Blue whale vocalizations recorded around New Zealand: 1964 - 2013

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ABSTRACT

Previous underwater recordings made in New Zealand have identified a complex sequence of low frequency sounds that have been attributed to blue whales based on similarity to blue whale songs in other areas. Recordings of sounds with these characteristics were made opportunistically during the Southern Ocean Research Partnership's recent Antarctic Blue Whale Voyage. Detections of these sounds occurred all around the South Island of New Zealand during the voyage transits from Nelson, New Zealand to the Antarctic and return. By following acoustic bearings from directional sonobuoys, blue whales were visually detected and confirmed as the source of these sounds. These recordings, together with the historical recordings made northeast of New Zealand indicate song types that persist over several decades, and are indicative of the year-round presence of a population of blue whales that inhabits the waters around New Zealand. Measurements of the four-part vocalizations reveal that blue whale song in this region has changed slowly, but consistently over the past 50 years. The most intense units of these calls were detected as far south as 53°S, which represents a considerable range extension compared to the limited prior data on the spatial distribution of this population.

KEYWORDS: BLUE WHALE, VOCALIZATIONS, BIOACOUSTICS, NEW ZEALAND

INTRODUCTION

Blue whales (*Balaenoptera musculus*) produce a variety of low-frequency sounds (Cummings and Thompson 1971; Rivers 1997; Ljungblad *et al* 1998; Stafford *et al* 1999; Rankin *et al* 2005), including complex, repeated series of tonal and pulsed units that together have been called "songs" (McDonald *et al* 2006). While there is some variation in the literature, we refer to the stereotypical pattern of pulsed and tonal sound units as a "call" and the repeated pattern of these calls as "song".

Blue whale calls are among the lowest frequency (typically less than 100 Hz) and most powerful sounds made by any animal. Širovic *et al* (2007) measured a mean source level of 189 dB re: 1 µPa rms @ 1 m for Antarctic blue whale calls. Globally, at least ten distinct blue whale songs have been identified that show distinct geographic patterns with overlapping call types in some areas (McDonald *et al* 2006). At least three additional song types have been identified since that study (Pangerc 2010; Cerchio *et al* 2010; Frank and Ferris 2011). Whether blue whale song types correlate with taxonomic units (eg. the three putative, but presently recognized subspecies) is a relatively open question (McDonald et al 2006), however investigation of call properties has been informative in understanding population structure in other large baleen whales including fin (Hatch and Clark 2004; Castellote *et al* 2010) and humpback whales (Cerchio *et al* 2001).

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Kibblewhite *et al* (1967) analyzed low-frequency sounds that were recorded in 1964 from recorders off New Zealand's North Island and speculated that at least one repeated pattern (Figure 1 bottom panel) might be produced by whales. McDonald (2006) attributed that pattern of sounds to blue whales based on their similarity to other blue whale calls, and noted that the same series of sound elements (Figure 1 middle panel) was repeated in recordings made in 1997 in waters off Great Barrier Island, North Island, New Zealand. This call has been referred to as the New Zealand blue whale song type (McDonald 2006; McDonald *et al* 2006, 2009) and consists of no less than four elements, at least three of which were consistently present in 1964 and 1997 (McDonald *et al* 2009). Although the elements have remained recognizable over this time period, their fundamental frequencies have decreased. This decrease is paralleled by similar decreases in frequency for blue whale song worldwide (McDonald *et al* 2009).

While the New Zealand type song has previously been reported off the north of New Zealand's North Island (Figure 2), the broader geographic distribution of this call type is not known. Here we analyze the first recordings of this song type made in the presence of blue whales, and we also present acoustically-derived bearings to these calls that are consistent with sighting locations of blue whales. We describe the distribution of detections of blue whale calls in January, February, and March 2013 around the South Island of New Zealand and along the southern edge of the Tasman Sea. Finally, we compare our recordings to previous recordings of blue whale songs and quantify change over time.

METHODS

Visual observations

Blue whales were detected visually on the western coast of the South Island, New Zealand, while the research vessel, *FV Amaltal Explorer*, was on passage to the main study area further south to undertake the Southern Ocean Research Partnership's Antarctic Blue Whale Voyage. Taking advantage of unused 'contingency time' during the return transit, acoustically-derived bearings to blue whales were followed yielding further sightings of blue whales on the eastern coast of the South Island. Upon sighting whales, the vessel altered course, closing to confirm species identification and obtain images for photo-identification.

Acoustic recordings

Audio recordings were made opportunistically during the transit south, and adaptively during the north-bound return transit using directional (DIFAR) sonobuoys (AN/SSQ 53D, Ultra Electronics Sonar Systems and AN/SSQ 53F, SonobuoyTechSystems). Signals from the hydrophones and sensors were broadcast over VHF radio and received onboard the research vessel via a 21 m-high aerial. The recording chain for all sonobuoy deployments consisted of a WiNRaDiO G39WSBe VHF receiver with the voltage output calibrated as a function of modulation frequency. The raw voltage output of the receiver was connected to the instrument input of an RME Fireface UFX sound board with the gain set to 20 dB (*ie* full scale input voltage with 20 dB gain was 8.39 V peak-to-peak). The digitized signals from the UFX were saved as 16-bit WAV files with a 48 kHz sample rate using passive acoustic monitoring software PAMGuard (www.pamguard.org, Gillespie *et al* 2008). PAMGuard also generated real-time spectrograms, while RME TotalMix software allowed the incoming audio to be monitored aurally.

