the spring. The first big increase in the number of detections during austral summer (February–March) 2002 was at the northern sites. Detections increased on the southern sites in April, but in May they were higher at northern sites. In October 2002, the first high detections occurred at the southern sites. In early November the detection peak shifted north, and in late November and early December it returned to the southern sites.

Fin whale calls showed a strong seasonal presence on all sites where calls were detected (Fig. 6). A few calls were detected on site 4 in October and November 2001 (5 and 2 detections, respectively). The highest call counts were at the northern sites. Low detection numbers or no call detections were characteristic of the shelf sites. Peaks in calls were delayed between the two northern sites by about 10 days. In 2002, peaks in calling at northern sites were preceded by calling at southern sites by approximately a month. Fin whale calls were detected on site 6 four days earlier than on site 5. The detections of fin whale calls typically stopped as the sea ice began to form.

The results obtained by the acoustic power analysis were not significantly different from the automatic detection results, except on the shelf site. Results on seasonality of blue whale calls were very consistent between the two methods (Fig. 7). However, there was a slight difference in fin whale presence patterns between the two methods (Fig. 8). Acoustic power method inferred a more continuous presence of fin whales and in some cases about a month longer presence than the automatic detection method. Manual inspection of data during fin whale presence revealed frequent fin whale calling, resulting in a persistent fin whale "noise" band, especially at northern sites, ranging in frequency between 15 and 30 Hz (and around 90 Hz). This band of calling "noise" decreased the signal-to-noise ratio of individual calls, therefore decreasing the number of automatic detections. The acoustic power method was better at detecting the continuous, fin whale calling band signal. This was quite pronounced at the two northern sites. The fin whale calling band (and acoustic power) was stronger at site 1, and fewer fin whale calls were detected there than at site 2, which had a weaker calling band. There were few calls detected at site 7 on the shelf, and these low calling rates caused the acoustic power method to be less robust relative to the automatic call detection method. Even though both methods yielded similar results, it is clear that each method has its advantages and disadvantages and the choice of method should vary depending on the species and their calling intensities. In general, the acoustic power method may be sensitive to more distant calls and provides

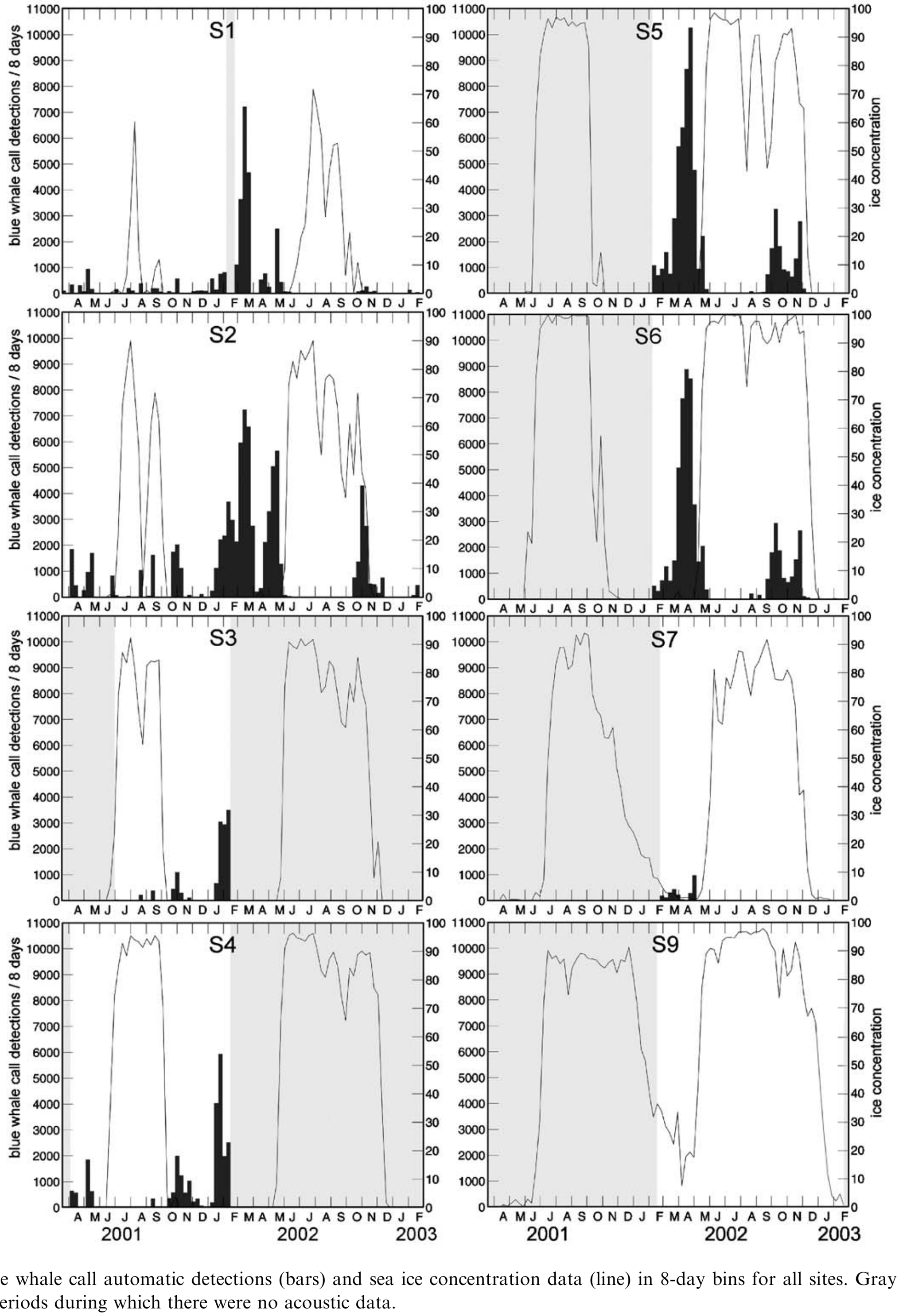

Fig. 4. Blue whale call automatic detections (bars) and sea ice concentration data (line) in 8-day bins for all sites. Gray rectangles represent periods during which there were no acoustic data.

