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The marine soundscape of the Perth Canyon

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A B S T R A C T

The Perth Canyon is a submarine canyon off Rottnest Island in Western Australia. It is rich in biodiversity in general, and important as a feeding and resting ground for great whales on migration. Australia's Integrated Marine Observing System (IMOS) has moorings in the Perth Canyon monitoring its acoustical, physical and biological oceanography. Data from these moorings, as well as weather data from a near-by Bureau of Meteorology weather station on Rottnest Island and ship traffic data from the Australian Maritime Safety Authority were correlated to characterise and quantify the marine soundscape between 5 and 3000 Hz, consisting of its geophony, biophony and anthrophony. Overall, biological sources are a strong contributor to the soundscape at the IMOS site, with whales dominating seasonally at low (15–100 Hz) and mid frequencies (200–400 Hz), and fish or invertebrate choruses dominating at high frequencies (1800–2500 Hz) at night time throughout the year. Ships contribute significantly to the 8–100 Hz band at all times of the day, all year round, albeit for a few hours at a time only. Wind-dependent noise is significant at 200–3000 Hz; winter rains are audible underwater at 2000–3000 Hz. We discuss how passive acoustic data can be used as a proxy for ocean weather. Passive acoustics is an efficient way of monitoring animal visitation times and relative densities, and potential anthropogenic influences.

1. Introduction

Australia's Integrated Marine Observing System (IMOS, http://www.imos.org.au/) has been in operation since 2008, funded by the Australian Federal Government and several State Governments. It consists of a network of oceanographic and remote sensors such as Argo floats, ocean gliders, shallow-water oceanographic reference stations, deep-water moorings, underwater acoustic arrays, autonomous underwater vehicles, ships of opportunity, radar, and satellite remote sensors, collecting physical, acoustical, chemical and biological data in Australia's oceans and coastal marine environments. All IMOS data are publicly available at the Australian Ocean Data Network Portal (http://portal.aodn.org.au/aodn/).

The Centre for Marine Science & Technology (CMST, https://cmst.curtin.edu.au/) at Curtin University in Perth, Western Australia, built and maintains the passive acoustic observatories that are part of IMOS. These observatories are located off the coasts of New South Wales, Victoria, South Australia and Western Australia, monitoring the underwater soundscape. The IMOS acoustic observatory in the Perth Canyon was the study site for this article, which gives a definition and summary of some of the major sea noise sources present in the IMOS Perth Canyon passive acoustic data sets. Each of the sources presented is a major research topic in its own right, thus only a summary of data is presented here. The marine soundscape can be split into its geophony (the sounds of physical events, such as wind, precipitation, breaking waves, earthquakes, ice breakup), biophony (the sounds of biota, e.g. whales, dolphins, fish, crustaceans), and anthrophony (man-made sounds, e.g. from ships or seismic surveys) (Krause, 2008).

1.1. Geophony

Wind-dependent noise is the prevailing noise in much of the world's oceans at frequencies between 100 Hz and 20 kHz, typically peaking around 500 Hz (Cato and Tavener, 1997; Knudsen et al., 1948; Wenz, 1962). It is due to the oscillation of air bubbles entrained at the surface (Banner and Cato, 1988; Medwin and Beaky, 1989). These can easily be seen as whitecaps and around small breaking waves at wind speeds greater than 5 m/s. The underwater sound from rain is due to the physical impact of drops on the sea surface and the entrainment and oscillation of bubbles (Medwin et al., 1992; Nystuen, 1986). Light rain (<10 mm/h, drop diameter 1 mm) creates a spectral peak at 13–25 kHz (Ma et al., 2005). The heavier the rain, the larger the drops, the more sound energy is produced at lower frequencies down to 500 Hz. Below

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10 kHz, the spectrum level increases with rainfall rate; above 10 kHz acoustic energy depends less on rainfall rate (Ma et al., 2005). Wind affects the rain spectrum. The spectral peak of light rain decreases with increasing wind due to the increasingly oblique impact of drops on the water surface, which impacts bubble generation (Medwin et al., 1990). The spectrum of heavy rain is less affected by wind. For strong winds > 10 m/s, breaking waves create a subsurface bubble layer that attenuates the sound of rain on the surface above 10 kHz (Nystuen et al., 1993). Given the proximity of these bubbles to the sea surface, the sound from wind and rain exhibits a dipole (bubble and its Lloyd's mirror image above the sea surface) pattern radiating vertically downward, which is why this noise can be detected at considerable depth below the sea surface (Barclay and Buckingham, 2013a). Bubbles are also largely responsible for the sound of breaking waves in the surf zone with energy up to 20 kHz (Deane, 1997).

In polar regions, the sound of colliding, oscillating, breaking and melting ice can cover a broad range of frequencies from <10 Hz to >10 kHz (Keogh and Blondel, 2009; Mikhalevsky, 2001). Ice noise of broadband and tonal character with energy up to 100 Hz can be detected thousands of miles away at tropical latitudes (Gavrilov and Li, 2007; Tolstoy et al., 2004). Underwater volcanoes and oscillating tabular icebergs appear as harmonic tremors of up to about 50 Hz at long ranges, and earthquakes produce long-lasting impulses within the frequency band from fractions of 1 Hz to about 100 Hz (Dziak and Fox, 2002; Fox et al., 2001; Hanson and Bowman, 2006; Tolstoy et al., 2004).

The Leeuwin current is a warm, low-salinity current flowing southward along the continental shelf of Western Australia, extending from the ocean surface up to a depth of typically 250–300 m in the Perth Canyon (Feng et al., 2009), being strongest in the austral winter, when the southerly winds are weakest. Interaction of the Leeuwin current with the bottom topography features over the shallow continental shelf and with offshore waters of different density result in the generation of mesoscale eddies which can spin off into the eastern Indian Ocean (Pattiaratchi, 2006; Waite et al., 2007). The Leeuwin current does not interact directly with the Perth Canyon topography, as it is too deep. The Leeuwin undercurrent, a deep cold-water northward flowing current, which hugs the continental shelf, interacts with the Perth Canyon, often setting up small-scale eddies along the Canyon length (Rennie et al., 2007). These sub-surface eddies interact with the Leeuwin current often resulting in counter-rotating surface eddies coupled to the deeper eddies. The Perth Canyon is highly dynamic with respect to ocean currents.

Ocean currents on their own are not noisy, however moorings can be noisy in currents as a result of vibrating ropes/wires, moving chains or metal joints. CMST deploys recorders on the seabed in the Perth Canyon, where currents are reduced, with the anchor system separated from the recorder and hydrophone and all joints seized, significantly reducing mooring noise. Water flow past the hydrophone can create pressure fluctuations that are not of acoustic origin and that do not travel as an acoustic wave, but which can interfere with acoustic measurements by the hydrophone. Such interferences are called pseudo sound or flow noise, are dominant at low frequencies (tens of Hz), yet can extend to hundreds of Hz in strong currents, and are due to turbulent water flowing past the hydrophone, and initially non-turbulent water flowing past the hydrophone creating turbulence behind the hydrophone (Strasberg, 1979). It is important to understand that this pseudo sound is not acoustic and is not part of the soundscape. Rather, it is an artefact of measurement, and dependent on the specific mooring. It does, however, appear in spectrograms and correlates with currents impinging on the hydrophone and mooring (Willis and Dietz, 1961), which is why it is discussed here.

1.2. Biophony

Many baleen whale species migrate seasonally between their summer feeding and winter breeding/resting grounds. Along the Western Australian coast, these migrations include pygmy blue whales (*Balaenoptera musculus brevicauda*) (Branch et al., 2007; Department of the Environment and Heritage, 2005a; McCauley and Jenner, 2010), humpback whales (*Megaptera novaeangliae*) (Chittleborough, 1965; Dawbin, 1966; Department of the Environment and Heritage, 2005b; Jenner et al., 2001), fin whales (*Balaenoptera physalus*) (Department of the Environment and Heritage, 2005a; Mackintosh, 1966), Antarctic blue whales (*Balaenoptera musculus intermedia*), southern right whales (*Eubalaena australis*), sei whales (*Balaenoptera borealis*) and Antarctic minke whales (*Balaenoptera bonaerensis*). Pygmy blue whales, and other baleen whales on migration, may seasonally aggregate in the Perth Canyon as a feeding stopover (Rennie et al., 2009) or in years of poor secondary production simply pass through on their northern migration. All mature male great whales regularly produce intense low-frequency sound under water, allowing them to be detected at long range (tens to many tens of km) in the open ocean by passive acoustic observatories.

Fish also produce sound, mostly related to reproductive (Tavolga, 1960) or feeding activity (McCauley, 2001; McCauley and Cato, 2000). Fish choruses are most commonly heard at night time, when so many animals come together and call at the same time that individual calls can no longer be detected in the overall chorus, which is characterised by a broadband increase in ambient noise levels for several hours (Cato, 1978, 1980; Knudsen et al., 1948; McCauley, 2012; Parsons et al., 2013). Marine choruses can also be caused by invertebrates, e.g., shrimp, lobsters and urchins (Cato and Bell, 1992; Latha et al., 2005; Radford et al., 2008), however, near the Perth Canyon IMOS recorder, at about 450 m depth, fish are the most likely performer of choruses detected.

