Blue and fin whale call source levels and propagation range in the Southern Ocean

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Blue (*Balaenoptera musculus*) and fin whales (*B. physalus*) produce high-intensity, low-frequency calls, which probably function for communication during mating and feeding. The source levels of blue and fin whale calls off the Western Antarctic Peninsula were calculated using recordings made with calibrated, bottom-moored hydrophones. Blue whales were located up to a range of 200 km using hyperbolic localization and time difference of arrival. The distance to fin whales, estimated using multipath arrivals of their calls, was up to 56 km. The error in range measurements was 3.8 km using hyperbolic localization, and 3.4 km using multipath arrivals. Both species produced high-intensity calls; the average blue whale call source level was 189±3 dB *re*:1 μPa-1 m over 25–29 Hz, and the average fin whale call source level was 189±4 dB *re*:1 μPa-1 m over 15–28 Hz. Blue and fin whale populations in the Southern Ocean have remained at low numbers for decades since they became protected; using source level and detection range from passive acoustic recordings can help in calculating the relative density of calling whales. *© 2007 Acoustical Society of America.* [DOI: 10.1121/1.2749452]

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I. INTRODUCTION

Blue (*Balaenoptera musculus*) and fin whales (*B. physalus*) were the primary targets of the commercial whaling industry that developed in the Southern Ocean during the twentieth century. Populations of both species were brought to near extinction before their hunt was banned in the 1960's and 70's (Clapham and Baker, 2001), and their population recovery has been slow (Best, 1993; Branch and Butterworth, 2001; Branch *et al.*, 2004). Both species produce calls that are likely to be an important part of the mating and feeding behaviors (Watkins *et al.*, 1987; McDonald *et al.*, 2001; Croll *et al.*, 2002; Oleson *et al.*, 2007), and it has been established that certain baleen whale calls can be detected at ranges of hundreds of kilometers (Cummings and Thompson, 1971; Payne and Webb, 1971; Clark, 1995; Stafford *et al.*, 1998). Payne and Webb (1971) postulated that long-range propagation might be important for communication with conspecifics over large distances, and the low population densities resulting from commercial whaling (Branch and Butterworth, 2001) could make this type of communication even more important for species survival.

Several methods have been developed for acoustic localization and source level estimation in the marine environment (e.g., Frazer and Pecholcs, 1990; Cato, 1998; Jensen *et al.*, 2000; Spiesberger, 2001). The theory was developed predominately for naval and seismic purposes, but similar methods can be used to determine locations and source levels of calling cetaceans in the wild (Watkins and Schevill, 1972; McDonald *et al.*, 1995; Stafford *et al.*, 1998; McDonald and Fox, 1999; Clark and Ellison, 2000; Thode *et al.*, 2000; Charif *et al.*, 2002). Blue and fin whales make distinctive low-frequency, high-intensity calls that vary geographically (Cummings and Thompson, 1971; Watkins, 1981; Edds, 1982; 1988; Clark, 1995; McDonald *et al.*, 1995; Ljungblad *et al.*, 1998; Stafford *et al.*, 1999; McDonald *et al.*, 2006), and their source levels have been estimated at several worldwide locations. Cummings and Thompson (1971) estimated source level of blue whale moans off Chile in the 14 to 222-Hz band to be 188 dB *re*:1 μPa at 1 m. Calls of blue whales from the eastern North Pacific Ocean had maximum intensity 180–186 dB *re*:1 μPa at 1 m over the 10–110-Hz band (Thode *et al.*, 2000; McDonald *et al.*, 2001). Fin whale downswept call source levels have been reported at 160–186 dB *re*:1 μPa at 1 m in the western North Atlantic and between 159 and 184 dB *re*:1 μPa at 1 m in the eastern North Pacific Ocean (Watkins, 1981; Watkins *et al.*, 1987; Charif *et al.*, 2002). Northrop *et al.* (1968) reported fin whale downsweeps of even higher intensity in the Central Pacific Ocean, ranging between 164 and 199 dB *re*:1 μPa at 1 m, albeit assuming relatively high transmission loss.

