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ABSTRACT

In 2013, the Southern Ocean Hydrophone Network (SOHN) was formed with a goal towards better standardizing and coordinating a circumpolar network of Southern Ocean acoustic recording devices for monitoring of marine mammals. Here we present sound levels from calibrated year-long continuous recordings from Australia's two inaugural SOHN sites. Custom autonomous recording devices were developed and deployed by the Australian Antarctic Division at two sites off east Antarctica in 2014 (IWC Antarctic management area IV). We investigated ambient noise levels and use long-term spectral averages as a preliminary means to identify bands of energy potentially attributable to ice, wind, and known vocalisations from marine mammals. We used remotely sensed observations of wind-speed and ice cover to conduct a preliminary investigation of the relationships among ambient sound levels and physical environmental processes. Such investigation is particularly suited to Antarctic waters where noise from shipping is minimal. Quantifying the relationships among ambient sound levels and noise-generating physical processes may help to address abiotic environmental factors that can cause site-specific variability in detections of marine mammals and may facilitate comparison of acoustic recordings from different instruments, locations, and times. A cursory and non-exhaustive list of marine mammal detections from these recordings included calls from Antarctic blue whales, fin whales, minke whales, killer whales, sperm whales, humpback whales, leopard seals, weddell seals, and crabeater seals.

KEYWORDS: PASSIVE ACOUSTICS, MARINE MAMMALS, SURVEY METHODS, LONG-TERM MONITORING

INTRODUCTION

In recent years there has been renewed interest in understanding ocean noise levels, not only to quantify and document potentially shifting baselines, but also to better understand the effects of man-made noise on marine fauna – especially marine mammals who rely on underwater sound as a primary sensory modality (Boyd et al., 2011). In the Southern Ocean, ad-hoc deployment of long-term passive acoustic recording devices has been conducted since 2002 (see the short review of deployments in the appendix of Van Opzeeland et al., 2013). These ad-hoc deployments were conducted by a variety of institutions in different years and locations using a variety of different instruments with different performance specifications (Gedamke et al., 2007; Samaran et al., 2013; Širović et al., 2009). Analysis of the data have typically focused on the spatio-temporal distribution of low-frequency calls produced by marine mammals, but the differences in timing, location, and instruments present challenges for interpretation of results and comparison of these datasets.

In 2013, the Southern Ocean Hydrophone Network (SOHN) was formed, with a goal towards better standardizing and coordinating a circumpolar network of Southern Ocean acoustic recording devices (Van Opzeeland et al., 2013). An important recommendation from the Acoustic Trends Steering Group has been the use of calibrated hydrophones and recording devices, so that each instrument will be capable of accurately and consistently measuring the intensity of received sounds (i.e. calibrated received sound pressure levels).

While the SOHN Steering Group has provided guidelines for standardization and calibration of acoustic recording devices, there are not presently any guidelines to address the site-specific variability in noise levels and sound propagation among the various recording locations. This site and time-specific variability presents additional challenges when comparing data within and among recording sites and devices. For low-frequency sounds, such as those produced by baleen whales, the probability of detecting a call can vary among by an order of magnitude when comparing detections across location or over time. This variability is largely due to site-specific environmental factors, namely ambient noise levels and acoustic propagation (Helble et al., 2013).

Quantitative study of ambient noise in the sea began in the mid-20th century (Knudsen et al., 1948), and played an important role in physical oceanography and sonar operations (Urick, 1983). Wenz (1962) presented an often cited study that investigated the variability and different processes that contribute to the ambient noise levels in the oceans. He suggested that the main processes that contributes to noise are: low-frequency turbulence (1-10 Hz), ambient noise from remote shipping (i.e. too far and diffuse to be attributed to an individual vessel; 10-1000 Hz), wind-driven surface noise (1-100 kHz), and high-frequency thermal-electric noise (> 100 kHz).

Wenz (1962) conducted his studies in the temperate Atlantic where shipping noise was dominant at low frequencies. Data collected more recently in Australian waters with reduced noise from shipping have indicated that wind-driven surface noise is also the main process responsible for noise at lower frequencies e.g. 30-1000 Hz (Cato and McCauley, 2002; Cato, 1997). However, in their study Cato and McCauley (2002) indicate considerable variability in the relationship between wind-driven surface and noise at different recording locations. They suggest that this variability among sites stems from different propagation conditions arising from differences in seabed-composition and water column structure among sites. In Antarctic waters, another major contribution to low-frequency underwater noise is that from the breakup, formation and movement of sea-ice (Lurton, 2010; Urick, 1983).

Here we present a snapshot of preliminary results from Australia's SOHN recording sites. We analyse sound levels from calibrated year-long continuous recordings from custom autonomous recording devices developed and deployed by the Australian Antarctic Division at two sites off East Antarctica. We then investigate ambient noise levels and use long-term spectral averages as a preliminary means to identify potential bands of energy that may be attributable to ice, wind, and known vocalisations from marine mammals. Using remotely sensed observations of wind-speed and ice cover, we investigate the relationship between ambient sound levels and physical environmental processes. It is hoped that a better understanding of the relationship between ambient sound levels and noise-generating physical processes in the environment can be used to reduce site-specific variability in the probability of detecting of marine mammals.

