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Sound Decisions: Moving forward with Acoustics

Icebergs and storms in the Southern Ocean as sources of low frequency noise along Australian southern coasts

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ABSTRACT

Owing to the cold waters south of the Antarctic Circumpolar Current, sound from sources near the ocean surface can efficiently couple into the sound channel and be ducted northwards to far distances. Recent research has shown ice-breaking and iceberg calving in Antarctica and the Southern Ocean as significant contributors to low frequency noise in the south Indian, Atlantic and Pacific Oceans. The Southern Ocean is also well known for its strong westerly winds (known by sailors as the “furious fifties” and “screaming sixties”) due to the combination of air flow from the Equator towards the South Pole, the Earth's rotation, and the scarcity of landmasses to serve as windbreaks. It was suggested 30 years ago that strong winds in the Southern Ocean were the distant sources of low-frequency noise observed in the deep temperate oceans at low latitudes. In this paper, we examine the characteristics of low-frequency ocean noise recorded off Australian coasts and their relationship with ice-breaking and winds in the Southern Ocean. Significant correlation was found between the low frequency noise levels and wind speeds south of the Antarctic polar front for some but not all situations. Whilst more comprehensive analysis is needed to draw definite conclusions, wind storms in the Southern Ocean may contribute to the low frequency noise floor observed at sites off Australian coasts where the sound propagation path from Antarctica is not blocked by land or shallow seabeds.

1 INTRODUCTION

Under the Integrated Marine Observing System (IMOS) passive acoustic observatory program (IMOS, 2019), sea noise data were collected near the continental shelf-break southwest of Kangaroo Island from December 2014 to October 2017 using autonomous recorders set on the seafloor at a water depth of about 170 m. Figure 1 shows the Power Spectral Density (PSD) levels of sea noise averaged in 1/3-octave bands at five different percentiles from aggregated data in summer (February 2015, 2016, 2017) and winter (August 2015, 2016, 2017).

The peaks around 1.2 kHz are from fish sounds (resonances of fish swim-bladders) and the peaks around 20 Hz are from vocalisations of blue and fin whales. The large differences between the percentiles at higher frequencies is due to the fluctuating local wind speeds within the respective months.

The focus of this paper is the noise at the lower frequencies. Below 80 Hz the ambient noise levels are persistently high at all percentiles, which could not be explained by local winds because:

(1) the low-frequency noise level is higher in summer (February) than in winter (August), whereas the local winds are stronger in August than February;
(2) to generate the median low-frequency noise levels observed in summer, e.g., 83 dB re 1 µPa2/Hz at 40 Hz, the local wind speeds need to be about 50 knots [Zhao et al, 2014], whereas the median wind speed in the region in February is about 15 knots [Wentz et al, 2015].

The persistently high levels at all percentiles could not be explained by ship noise either. To generate the median low-frequency noise levels shown in Fig.1, “heavy shipping” density is required (Urick, 1983), which is not the case according to Automatic Identification System (AIS) data from the Australian Maritime Safety Authority. Furthermore, examination of the recordings shows identifiable noise from ships only on rare occasions.

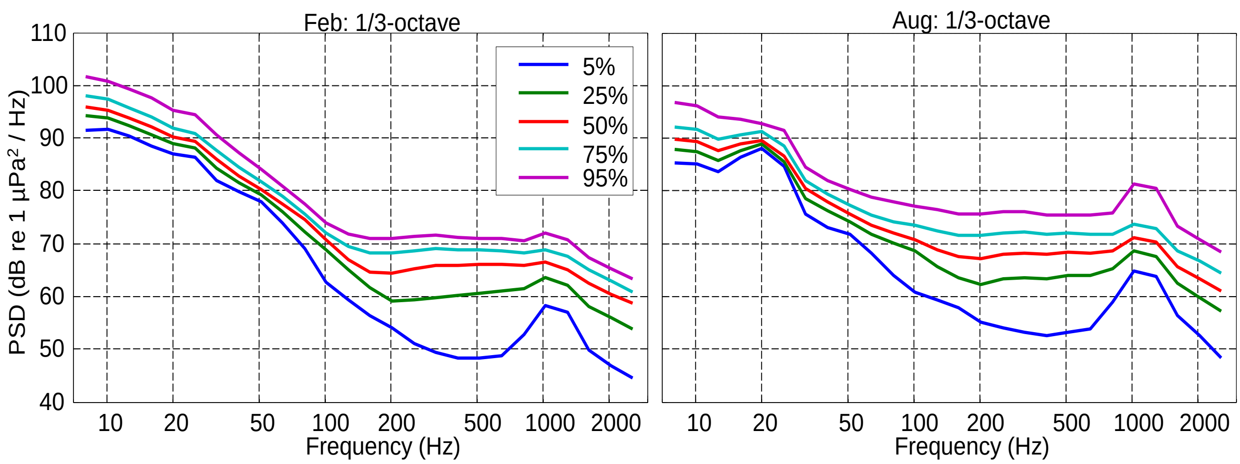

Figure 1: PSD levels of sea noise averaged in 1/3-octave bands at five different percentiles from monthly data in February and August aggregated over three years.