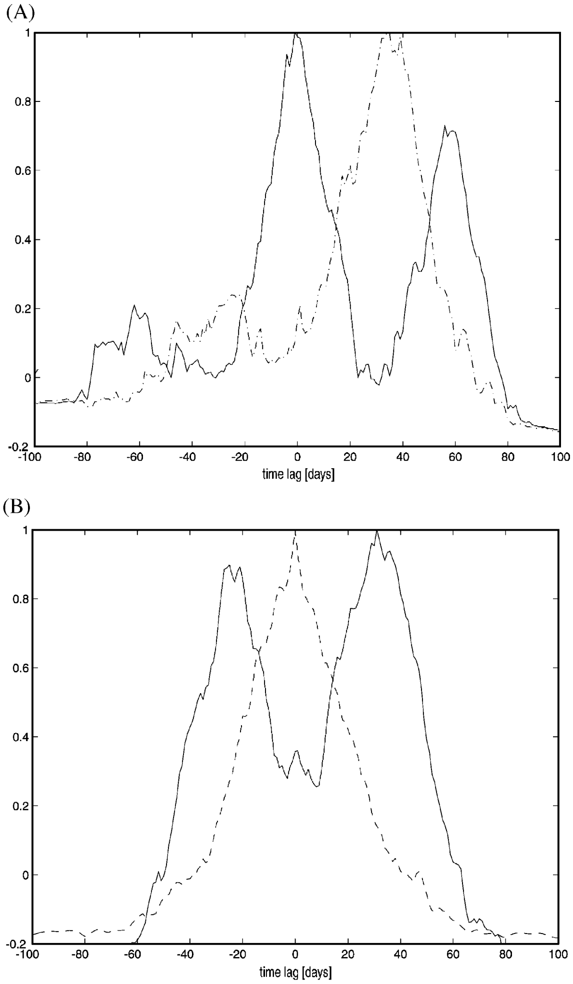

Fig. 5. Time-delayed correlations between blue whale call detections at different sites. (A) Solid: sites 1 and 2; dash-dotted: sites 1 and 5 (both 1 March 02–17 February 03). (B) Solid: sites 2 and 5; dashed: sites 5 and 6 (both 1 March 02–17 February 03).

better results during periods of intense calling, whereas the automatic call detection method is superior for periods of sparse calling and nearby animals.

At some point during the year, sea ice extended over all the instruments during both deployment years (Figs. 4 and 6). On average, sea ice started to form a month earlier and retreated a month later in 2002 than in 2001. As expected, sea ice started forming first on the central and southern sites in May and June, and it fully retreated from these sites in November and December. During at least half of the time, the sea ice cover was over 90% at the southern sites, and over 80% at the central sites. Sea ice at the shelf sites formed approximately at the same time as on the central and southern sites, but the coverage was less than 80% during half of the time. Also, the sea ice never completely melted at those sites between the two years. At northern sites the sea ice formed in June and July and retreated by October or November. The average sea ice concentration during the time of coverage for sites 1 and 2 was 32% and 61%, respectively.

Sea ice concentration had a longer integral time scale for independence of estimates at all sites than call detections from either species, ranging from 8 to 53 days. There was a negative correlation between blue and fin whale calls and sea ice concentration at all sites on these weekly to monthly scales during the entire deployment period, although none of the p-values were statistically significant (Table 1; Figs. 4 and 6). On the annual scale, however, the year with longer sea ice coverage had more whale calls of both species.

While making minimum density estimates, we found one-minute intervals with more than one blue whale call on all the shelf break sites in a given day. Therefore we assumed two blue whales calling at each site on the shelf break, and no blue whales calling at the shelf sites, and obtained a blue whale density of 0.43 calling whales per 1000 n mi^2. To obtain the fin whale calling intensity that we observed on the northern sites, there had to be at least one fin whale calling for every second of the intercall interval, which is 13 s. So we assumed 15 simultaneously calling whales at each of the two northern sites, and no calls at other sites, and obtained a fin whale density of 1.30 calling whales per 1000 n mi^2 over the whole area, or 4.55 calling whales per 1000 n mi^2 at the northern sites.

4. Discussion

Blue whale calls were recorded intermittently year round, while fin whale calls were recorded

