Passive acoustic monitoring of baleen whales in Geographe Bay, Western Australia

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ABSTRACT

Baleen whales were monitored in Geographe Bay, Western Australia between 2008 and 2011 using passive acoustics. We aimed to monitor migratory timing through Geographe Bay, characterise whale vocalizations, and estimate detection ranges of vocalising whales in different background noise conditions. The results indicated that humpback and blue whales migrated through Geographe Bay every year, however the frequency and timing of their vocalisations varied among years. Humpback whale songs changed in composition among years, but most energy was consistently between 200-500 Hz. Blue whale calls were those of the eastern Indian Ocean pygmy blue whale with low quasi-tonal sounds with harmonics ranging from 20-100 Hz and variable down-sweep impulses with frequencies decreasing from ~100 Hz to ~20 Hz. No significant changes in calls were observed among years. Based on a range independent propagation model, the detection range for vocalising pygmy blue whales was estimated to be between 6-8 km, and for humpback whales ~20-30 km. The prevalence of high levels of noise from vessel traffic affected the detection range significantly for passive acoustic monitoring, and would have also affected the capacity for whales to communicate and perceive important cues in their environment.

INTRODUCTION

Monitoring of the migration of baleen whales through an area is usually based on visual methods (boat, land or aerial based). Such methods depend entirely on detection during the limited time in which whales come to the surface and are restricted to good weather, high visibility conditions, and often to relatively short distances from the coast. These limitations often make visual surveys expensive and the resulting sample size too small for accurate estimates.

Passive acoustic methods provide efficient and relatively inexpensive means for monitoring vocal animals such as baleen whales (Cato, Noad & McCauley 2005). Because these methods allow for a high temporal resolution over long periods, independent of weather conditions and visibility, they increase the success of baleen whales monitoring programs in remote locations and with target species that are difficult to see.

Geographe Bay in Western Australia is known for a large number of whales that seasonally migrate through its waters. Among the various baleen whales that migrate through Geographe Bay, humpback (*Megaptera novaeangliae)* and pygmy blue whales (*Balaenoptera musculus brevicauda*) occur in the greatest numbers, travelling close to the coast during their southward migration (Salgado Kent et al. 2011). Beyond general knowledge, however, limited information is available on their migration and behaviour through the area (including their vocal behaviour).

In this study, we used a noise logger deployed between the years 2008 and 2011 to: 1) monitor the migration of humpback and blue whales through Geographe Bay; 2) characterise their vocalisations; and 3) estimate the range over which whales were detected in different background noise conditions. The information obtained helps to establish the migratory timing of whales through Geographe Bay, defines the acoustic environment in which whales migrate through, and provide information for efficient acoustic monitoring methods for baleen whales. This type of information is vital for effective state and federal conservation and management plans, and future monitoring programs.

METHODS

Study area and data collection

Three long-term recordings were made in Geographe Bay (Western Australia) using a noise logger deployed at 30 m depth. The first recoding was made from November 27th 2008 to July 7th 2009, the second from November 12th to December 13th 2010, and the third from November 12th to December 16th 2011. The deployment location was within 2.5 km of the shore (Figure 1).

The three recordings were made with noise loggers programmed with different sampling schedules, sample rates, and anti-aliasing filters. The settings are presented in Table 1. All noise loggers were set to have a low frequency roll-off at 8 Hz and a total gain of 40 dB.

Table 1. Noise logger settings for deployments in Geographe Bay.

Year	Sampling schedule	Sample rate	Anti aliasing filter
2008-9	200 s every 900 s	6 kHz	2.8 kHz
2010	800 s every 900 s	12 kHz	5 kHz
2011	800 s every 900 s	12 kHz	5 kHz

Calibration and Data processing

The electronic part of the logger receiver channel was calibrated by applying white noise of known power spectral density to the channel input with either the hydrophone or a capacitor of equivalent capacitance connected in series with

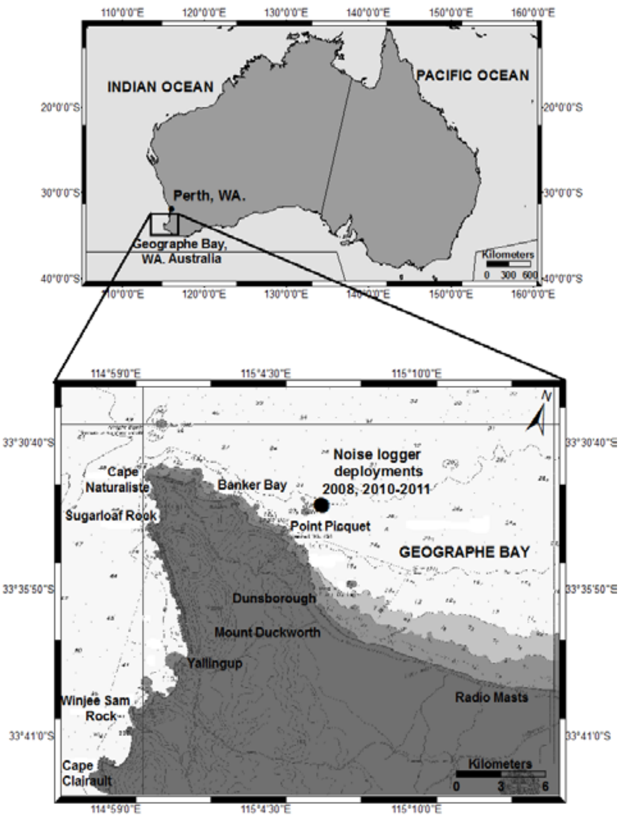


Figure 1. Study area and noise logger position indicated by the black circle.