Another feature of the low frequency noise is its seasonal variation. Figure 2 shows the variation of the noise level in 30 to 80 Hz band, low-pass filtered with a median filter of one week length, which excludes the contribution of blue and fin whale sounds in the roughly 15-30 Hz band. It shows a regular pattern: a maximum in February-March each year and minima from July to October. A similar seasonal pattern has also been observed in 15 years of noise data collected by the International Monitoring System (IMS) of the Comprehensive Test-Ban Treaty Organization (CTBTO) at the hydroacoustic station HA01 southwest of Cape Leeuwin (Harris et al, 2019).

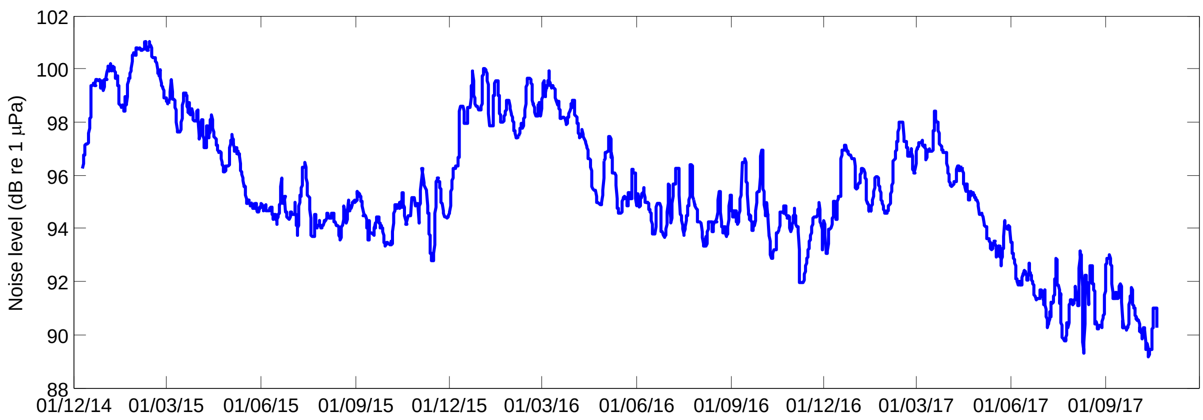

Figure 2: Weekly median underwater noise level averaged in the 30-80 Hz band from December 2014 to October 2017.

We examine two possible explanations for the sources of the persistently high level noise at low frequencies and their seasonal variation: strong winds in the Southern Ocean and ice/iceberg breakup events near Antarctica. The oceanography in the Southern Ocean provides favourable conditions for such noises generated at the sea surface to propagate over long distances to the temperate ocean, and the seasonal variation of the low frequency noise is consistent with the seasonal variation in the sea ice extent and the intensity of ice breakup activity in Antarctica.

2 METEROLOGY AND OCEANOGRAPHY IN THE SOUTHERN OCEAN

There is no universally accepted definition of the Southern Ocean. It is undefined in the third edition of International Hydrographic Organisation (IHO) publication “Limits of Oceans and Seas”, where the Atlantic, Pacific and Indian Oceans extend to the Antarctic Continent (IHO, 1953). A draft fourth edition of IHO publication defines the Southern Ocean as the body of water extending from the coast of Antarctica to the line of latitude at 60 degrees South (IHO,2002). This paper uses the definition of the Australian Hydrographic Office, which includes the entire body of water between Antarctica and the south coasts of Australia and New Zealand, and up to 60°S elsewhere (AHO, 2019).

The Southern Ocean has some meteorological and oceanographic features that are particularly relevant to the generation and propagation of underwater sound in the ocean. A prominent meteorological feature is the strong circumpolar westerly wind (known by sailors as the 'furious fifties'), which is caused by the combination of air being displaced from the Equator towards the South Pole, the Earth's rotation, and the scarcity of landmasses to serve as windbreaks (Fig.3). The winds are particularly strong within the Indian Ocean and Australian sectors (Gille and Gordon, 2019).