METHODS

Acoustic Measurements

Calibrated measurements of noise levels were made using a custom moored acoustic recorder – designed by the Science Technical Support group of the Australian Antarctic Division. This recorder was designed to operate for year-long, deep-water, Antarctic deployments. Each moored acoustic recorder included a factory calibrated HTI min 96 hydrophone and workshop-calibrated frontend electronics (hydrophone preamplifier, bandpass filter, & analog-digital converter), and used solid state digital storage (SDHC) to reduce mechanical self-noise (e.g. from hard-drives with motors and rotating disks). Electronics were placed in a glass instrumentation sphere rated to a depth of 3000 m, and the sphere was attached to a short mooring with nylon straps to decouple recorder and hydrophone from sea-bed. The hydrophone was mounted above the glass sphere with elastic connections to the mooring frame to reduce mechanical self-noise from movement of the hydrophone. The target noise floor of each recorder was below that expected for a quiet ocean at sea state zero. The 16-bit analog-digital converter provided 96 dB of dynamic range.

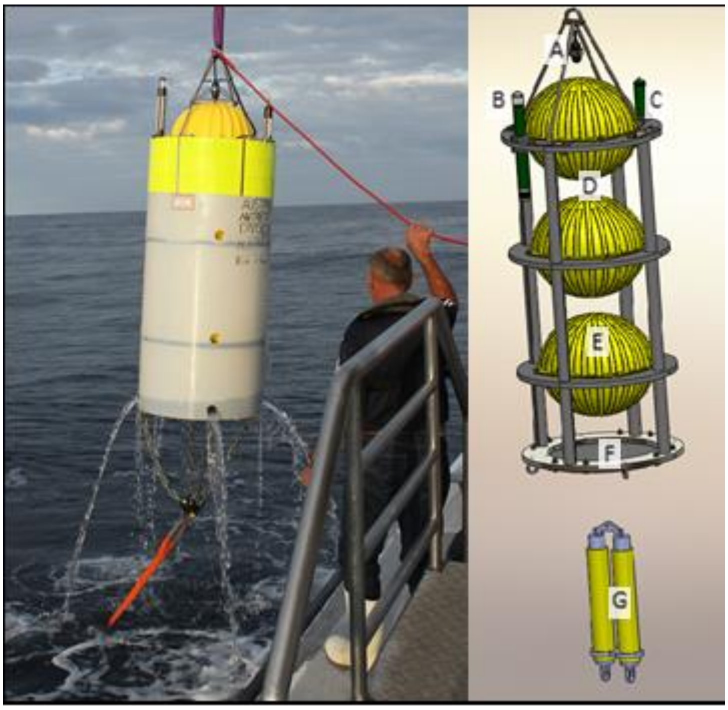

Figure 1 –Left: Recovery and schematic of an AAD moored acoustic recorder. A) Hydrophone. B) Strobe light recovery aid. C). GPS-Iridium locator beacon (recovery aid). D) Glass floatation sphere. E). Instrumentation sphere. F). Ballast plate. G). Acoustically activated releases.

Sound level measurements were made at two locations in the Southern Ocean off East Antarctica Figure 2. One recorder, Casey2014, was deployed at 63° 47.730’ S, 111° 47.225’ E at an approximate depth of 2800 m along the resupply route to Casey Station. The other recorder, Kerguelen2014, was deployed on the Southern Kerguelen Plateau at 62° 23.0’ S, 81° 49.0’ E at an approximate depth of 1800 m. These locations comprise the SOHN recording sites for IWC management area IV, and are in similar locations to acoustic recording sites used by the AAD in 2004 (Casey) and from 2005-2006 (Kerguelen) (Gedamke et al., 2007). Casey2014 yielded underwater acoustic data from 25 Dec 2013 – 09 Dec 2014. Kerguelen2014 yielded underwater acoustic data from 22 Feb 2014 to 23 Jan 2015. Recorders operated continuously throughout the deployment at a sampling rate of 12 kHz.

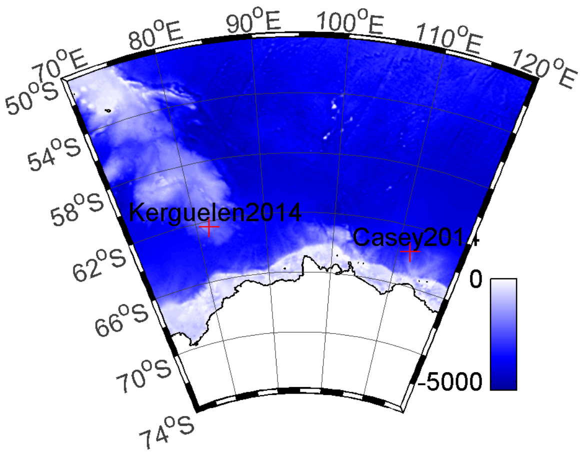

Figure 2 - Map of Antarctic deployment locations of AAD moored acoustic recorders in 2014.