the noise generator. This gave the total system gain versus frequency, which combined with the hydrophone sensitivity, provided the overall gain or data conversion factor in Volts (ADC input) per 1µPa. The system gain as a function of frequency measured is shown in Figure 2.

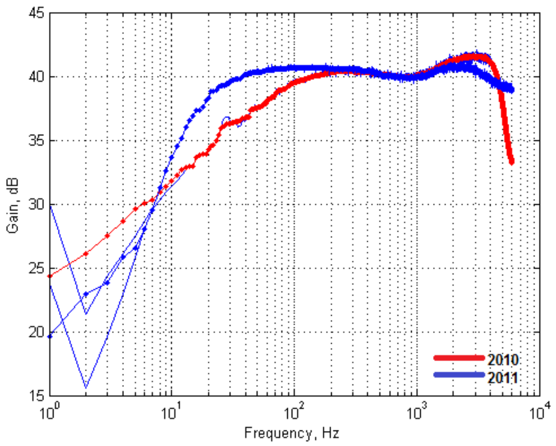


Figure 2. System gain curves for 2010 and 2011 of Geographe Bay noise loggers.

Data analysis

The recordings were analysed in Matlab using the Centre for Marine Science and Technology (CMST) developed Matlab toolbox 'CHORUS' (CHaracterisation Of Recorded Underwater Sound). Processing and analysis of sea noise data involved two stages:

1. Firstly, the power spectral density (PSD) of sea noise (i.e. noise spectrum) was calculated for each individual recording (200 or 800 s long, depending upon the recording). The PSD was corrected for the frequency response of the acoustic receiving system derived from the calibration data, so that the noise spectra and spectral levels were represented in absolute values (μPa^2/Hz and dB re 1 μPa^2/Hz respectively).

2. The CMST-developed noise Matlab toolbox with a graphic user interface was used to: 1) visualise spectral features of sea noise and their long-term variations by collating the pre-calculated spectra in spectrograms that represent the time period chosen to review; 2) select particular recording times based on the spectral features of interest visible in the spectrogram of low temporal resolution; and 3) analyse the waveform and spectrogram of sea noise within the individual recording made at the selected time. In this stage, the time-frequency characteristics of sea noise can be investigated in more detail using spectrograms of high resolution. In addition, high, low and band-pass filtering can be applied to selectively suppress unwanted noise, e.g. noise of non-acoustical origin.

Detection range

To determine the extent of the area in which vocalising whales were monitored by the noise logger, it was necessary to estimate the detection range of the logger. To achieve this, we needed to: 1) know the source level of whale calls, 2) estimate the transmission loss as a function of range at frequencies of whale calls, and 3) compare the received signal level (predicted from the source level and the transmission loss at different ranges) with the ambient noise level at the detection frequencies. The condition for detection can be approximately formulated as:

$$RL = SL - TL(R) \geq NL + SNR \qquad (1)$$

where *RL* is the received signal level, *SL* is the source level, *TL(R)* is the transmission loss increasing in general with the range *R*, *NL* is the noise level, and *SNR* is the minimum signal-to-noise ratio required for detection.

For the harmonic calls of pygmy blue whale, the source level has been estimated to be 179±2 dB re 1 µPa at 1 m (Gavrilov et al., 2011). The source level of humpback whale calls varies within a much wider range, from approximately 150 dB to 180 dB depending on song type and frequency content (Au, James & Andrews 2001). We considered different source levels of both species to estimate the minimum and maximum detection range.

The transmission loss was modelled using a numerical model of sound propagation in the ocean and a model of the underwater acoustic channel, which is characterised by the water depth, sound speed in the water column, and geoacoustic properties of the seafloor. Finally, a wave number integration method was used for numerical modelling of the acoustic propagation. This method was chosen because it is capable of modelling the interaction of sound with elastic media in the bottom and accurately predicting the transmission loss at short and long ranges from the acoustic source.

RESULTS

Whale sounds and their seasonal occurrence

Humpback and pygmy blue whale vocalisations were audible in all recordings made in Geographe Bay. Humpback whale songs were detected during June to July 2009 (when the recording finished) which coincides with the period of their northerly migration off the coast of Australia on route to calving grounds in the Kimberleys. Humpbacks whales were also detected from the time when the recordings commenced again in November until January. This period coincides with their southern migration on route to feeding grounds in the Antarctic. Blue whales were audible during November and December in 2008 and 2011, and only in November in 2010.

