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An acoustic survey of baleen whales off Great Barrier Island, New Zealand

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Abstract Acoustic recordings of baleen whale calls were analysed for the calendar year 1997 from a pair of fixed hydrophones located 5 km east of Great Barrier Island, New Zealand. The primary goal of the study was to examine blue whale seasonality and song type as part of a larger worldwide study. Calls were recorded from blue whales of two song types, fin whales, humpback whales, Bryde's whales, and of two unknown call types, each probably produced by Bryde's whales. The peak of calling density was May through September for the blue, fin, and humpback whales. The known Bryde's whale calls occurred year-round and the probable Bryde's whale calls occurred from May through December. Blue whale songs of a type so far known only from New Zealand waters were detected within 2 km of shore and occurred four times from June to December, whereas the Southern Ocean blue whale songs were detected only further offshore in mid-winter. Bryde's whale calls were the most abundant type and often occurred near the hydrophones. These data provide a baseline from which future recordings from the same hydrophones could be compared.

Keywords whale; *Balaenoptera*; cetacean; whale calls; song; New Zealand; hydrophone

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INTRODUCTION

Most species of baleen whales routinely produce loud low-frequency underwater sounds (Edds-Walton 1997). The function of these sounds is often poorly understood (Tyack 2000), and our knowledge of the acoustic call repertoire is incomplete for many species, but much can be learned from acoustic recordings nonetheless. Passive acoustic monitoring allows study of the seasonality, minimum and relative density of these whales and provides information relevant to stock and taxonomic questions (Mellinger & Barlow 2003). For sperm whales, a species which is particularly active acoustically, passive acoustic methods are being used to estimate absolute abundance (Barlow & Taylor 2005). In New Zealand, passive acoustic studies of marine life and ambient noise have been conducted using a sea-floor hydrophone array located off Great Barrier Island since at least 1958 (Fish 1964; Kibblewhite et al. 1967; Helweg 1998).

Bryde's whales (*Balaenoptera edeni*, Anderson 1879) are the most common baleen whale in the area of Great Barrier Island year-round (Gaskin 1968; O'Callaghan & Baker 2002). Humpback (*Megaptera novaengliae*, Borowski 1871), fin (*B. physalus*, Linnaeus 1758), and blue whales (*B. musculus*, Linnaeus 1758) migrate past Great Barrier Island, though usually well offshore, and minke whales (*B. acutorostrata* subspecies and *B. bonarensis*, Burmeister 1867) are uncommon (Gaskin 1968, 1972). Sei whales (*B. borealis*, Lesson 1828) are also present in New Zealand waters, though more common in waters colder than those at Great Barrier Island (Gaskin 1968, 1972). There are at least nine types of blue whale song worldwide (McDonald et al. in press), each of which has maintained a distinct character over the 10 to 40 years of observation, although the relationship between these song types and blue whale subspecies (*B. m. brevicauda*, *B. m. musculus*, *B. m. intermedia*, and *B. m. indica*), stocks, and populations remains unclear.

The New Zealand study conducted by Kibblewhite et al. (1967) describes calls now known to be