Frequency and temporal characteristics of blue and fin whale calls in the Southern Ocean have been described previously (Ljungblad *et al.*, 1998; Širović *et al.*, 2004; Rankin *et al.*, 2005). Blue whale calls last up to 18 s and generally consist of three segments: a 9-s-long, 27-Hz tone, followed by a 1-s downsweep to 19 Hz and another, longer-lasting downsweep to 18 Hz (Širović *et al.*, 2004; Rankin *et al.*, 2005). Fin whales produce short (< 1 s) downsweeps from 28 to 15 Hz (Širović *et al.*, 2004, 2006). Calls of both species are usually repeated at regular intervals. No call source levels from either species have been reported for the Southern Ocean.

Call intensity may be important for successful intraspecific communication over long distances, and needs to be quantified before we can understand the potential impacts of

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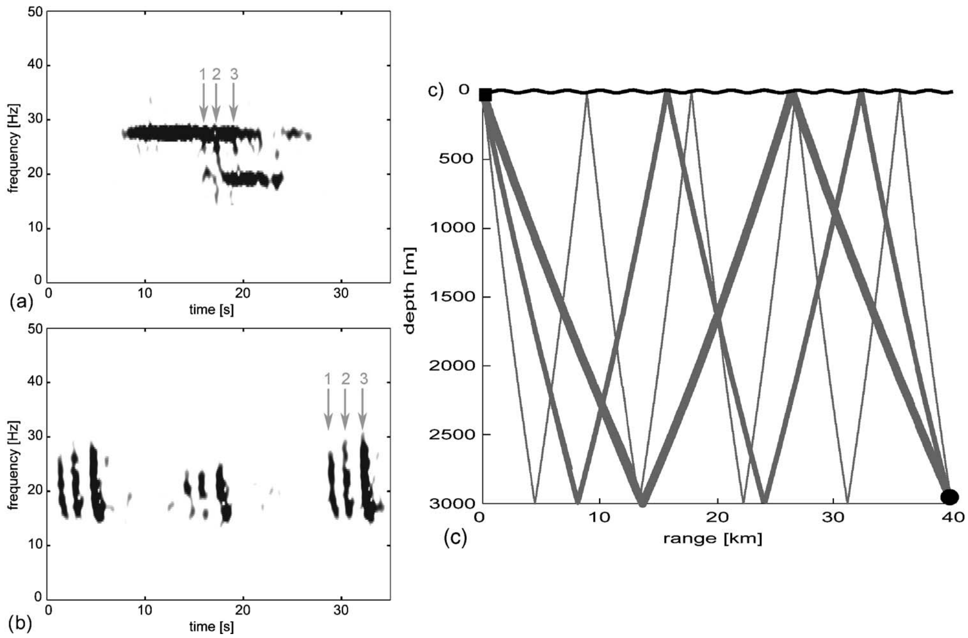

FIG. 1. Blue (a) and fin whale (b) calls recorded off the Western Antarctic Peninsula, showing multipath arrivals. In both examples, paths shown were first, second, and third bounces (marked 1, 2, and 3, respectively); direct path is not visible. Calculated ranges were 33 km for the blue whale and 40 km for the fin whale. Theoretical contributing bounces for the fin whale path arrivals are shown in part (c), with the thick line representing the first bounce, the medium thickness line for the second bounce, and the thin line for the third bounce. Calling whale location is denoted with a black square and the receiving ARP location is shown by a black circle.

anthropogenic noise on these animals. In this paper, we report the average estimated source levels for blue and fin whale calls recorded off the Antarctic Peninsula and investigate the variation in the source levels within the population. Also, we calculate the ranges over which these calls can be expected to propagate, using the average noise levels for this region.

II. METHODS

Acoustic data were recorded using Acoustic Recording Packages (ARPs) deployed off the Western Antarctic Peninsula between March 2001 and February 2003. Detailed information on ARPs, these deployments, and temporal characteristics of blue and fin whale calls used in the analyses is given in Wiggins (2003) and Širović *et al.* (2004). The ARPs were not navigated after deployment for precise locations and the maximum error in the deployment locations is less than 1 km, given the average ARP sinking speed (40 m/min to 3500-m depth) and assuming maximum speed of the Antarctic Circumpolar Current [15 cm/s, Pickard and Emery (1990)].

The goals of the study were to calculate blue and fin whale call source levels and to estimate the maximum range over which these calls can be heard. Data needed for call source level estimation are the instrument response, distance to the calling whales, and knowledge of the ocean propagation environment. Two methods were used to determine range to the calling whales: multipath arrivals and time difference of arrivals.

