The underwater soundscape around Australia

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ABSTRACT

The Australian marine soundscape exhibits a diversity of sounds, which can be grouped into biophony, geophony and anthrophony based on their sources. Animals from tiny shrimp, to lobsters, fish and seals, to the largest animals on Earth, blue whales, contribute to the Australian marine biophony. Wind, rain, surf, Antarctic ice break-up and marine earthquakes make up the geophony. Ship traffic, mineral and petroleum exploration and production, construction, defence exercises and commercial fishing add to the anthrophony. While underwater recorders have become affordable mainstream equipment, precise sound recording and analysis remain an art. Australia's Integrated Marine Observing System (IMOS) consists of a network of oceanographic and remote sensors, including passive acoustic listening stations managed by the Centre for Marine Science & Technology, Curtin University, Perth. All of the acoustic recordings are freely available online. Long-term records up to a decade exist at some sites. The recordings provide an exciting window into the underwater world. We present examples of soundscapes from around Australia and discuss various aspects of soundscape recording, analysis and reporting—the to-dos and not-to-dos.

1. INTRODUCTION

The marine soundscape is a rapidly growing field of research. At relatively low cost, marine soundscapes can be monitored over long periods of time. They provide information on geophysical events and weather, on human activities and on the animals living in the environment—entirely non-invasively by passively listening at a distance. Soundscapes are often compared to identify good versus bad habitat, or changes of an environment over time. However, comparisons can be difficult because of differences in sound measurement, analysis and reporting. The development of acoustic standards would help overcome some of these challenges, but is a long and tedious process depending entirely on voluntary time (Erbe, Ainslie, et al. 2016). Also, people working in slightly different fields of research sometimes use terminology differently.

International Standard ISO 12913-1 (2014) defines an *acoustic environment* as the "sound at the receiver from all sound sources as modified by the environment" (International Organization for Standardization (ISO) 2014). The *soundscape*, however, is a perceptual construct and requires a listener: "acoustic environment as perceived or experienced and/or understood by a person or people, in context". In underwater acoustics, the term *soundscape* is often used synonymously with *acoustic environment* and includes all sounds of an environment independent of a listener who might "filter" the received sound.

The sounds of an acoustic environment are often grouped into geophony, anthrophony and biophony comprising abiotic, anthropogenic and biotic sounds respectively. These sounds vary with geographic location, recording depth below the sea surface, time of day, season and year. The sound propagation environment (characterised by the bathymetry, seafloor geology, water temperature, salinity, etc.) varies on similar scales and affects the spectral and temporal features of the sounds received. Finally, the chosen sound recording and analysis parameters (system calibration, sampling frequency, duty cycle, Fourier analysis settings, any filtering or averaging applied, etc.) affect the measured or displayed features of a soundscape.

Here, we show examples of Australian marine soundscapes and provide some suggestions for soundscape recording, analysis and reporting.

2. RECORDING SOUNDSCAPES

There are a few common ways to deploy acoustic recorders, often moored on the seafloor for long-term recording, or deployed from the surface for short-term recording. All moorings create artefacts, such as noise from vibrating ropes or clonking chains. In strong currents, the recorder in Fig. 1a might even be knocking on the ground. Currents cause flow noise, which is non-acoustic but hydrodynamic pseudo noise, resulting from turbulent pressure fluctuations at the hydrophone. Such turbulence might be generated upstream of the hydrophone and flowing over it, or at the hydrophone itself. Recordings made with a hydrophone deployed over the side of a boat (Fig. 1b) will also contain sounds originating on and at the boat, such as waves splashing against the vessel hull. Better options with regards to minimising mooring artefacts are deployments right on the seafloor, where any mooring parts including floats are at some distance from the hydrophone (Fig. 1c) or a recorder set to drift freely with the currents (Fig. 1d).

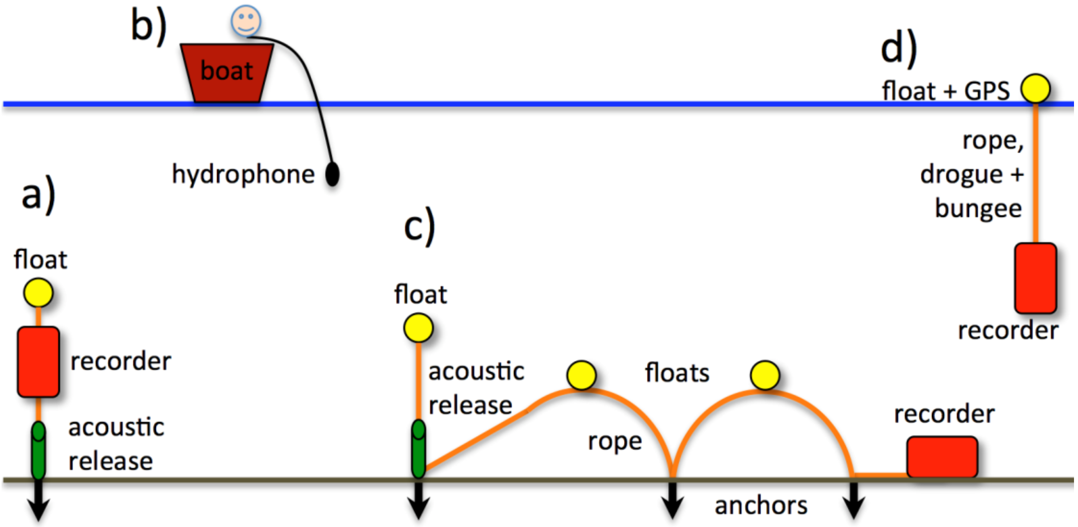

Figure 1: Mooring designs; a) and b) typically create more artefacts than do c) and d)

The Centre for Marine Science & Technology (CMST) typically uses moorings as in Fig. 1c for 6-12 month deployments (including the IMOS passive acoustic observatories). Some of the locations where the Australian marine soundscape has been recorded are shown in Fig. 2.