The maximum number of humpback whale vocalisations recorded varied between years. In 2008, humpback whale vocalisations were recorded from the first day of recording in late November to late December. The highest rate of detections was during the first two weeks of December, then the vocalisation events became sparsely detected, and at the end of December they were no longer audible. In contrast, in 2010 and 2011, the number of vocalisations was considerably higher in mid-late November and, although they became sporadic in December, they continued to be audible until the last day of sampling in mid-December.

Humpack whale vocalisation for the population migrating through Geographe Bay is characterised by a majority of components at frequencies between approximately 200 Hz and 500 Hz (Figure 3a), and fewer components at lower frequencies down to around 20 Hz (Figure 3b) and higher frequencies between 500 to 1000 Hz (Figure 4b, left pannel). The vocalizations of humpback whales consist of an ordered sequence of sounds organized into phrases which make up themes. Several themes make up a song that is unique to each population and repeatedly sung by individuals of the population (Winn 1981, Payne & Guinee 1983). Phrases within the humpback song recorded in Geographe Bay changed between years (Figure 4), however, the frequency range of the sounds remained the same.

During all years, phrases were formed by two to three units (sounds), except for one phrase in the 2011 song which was made up of only one unit (Figure 4b, middle panel). The units in the phrases were mainly downseeps and/or upsweeps spanning frequencies from about 50 Hz to 200 Hz (Figure 3-4). The received acoustic pressure of these calls varied from about $1 \cdot 10^5$ µPa RMS to $1 \cdot 10^6$ µPa RMS (i.e. from 100 dB to 120 dB re 1µPa RMS).

The second species recorded in Geographe Bay was the pygmy blue whale. The number of pygmy blue whale calls audible in the recordings was significantly lower than that of humpback whales. As with humpback whales, the period of time in which the maximum number of blue whale vocalizations was detected varied between years. In 2008, blue whales were audible from the first day of sampling in late November up to late December, with maximum number of calls in early December. In comparison, in 2011 the maximum number of calls was observed from mid to late November. In 2010 only one individual was detected in mid November.

Typical pygmy blue whale song consisted of a number of harmonics with frequencies from 20 Hz to about 100 Hz (Figure 5). The received acoustic level of these calls was up to $1 \cdot 10^6$ µPa RMS (120 dB re 1µPa RMS).

Blue whale song consisted either of two or three units or parts lasting from about 20 s to 40 s, repeated and sometimes combined or varied. A less common type of pygmy blue whale vocalisation which appeared to be produced independently from the song described above was also audible in the Geographe Bay recordings. The calls consisted of downsweep impulses approximately 2 s long with frequencies decreasing from around 100 Hz to 20 Hz, which were repeated with 40 to 50 s intervals (bottom left panels in Figure 5). Sometimes, harmonics of the principal frequency was also distinguishable in the signal spectrum. The received acoustic pressure of these signals reached $1 \cdot 10^7$ µPa RMS, i.e. 140 dB re 1µPa RMS. There was no evidence of major changes to the composition of the blue whale song during these three years.

Ambient noise

To estimate the detection range of whale vocalisations from the noise logger, the acoustic environment in which recordings were being made must be known. Ambient noise in Geographe Bay typically ranged from 65-75 dB re 1 uPa^2/Hz in the absence of vessels to 110 dB re 1 uPa^2/Hz when vessels were near the noise logger. Physical noise driven by wind or breaking waves generated differences in the power spectral density of ambient noise in the area. Figure 8 shows an example of this effect over two different time periods of 6 hours duration during one typical day in December in 2008: at night between 11pm and 5am (blue) and in the afternoon between 12am and 8pm (green). It is clear that the afternoon breeze forcing wind waves increases the noise level noticeably over the entire frequency range from 10 Hz to 3 kHz. The increase is more significant at frequencies higher than 50 Hz.

The red line in Figure 8 shows the maximum value taken form the PSD calculated for every 200-s recording made in the morning from 6am to 12pm during one day of the Christmas holiday in December. It is evident that the vessel noise, made primarily by fishing and recreational boats, changed the noise environment substantially in the area, adding more than 20 dB to the ambient noise. This occurred on most days with a somewhat smaller contribution from vessel noise on working days and during bad weather.

The anthropogenic noise in Geographe Bay was mainly from vessel noise that was more or less regular. However, there were other sources of low frequency man-made noise detected in the sea noise recordings which also significantly contributed to the noise environment over some periods. For example low-frequency noise was evident in late December to early January and had a maximum PSD of more than 100 dB at frequencies between 20 Hz and 40 Hz. This level is much higher than the regular noise level at those frequencies, even for the busiest vessel traffic period.