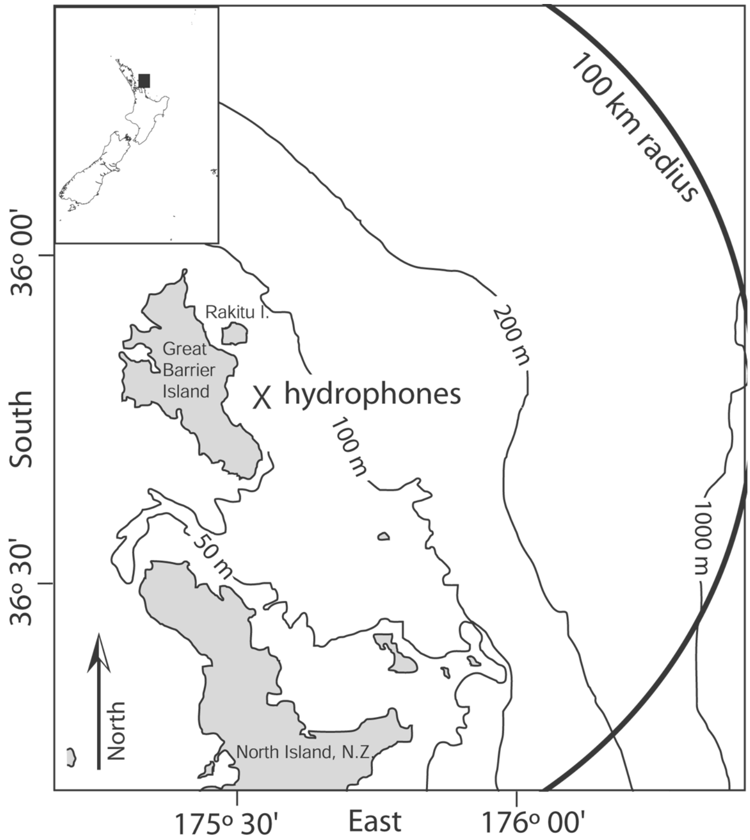

Fig. 1 Location of the hydrophone pair 5 km offshore Great Barrier Island, New Zealand. Edge of the continental shelf is near the 100 km radius from the hydrophones.

associated with Bryde's whales, blue whales and humpback whales, whereas the latter study (Helweg 1998) describes an automated detection technique as applied to sounds now known to be associated with Bryde's whales. The goal of the latter study (Helweg 1998) was the detection of humpback whale song, which was unsuccessful, but only 391 h of data recorded as 5 min out of every 90 min were examined. Neither of the previous studies provided year-round coverage necessary to examine the seasonality of call types. The work described in Fish (1964) describes calibrated ambient noise levels, urchin sounds and fish sounds, but does not discuss whale calls.

The initial goal of this study was to detect blue whale songs from the New Zealand region to better understand the worldwide distribution and seasonality of such songs. As many other baleen whale calls in these data were recorded, the goal of this paper is to present an account of all the low-frequency whale calls at the study location.

METHODS

Hydrophones and recording system

One year of acoustic recordings were analysed for whale calls from a pair of fixed hydrophones located 5 km east of Great Barrier Island, New Zealand (Fig. 1). This pair of hydrophones located 600 m apart was recorded during the calendar year 1997 by the Center for Monitoring Research (CMR) of Arlington, Virginia in conjunction with a feasibility study for monitoring underwater nuclear testing under the Comprehensive Test Ban Treaty. 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 and remain operational (Chris Tindle, pers. comm. 2003).

For this study, CMR provided all available recordings for the calendar year 1997. No absolute calibration data are available for the hydrophones and the gains were seen to shift periodically throughout the year, presumably owing to changes in the recording system. The 20 bit dynamic range of the data almost always prevented loud underwater sounds from clipping the recording. Data were recorded at 160 samples per s with an anti-alias filter at 70 Hz.

Because of technical problems with the recording system, data were not recorded from this hydrophone pair 42% of the time. The longest data gaps were 44, 26, 23, 10, 10, and 9 days, respectively on 16 September – 29 October, 13 March – 7 April, 20 May – 11 June, 22–31 December, 28 June – 7 July, and 1–8 November. The remaining data gaps were each less than 3 days in duration. Additional loss of useable whale detection data was caused by high noise levels owing to storm-driven wind waves. The noise level at which the data were considered unusable is subjective, but a level was chosen at which even moderate strength calls would no longer be detected, resulting in loss of 12% of the remaining data (7% of the year). The lost data from storms had durations ranging from less than 1 day to 5.5 days. There were data losses owing to the noise of passing ships of 11% of the remaining data (5.6% of the year). The typical duration of unacceptably high noise owing to a passing ship was c. 50 min. In total, 54.6% of the potential recordings were either missing or judged unusable.

Whale call identification and occurrence

All recordings were visually examined as scrolling spectrograms (FFT 1.6 s, 78% overlap, Hann window). Sounds recognised as whale calls were categorised visually based on previously published spectrograms for which the species producing the sound had been visually identified (Table 1). The species of whales whose calls would be identifiable within the available 10 to 70 Hz frequency band of the present recordings included blue, fin, humpback, minke and Bryde's whales.