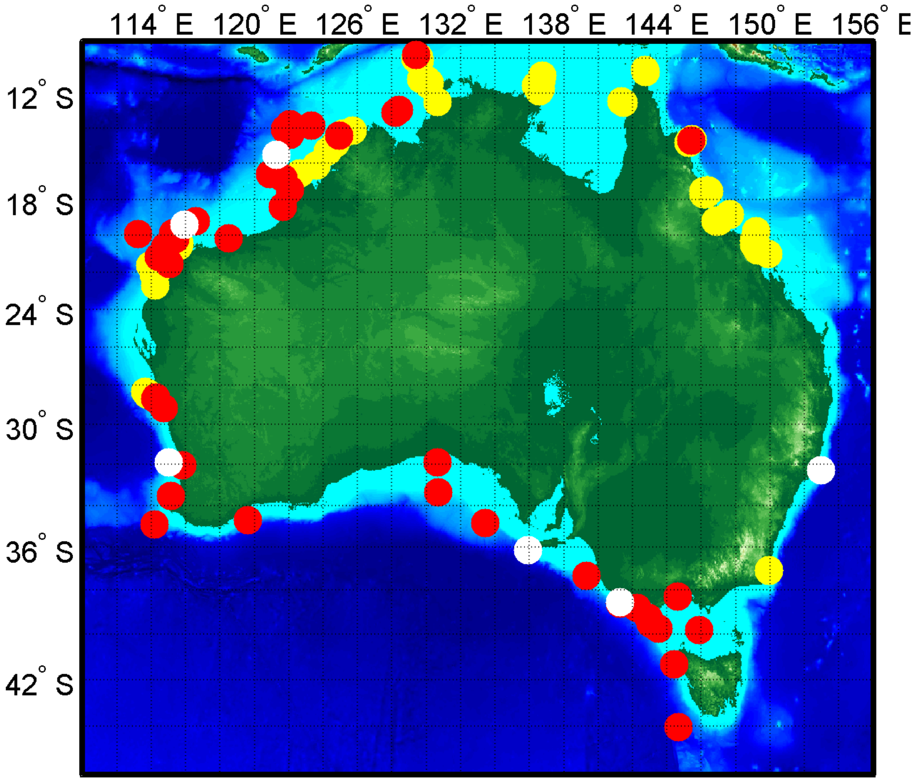

Figure 2: Sites around Australia where CMST has recorded underwater sound since 1987 (yellow: sites sampled with DAT tape decks 1987-1998, red: sites sampled with digital systems 1998-2016, white: IMOS Passive Acoustic Observatories http://imos.org.au/acousticobservatories.html)

Some a priori knowledge about the acoustic environment is needed in order to choose the recorder settings. The self-noise of the recorder should be below the quietest signals of interest. The dynamic range and gain settings should cover the variety of signals of interest. The sampling frequency must be high enough so that signals of interest are below the Nyquist frequency. The duty cycle needs to take into account any expected temporal patterns. For example, to adequately sample the entire soundscape, the recorder should evenly sample any 24 h period. Or, if only recording a couple of times per day, it should not record the same time of day every day, but rather shift the onset of recording from day to day. Recorders should be calibrated, ideally with input white noise in series with the hydrophone in order to get the system response at all frequencies, before and after deployment, and the clock should be synchronised before and after deployment to account for any clock drift.

3. ANALYSING AND DISPLAYING SOUNDSCAPES

One of the first things acousticians do when a recorder returns from the field is to listen to the recordings and look at their spectrograms. Spectrograms are based on Fourier transform of the recorded pressure time series with the transform window moving in time, and display the spectral and temporal features of sound (Fig. 3). Long-term spectrograms show patterns like nightly choruses, or the seasonal presence of migrating great whales. Short-term spectrograms highlight specific sounds. Different Fourier transform settings are typically used to optimise the display of narrow- versus wide-band and transient versus continuous sounds.

It would be impossible to analyse long-term recordings solely by ear and eye and therefore a multitude of auto-detection and classification algorithms have been developed. These include matched filtering (Stafford, Fox & Clark 1998), spectrogram correlation (Mellinger & Clark 1997), peak energy detection in certain frequency bands or ratios of energy in target to non-target frequency bands for clicks (Klinck & Mellinger 2011) and tonal sounds (Erbe et al. 2015), Shannon entropy (Erbe & King 2008) or Teager-Kaiser energy computation (Madhusudhana, Gavrilov & Erbe 2015), image-processing techniques such as edge and ridge detection (Kershenbaum & Roch 2013), neural networks (Erbe 2000) and other techniques. Detectors are often tuned to search for specific signal features and they perform well in a limited range of environments with which they were trained. The sound propagation environment changes the spectro-temporal features of signals, hence detectors need to focus on the most robust features. Once signals of a certain type are found, they can be counted, e.g., as an indicator for animal density; and by comparing counts across sites, great whale migrations may be mapped. CMST's pygmy blue whale detector (Gavrilov & McCauley 2013) identified times with blue whales in several data sets from around Australia, and the number of simultaneous blue whale songs was measured as an indicator of the minimum number of animals within the listening range of each recorder. The resulting time series of blue whale detections illustrates this species' migration along the Western Australian coast (Fig. 4). The monthly and seasonal presence of specific sound sources can be conveyed in polar plots (Fig. 5).