A. Multipath arrivals

As sound travels through the water column from the source to the receiver, it can follow a direct path, or it can be reflected off the surface and the bottom. The arrival time differences of those multipaths to a single receiver can be used to determine the distance between the source and the receiver. Both blue and fin whale calls were suitable for this analysis because the downswept parts of their calls made it possible to distinguish exact multipath arrival times (Fig. 1). Arrival time for the downsweep was measured in the time-frequency domain at the time of the highest frequency for all multipaths, and the differences between the multipath arrival times were calculated. Spectral parameters were set to 500-point FFT and 90% overlap. Calls with multiple arrivals were found only at one instrument at a time and only calls with three or more multipath arrival times and good signal-to-noise ratios were used in the analysis. The error in the calculation of the arrival time differences was determined by taking multiple measurements of the multipath arrival times of an individual whale call. The range to the calling whale was calculated separately for each measurement and the standard deviation of those ranges was reported.

The following assumptions were made in the multipath arrival model: whale calling occurred near the surface, instruments were located on the bottom, the sound-speed profile was homogeneous ($c = 1480$ m/s), and the bottom was flat. Blue whales are known to make calls at depths of 20–30 m (Thode *et al.*, 2000; Oleson *et al.*, 2007), and the calling depth for fin whales is reported to be around 50 m (Watkins *et al.*, 1987). The hydrophone was suspended 10 m above the ocean floor. Given the water column depth of around 3000 m, differences in water column depth < 100 m could reasonably be approximated as calling at the surface and receiver on the bottom. All the ARPs used in these analyses were deployed in locations close to the shelf break, but the regions away from the shelf break had a relatively flat or slightly sloping bottom. This region is an upward-refracting environment (Urick, 1983), so the calls produced in the relatively shallow water on the shelf and shelf break could not be recorded by the ARPs located in deep water (see Sec. II D below). Therefore, whales that were recorded on the ARPs were known be located in the region away from the shelf break, and flat bottom was a good assumption.

The range was determined by comparing the measured arrival time differences with the modeled data. The measured arrivals were assigned to successive modeled bounce times to determine a possible range for each arrival separately, starting from the direct path and the first measured arrival and stopping at the sixth bounce and the last measured arrival. The average range and standard deviation were calculated for each sequence of measured arrival-bounce path pairs. The range with the lowest standard deviation was used for all further calculations.

Determining the range to calling animals using multipath arrivals was possible only at times when there were no overlapping calls. This method estimated only the distance to the calling whale from the ARP, not the location of the calling whale. The range information, however, was sufficient for source level calculations.

B. Time difference of arrival and hyperbolic localization

Blue whale calls were recorded on an array of ARPs, enabling comparisons of arrival times of the same call to multiple instruments. To use time difference of arrival (TDOA) for determining range and location, a minimum of three instruments needs to receive the same call (Spiesberger, 2001). Periods when the same calls were recorded on multiple instruments were identified by finding sections that had blue whale call sequences with matching intercall intervals. This was possible because the ambient noise at this frequency range is low in the Antarctic, there were not many other calling animals present, and blue whale calls are produced in long, repetitive sequences. Search times were limited by the maximum possible travel time difference between the instruments. Once a matching sequence was identified on three instruments, arrival times of blue whale calls to each instrument were measured by an analyst in the time-frequency domain (i.e., using spectrograms with 500-point FFT and 90% overlap). The point used as the arrival time was the beginning of the first downswept segment of the blue whale call (Fig. 1). Instrument clocks drifted between 2:54 and 5:57 over the course of the deployment period (321 days). We corrected the times assuming linear drift and calculated the TDOA for each instrument pair.

The TDOA between pairs of instruments confine possible locations of the calling animal in two dimensions to a hyperbola. When multiple pairs of instruments are used, the intersections of these hyperbolas give the location of the caller. Hyperbolic localization software developed and made available by Mellinger was used for localization. This localization method assumed homogeneous sound-speed profile ($c = 1480$ m/s). The location of the caller was calculated using the Lavenberg-Marquardt nonlinear least-squares optimization of the resulting intersections of the three hyperbolas. Range from the whale to each instrument was calculated from the resulting location. The mean error was calculated as the difference between the actual and theoretically calculated optimized TDOA (Clark and Ellison, 2000). The geometry of the ARP array resulted in an east-west ambiguity for all the localizations. The ambiguity was resolved due to the bathymetric constraints of the environment (Spiesberger, 2001), using BELLHOP ray trace modeling (see Sec. II D below). However, the range value is the same for both solutions, so even if the ambiguities in the hyperbolic localization results were not resolved, the source level results would not be affected. This method was feasible only for blue whale localization.