1.3. Anthrophony

Marine industrial operations add noise to the marine soundscape (Boyd et al., 2011; Richardson et al., 1995). Anthropogenic sources include seismic exploration (Erbe and King, 2009; Gavrilov et al., 2007; Greene and Richardson, 1988), pile driving (Erbe, 2009), dredging (Reine et al., 2014), petroleum production operations (Erbe et al., 2013; Wyatt, 2008), equipment such as sonars, echosounders, acoustic tags and pingers (Ainslie, 2010; Erbe and McPherson, 2012), explosions (Soloway and Dahl, 2014), as well as ships of all sizes (Erbe, 2002, 2013a; Erbe et al., 2012; Ross, 1976; Scrimger and Heitmeyer, 1991). Propeller cavitation is typically the strongest source of ship noise from large vessels and exhibits a broadband spectrum, amplitude modulated at the propeller blade rate (i.e. at the frequency equal to the number of blades times the rotations per second). This cavitation spectrum is overlain by engine and machinery tonals plus harmonic overtones.

It is not just the distribution of sources and their sound emission spectrum that determine the soundscape at a certain place, but also the sound propagation environment characterised by its bathymetry, as well as hydro- and geoacoustic properties of the water column and seafloor respectively. The sound-generating physical, biological and anthropogenic processes can be measured and monitored by a variety of sensors. IMOS provides a unique opportunity to correlate the various acoustical, physical and biological data in an attempt to characterise and quantify the marine soundscape, and to determine the spectral contribution of the various sources to the marine soundscape. We studied these correlations with IMOS data from the Perth Canyon off Western Australia.

2. Methods

2.1. Acoustic data

Since 2008, CMST has operated the passive acoustic observatory of IMOS (Integrated Marine Observing System, 2013) in the Perth Canyon at approximately 32°S, 115°E, at 430–490 m water depth, 70 km offshore from the coast of Perth (Fig. 1). This passive acoustic observatory consists of two to four moorings with CMST underwater sound recorders, collecting sea noise data for a period of eight to twelve months, at which stage the gear is recovered and a new set of recorders deployed. The hydrophone and the recorder are connected via a 3 m cable resting on the seafloor and are decoupled from the main mooring as shown in Fig. 2. The recorder is typically set to sample at fs = 6 kHz, 16 bit, for 5–10 min every 15 min. The hydrophone sensitivity is about −198 dB V/μPa; a pre-amplifier of 20 dB gain is used and an anti-aliasing low-pass filter of 2.8 kHz. Recordings are high-pass filtered with a cut-off at 5 Hz to flatten naturally high levels of low-frequency sea noise. Each recorder is calibrated before and after deployment by inputting white noise of known spectral level in series with the hydrophone. For spectrum analysis, calibrated pressure time series were Fourier transformed in 1 s Hanning windows without overlap. For time series correlations, 1/3 octave band levels were computed every second from the spectrograms by integrating the mean square pressure within each band.

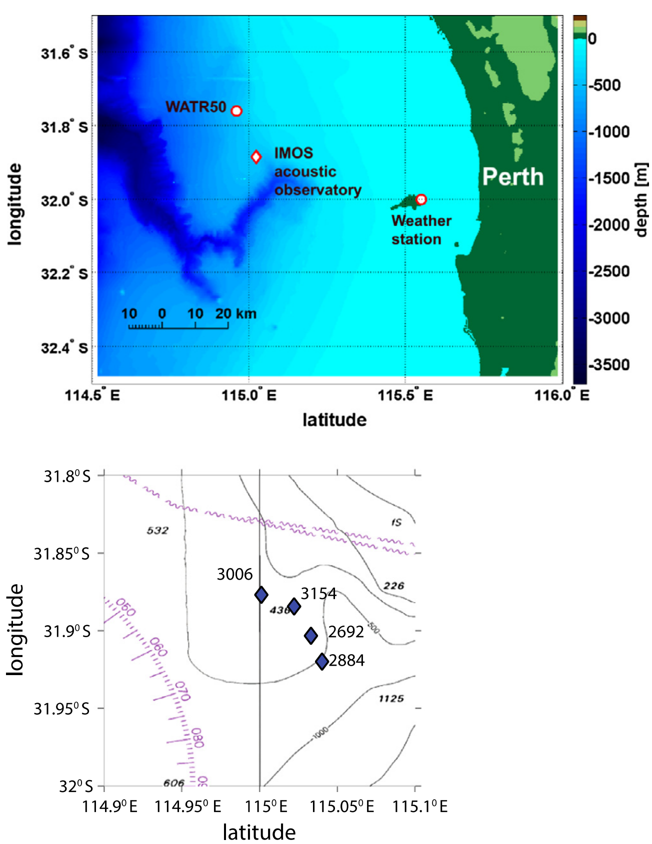

Fig. 1. Location of the IMOS passive acoustic observatory at the edge of the Perth Canyon, IMOS Australian National Moorings Network Regional Mooring (WATR50), Bureau of Meteorology weather station at Rottnest Island and the bathymetry of surrounding waters (top); acoustic recorder deployment sites for the years 2009–13 identified by their unique set numbers 2692, 2884, 3006 and 3154 respectively (bottom).

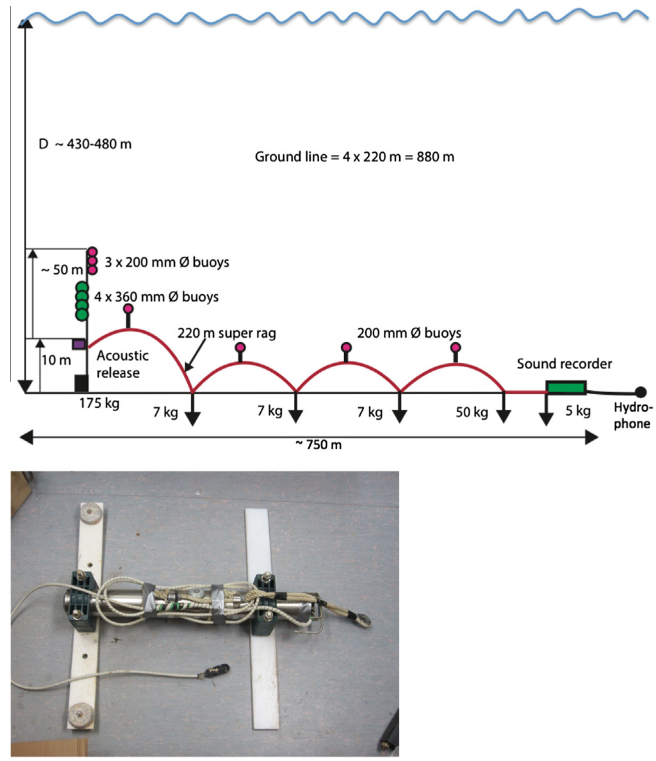

Fig. 2. Sketch of the IMOS passive acoustic mooring in the Perth Canyon (top panel) and photo of one CMST sound recorder (bottom panel).

2.2. Weather data

Weather data (wind speed, wind direction, rainfall rate) were purchased from the Bureau of Meteorology (BoM), Australia, from the nearest weather station located at Rottnest Island at 32° 02.00′ S and 115° 30.08′ E (Fig. 1), about 47 km from the passive acoustic observatory. Rottnest Island is 18 km from shore, 19 km^2 in size and has a maximum elevation of 46 m. Wind speed was received from BoM as 30-min averages. Cumulative rainfall (mm) was received in 30-min samples for every 24 h period and converted to rainfall rate (mm/h) every 30 min. To determine the correlation between wind speed and underwater noise, recordings from November 2012 to February 2013 were considered, as the summer months exhibited strong winds and had no whales vocalising in the frequency band of wind-dependent noise.

2.3. Ocean currents

Ocean current data were obtained for the period September–December 2012 from the Western Australian IMOS mooring (Integrated Marine Observing System, 2012) at Two Rocks at 31° 46.09′ S and 114° 56.20′ E (WATR50, Fig. 1), 14 km from the acoustic observatory. This station was equipped with an Acoustic Doppler Current Profiler (ADCP) measuring the speed and direction of ocean currents at depths ranging from 24 to 530 m every 10 min.

2.4. Biological data

While there were no biological surveys in the Perth Canyon at the time of acoustic recording, information on whale presence is available in the literature from previous surveys (Department of the Environment and Heritage, 2005a, 2005b; Gavrilov et al., 2012). Information on the sounds emitted by marine fauna is available in the literature as well and is discussed below.

2.5. Ship traffic

To incorporate the contribution of ships to the anthrophony of the region, Automatic Identification System (AIS) data consisting of ship identification number, geographic position, time of position, size, type and speed were sourced from the Australian Maritime Safety Authority (AMSA) (Australian Maritime Safety Authority, 2013). Ship tracks were computed over 100 km range for each ship identification number and interpolated to 1-min resolution. The closest points of approach were computed for all ships for the month of November 2012, i.e. outside of the peak whale season. Spectrograms were investigated for three hours before and after each closest approach to determine over what ranges ships were detectable in which frequency band.