There is a tendency to squeeze the information contained within a soundscape into a handful of numbers. One such approach is that of pie charts showing so-called noise budgets, i.e., the relative contributions to a soundscape by different sources. Such pie charts largely depend on the bandwidth used and the acoustic quantity being compared and can be hugely misleading (see e.g., Erbe, McCauley & Gavrilov 2016; Erbe & McPherson 2012). Acoustic indices (just one number) have been used to quantify the complexity of a soundscape or the biodiversity. A plethora of such indices exists (Sueur et al. 2014) and most have been derived to answer specific questions on specific soundscapes. A comparison across soundscapes needs to be done with care, as many of the indices vary with recording and analysis parameters (e.g., duty cycle, sampling frequency, analysis and averaging window).

A perhaps more informative way to quantify an acoustic environment is by means of a statistical representation of power spectral density (PSD). The n^{th} percentile gives the level that is exceeded n% of the time. The 50^{th} percentile is the median. Strong and frequent sources can often be identified from the shapes of the PSD% curves. How often each level is reached, i.e., its probability density, can be illustrated by plotting a colour histogram of PSD levels at each frequency (Merchant et al. 2013). This further helps to identify possible sources. At the IMOS Perth Canyon site (Fig. 6), Antarctic blue whales, pygmy blue whales, fin whales, an unidentified baleen whale and vessels emit strong sound below 200 Hz—the baleen whales in the form of tones or very narrow-band signals and vessels in the form of broadband noise with tones overlain. Each vessel emits tones at different frequencies, whereas baleen whale calls are consistent in frequency and hence can be easily identified by their characteristic peaks, which in the case of pygmy blue whales are at about 18, 23, 27 and 68 Hz. Baleen whales were present for more than 50% of the time, at various distances, as their tones are visible in the 1^{st} – 50^{th} percentiles. Distant traffic noise was common, seen as the peak in probability density (yellow area) around 80 dB re 1 $\mu Pa^2/Hz$. Wind noise between 300 Hz and 3 kHz was also common with levels mostly around 58-67 dB re 1 µPa^2/Hz corresponding to a sea state of 4. Humpback whales dominated the soundscape at around 300 Hz for half of the time, as their spectral peak can be seen in the 1st – 50th percentiles. The nightly fish chorus, which is strongest in the austral winter, dominated at 1.8 – 2.5 kHz. The peak at 500-600 Hz in the 95th – 99th percentiles might be related to another, weaker fish chorus.