We compared the two methods using blue whale calls which exhibited multipath arrivals and which could be located using TDOA. The range results were calculated from 14 blue whale calls, from assumed at least four different whales on three different days using the two methods. A paired t-test was performed to determine if the results obtained using these two methods were significantly different and the average difference between the results is reported.

C. Source level calculations

The call source level was calculated as the sum of the measured received level (RL) and the calculated transmission loss (TL). The received level was measured for all calls with calculated range from time-averaged power spectrum densities. Power spectra were calculated using 500-point FFT, 90% overlap, and Hanning window. Parseval's theorem was applied to calculate the total received level in the frequency band of interest. For blue whale calls, 6 s of the call over the 25–29-Hz frequency band prior to the first downsweep were used. Fin whale call received level was measured over a frequency band 15–28 Hz starting at the beginning of the call and lasting 1 s. The hydrophones used for received level measurements were calibrated at the U.S. Navy facility in Point Loma, CA. System frequency response from 10–250 Hz was measured and a calibration of -71.3 dB $re:\text{counts}^2/\mu\text{Pa}^2$ in the 20–30-Hz band was applied to the measured received levels (McDonald, 2005).

The transmission loss can be described as a function of range (r) as follows:

$$\mathrm{TL} = X \log\left(\frac{r}{r_0}\right),$$

where X is the environment-dependent transmission loss coefficient, and r_0 is the reference range, taken to be 1 m. X has the value of 10 under cylindrical and 20 under spherical spreading conditions. While the ranges over which the calls propagated were much larger than the depth of the seafloor and thus spherical spreading did not apply, the polar environment is generally upward refracting (Urick, 1983) and is a propagation environment that is an intermediate between cylindrical and spherical spreading assumptions. To estimate the value of X applicable for this study, we used an empirical method where the transmission loss coefficient was calculated from the relationship between the received levels and the ranges of blue whale calls calculated using hyperbolic localization,

$$X = \frac{\mathrm{RL}_2 - \mathrm{RL}_1}{\log(r_1) - \log(r_2)}.$$

Data from all the blue whale calls had to be pooled to obtain a large enough range distribution to smooth out convergence effects and provide a robust X estimate. This empirical value of X was verified theoretically using BELLHOP incoherent transmission loss models with the appropriate environmental parameters (see Sec. II D below). In this case, bathymetry was assumed to be upwards sloping, with a steep shelf break on one side.

The source level of each blue whale call was calculated separately for each instrument, giving three estimates. The average of these three values was used as the calculated source level of each call. Standard deviation of each estimate was calculated, and their average is reported and compared to the expected variation in the source level based on the error in range estimation. Only one source level estimate was available for each fin whale call because each range was calculated using only a single instrument recording.

D. Sound propagation modeling

BELLHOP ray-trace modeling was used to verify if calls produced on the shelf could be heard on the ARPs, to resolve the east-west ambiguity in the hyperbolic localization results, and to check the flat bottom assumption from the multipath model. For this problem, we assumed the calling whale was 5 km from the edge of the shelf (which was less than the minimum distance from the hyperbolic localization results) and that the depth increased from 500 m on the shelf to 3500 m off the shelf, over a 15-km distance, and then sloped gradually. The following assumptions were the same for both transmission loss modeling, and the resolution of the east-west ambiguity. The ocean and the bottom sound-speed properties were range independent. The sound-speed profile was obtained from the average of expendable bathythermograph (XBT) casts in the vicinity of the instruments during the seasons when calls were localized. Source depth was 30 m, and we used multiple receiver depths and ranges, at 100-m and 1-km intervals, respectively. The modeling was done for 27 Hz (the frequency of the blue whale tonal segment) and 22 Hz (the middle frequency of the fin whale call).