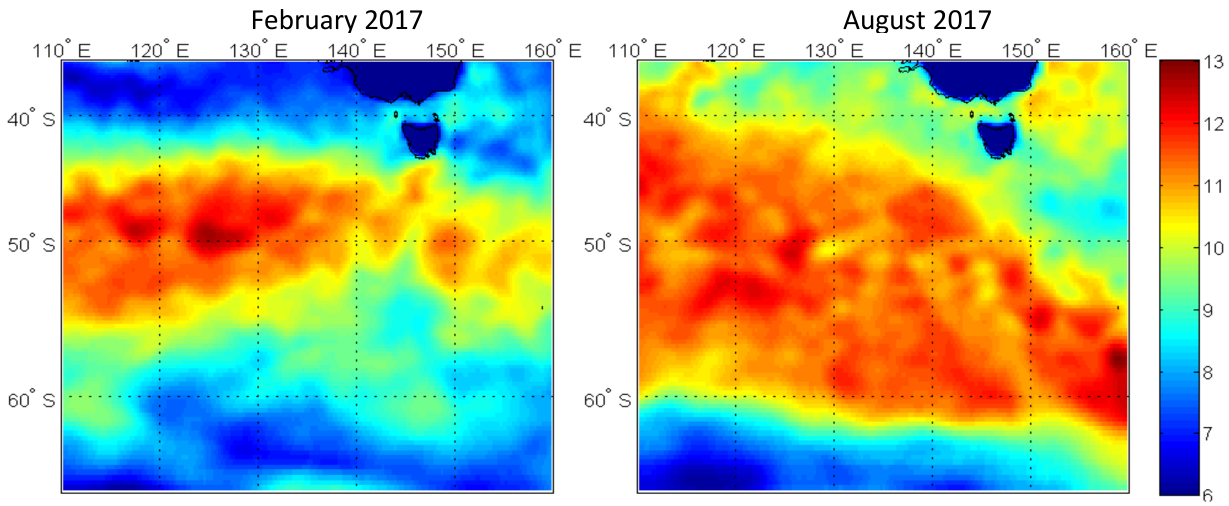

Figure 3: Monthly averaged wind speed (m/s) at 10 m above the sea surface in February and August 2017 (data from CCMPv2 database, Wentz, 2015).

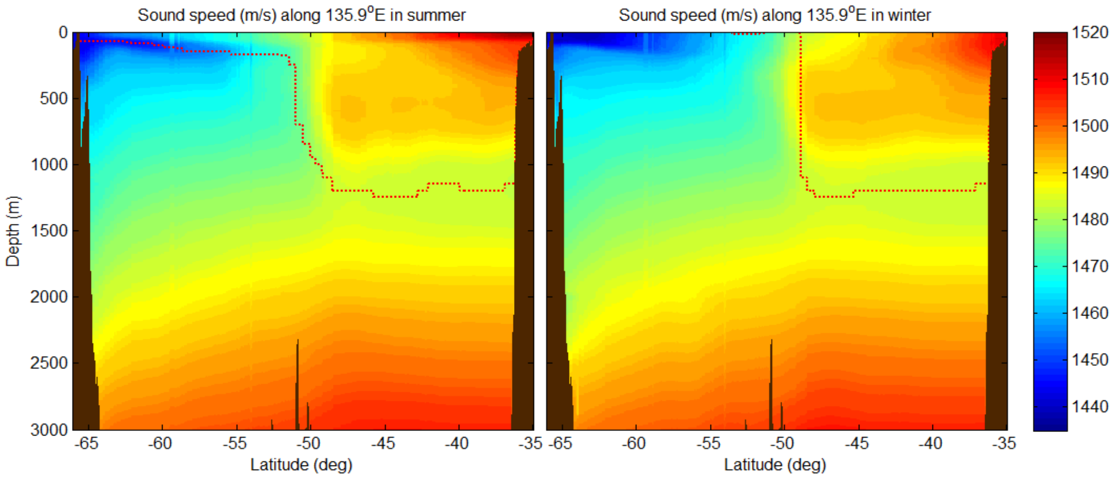

Figure 4: Sound speeds along longitude 135.9°E computed from summer (left panel) and winter (right panel) climatology of the World Ocean Atlas 2013. The red dashed lines show the minima of the vertical sound speed profiles (sound channel axis). The rapid sound speed variation between 50°S and 55°S agrees well with studies on the Antarctic Circumpolar Current (ACC) south of Australia, where at 136°E, the Sub-Antarctic Front and the Polar Front occur at about 50° S and 55°S respectively (Sokolov and Rintoul, 2007, 2009).