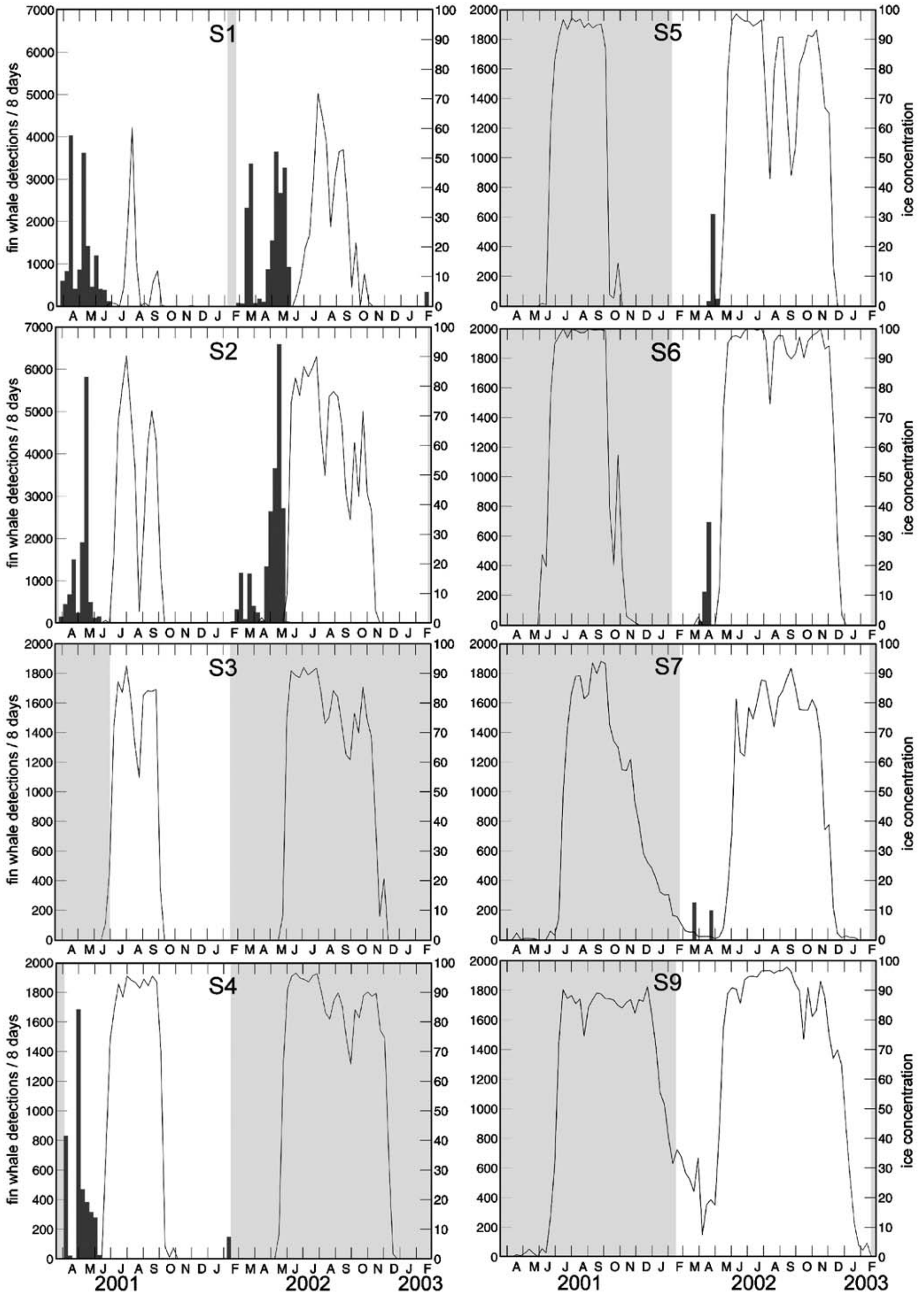

Fig. 6. Fin whale call automatic detections (bars) and sea ice concentration data (line) in 8-day bins for all sites. Gray rectangles represent periods during which there were no acoustic data. Note different scales for automatic detections between northern and all other sites.

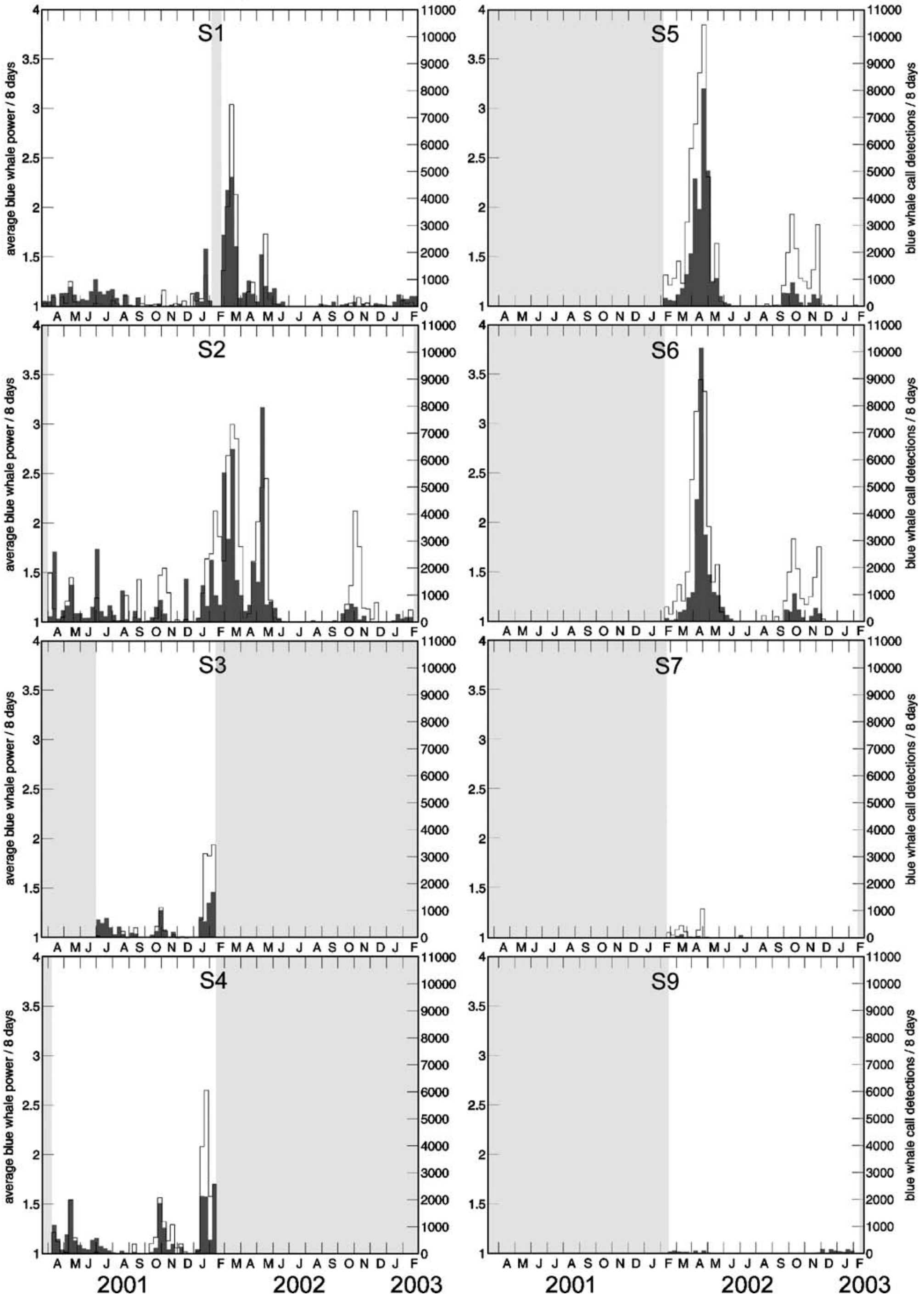

Fig. 7. Comparison of blue whale seasonality obtained by acoustic power (shaded bars) and automatic detection (clear bars) methods for all sites. Gray rectangles represent periods during which there were no acoustic data.