3. Results

3.1. Overview

The underwater soundscape in the Perth Canyon is complex due to multiple, simultaneous contributors. Whales and fishes are the primary contributors to the biophony and the overall ambient noise level between 15 and 2500 Hz for many months of the year. The anthrophony in our recordings consisted primarily of vessels travelling into and out of Perth/Fremantle. The geophony was dominated by wind-dependent noise with very little precipitation. The spectrogram shown in Fig. 3 is made of power spectral density of sea noise averaged over the recording duration of 5 min. It shows the major sources of underwater sound in the Perth Canyon during the month of September 2012. A biological evening chorus is regularly seen at 1800–2500 Hz (blue ellipse). We expect this is a fish chorus due to the depth of the recorder (about 450 m). Individual calls from fin whales were observed only at the beginning of the month (purple ellipse). The low-frequency downsweep component of their calls spans the same frequency band as that of Z-shaped calls of Antarctic blue whales. So it is not fully certain whether the band noise, prominent from about 17–27 Hz throughout the whole period, resulted only from a superposition of calls from many remote blue whales (sometimes referred to as whale chorus) or fin whales also contributed to this band noise. The presence of Antarctic blue whales is evident from the prominent narrow-band noise around 26–27 Hz, which is constituted by the first, most intense tonal part of their Z-shaped calls. Humpback whales can be identified from energy between 100 and 500 Hz in this figure (purple ellipse). Ship passes within 20 km of the sound recorder are identified by black dots. The ship spectra in this figure consist of tones with overtones between 8 and 100 Hz. Ships passed several times per day, with two episodes highlighted by the red ellipses. The green ellipse between 200 and 3000 Hz indicates wind and rain noise.

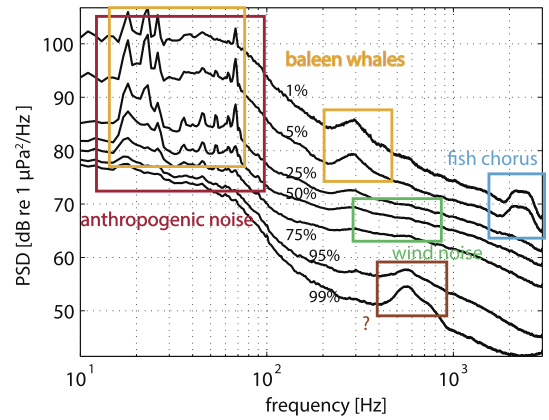

Fig. 4. Power spectral density (PSD) percentiles for set number 3154 deployed from August 2012 to June 2013. Humpback whales dominate at 300 Hz; pygmy blue, Antarctic blue and fin whales contribute narrow-band (tonal) sound below 100 Hz.

The statistical variability of underwater sound from August 2012 to June 2013 over the frequency range of 10–3 kHz was computed and illustrated as power spectral density percentile graphs, where the *n*th percentile gives the level that was exceeded *n*% of the time (Fig. 4). The 50th percentile is the median. These annual percentile plots were very similar for all of the data sets since 2008. Significant contributors to the underwater soundscape were labelled and colour coded. Between ~10 and 80 Hz, the soundscape is dominated by great whales and ships. Pygmy blue whales generate strong tones from about 17 Hz to 70 Hz, fin whales produce impulsive signals from about 15 Hz to 30 Hz, Antarctic blue whales make tonal calls at 26–27 Hz and Z-shaped calls from 17 Hz to 27 Hz. Vessels emit various frequencies corresponding to their propeller blade rate, engine tones and overtones. Humpback whales are present for several months per year and dominate at about 300 Hz, seen as the hump in the 1st, 5th and 25th percentiles. The fish or invertebrate chorus is seen throughout the year, and there is no other source louder than this chorus in the band from 1800 to 2500 Hz. Wind-dependent noise is seen at mid-frequencies, 400–2000 Hz. There is a hump in the 95th and 99th percentiles at 500–600 Hz. This hump is present in all of the data sets since 2008. It never gets quieter than this level. We do not know the source of this energy. This could be a very faint fish chorus from a different species.

3.2. Geophony

3.2.1. Wind-dependent noise

The polar plot in Fig. 5 illustrates the variation in wind direction and wind speed at Rottnest Island from 1 June 2012 to 31 May

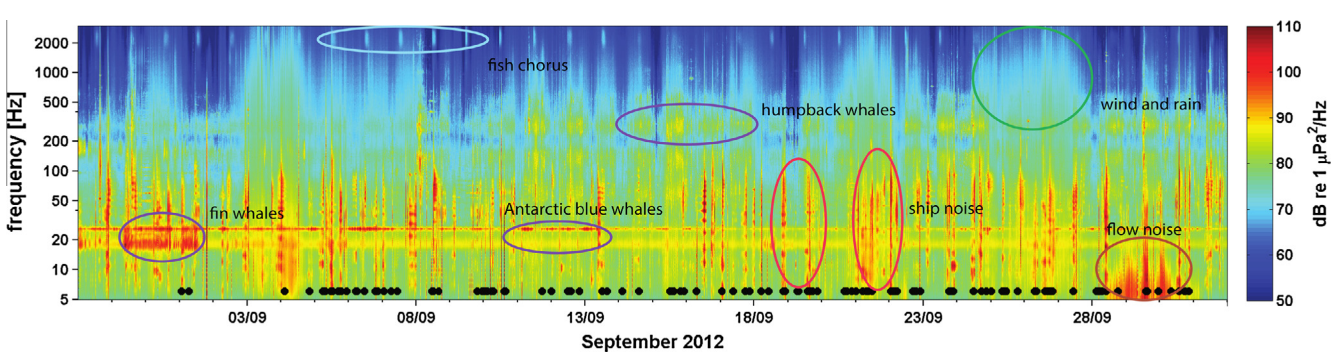

Fig. 3. Spectrogram for September 2012 showing the main contributors to the marine soundscape in the Perth Canyon. The black dots indicate ship passes within 20 km of the sound recorder (NFFT = 6000, fs = 6 kHz, 0% overlap).

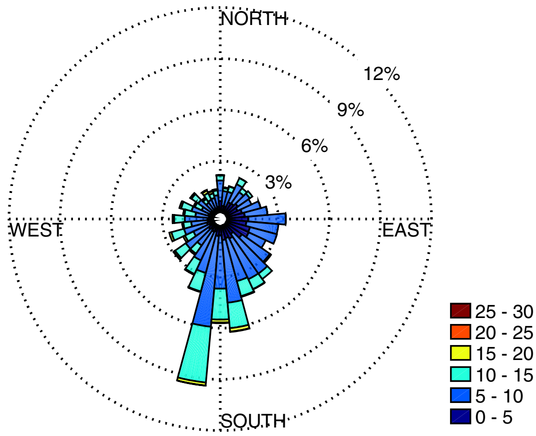

Fig. 5. Polar plot of the wind direction and speed (m/s) between June 2012 and May 2013, recorded at the Bureau of Meteorology weather station at Rottnest Island, Western Australia.

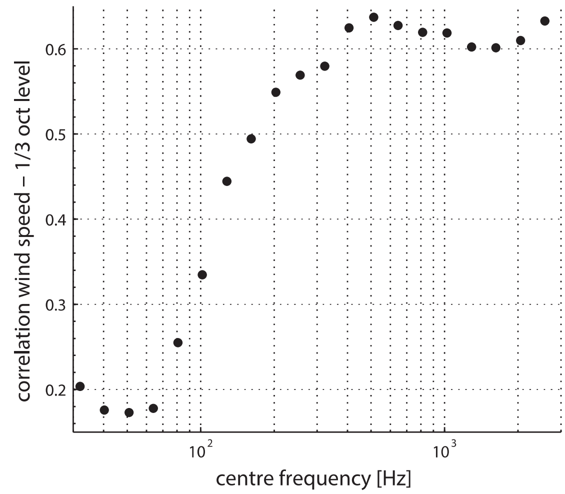

Fig. 7. Correlation coefficient of wind speed and 1/3 octave band level versus centre frequency.

2013. The wind was stronger from the S and W than the E and N, though most frequently blowing from the S. The most frequent wind speed was 5–15 m/s.

With a recording duty cycle of 5 min every 15 min, power spectral density was averaged over 5 min and integrated in 1/3 octave bands. Wind speed was interpolated from the BoM time series to the time of each 5-min recording. Wind speed was rounded into bins of 0.1 m/s width, and the 1/3 octave band levels recorded at each wind speed were noted and averaged for each wind speed bin. One-third octave band levels were correlated with the logarithm of the wind speed. An increase in noise with wind speed was seen at 256 Hz for wind speeds > 5 m/s, at 512 and 1024 Hz for wind speeds > 4 m/s and at 2056 Hz for wind speeds > 3 m/s (Fig. 6). The peak 1/3 octave level reached at the maximum wind speed of 25 m/s varied from 95 dB re 1 μPa^2 at 256 Hz to 100 dB re 1 μPa^2 at 2048 Hz.

Fig. 7 shows the correlation coefficient for wind speed and 1/3 octave band level as a function of centre frequency. The correlation coefficient increased with frequency from about 80 Hz to 500 Hz and then leveled off, partly due to the interference with the nightly biological chorus above 1000 Hz.

3.2.2. Rain noise

Rottnest Island witnesses sparse rainfall often accompanied by strong wind. Of the 17,520 half-hour samples in the year, only 573 samples measured some rainfall, which accounted for rainfall about 3.2% of the time. The maximum rainfall rate measured between June 2012 and May 2013 was 30 mm/h (Fig. 8).