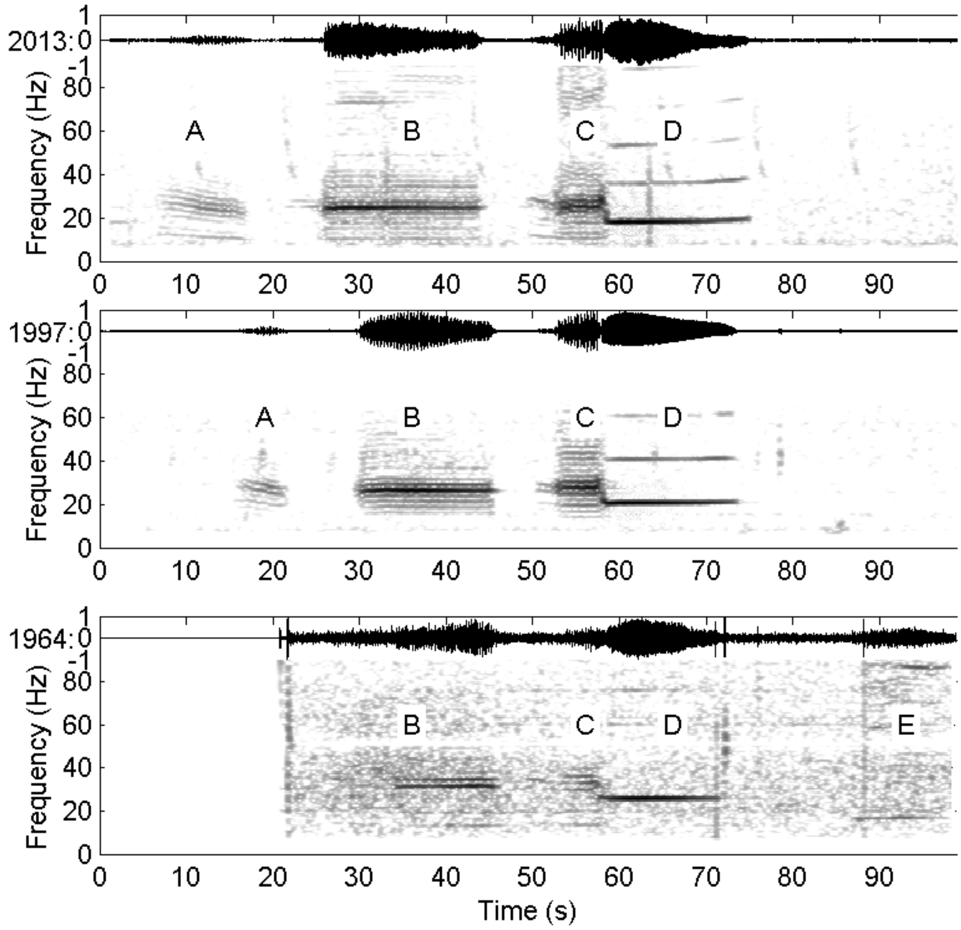

Figure 1 - Pressure waveform and spectrogram of four-unit call produced by New Zealand blue whales in 2013 (top), 1997 (middle) and 1964 (bottom). Spectrogram parameters: 400 Hz sample rate, 512 point FFT with Hamming window, 93.75% overlap. All spectrograms are aligned on the sharp transition between the pulsed and tonal units (C and D) at approximately 60 s. Note: A notch filter at 50 Hz was applied to the recording from 1964 to remove constant tonal noise at that frequency that would otherwise obscure the whale call in the pressure waveform.

Acoustic localization

Analysis of the directionality of sound sources largely followed methods described by McDonald (2004) and Gedamke and Robinson (2010). This involved saving audio clips of sound sources (*eg* units of whale calls) and performing a series of signal processing steps on these clips via a suite of Matlab scripts (version 7.0.4; The

Mathworks Inc. Natick USA). Signal processing included the 'validation' of the sonobuoy compass and measurement of a compass correction for each sonobuoy as described below. The final output of the signal processing was a true bearing from the sonobuoy to the sound source of interest.

Direction of whale calls

Audio clips of blue whale calls were saved separately from the raw audio stream for further processing in order to extract the direction of arrival of the call. This step was facilitated by a custom PAMGuard module that automatically created a WAV file containing the audio of any user selection made on the PAMGuard spectrogram window.

For each audio clip, DIFAR directional signals were demodulated using a version of Greenridge Science's demodulation software (http://www.greeneridge.com/software.html) running under Matlab. The demodulator produced three binary files that represented the audio signals from the omnidirectional hydrophone and the two orthogonal directional hydrophones. These audio signals were low-pass filtered and resampled at a lower sampling rate to reduce processor and memory demands for subsequent signal processing steps. Calls classified as blue whale vocalizations were resampled at a rate of 250 Hz, while all other calls, such as audio clips of the research vessel, were resampled at a rate of 4800 Hz.