For each recorder, the power-spectral density, PSD, was calculated for 1-hour long time periods using Welch's method (Welch, 1967) as implemented in Matlab version 2014a. The length of the FFT was 16384 with no overlap between samples, and a Hann window was applied to the 16384 FFT samples. PSD measurements were calibrated by applying the factory-calibrated hydrophone sensitivity, the measured voltage limits of the analog-digital converter, the gain of the preamplifier, and the frequency response of the frontend bandpass filter. Calibrated PSD slices were assembled and viewed as a long-term spectral average, and seasonal bands of energy that were potentially attributable to marine mammals were identified. Visual inspection of the spectrograms was conducted at the times of peak-energy to confirm the presence of vocalisations from the putative species believed to be associated with that band.

Wind Speed Measurements

For each recorder, measurements of wind speed were obtained from the Blended Sea Winds database (Zhang et al., 2006). The Blended Sea Winds database contains a spatial resolution of 0.25°, and a temporal resolution of 6 hours. Wind speeds at the four points nearest to the recorder location were extracted for each recorder and the maximum of these was used as input for Equation (3).

We used measured wind speeds as input to the noise model below, and compared the modelled noise levels over the band 950-1050 Hz to those at each of the recording sites. We also investigated whether there was a relationship between wind speed and sound level in the band around 200 Hz. Wind speed measurements were sampled at 6 hour intervals (see below), so we used the mean PSD surrounding the time of each wind speed measurement as our measured value when investigating the relationship between wind speed and sound level.

Noise model

We used the model of Knudsen et al., (1948; as described in Lurton, 2010) to predict wind-dependent surface noise, N_{surf}, at 1 kHz:

$$N_{surf}(f) = 44 + 23 \log_{10}(v + 1) - 17 \log_{10}(f); \qquad \text{if } f > 1 \text{ kHz} \qquad (1)$$

$$N_{surf}(f) = 44 + 23 \log_{10}(v + 1); \qquad \text{if } f > 1 \text{ kHz}$$

Where v is the wind speed in m/s and f is the acoustic frequency of interest in kilohertz. This model is traditionally used as a standardized reference level when evaluating sonar performance regardless of its actual physical accuracy. It is generally applicable for frequencies from 1 to 100 kHz, but may not appropriate at frequencies below 1000 Hz (see discussion).

For a widespread diffuse noise source such as wind-driven noise, the propagation effects are believed to depend primarily on the depth of the hydrophone (Lurton, 2010). We applied the formula of Lurton (2010) to account for these propagation effects:

$$PL = a_f d - 10 \log_{10}(1 + a_f d/8.686) \qquad (2)$$

Where PL is the propagation loss in dB, a_f is the absorption coefficient (Fisher and Simmons 1977), and d is the depth, in metres, of the hydrophone. Depths of recorders were used as input to the propagation loss model for wind-dependent noise. Predicted propagation loss at each frequency was subtracted from the predicted surface noise at that frequency:

$$NL(f,d) = NL_{surf} - PL \qquad (3)$$

Ice Cover Measurements

Measurements of ice cover were obtained from the AMSR2 data set (Spreen et al., 2008). For each recorder the total proportion of ice cover was calculated in within a 50 km radius of the recording site. Data on sea ice cover were available as daily measurements, so mean daily sound levels (i.e. the average of 24 of the 1-hour PSD time periods) were used when investigating the relationship between ice-cover and sound level.

A linear relationship was fit between the sound level in dB, and the proportion of ice cover. A separate curve was fit for each combination of frequency band and recording site. Due to time constraints, only three frequency bands were considered: 70-90, 175-225, and 950-1050 Hz.

RESULTS

Long term spectral averages

The long-term spectral averages of both recorders showed seasonal changes in ambient noise levels (Figure 3). Additionally, seasonal occurrence of energy in particular frequency bands could readily be attributed to known vocalisations from different marine mammal species. Seasonal bands of energy at 26 and 18 Hz with peak-energy from May-June were confirmed to correspond to tonal calls from Antarctic blue whales (Rankin et al., 2005). From May-June the frequency bands from 30-20 Hz and 99 Hz showed peaks above background levels, but only at the Kerguelen2014 site. Inspection of raw audio confirmed the presence of calls that match previously described "20 Hz" calls (Gedamke and Robinson, 2010; Gedamke, 2009) of fin whales. Close inspection of the band from 100-200 Hz from July-October revealed the presence of recently identified (Risch et al., 2014) calls of Antarctic minke whales. Energy in the band between 300-400 Hz from Dec-Jan matched with known calls of pinnipeds (Van Opzeeland et al., 2010), and cursory inspection of this time-frequency band revealed calls predominantly from leopard seals.

Inspection of a few hours of audio from the faint band between 200-300 Hz from late April-early June on the Kerguelen recorder did not readily yield a definite classification (Figure 4). The timing of peak-energy in this band corresponded to that of peak energy in the band for fin whales, and a "chorus" was present (i.e. energy was continuously elevated compared to adjacent frequencies such that the start and end of individual calls could not be discerned). The frequency of this band is nearly double that of the 99 Hz fin whale call-component and initially it was thought this might represent a harmonic. However, inspection of an hour of calling (an admittedly insufficient duration) revealed both unidentified calls as well as humpback whale song. The small amount of humpback whale song that was inspected had only a small amount of energy between 200-300 Hz, while the unidentified calls were largely in the 200-300 Hz band. More work is required to determine whether these unidentified calls are attributable to humpbacks. Sei whales are also known to produce similar shaped calls in this frequency band, though they have seldom been recorded and hardly anything has been reported about their seasonality (McDonald et al., 2005).

