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Sei whales are the least well known acoustically of all the rorquals, with only two brief descriptions of their calls previously reported. Recordings of low-frequency tonal and frequency swept calls were made near a group of four or five sei whales in waters west of the Antarctic Peninsula on 19 February 2003. These whales also produced broadband sounds which can be described as growls or whooshes. Many of the tonal and frequency swept calls (30 out of 68) consist of multiple parts with a frequency step between the two parts, this being the most unique characteristic of the calls, allowing them to be distinguished from the calls of other whale species. The average duration of the tonal calls is 0.45±0.3 s and the average frequency is 433±192 Hz. Using a calibrated seafloor recorder to determine the absolute calibration of a sonobuoy system, the maximum source level of the tonal calls was 156±3.6 dB *re* 1 μPa at 1 m. Each call had different character and there was no temporal pattern in the calling. © *2005 Acoustical Society of America.* [DOI: 10.1121/1.2130944]

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I. INTRODUCTION

Sounds produced by the sei whale (*Balaenoptera borealis*) are perhaps the most poorly documented for any rorqual. The two extant descriptions (Thompson *et al.*, 1979; Knowlton *et al.*, 1991) are for sei whales encountered near Nova Scotia in the North Atlantic, where two-part stereotyped pulsive bursts in the 1.5 to 3.5 kHz frequency range were recorded.

The taxonomy of sei whales has a complex history, particularly in relation to Bryde's whales, these species sometimes being grouped as the sei/Bryde's complex (Dizon *et al.*, 1996, 2000). New species within this group continue to be described (Wada *et al.*, 2003). At-sea identification of these species is difficult, but fortunately the geographic location of the observations reported here minimized the potential confusion, with only southern hemisphere sei whales (*Balaenoptera borealis schlegellii*) presumed to occur at the recording site (Rice, 1998).

Sei whales found in the Antarctic are migratory, spending the summer at high latitudes for feeding and the winter at lower latitudes for calving and breeding (Horwood, 1987). Only large animals are observed south of the Antarctic convergence (Lockyer, 1977). More than 130 000 sei whales have been harvested from south of 40 degrees latitude, reducing this population from about 100 000 in 1930 to about 16 000 in 1979 when harvesting stopped (Horwood, 1987). From historic data, the most common group sizes for sei whales south of 60° are one to four with ten being a maximum (Lockyer, 1977).

We present recordings of sounds produced by sei whales at frequencies below 1 kHz, west of the Antarctic Peninsula. These low-frequency sounds are distinctly different from the sounds previously described for sei whales, and possible explanations for the differences are discussed.

II. METHODS

A. Visual observations

The initial sighting of the sei whales we later recorded acoustically occurred during the recovery of a seafloor acoustic recording package (ARP) (Wiggins, 2003) with the Research Vessel *Laurence M. Gould* on 19 February 2003 at 1329 in approximately 3000 m of water. This work was part of a long-term project for monitoring whales acoustically with seafloor recorders, as part of the Southern Ocean GLOBEC project (Hofmann *et al.*, 2002; Širović *et al.*, 2004). The wind speed was 20 to 26 kts with an average sustained wind of 23 kts. Three experienced observers (Thiele, Moore, and Glasgow) were on the bridge wings with binoculars and cameras. Numerous photos were taken of dorsal fins, heads, and backs, although not of the lateral ridges on the rostrum. All observations were noted in a logbook, and ship locations and meteorological measurements were recorded by the ship's automated data logging systems.

B. Recording equipment

Two sonobuoys were deployed, the first a type SSQ-53D DIFAR buoy which provides magnetic bearing information to the whale calls (McDonald, 2004) and a type SSQ-57B omni directional broadband buoy. The recording system consisted of calibrated radios custom built by Greeneridge Sciences (Goleta, CA) and a Sony TCD-D8 digital recorder sampling at 48 kHz. Postcruise analysis of the data was done by digitally transferring the recordings to a computer hard drive with a Roland UA-30 external computer interface.

The frequency response of the radios is flat (±1 dB) across the 100 to 1000 Hz band where the whale calls occur, then rolls off 5 dB from 1 to 10 kHz. The frequency response of the 57B sonobuoy is considered usable from 20 Hz to 40 kHz and has slightly greater than 4.5 dB per octave greater sensitivity on the higher frequencies up to approximately 10 kHz. The 53D DIFAR sonobuoy has useful frequency response from 10 Hz to 4 kHz (McDonald, 2004) and has slightly greater than 6 dB/oct greater sensitivity on higher frequencies up to approximately 1200 Hz. The Sony D8 recorder has a flat frequency response (±1 dB) from 20 Hz to 20 kHz.