Periods of high rain were searched and the corresponding power spectral density was plotted to visualise the acoustic spectrum of rain at the IMOS recorder (Fig. 9). Three weather scenarios

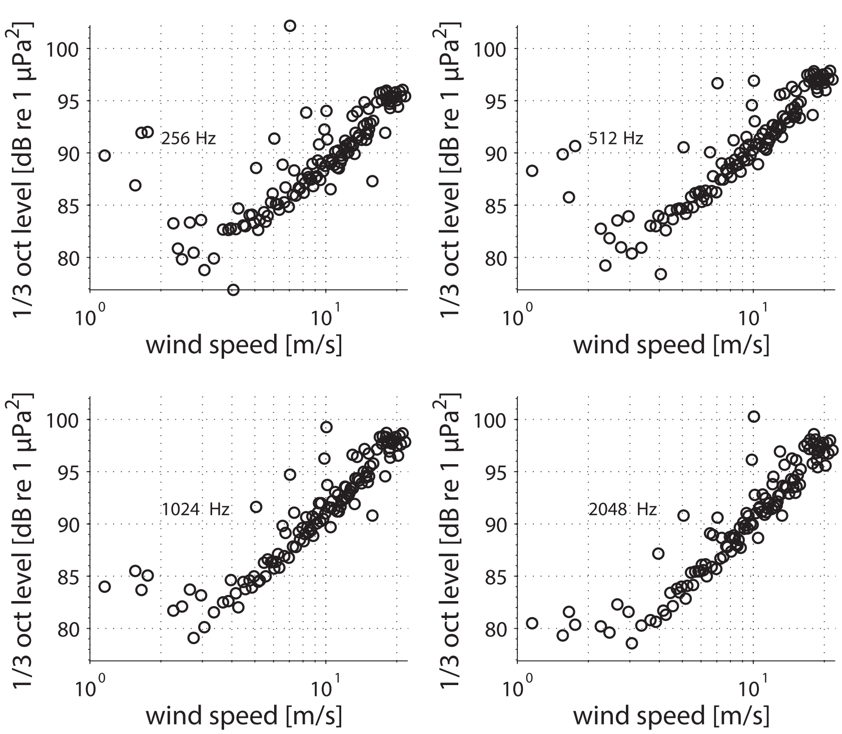

Fig. 6. Scatter plots of average 1/3 octave band levels in bins of 0.1 m/s wind speed for four centre frequencies: 256, 512, 1024 and 2048 Hz.

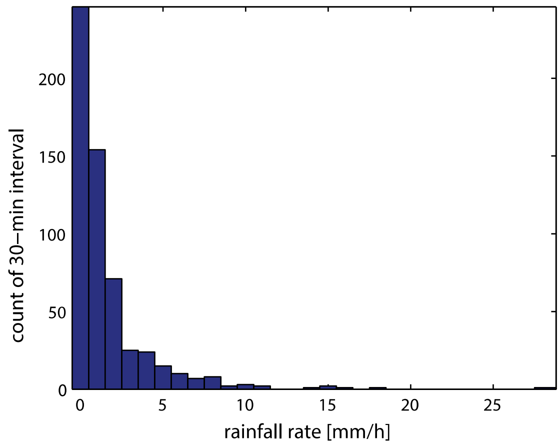

Fig. 8. Histogram of the number of 30-min samples with rain versus the rainfall rate in bins of 1 mm/h, based on BoM rainfall data from 1 June 2012 to 31 May 2013.

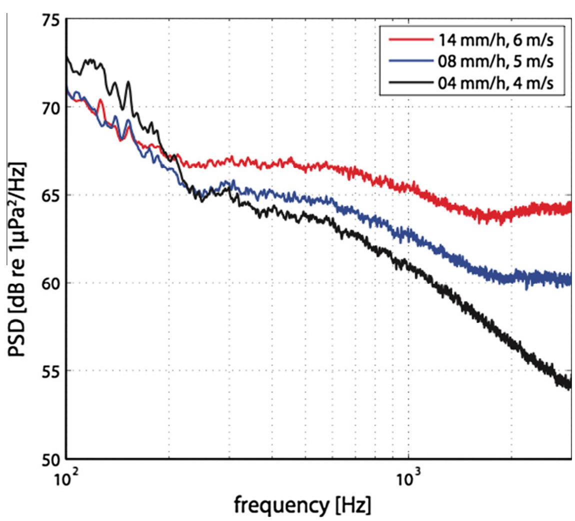

Fig. 9. Power spectral density levels at three weather scenarios illustrating the increase in spectral level under the impact of increasing rainfall rate (mm/h) and wind speed (m/s).

are shown with increasing wind speed and rainfall rate. At low wind and rain (black curve), the power spectral density decreased monotonically from about 200 Hz to 3 kHz. The slope above 1 kHz was about −5 dB/octave in alignment with the Knudsen curves (Knudsen et al., 1948), and the spectral density levels were within 1 dB of the Knudsen curves at winds of 4 m/s (sea state 2). This spectrum did not show any characteristics of rain noise; rain at this rate and wind speed is expected to be recordable at frequencies of 10–25 kHz (Ma et al., 2005), above the IMOS recorder bandwidth. At medium (blue curve) and high (red curve) wind and rain, a notch was seen in the spectrum at about 1.7 kHz; the broad peak developing above this frequency has been associated with the impact of medium to large rain drops (1.2–3.5 mm diameter) during heavier rainfall rates (Barclay and Buckingham, 2013b). Our spectrum at 14 mm/h rain and 6 m/s wind is about 3 dB above that of Ma et al. (2005) and 5 dB below that of Barclay and Buckingham (2013b), with the variability likely due to different water depths and ranges to the rain epicentre and ranges to the weather station.

3.2.3. Flow noise

Spectrograms were averaged over each 5-min recording and integrated into adjacent 1/3 octave band levels. Current speed was interpolated from the WATR50 time series to the time of each 5-min recording. Fig. 10 demonstrates long-term variations in the spectrum level of sea noise along with changes in the current speed over the same time period, showing a correspondence between the current speed and the noise level below 40 Hz. The correlation increased with decreasing frequency, to its maximum at 5 Hz (Fig. 11, top). Note that the acoustic data are routinely high-pass filtered above 5 Hz. Rounding the current speed into bins of 0.01 m/s, and averaging the 1/3 octave band levels (centred at 5 Hz) measured at each current speed, demonstrates the increase in noise with increasing current (Fig. 11, bottom). This noise could be due directly to flow noise or indirectly to motion of the hydrophone or sediment particles under strong currents.

3.2.4. Earthquake

While we did not specifically search for earthquakes, one clear earthquake in the absence of any other noise was detected in the IMOS Perth Canyon data on 18 December 2009, likely from the Mid-Indian-Ocean-Ridge or the Java Trench (Fig. 12).

3.3. Biophony

3.3.1. Pygmy blue whales

Pygmy blue whales produce tonal sounds with harmonic overtones from about 18 Hz to nearly 200 Hz, see Fig. 13 (Gavrilov et al., 2011; Gavrilov and McCauley, 2013; McCauley et al., 2000; McCauley and Jenner, 2010). We programmed a simple band level difference detector that calculated the difference of the band levels ($10\log_{10}$ of mean square acoustic pressure) in the bands of pygmy blue whale signals (17–18, 22–23, 25–27, 67–69 Hz) and in the adjacent noise bands (30–32, 40–41, 50, 57, 75–77 Hz). This band level difference can also be thought of as a signal-to-noise ratio (SNR), where the mean square pressure of the signal was computed over the band levels of the call, and the mean square pressure of the noise was computed over adjacent, non-call bands. The band level difference was low-pass filtered by a 5-day sliding average window yielding the intra-annual variation shown in Fig. 14. While there is some variability from day-to-day and year-to-year in the band levels of pygmy blue whale calls and hence underlying

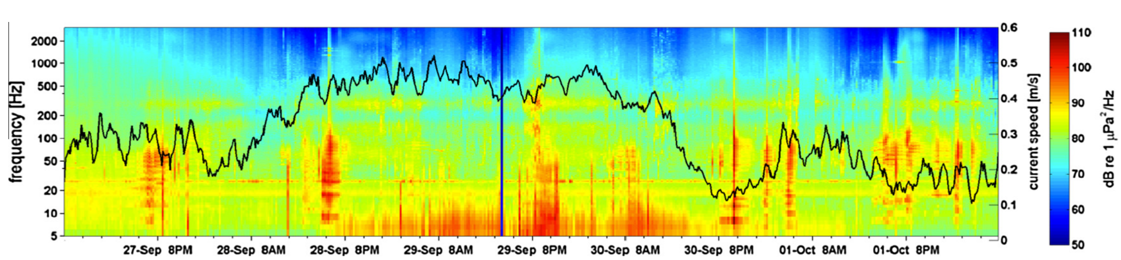

Fig. 10. Spectrogram and time series of current speed illustrating flow noise below 20 Hz (NFFT = 6000, fs = 6 kHz, 0% overlap).