While not visible in the long-term spectral averages, echolocation clicks, burst pulses, and whistles, most likely from killer whales, were audible during inspection of various portions of audio. Similarly "usual" echolocation clicks from sperm whales were also audible when inspecting some of the other low-frequency bands.

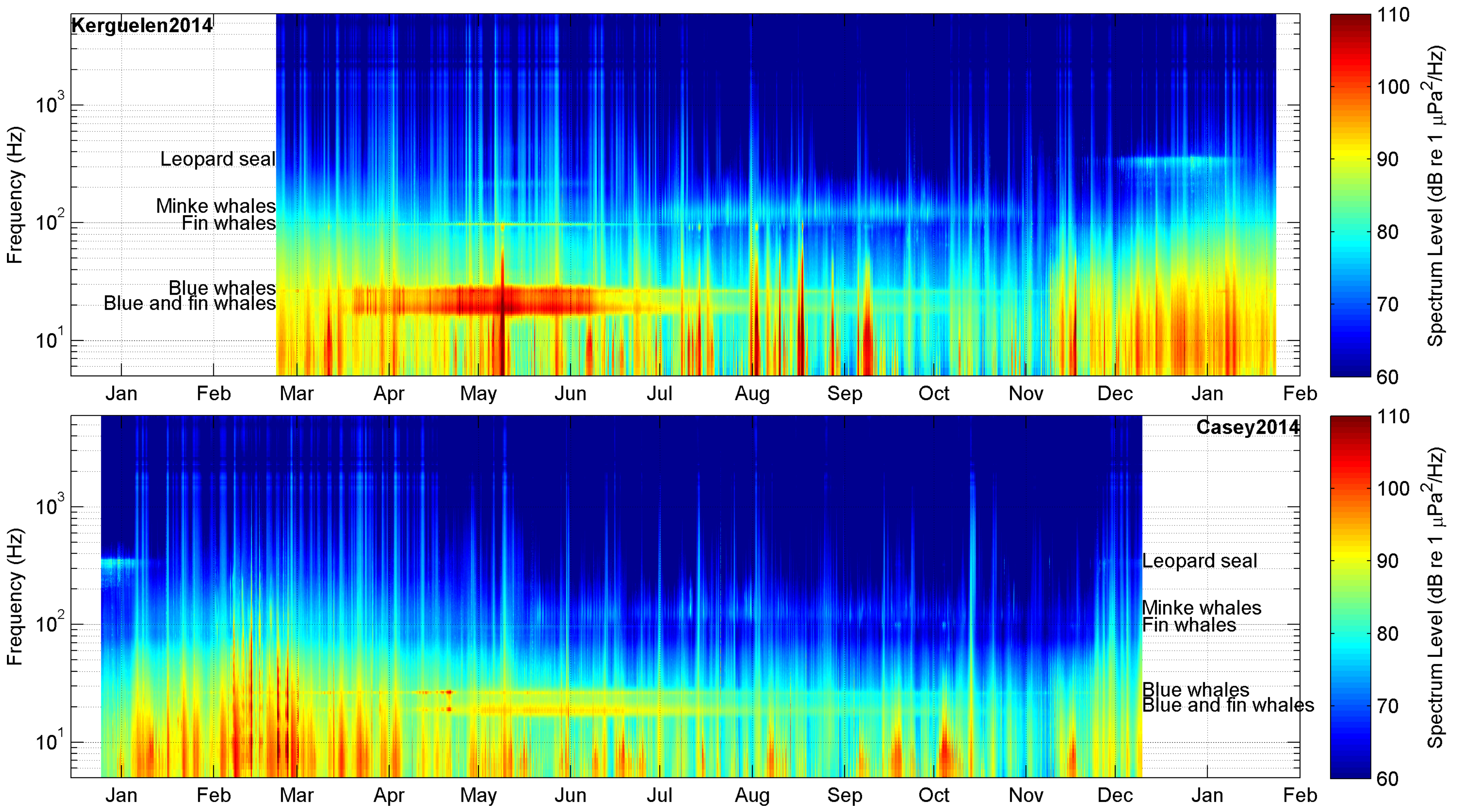

Figure 3 - Long-term spectral averages for Kerguelen2014 (top) and Casey2014 (bottom) recording sites. Seasonal bands of energy at 26 and 18 Hz with peak-energy from May-June are from Antarctic blue whale song calls. The bands from 30-20 Hz and 99 Hz that also peak in May-June on the Kerguelen2014 site are from fin whale "20 Hz notes". The seasonal band of energy from Jul-Aug from 100-200 Hz are from Antarctic Minke whale calls (AKA bioduck). Leopard seal trills between 300-400 Hz show peak energy from Dec-Jan.

