

Seasonal occurrence of low frequency whale vocalisations across eastern Antarctic and southern Australian waters, February 2004 to February 2007

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ABSTRACT

Long term acoustic records of underwater sound can be used to assess the timing of migrations, peak periods of relative abundance, and seasonality and overlap of different species' presence over large spatial scales. Long-term acoustic data was collected over large portions of the Southern Ocean between Australia and the Antarctic continent. A three year hydro-acoustic record (<~100 Hz) from the Comprehensive Nuclear-Test Ban Treaty Organization (CTBTO) was obtained from lower latitude waters off Western Australia between January 2004 and February 2007. Bottom mounted autonomous recording packages (ARPs) were deployed off eastern Antarctica (between 115-175° E) in the waters near Casey station from February 2004 through February 2005, and near Prydz Bay and the southern Kerguelen Plateau from February 2005 through February 2007. The ARPs recorded low frequency (<250Hz) sound continuously over this period. Three additional acoustic loggers (recording <2000Hz) were deployed roughly along a line of longitude (141°E) between Tasmania and the Antarctic continent between October 2006 and February 2007. Power spectral density (PSD) analyses of the frequency bands of blue (Antarctic and pygmy) and fin whale calls was carried out. The peak acoustic presence of pygmy blue whales that occurred at the more northerly recording sites was consistently earlier (March-May) than peak Antarctic blue whale acoustic presence (May-August) at these sites. At the northerly CTBTO site, fin whale and Antarctic blue whale acoustic seasonal presence appeared nearly identical. Fin whale acoustic presence in the Antarctic data appeared to be over a much shorter time (April-June) than Antarctic blue whales, which maintained some acoustic presence nearly year round, but had seasonal peaks between March and July/August. In addition, two previously identified types of pygmy blue whale calls (West Australia and Madagascar) were detected representing, as far as we are aware, the furthest south these sounds have been recorded.

INTRODUCTION

The relatively recent development of autonomous sea-floor instruments capable of long-term acoustic monitoring (Wiggins, 2003; McCauley *et al.*, 2000, Hatch *et al.*, 2006) enables detection of calling animals when sighting surveys are not feasible and permit year-round acoustic surveys of regions that are normally inaccessible due to weather or ice cover. For instruments deployed in a single location for long periods, peaks in acoustic detections can be used to assess the timing of migrations, peak relative abundance, and seasonality and overlap of different species' presence (Burtenshaw *et al.*, 2004; Širovic *et al.*, 2004). Comparison of recording packages from different locations can be used to assess different times of residence and potentially migratory movements. Finally, comparison of acoustic detections from individual locations over multiple years can permit changes in presence, relative abundance

and timing through seasons to be assessed. These data can then be compared to other biological and oceanographic data collected from vessel-based surveys and remote satellite sensing to correlate whale behaviour with such variables as sea-ice presence, water temperature, and productivity.

Blue and fin whales are ideal candidates for acoustic monitoring. Both produce intense, repetitive stereotypic low frequency vocalizations that travel long distances. Blue whales all around the Antarctic have been shown to produce a three part call beginning with a long (~10s) 28Hz tone, followed by a short (~2s) downsweep (28→20Hz), and ending with a slightly modulated 20→19Hz tone (Rankin *et al.*, 2005; Širovic *et al.*, 2004; McDonald *et al.*, 2003; Ljungblad *et al.*, 1998). The initial 28Hz tone appears to be a useful identifying feature as the 2nd and 3rd components are often missing (Rankin *et al.*, 2005). Suspected pygmy blue whales off Madagascar and Western Australia produce similar low frequency, but regionally distinctive sounds that can be distinguished based on differing frequencies and patterns of sound production (Ljungblad *et al.*, 1998; McCauley *et al.*, 2000). Fin whales throughout the northern hemisphere produce short (~1s) repetitive pulses centered around 20Hz (Watkins, 1981; Thompson *et al.*, 1992). Similar sounds have recently been reported in the Southern Ocean and have been used to acoustically monitor for this species (Širovic *et al.*, 2004).

Long term recordings have shown that blue and fin whales produce these calls year round (Clark and Chariff, 1998; Širovic *et al.*, 2004; Richardson *et al.*, 1995) though seasonal variation in the relative abundance of these calls is apparent (Watkins *et al.*, 1987; Širovic *et al.*, 2004; Clark and Chariff, 1998; Moore *et al.*, 1998; Stafford *et al.*, 2001). In the last 5 years in the Antarctic, bottom mounted acoustic recording packages (ARPs) (Wiggins, 2003) have been used to record low frequency sound for periods of a year or more off the West Antarctic Peninsula (Širovic *et al.*, 2004; Moore *et al.*, 2003), and at a number of locations off east Antarctica (Gedamke *et al.*, 2006; McKay *et al.*, 2005). In the WAP region, the two year dataset (2001-2003) indicates year round presence of blue whale calls, with peaks in relative abundance occurring in March and April and a secondary peak in October and November. Fin whales were detected between February and June with a peak in May.