The persistent, strong westerly winds drives the eastward Antarctic Circumpolar Current (Gille and Gordon, 2019) within a latitudinal range from 45 to 65°S and the associated various fronts (Rintoul and da Silva, 2019), where the cold, less saline Antarctic water meets the warmer, high-salinity waters to the north, leading to strong spatial variation in temperature, salinity, and hence sound speed. Across the ACC from the north, the sound channel axis ascends from over 1000 m depth to the surface, with a more rapid transition in winter than that in summer (Fig.4).

Ambient noise generated by strong winds and ice events, where the sound channel axis is near the sea surface, can efficiently couple with the deepening sound channel and be ducted northwards. Low-frequency noise in the sound channel can propagate over great distances because of low surface and bottom interaction losses, cylindrical spreading of energy that are much slower than spherical spreading, and low absorption losses at low frequencies.

Further south, along the continental shelf around much of Antarctica, there is a westward/counter-clockwise Antarctic Coastal Current which is driven by cold air descending from the south pole and flowing westward due to the Coriolis force (Baines, 2006; Alder et al, 2017). The Antarctic Coastal Current is also called Antarctic Counter Current (ACoC), because it is counter to the direction of the ACC (Stern et al, 2016, Thompson et al, 2018). The Antarctic Coastal Current and Antarctic Circumpolar Current affect the movement of the near-shore and off shore pack sea-ice and icebergs (Tournadre et al, 2016).

3 OCEAN NOISE FROM THE SOUTH

The ocean noise recorded off the Australian coast and in the south Indian Ocean contains both low frequency transients and ambient noise backgrounds. Studies on noise directionality of both types of noise indicate they are generated in the south, and localisation of the acoustic transients indicates they originated near Antarctica.

3.1 Location of Acoustic Transients from Ice-breaking

There are two forms of ice around the Antarctic continent: (1) glacier-fed semi-permanent ice shelves, which slowly move outwards and produce icebergs (“calving”), which in turn calve into smaller icebergs, and (2) land-fast ice and pack ice from sea-water, which annually freezes and melts along the coastline.

Various ice-related processes in Antarctica generate underwater noise of different waveforms and frequencies. The acoustic signature of iceberg calving, which involves various stages with different time and frequency characteristics, has been studied at close range (Pettit, 2012; Glowacki, et al, 2015). Several studies localised the sources of acoustic transients and associate them with the calving/breaking or grounding of satellite-tracked large icebergs over thousands of km away (Chapp et al, 2005; Muller et al, 2005; Tanlandier et al, 2006).

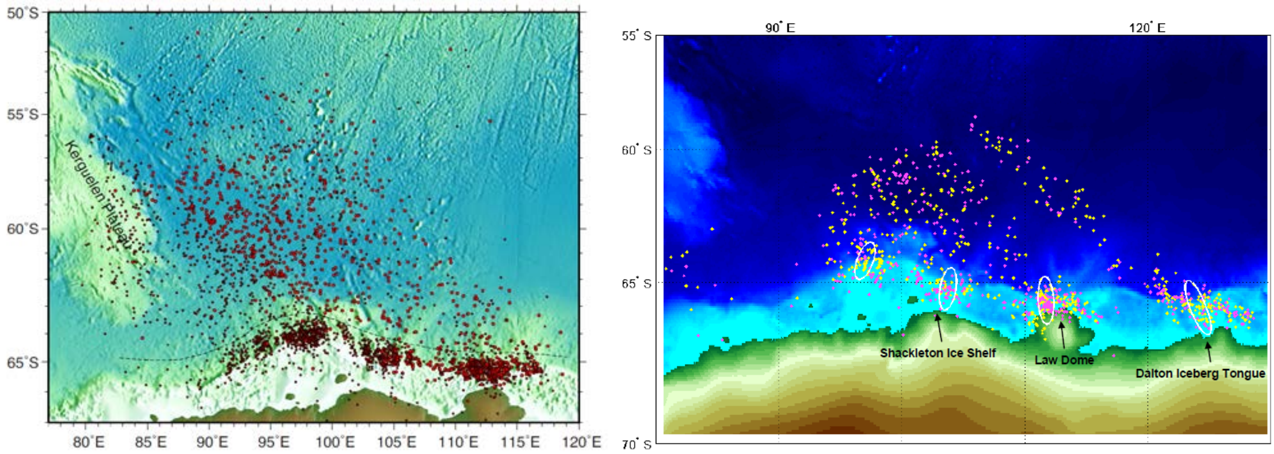

Figure 5: (left, a) Geographic distribution of acoustic events detected and localised between 1 October 2006 and 31 January 2008 by an array of temporary and permanent (CTBTO) hydrophones located in the Indian Ocean (Royer et al, 2015). (right, b) Location of acoustic events detected at two CTBTO stations in 2002 (yellow dots) and 2003 (light magenta dots). Error ellipses show typical regions of 95% confidence level (Gavrilov and Li, 2011).