Transmission loss

To estimate the acoustic transmission loss in the absence of experimental data over the continental shelf in Geographe Bay, we used a numerical model of sound propagation in the ocean and a model of the underwater acoustic channel, which is characterised by the water depth, sound speed in the water column, and geoacoustic properties of the seafloor. In shallow water of 30-40 m in Geographe Bay, the sound speed does not vary much with depth, so we assumed it to be constant (1520 m/s). The detailed structure and characteristics of the bottom sediments in Geographe Bay are not known. Therefore, we used a model based on the most common structure of the sediments found on the Western Australian continental shelf. This model consists of a relatively thin layer of sand overlaying a limestone basement. We assumed that the sand layer was 0.5 m thick. The compressional wave speed in sand was taken to be 1750 m/s, the density to be 1800 kg/m^3, and the sound attenuation to be 0.1 dB/m•kHz.

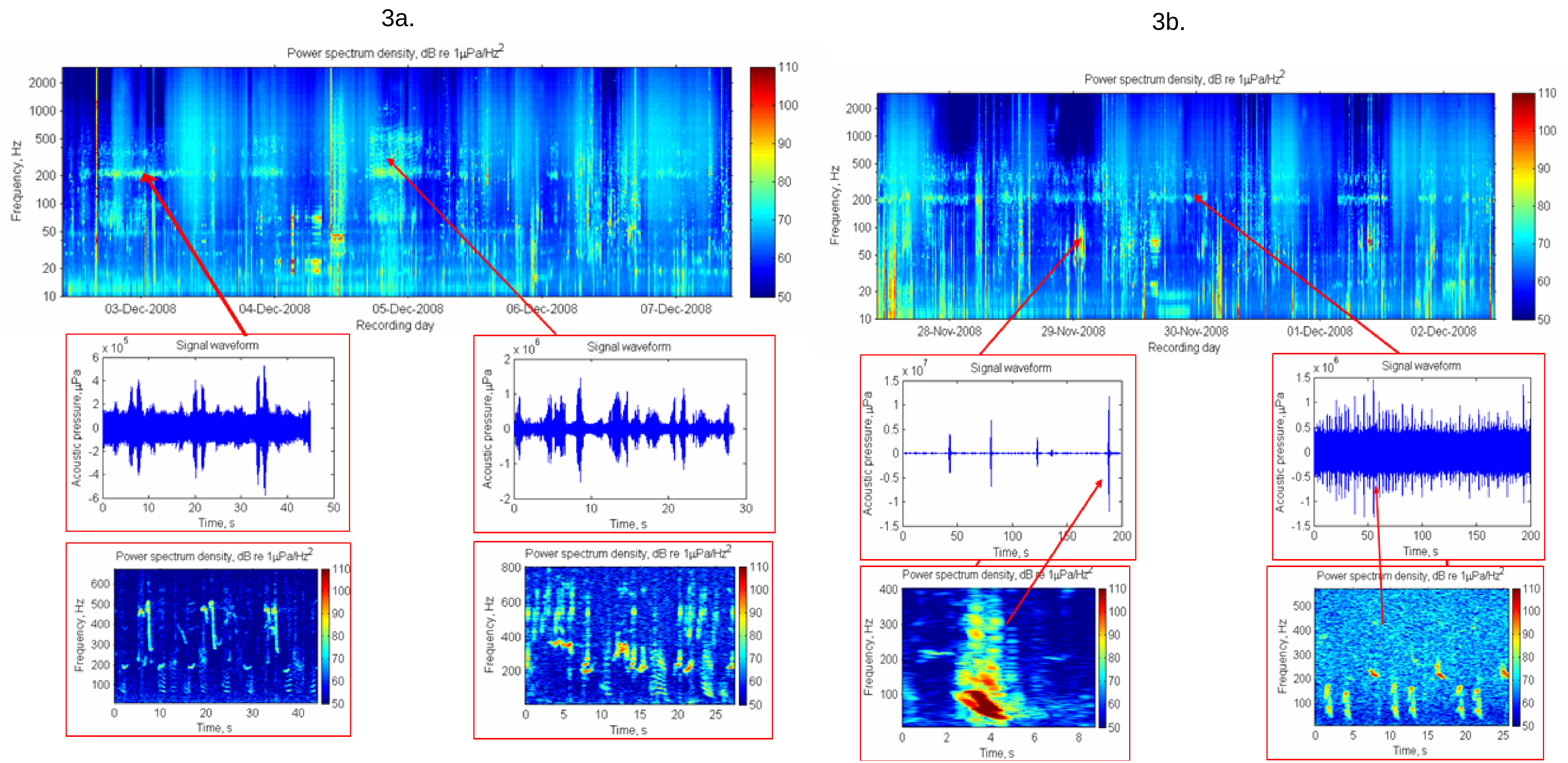
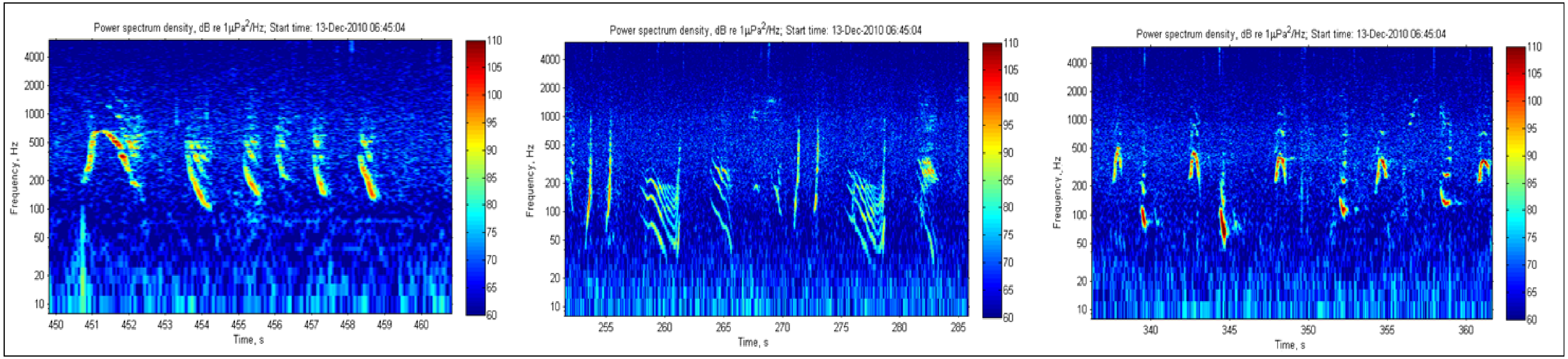