The seafloor ARP was calibrated at the U.S. Navy's Transducer Evaluation Center (TRANSDEC) in San Diego. The sampling rate for the ARP was 500 samples per second and recording was continuous throughout the deployment. The hydrophone is floated 10 m above the seafloor, except when the recorder is floating on the surface and the hydrophone is suspended 1 to 2 m below the surface.

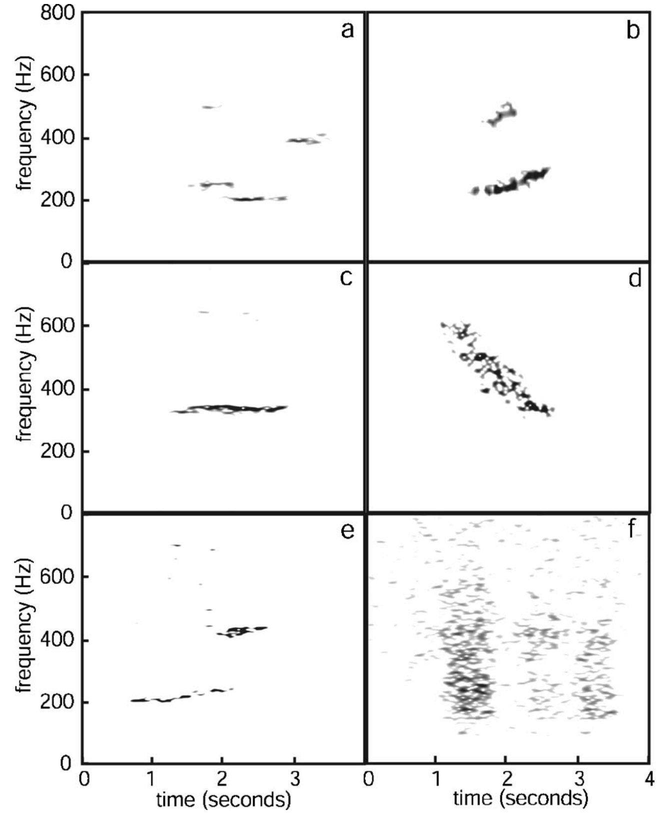

FIG. 1. Spectrograms are shown for an example in each call category: (a) multi-part frequency stepping tonals, (b) upsweep, (c) tonal, (d) downsweep, (e) upsweep stepping up, and (f) a series of three broadband calls. All spectrograms were made with a FFT length of 0.25 s, 95% overlap, and a Hanning window.

III. RECORDINGS

When the seafloor ARP was spotted floating at the surface, a group of sei whales (four to five individuals) was seen near it at 63° 51.63′ S 67° 0.82′ W. The recorder was brought on board at 1350 while the whales remained within 1–2 nm of the vessel. A second group of four to five sei whales was subsequently seen within 4 km of the first group. Both groups exhibited active surface behaviors and very dynamic group composition—the whales appearing to split and merge in the short time we could observe them before steaming on.

We began deploying sonobuoys as we departed the ARP recovery site. Multiple groups of whales could be seen ahead of the ship at this time, with one group directly in the track of the ship. We deployed a DIFAR buoy at 1400 to a depth of 1000 ft (305 m) and an omnidirectional buoy at 1405 to a depth of 90 ft (27 m), while taking photos of a group of sei whales which passed directly off the starboard side of the vessel. These individuals could be seen within 200 m of the vessel, including from the starboard portholes while starting the recording system. The precise time of this observation was unfortunately not recorded, but it is presumed to have been just after 1401. There were four individuals in this group and side lunge feeding behavior was observed.

At 1413, the ship's 3.5-kHz sonar was secured to reduce acoustic interference with the recordings. At 1421 the R/V *Gould* was stopped at a distance of 5 to 6 km from the sonobuoys, well within radio range, and the propellers were declutched. Ship noise, which was apparent on the sonobuoys while the ship was underway, was thereby reduced to a nearly undetectable level when the ship was stopped. After the ship was stopped, three groups of surface active whales remained under observation: six animals, four animals, and four animals with one group within 2 km of the sonobuoys. The whales did not appear to react to the vessel, but continued with the feeding and surface-active behaviors as seen upon ship's approach. Overall, sei whale calls were recorded from 1408 until 1528 when radio reception for the sonobuoys became poor. No marine mammals of other species were sighted for many hours before or after the sei whale sightings.