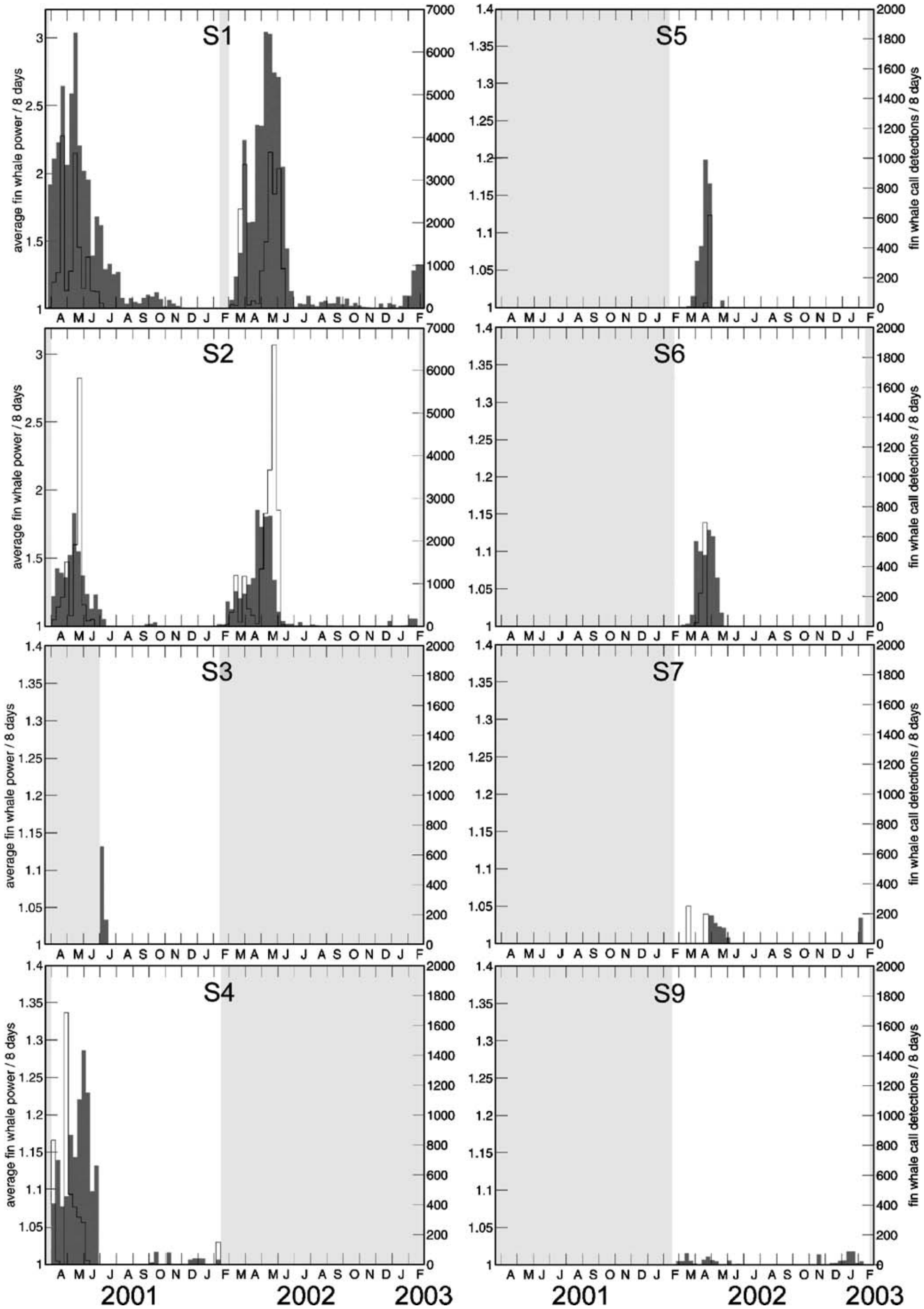

Fig. 8. Comparison of fin whale seasonality obtained by acoustic power (shaded bars) and automatic detection (clear bars) methods for all sites. Gray rectangles represent periods during which there were no acoustic data. Note different scales between northern and all other sites.

Table 1
Correlations between the number of blue and fin whale call detections and sea ice concentrations binned in N-day bins by year (a) and overall (b, when applicable)

(a)

	2001/02					2002/03				
	Blues		Fins			Blues		Fins		
Site	r	p	r	p	N	r	p	r	p	N
1	−0.052	>0.2	−0.163	>0.2	36	−0.225	>0.1	−0.295	>0.05	37
2	−0.321	>0.2	−0.297	>0.2	13	−0.469	>0.1	−0.346	>0.2	11
3	−0.640	>0.1	—	—	7	—	—	—	—	—
4	−0.488	>0.1	−0.379	>0.2	10	—	—	—	—	—
5	—	—	—	—	—	−0.300	>0.2	−0.283	>0.2	8
6	—	—	—	—	—	−0.120	>0.2	−0.207	>0.2	7
7	—	—	—	—	—	−0.461	>0.2	−0.462	>0.2	5

(b)

	Overall				
	Blues		Fins		
Site	r	p	r	p	N
1	−0.253	>0.2	−0.327	>0.1	21
2	−0.394	>0.05	−0.285	>0.2	19

Data for site 9 were not included since there were no whale call detections at that site.

only seasonally in continental slope and shelf waters off the Western Antarctic Peninsula. There was a clear temporal overlap in occurrence, as indicated by simultaneous reception of calls from the two species. More calls of each species were detected in the second year of deployment, which was also a year with longer sea ice coverage. On weekly to monthly time scales, however, whale calls from both species were negatively correlated with sea ice concentrations. Whales may have left the area or stopped calling as the sea ice began to form. The peak in calling for both species occurred about a month later during both years (March–May) than predicted from whaling data (February–March) (Mackintosh and Brown, 1956; Laws, 1961).