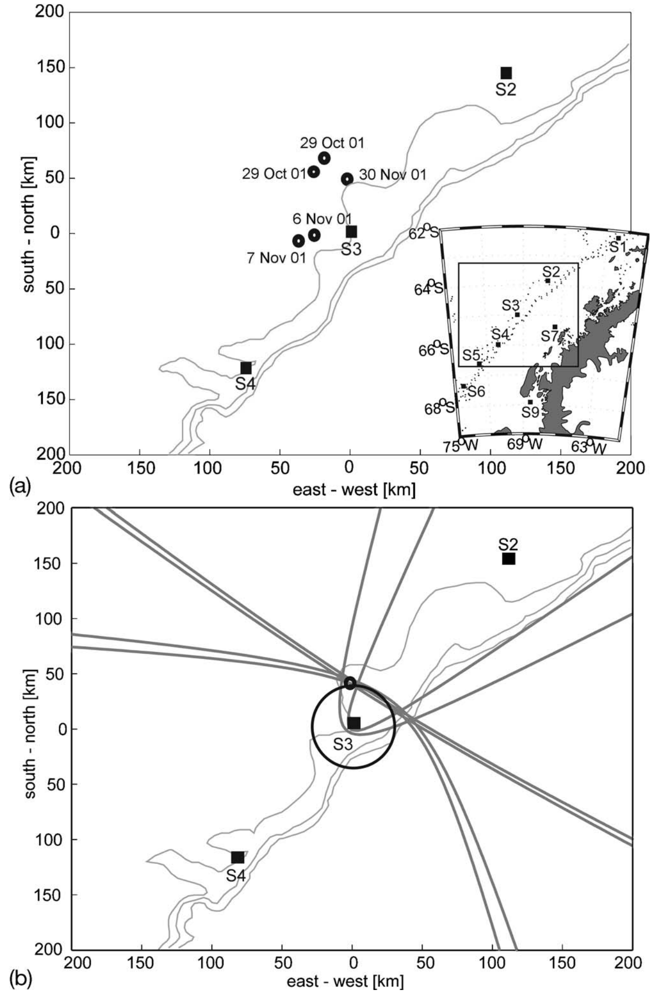

FIG. 2. (a) Locations of calling whales (circles) and dates when they were recorded. Squares show ARP locations and gray lines are 1000-, 2000-, and 3000-m bathymetry contours. Inset shows a larger area of the Western Antarctic Peninsula (dark gray) where the ARPs numbered S1 to S9 were deployed, with area of localizations indicated with a box. (b) Comparison of multipath and hyperbolic localization results for one of the calls recorded on 30 November 2001.

III. RESULTS

The range to calling blue and fin whales and the source levels of their calls were calculated using multiple calls. Detections useful for localization and range determination were limited to the austral spring for blue whales and the early fall for fin whales, because those were the times during which there was less calling (Širović *et al.*, 2004), making it possible to find periods without overlapping call sequences from multiple whales.

A. Blue whales

At least five blue whales were localized on four different days using 84 individual calls in October and November 2001 (Fig. 2). The longest track (a series of whale locations calculated from a number of sequential calls) lasted 1 h 17 min, while the shortest was 13 min. Owing to the changes in the ARP array geometry, calls from the same blue whale could be heard on instruments at sites 2, 3, and 4 only during one deployment year. It should be noted that the original experiment design intended each instrument to be independent and individual calls recorded on one instrument would not be recorded by other ARPs. The linear array geometry limited the detection area to a relatively tight region. However, due to high intensity of the sounds and good propagation characteristics, blue whale calls could be detected up to the 200-km range. The mean error in the TDOA method was 2.6 s, or the equivalent of 3.8 km. (We do not report percent error because it was different for each instrument used for localization.) Propagation modeling under typical spring conditions showed that sounds produced in shallow water do not propagate easily into deep water. Therefore, all localized animals were assumed to be calling off the shelf, in deep water, from where their calls could be recorded by the ARPs.

The transmission loss coefficient (X), corresponding to linear least-squares fit of call received levels and logarithmic of calculated ranges, was 17.8 dB/m (Fig. 3). This matched closely (within 2 dB re:1 m) the results of the modeled transmission loss at two depths (Fig. 4). The empirical value at short ranges (< 80 km) fit the propagation model at 2000-m depth better, while for ranges over 80 km the fit was