A statistical scoring system described previously by McDonald & Fox (1999), was used in which all calls occurring within a given time interval were counted as one whale detection. Frequently, multiple whales were calling within the acoustically monitored area, but it was difficult to count each one and not double-count the passage of a single whale through the area. For example, 6 h of continuous calling would be scored as six detections with a 1-h time interval, two detections with a 4-h time interval, or one with an 8-h time interval. A typical recording might consist of 2 h of calling followed by 4 h of silence and 3 h of calling, a sequence which would score five with a 1-h time interval, two with a 4-h time interval and two with an 8-h time interval.

Choice of time interval is related to the detection range of a hydrophone for a given whale species and to the speed an individual whale could reasonably be travelling, with a longer detection range corresponding to a longer time interval. The time interval needs to statistically represent the average time required for a whale to pass through the detection zone (McDonald & Fox 1999). If the whale is not travelling and continues calling, it is appropriate to count the whale again in the next time interval, as though a new calling animal density survey was conducted. When the scoring system approaches saturation the number of animals are being undercounted, but this approach is intended only to provide a minimum species density, rather than an absolute density estimate (McDonald & Fox 1999). A single time interval of 12 h was chosen for this analysis, setting the maximum possible density estimate equal to one whale detection per 12-h period. The 12-h interval used here equates to an average straight line travel speed of 3.25 km/h and an estimated average detection zone radius of 45 km.

Table 1 Association of whale calls detected in this study with whale species based on previous descriptions of calls known to be produced by visually identified whale species.

Call type	References
New Zealand blue whale song	Kibblewhite et al.1967; McDonald et al. in press
Southern Ocean blue whale song	Širovic et al. 2004; Rankin et al. 2005; McDonald et al. in press
Blue whale song temporal patterns	Cummings & Thompson 1971; McDonald et al. 2001; Oleson 2005
Non-song blue whale calls	Thompson et al. 1996; Thode et al. 2000
Fin whale song	Watkins et al. 1987; Croll et al. 2002
Fin whale counter-calls	Thompson et al. 1992; McDonald et al. 1995; McDonald & Fox 1999
Humpback whale song	Kibblewhite et al. 1967; Winn et al. 1981; Cerchio et al. 2001
Bryde's whales	Helweg 1998; Oleson et al. 2003; Heimlich et al. 2005

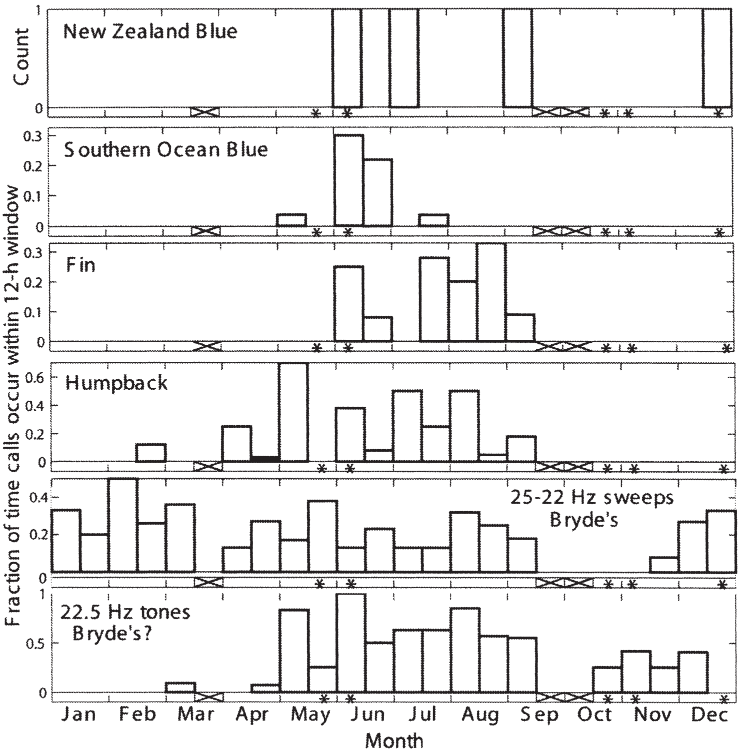

Fig. 2 Seasonal occurrence of six types of baleen whale calls plotted for each half month. Vertical axis is the fraction of 12-h time windows during which calls occurred, except for the blue whale songs known only from New Zealand where the vertical axis is count. (X below the graph baseline, no data were available for that period; asterisk, less than 50% of the possible data were available.)