The beamforming method described by McDonald (2004) was applied to the resampled signals in order to compute relative received power as a function of bearing and frequency referred to as an 'ambiguity surface plot'. The spectrogram and the ambiguity surface plot were plotted side-by-side with identical frequency scales, allowing the operator to select the bearing that most clearly represented the signal of interest from the ambiguity surface plot. Typically this corresponded to the frequency bin of the sound source that contained the highest signal-to-noise ratio, rather than simply the peak energy. Care was taken by the operator to avoid frequency bins that also contained non-target noise sources as these could have potentially biased the bearing towards the noise source and away from the target. Typical noise sources included the research vessel, other vessels, non-target whales, sounds from seismic airguns, and radio noise that occurred as VHF reception degraded with distance from the sonobuoy.

Sonobuoy compass correction

The magnetic compass in each sonobuoy was "calibrated" in order to obtain a correction that included the compass deviation and local magnetic anomaly (variation). The location of the sonobuoy deployment and the subsequent positions of the vessel were collected via a GPS receiver. 10-second audio clips were then collected every 30 seconds as the vessel steamed away from the sonobuoy after deployment. Acoustically-derived bearings to the research vessel, θ_a, were computed from these audio clips. The "true" bearings between the sonobuoy's deployment location and the vessel, θ_t, were also computed using the GPS onboard the vessel. The correction angle, θ_c, for each 10 second audio clip was computed as: $\theta_c = \theta_t - \theta_a$. Typically 15-20 measurements of angle θ_c were made as the vessel moved away from the sonobuoy, and the angular mean, $\bar{\theta}_c$, and standard deviation, σ_c, of these measurements were calculated. The sonobuoy was considered unreliable for bearing measurement if σ_c was greater than 10°. For reliable sonobuoys, $\bar{\theta}_c$ was used as a single correction that incorporated both the inherent error in the magnetic compass of the sonobuoy and the local magnetic variation. Vessel speed during these measurements was typically around 10 knots.

Tracking and targeting

The bearing to whale calls was plotted on an electronic chart along with the position of the ship and deployment location of the sonobuoy. Groups of bearings that appeared to come from the same direction and had regular repetition rates were *tracked* as a group of whales that were then given a unique designation. On the return transit the ship *targeted* these groups of whales, diverting towards the whales and deploying additional sonobuoys as necessary. *Tracking* and *targeting* were conducted in real-time on the transits while the sightings team maintained visual observations.

In order to present a more accessible summary plot of the directional information from all sonobuoys, kernel smoothing (Wand and Jones 1995) was applied to all the bearings to whale vocalizations for each sonobuoy to yield a continuous bearing density function (BDF). Peaks in the BDF that were greater than a threshold value were selected as representative of a target group. The threshold value was computed per sonobuoy as $1/(2\sigma n)$ where σ represents the nominal angular precision of bearings from the sonobuoy, and n was the total number of bearings obtained at that sonobuoy. The value of σ was set to 10° for all sonobuoys.

Analysis of calls and comparison with historic recordings

Only call units that were clearly discernible above the background noise and had no obvious sources of masking noise were selected for duration measurements. Frequency and pulse repetition rate characteristics were measured for each unit only when the SNR of the entire four-part call was greater than 3 dB. This comprised a small portion of the total number of recorded vocalizations. In addition to the recordings from 2013, nine hours of recording from 1997 made by the Center for Monitoring Research (CMR) of Arlington, Virginia (part of the same dataset analyzed by McDonald 2006), and five calls recorded in 1964 by Kibblewhite (1967) were analyzed using the same methods described below.

Recordings from 1997 came from a year-long recording made for the duration of the calendar year using a pair of fixed hydrophones located 5 km east of Great Barrier Island, New Zealand (ie the triangle in Figure 2). The two hydrophones are located at 36.2185°S 175.5449°E and 36.2228°S 175.5408°E. The hydrophones are near the sea floor in 70 m of water. Blue whale song calls were detected on four occasions, one in each of June, July, September, and December (McDonald 2006).

Recordings from 1964 were made as part of a field study by the New Zealand Naval Research Laboratory of local ambient sea noise and were made at “temporary installations established for periods of a few hours only at various sites around the New Zealand coast” (Kibblewhite et al 1967). The vocalizations reported by Kibblewhite et al (1967) that match the blue whale vocalizations reported here came from recordings made near Three Kings Island, west of North Cape (ie the square in Figure 2). While the month of these recordings is unknown the archives from which they were digitized indicate that these recordings were made in 1964 (McDonald et al 2009).