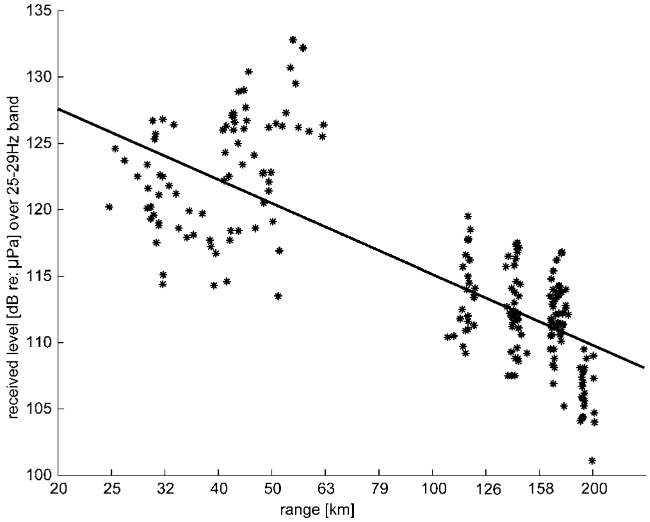

FIG. 3. Plot of blue whale received levels versus log of calculated range ($N=252$). Black line is the best-fit line through the data; the slope of this line corresponds to the value of the transmission loss coefficient, X, and is 17.8 dB/m. An increase in X leads to an increase in the difference from the theoretical model at higher ranges, while a decrease in X leads to an increase in the difference at lower ranges.

better for the 200-m depth. The difference between propagation models of 200 and 2000 m, however, was generally not larger than 5 dB *re*:1 m.

The average source level of blue whale calls off the Western Antarctic Peninsula was estimated to be 189 ± 3 dB *re*:1 μPa at 1 m over the 25–29-Hz band [Fig. 5(a)]. The average standard deviation of each source level calculation was 2.8 dB *re*:1 μPa at 1 m, which estimated the measurement error of our system. If the difference in the range to a calling whale between two consecutive calls was greater than 10 km, we assumed there were at least two different blue whales calling. We also assumed two calling whales if the intercall interval between the calls was less than 60 s (Širović *et al.*, 2004; Rankin *et al.*, 2005). With those assumptions, we found that the received levels of an individual blue whale during a calling bout on one instrument had a maximum variation up to 6 dB *re*:1 μPa at 1 m.

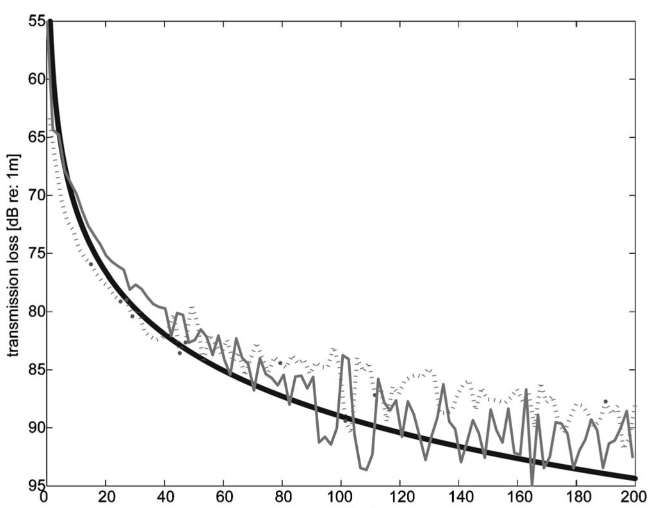

FIG. 4. Results of BELLHOP incoherent transmission loss calculations for Antarctic Peninsula spring conditions at 27 Hz. Solid gray line is the transmission loss at 200-m depth, and the dashed line is the loss at 2000-m depth. Black line is the empirically determined transmission loss, $TL = 17.8 * \log(r)$.