It is possible that the differences in the detections of the two species are due to the fact that the area we sampled is not an equally preferred habitat by blue and fin whales (Mackintosh, 1965). The sites on the continental shelf break (1–6) were located along the flowpath of the Antarctic Circumpolar Current (Hofmann et al., 1996). Those were the sites with high call detection rates for both species and they all had periods of open ocean as well as times with sea ice coverage. While blue whales are known to associate with sea ice (Mackintosh, 1965; Kasamatsu et al., 1988), fin whales are not (Mackintosh and Wheeler, 1929) and could be staying farther north. Notably, there were fewer fin whale calls on the southern sites, while blue whale call detections were highest at those sites. Sites 7 and 9, which were both on the continental shelf, had few or no calls from either species. It appears that blue and fin whales did not come onto the continental shelf for long periods of time and probably did not go into Marguerite Bay even at times when the sites were free from sea ice.

While it has been reported in both the northern and the southern hemispheres that blue whales can overwinter at high latitudes (Kellogg, 1929; Clark and Charif, 1998; Watkins et al., 2000; Stafford et al., 2001), Antarctic-type blue whale calls have been detected in the Eastern Tropical Pacific in

July (see Figs. 3A and B in Stafford et al., 1999a). The blue whale calling rate decreased at our instruments between June and August, suggesting that some northward migration may have taken place during the winter. Blue whale calls were detected at northern sites intermittently throughout the winter (June–October) 2001, indicating presence of at least some calling whales. This intermittent calling could be an implication of a time-lagged migration, or that some individuals skip migration. Our data are consistent with the IWC sightings data indicating that blue whale population in the Antarctic does not increase dramatically between November and February (Kasamatsu et al., 1996) and the whaling data showing blue whale presence in September and October (Horwood, 1986).

The cessation of fin whale calls in May is most likely an indication of fin whale migration out of the area, as it coincided with the sea ice formation across all sites. Fin whales did not start calling again before the middle of February. There have been suggestions that fin whales use repetitive calls as reproductive displays (Watkins et al., 1987; Croll et al., 2002) so in spring they could be present off the Western Antarctic Peninsula feeding (Mackintosh and Wheeler, 1929; Gaskin, 1982), but producing few or no calls. Autumn is the onset of their mating season (Laws, 1961) at which time they could start to engage in more frequent calling. Whaling records, however, show a higher proportion of fin whale catches after January (Kellogg, 1929; Mackintosh, 1965), just as the more recent IWC sightings data show increased sightings in January (Kasamatsu et al., 1996), indicating that a late-summer arrival to the Antarctic is a likely explanation for the February start of calling.

While more calls were detected during the year with longer sea ice cover, on shorter time scales sea ice concentration and whale calls were negatively correlated. This negative correlation on a shorter time scale is consistent with previous observations (Mackintosh, 1965), but the lack of significance in most cases could be due to the small independent sample sizes. The big increase in the number of calls between the two deployment years was not expected. It cannot be attributed to population growth because it would imply an increase of more than 30% in 1 year, which is an unrealistic growth rate. This increase in relative abundance could have resulted from the movement of animals from other areas of the Antarctic. However, the whaling and sightings data suggest limited meridional movement (Brown, 1954; Kasamatsu et al., 1996). Or it might be possible the differences between the years were related to the observed differences in sea ice conditions (Fraser et al., 1992; Nicol et al., 2000). Longer acoustic time series with year-round coverage could shed more light on this observation. Also, further comparisons of whale calls with other biological parameters (e.g. krill abundance) could reveal the causes of this increase in relative abundance.

Such comparisons also could further understanding of the apparent movements of these two species of whales. Both blue and fin whale calls were detected sequentially on instruments distributed along the continental shelf break, moving in the southwest–northeast direction. Since blue and fin whales feed in Antarctic waters (Mackintosh and Wheeler, 1929; Kawamura, 1980; Gaskin, 1982; Kawamura, 1994), their movement along the shelf could reflect the seasonality of their prey (Kellogg, 1929; Nemoto, 1957; Springer et al., 1999) and sea ice conditions. For example, the notable decline in blue whale call detections in late December and early January, which would not be predicted from the catch data (Mackintosh and Wheeler, 1929), could indicate that blue whales use a larger area for foraging than the area covered by our acoustic array and they could be further south during this period of low detections. A northeast–southwest movement pattern along the shelf break was especially noticeable from both blue and fin whale calls during the second year of deployment. During the austral summer this movement for both species was from the northern sites towards the southwest, and it reversed towards the northeast in the fall. In spring, blue whale calling occurred first at the southern sites and moved northeast again, but it reversed in late October and returned to the southern sites. There is clearly a bias in this interpretation due to the locations of instruments. However, this movement may be explained by productivity and sea ice patterns in the area (Siegel, 1988; Holm-Hansen and Mitchell, 1991; Ross and Quentin, 1996; Stammerjohn and Smith, 1996). During autumn, the whales may be moving north as the sea ice begins to form. In the spring, on the other hand, the first high blue whale call detections occurred at the southern sites, during a period when the sea ice cover was still substantial. At this time the whales could be following productivity blooms to the retreating ice edge.

We can make a comparison of whale densities between the acoustic data and visual census. Data from the circumpolar visual surveys conducted by the International Whaling Commission indicate an average density in the Antarctic of 0.32 blue whales per 1000 n mi^2 and 1.59 fin whales per 1000 n mi^2 (Branch and Butterworth, 2001). Minimum density estimates from the acoustic data can be considered conservative because we based them on the automatic detections, which are an underestimate of the total number of calls due to the omission of calls with a low signal-to-noise ratio. Also, we did not take into account gender (McDonald et al., 2001; Croll et al., 2002) or other factors that could affect calling. Still, our blue whale estimate is about one-third higher than the density estimate from visual surveys. Fin whale density values are equal to the values predicted from the visual surveys. In both the blue and fin whale cases presented here, the assumptions were very conservative given the real acoustic data, which indicates that, locally, both species are more abundant than the Antarctic-wide visual estimates predict. The calling ecology of blue and fin whales, however, is not well understood and needs to be explored further before we can interpret acoustic data in terms of blue and fin whale absolute abundance.