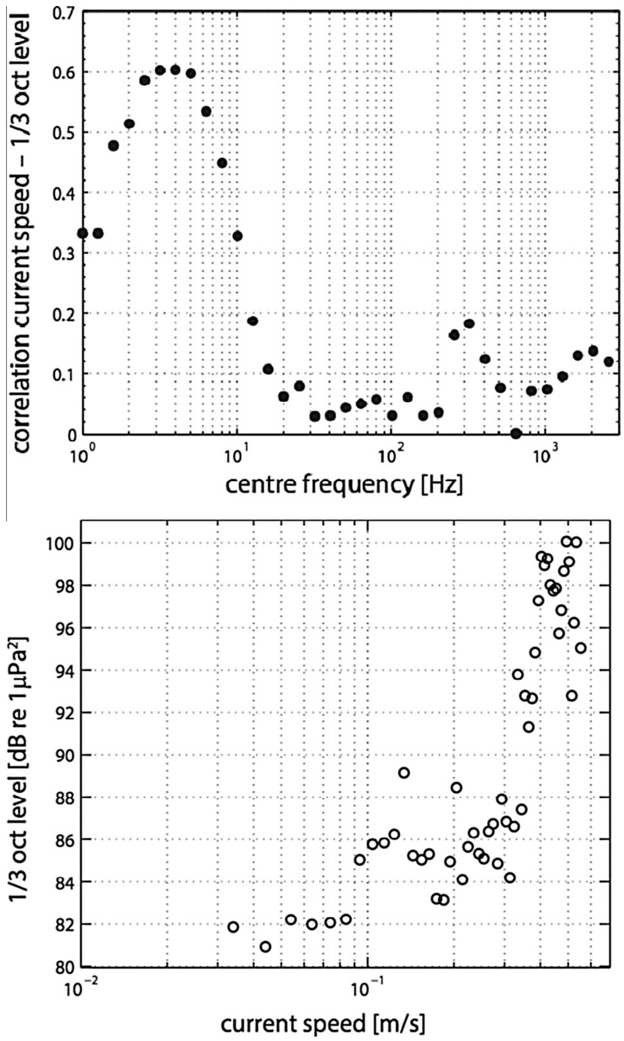

Fig. 11. (Top) Correlation coefficient of current speed and 1/3 octave band level versus centre frequency over the period 26 September–3 October 2012. Note that the frequency response of the acoustic recording system sharply decreased below 5 Hz due to a high-pass filter. (Bottom) Scatter plot of the mean 1/3 octave band level at 5 Hz as a function of ocean current speed.

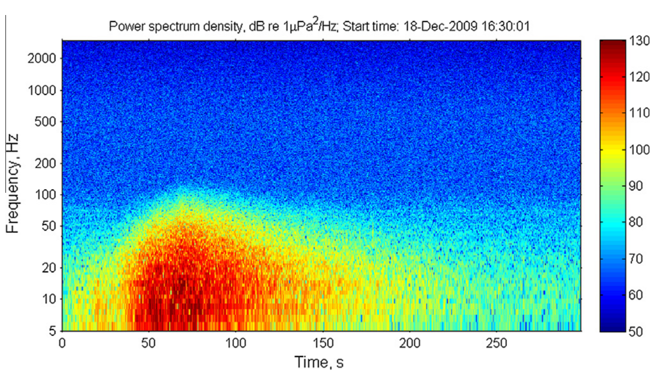

Fig. 12. Spectrogram of an earthquake detected at the IMOS Perth Canyon recorder (NFFT = 6000, fs = 6 kHz, 0% overlap).

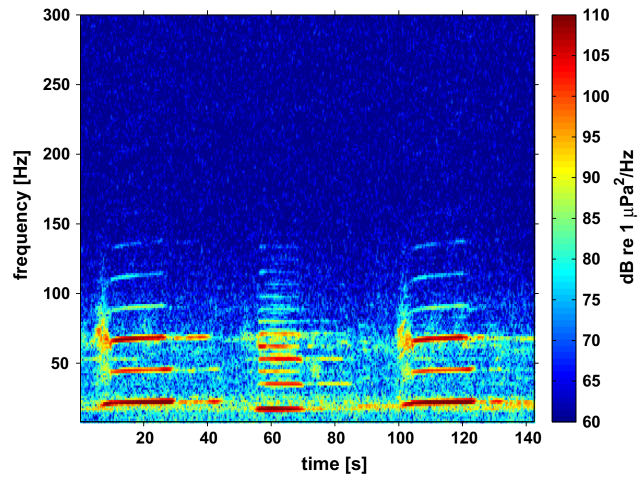

Fig. 13. Spectrogram of pygmy blue whale calls recorded in the Perth Canyon (NFFT = 6000, fs = 6 kHz, 0% overlap).

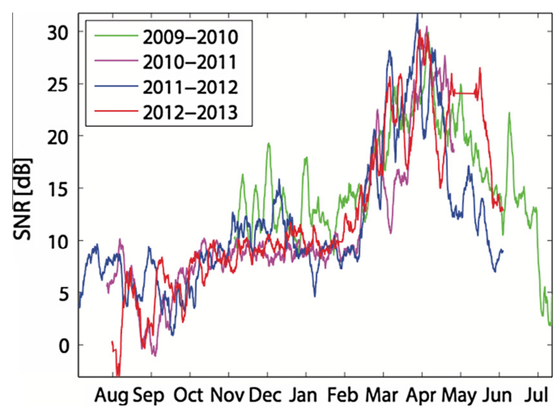

Fig. 14. Output of the pygmy blue whale detector from November 2009 to June 2013, demonstrating the presence of pygmy blue whales from November to June, peaking from March to June.

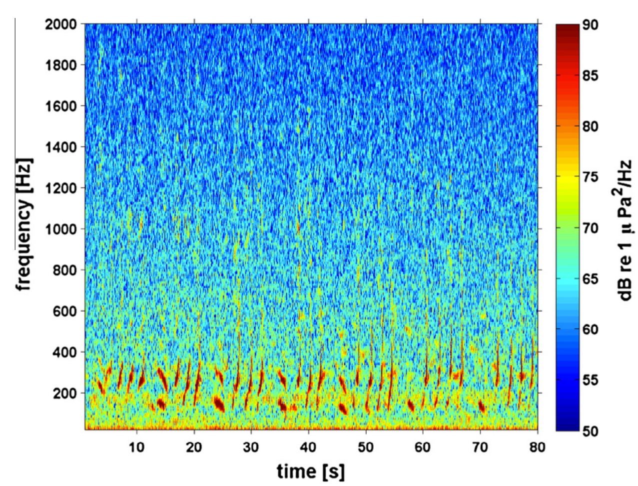

Fig. 15. Spectrogram of humpback whale song recorded in the Perth Canyon (NFFT = 6000, fs = 6 kHz, 0% overlap).

animal density at this site, a consistent visitation pattern is obvious. Pygmy blue whales on their southern migration pass through the Perth Canyon from November to January. They are detected at the IMOS acoustic observatory with more frequent and stronger signals on their northern migration from February to June (Gavrilov et al., 2012).

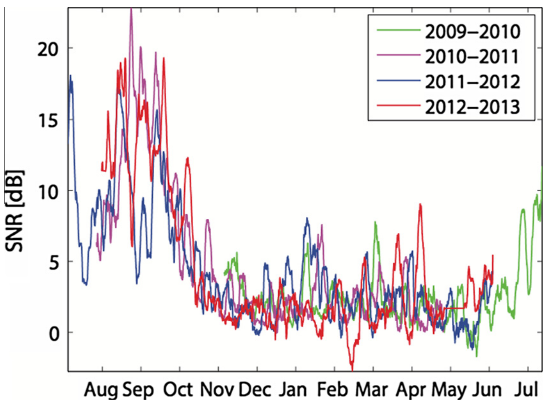

Fig. 16. Output of the humpback whale detector from November 2009 to June 2013, demonstrating the presence of humpback whales from July to late October.

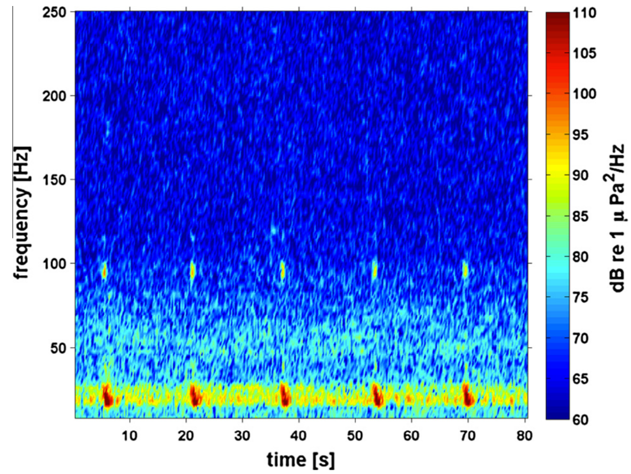

Fig. 17. Spectrogram of fin whale calls (NFFT = 6000, fs = 6 kHz, 0% overlap).