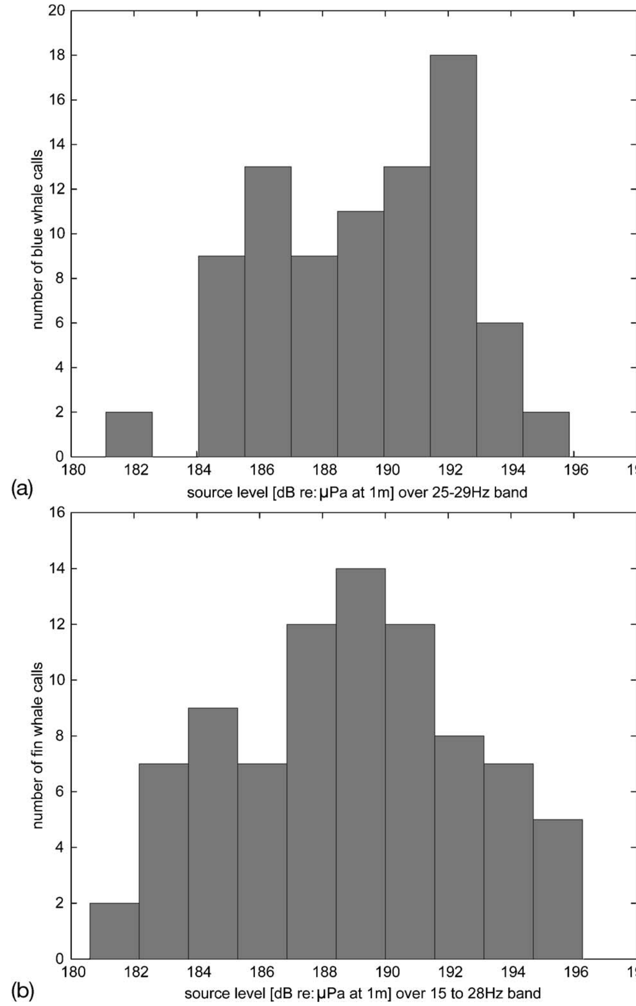

FIG. 5. Distribution of (a) blue whale call source levels, with the mean of 189 ± 3 dB *re*:1 μPa at 1 m over the 25–29-Hz band ($N=84$) and (b) fin whale call source levels, with the mean of 189 ± 4 dB *re*:1 μPa at 1 m over the 15–28-Hz band ($N=83$).

There was a significant difference between the results of the hyperbolic localization and multipath arrival methods (df=13, $t=-1.17$, $p=0.262$), and the average difference between the calculated ranges to calling blue whales was 1.8 ± 5.6 km (between 3% and 7%), which is of the same order as the error in each method. Since the downswept part of the blue whale call used in these measurements is very similar to the fin whale call, it is reasonable to assume that the method works equally well for both species, and that the range results obtained for the two species using these different methods are comparable.

B. Fin whales

A total of 83 fin whale calls from 12 different days between March and June 2001 were analyzed for range and source levels. The longest period during which ranges to fin whale calls were determined was 21 min. Calls with clear, three or more multipath arrivals, however, generally occurred only every 3–4 min and it was not possible to determine whether the calls originated from the same animal, so the variation in received levels is not reported. The maximum range to calling fin whales determined using multipath arrivals was 56 km. The average error in the measurement of multipath arrival times was 0.1 s, and the error in range determination resulting from this measurement error was 3.4 km (6%). There were no differences between the transmission loss at 27 and 22 Hz at different depths and different seasons, so we used the transmission loss coefficient calculated from the blue whale data ($X=17.8$ dB/m) for the estimation of transmission loss for fin whale calls. The average source level of fin whale calls was estimated to be 189 ± 4 dB *re*:1 μPa at 1 m, over the 15–28-Hz band [Fig. 5(b)].

IV. DISCUSSION

Blue and fin whale call source levels reported here are among the highest intensity calls reported for these two species. The maximum source levels reported for previous studies at other locations (e.g., Cummings and Thompson, 1971; Thode *et al.*, 2000; Watkins, 1981) are close to the mean levels reported here. Given the low population densities of these two species in the Southern Ocean (Branch and Butterworth, 2001), these high source level calls would be beneficial for long-range propagation and successful communication with conspecifics. Our empirical estimate of transmission loss was comparable to the theoretical transmission loss calculations across the range, with better correspondence at ranges below 60 km, where all the calls with the range determined from multipath arrivals occurred. Even though there was some discrepancy between the empirical and theoretical transmission losses at longer ranges, the average difference between blue whale call source levels obtained from calculations at three different ranges was low (2.8 dB *re*:1 μPa at 1 m) and without a consistent pattern between near and far calls, indicating that our transmission loss method did not create a bias. So, the observed difference between this study and previous ones is not likely caused by biased transmission loss estimation.

From the source levels reported here and the calculated transmission loss coefficient, it is possible to estimate theoretical maximum range over which these calls could be detected by conspecifics. The average noise levels in this region are 75 dB *re*:1 μPa^2/Hz at 220 Hz (McDonald *et al.*, 2005), and at lower frequencies where blue and fin whale calls occur (15–30 Hz), they were up to 5 dB *re*:1 μPa^2/Hz higher during periods when call ranges and source levels were calculated for this study. Even though there are no reports on threshold signal-to-noise (S/N) ratios for blue and fin whales, critical ratio functions are similar among vertebrates (Richardson *et al.*, 1995), so if we assume zero threshold S/N ratio for the calls to be intelligible by conspecifics (Miller *et al.*, 1951; Scharf, 1970), these whales could be heard out to a distance of about 1300 km. This theoretical range, however, is shortened by the real-life constraints imposed on call propagation by the changes in the physical properties, such as the sound-speed profile, at the fronts of the Antarctic Circumpolar Current.