Figure 5 shows the distribution of acoustic events localised in the Indian Ocean by different hydrophone arrays in different years. Figure 5a shows over 3600 detected events, with different seasonal trends observed for events from the Antarctic margin, compared to those from drifting icebergs at lower (up to 50°S) latitudes. Most events (2085) cluster within 100 km from the Antarctic continental shelf (south of the dashed line in Fig 5a). These events may be related to iceberg calving, colliding and rubbing as they drift counter-clockwise around Antarctica within the Antarctic Coastal Current, which moves counter to the eastward Antarctic Circumpolar Current to the north. Some wander into the ACC in the north (shown north of the dashed line), break up into smaller bergs due to the warmer water and disintegrate over a number of years. The near shelf events occur from late Summer to early Spring, whereas the icebergs drifting in the ACC mostly crack and disintegrate in the summer and are many fewer in the winter.

An iceberg calved from a glacier usually begins by moving westward with the Antarctic Coastal Current, with the coastline on its left. The Coriolis force owing to Earth's rotation also slightly turns its trajectory to the left into the southward direction, which may cause the icebergs to run aground or remain close to the coast. Icebergs tend to break away from the coastal current and enter the Antarctic Circumpolar Current in four well-defined longitudes ranges, so-called "retroflection zones": one of them is near the Kerguelen Plateau at longitude around 90°E (Merino et al, 2016; Stern et al, 2016).

Icebergs in the Antarctic Circumpolar Current generally go eastward, driven by both the current and the wind. Also, the Coriolis force pushes the icebergs slightly northward, making them move in a northeast direction, to finally disintegrate in relatively warm waters at low latitudes (Barbat et al, 2019).

A detailed discussion of these processes and their differences is beyond the scope of this paper, but we note that the distribution of the acoustic events in Fig.5 closely matches the spatial distribution of open-ocean free icebergs estimated by satellite remote sensing (Tournadre et al, 2012, 2016) and ship observations (Romanov et al, 2017). For example, Tournadre et al. (2012) identified the maximum open ocean iceberg concentration between 65°E and 120°E.

3.2 Direction of Acoustic Ambient Background

Studies on the directionality of the low frequency ambient noise background also indicate that it originates from the South, although the nature of the background is such that no individual events can be identified and localised. Ambient noise interferometry, a technique that extracts coherent propagation waveforms by cross correlating the ambient noise in a pair of sensors, was applied to the noise recorded at CTBTO stations in the Indian Ocean. High amplitude acoustic transients were suppressed by whitening the spectra and clipping the signal amplitudes. The results show that the ambient noise comes from the direction that spans the section of Antarctica's coastline in the direct line of sight from these two hydroacoustic stations (Sabra et al, 2013).

There is a large (up to 20 dB) reduction in the noise level from 5 to 100 Hz recorded from deep to shallow sites along a meridional transect up the Great Australia Bight, which is a result of the energy loss to the shelf seafloor when the noise propagates upslope from the south (McCauley et al, 2016).

3.3 Correlation of Noise with Winds in the Southern Ocean

Over 30 years ago it was also suggested that strong winds at high latitudes in the Southern Ocean were distant sources of low-frequency noise at low latitudes, and preliminary modelling was used to explain some observations in the deep oceans (Bannister, 1986). We test this premise by examining the correlation between wind speeds in the Southern Ocean with the received noise level off Australia coast.

Figures 6 and 7 show the correlation of the wind speed in the Southern Ocean off Australia with the 50% percentile noise level in low and high frequency bands at the Kangaroo Island IMOS acoustic site in Austral summer and winter months. The lower bound was set at 30 Hz to exclude the contribution of noise generated by blue and fin whale vocalisations. In summer, the correlation in the low-frequency band with the wind speed south of latitude 60°S is significant (nearly 0.7, p-value < 0.01), whereas it is very low (<0.3) for the local wind around the site. In winter, the situation is opposite: the correlation is high for winds near the site and low for distant winds south of latitude 45°S. Noise at higher frequencies is mainly generated by local winds and the correlation is high in both summer and winter.