Figure 3. Spectrograms of ambient noise compiled from the PSD of 200-s recording from: (3a) 02/12/08 to 07/12/08 where the bottom panels show examples of the waveform and spectrogram of humpback whale calls of broader frequency spectrum, and (3b) 27/11/08 to 02/12/08 where the bottom left panels show the waveform and spectrogram of a series of downsweep calls by pygmy blue whales and the bottom right panels show the waveform and spectrogram of low frequency humpback whale call. The time is Western Standard Time.

4a

2010



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2011

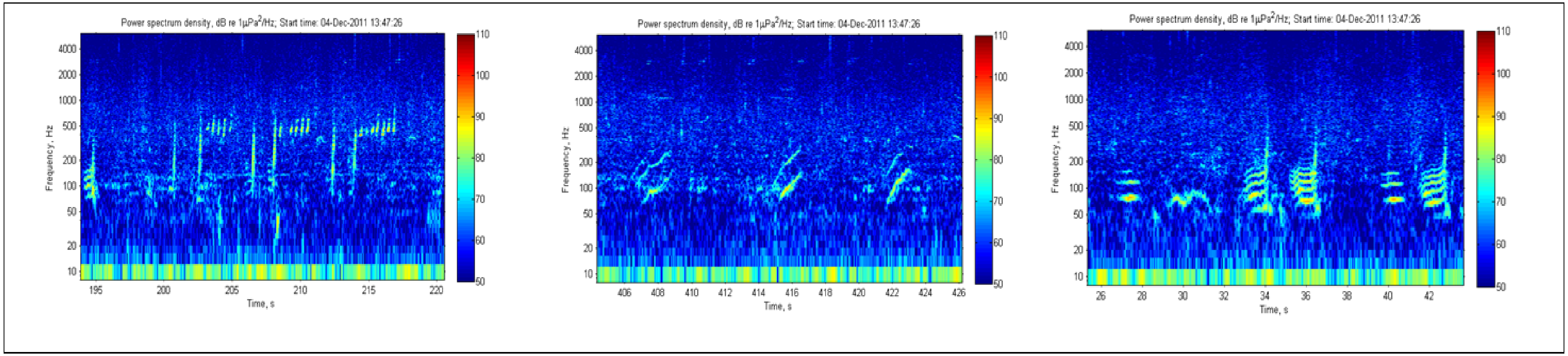

Figure 4. Spectrograms of example phrases making up themes in humpback whale song recorded in Geographe Bay, where (4a) shows examples of song phrases in 2010 and (4b) of song phrases in 2011.