Minimum density estimates

To estimate minimum density of blue and fin whales at the site, a 100 km detection range was assumed through a 140 degree arc for which the hydrophones were not blocked by land. The 12-h detection interval used to score detections was applied over 12 200 km^2. Blue whale calls can be readily identified in spectrograms from omni-directional hydrophones at 250 km (Širovic et al. 2004) when in an upward refracting deep water region, but at lesser ranges over a continental shelf such as the Great Barrier Island region or in a downward refracting ocean environment (McDonald et al. 1995).

Humpback whale calls are detectable at a considerably greater than 50 km range in a strong surface sound channel environment (Swartz et al. 2003) where propagation is expected to be slightly better than the continental shelf region off Great Barrier Island. Therefore, a 50 km detection range through a 140 degree arc was used for the humpback and the presumed Bryde's whale calls. The 12-h detection interval used to score detections was applied over 3050 km^2.

RESULTS

Blue whales

There were four detections of a blue whale song type known only from New Zealand waters (Fig. 2). Two of the detections contained only weak signals not suitable for further analysis, but the detections on 15 June and 21 December contained high signal to noise ratio (SNR) recordings. This blue whale song consisted of four parts, repeated nearly identically every 115 s (Fig. 3). The pulsive parts of the call appear as sidebands around the fundamental frequency (1.6 s FFT, Hann window, 87.5% overlap). Part one is a 2.8 pulse per s downsweep from 27 to 24 Hz of 5 s duration. Part two is a 2.6 pulse per s tone at 25–26 Hz of 15 s duration. Part three is a 2.7 pulse per s tone at 27 Hz and 5 s duration, though there is a faint pulsive downsweep precursor of 2 s. Part four is a 20 Hz harmonic tone of 15.5 s duration. In the 15 June encounter, the blue whale produced 145 high SNR four part calls (Fig. 3A) with additional low SNR calls before and after these. The calls were patterned with longer gaps corresponding to times when the

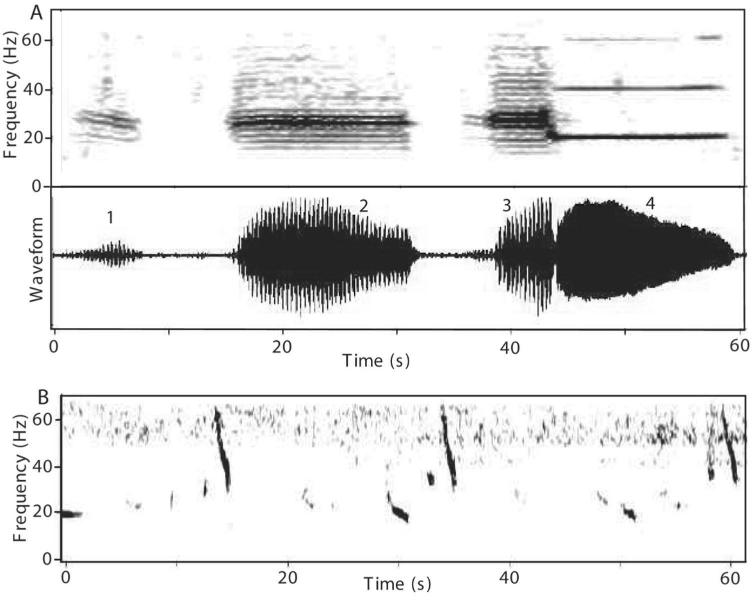

Fig. 3 **A**, The New Zealand blue whale (*Balaenoptera musculus*) song consists of four parts, repeated nearly identically every 115 s. **B**, Associated with the New Zealand blue whale song of 21 December, were non-song blue whale calls.

whale surfaced. The average interval between calls during a dive for this animal was 115.2 s with a standard deviation of 0.9 s on 115 measurements. The overall standard deviation does not fully express the consistency of the calling interval as there tended to be a gradual drift in the call interval with more consistent intervals associated with calls nearer in time. The gaps associated with surfacing times were much more variable with a median value of 220 s and extreme values of 109 and 477 s on 28 measurements. The average dive time was 727 s based on the calling pattern.