IV. ANALYSIS

A. Classification

We broadly categorize the calls into (1) tonal and frequency swept calls and (2) broadband calls (Fig. 1). The audible character of the tonal and frequency swept sounds can be described as "moans" while the broadband sounds have been variously described as "growls," "blows," or "whooshes" by different listeners hearing the same sounds. We recorded 68 distinct calls in the tonal and frequency swept category and some greater number of broadband calls. It is not possible to describe precisely how many sounds were produced by the whales because the signal-to-noise ratio of the calls becomes the determining factor in deciding if a sound should be counted as a whale call.

Of the 68 calls in the tonal and frequency swept category, we consider 18 to be frequency swept and 50 to be

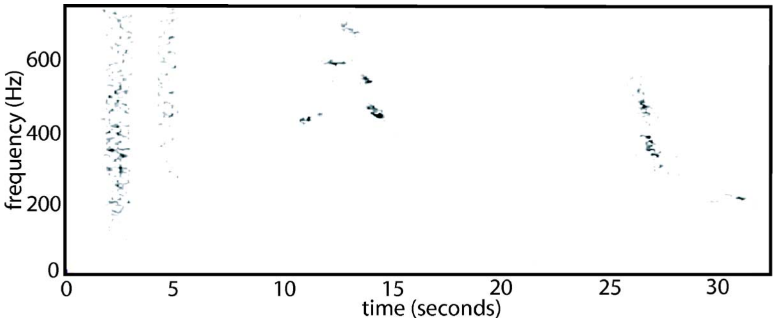

FIG. 2. A cluster of sei whale calls is illustrated, starting with two broadband calls at 2 and 4 s, followed by a five component call starting at 10 s, a broken or two part downsweep at 27 s and a weak downsweep at 31 s.

tonal sounds. Of the tonals, 28 were multi-part calls, stepping in frequency, though each part is of relatively constant frequency. Calls were judged to be multi-part only when the end of one part coincides with the beginning of another, without pause. Calls were clustered in time (Fig. 2), although this may be in part due to the location of the whales relative to the sonobuoys with the more distant calls not clearly recorded above the ambient noise.

B. Quantitative call descriptors

Duration and frequencies were measured for the 50 tonal calls. Of the 50 tonal calls, 22 consisted of one part, 16 of two parts, 9 of three parts, 2 of four parts, and 1 of five parts. There were 94 tones identified within the 50 tonal calls with durations [Fig. 3(a)] and frequencies [Fig. 3(b)] averaging 0.45 ± 0.30 s and 433 ± 192 Hz, respectively. The mean duration of the two-part calls was 0.9 s, very near twice the mean of the duration of the single-tonal sounds, suggesting tonal components are static components of multi-part calls.

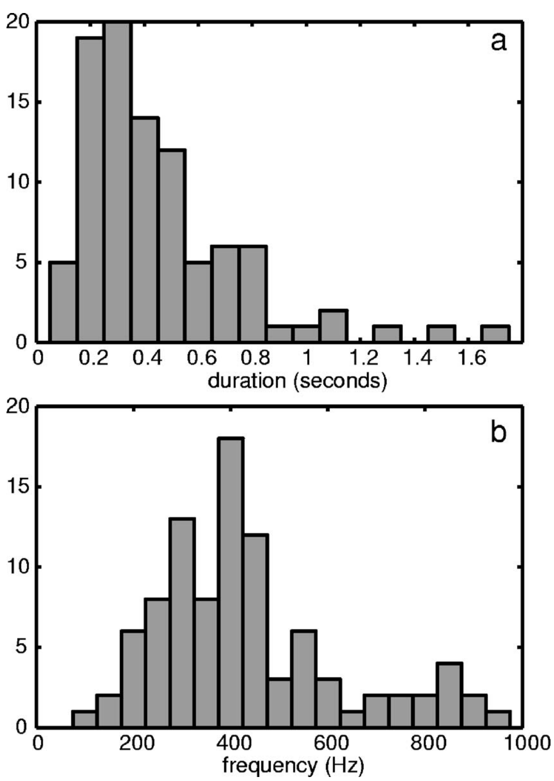

FIG. 3. Histograms of the (a) duration and (b) frequency of the 94 tonal call components from the 50 tonal calls.