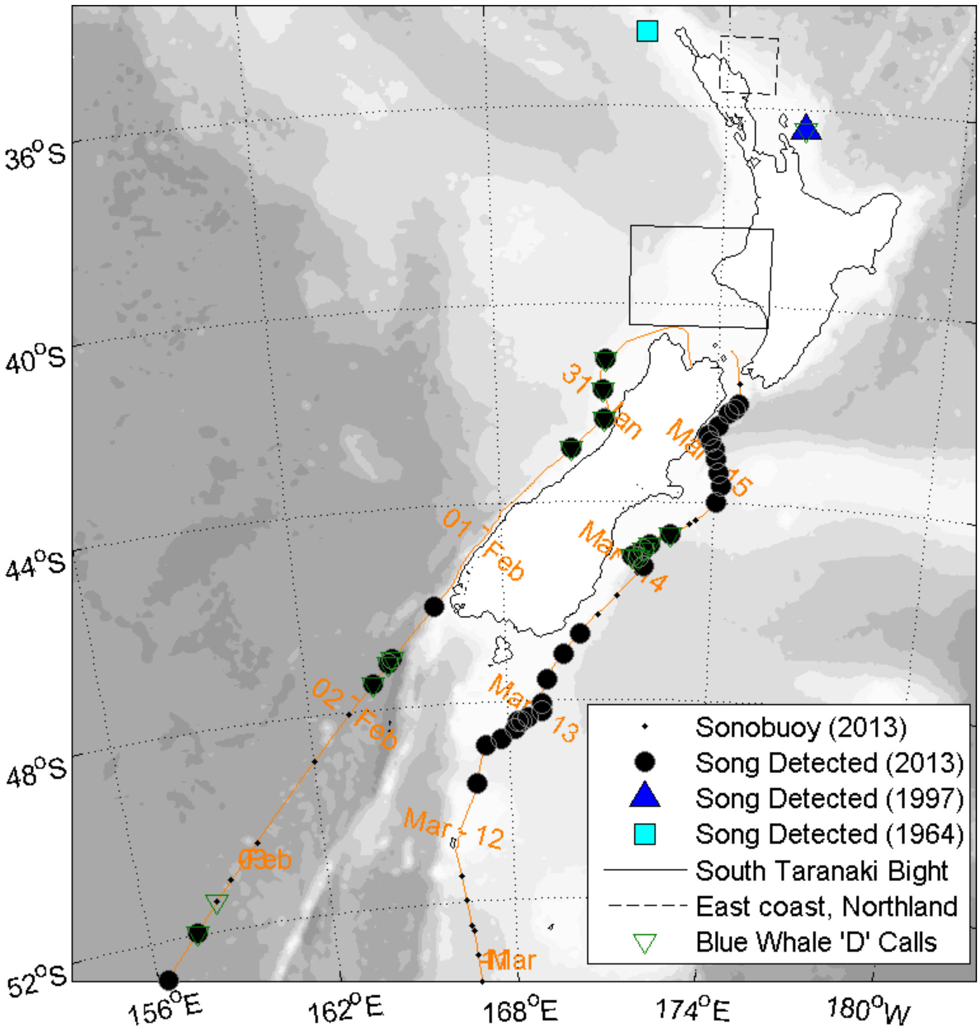

Figure 2 (Color online) - Geographic distribution of blue whale song described in this study and areas of concentration described by Torres (2013). Dots show the location of sonobuoy deployments from 2013. Circles show the location where calls were detected. The triangle shows the location of recordings made in 1997 (McDonald 2006), and the square shows the approximate location of the calls recorded in 1964 by Kibblewhite (1967). The line shows the ships track during the 2013 voyage, and tick marks indicate the start of the day in GMT. The solid and dashed black boxes indicate the South Taranaki Bight and east coast of Northland areas of concentration suggested by Torres (2013).

When measuring units of calls, we followed the naming scheme of Cummings and Thompson (1971) where each unit was assigned a letter sequentially, starting with A. Thus, the four-part call was represented as ABCD, which departs slightly from the numeric scheme used by McDonald (2006). As described by McDonald (2006), units A and B were clearly separated by a short silence, which we refer to as the inter-unit interval, while units C and D were differentiated by an abrupt change from a pulsed to a tonal signal. Within recordings with high signal-to-noise ratio

(SNR), unit C was often associated with a faint downswept precursor which was also noted by McDonald (2006). This precursor, however, was not included in unit C measurements to enable a more consistent representation of this unit throughout the 2013 recordings and during comparisons with McDonald's (2006) analysis.

For measurements, recordings were re-sampled from the original sample rate of 48 kHz to a sample rate of 1,000 Hz. Signal-to-noise ratio of calls was obtained by measuring the noise in the time period just before the call, and was used to test whether the signal-to-noise ratio affected the measurement of duration of units. The following characteristics were measured: duration, inter-unit interval, inter-call interval, peak-frequency, intra-unit change in frequency, and pulse repetition rate. Inter-unit interval was measured from the end of one unit to the start of the next unit. Inter-call interval was measured from the start of unit B to the start of the next unit B. Peak-frequency was measured as the frequency of maximum amplitude in the power spectrum. For frequency modulated units (A and D) we measured the peak frequency at the start and end of the call (ie. power spectra of the first and last time-slices).

Temporal and frequency characteristics were measured by manually selecting points from spectrograms and power spectra (bandwidth 0-60 Hz, 2048 FFT, Hanning window with 90% FFT overlap) using Adobe Audition 1.5 (Adobe Systems Incorporated 2004) and SpectraPLUS 5.0 (Pioneer Hill Software LLC, 2010), respectively. Pulse repetition rates were measured from waveforms displayed in Audacity 2.0.3 (2013).

Within SpectraPLUS the average spectrum function was used to measure the peak frequencies of units B, C and D while the start and end frequencies of units A and D were hand-picked from the spectrogram. To facilitate pulse repetition rate measurements within Audacity, a very steep low pass filter (roll off = 48 dB, cut off frequency = 40 Hz) was applied to calls to remove any higher frequency sounds that might have masked the waveform of the vocalization. Furthermore, amplification was applied to the signal in order to re-scale the amplitude of whale vocalizations so they would fit within the amplitude limits of the waveform display panel in Audacity. Pulse rate was measured as the total number of pulses in the envelope of the waveform divided by the duration of the unit.