5. Conclusion

We have found passive acoustic detections to be a powerful tool for studying blue and fin whale seasonal occurrence in the Western Antarctic Peninsula. Acoustic data can be collected year-round despite the harsh environmental conditions present in the Southern Ocean. Periods of whale presence were revealed over the 24-month deployment period, showing different degrees of seasonality in the presence of both blue and fin whales. These results suggest that acoustic monitoring may be an efficient method of studying these animals in the Southern Ocean.

Our initial analysis has considered only the relationship between the sea ice and blue and fin whale calls. However, sea ice alone is not enough to provide a full explanation of the changes in whale calling and future analyses will include data on other biological and physical factors, which are available from the SO GLOBEC data sets. Knowledge of the behavioral context of calling is limited, despite some suggestions that calling sequences such as those reported here are primarily breeding displays by males (Watkins et al., 1987; McDonald et al., 2001; Croll et al., 2002). Knowledge of the ecology of calling, however, is necessary for understanding the role of calling in the life histories of these species. In addition, to census populations acoustically, data are needed to quantify the number of calling animals at any one time and the proportion of animals present that are calling. A combination of acoustic and behavioral data would enhance our ability to monitor calling whales over large regions and long time periods.

Acknowledgments

This work was supported by NSF Office of Polar Programs grant OPP 99-10007 as part of the SO GLOBEC program, with program guidance by Polly Penhale. We are grateful for the assistance of Raytheon Polar Services marine and science support personnel, the Masters, Officers and crew of ASRV L.M. Gould during cruises LMG01-03, LMG02-01A, and LMG03-02. We also acknowledge National Snow and Ice Data Center for the processing and distribution of sea ice concentration data. We thank Dr. Allan Sauter for assistance with ARP preparation and deployment, Jessica Burtenshaw for her help with sea ice data acquisition, and editor Dr. Daniel Costa and anonymous reviewers for helpful advice on this manuscript. This is U.S. GLOBEC contribution number 468.

References

Beklemishev, C.W., 1960. Southern atmospheric cyclones and the whale feeding grounds of the Antarctic. Nature 187, 530–531.

Bowen, W.D., Siniff, D.B., 1999. Distribution, population biology and feeding ecology of marine mammals. In: Reynolds, III, J.E., Rommel, S.A. (Eds.), Biology of Marine Mammals. Smithsonian Institution Press, pp. 423–484.

Branch, T.A., Butterworth, D.S., 2001. Estimates of abundance south of 60 S for cetacean species sighted frequently on the 1978/79 to 1997/98 IWC/IDCR-SOWER sighting surveys. Journal of Cetacean Research and Management 3, 251–270.

Brown, S.G., 1954. Dispersal in blue and fin whales. Discovery Reports 26, 355–384.

Brown, S.G., 1962. A note on migration of fin whales. Norsk Hvalfangst-Tidende 51, 13–16.

Clapham, P. J., Baker, C. S., 2001. How many whales were killed in the Southern Hemisphere in the 20th century? Report of the International Whaling Commission 53, 3 pp.

Clapham, P.J., Mattila, D.K., 1990. Humpback whale songs as indicators of migration routes. Marine Mammal Science 6, 155–160.

Clark, C.W., Ellison, W.T., 1988. Number and distributions of bowhead whales, *Balaena mysticetus*, based on the 1985 acoustic study off Pt. Barrow, Alaska. Report of the International Whaling Commission 38, 365–370.

Clark, C.W., Ellison, W.T., 1989. Numbers and distribution of bowhead whales, *Balaena mysticetus*, based on the 1986 acoustic study off Pt. Barrow, Alaska. Report of the International Whaling Commission 39, 297–303.

Clark, C.W., 1990. Acoustic behavior of mysticete whales. In: Thomas, J., Kastelein, R. (Eds.), Sensory Abilities of Cetaceans. Plenum Press, New York, pp. 571–583.

Clark, C. W., Charif, R. A., 1998. Acoustic monitoring of large whales to the west of Britain and Ireland using bottom-mounted hydrophone arrays, October 1996—September 1997. JNCC Report No. 281.

Clark, C. W., Fowler, M., 2001. Status of archival and analysis effort of acoustic recordings during SOWER and IWC cruises 1996-2000. Report of the International Whaling Commission SC/53/IA28, 9pp.

Clark, C.W., Fristrup, K.M., 1997. Whales '95: A combined visual and acoustic survey of blue and fin whales off Southern California. Report of the International Whaling Commission 47, 583–600.

Comiso, J., 1991. updated 2002. In: Maslanik, J., Stroeve, J. (Eds.), DMSP SSM/I Daily Polar Gridded Sea Ice Concentrations. Boulder CO, National Snow and Ice Data Center (Digital Media).

Costa, D.P., Crocker, D.E., 1996. Marine mammals of the Southern Ocean. In: Ross, R.M., Hofmann, E.E., Quentin, L.B. (Eds.), Foundations for Ecological Research West of the Antarctic Peninsula, vol. 70. American Geophysical Union, Washington DC, pp. 287–301.

Croll, D.A., Tershy, B.R., Hewitt, R.P., Demer, D.A., Fiedler, P.C., Smith, S.E., Armstrong, W., Popp, J.M., Kiekhefer, T., Lopez, V.R., Urban, J., Gendron, D., 1998. An integrated approach to the foraging ecology of marine birds and mammals. Deep-Sea Research II 45, 1353–1371.

Croll, D.A., Clark, C.W., Acevedo, A., Tershy, B.R., Flores, S., Gedamke, J., Urban, J., 2002. Only male fin whales sing loud songs. Nature 417, 809.

Croxall, J.P., Trathan, P.N., Murphy, E.J., 2002. Environmental change and Antarctic seabird populations. Science 297, 1510–1514.