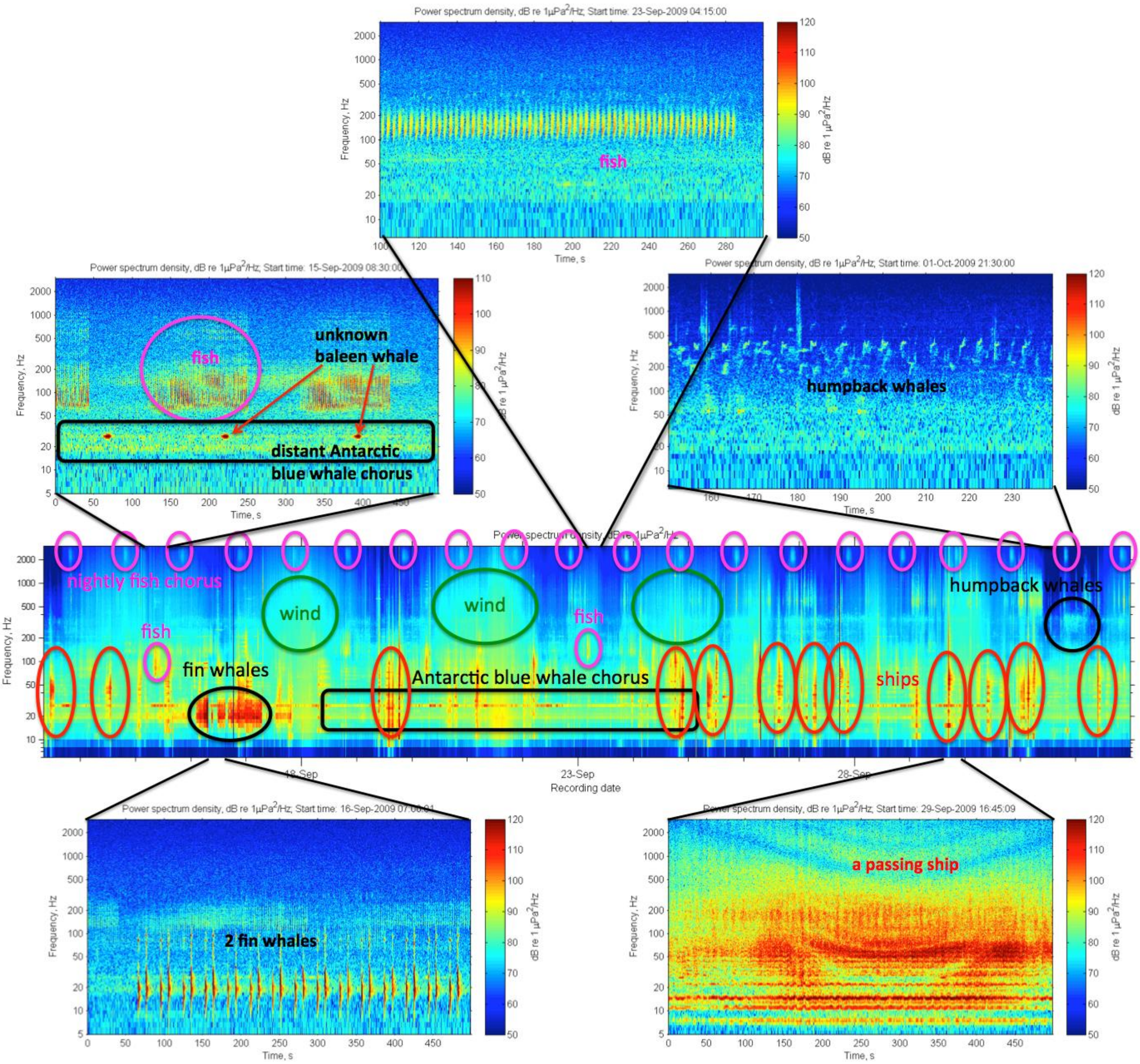

Figure 3: Underwater soundscape at the IMOS Perth Canyon site, WA. The middle panel shows a 3-week spectrogram. The sounds of fish (individual fish sounds and regular night-time fish chorus), Antarctic blue whales, fin whales, humpback whales, an unidentified baleen whale, wind, as well as passing ships are labelled. The five panels around the middle panel display short-term spectrograms of a few example sounds. Spectrograms computed with CHORUS (Gavrilov & Parsons 2014)

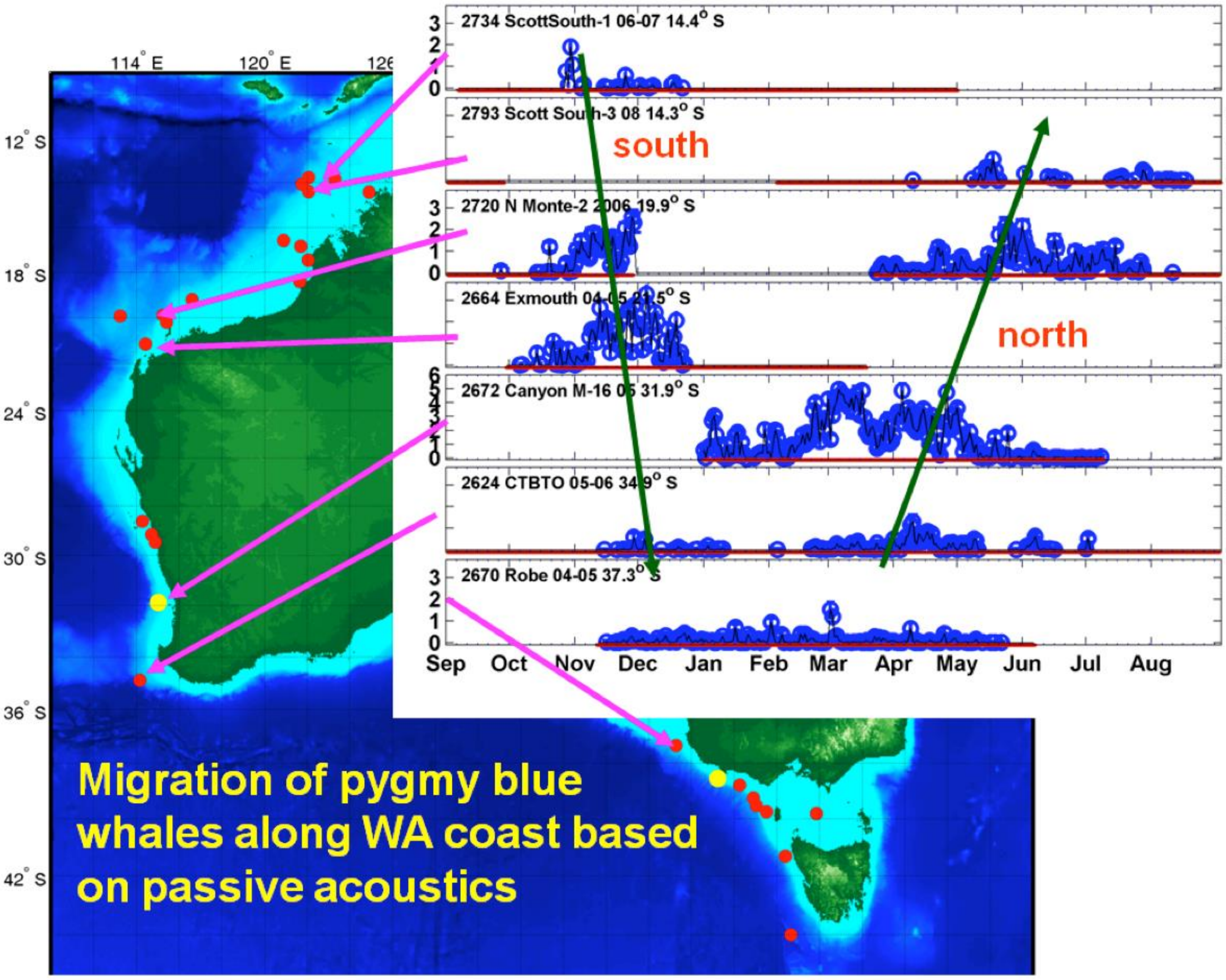

Figure 4: Mean number of pygmy blue whales counted in every 15 min sample, averaged over 24 h, tracking these animals' southern and northern migrations. Red horizontal lines indicate when recorders were deployed; no recordings were obtained during months without red lines