RESULTS

Visual observations

At least 18 individual blue whales were sighted around the South Island of New Zealand during this study. Eleven animals, comprising two loose aggregations were seen on the west coast, and during these encounters sonobuoys were deployed in the vicinity of the blue whales after initially approaching. Seven blue whales were encountered at three widely spaced locations on the east coast during the return transit. All of the whales on the east coast were encountered as a result of following bearings to New Zealand type blue whale songs that were detected in real time (see Figure 3).

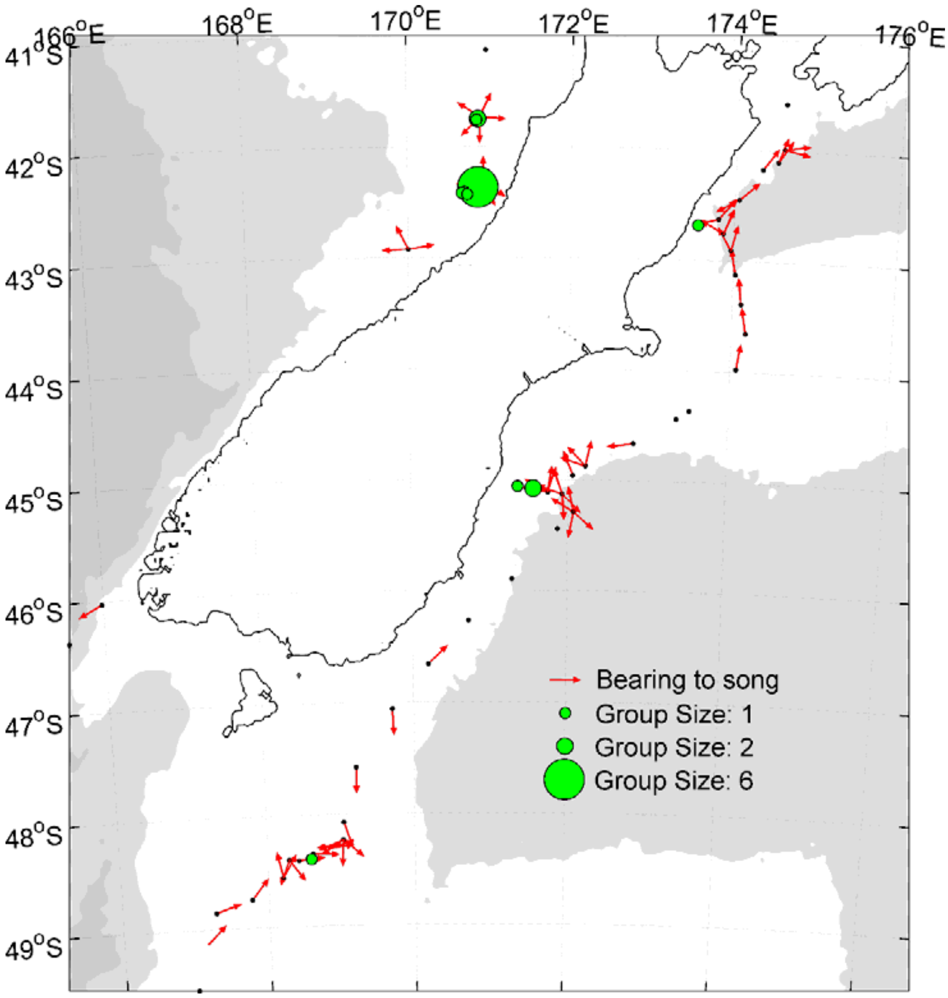

Figure 3 (Color online) - Visual and acoustic locations of blue whales during the 2013 transit. Dots show location of listening stations, while arrows indicate the mean direction of clusters of blue whale 'song' vocalizations. Visual sightings of blue whales are indicated by circles.

Acoustic recordings

New Zealand type blue whale calls were recorded on 44 of 61 sonobuoys deployed around the South Island of New Zealand and subantarctic waters south of New Zealand (between 155 to 175°E longitude and 41 to 54°S latitude; Figure 2). From these sonobuoys a total of 130 hours of audio was recorded, with 30% of this audio consisting of simultaneous recordings from two sonobuoys deployed in different locations.

Typically detections comprised only the most intense components of the most intense units, *ie* the 24 Hz component of the units B and C, and/or the 18 Hz component of unit D. Only on recordings from sonobuoys deployed within a few kilometers of whales were all four units consistently detected within each call.

Acoustic localization

A total of 1617 blue whale vocalizations were analyzed for directionality in real-time during the transits. Peaks in the bearing-density function of each sonobuoy are plotted to show a summary of these 1617 bearings to blue whale sounds (Figure 3). In general, the received levels of vocalizations showed inverse correlation with estimated distance to a group of whales.

Analysis of calls and comparison with historic recordings

A total of 14.5 hours of recordings of high enough quality for measurements of calls of New Zealand blue whales was made during the 2013 voyage. These recordings were made on three separate occasions, two of which were recordings of solitary individuals while the third was of at least two singing whales.

The blue whale song recorded in 2013 and 1997 consisted of a four-unit call (as described in detail by McDonald (2006)), while the recording from 1964 contained the last three units of the 1997/2013 calls followed by an additional unit E that was not found in the later recordings (Figure 1). In the 2013 recordings, the four different vocalization units associated with New Zealand blue whales comprised two different call variants. Call variant one was the same as that described by McDonald (2006) and consisted of each of the four units in sequence (*ie* ABCD; Figure 1), while call type two consisted of only the last two units from call type one (*ie* CDCDCD; Figure 4). Call type one was recorded on most occasions, while call type two was recorded only once on the western coast of the South Island. In order to give qualitatively similar units the same names, we named the four units comprising calls from 1964 as BCDE.