In Gedamke *et al.* (2006), we presented initial results from two ARP deployments off east Antarctica between February 2005 and February 2006 which suggested a larger acoustic presence of both these species from April through June with the strongest peak occurring in April-May. In 2006 these instruments were redeployed, and a separate series of three acoustic loggers running north-south from Tasmania to the Antarctic continent was put in place. We also obtained a 3 year record of acoustic data collected off West Australia from the Comprehensive Test Ban Treaty Organization (CTBTO). This collection of data and comparison between datasets will greatly expand the geographic and temporal coverage of long-term acoustic records around the Antarctic continent and southern Australian coast.

METHODS

Recordings were obtained from three different instrument types in seven different locations in the waters off southern Australia and the Antarctic (Figure 1).

1) Comprehensive Test Ban Treaty Organization (CTBTO) nuclear test monitoring station: Recordings were obtained from the CTBTO which operates a hydroacoustic monitoring array approximately 114km SW of Cape Leeuwin, off the south-west coast of Australia (34.4° S, 115.1° E). The 3 hydrophones in this array are suspended in the SOFAR channel (~1050m depth) and acoustic sampling is conducted at a rate of 250Hz, with an effective bandwidth of up to 100+Hz. The data from a single hydrophone channel (#1) between January 2004 and April 2007 was analyzed.

2) Autonomous acoustic recording packages (ARPs): ARPs (Wiggins, 2003) sit on the sea floor and passively record acoustic signals for a continuous period of a year or more sampling at 500Hz and giving an effective acoustic recording bandwidth of up to 250Hz. One ARP was deployed February 25, 2004 off Casey Station Antarctica (63° 49.22' S, 111° 45.24' E), in water depth of approximately 3000m. Due to problems with the datalogger (data corruption and battery failure), useable data was obtained for the period of March 11, 2004 through January 2, 2005.

On January 31 2005, an ARP was deployed in 1800m of water on the southern edge of the Kerguelen plateau ($62^{\circ} 35.44' S$, $81^{\circ} 15.64 E$), an area where previous research indicates high concentrations of marine mammals occur (Tynan, 1996). On February 7, 2005 a second ARP was deployed approximately 500km to the southwest on the edge of the continental shelf off Prydz Bay ($66^{\circ} 12.864' S$, $74^{\circ} 30.612 E$) in 2700m of water. The two ARPs were recovered and new instruments were redeployed in approximately the same locations on February 25, 2006, and February 21, 2006 respectively. The ARPs were finally recovered on March 5 and 7 2007, respectively, providing continuous recordings from these two locations for over 2 years.

3) Curtin University acoustic loggers (CU loggers): Custom acoustic loggers were developed at Curtin University (similar to those described in McCauley *et al.*, 2000) in conjunction with the Australian Antarctic Division. These loggers sampled sound from HTI 90-U hydrophones (High Tech. Inc., Gulfport, Mississippi) at 4000Hz, giving an effective acoustic recording bandwidth of up to 2000Hz. Due to the increased data recorded at the higher sampling rate and limitations in hard drive space, a sampling schedule was set up to record 13 minutes of sound every hour for the full deployment of up to more than a year.

Three CU loggers were deployed roughly along a line of longitude in the waters between Tasmania and the Antarctic continent (Figure 1). The central logger was deployed on an in-place oceanographic mooring (CSIRO's SAZ mooring at $53.74^{\circ} S$, $141.77^{\circ} E$) along the mooring cable at a depth of approximately 1500m. The logger began sampling on December 18, 2005 and sampled through the recovery on October 5, 2006.

The other two of the CU loggers were deployed as part of autonomous mooring packages that sat on the seafloor. One was deployed on January 21, 2006 off the edge of the Antarctic continental shelf near Dumont D'Urville ($65^{\circ} 33.2' S$, $140^{\circ} 32.6' E$) in a water depth of approximately 1100m. It sampled a full year until recovery on January 25, 2007. The last instrument was deployed on a seamount to the south-west of Tasmania ($44^{\circ} 00.138' S$, $144^{\circ} 39.914' E$) in 1866m of water. It began sampling on March 11, 2006 and sampled over 10 months until its recovery on January 18, 2007.