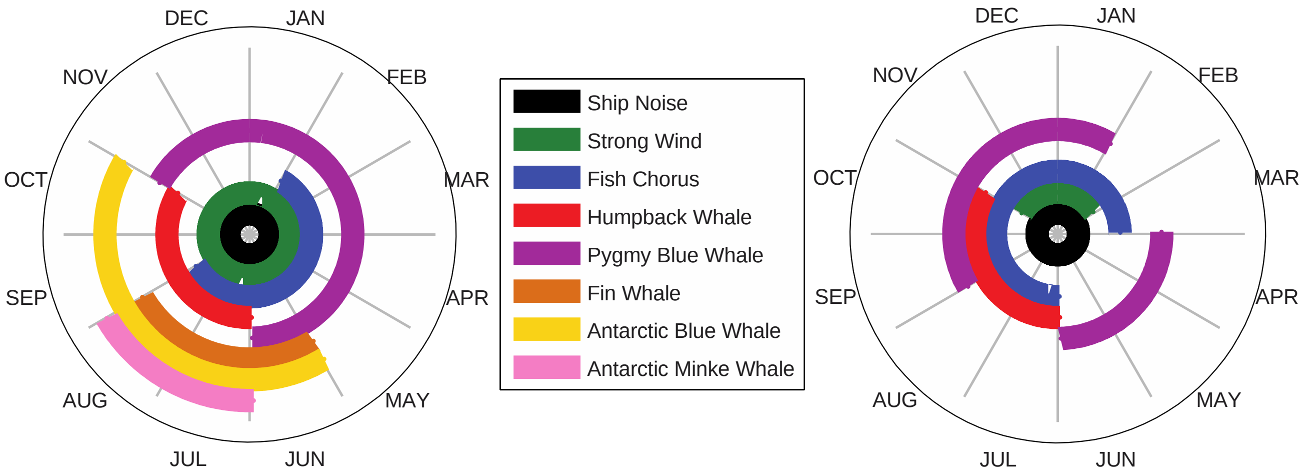

Figure 5: Presence of ship noise, strong wind noise, fish choruses and different species of baleen whale throughout the year in the Perth Canyon (left) and off Scott Reef (right). Again, semi-annual migrations can be seen for pygmy blue whales in the Scott Reef plot

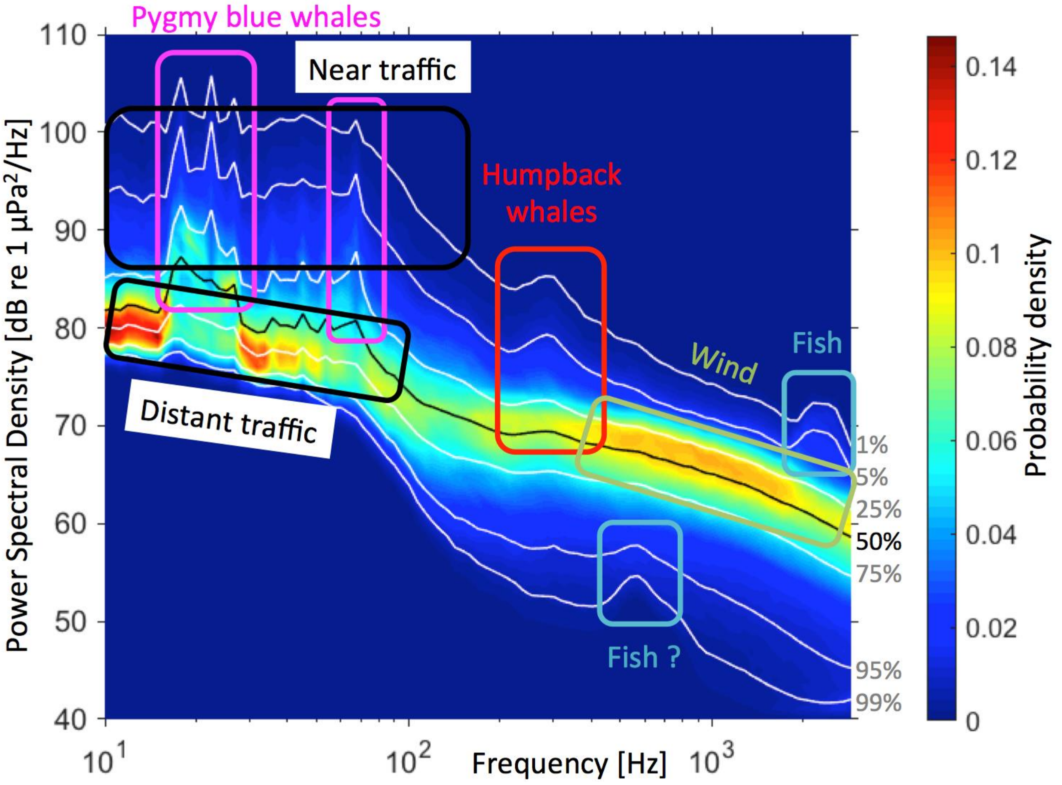

Figure 6: PSD percentiles (1, 5, 25, 75, 95 and 99% shown as white lines; 50% shown as a black line) computed over 11 months of recording at the IMOS Perth Canyon site, Jul 2011—Jun 2012, and probability density of PSD levels (shown in colour)