Data for both hydrophones were analysed, but there was no difference in the recorded whale calls, except for the time offset relating to the bearing angle to the call. Examination of time delays between the two hydrophones for the encounter of 15 June showed the whale unambiguously departed the area of the hydrophones to the northwest along the shoreline between Rakitu and Great Barrier Islands, about 7 km northwest of the hydrophone pair. The departure route was evidenced by the bearing angles and the rapid decline in signal amplitude while the animal continued to call. The initial bearing to the whale was ambiguous owing to the nature of any bearing computed from only two hydrophones. The initial bearing to this animal was likely 260 degrees because the area due north of the hydrophones is charted as foul ground where acoustic propagation was expected to be poor. The bearing angles changed steadily, but with decreasing rate of change throughout the 4 h and 25 min of strong calls. The probable track corresponded to an average travel speed of c. 2 km/h. The call amplitudes at the beginning of the call series increased more rapidly than would be expected for open water propagation, further supporting a track inshore of the hydrophones as most probable. The encounter of 21 December consisted of both songs and a variety of other frequency downswept calls (Fig. 3B). This acoustic encounter lasted c. 7 h, but had many gaps of more than 10 min and did not show as much consistency in call spacing as was seen in the encounter of 15 June. Call type changed several times between the song (four part calls) and the shorter duration downswept call type (Fig. 3B).

Ten detections of Southern Ocean blue whale song occurred from May through July (Fig. 2) and had low SNR, indicating these whales remained further offshore. The lower intensity second and third portions of these calls (Rankin et al. 2005) were not observed in the recordings. Identification of these calls (Fig. 4A) as Southern Ocean blue whales was based on the 60–65 s interval between calls, the centre frequency (28.14 Hz ± 0.07, n = 81), a slight downward sweep in frequency, and the c. 7 s duration of these calls.

Fin whales

Fin whale recordings can be divided into two basic types: patterned doublets which may be referred to as song, and irregular calls, sometimes used as counter-calls. There was a seasonal occurrence based on 26 detections of fin whales from June through September (Fig. 2). All fin whale detections had a low SNR, indicating these animals remained offshore from the hydrophones. A patterned doublet fin whale call was the more common type recorded (Fig. 4B), though both types occurred. This example is of the patterned doublet type with a 35–17 Hz pulse alternately followed by a 21–18 Hz pulse. In some recordings none of the pulses had frequencies higher than 25 Hz. In this example the spacing was 17 s and 9 s alternately.

Humpback whales

The seasonal occurrence of humpback whales was from February to September based on 65 detections (Fig. 2). The individual calls (Fig. 4C) were typically 4 s each in duration and typically grouped in patterns, as expected for the low frequency components of humpback song. These call sequences typically lasted c. 2 h with clear beginning and end points, although some lasted more than 24 h. There were no obvious diel patterns in these calls.

Bryde's whales

Calls with a downward sweep in frequency from 25 to 22 Hz and an impulsive broadband sound at the start of each call (Fig. 4D) were identified as Bryde's whale calls. Unlike the 22 Hz tonal calls, regular repeat intervals were not evident for this call type. There were no significant diel patterns observed in these calls and the calls occurred year-round (Fig. 2).

A 5 s duration 22 Hz tonal call type (Fig. 4E) was detected 141 times with a seasonal pattern (Fig. 2). The association of this call type with a baleen whale species was less apparent than with the call types described above. The calls usually occurred in a regular pattern with repeated calls for a particular animal occurring with a precise repeat interval, though this interval varied from 2 to 5 min. Multiple animals often appeared to begin calling at nearly the same time. The duration of individual calls was 4 to 7 s, although this was partially dependent on the SNR of the calls. The frequency was 22.1 ± 0.17 Hz (n = 100). There were no significant diel patterns in these calls.

On two occasions, 17 May and 14 June, 26 Hz paired whale calls (Fig. 4F) were detected. These paired calls (each part presumed to be from the same whale) repeated at c. 2-min intervals, with a dominant frequency of 26.1 Hz. The duration of the first tonal part of each call pair was c. 4 s whereas the second part was typically of 5 s duration and slightly downswept in frequency.