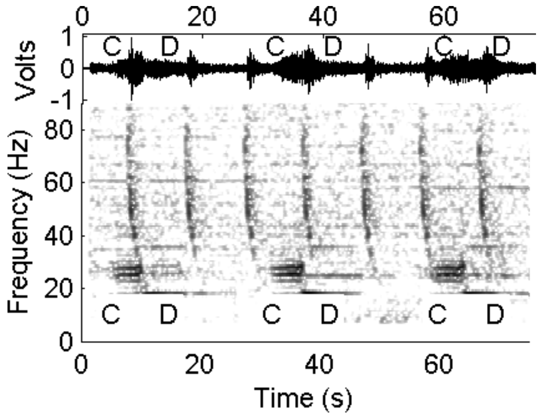

Figure 4 - Top: Pressure waveform of two-unit call produced by New Zealand blue whales. Bottom: Spectrogram of blue whale sounds. Spectrogram parameters: 200 Hz sample rate, 512 point FFT with Hamming window, 93.75% overlap. Note: the slightly downswept pulses that repeat every 10 s are from seismic airguns rather than blue whales.

Variation in the SNR throughout the recordings, as well as variation in the relative amplitude of units, resulted in differences in the number of measurements that were made among units, intervals, and calls. Frequency and pulse repetition rate characteristics were made only from calls that had SNR > 3 dB (2013: n=31, 1997: n=41). The lower relative amplitude of the A unit, however, resulted in only six measurements of pulse repetition rate from 2013 recordings and four from 1997 recordings. Measurements of the duration of call units showed no correlation with SNR.

The duration of units A and B appeared to increase from 1964 to 2013, while the duration of units C and D appeared stable over this time period (Figure 5a). Simple linear regression of frequency over year revealed a decrease in peak-frequency as a function of time for all units (Figure 5b). Units B, C, and D showed decreases of -0.135, -0.153, and -0.157 Hz/year (SE=0.0013; 0.0018; 0.0005) respectively. In addition to a decline in peak-frequency units A, B, and C also showed a decline in pulse rate. However, it appears that simple linear regression may only describe the decline in pulse rate for unit C (Figure 5c). Mean values and standard deviations of all measurements can be found in Tables I, II, and III.

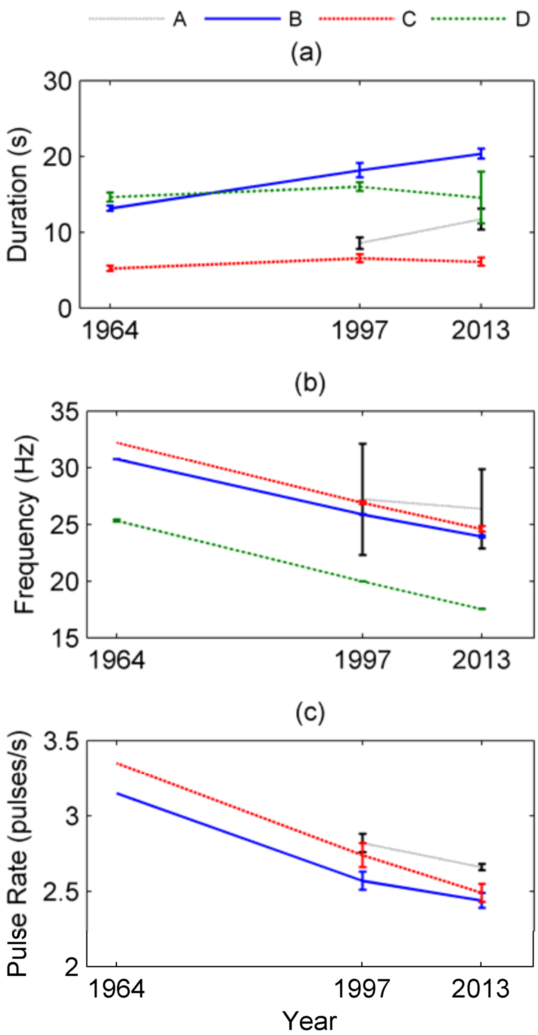

Figure 5 (Color online) – (a) Duration of vocalization units from New Zealand blue whale calls as a function of time. (b) peak-frequency of vocalization units from New Zealand blue whale calls. (c) Pulse rate of vocalization units from New Zealand blue whale calls. In all cases lines connect mean values for each year and error bars show standard deviations. Dotted line represents unit A; solid line unit B; dashed line unit C, and dashed-dotted line represents unit D.

DISCUSSION

A. Visual observations and acoustic localization

We have presented the first recordings of the New Zealand song type with concurrent visual confirmation that these songs were produced by blue whales. Acoustically-derived bearings from directional sonobuoys unambiguously pointed to these whales as the source of these calls, confirming hypotheses regarding the origin of these sounds (Kibblewhite 1967; McDonald 2006; McDonald *et al* 2006). Furthermore, acoustically-derived bearings from these sounds led us to encounters with these animals from initial detections that were tens to hundreds of kilometers away (Figure 3).