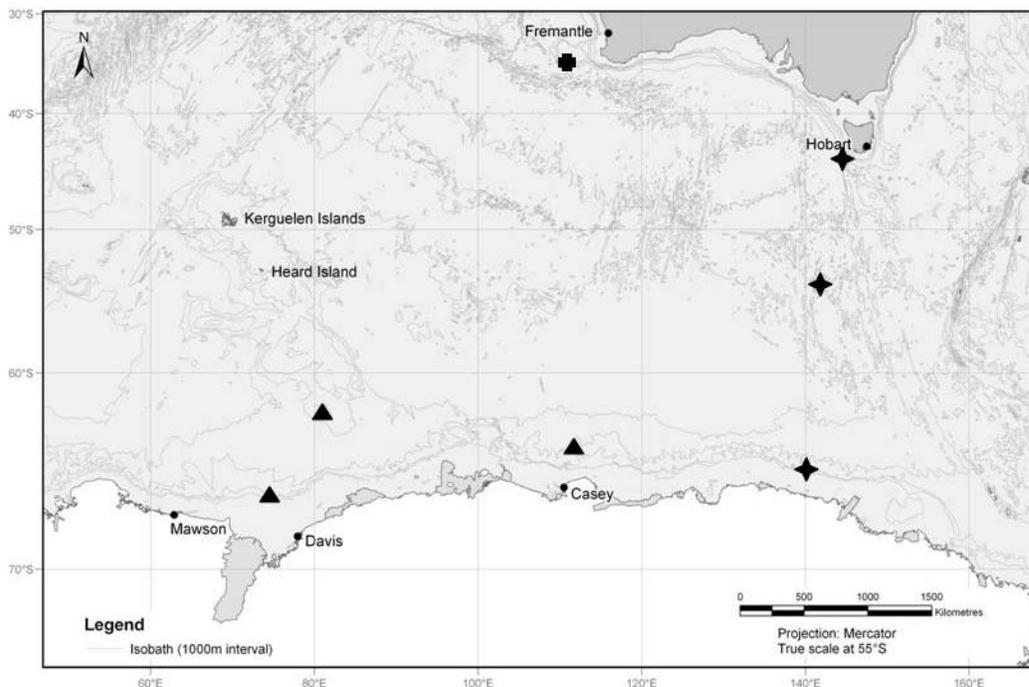


Figure 1— Locations of where acoustic records were obtained from [Circle-CTBTO hydroacoustic array, triangles-ARPs, diamonds-CU loggers]. See text for description of the acoustic logger types

Power Spectral Density (PSD) Analysis

As a preliminary means of assessing the broad scale presence or absence of calling whales, the recordings were analyzed by comparing the acoustic power in the frequency bands of whale vocalizations to acoustic power in adjacent frequency bands in a similar manner to that used by Širovic *et al.* (2004) and Gedamke *et al.* (2006). The power spectral density (utilizing the Pwelch function in Matlab 7.1 [www.mathworks.com]) was calculated over the entire dataset from each acoustic record (250, 500, and 4000-point FFTs for the CTBTO data, ARPs, and CU loggers, respectively, leading to 1Hz frequency bins for each dataset, 50% overlap, Hanning window) and averaged over 15 minute samples using custom written Matlab code.

For Antarctic blue whales, we used power at 28 Hz as the calling band and compared it to an average of the powers at 15 and 41Hz, (due to very low frequency noise on the CU loggers, we used 27Hz as the calling band with surrounding frequencies of 23 and 31Hz) assuming linear noise between the two. To monitor for the distinct blue whale song of suspected pygmy blue whales off Western Australia and to avoid overlap between its sounds and Antarctic blue and fin whale calls, we used power at 71 Hz as the calling band (a prevalent harmonic seen in McCauley *et al.*, 2000 and McDonald *et al.*, 2003) and compared it to an average of the powers at 63 and 79Hz. To avoid the overlap between fin whale 20 Hz calls and the 20Hz component of blue whale calls, we used a higher frequency component of fin whale calls that is often apparent (Širovic *et al.*, 2004). Based on clear recordings of fin whales in the ARP and CTBTO data, we compared the power at 99 Hz with an average of the powers at 89 and 108Hz. These 15 minute samples were averaged over 1 week periods to plot relative changes in power spectral density (PSD) ratios with time over the year long deployment.

RESULTS AND DISCUSSION

The stereotypic 3 part calls of Antarctic (Figure 2) and pygmy blue whales off Western Australia (Figure 3), and the 20Hz pulses of fin whales (Figure 4) that are analysed here are illustrated below.