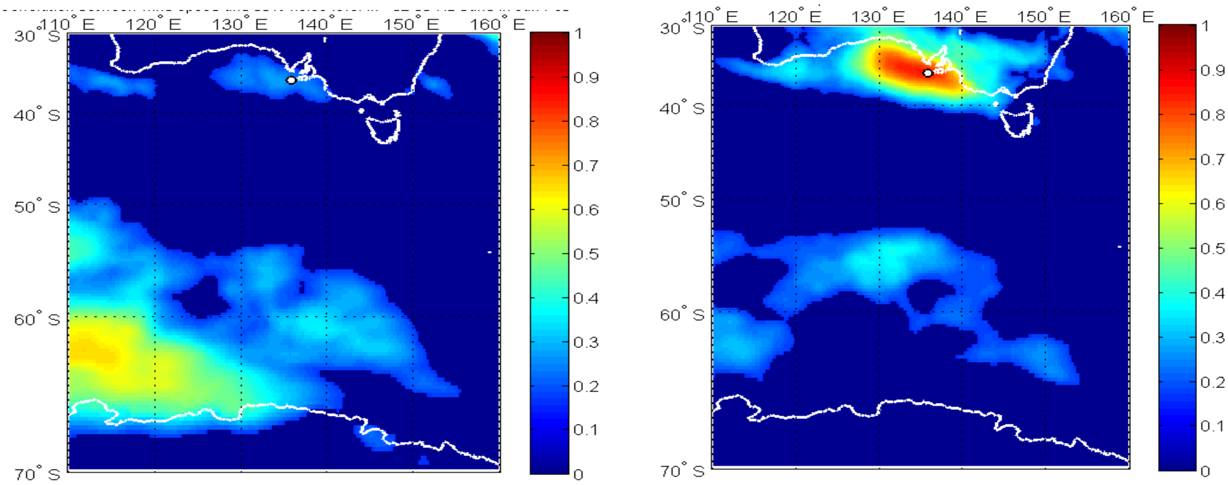

Figure 6: Correlation between wind speed in the Southern Ocean and median noise level recorded off Kangaroo Island (the white dot) in Austral summer (January to February 2017): low frequency (left, 32-50 Hz) and high frequency (right, 50-3000 Hz) band.

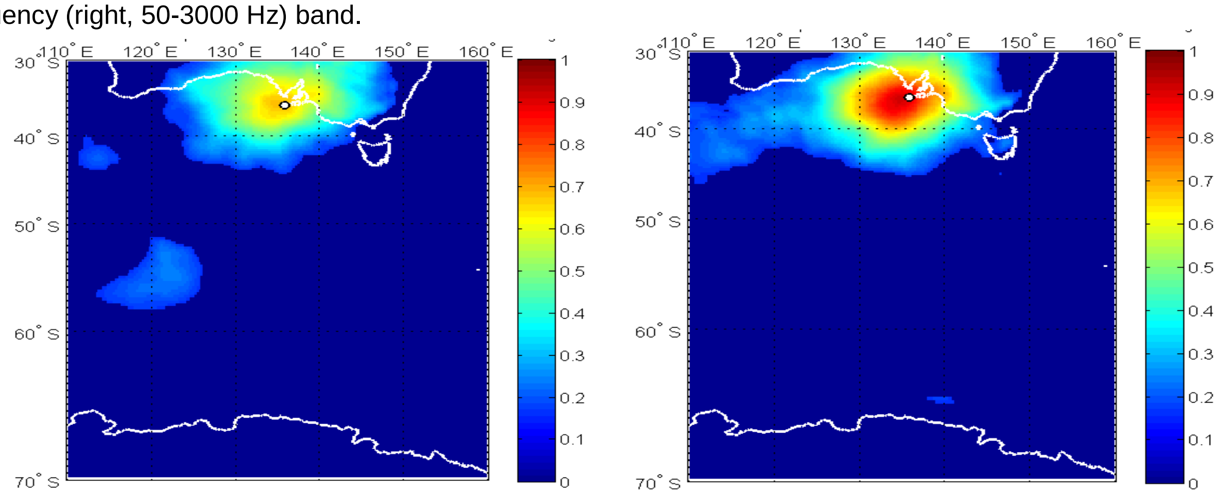

Figure 7: Correlation between wind speed in the Southern Ocean and median noise level recorded off Kangaroo Island (the white dot) in Austral winter (July to August 2017): low frequency (left, 32-50 Hz) band and high frequency (right, 50-3000 Hz) band.

We note that the region of higher correlation of the low-frequency noise in summer in Fig.6 roughly corresponds to the area of detected acoustic events in Fig.5.