Minimum whale density

The maximum allowable whale density corresponding to a density of 1.0 in Fig. 2 is 0.082 whales per 1000 km^2 for blue and fin whales and 0.328 whales per 1000 km^2 for humpback and Bryde's whales, based on the method described above. The 22 Hz tonal calls were detected during 50% of the possible detection periods from May through September (Fig. 2), thus the minimum density was 0.164 whales per 1000 km^2. Humpback whale calls were present c. 30% of the time during the May through August peak for a minimum density of c. 0.100 whales per 1000 km^2. Fin whale calls were present c. 20% of the time during their June through August seasonal peak for a 0.016 whales per 1000 km^2 minimum density, and Southern Ocean blue whale calls were present c. 20% of the time during the peak season for a 0.016 whales per 1000 km^2 minimum density.

DISCUSSION

Blue whale song

The New Zealand blue whale song was previously described in New Zealand waters by Kibblewhite et al. (1967), though its association with blue whales was not established at that time and the technology for describing the song with spectrograms was not as well developed as today. This song type is compared with other blue whale songs in McDonald et al. (in press), where the species association is evident from the similarity in character, frequency and duration relative to the calls of other species. Southern Ocean blue whale song was first directly tied to visual identification of the species by Rankin et al. (2005) using directional sonobuoys, although it had been assumed these calls were from blue whales in earlier publications (Sirovic et al. 2004). The low SNRs for the Southern Ocean blue whale songs recorded in this study suggests these animals were travelling at or beyond the edge of the continental shelf. The temporal patterns in blue whale song were first related to dive durations by Cummings & Thompson (1971) and have since been confirmed using directional sonobuoys (McDonald et al. 2001) and acoustic recording tags (Oleson 2005; Oleson