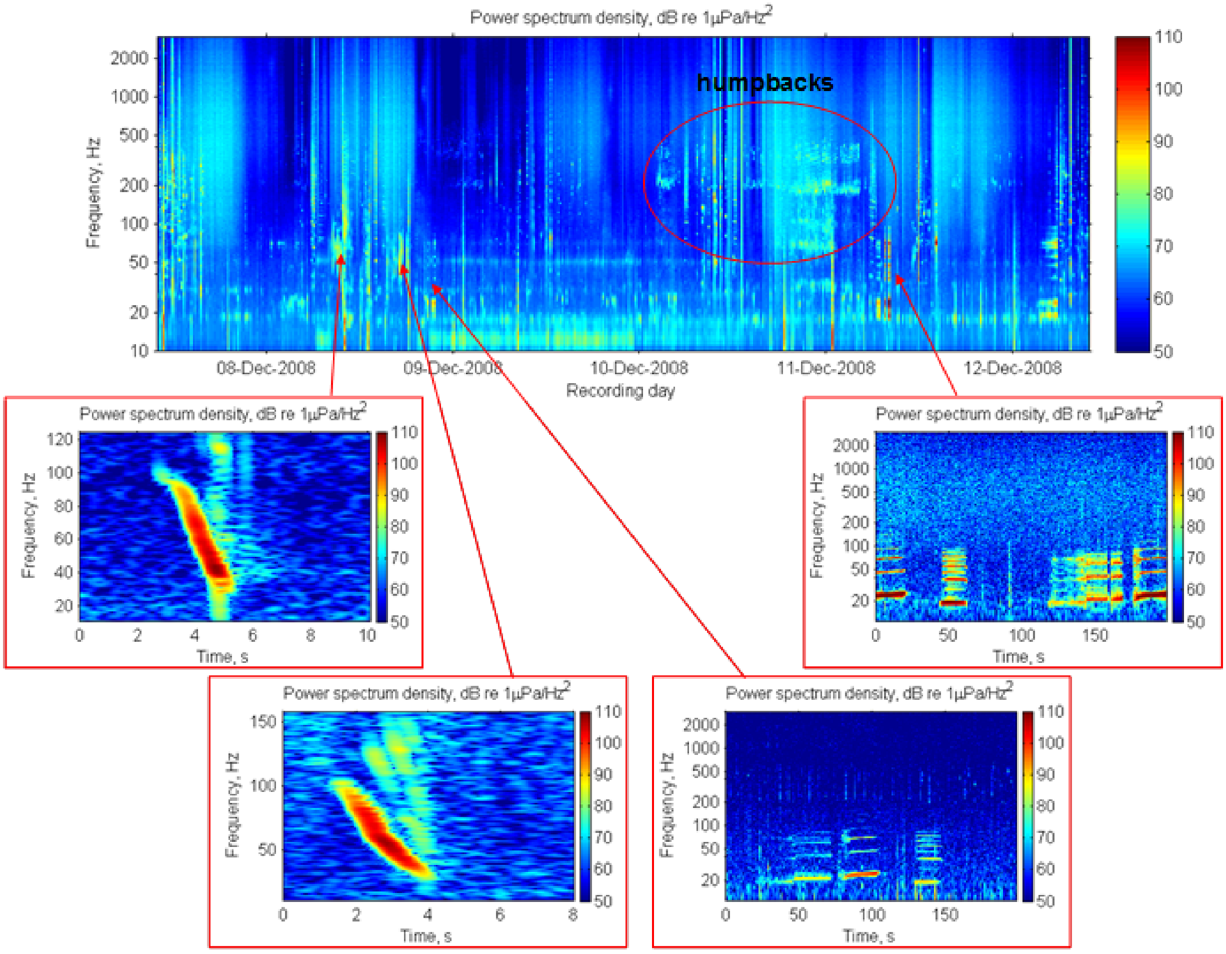

Figure 5. Spectrogram of ambient noise compiled from the PSD of each 200-s recording from 07/12/08 to 12/12/08. The small left panels show the spectrograms of downsweep calls from pygmy blue whales. The right panels show the spectrograms of a typical 3-part harmonic song of pygmy blue whales.

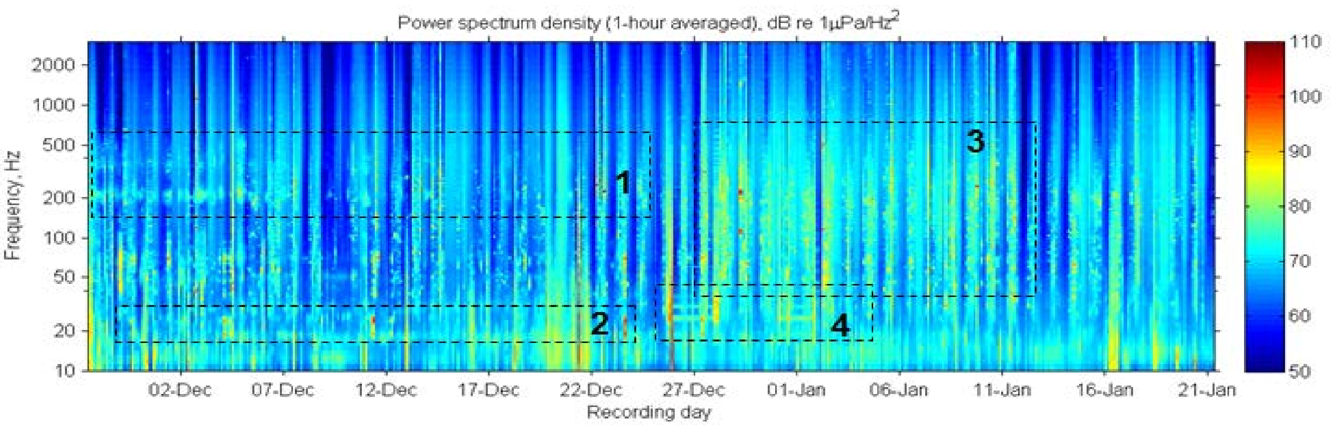

Figure 6. Spectrogram of ambient noise compiled from hourly averaged PSD for the period from 27/11/08 to 21/01/09 (in Western Australian Standard Time). The rectangles indicate the time and frequency span of noises from some typical noise sources in Geographe Bay: 1 – humpback whale vocalisation; 2 – pygmy blue whale vocalisation; 3 – intensification of shipping noise during Christmas holydays; and 4 – long lasting industrial noise of unknown origin.