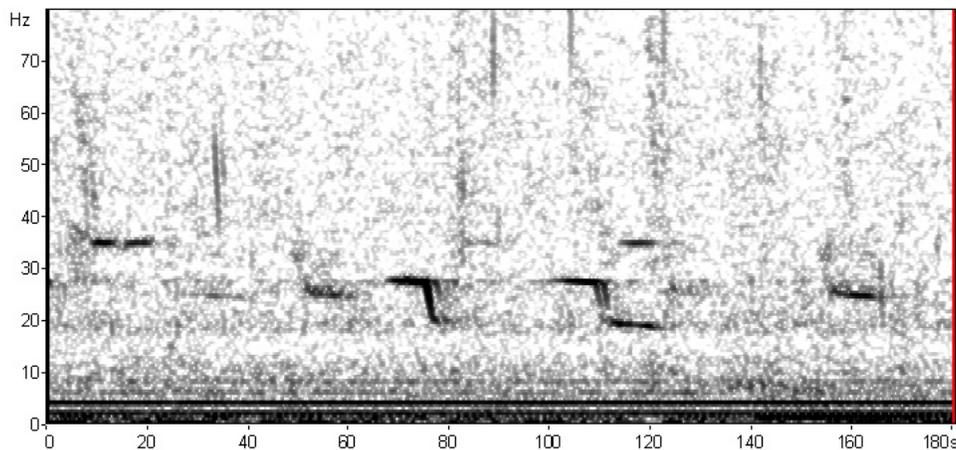


Figure 2—Antarctic blue whale 3 part song (central 'Z' shaped calls) along with blue whale Madagascar type two part song (around 35 and 27-26 Hz) on either side.

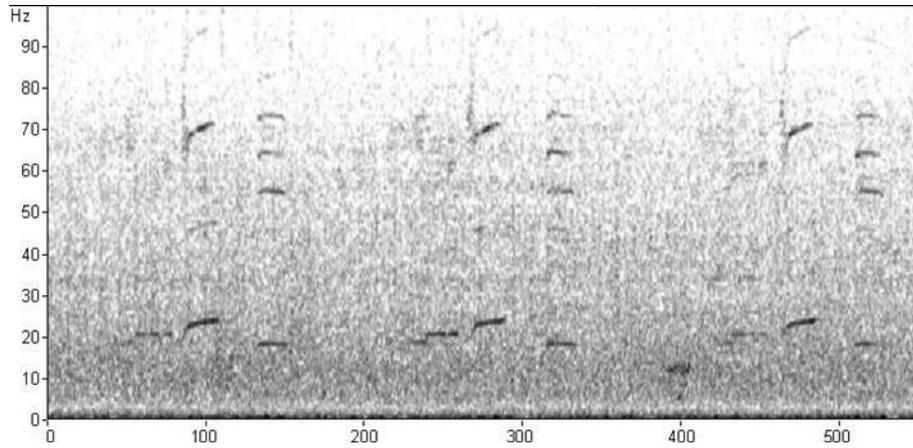


Figure 3—Western Australia type pygmy blue whale song with the prevalent harmonic around 71 Hz

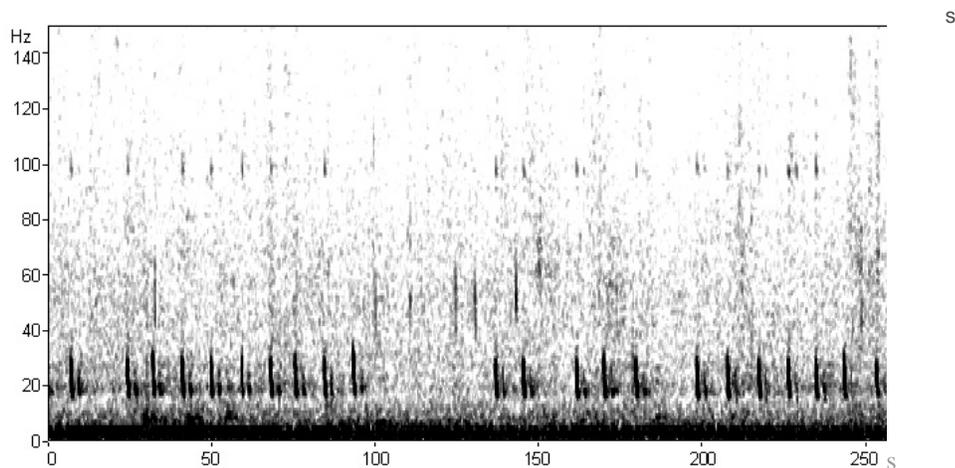


Figure 4—Fin whale 20 Hz pulses with accompanying higher frequency component around 99Hz

The secondary upper frequency component that often accompanies the 20 Hz fin whale pulses on the ARP and CTBTO recordings appears at ~99Hz (Figure 4). This can be contrasted with recordings from the West Antarctic Peninsula, where a similar component was reported around 89 Hz (Širovic *et al.*, 2004). Geographic variation in call types has previously been proposed as a means of identifying populations of blue whales (McDonald *et al.*, 2003) and is evident in the 3 different types of blue whale songs illustrated in figures 1 and 2. If the difference in fin whale calls is found to be consistent between locations, it could be an example of slight, but identifiable, variations in call types between geographic locations. Slight differences have previously been identified between North Pacific, North Atlantic, and Mediterranean fin whale calls (Hatch and Clark, 2004), though this is the first indication we are aware of that Southern Ocean fin whales in different regions may exhibit similar geographically distinct acoustic characteristics.