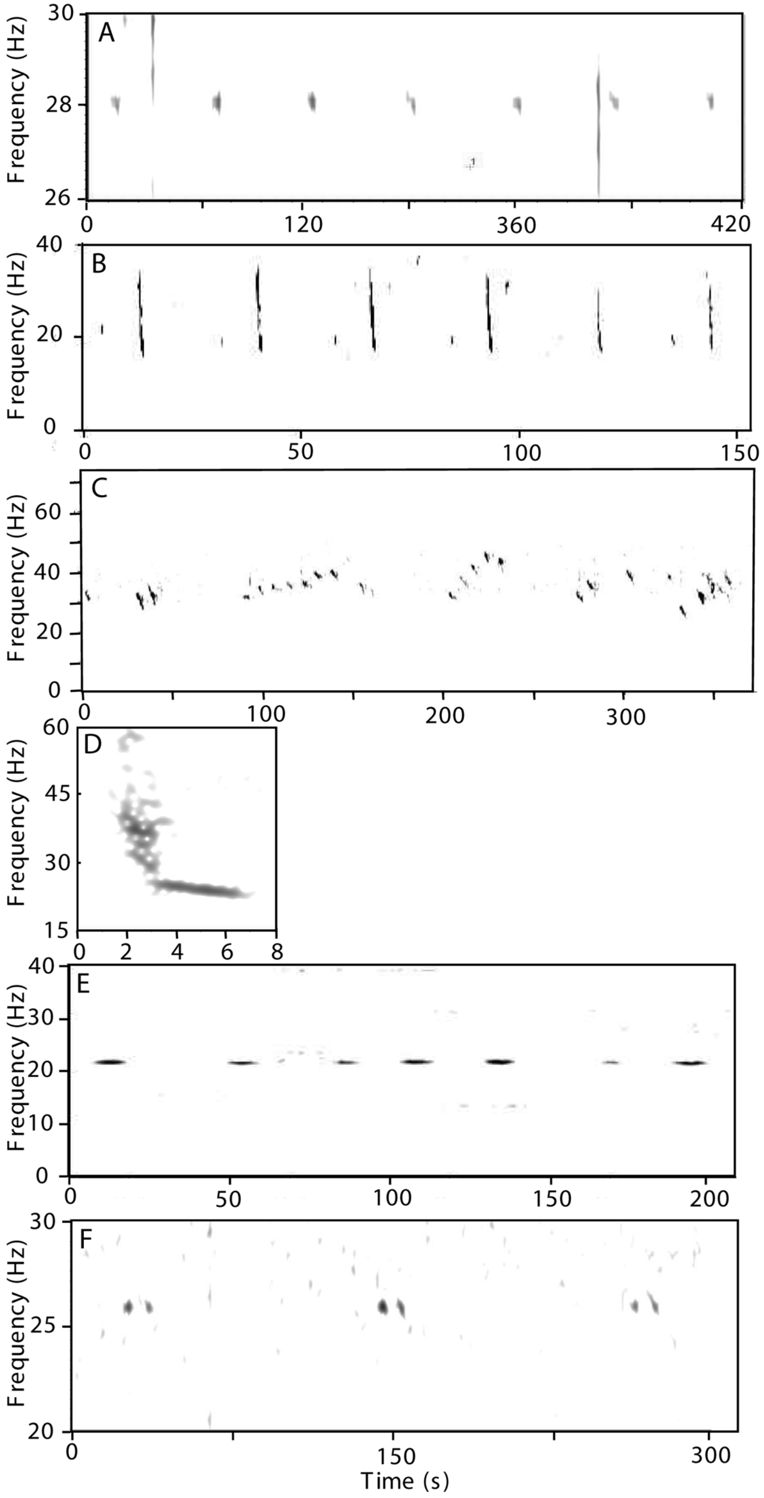

Fig. 4 **A** Southern Ocean blue whale (*Balaenoptera musculus*) song, 5 s FFT, 95% overlap. **B**, Fin whale (*B. physalus*) calls, 0.8 s FFT, 87.5% overlap. **C**, Humpback whale (*Megaptera novaengliae*) calls most of which occured above the 70 Hz frequency limit, 1.6 s FFT, 87.5 % overlap. **D**, 25–22 Hz downsweep associated with Bryde's whales (*B. edeni*). **E**, 22.5 Hz tonal call, showing overlapping call series from four animals, probably Bryde's whales. **F**, Whale call pairs from unknown species, probably Bryde's whales.

et al. in press). The downswept blue whale calls have been previously described from other regions (Oleson 2005; Oleson et al. in press).

Fin whales

Geographic variation in fin whale song has been observed, but is not well understood (Thompson et al. 1992). In some regions a patterned doublet or song is the primary call type detected (Watkins et al. 1987) whereas in other regions counter-calls are dominant (McDonald et al. 1995). It is probable that only males produce song (Croll et al. 2002), although both sexes may produce counter-calls. The low SNR of the fin whale calls suggests these animals were at or beyond the continental shelf edge.

Humpback calls

Most humpback whale calls occur above the upper frequency limit of the recordings used for this study; thus only components of humpback whale song relatively low in pitch were recorded in the data used here (Fig. 4C). Detection rates for humpback whale calls would have been higher if more bandwidth had been available for this study. The spacing, duration and character of the humpback whale calls which were detected (Fig. 4C) provided the species association with humpback whales even though the complete songs were not recorded. The alternative to associating these patterned calls with humpback whales would be to suggest another whale species produces similarly patterned songs. Previous researchers using the same hydrophones recorded with greater bandwidth have described humpback whale song (Kibblewhite et al. 1967) and would likely have noted the presence of any non-humpback whale complex sound sequences if present.

The seasonality of humpback whales at Great Barrier Island has been previously studied from whaling records (Dawbin 1997) with catches of adult males occurring from late May to the beginning of August during the northbound migration, and relatively few catches during the southbound migration from mid-September to late October. Adult males are presumed responsible for most breeding season calling (Darling & Bérubé 2001). Kibblewhite (1967) described humpback calls as being present all year long in 1958, but more pronounced in the months April to September and practically non-existent by 1961. From 1959 through 1961, at least 264 humpbacks were killed in the area where the recordings were made (Dawbin 1997), but large-scale Soviet whaling to the south presumably caused the crash of this population (Zemsky et al. 1995; Clapham & Baker 2002). Humpback calls were reported to be non-existent in the area by 1963 (Kibblewhite et al. 1967), presumably because few animals were left. This stock is still considered to be highly depleted (Garrigue et al. 2002). The May to August peak in humpback whale calls at this site is consistent with the migration of male humpback whales through this area (Dawbin 1997).