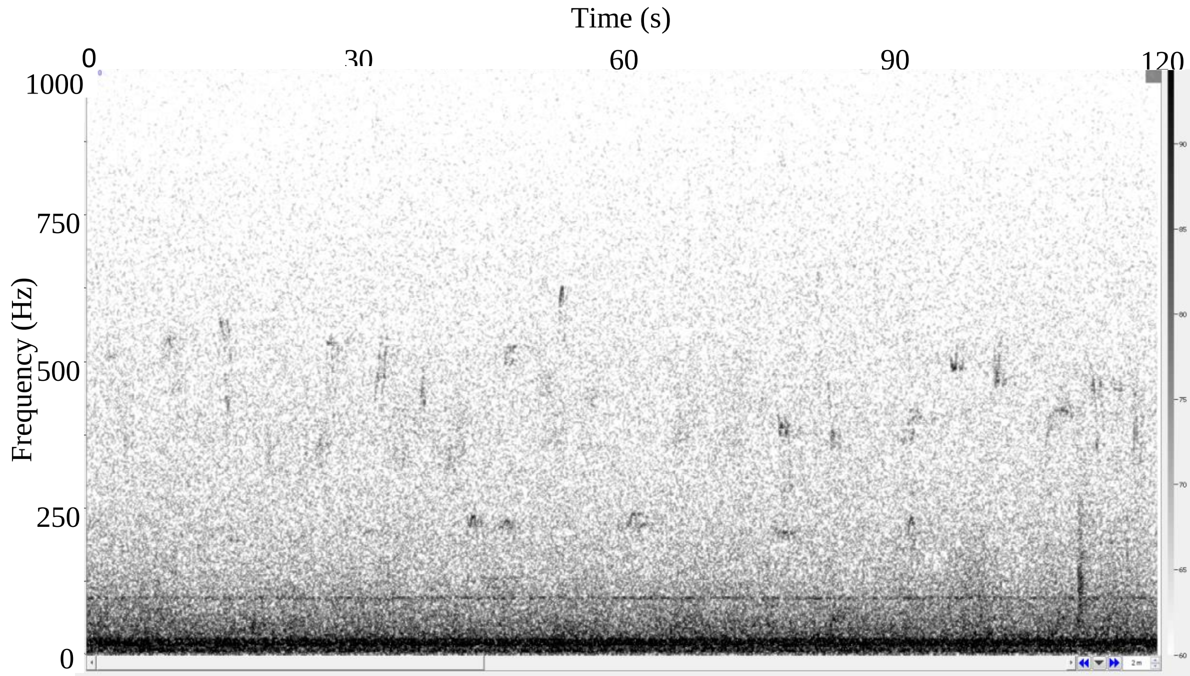

Figure 4 - Spectrogram of fin whale chorus from 20-30 & 99 Hz and unidentified calls with energy between 200-300 Hz. Likely sources for the unidentified calls include humpback and/or sei whales. This spectrogram is from May 7 2017 at the Kerguelen recorder.

Wind speeds

Wind speeds were not evenly distributed, with both sites having mean wind speeds around 8 m/s and few occurences of wind speeds below 5 m/s and above 10 m/s (Figure 5). Blended wind speeds were not available from June – December at either location, so the relationship between modelled and measured sound levels could only be tested during Austral summer and autumn (Figure 6). Sound levels were generally lower in Austral winter and spring than in summer and autumn (Figure 6).

When wind speed data were available there was reasonable agreement between measured and modelled sound levels at 1 kHz for both recording sites (Figure 7). We also found a relationship between wind speeds and sound levels at low frequencies, though levels were higher than predicted by our extremely simple model of wind-driven noise (Figure 7).

Ice cover

The distribution of ice cover was bimodal with peaks at zero (ice-free) and one (fully covered) for both recording sites. The Casey site had more days fully covered than the Kerguelen site (Figure 5).

There was a strong inverse correlation between the proportion of the area covered by sea ice and the sound levels at the three frequency bands investigated and at both sites. When ice fully covered the 50 km radius around the recorder levels were 6-9 dB lower than in ice-free recordings at all bands and sites (Figure 8). On average, curve fits yielded the best correlation coefficient at the lowest frequency band, and the worst correlation coefficients at the highest frequency band.

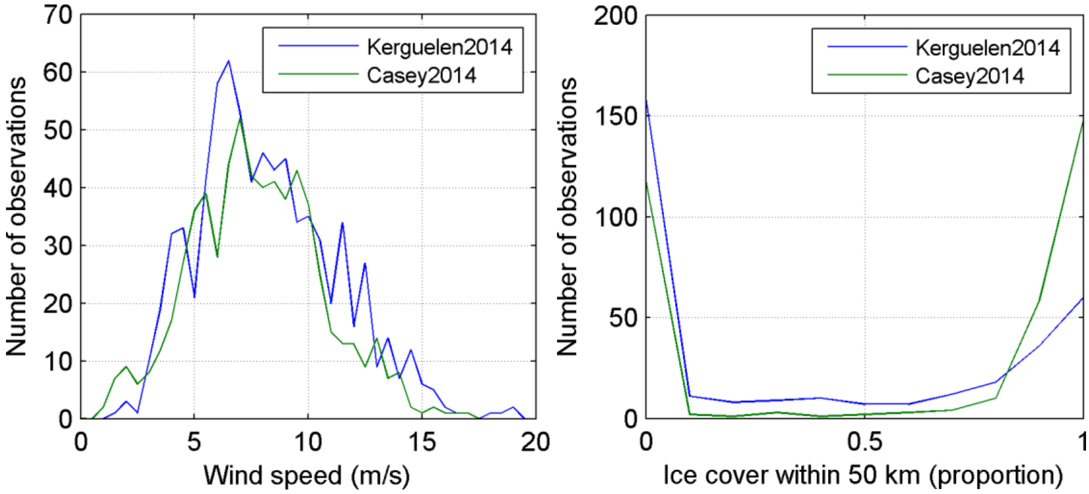

Figure 5 – Distribution of wind speeds from the Blended Sea Winds Database and ice cover from AMSR2 measured at two Antarctic recording sites.