3.4 Seasonal Variation of Low Frequency Noise

The seasonal variation of low frequency noise—summer-high, winter-low—shown in Fig. 2 was also observed at CTBTO Cape Leeuwin (Harris et al, 2019) and other Indian Ocean sites (Tsang-Hin-Sun et al, 2015). This can be interpreted as follows.

In summer there is much less sea ice coverage around Antarctica. There is a greater open-water area for wind to generate the underwater noise. For ice-generated noise, in summer warmer air and sea water lead to more calving events from glaciers and icebergs (Tsang-Hin-Sun et al, 2015). There are also greater volumes of free-floating icebergs in the open ocean (Matsumoto et al, 2014) whereas in winter the sea ice traps some of the calved icebergs.

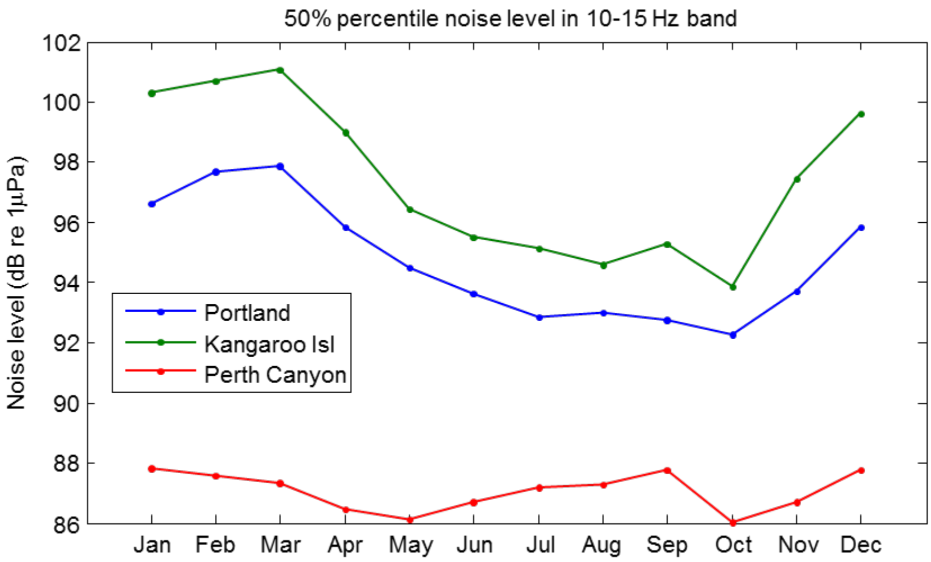

Figure 8: Monthly median noise level in 10-15 Hz band at three IMOS sites around Australia.

Figure 8 shows the monthly median noise level in 10-15 Hz band at three sites of the IMOS passive acoustic observatory program. Both the Kangaroo Island site and the Portland site show seasonal variations of higher levels in summer and lower levels in winter. The low-frequency noise level at the Perth Canyon site is much lower and shows little seasonal variation because the wide continental shelf west of Geographe Bay and Cape Naturaliste blocks most of the noise from East Antarctica.

4 Ocean Noise and Climate Change

The Southern Ocean plays a crucial role in climate change and climate modelling. Because acoustic transients from calving of icebergs and movements of glaciers can be detected at ocean-basin scales, ocean noise data can be used to support research on disintegration of Antarctic ice as an indicator of warming. There is also evidence that climatic factors such as iceberg volumes influence the overall basin-wide low-frequency noise levels. The correlation shown in this paper also indicates a possible link between wind speeds in the Southern Ocean and the low-frequency noise off the Australian coast. Hence measurements of the long-term trends of ocean noise off the Australian coast may be a potentially inexpensive, remote sensing method for studies of long-term trends in ice and wind processes in the Southern Ocean.

Both ocean noise and climate processes have very high intra-annual and inter-annual variability in comparison to their long-term trends, making detection of their long-term trends challenging. Below we briefly mention some results of interest in relation to this discussion.

4.1 Trends in Ocean Noise off Cape Leeuwin

The CTBTO Cape Leeuwin station has been in operation since 2002 and has the longest records of ocean noise data off Australia. Analysis of 15 years (2003-2017) of data shows, after removing seasonal variations, statistically significant reductions in noise levels at all statistical percentiles at frequencies from 5 to 105 Hz, with the noise level at higher percentiles decreasing faster than that at lower percentiles, and the noise in 40-60 Hz band having the greatest decrease, 0.16 dB/year for the median and 0.25 dB/year for the 99 percentiles (Harris et al, 2019).

To look for an explanation of this decreasing trend, let's look at the trends in the potential contributors to the noise: wind in the southern ocean, shipping off southwest of Australia and in the Indian Ocean, and whale vocalisations.