Bryde's whale calls

The 25–22 Hz frequency downswept calls have been described by Kibblewhite et al. (1967) and Helweg (1998) in New Zealand waters. A very similar call was subsequently correlated to Bryde's whales by Oleson et al. (2003) in the Eastern tropical Pacific and the geographic range of similar calls was extended westward across the Pacific by Heimlich et al. (2005). Helweg (1998) suggested a nocturnal or crepuscular pattern occurred in these calls in October, but not during July–August, the two time periods examined in that study. Oleson et al. (2003) named a very similar call "Be3" and Heimlich et al. (2005) referred to a similar call as "low-burst tonal". The calls described here are similar but not exactly the same as either the Be3 or the low-burst tonal.

22 Hz tonal and 26 Hz paired calls

The best species association with the 22 Hz tonal call is the Bryde's whale. Early accounts of Bryde's whale calls (Cummings et al. 1986; Edds et al. 1993) are unlike those recorded here, but later recordings by Oleson et al. (2003) show Bryde's whales produce calls similar to that recorded here and by Kibblewhite (1967). The near year-round occurrence of these calls is the best match to the year-round occurrence of Bryde's whales, the most abundant baleen whale in this region and the most common call type (Gaskin 1968, 1972). The observation of multiple animals starting to call at the same time suggests the calls of one animal encourage others to call.

The differing seasonality of the 25–22 Hz Bryde's whale calls and the 22 Hz tonal whale calls may indicate the presence of several species or stocks of Bryde's whales in this region. Bryde's whale taxonomy continues to be examined, and the status and ranges of the closely related species *B. edeni*, *B. brydei*, and *B. omurai* are not yet well determined (Best 2001; Wada et al. 2003). Two stocks of Bryde's whales with different seasonality have been reported off South Africa, where one stock migrates inshore/offshore and the other stock is resident (Best 2001); perhaps analogous to the two call types observed here, one seasonal and one year-round. An alternative explanation for the differing seasonality would be that one call type is produced seasonally and the other produced year-round even though all the whales responsible may be present year-round.

Other species

Sei whales are not known to produce calls within the frequency range of these recordings (McDonald et al. 2005), thus were not expected to be detected in these data even though they may have been present. Right whales (*Eubalaena australis*, Desmoulins 1822) are expected to produce calls within the 10–70 Hz recording bandwidth of this study (Clark 1982), but it would be difficult to distinguish these from the low frequency portions of humpback whale calls. No minke whale calls were detected in the present data, though only the lowest pitch minke whale calls would fall within the bandwidth of these recordings and identification of these as minke whales would be difficult.

Minimum density estimates

It would be ideal to compute ranges for each of the acoustic whale detections, such that point transect methods could be used to statistically estimate the population density of calling animals (Buckland et al. 2001). Range data are commonly obtained with three omni-directional hydrophones or with two directional hydrophones, such that geographic positions can be directly calculated for each calling animal (Swartz et al. 2003; Wiggins et al. 2004; Širovic et al. 2004; Munger et al. 2005). Ranges without geographic positions can often be obtained using single hydrophone multipath approaches (Cato 1998; McDonald & Fox 1999; Wiggins et al. 2004). An effort to estimate range for each calling animal detected is beyond the scope of this paper.

With some species in some areas, the best estimates of animal density are from acoustic surveys. Examples of these instances include minke whales (Rankin & Barlow 2005), sperm whales (Barlow & Taylor 2005), and fin whales (McDonald & Fox 1999). It appears there are no animal density estimates for the species under study in the New Zealand region. Because acoustic surveys detect only calling animals, density estimates are only provided as minimum densities. Even an estimate with a large error bound can be useful when no other data are available. An error model for these minimum density estimates can be calculated by changing the detection range and average straight line travel speed used in the calculations.

Future studies

With these data available for re-analysis and the potential to analyse long-term recordings from these hydrophones in the future, it should be possible to measure changes in baleen whale call activity at this site. The different geographic distributions of Bryde's whale call types (Oleson et al. 2003; Heimlich et al. 2005) suggests the utility of call type in determining stocks and identifying new species, although more study is needed. The two different call types produced each by Bryde's whales and blue whales at this site, may allow future real time direction of small vessels to animals of a known call type such that genetics sampling can be combined with acoustics to provide a better understanding of these calls.

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