Cummings, W.C., Thompson, P.O., 1971. Underwater sounds from the blue whale, *Balaenoptera musculus*. The Journal of the Acoustical Society of America 50, 1193–1198.

Curtis, K.R., Howe, B.M., Mercer, J.A., 1999. Low-frequency ambient sound in the North Pacific: long time series observation. The Journal of the Acoustical Society of America 106, 3189–3200.

Dawbin, W.H., 1966. The seasonal migratory cycle of humpback whales. In: Norris, K.S. (Ed.), Whales, Dolphins, and Porpoises. University of California Press, Berkeley, pp. 145–170.

Edds, P.L., 1982. Vocalizations of the blue whale, *Balaenoptera musculus*, in the St. Lawrence River. Journal of Mammalogy 63 (2), 345–347.

Edds, P.L., 1988. Characteristics of finback *Balaenoptera physalus* vocalizations in the St Lawrence estuary. Bioacoustics 1, 131–149.

Fiedler, P.C., Reilly, S.B., Hewitt, R.P., Demer, D., Philbrick, V.A., Smith, S., Armstrong, W., Croll, D.A., Tershy, B.R., Mate, B.R., 1998. Blue whale habitat and prey in the California Channel Islands. Deep-Sea Research II 45, 1781–1801.

Fox, C.G., Matsumoto, H., Lau, T.-K.A., 2001. Monitoring Pacific Ocean seismicity from an autonomous hydrophone array. Journal of Geophysical Research (Solid Earth) 106 (B3), 4183–4206.

Fraser, W.R., Trivelpiece, W.Z., Ainley, D.G., Trivelpiece, S.G., 1992. Increases in Antarctic penguin populations: reduced competition with whales or a loss of sea ice due to environmental warming? Polar Biology 11, 525–531.

Gaskin, D.E., 1982. The Ecology of Whales and Dolphins. Heinemann Educational Books Ltd., London, p. 459.

Hart, T.J., 1935. On the diatoms of the skin film of whales, and their possible bearing on problems of whale movements. Discovery Reports 10, 247–282.

Hofmann, E.E., Klinck, J.M., Lascara, C.M., Smith, D.A., 1996. Water mass distribution and circulation west of the Antarctic Peninsula and including Bransfield Strait. In: Ross, R.M., Hofmann, E.E., Quentin, L.B. (Eds.), Foundations for Ecological Research West of the Antarctic Peninsula, vol 70. American Geophysical Union, Washington, DC, pp. 61–80.

Holm-Hansen, O., Mitchell, B.G., 1991. Spatial and temporal distribution of phytoplankton and primary production in the western Bransfield Strait region. Deep-Sea Research 38, 961–980.

Horwood, J.S., 1986. The distribution of the Southern blue whale in relation to recent estimates of abundance. Scientific Reports of the Whales Research Institute 37, 155–165.

IWC, 2001. Report of the sub-committee on the comprehensive assessment of whale stocks—other stocks. Journal of Cetacean Research and Management 3 (Suppl), 209–228.

Kahru, M., 2000. Windows Image Manager—Image display and analysis program for Microsoft Windows with special features for satellite images, WWW page, http://wimsoft.com.

Kasamatsu, F., Hembree, D., Joyce, G., Tsunoda, L., Rowlett, R., Nakano, T., 1988. Distribution of cetacean sightings in the Antarctic: results obtained from the IWC/IDCR minke whale assessment cruises, 1978/79 to 1983/84. Report of the International Whaling Commission 39, 449–473.

Kasamatsu, F., Joyce, G.G., Ensor, P., Mermoz, J., 1996. Current occurrence of baleen whales in Antarctic waters. Report of the International Whaling Commission 47, 293–304.

Katona, S.K., Beard, J.A., 1990. Population size, migrations and feeding aggregations of the humpback whale (*Megaptera novaeangliae*) in the western North Atlantic Ocean. Report of the International Whaling Commission 12 (Special issue), 295–305.

Kawamura, A., 1980. A review of food of Balaenopterid whales. Scientific reports of the Whales Research Institute 32, 155–197.

Kawamura, A., 1994. A review of baleen whale feeding in the Southern Ocean. Report of the International Whaling Commission 44, 261–271.

Kellogg, R., 1929. What is known of the migrations of some of the whalebone whales. Smithsonian Institution Annual Report 1928, 467–496.

Laws, R.M., 1961. Reproduction, growth and age of southern fin whales. Discovery Reports 31, 327–486.

Ljungblad, D., Clark, C.W., Shimada, H., 1998. A comparison of sounds attributed to pygmy blue whales (*Balaenoptera musculus brevicauda*) recorded south of the Madagascar Plateau and those attributed to 'true' blue whales (*Balaenoptera musculus*) recorded off Antarctica. Report of the International Whaling Commission 49, 439–442.

Loeb, V., Siegel, V., Holm-Hansen, O., Hewitt, R., Fraser, M., Trivelpiece, W., Trivelpiece, S., 1997. Effects of sea-ice extent and krill or salp dominance on the Antarctic food web. Nature 387, 897–900.

Mackintosh, N.A., 1965. The Stocks of Whales. Fishing News (Books) Ltd., London, p. 232.

Mackintosh, N.A., 1966. The distribution of southern blue and fin whales. In: Norris, K.S. (Ed.), Whales, Dolphins, and Porpoises. University of California Press, Berkeley, pp. 125–144.

Mackintosh, N.A., Brown, S.G., 1956. Preliminary estimates of the southern populations of the larger baleen whales. Norsk Hvalfangst-Tidende 45, 469–480.

Mackintosh, N.A., Wheeler, J.F.G., 1929. Southern blue and fin whales. Discovery Reports 1, 257–540.

Mate, B.R., Lagerquist, B.A., Calambokidis, J., 1999. Movements of North Pacific blue whales during the feeding season off Southern California and their southern fall migration. Marine Mammal Science 15, 1246–1257.

Matsuoka, K., Murase, H., Nishiwaki, S., Fukuchi, T., Shimada, H., 2000. Development of a retrievable sonobuoy system for whale sounds recording in polar region. Presented to the IWC Scientific Committee (unpublished), 7pp.