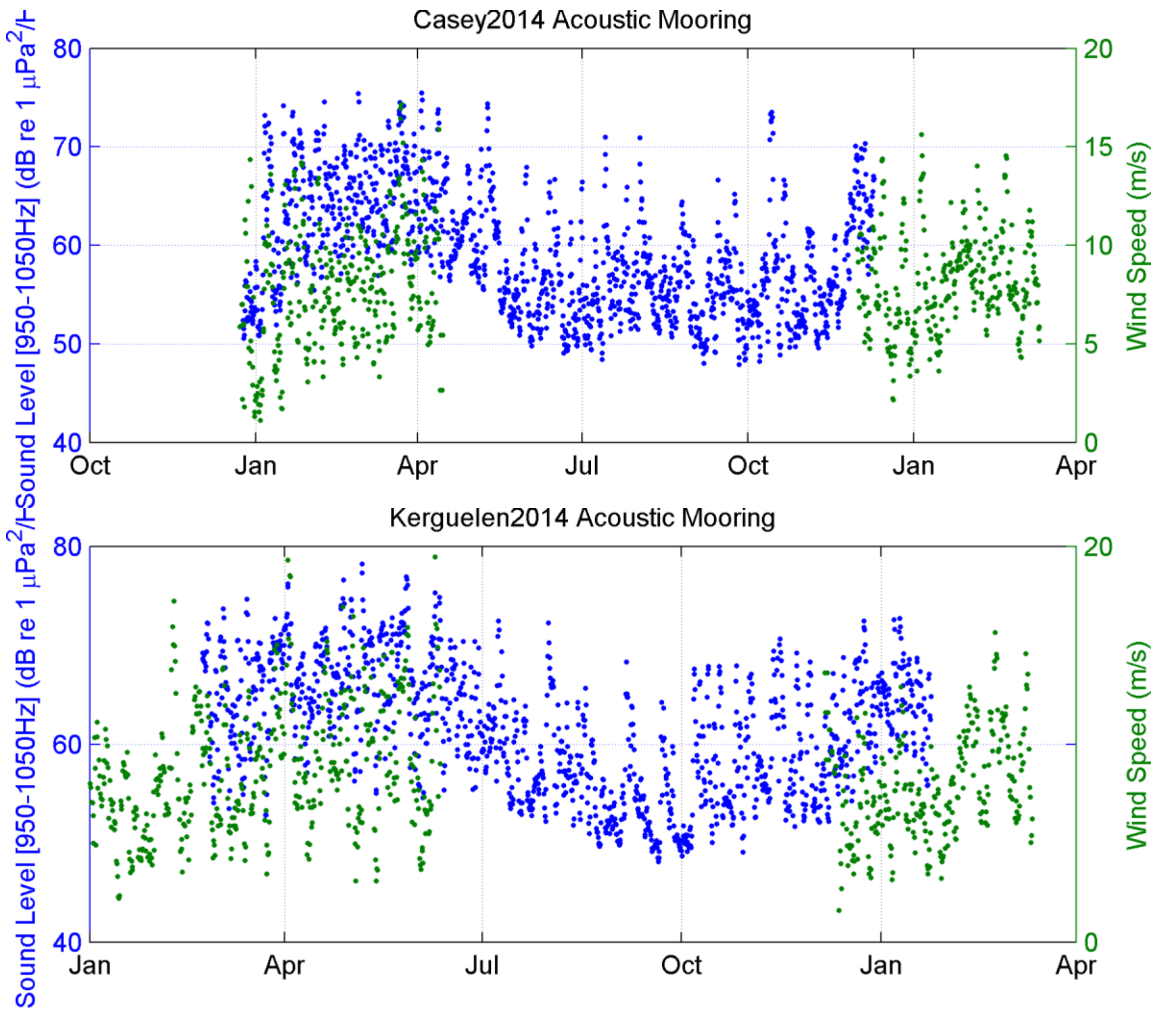

Figure 6 - Time series of wind and sound level measurements at 1 kHz for two deep water Antarctic recording sites.