Fig. 7 compares PSDs between four other IMOS sites encompassing western, southern and eastern Australia. Off Dampier, WA, there was a lot of anthropogenic noise from machinery, vessels and distant seismic surveys below 300 Hz. The same band also had pygmy blue whale and Bryde’s whale sounds in the austral winter. Humpback whales were detected at 100-500 Hz, Jul – Sep. Off Kangaroo Island, SA, ship noise was detected below 100 Hz, with Antarctic blue whales, fin whales and an unidentified baleen whale sound contributing to the same band. Fish dominated at 1-2 kHz all year round. The same fish chorus dominated at Portland, VIC. Sound at low frequencies due to Antarctic and pygmy blue whales, fin whales and the same unidentified baleen whale was lower in level than sound at Kangaroo Island. Ship noise at Portland, VIC, and Tuncurry, NSW, had a broad peak from 20 to 200 Hz. Tuncurry also had distant Antarctic blue whales, fin whales, some New Zealand blue whales and the same unidentified baleen whale as recorded off Perth, Kangaroo Island and Portland. Weak fish choruses were present at different times of the year. Peak levels (1st and 5th percentiles) of low-frequency (<200 Hz) ambient noise were highest off Tuncurry due to ships travelling to and from Sydney. Kangaroo Island, however, had the highest noise floor (95th and 99th percentiles) at low frequencies, likely due to noise ducting in the deep sound channel reaching the site from a broad azimuth across the southern ocean all the way to Antarctica.

4. QUALITY CHECKS

There are quick and easy ways to determine whether recorder gain settings and sampling regime were optimal. Fig. 8 shows PSD percentiles and probability density from another site on Australia’s Northwest Shelf. It is interesting to note that the PSD probability density below 200 Hz is bimodal, likely due to two different sources, one with a received level around 80 dB re 1 µPa^2/Hz, the other quieter at around 60 dB re 1 µPa^2/Hz. (There were two seismic surveys occurring at different ranges in the environment of Fig. 8.) The vast majority of received levels between 10 and 20 Hz are 50 – 60 dB re 1 µPa^2/Hz. This recorder did not sample evenly about the mode or most common received level at low frequencies, but might have missed quiet signals in favour of louder signals. If one wanted to resolve the quieter signals at low frequencies, a low-pass filter and higher gain setting would be required. This dataset highlights that the median and mode can be very different.