New Zealand blue whale calls were detected all around the South Island of New Zealand and as far south as 53°S latitude. While bearings from a sonobuoy at 52°S indicated whales to the south, bearings from vocalizations received at 53°S pointed back to the north, potentially indicating that these detections may be beyond the actual southern limit of distribution of this population during this time of year. On the basis of a single return transit and a typical detection range of approximately 60 nmi, our results would be consistent with a lower latitude distribution of between 52°S and 53°S.

In New Zealand waters, a compilation of incidental visual sightings and strandings demonstrates that blue whales have a broad distribution throughout the region, with two areas of apparent concentration in coastal waters off the North Island (Torres 2013). Torres (2013) provides evidence of year-round presence of blue whales in the South Taranaki Bight (Figure 2 box with solid line) as well as evidence that this area has biological and environmental characteristics of a feeding ground for blue whales. Torres (2013) suggests that the cluster of sightings off the east coast of Northland (Figure 2 box with dashed line), may be a migratory corridor, or may simply be due to higher amount of sighting effort due to higher amounts of boating and fishing in that area.

Acoustic detections may provide a complimentary view of cetacean presence and distribution (Morano et al 2012), particularly when combined with visual sightings (Barlow and Taylor 2005). The acoustic detections measured in this study, and in McDonald (2006), and Kibblewhite et al (1967) are all outside of the areas of apparent concentration of blue whales identified by Torres (2013). The acoustic data from the 2013 voyage cover a large area over a short time period (Late January – early February and mid-March), while the acoustic data from 1997 cover a small area for an entire year (Figure 2 – triangle). Between these two acoustic surveys, blue whale vocalizations have now been detected in New Zealand waters in the months of January, February, March, June, July, September, and December.

However, without additional data collection it is not yet possible to draw conclusions regarding distribution or abundance of blue whales from the acoustic recordings made to date. The relative scarcity of New Zealand blue whale song at the Great Barrier Island site in 1997 (four encounters during a year of near-continuous recording) may be indicative that these whales are much more common off the South Taranaki Bight, and/or that the density of the whales has increased around New Zealand since 1997. The relative lack of song in the northeast of New Zealand in 1997 might also result from differences in whale movement patterns and/or vocal behavior. Additionally, environmental factors specific to the recording site such as acoustic shadowing or increased ambient noise have been found to alter the probability of detection of humpback whale vocalisations by two orders of magnitude (Helble et al *in press*). Thus, environmental acoustical factors may also contribute to the low number of detections of blue whale vocalizations at the Great Barrier Island site. Further collection of long-term acoustic recordings as well as simultaneous collection of sightings and acoustic recordings would be required to provide further insight into habitat use, seasonal migrations, seasonal changes in vocal behavior, and potentially long term changes in apparent density of this blue whale population.

The acoustic detections in 2013 provide updated information on the geographic distribution of this 'acoustic population' of blue whales. The long range over which these sounds were detected indicates that these acoustic methods may represent a particularly efficient means to examine the spatial distribution and abundance of this population. Furthermore, as a novel method to find individuals of this (infrequently sighted and poorly known) population, acoustic localization using DIFAR sensors could greatly enhance the efficiency of any potential future in-depth studies on blue whales. Acoustic localization of blue whales could also be used opportunistically to add value to oceanographic and biological surveys, as was done by Gedamke and Robinson (2010). The fact that a substantial number of detailed acoustic recordings, identification photographs (Olson *et al* 2013), and behavioral observations were successfully obtained opportunistically at several, widely separated, geographic locations during the transit to and from the Antarctic, further highlights the value and utility of these acoustic methods.

Analysis of calls and comparison with historic recordings

Visual inspection of the spectrograms of calls with high signal-to-noise ratio reveals that these sounds appear, at least qualitatively, to be the same call-types as Kibblewhite *et al* (1967) and McDonald (2006) recorded. However, close analysis of digitized recordings made in 1964 by Kibblewhite *et al* (1967) reveal what may be an additional unit on the end of the call, as well as ambiguity about whether the modern-day unit A was present in the historic calls.

Ambiguity regarding the number of units from the calls recorded in 1964 arises due to relatively low signal-to-noise ratio of the original recordings. Inspection of unit E from a digitized copy of the original recording reveals that this unit has a relatively low peak amplitude, approximately -15 dB with respect to the loudest unit, unit D. Furthermore, the peak-frequency of 16 Hz appears to be one of the lowest peak-frequencies observed in any blue whale population. This likely explains why neither Kibblewhite *et al* (1967) nor McDonald (2006) include unit E in their description of the calls. However, the consistent DE inter-unit interval and slightly longer inter-call interval from 1964 suggests that these units may indeed be part of the call. By analyzing only calls with high signal-to-noise ratio from 1997 and 2013, we can however confirm that blue whales calls recorded in these years did not contain this unit E, thus highlighting changes in this song that are more overt than a subtle decline in tonal frequency.

Similarly, in recordings from 2013 we observed that unit A also has a relatively low amplitude compared to the other extant units. In these recordings, we found the peak amplitude of unit A was regularly 20 dB below that of unit D. If we assume the relative amplitude of the unit has remained stable, then even if unit A was produced by the whales in 1964, it would have been below the noise floor of the available recordings. Thus, without additional historic recordings we cannot say whether or not unit A was part of New Zealand blue whale calls in 1964, or whether unit A was introduced only after the cessation of the production of unit E.