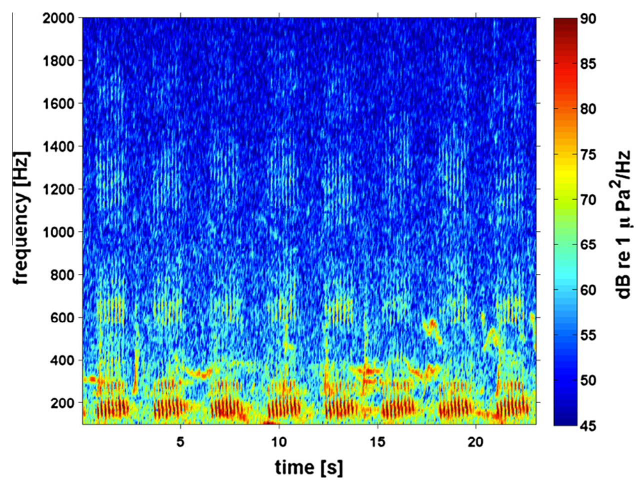

Fig. 18. Spectrogram of possible minke whale pulses with humpback whale tonal sounds in the background (NFFT = 6000, fs = 6 kHz, 0% overlap).

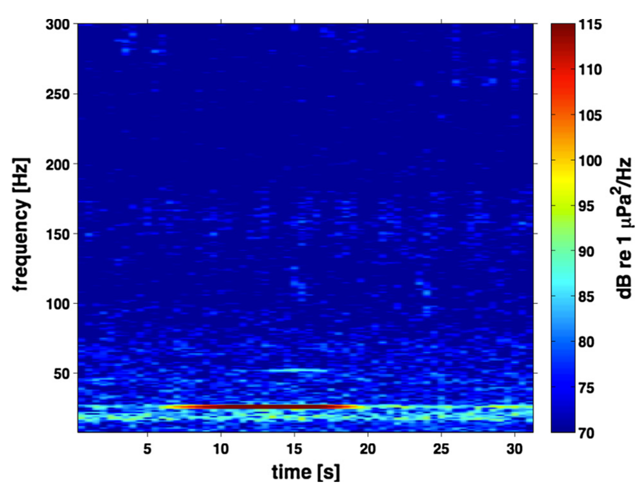

Fig. 19. 26 Hz tone possibly from an Antarctic blue whale (NFFT = 6000, fs = 6 kHz, 0% overlap).

3.3.2. Humpback whales

Humpback whales produce tonal and pulsed sounds between 20 Hz and >15 kHz. Males sing "songs" for many hours at a time (Dunlop et al., 2008, 2013, 2007; Garland et al., 2013). Fig. 15 shows a distant humpback song spanning frequencies from about 50 Hz to 2 kHz, with the more intense part at 100–400 Hz. In the SNR detector similar to that for pygmy blue whale calls, a frequency band of 120–330 Hz was chosen as an indicator of the presence of humpback whales and a band of 700–1200 Hz for background noise. The detector indicated humpback whale presence in the Perth Canyon from July to late October (Fig. 16). There might be two peaks, one during the northern migration (June–July) and one during the southern migration (August–October), however, given that the IMOS acoustic recorders are typically recovered, serviced and redeployed in winter, fewer data exist in the winter months to adequately resolve the two migrations at this stage.

3.3.3. Fin whales

Fin whales in the Eastern Antarctic produce 1 s downsweeps from about 30 to 15 Hz with a simultaneous higher-frequency (95–100 Hz) tonal signal, typically repeated every 10 s (Sirovic et al., 2009). Fin whales in other parts of Antarctica emit a lower, high-frequency tonal (85–90 Hz). In the Perth Canyon (of similar longitude as Eastern Antarctica), fin whale calls were of the Eastern Antarctic type. Fin whales were recorded in Eastern Antarctica from March to June, with no detections from July to February (Sirovic et al., 2009). In the Perth Canyon (Fig. 17), fin whales were recorded from June to August. However, their calls were too infrequent and weak and, moreover, overlapping with Antarctic blue whale calls in frequency, so that a simple SNR detector could not reliably reveal their seasonal presence. We assume this is the same population as the Eastern Antarctic population, stopping in the Perth Canyon on its northern migration.

3.3.4. Antarctic minke whales

Vocalizations believed to be the "bioduck" sound of Antarctic minke whales (Risch et al., 2014) were detected during July and August. Fig. 18 shows the broadband pulses attributed to minke whales, as well as frequency-modulated sounds from humpback whales in the background. Minke whale sounds were too weak and few for the SNR detection process.

3.3.5. Possible antarctic blue whales

Tones of 12–15 s duration at about 26 Hz were detected from late June through October (Fig. 19). These signals at a first glance would appear to be from Antarctic blue whales but, in contrast to Z-shaped calls are missing the second (downsweep transient) and third (slightly frequency modulated tone at about 17 Hz) parts (Rankin et al., 2005). The call frequency corresponds

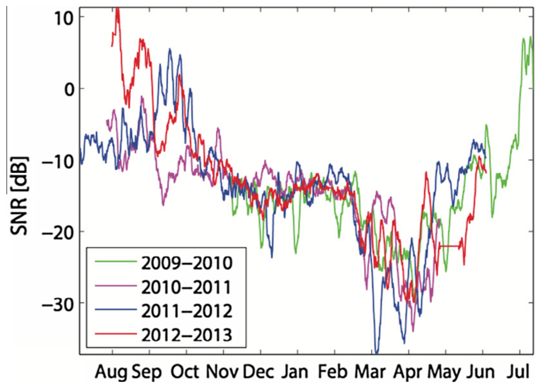

Fig. 20. Output of the 26 Hz tone detector from November 2009 to June 2013, indicating the presence of this signal from late June through October.

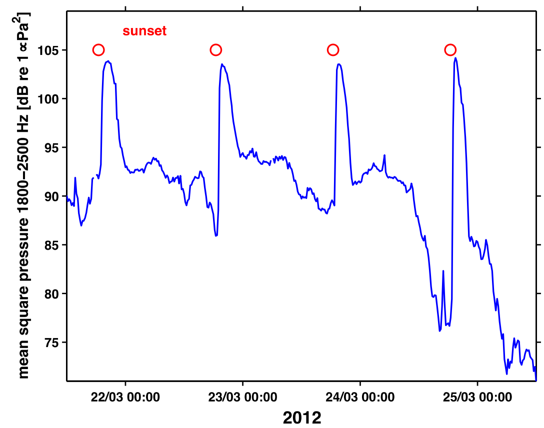

Fig. 22. Mean square sound pressure in the frequency band 1800–2500 Hz over a 4-day period. Each sample is a 5-min average. The chorus typically lasts for 2 h. Time is shown in day/month hour:minute.

approximately to that of the Antarctic blue whale calls recorded in Antarctica and along the southern coast of Australia. Fig. 20 shows the long-term variation in the SNR in this call frequency band (26–27 Hz) and adjacent (25–26, 27–28 Hz) noise bands. The noise bands included the 25–26 Hz band of pygmy blue whale calls. Therefore, the SNR is strongly negative at the time of Antarctic blue whale absence and pygmy blue whale presence.

3.3.6. Evening chorus

Fig. 3 shows a spectrographic example of the biological evening chorus in the Perth Canyon. The species responsible for this chorus is unknown, however, we believe this to be fish as active fish sources have been identified in the water column. The chorus contributed to the underwater soundscape in the frequency band from 1000 to 2500 Hz (peaking at 1800–2500 Hz) every night all year round. Fig. 21 shows variations in the mean square sound pressure in this frequency band for a 5-week period. Each sample is a 5-min average. With the exception of a few ship passes close to the sound recorder site, and occasional strong winds and rare occurrences of rain, the chorus dominated the marine soundscape in this frequency band throughout the year. Fig. 22 displays a 4-day time series of the mean square pressure in this frequency band, again averaged over 5 min. The chorus commenced after sunset and lasted for about 2 h. The peak band level of this nightly chorus is plotted in Fig. 23 for an 11-month period. The nightly mean square pressure level of this chorus is on average 100.9 ± 2.6 dB re 1 μPa^2

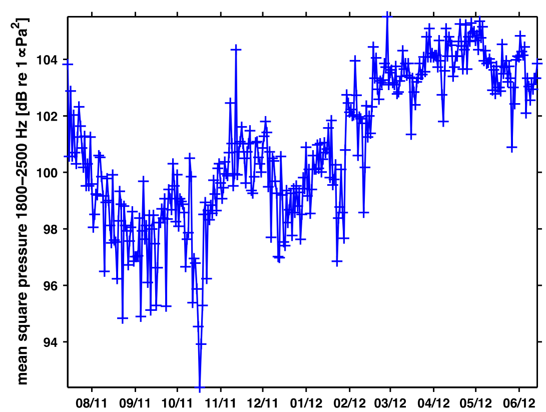

Fig. 23. Peak band level of choruses observed in the frequency band 1800–2500 Hz every night for an 11-month period from mid-October 2011 to mid-June 2012. The first day of each month is indicated on the *x* axis (month/year).

over the year. A strong seasonal cycle is obvious with the chorus being stronger in winter than in summer. The peak of the chorus activity happened 2.31 ± 1.08 h after sunset over the 11-month recording period.