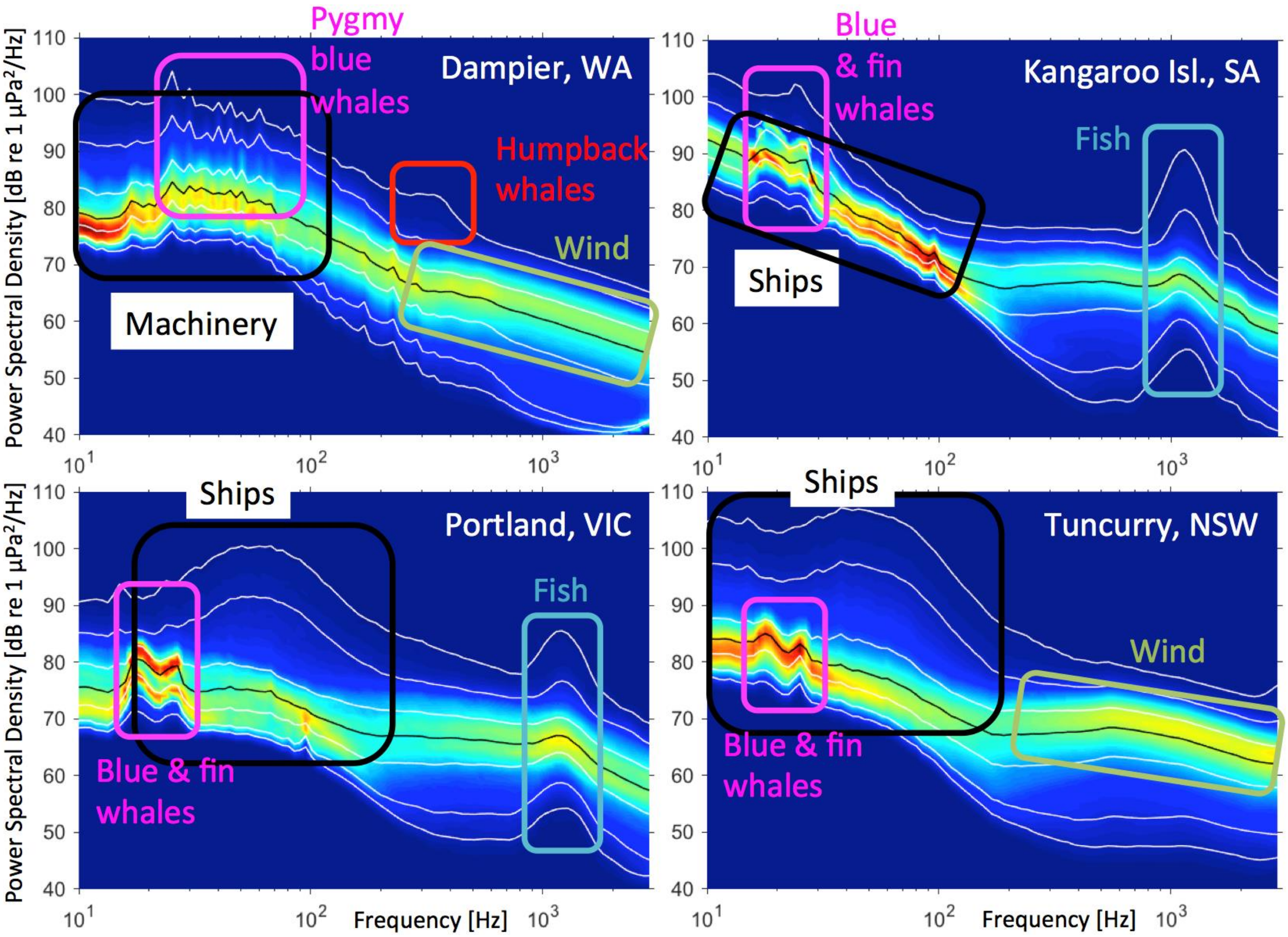

Figure 7: PSD percentiles (1, 5, 25, 75, 95 and 99% shown as white lines; 50% shown as a black line) and probability density for four other IMOS sites: off Dampier, WA, Nov 2012 – Sep 2013; Kangaroo Island, SA, Dec 2014 – Nov 2015; Portland, VIC, Dec 2013 – Nov 2014; and Tuncurry, NSW, Apr 2011 – Apr 2012

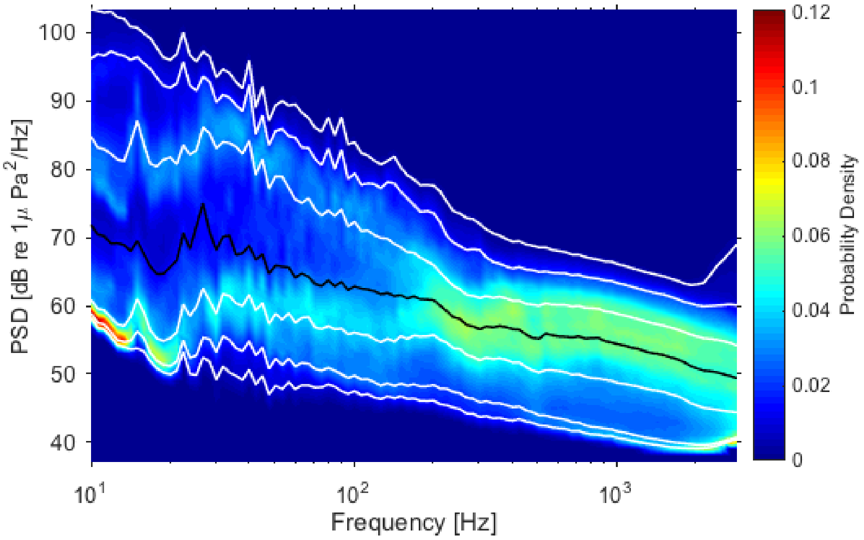

Figure 8: PSD percentiles (1, 5, 25, 75, 95 and 99% shown as white lines; 50% shown as a black line) and probability density computed over eight months of recording at a coral reef on Australia's Northwest Shelf, Nov 2007—Aug 2008

The box and whisker plots of PSD averaged into 1/3 octave bands for yet another site on Australia's Northwest Shelf (Fig. 9) show the median as a red line, with the upper and lower edges of the boxes representing the first and third quartiles (q). The whiskers extend to the most extreme data points that are not yet considered outliers. Outliers, plotted as red crosses, are larger than $q_1 + 1.5 \times (q_1 - q_3)$ or smaller than $q_3 - 1.5 \times (q_1 - q_3)$. This recorder was able to log both very quiet and very loud events at frequencies above 160 Hz. Below 160 Hz, the median becomes very low (60 dB re 1 µPa^2/Hz); there are no quiet outliers at low frequencies. Either the recorder was at its self-noise limit or the acoustic environment was its quietest at these levels and frequencies, and it was quiet most of the time. It would be difficult to resolve quieter signals in this environment, due to the large dynamic range of signals (up to 160 dB re 1µPa^2/Hz) at low frequencies.

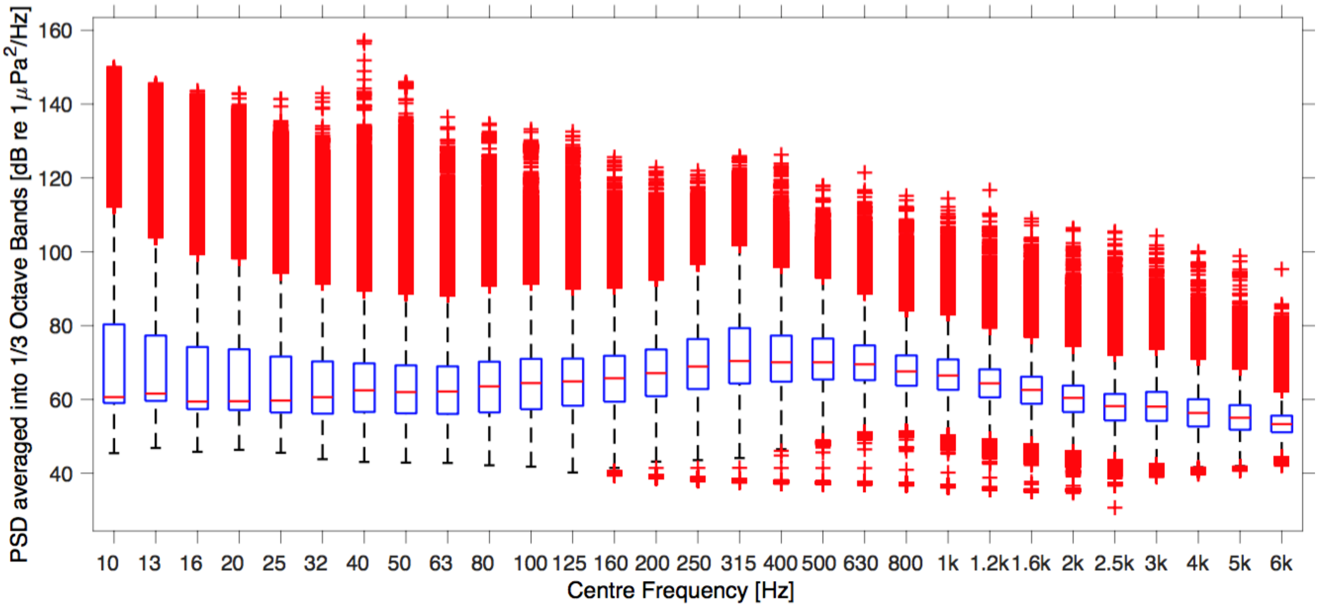

Figure 9: Occurrence of PSD levels averaged into 1/3 octave bands, shown as box and whisker plots