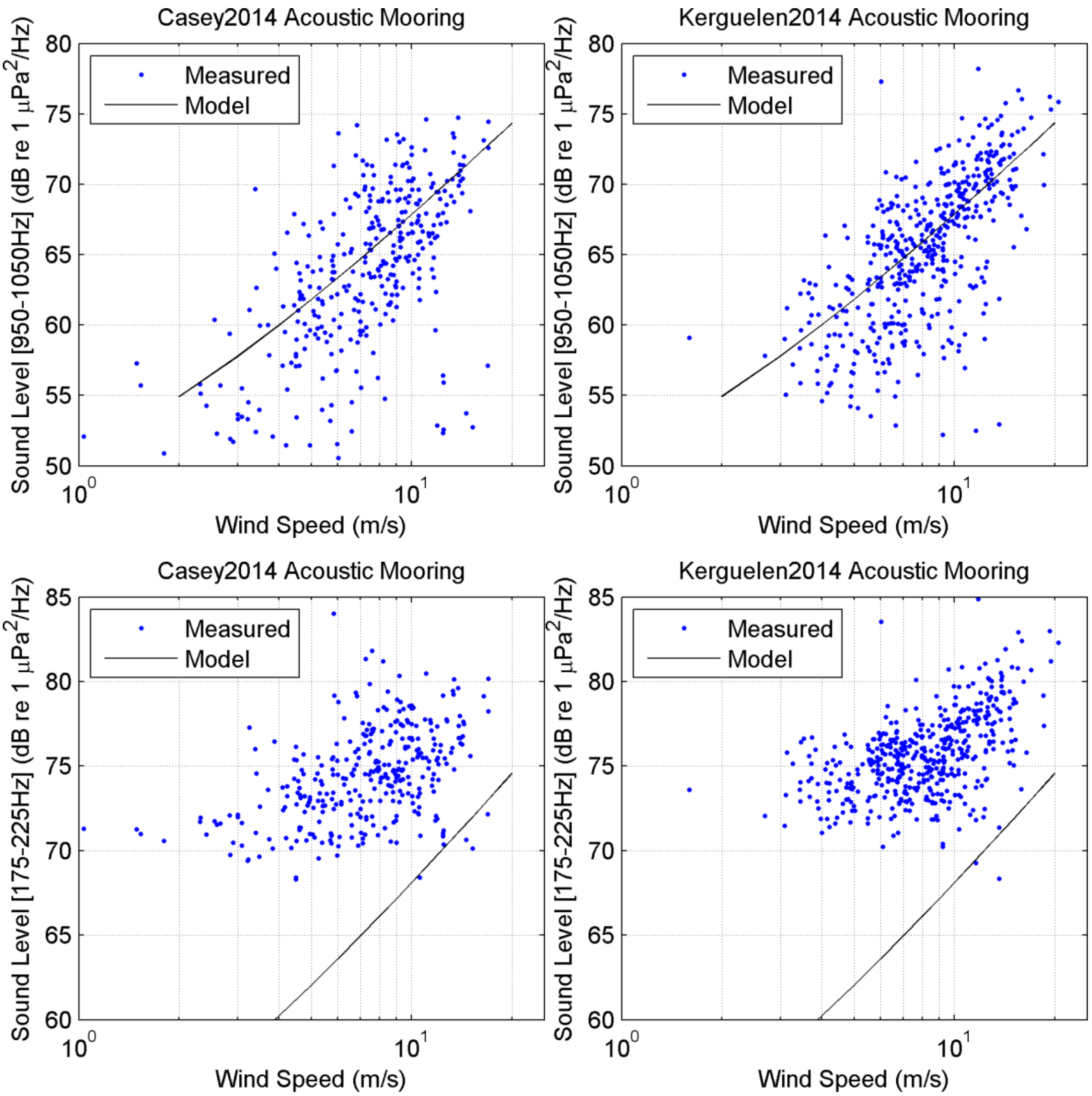

Figure 7- Measured and modelled sound levels around 1 kHz (top panels), and 200 Hz (bottom panels) as a function of wind speed at two different, deep underwater Southern Ocean recording sites.