Figure 5 (top) illustrates the presence of spectral bands that we used in the PSD analysis in a spectrogram of the three year CTBTO dataset. The most obvious band occurs around 20-28 Hz and is comprised of a combination of blue and fin whale sounds. The top of this band, however, is predominantly comprised of Antarctic blue whale 28 Hz tones. Two other frequency bands are also visible, though considerably more faint. The one at 71 Hz is the Western Australian blue whale song, while the 99Hz band near the top of the spectrogram is comprised of the 99Hz component of fin whale calls. The seasonal nature of song presence is clearly visible in the spectrogram, and is more clearly illustrated in the PSD analysis of Figure 5 (bottom).

The seasonal acoustic presence is distinct and repeated each year over the three years analyzed, with Antarctic blue and fin whales following a similarly timed pattern, while pygmy blue whale acoustic energy peaks distinctly prior to the strongest acoustic presence of Antarctic blue and fin whales. Acoustic energy from Antarctic blue and fin whales is typically detectable initially around February-March, and fading by November. The peak ratio of acoustic power to ambient noise occurs each year between approximately May and August. Pygmy blue whale song (as measured at 71 Hz) is similarly seasonal, but is present for a shorter period of time each year. It is initially detectable around February, with a short 2-3 month peak centred around April-May, and fading completely by June-July each year.

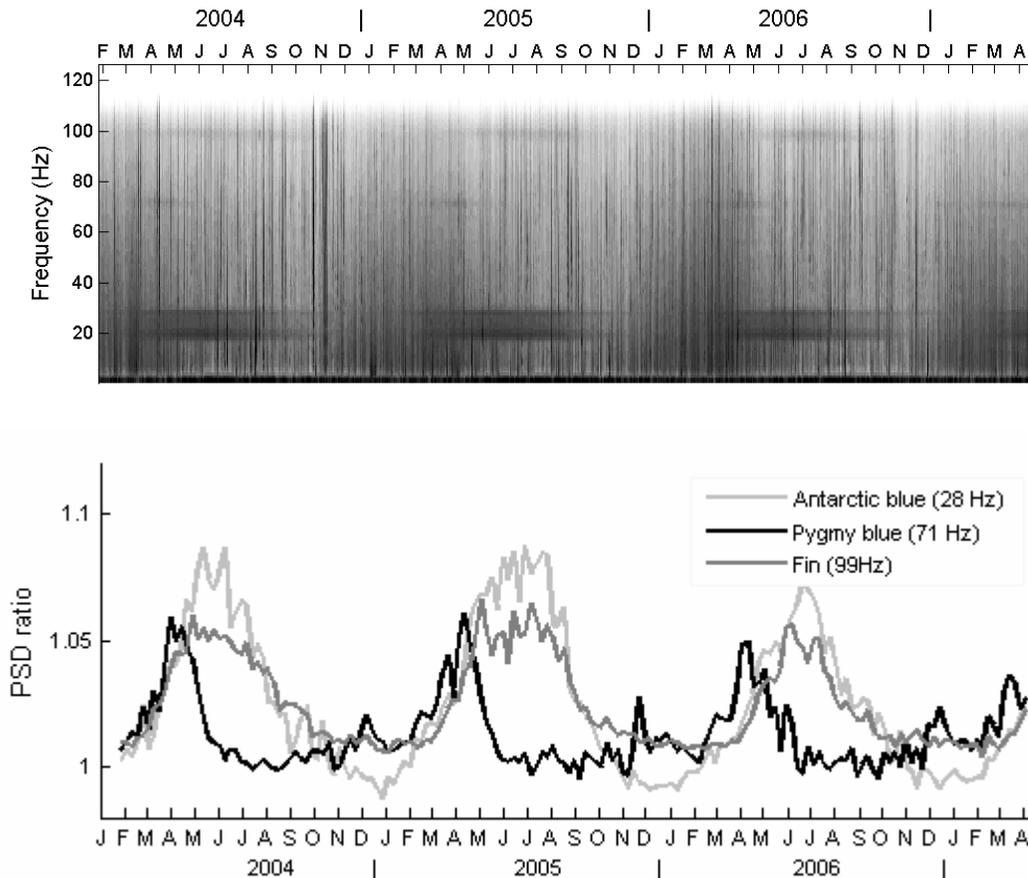


Figure 5—(Top) 3 year spectrogram illustrating the whale call bands and their seasonal presence. (Bottom) PSD ratio analyses of Antarctic blue whale calls, Western Australia pygmy blue whales, and fin whales.

Figure 6 compares the Antarctic blue whale acoustic presence (28Hz) as measured at the lower latitude CTBTO site and the high latitude Antarctic ARPs over 3200km due south (Casey) and south-west (Kerguelen and Prydz). Peak presence on both the Kerguelen and Prydz ARPs appears a bit earlier than at the CTBTO site. There are distinct strong peaks in both years at the Kerguelen site in early April-May, but then a lower level presence through to September or October. The Prydz data is less clear, though the peaks in both years appears to begin around February-March, with a noticeable drop by July. Again, though, a low level presence is apparent for some months afterward. Finally the Casey data actually indicates a peak roughly occurring slightly later than the peak in the CTBTO data between May and August of 2004. [Note that the Casey 2004 and Prydz 2006 datasets were both collected by a logger that exhibited sampling problems and hence the data will need closer inspection].