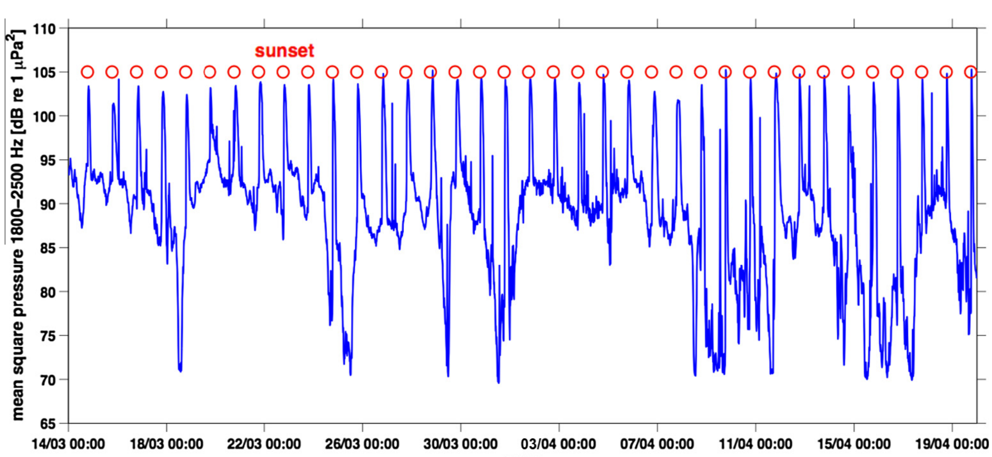

Fig. 21. Mean square sound pressure in the frequency band 1800–2500 Hz. Each sample is a 5-min average. A 5-week time series is plotted, showing the peak in chorusing soon after sunset each night. Time is shown in day/month hour:minute.

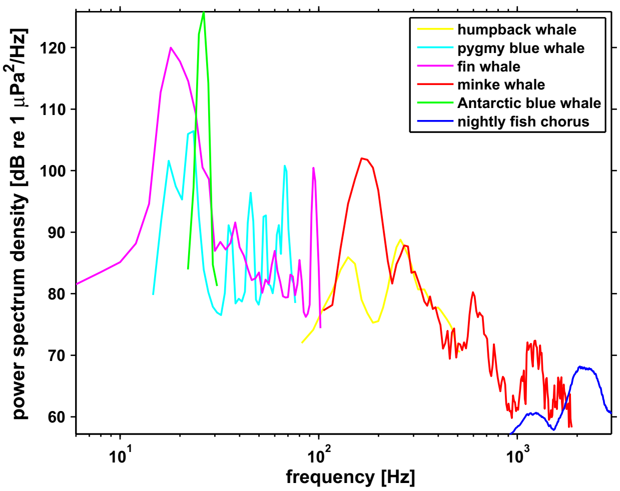

Fig. 24. Power spectrum levels associated with different biological sources observed in the Perth Canyon.

Fig. 24 summarises the power spectral density levels measured when one biological source dominated, over the corresponding bandwidth. Antarctic blue and pygmy blue whales were recorded at the highest received levels. Humpback whales were recorded at lower received levels, possibly due to their larger distance to the recorder.

3.4. Anthrophony

3.4.1. Ships

Fig. 25 shows the four ship tracks that passed closest to the recorder in the month of November 2012. For each ship pass, power spectral density was computed every second and averaged into adjacent 1/3 octave bands. Fig. 26 (top) shows the mean power spectral density every second in the 1/3 octave band centred at 203 Hz (blue lines) for the black ship track in Fig. 25. The recording duty cycle of 5 min every 15 min is obvious. The distance of the ship from the sound recorder is shown as a black line using the right axis. At the point of closest approach (200 m, 2:07 am), the received level was maximum. The vessel approached and passed the recorder in a straight line, then turned East at 3:00 am.

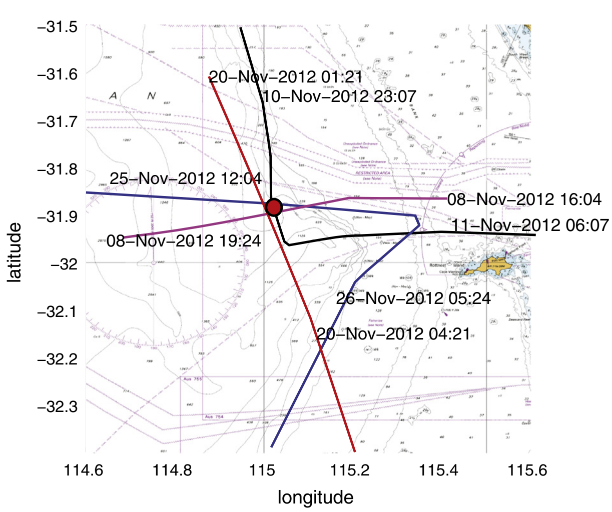

Fig. 25. The four ship tracks closest to the recorder in November 2012.

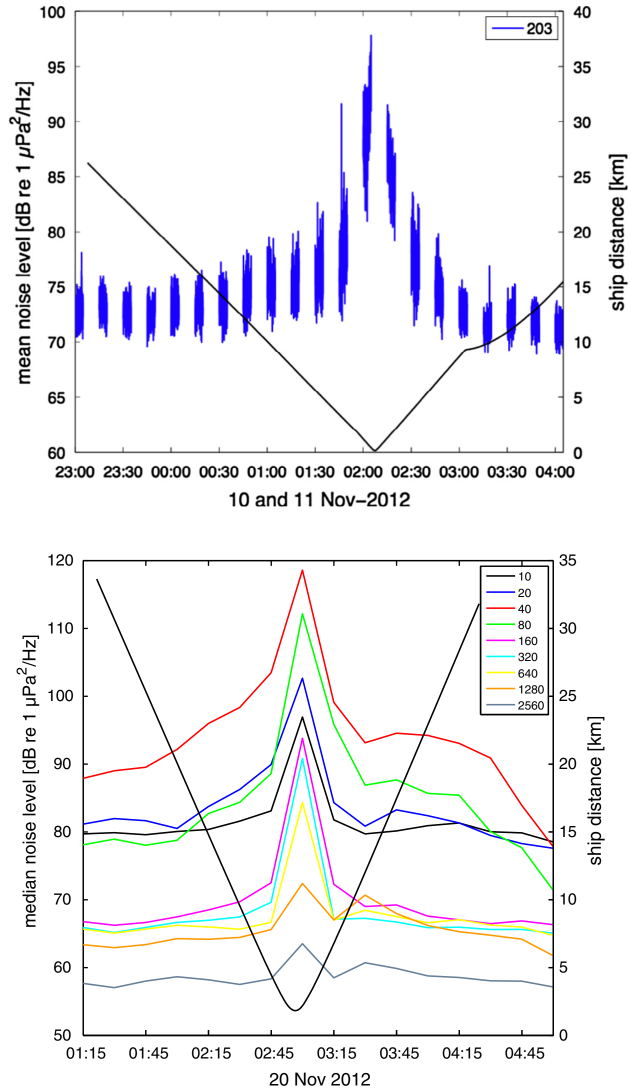

Fig. 26. (Top) Power spectral density averaged over the 1/3 octave band centred at 203 Hz, computed every second (at a duty cycle of 5 min recording every 15 min) while a vessel passed within 200 m of the recorder. (Bottom) Median over each 5-min recording of the 1s power spectral density within a series of 1/3 octave bands. Only every third band is plotted. The closest point of approach of this vessel was 1.8 km.

Fig. 26 (bottom) shows the median power spectral density level over each 5-min recording at a number of frequencies for the red ship track of Fig. 25. The levels were computed by taking the 5-min median of the 1s power spectral density levels within each 1/3 octave band. Only every third 1/3 octave band is plotted in Fig. 26 (bottom). At the closest point of approach (1.8 km, 2:56 am), power spectral density levels peaked at all of the 1/3 octave centre frequencies computed. Power spectral density was highest in the 1/3 octave band centred at 40 Hz. At this frequency, the ship was detectable for about 3 h around the closest point of approach. At frequencies above 160 Hz, the ship was detectable for less than one hour or 10 km in range.

Using AIS data for one full year from September 2012 to August 2013, the percentage of time that at least one vessel was within a certain distance from the recorder was computed (Table 1). Ships came within 5 km of the recorder for less than 1% of the year. There was at least one vessel within 10 km from the recorder for 4% of the time. For half of the time, at least one vessel was within 35 km.

Table 1
Percentage of time that at least one vessel came within a given range from the recorder.

Distance from recorder (km)	5	10	15	20	25	30	35	40
Percentage of time ships are present (%)	0.76	4.12	10.16	17.28	26.59	38.42	50.38	59.84

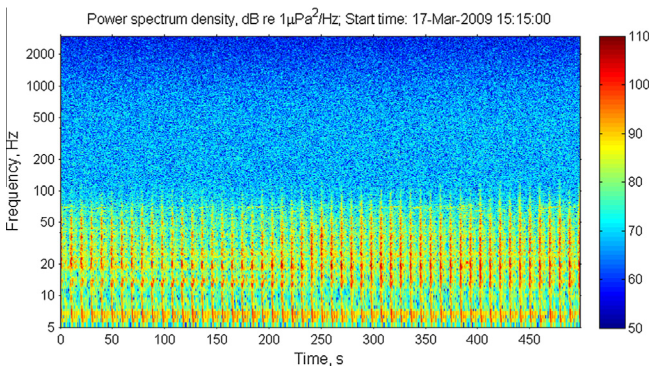

Fig. 27. Spectrogram of a seismic survey recorded (NFFT = 6000, fs = 6 kHz, 0% overlap).