McDonald, M.A., Hildebrand, J.A., Webb, S.C., 1995. Blue and fin whales observed on a seafloor array in the Northeast Pacific. The Journal of the Acoustical Society of America 98, 1–10.

McDonald, M.A., Calambokidis, J., Teranishi, A.M., Hildebrand, J.A., 2001. The acoustic calls of blue whales off California with gender data. The Journal of the Acoustical Society of America 109, 1728–1735.

Mellinger, D. K., 2001. Ishmael 1.0 User's Guide. NOAA Technical Memorandum OAR PMEL-120, available from NOAA/PMEL, 7600 Sand Point Way NE, Seattle, WA 98115-6349

Mellinger, D.K., Clark, C.W., 2000. Recognizing transient low-frequency whale sounds by spectrogram correlation. The Journal of the Acoustical Society of America 107, 3518–3529.

Mizroch, S.A., Rice, D.W., Breiwick, J.M., 1984. The blue whale, *Balaenoptera musculus*. Marine Fisheries Review 46 (4), 15–19.

Murase, H., Matsuoka, K., Ichii, T., Nishiwaki, S., 2002. Relationship between the distribution of euphausiids and baleen whales in the Antarctic (35 E–145W). Polar Biology 25, 135–145.

Nemoto, T., 1957. Foods of baleen whales in the Northern Pacific. Scientific Reports of the Whales Research Institute 12, 33–89.

Nicol, S., Pauly, T., Bindoff, N.L., Wright, S., Thiele, D., Hosie, G.W., Strutton, P.G., Woehler, E., 2000. Ocean circulation off east Antarctica affects ecosystem structure and sea-ice extent. Nature 406, 504–507.

Norris, T.F., McDonald, M., Barlow, J., 1999. Acoustic detections of singing humpback whales (*Megaptera novaeangliae*) in the eastern North Pacific during their northbound migration. The Journal of the Acoustical Society of America 106, 506–514.

Reid, K., Brierley, A.S., Nevitt, G.A., 2000. An initial examination of relationships between the distribution of whales and Antarctic krill *Euphausia superba* at South Georgia. Journal of Cetacean Research and Management 2, 143–149.

Reilly, S.B., Thayer, V.G., 1990. Blue whale (*Balaenoptera musculus*) distribution in the Eastern Tropical Pacific. Marine Mammal Science 6, 265–277.

Ross, R.M., Quentin, L.B., 1996. Distribution of Antarctic krill and dominant zooplankton west of the Antarctic Peninsula. In: Ross, R.M., Hofmann, E.E., Quentin, L.B. (Eds.), Foundation for Ecological Research West of the Antarctic

Peninsula, vol 70. American Geophysical Union, Washington, DC, pp. 199–217.

Siegel, V., 1988. A concept of seasonal variation of krill (*Euphausia superba*) distribution and abundance west of the Antarctic Peninsula. In: Sahrhage, D. (Ed.), Antarctic Ocean and Resources Variability. Springer, Berlin Heidelberg, pp. 219–230.

Smith, W.O., Nelson, D.M., 1985. Phytoplankton bloom produced by a receding ice-edge in the Ross Sea: spatial coherence with the density. Science 277, 163–167.

Springer, A.M., Piatt, J.F., Shuntov, V.P., Van Vliet, G.B., Vladimirov, V.L., Kuzin, A.E., Perlov, A.S., 1999. Marine birds and mammals of the Pacific Subarctic Gyres. Progress in Oceanography 43, 443–487.

Stafford, K.M., Fox, C.G., Clark, D.S., 1998. Long-range acoustic detection and localization of blue whale calls in the northeast Pacific Ocean. The Journal of the Acoustical Society of America 104, 3616–3625.

Stafford, K.M., Nieukirk, S.L., Fox, C.G., 1999a. Low-frequency whale sounds recorded on hydrophones moored in the eastern tropical Pacific. The Journal of the Acoustical Society of America 106, 3687–3698.

Stafford, K.M., Nieukirk, S.L., Fox, C.G., 1999b. An acoustic link between blue whales in the Eastern Tropical Pacific and the Northeast Pacific. Marine Mammal Science 15, 1258–1268.

Stafford, K.M., Nieukirk, S.L., Fox, C.G., 2001. Geographic and seasonal variation of blue whale calls in the North Pacific. Journal of Cetacean Research and Management 3, 65–76.

Stammerjohn, S.E., Smith, R.C., 1996. Spatial and temporal variability of western Antarctic Peninsula sea ice coverage. In: Ross, R.M., Hofmann, E.E., Quentin, L.B. (Eds.), Foundations for Ecological Research West of the Antarctic Peninsula, Vol. 70. American Geophysical Union, Washington DC, pp. 81–104.

Thompson, P., Findley, L.T., Vidal, O., 1992. 20-Hz pulses and other vocalizations of fin whales, *Balaenoptera physalus*, in the Gulf of California, Mexico. The Journal of the Acoustical Society of America 92, 3051–3057.

Tynan, C.T., 1998. Ecological importance of the southern boundary of the Antarctic Circumpolar Current. Nature 392, 708–710.

Watkins, W.A., 1981. Activities and underwater sounds of fin whales. Scientific reports of the Whales Research Institute 33, 83–117.

Watkins, W.A., Tyack, P., Moore, K.E., Bird, J.E., 1987. The 20-Hz signal of finback whales (*Balaenoptera physalus*). The Journal of the Acoustical Society of America 82, 1901–1912.

Watkins, W.A., Daher, M.A., Reppucci, G.M., George, J.E., Martin, D.L., DiMarzio, N.A., Gannon, D.P., 2000. Seasonality and distribution of whale calls in the North Pacific. Oceanography 13, 62–67.

Whitehead, H., Glass, C., 1985. The significance of the Southeast Shoal of the Grand Bank to humpback whales and other cetacean species. Canadian Journal of Zoology 63, 2617–2625.

Wiggins, S., 2003. Autonomous Acoustic Recording Packages (ARPs) for long-term monitoring of whale sounds. Marine Technology Society Journal 37 (2), 13–22.