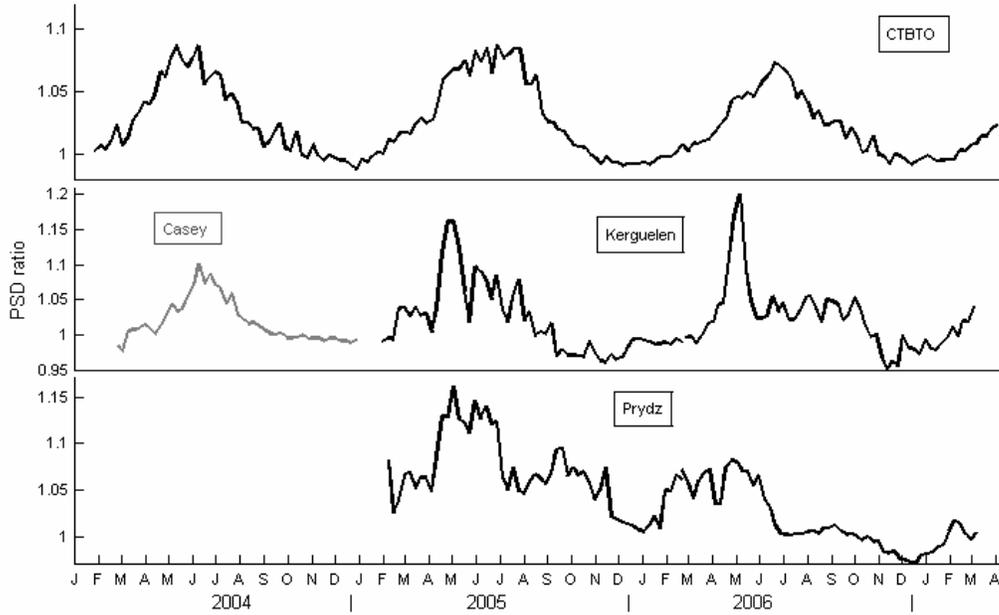


Figure 6— Antarctic blue whale (28Hz) seasonal acoustic presence recorded on the Antarctic ARPs vs. the CTBTO data. Note the different Y-axis scales

The peaks in 2005-2006 fin whale acoustic power on the Kerguelen and Prydz Antarctic ARPs versus the CTBTO data is shown in Figure 7.

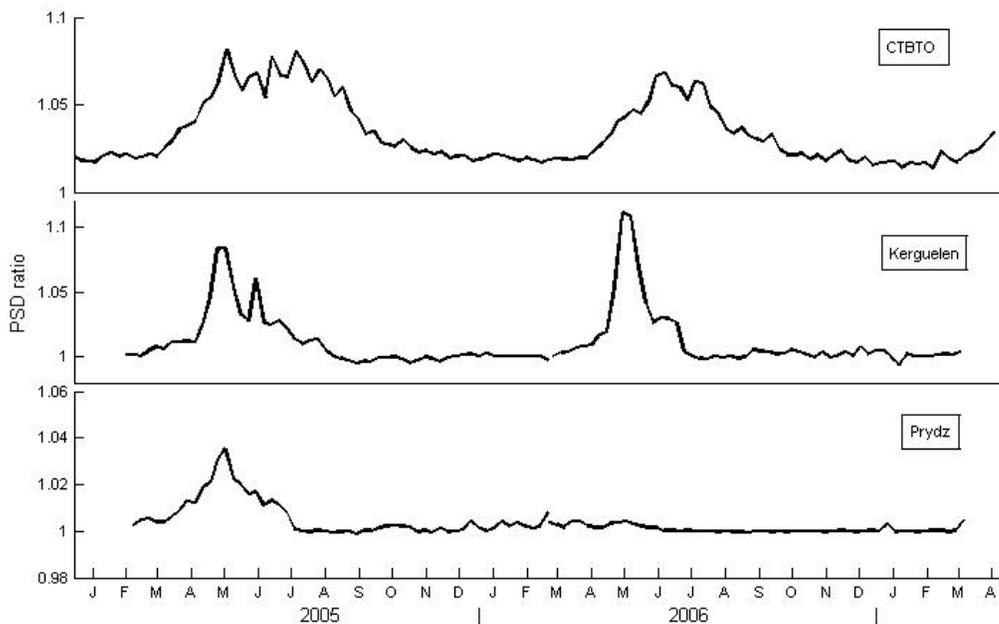


Figure 7— Fin whale acoustic presence (99Hz) comparison between Antarctic ARPs and CTBTO data. Note the different Y-axis scales.