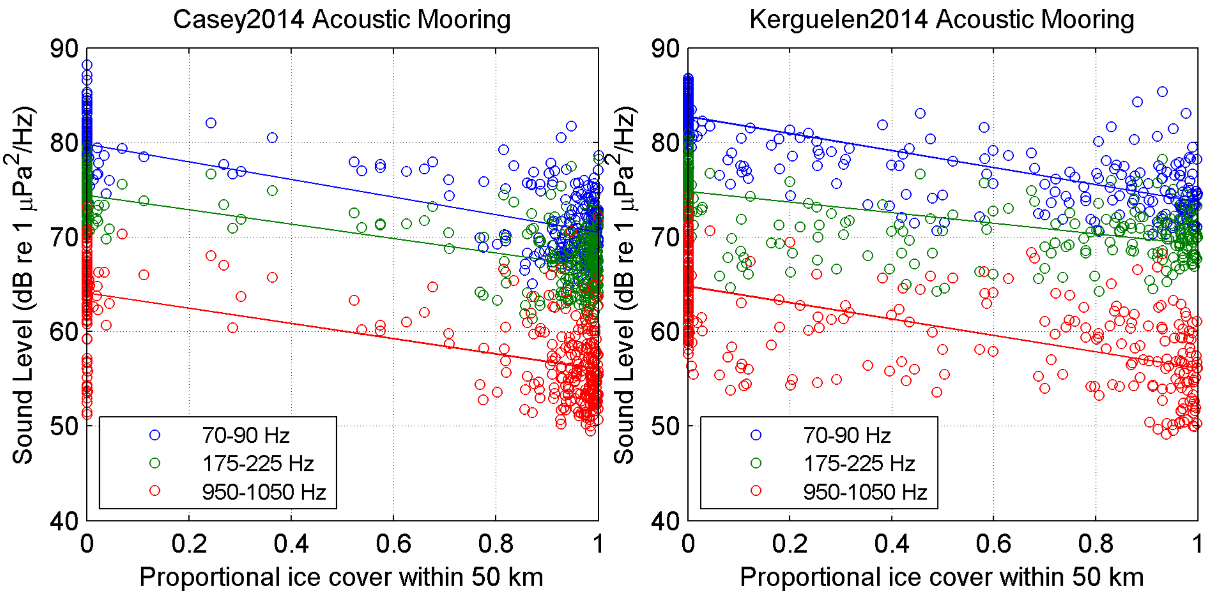

Figure 8 - Measured sound levels as a function of proportion of the area covered by ice within a 50 km radius. Bottom panels show levels at 200 Hz while top panels show levels at 1000 Hz. The left panels show the Casey recording site, while the right panels show data from the Kerguelen Plateau site. Ice cover was measured using data from AMSR2 (Spreen et al., 2008)

Table 1 – Slope, intercept, and correlation coefficients for linear curve fits between sound levels and proportion of area within a 50 km radius covered in sea ice.

Band (Hz)	**Site**	**Slope (dB/proportion covered)**	**Intercept (dB)**	**Correlation coefficient (R)**
70-90	Casey2014	-9.28847	79.7833	0.791832
	Kerguelen2014	-8.99579	82.7339	0.815596
175-225	Casey2014	-7.64684	74.4018	0.767562
	Kerguelen2014	-5.61112	74.815	0.6483
950-1050	Casey2014	-8.04849	64.0627	0.656984
	Kerguelen2014	-8.67733	64.7962	0.656981

DISCUSSION

The results here represent an extremely preliminary analysis of sounds recorded in 2014 in Eastern Antarctica by fixed long-term passive acoustic recording devices for the SOHN. Despite the cursory nature of this preliminary analysis, the results reveal a rich and high-quality dataset. These preliminary results also help to illustrate how developments in acoustic recording devices have expanded capabilities and improved upon the quality of underwater recordings. The ability to record continuously should allow for a smaller coefficient of variation when comparing acoustic detections within and among recording sites (Thomisch et al., 2015). The increased bandwidth of these new recorders (6000 Hz compared to 250 Hz from prior ARP deployments) allows for monitoring of additional species such as humpback, sperm, and killer whales as well as pinnipeds. Lastly, the use of calibrated acoustic recorders with noise floor below sea-state zero allows for robust investigation of ambient noise, e.g. the relationship among sound levels, wind-driven noise, and ice noise.

As has been found at locations throughout the world's oceans, wind-dependent surface noise at 1 kHz was strongly correlated with sound levels at both of our Antarctic recording sites. Because it is likely to be a major source of ambient noise on all Antarctic recording devices, wind-driven surface noise at 1 kHz may provide a useful check of the calibration of historic and future Antarctic recordings. At 200 Hz, wind speed and noise levels were also correlated when wind speeds were greater than 5 m/s. This suggests that wind-driven surface noise, rather than shipping, is indeed a major source of ambient low-frequency noise in the Antarctic. This relationship appears qualitatively similar to the "Cato curves" described for Australian waters with low shipping traffic (Cato and McCauley, 2002).

The relationship between wind-speed and sound levels have only been investigated during austral summer and autumn, and could not be tested during winter or spring due to a lack of observations of wind speed. Use of an alternative source of sea wind data, e.g. NCEP2, may allow for more detailed investigation of these relationships in austral winter and spring. Additionally, sea-wind data from winter and spring are required to investigate the relationship between sound levels and the combined effect of sea-ice cover and wind. Possible explanations for the missing sea-wind data (listed in order of increasing likelihood) include poor satellite coverage, a user-error in reading or interpreting the data, or that data from the blended sea-winds database are simply unavailable when sea-ice is present. Cursory inspection suggests that the time periods missing sea wind data matches those with ice-cover, however further investigation of the limitations of the Blended Sea Winds is required to determine the nature of the cause(s) of the missing wind speed data.

Ice-cover is known to alter the ambient sound levels (Buck, 1966; Kibblewhite and Jones, 1976), but there are fewer reported studies sound levels in deep water underneath sea ice. The process of wind-driven surface noise likely arises from bubble formation and breaking waves, and these mechanisms do not occur when the surface is covered by ice. The relationship that we found among sound levels, ice cover, and acoustic frequency suggesting that ice-cover may be better correlated with sound levels at lower frequencies. However, due to time constraints in this preliminary study we only considered three narrow frequency bands, and a single area for estimating ice cover. Using a smaller radius when considering the area covered by ice may yield a better correlation coefficient given the greater absorption of sound by seawater as a function of distance at higher frequencies. Thus, further analysis across the entire spectrum and more robust consideration of metrics for ice-cover are both warranted. Similarly, further work is required to investigate the *interactions* between wind and ice and the effects on sound level.

Further analysis of acoustic data from these sites will focus on more robust methods for determining the presence of marine mammals. This will likely involve creation of libraries of annotated recordings for quantifying the performance of automated detectors and for training and testing machine learning algorithms for detectors. Eventually, the presence of marine mammal species at these SOHN recording sites will be compared with that from other SOHN recording sites throughout the Antarctic.

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