Analysis of global satellite remote sensing data over 33 years from 1985 to 2018 shows an increases in the mean wind speed and significant wave height in most of the world's oceans, with the largest increases in the Southern Ocean (Young and Ribal, 2019). There has been a strengthening of westerly winds in recent decades in the Southern Ocean (Swart et al., 2015).

Preliminary investigation of AIS data from the Australian Maritime Safety Authority shows that shipping activities off southwest Australia have been light and have not decreased during the period 2003-2017. Furthermore, analysis of the underwater soundscape recorded at the CTBTO Cape Leeuwin station show little shipping activity (Zhang et al, 2019).

The contribution from vocalization of whales in the area is also expected to be increasing because the whale population is also likely to be increasing, which is partly supported by acoustic observations (Gavrilov and McCauley; 2012; Gavrilov et al. 2013).

The remaining explanation seems to be related to the sea-ice extent around Antarctica and the number and intensity of ice-breaking/iceberg calving events. In the South Indian Ocean, there is a general increase in sea-ice extent from 2002 to 2014. The volume of free-floating small icebergs in the open sea increased from 2002 to 2005, decreased from 2005 to 2007 and almost did not change from 2007 to 2014 (Tournadre et al, 2016). This gives a plausible, but not very convincing, explanation.

To understand the trends shown in Harris et al (2019), one also needs to take into account of the effect on sound transmission due to the warming of the Southern and south Indian Oceans. In recent years (2005-2017), the Southern Ocean was responsible for an increased proportion of the global ocean heat increase (of 45 to 62%) despite occupying 25% of the global ocean area (Shi et al., 2018; Swart et al., 2018). Surface warming during 1982-2016 was strongest along the northern flank of the Antarctic Circumpolar Current (ACC), contrasting with cooling further south. Interior warming was strongest in the upper 2000 m, peaking around 40-50°S (Armour et al., 2016).

4.2 Trends in Ocean Noise South of Diego Garcia

Analysis of a decade (2002–2012) of recordings south of the island of Diego Garcia in the Indian Ocean shows a small (< 2 dB) increase in the ocean noise floor (lower percentiles) (Miksis-Olds et al, 2013).

We note that the median noise level in 40-60 Hz band at the Diego Garcia South CTBTO station is about 86 dB (Miksis-Olds et al, 2013: Table II), which is about 2 dB greater than the median value measured in the same frequency band off Cape Leeuwin (Harris et al, 2019: Figs.4 &5). Harris et al (2019) used in the 40-60 Hz whereas Miksis-Olds et al (2013) used spectral values, so the broadband values in Harris et al (2019), 97 dB, need to be reduced by 10*log(20) = 13 dB to be comparable with the spectral values in Miksis-Olds et al (2013).

Given that the distance between the Diego Garcia South station and Antarctica is about twice the distance between Cape Leeuwin and Antarctica, this indicates that the dominating low frequency noise source at the Diego Garcia site is not from Antarctica or the Southern Ocean, although some intense acoustic transients events in Antarctica can be detected at the Diego Garcia South station (Royer et al, 2015; Gavrilov and Li, 2011). For example, about twelve thousand transient signals from Antarctica were detected at HA01 Station off Cape Leeuwin in 2002-2003. However, only 1035 signals were identified at both the Cape Leeuwin and Diego Garcia South stations as signals from the same events.

5 CONCLUDING REMARKS

There is strong evidence that ice-breaking and iceberg calving processes in East Antarctica and the Southern Ocean are significant sources of ocean noise in the deep ocean waters of the Southern Hemisphere including the continental shelf-break of Australia where the sound propagation path from Antarctica is not blocked by land or seafloor that are shallower than the depth of the underwater sound channel axis at roughly 1000 m depth.

The low frequency noise also seems to be correlated with strong winds in the Southern Ocean. However, examination of the long-term (15 years) trends in ocean noise and wind speeds in the Southern Ocean does not support wind to be the dominate source of low frequency noise. Simple propagation modelling by Bannister (1986) at 50 Hz predicted omnidirectional noise levels showing seasonal and latitude dependence that match observations at some deep water sites in the South Pacific and Indian Ocean. However, we note that the modelling by Bannister (1986) contains several approximations, including the uncertainty associated with wind-driven noise source levels, the assumption of cylindrical spreading loss at all distances, and the neglect of spatial variation of the wind speeds.

Stronger storms in the Southern Ocean may also lead to more calving events of icebergs, so it will be difficult to separate the effect on ambient noise levels due to wave breaking from the effects due to iceberg calving.

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