In both 2005 and 2006 the Kerguelen ARP, and in 2005 the Prydz ARP had distinct fin whale peaks in May, and an overall acoustic presence that was shorter and earlier than the peak power in the CTBTO dataset (Figure 7). Notably, the 2005 peak on the Prydz dataset is much smaller than the Kerguelen peaks and there is no noticeable 99Hz fin whale presence in either the 2004 Casey dataset or the 2006 Prydz dataset. This is possibly due to fact that fin whales are not generally thought to migrate as far south as for example, blue or minke whales, so their calls might be

more prevalent at the nearly 400km more northerly ARP (also north of the southern boundary of the Antarctic circumpolar current). But it is also possible that the Kerguelen plateau region has high concentrations of marine mammals (Tynan, 1996). However, as noted above, there were sampling problems with the Casey 2004 and Prydz 2006 data, so whether this is due to an actual lack of calls or an artefact of problems with the datalogger as mentioned above is uncertain at this point and needs further examination.

Finally, the preliminary analysis of the CU loggers is presented in Figure 8. Most of this data was just received in March, 2007 so analysis is very preliminary at this point and the patterns are less clear than in data from some of the other locations. However, a few potential features are worth mentioning. On the most northerly logger, Antarctic blue whales have a faint but lengthy acoustic presence through most of the deployment that appears to be somewhat later in the year than both the 54° and 65° S loggers. The most southerly logger appears to have a similar seasonal pattern as the other Antarctic ARPs, with an increase beginning around February, and fading by July-August, though again there is a low level presence nearly year round.

Also, both the 44° and 54°S loggers show a similar earlier seasonal presence of 71Hz pygmy blue whale acoustic energy as seen with the CTBTO data, with its presence beginning in January and peaking around March before dropping off around June. There was no appreciable 71Hz pygmy blue whale energy at the most southerly logger. However, a rigorous analysis will be required to determine whether or not any individual pygmy blue whale calls can be detected on this southernmost logger. Previously on the Prydz and Kerguelen ARPs, while no appreciable pygmy blue whale (Madagascar type) energy was noticeable with this kind of long term spectral averaging, there were individual instances where these sounds were clearly recorded on both ARPs. They occurred on days in February, April, and May on the Kerguelen ARP, and in December and February on the Prydz ARP, though this was not a comprehensive analysis. As far as we are aware, this is the furthest south that calls attributed to pygmy blue whales have been recorded.

Fin whale acoustic presence at 99Hz was not readily noticeable in this initial analysis of the CU loggers.

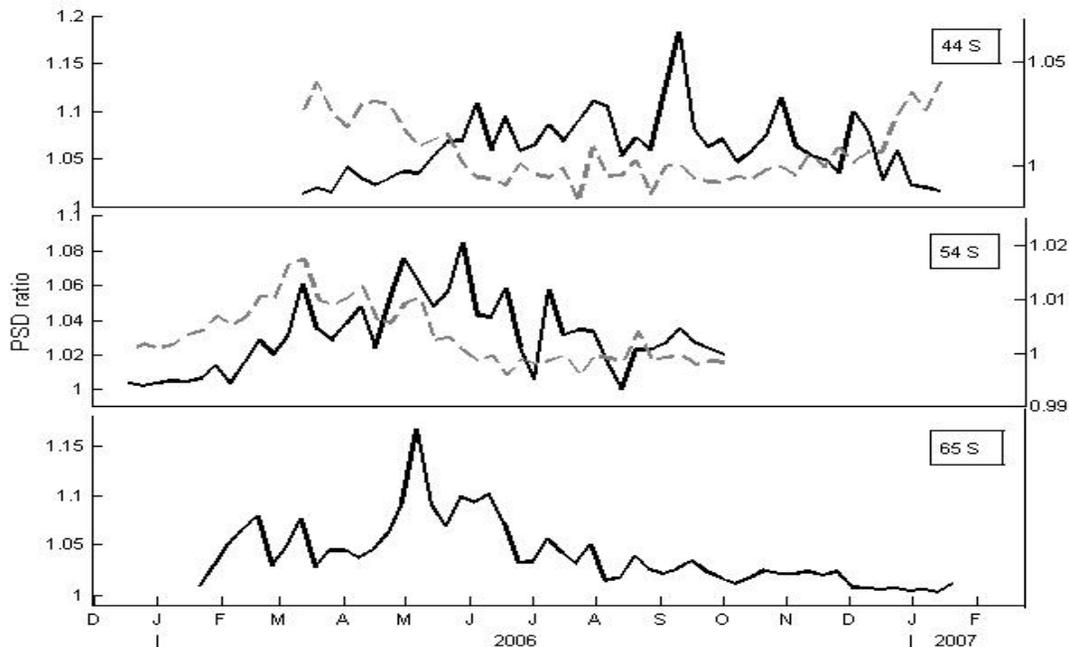


Figure 8— Antarctic blue (black) 28Hz and pygmy blue whale (gray) 71Hz acoustic presence (99Hz) across the three CU loggers deployed between Tasmania and the Antarctic continent. Approximate latitude is listed in the upper right corner. Note the different Y-axis scales with the Antarctic blue whale PSD ratio on the left, and pygmy blue whale on the right.