An automatic ship detector was employed by searching for at least four spectral peaks within the frequency band of 10–60 Hz, that lasted for at least one hour. The detector identified ship noise 23% of the time. We also checked the acoustic recordings by listening and inspecting spectrograms at 100 randomly distributed times during the 2012–2013 deployment. This was done twice and resulted in detections 23% and 26% of the time.

3.4.2. Seismic surveys

Signals from a seismic survey were detected for several days in 2009 only, with an example shown in Fig. 27. The survey did not contribute significantly to the underwater soundscape, in the sense that it was not detectable in the annual power spectral density percentile plot for the year 2009/10.

4. Discussion/conclusion

In this study, four years of IMOS passive acoustic recordings were analysed for dominant sources and time series of sound pressure levels were compared to time series of physical oceanographic data (wind, rain, currents), biological oceanographic information on whale presence, and anthropogenic activity (ship traffic). Positive correlations were found for all of the parameters tested—in certain frequency bands. This implies that acoustical oceanographic data at specific frequencies can be used as a proxy for certain physical and biological oceanographic data. The following paragraphs discuss these relationships by source type: abiotic, biotic and anthropogenic.

4.1. Geophony

While we did not have a weather buoy above our recorder, but instead used data from a weather station at 47 km range, correlations of wind and rain with underwater noise were obvious at 200–3000 Hz and above 2000 Hz respectively. Wind data from the Rottnest weather station were previously shown to correlate well with underwater noise 22 km off Rottnest at 40 m depth (Cato and Tavener, 1997). Offshore weather patterns can be of larger scale and the CMST recorder at 430–490 m depth received levels originating from a larger surface area than a recorder at shallower depth. The IMOS recorder is typically set to sample at 6 kHz, preventing studies of the full rain spectrum. Underwater noise in the band of 1–25 kHz can be used as a proxy for wind speed, rainfall rate and drop size at the sea surface (Nystuen, 2001; Nystuen et al., 2000; Nystuen and Selsor, 1997; Vagle et al., 1990), and passive acoustic observatories can be a cost-effective and efficient way of monitoring offshore weather.

At the IMOS Perth Canyon site, we detected one earthquake in 2009, either from the Mid-Indian-Ocean-Ridge or the Java Trench. We did not detect other contributors to the geophony, such as breaking waves due to the long range from shore, or Antarctic sea ice due to the south-western Australian landmass blocking sounds from Antarctica.

A common problem with soundscape recordings is pseudo noise from turbulent flow at the hydrophone, which interferes with the recording of ambient noise. Also called flow noise, these pressure fluctuations are not acoustic and not part of the soundscape. Pseudo noise can be identified if one deploys a pair of hydrophones and considers the phase of the pressure wave at each hydrophone. Pseudo noise will be uncorrelated, i.e. incoherent, at the two hydrophones (Barclay and Buckingham, 2013b; Deane, 2000). With only one hydrophone, we could not study the coherence of noise, but we showed a positive correlation of this pseudo noise below 10 Hz with the speed of currents. Increasing flow noise with increasing current speed is commonly observed (e.g., (Urick, 1984; Willis and Dietz, 1961). The level and spectrum of the flow noise, however, depend on the specific hydrophone and its mooring arrangement, which will differ between moorings. Flow noise also increases if the hydrophone moves (e.g., in the case of acoustic recording tags on animals (Merchant et al., 2015) and has been used as a proxy for swim speed (Burgess et al., 1998; Insley et al., 2008).

4.2. Biophony

Potentially seven baleen whale species migrate twice annually along the WA coast and enter the Perth Canyon. We identified humpback whales (50–2000 Hz), pygmy blue whales (17–70 Hz), fin whales (15–100 Hz), minke whales (50–2000 Hz) and on a few occasions Antarctic blue whales (17–27 Hz) for several months each year. Whale noise peaked in winter for most species, except pygmy blue whales detected from summer to autumn. While pygmy and possible Antarctic blue whales were recorded at strong levels, i.e. likely near the sound recorder, humpback whales were only detected at low received levels, likely further away from the recorder. At times when multiple acoustic recorders were deployed simultaneously, whales could be tracked swimming past the IMOS mooring (Gavrilov et al., 2012). Computing the mean square pressure in the frequency bands specific to animal call types showed some variability in amplitude and hence a crude (since it is biased by animal proximity to the receiver) measure of underlying population density at the site of the observatory, as well as consistent visitation patterns over the years. Passive acoustic data can be used instead of or in addition to biological data collected by other means, such as boat-based visual observation, for population monitoring. Passive acoustics works continuously, day and night, in all weather and over long ranges; however, only if animals vocalise.

Biological choruses are produced by large numbers of animals so that individual calls cannot be detected, but rather, the chorus appears as band-limited white noise. Choruses of fish, invertebrates and whales (e.g. sperm whales) are common around Australia (Cato, 1978). In the Perth Canyon, choruses (1000–2500 Hz) likely due to fish were seen all year round. The unknown hump at 600 Hz (Fig. 4) could be another type of fish or invertebrate chorus. A chorus of distant Antarctic blue whales was obvious in June–October.

Some species, such as the pygmy blue whale, stop over in order to feed in the Perth Canyon, as the Perth Canyon experiences seasonal and localised upwelling, resulting in enhanced productivity (Rennie et al., 2009). Odontocetes were not recorded at this site. Deep-diving odontocetes produce foraging clicks, which are beyond the Nyquist frequency of the IMOS recorders. Crustaceans, which are a dominant source at 2–20 kHz in shallow waters around Australia (Erbe, 2009), are not heard at this depth either. If the acoustic repertoires of animals are known, as is the case with many of the baleen whale species, passive acoustic observatories like the IMOS moorings can provide a cost-effective and autonomous way of monitoring animal populations, i.e. their visitation patterns, migration timing, and relative abundance (Erbe, 2013b).

4.3. Anthrophony

The majority of anthropogenic sounds detected were those from ships. Ship noise at the IMOS acoustic observatory in the Perth Canyon was present 25% of the time, dominated at frequencies between 8 and 100 Hz, with sound energy at 40–80 Hz detectable over the longest ranges. Not all of the large vessels seem to log their position regularly; hence some vessel passes were likely missed in our analysis (Fig. 3). The Australian Maritime Safety Authority does not publish the names of vessels tracked, hence we were unable to correlate noise levels with technical vessel specifications. Small vessels typically do not log AIS positions; however, we expect the number of small, private boats to be small this far (70 km) from the mainland. Large-ship traffic into and out of Fremantle Harbour did not show any seasonality.

Comparing the sound budgets amongst the geo-, bio- and anthrophony (Fig. 4), baleen whales are a significant contributor to the underwater soundscape at the IMOS observatory for up to 10 months per year with peak received power spectral density levels of 130 dB re 1 $\mu Pa^2/Hz$. Biological signals are recorded at intensities similar to large, nearby vessels at this site and occupy the same dominant frequency band (10–100 Hz). The dominant spectrum of the anthrophony is limited to frequencies below 100 Hz. The biophony also dominates at 200–400 Hz due to humpback whales, and at 1800–2500 Hz due to fish. Sounds of the geophony are significant only during strong winds and storms; but even then, geophony power spectral density levels are below 67 dB re 1 $\mu Pa^2/Hz$ in the band from 200 to 3000 Hz (Fig. 9), less than the levels of the biophony of 102–68 dB re 1 $\mu Pa^2/Hz$ in the same band in the presence of whales and fish (Fig. 24).

While some of the IMOS Acoustic Observatories had arrays of recorders deployed in some years, often, only a single hydrophone was available. With a single hydrophone, usually the position of the sound source (bearing, range, depth) cannot be calculated, unless the signal is a short pulse and multipath signals can be discerned, in which case range and depth can be derived (Cato, 1998). The underwater environment, characterised by its bathymetry, salinity, temperature, sediment, etc., determines how sound propagates from the source to the recorder. The acoustic spectrum recorded by the observatory can be quite different, depending on where the source is located. Therefore, the soundscape recorded at the observatory is a snapshot in space and time. However, long-term recordings, like those at the IMOS observatories, show distinct patterns. Certain baleen whales are present during specific months, with their seasonality being consistent over the years. Biological choruses have a diurnal pattern occurring only at nighttime, yet throughout the year. Cargo vessels into and out of Fremantle follow distinct shipping lanes. Any spatio-temporal changes of the sources and their distribution are detectable by passive acoustic monitoring, and can highlight changes in weather patterns (e.g., climate change), changes in animal distribution and density, changes in the level of local industrialisation (e.g., increased marine export), and correlations between these changes (e.g., noise impacts on whale presence). Passive acoustic monitoring can hence be an indicator of biologically significant ecosystem effects.

Author contributions

CE: project manager, designed the study, supervised data analysis, contributed to data analysis and software development for data analysis, wrote most of the article.

AV: data sourcing, software development, data analysis, wrote sections of the article.

RM: sourced, designed and project-manages the IMOS Acoustic Observatories, responsible for acoustic data collection, background information, discussions and ideas on data analysis.

AG: designed the IMOS Acoustic Observatories, software development for acoustic data analysis, discussions on data analysis, revision of manuscript.

IP: contributed to software development for data analysis, discussions on data analysis, commented on the draft manuscript.

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