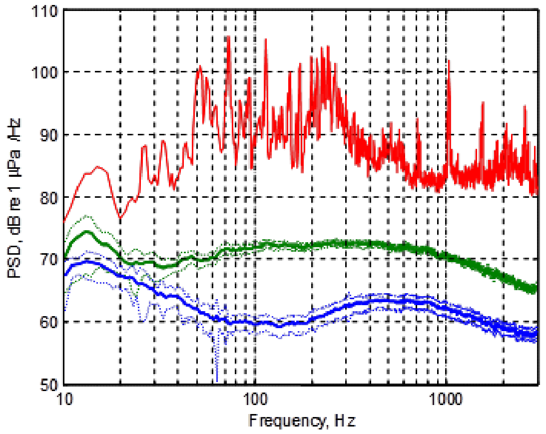

Figure 8. Power spectrum density of ambient noise averaged over 6-hour periods of no wind (blue) and high wind (green) during one day in December 2008. The dotted lines show the standard deviation of fluctuations at different frequencies. The red line shows the maximum vessel noise observed from 6am to 12pm.

The limestone basement is an elastic medium, so that it is necessary to take into account shear waves in the basement in the acoustic propagation model. Based on existing data (Duncan, Gavrilov & Fan 2009), the sound (compressional wave) speed in limestone was chosen to be 2400 m/s, shear wave speed to be 1200 m/s, and the density to be 2400 kg/m^3. The attenuation of compressional and shear waves was modelled as 0.2 and 0.6 dB/m·kHz, respectively.

A wavenumber integration method was used for numerical modelling of acoustic propagation. This method was chosen because it is capable of modelling the interaction of sound with elastic media in the bottom and accurately predicting the transmission loss at short and long ranges from the acoustic source. The changes in bathymetry within 30 to 40 m in Geographe Bay are gradual, hence we assumed the water depth to be constant and equal to 35 m in the acoustic propagation model. The transmission loss was predicted numerically for a source placed at 15 m below the sea surface, a receiver put on the bottom, and for frequencies from 15 Hz to 1 kHz. The narrow horizontal bands of lower transmission loss at low frequencies below 200 Hz in Figure 9 are due to the critical frequencies of the low-order normal modes interacting with the elastic bottom (Au, James & Andrews 2004). At frequencies other than the critical ones, the transmission loss below 200 Hz is very high, mainly because the acoustic wavelength at such frequencies is comparable to or larger than the sea depth.

Detection range

During quiet periods (no vessel and low wind/wave noise), the ambient noise level was about 65 dB re 1 µPa^2/Hz at the frequencies of pygmy blue whale calls from 20 Hz to 100 Hz.

The lowest frequency of pygmy blue whale calls of ~20Hz carries about 75% of the signal power (e.g. only about 1.5 dB less than the broadband signal level). If a whale signal is to be detected in a 1-Hz frequency band, then the transmission loss at 20 Hz should not exceed 108 dB and 102 dB for the loudest and weakest calls, respectively, for reliable detection with at least 6-dB SNR.

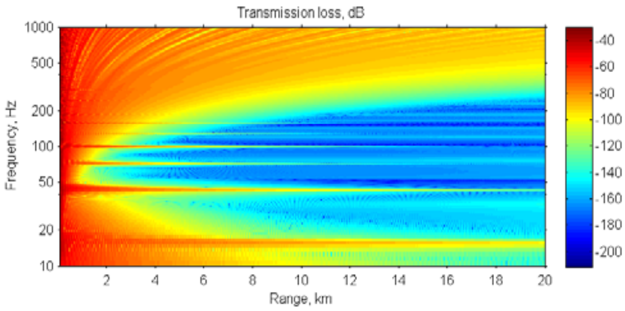

Figure 9. Transmission loss versus range and frequency modelled numerically for the ocean acoustic channel in Geographe Bay.

According to the modelling result plotted for five different frequencies in Figure 10, the transmission loss of 108 dB at 20 Hz is expected at approximately 8 km, and that of 102 dB at about 6 km from the source. So, the maximum detection range for pygmy blue whale vocalisations monitored from the noise logger in Geographe Bay is estimated to be between 6 km and 8 km. This estimate could be slightly different, if a different seafloor model with a different thickness of the sand layer and different speed of elastic waves in the basement was assumed.