Fig. 10 helps decide how long to sample in order to adequately characterise a soundscape. The mean dynamic range of the environment is the difference between the 1st and 99th PSD percentiles, averaged over all frequencies. In detail, PSD was computed in 50 s windows (with four 50 s windows recorded every 900 s) and in adjacent 1/12 octave bands in order to yield a finer resolution than the above 1/3 octave bands, while reducing the computational burden of keeping 1 Hz bands. The 99th percentile 1/12 octave band level was subtracted from the 1st percentile, yielding the environment's dynamic range at each 1/12 octave centre frequency. The environment's dynamic range was averaged over the full bandwidth of the recording. Fig. 10 shows the mean dynamic range of the environment calculated cumulatively with time, where a sample represents a 50 s recording. At the beginning of the recording, there are very few samples and hence the difference between the 1st and 99th percentiles is small. As the recording continues, more extreme (louder and quieter) levels are recorded and the mean dynamic range increases. It levels off with time. This is because there are now so many samples that any extremes will lie beyond the 1st and 99th percentiles and hence do not contribute to the dynamic range computed. In the example of Fig. 9, after 40,000 samples (110 days of recording), the change in the mean dynamic range of the environment was less than 8%. Only new and extreme events (either loud or quiet periods) that last for more than 1% of the existing deployment duration would increase the environment's dynamic range after 100,000 samples.

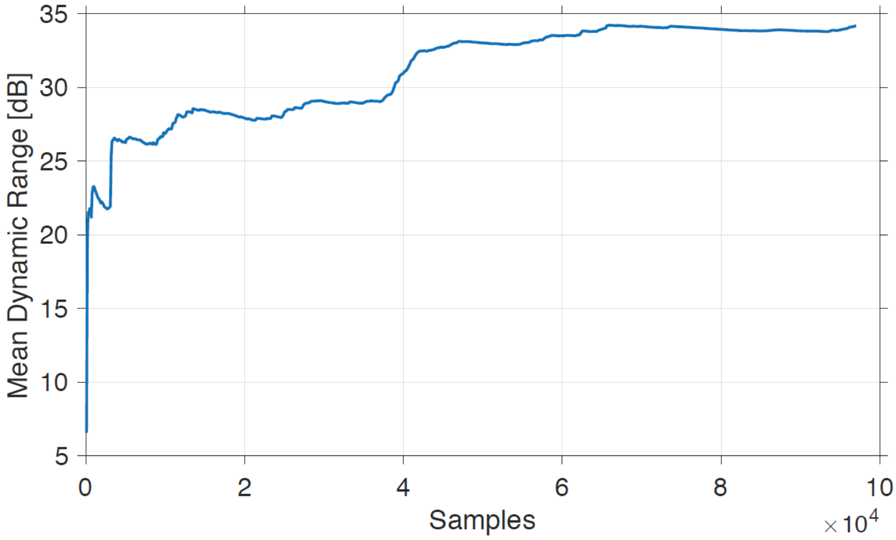

Figure 10: Cumulative dynamic range as a function of deployment duration

5. FINAL REMARKS

The literature on marine soundscapes is rapidly growing, partly due to the ease of access to and the affordability of equipment. Making sense of the data, including the identification of the myriad of sounds recorded, is often challenging. An 8 – 10 s, 23 – 26 Hz signal, repeated every 120 – 200 s, with received levels sometimes >150 dB re 1 µPa, has been consistently heard along the southern coast of Australia, from the Perth Canyon, WA, to Portland, VIC, with year-round presence in the Great Australian Bight over the period 2001 to present, yet we have no idea which source (likely a baleen whale) produces this sound.

The sounds emitted by anthropogenic operations remains an active area of research, with ship noise perhaps best studied as a result of defence driven research during the Second World War. Nowadays, Automatic Identification System (AIS) data on commercial ships are increasingly used to estimate the contribution of vessel traffic to the underwater soundscape (e.g., Erbe, MacGillivray & Williams 2012). However, only large vessels in transit will emit AIS signals, often at irregular times, and many don't. Small and private vessels are not normally equipped with AIS, but noise from these vessels can be substantial in coastal and riverine areas (Erbe, Liong, et al. 2016; Marley, Erbe & Salgado Kent 2016).

Our understanding of sound production, sound propagation and soundscape contribution is steadily growing. Long-term datasets are becoming available from many locations, not just around Australia but globally, letting us monitor changes in soundscapes, which might reflect changes to ecosystems and potential impacts of sound on marine life. Passive acoustic monitoring is a powerful tool (Erbe 2013) and as we build up catalogues of biotic, anthropogenic and abiotic sounds, and as we develop common guidelines for data collection, calibration, analysis and reporting, the potential of comparative soundscape analysis is substantial.

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