The 18 frequency swept calls have an average midpoint (halfway in time from start to finish) frequency of 432 ± 151 Hz and an average duration of 1.1 ± 0.6 s. The average frequency sweep was 178 ± 141 Hz. Only two of the frequency swept calls also contained a frequency step, as illustrated in Figs. 1(e) and 2. The total durations of the two multipart calls containing sweeps were 1.9 and 3.7 s.

The frequency shifts in the sei whale calls range from less than one semitone to almost one octave or one harmonic. Note that none of the shifts are greater than one octave even though the frequency range of the calls covers more than two octaves. There is no apparent bias in frequency step size associated with the start frequency or the direction of the frequency step. Neither are there any dominant ratios in the frequency changes.

C. Acoustic localization of calls

Using the bearings to calls from the DIFAR sonobuoy together with the time difference of arrival (TDOA) of the sounds on the two sonobuoys, we compute locations for whale calls which had a sufficient signal-to-noise ratio on both sonobuoys (Fig. 4). The locations are at the intersection of the hyperbola resulting from the TDOA and the line from the DIFAR bearing. Errors in these locations can be roughly estimated from the previously established errors in similar DIFAR bearings to whale calls (McDonald, 2004) and an estimate of the errors in picking TDOA from the spectro-

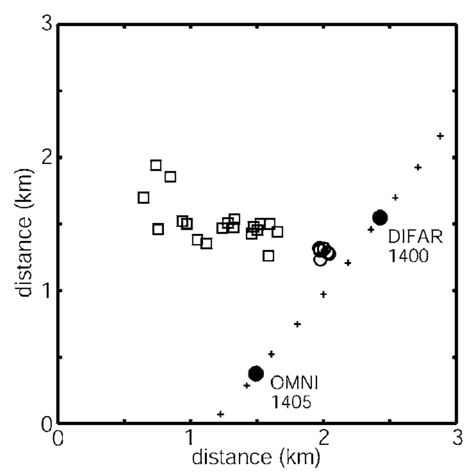

FIG. 4. The open squares indicate the locations of tonal and sweep calls, while the open circles indicate the location of broadband type calls. The plus symbols indicate the ship track at 1-min intervals and the filled circles indicate the sonobuoy locations.

grams. We consider the 95% confidence interval to be on the order of 500 m, primarily due to picking errors in TDOA. Tonal and frequency swept calls are most easily localized, while the signal-to-noise ratio prevents localization of broadband calls except at locations almost between the sonobuoys. The coincident locations and times of some of the broadband calls with the locations of tonal and frequency swept calls gives us confidence these calls were produced by the sei whales.

D. Source levels of calls

We cannot provide direct measurements of received sound pressure level for the sei whale calls because our sonobuoy recording system was not calibrated in absolute terms, but only in frequency response and as one sonobuoy relative to the other. However, the ARP was calibrated and gives an ambient background noise spectral density of 72.5 dB *re* 1 $\mu\mathrm{Pa}^2/\mathrm{Hz}$ at 220 Hz on the seafloor averaged over the hour before the ship arrived on location. For comparison purposes a one-week average level before the ship arrived in the area was determined by averaging 200-s windows, one every 4.4 min, yielding an average noise spectral density of 72.2 dB *re* 1 $\mu\mathrm{Pa}^2/\mathrm{Hz}$ at 220 Hz.

While the ARP was on the surface and distant from the ship, as it serendipitously was for 4 h in this case, the noise spectral density was 75 dB *re* 1 $\mu\mathrm{Pa}^2/\mathrm{Hz}$ at 220 Hz, as averaged from numerous 5-s intervals which were chosen to be in between obvious breaking wave noise and the greatest hydrophone movement noise. The average noise spectral density including all the hydrophone movement and breaking waves was 80 dB *re* 1 $\mu\mathrm{Pa}^2/\mathrm{Hz}$ at 220 Hz.

Based on our measured spectral densities at 220 Hz of 72.5 dB at depth when wind speed was 17 kts (9 m/s) and 75 dB at the surface when wind speed had increased to 23 kts (12 m/s) we estimate the 220-Hz noise spectral density at the sonobuoy hydrophone depths of 120 and 300 m to be 73 ± 2 dB. Not all the hydrophone motion could be avoided in the measurements at the surface and we expect the surface noise to be slightly higher than the seafloor noise in an environment where the SOFAR channel is at the surface (Wagstaff, 1981; Bannister, 1986). We use the 73 ± 2 dB ambient noise spectral density estimate at 220 Hz at the sonobuoy hydrophones as our basis and the known frequency response of each component in the recording system to estimate the received sound pressure levels of the whale calls. The ambient noise spectra calculated from the two sonobuoys agree within 2 dB across the frequency range 200 to 900 Hz, the frequency band important to the whale calls and the ambient noise reference, but diverge outside these frequencies. The divergence may be caused by the difference in deployment depths of the sonobuoy hydrophones (27 and 305 m) coupled with the high sea state and hydrophone suspension limitations.