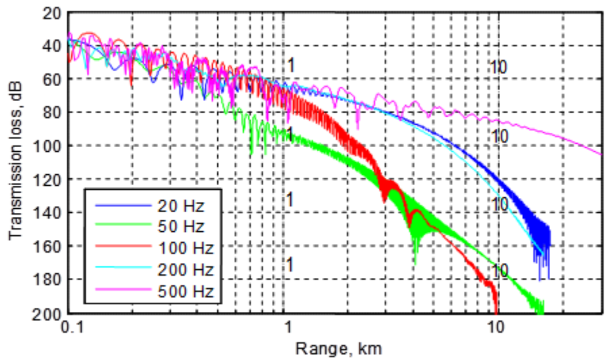

Figure 10. Transmission loss versus range at five frequencies of humpback and pygmy blue whale calls modelled numerically for the ocean acoustic channel in Geographe Bay.

Humpback whales sung some parts of their songs at frequencies up to 500 Hz and sometimes even higher, so that the acoustic wavelength of about 3 m at 500 Hz was significantly smaller than the sea depth of 30-40 m. Therefore, the signals of their calls attenuate with range much slower than the signals from pygmy blue whale calls (Figure 10). In the absence of vessel noise, the level of ambient sea noise at frequencies higher than 50 Hz did not usually exceed 75 dB re 1 µPa^2/Hz. Therefore, the maximum transmission loss acceptable for detecting a moderately weak humpback call of 165-dB source level with the SNR of 6 dB at the receiver is approximately 85 dB. According to the modelling results shown in Figure 10, the transmission loss exceeds this value at distances of about 4 km and 10 km at 200 Hz and 500 Hz respectively. If the source level was 175 dB, which is quite likely for humpback whale calls, then the detection range would increase to about 20 km at 500 Hz. During the quiet periods, when the noise level at 500 Hz was about 60 dB, the detection range at 500 Hz can be greater than 30 km.

DISCUSSION AND CONCLUSIONS

This study monitored two species of whales – humpback and blue whales migrating through Geographe Bay - by using passive acoustic techniques. The number of pygmy blue whale calls detected in the acoustic recordings was significantly lower than that of humpback whales. This is likely due to fewer numbers of pygmy blue whales than humpback whales migrating through the area, since the population size of pygmy blue whales occurring off the coast of Western Australia is thought to be as little as 6% of the size of the population of humpback whales (McCauley & Jenner 2010; Salgado Kent et al. 2012). There are other factors that may explain the difference in frequencies of acoustic detections between species, such as differences in vocal behaviour, in that blue whales perhaps call less frequently, have a lower call repetition rate, or have a smaller proportion of vocalising whales. Also, the differences in the detection range between the two species must not be ignored. The detection range of vocalising blue whales was estimated to be up to three times shorter than that of humpback whales, hence the sampling area for blue whales could be as much as 10 times smaller than for humpback whales.

The timing of the peak numbers of whales vocalising varied between years for both species, indicating that the timing of migration shifts. Identifying the causes of such shifts such as environmental or anthropogenic factors merit further investigation. In addition, in contrast to 2008 and 2011, in 2010 there was only a single calling pygmy blue whale detected during the entire recording period. There are three possible explanations for this: 1) blue whales migrated early that season and hence were not present in Geographe Bay during the period of recording, 2) blue whales were present but did not vocalize, or 3) most blue whales did not migrate through Geographe Bay that year. From concurrent visual surveys undertaken by the authors and the Dunsborough Coast and Land Care (D-CALC, pers. comm.) as part of a separate study, blue whales were observed in the study area at the time of acoustic recordings, but in fewer numbers than have been recorded in previous years. Hence, the single blue whale vocalisation observed in 2010 was likely due to a small number of whales migrating through the area, and most of which were not vocalising. It is still unclear whether both females and males produce calls, or whether only males produce calls as is true for the production of humpback whale song. If only male blue whales produce calls, then a cohort of females could have passed through at the time that the noise logger was recording. The use of passive acoustic monitoring over a longer period to ensure that the entire migratory cycle is captured in future studies will help to better understand and verify shifts in the timing of peak numbers of vocalising whales. This information is vital for effective management of critical whale habitat.

In analysing whale songs, changes in the song composition of humback whales between years such as those documented here, have been reported in different areas of the world and are part of humpback whale song evolution (Payne, Tyack & Payne 1983; Payne & Payne 1985). The results of this study indicated that changes in humpback whale songs recorded in Geographe Bay are mainly in the organisation of the units. The unit types and frequency ranges remained relatively constant. In contrast with humpback whale song, pygmy blue whales call composition did not change significantly within seasons and no consistent changes were detected among years. Gavrilov et al. (2011) report on a 1 Hz decrease in frequency of Indian Ocean pygmy blue whale calls, however this trend was detected over an eight year long period.

In terms of the acoustic environment in which humpback and blue whales migrate through, Geographe Bay was demonstrated to be a highly dynamic environment. The prevalence of high levels of noise from vessel traffic not only significantly affected the detection range of the noise loggers for passive acoustic monitoring, but would have also affected the capacity for whales to communicate with each other and perceive important cues in their environment. It is imperative that the way in which masking affects whale behaviours and their ability to respond to critical acoustic cues be investigated further.

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