Notably, in May-June, 2006 a seismic survey was taking place to the northwest of Tasmania and was recorded on all of the loggers including the most southerly at more than 2500km south indicating that at least at low levels, the entire ocean basin was ensonified. Further analyses will examine the received levels of the seismic shots and frequency composition of the signals.

CONCLUSIONS

Preliminary PSD analyses like that presented here are useful for illustrating a broad pattern and approximating relative acoustic presence of whales at a single location. The peak presence of pygmy blue whales that occurred at the more northerly recording sites was consistently earlier than Antarctic blue whale acoustic presence. At the northerly CTBTO site, fin whale and Antarctic blue whale acoustic presence appears to be nearly identical, seasonally similar and temporally overlapping. In the ARP data where it could be measured, fin whale acoustic presence appeared to be over a much shorter time than Antarctic blue whales, which maintained some acoustic presence nearly year round.

A comparison of temporal differences in peak acoustic presence between northerly and southerly loggers might give some indication of migratory movements. There does seem to be some indication of this in the data presented here. This is far from clear however. In fact, while blue whales are known to sing year-round, if there is a strong seasonal component to singing behaviour (i.e. more whales and/or whales singing more often), this could mask or distort potential seasonal patterns. It is important to recognize that while the peaks in PSD values could accurately reflect relative abundance of whales, these values are also certainly linked to acoustic behaviour. If significantly larger percentages of whales begin to vocalize, or vocalize more often, in the lead-up to the breeding season, than even if more animals are migrating away and fewer animals are present near the acoustic loggers at these times, the ratio of acoustic power may not drop proportionally.

Lastly, it is important to realize that PSD ratio values are entirely ambient or background noise dependent. In other words, if ocean noise is high at the frequencies surrounding the whale call band, the ratio of whale call band power compared to surrounding frequencies' power will be lower. Therefore, differences in underwater noise at the two locations, or even just between two different weeks at the same location, could account for some of the differences in PSD values. Figure 9 is a relative plot of averaged weekly PSD values at 15 Hz for the entire 3 year CTBTO dataset.

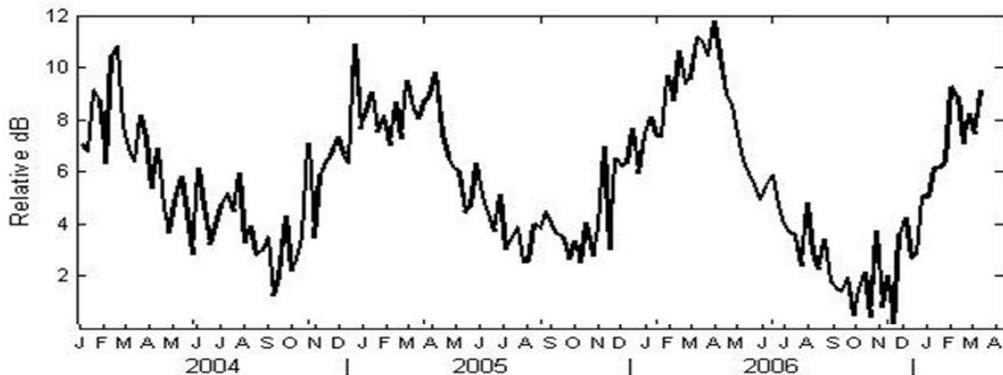


Figure 9—Relative ambient noise at 15 Hz over the three year CTBTO dataset.

There is clearly a seasonal increase in background noise every January through April/May of up to 10 or more dB over July through November/December. This pattern is mimicked in the Antarctic when ice covers the acoustic loggers leading to greatly reduced ambient noise. While the decrease in background noise in winter would suggest that any drop in acoustic power is actually due to less singing, or reduced whale presence during this time, the increased noise through April/May, would likely mask any initial increase in acoustic power ratios of whale calling bands. Therefore, the apparent onset of peaks in whale acoustic power (i.e. March-May) may appear artificially shifted or delayed due to increased background noise. As the background noise decreases, the acoustic power from whale calls will be more prominent.

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AADC 2007 Map produced by the Australian Antarctic Data Centre © Commonwealth of Australia. The bathymetric data is from "Centenary Edition of the GEBCO Digital Atlas", 2003, published on behalf of the Intergovernmental Oceanographic Commission and the International Hydrographic Organization as part of the General Bathymetric Chart of the Oceans; British Oceanographic Data Centre, Liverpool. The antarctic coastline data is from the Antarctic Digital Database version 4.0 © Scientific Committee on Antarctic Research 1993-2003.

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