Quantitative comparison of each call unit over time revealed differences in the durations, peak-frequencies, and pulse rates of some units. The observed decline in tonal frequency is in accord with previous observations (McDonald *et al* 2009), while the changes in duration and pulse rate represent new observations that have become available due to the recent opportunistic recordings from the transit of the Antarctic Blue Whale Voyage. The small number of individual whales and relatively short duration of recordings in our study precluded a thorough statistical analysis of seasonal trends as was done for pygmy and Antarctic blue whales recorded off Australia (Gavrilov et al 2011; 2012; 2013). While it is possible that the observed changes in New Zealand blue whale song may arise from individual or seasonal differences, the long-term decline in tonal frequencies is in accord with population-wide trends observed in pygmy and Antarctic blue whales (Gavrilov et al 2011, Gavrilov et al 2012). In addition to the qualitative observations of song structure, these quantitative observations may form a basis for further investigation of the evolution of blue whale song in New Zealand waters.

Understanding the evolution of blue whale song may provide insight into the biological function of song, the mechanism of sound production (Adam et al 2013), and also the hypothesized relationship between blue whale song and population structure (McDonald 2006). However, quantification of both historic and present day song of other populations of blue whales, as well as collection of acoustic recordings, photographic identification and genetic samples of blue whales around New Zealand, are likely to be required in order to further investigate questions of population structure and distribution.

CONCLUSIONS

We have confirmed the hypothesis that the unique series of pulsed and tonal sounds described by Kibblewhite *et al* (1967) and McDonald (2006) are produced by blue whales in the New Zealand region. Furthermore, evidence suggests this acoustic population of blue whales can be found all around New Zealand and at least as far south as 52°S in the Southern Ocean. We have confirmed a steady tonal decrease in peak frequency first observed by McDonald *et al* (2009) and have further quantified changes in the duration and pulse rate of the units of these calls, thus more completely describing the evolution of this variety of blue whale song over a span of 50 years. Lastly, we have demonstrated a very successful, efficient acoustic method for long-range detection and localization of blue whales that could greatly facilitate future research on the distribution, abundance, and behavior of this poorly known population of blue whales in New Zealand waters.

ACKNOWLEDGMENTS

This research was made possible due to the large and efficient team, both at sea and at the AAD headquarters. Thanks to all the scientists and support staff on the voyage and at the AAD/AMMC for science support. Thanks to all those at the AAD for operational and shipping support. Thanks to Christopher Donald from Australian Defence for provision of the expired 53D sonobuoys. Particular thanks are due to Talley's Group Ltd and Gardline Shipping Ltd and to the excellent and professional crew of the *FV Amaltal Explorer*.

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TABLES

Table I- Duration measurements of units, intervals, and four-part calls of New Zealand blue whales. All measurements except inter-call interval are of the form mean ± standard deviation in seconds with sample size in parenthesis. Inter-call interval is the median value with sample size in parenthesis.

	Year					
	1964		**1997**		**2013**	
A	-		8.57 ± 0.75	(45)	11.72 ± 1.36	(84)
B	13.15 ± 0.36	(5)	18.17 ± 0.94	(168)	20.33 ± 0.66	(186)
C	5.24 ± 0.36	(5)	6.59 ± 0.53	(145)	6.12 ± 0.52	(164)
D	14.64 ± 0.59	(5)	16.02 ± 0.57	(145)	14.56 ± 3.40	(162)
E	13.38 ± 0.36	(2)	-		-	
Call	-		60.51 ± 0.89	(44)	68.26 ± 3.41	(78)
A-B interval	-		5.68 ± 0.58	(45)	7.53 ± 1.18	(84)
B-C interval	5.95 ± 0.59	(5)	5.30 ± 0.63	(145)	7.40 ± 0.55	(164)
D-E interval	13.83 ± 0.97	(2)	-		-	
Inter-call interval	153.82	(2)	115.44	(167)	132.62	(180)

Table II- Mean peak-frequency measurements of units of New Zealand blue whale calls. Units for all measurements are Hz, and measurements are of the form mean ± standard deviation. Reduced sample size in parenthesis.

	Year		
	1964 (n=5)	**1997 (n=41)**	**2013 (n=31)**
A Start	-	27.20 ± 4.90	26.36 ± 3.50
A End	-	22.33 ± 4.35	20.72 ± 2.77
B	30.75 ± 0.01	25.87 ± 0.02	23.93 ± 0.09
C	32.22 ± 0.01	26.90 ± 0.14	24.60 ± 0.24
D	25.33 ± 0.10	20.00 ± 0.00	17.55 ± 0.01
D Start	25.33 ± 0.10	20.00 ± 0.00	17.53 ± 0.13
D End	25.33 ± 0.10	20.82 ± 0.15	18.88 ± 0.57
E	16.08 ± 0.00 (2)	-	-

Table III- Mean pulse rate measurements of units of New Zealand blue whale calls. All measurements in pulses/s and are of the form mean ± standard deviation. Reduced sample size in parenthesis.

	Year		
	1964 (n=5)	**1997 (n=41)**	**2013 (n=31)**
A	-	2.82 ± 0.06 (4)	2.66 ± 0.02 (6)
B	3.15 ± 0.02	2.57 ± 0.06	2.44 ± 0.05
C	3.23 ± 0.09	2.74 ± 0.08	2.49 ± 0.06
E	2.63 ± 0.01 (2)	-	-