The recorded sound pressure levels of the sei whale calls were measured in 10-Hz bands rather than as 1-Hz spectral densities because the duration of the calls were so short that a 1-Hz bin would have necessarily included times outside the call duration. Little or no correction is needed to reduce these sound pressure levels to the standard 1-Hz spectral density reference because the signals analyzed are all greater than 10 dB above the background noise level and are considered to be contained within a 1-Hz bandwidth. The calls analyzed were 12 to 22 dB above background noise at 0.9- to 1.8-km distances from the sonobuoys. Many calls detected were beyond these ranges, but could not be analyzed because they could not be localized. Assuming spherical spreading loss and no significant absorption, the propagation losses are 59 to 65 dB, respectively, for ranges 0.9 and 1.8 km. Calculated source levels are 147 to 156 dB rms *re* 1 μPa at 1 m using the aforementioned 73 dB background ambient level to calibrate the sonobuoy systems. The lower bound on source level is biased by the limits of our ability to measure the source level rather than an actual lower bound on call sound pressure levels, but the 156 dB rms *re* 1 μPa at 1 m is considered an approximate limit for the highest sound pressure levels recorded. Estimation of error for the 156 dB maximum call level is a combination of our 95% error estimate for the ambient noise spectral density of ±2 dB and the error in propagation loss due to error in call localization. The 95% confidence interval for the propagation loss error due to localization error (±500 m) averages 3 dB, more at shorter ranges and less at the furthest ranges. Combining the two errors as the square root of the sum of the errors squared gives a 95% error estimate of ±3.6 dB.

V. DISCUSSION

Sei whale calls recorded in the North Atlantic are stereotyped two part calls in the 1.5 to 3.5 kHz band, as reported by Knowlton *et al.* (1991) and Thompson *et al.* (1979). These mid-frequency calls are distinctly different from the low-frequency calls we report here for sei whales recorded west of the Antarctic Peninsula. All reported sei whale recordings, including our own, were made during late summer, which is believed to be the breeding season (Horwood, 1987; Budylenko, 1977). Knowlton *et al.* (1991) reports recording the 1.5 to 3.5 kHz sound on all 16 of the recording sessions during which sei whales were seen and on 6 of 16 sessions when sei whales were not seen. Our recordings covered the 10 Hz to 24 kHz band yet careful review detected no sounds resembling those of Knowltons' recordings. Undoubtedly habitat, season, location and specific activity influences the type of sounds produced by sei whales.

While reasons for differences between the North Atlantic and Antarctic sei whale calls are unclear, it may be that stereotyped high-frequency sounds reported for sei whales by Knowlton *et al.* (1991) and Thompson *et al.* (1979), represent a reproductive "song," while the lower-frequency sounds that we report represent feeding or social calls. Such a dichotomy may be analogous to minke whales which produce both relatively simple low frequency calls, and more complex high frequency stereotyped calls. The high frequency stereotyped calls appear to vary geographically and to be produced seasonally (Edds-Walton, 1997; Mellinger *et al.*, 2000; Gedamke *et al.* 2001, 2003; S. Rankin and J. Barlow, unpublished manuscript; Thompson and Friedl, 1982; authors, unpublished data).

The frequency stepping character of the tonal calls [e.g., Fig. 1(a)] make the sei whale calls reported here distinctive from any other known whale calls. While we cannot rule out the possibility that the two part calls were in fact made by two nearby animals interacting, the coincidence of the end of the previous part coinciding with the start of the next part at a different frequency suggests these are multipart calls made by one whale.

We find no temporal pattern in the recorded calls and each call shows different frequencies and character. Given the irregular nature of these calls, the relatively low source levels as compared to other baleen whale calls (Richardson *et al.*, 1995) and the offshore distribution of sei whales (Horwood, 1987; Gregr and Trites, 2001), perhaps it is not surprising that these calls have not been previously reported in the published literature.

The production of low frequency calls by sei whales is consistent with the behavior of all other rorquals. The low source levels of these calls suggest that they are intended for communication over limited distances of at most a few kilometers. Knowledge of these calls, however, may allow for monitoring of sei whale presence using long-term passive acoustic recordings (Clapham *et al.*, 1999).

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