The detection of a call by a conspecific also depends on the product of call duration and bandwidth. Long calls with narrow bandwidth and short, broadband calls can have similar detectability. Blue whale calls have the highest intensity in a very narrow, 1-Hz band, but they last several seconds (8–18 s). Fin whale calls, on the other hand, are short (<1 s) and cover 5–10 Hz of effective bandwidth. These different temporal and frequency characteristics make blue whale calls about 2 times easier to detect than fin whale calls. Production of repetitive calls further increases the probability they will be detected by a conspecific (Payne and Webb, 1971) and both species regularly repeat calls.

The range over which calls were detected in this study are comparable to earlier results. Stafford *et al.* (1998) reported detecting blue whales in the North Pacific over ranges of 400 to 600 km and Clark (1995) detected them in the Atlantic Ocean at ranges of up to 1600 km. Cummings and Thompson (1971) detected fin whales to a distance of 100 mi. The sensors Clark (1995) and Stafford *et al.* (1998) used, however, were placed in the sound channel, and they summed multiple beams to enhance the S/N ratios. Our instruments were in approximately 3000 m of water, in the polar region where the sound channel comes close to the surface (Jensen *et al.*, 2000), so the propagation was less than optimal and the signal was not enhanced by processing.

The accuracy in the measured arrival times of both methods was limited by the ability of the human analyst to pick the arrival times, and the difference between the methods was comparable to levels of measurement error. Multipathing, which was the result of the complex propagation environment, made it impossible to automatize call cross correlation, as in Tiemann *et al.* (2004), for example. This produced errors of several kilometers in the range estimation, so it was impossible to determine blue and fin whale swim speeds. But, as the calls were detected over long ranges, the relative percentage errors are comparable to other localization studies (e.g., Clark and Ellison, 2000).

Variation in source levels of 5 dB has been reported previously for fin whales (Watkins, 1981), and we found a variation in individual blue whale received levels of 6 dB *re*:1 μPa. By using received levels we eliminated the 2.8-dB error introduced by range determination. We assumed that this variation is a result of a single calling animal, but it is possible there were multiple animals calling close to each other, each at a different source level. Usually, however, the calls were repeated at very regular intervals, which indicate that a single whale was likely calling. Even though many calls showed multipath arrivals, the full range could not be accounted for by the changes in the multipath, because the movement of the whale between successive calls (always less than 2 min) would not be large enough to cause large changes in the propagation characteristics over these distances. Likewise, the variation is not likely caused by variations in the calling depth since blue whales appear to produce calls at consistent depth (Oleson *et al.*, 2007). Therefore, it appears that the total variation in the source levels of the analyzed population sample is comparable to the variation in the calls of individual whales.

Although we found there was likely some variation in the call source levels within an individual blue whale, we could not establish if there was a seasonal difference in call levels. Our ability to localize and range on animals during very short seasonal periods was not caused by the seasonal changes in the propagation characteristics, but by the number of calling animals. While hundreds of thousands of calls were present in the data set (Širović *et al.*, 2004), calls could be used for the analyses only when calls were not too abundant, as it was necessary to distinguish between individual calls. Therefore, the methods used here would not be useful in areas with a large number of calling animals, or times with overlapping calls.

Another correlation worth investigating is possible change in the source levels during periods of high acoustic noise. Fin whales present in the northern region of the array create a "noise band" in the 15–28-Hz band during peak presence (Širović *et al.*, 2004). If blue whales, for example, use the calls for communication with conspecifics, they would have to overcome that noise by increasing their source levels, or changing their call frequency. The blue and fin whale calls measured in this study, however, occurred at times when there was no fin whale "noise band." As blue whale calls in the Southern Ocean have a consistent frequency (Širović *et al.*, 2004; Rankin *et al.*, 2005), it would be interesting to determine if blue and fin whale call source levels exhibit a Lombard effect (higher source levels) during periods of higher noise, which was not possible in this study.

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