

ANTARCTIC'S SIREN CALL: THE SOUND OF ICEBERGS

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Abstract: *While the steady increase in global shipping traffic has been identified as a primary cause of rising ocean noise level, in the Southern Hemisphere, the disintegration of large icebergs was found to be a significant noise source that influences the soundscape of ocean basins. Two large icebergs, B15a and C19a, calved off the Ross Ice Shelf in the early 2000s and drifted eastward to the warmer South Pacific Ocean in late 2007. For the next 1.5 years, while these icebergs were rapidly melting, they not only affected water circulation and the marine ecosystems in their vicinity but also influenced the low-frequency ambient noise level of the South Pacific basin. From 2008 to early 2009, the disintegration of B15a and C19a continuously projected loud, low-frequency sounds into the water column. The sounds propagated efficiently to lower latitudes, influencing the soundscape of the entire South Pacific basin. The icebergs' sounds were recorded at Juan Fernández Islands (34°S, 79°W) by deep-water hydrophones maintained by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO). The sounds also propagated across the equator (~10,000 km from the icebergs) and were recorded by a deep-water hydrophone at 8°N, 110°W, maintained by the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory and Oregon State University. In the 30–36 Hz range, the noise level was ~6 dB and ~2.5 dB higher than in baseline years at the respective location. Spectrogram plotting shows that at CTBTO hydrophones, icebergs' sounds dominate the frequency range below 100 Hz at which baleen whales vocalize. Some large icebergs in the Southern Ocean have lifespans over a decade. We suggest that icebergs calved off Antarctica can collectively generate a considerable amount of sound energy, which then propagates across ocean basins, influencing the ocean soundscape and marine environment for the duration of the icebergs' disintegration.*

Keywords: *CTBTO, iceberg noise, polar acoustics, ambient noise*

INRODUCTION

Marine animals rely on sound to aid in migration, feeding, and breeding [1][2][3]. Low-frequency ocean noise has been rising at an alarming rate (+3dB/decade [4]) and raising concerns as to its impact on marine ecosystems. There is a general consensus that anthropogenic sounds, most notably noise from ship and seismic air-guns, are the primary source of noise level increases [4]. These studies are based on historic data from US Navy hydrophones collected since the early 1960s [5],[6] from off the US West Coast near major shipping lanes. Long-term hydroacoustic records of the International Monitoring System (IMS) of the Comprehensive Nuclear-Test Ban Treaty Organization (CTBTO) have also become available for research purposes. Miksis-Olds *et al.* [7] found, from the records of Diego Garcia (HA08) in the Indian Ocean, that one of the arrays near the shipping lanes showed a significant increase in baseline noise levels caused by a recent increase in shipping, confirming that ship traffic is a significant contributor to ambient noise. Brown *et al.* [8] examined the entire CTBTO hydroacoustic data and suggested that the global average of low and high noise spectral curves agreed with Urick's oceanic ambient noise curves [9] for moderate to heavy traffic shipping noise levels of 1984. Today's light ship traffic noise between 10 and 100 Hz is at most ~7 dB higher than the Urick's light ship traffic noise curves [9]. In contrast, the increase in sound levels in the 15–25 Hz is due primarily to increased baleen whale call energy [8]. However, it is still not clear how thousands of large ships scattered across a million square kilometres in mid-latitudes can collectively influence the soundscape across ocean basins and raise baseline noise levels, or if there is another natural or anthropogenic noise producing process that should also contribute to the global noise budget.

Since 1996, the National Oceanic and Atmospheric Administration (NOAA) and Oregon State University (OSU) have operated a deep-water autonomous hydrophone (AUH) array in the Southern Hemisphere, including the Bransfield Strait off the Antarctic Peninsula [10], Scotia Sea [11] and the eastern equatorial Pacific (EEP) [12]. In 2008, an EEP-NW record at 8°N, 110°W showed an unusually high level of wideband noise for a period of one year. Also, even higher elevated noise levels over the same time period, were observed at the IMS-HA03N hydrophone off Chile's Juan Fernández Islands (33.4°S, 78.9°W) [13]. The source of the noise was identified as the two unusually large icebergs, C19a and B15a, which both drifted into the South Pacific. We discuss the timeline of the two icebergs' disintegration, the nature of their wideband noises, and the northward propagation of sound across the equator in the Pacific Ocean. We also discuss the cryogenic iceberg breakdown processes in the open ocean, the seasonal fluctuations of iceberg volume as the major driving force of noise in the South Pacific, and how this process influences the soundscape across ocean basins.

ICEBERGS C19A AND B15A

From late 2007 to early 2008, two large tabular icebergs, C19a (~4,500 km² on 338, 2007) and B15a (~1,700 km²) drifted out to the sea-ice free regions of the open ocean off the Ross Sea Antarctic coast. These icebergs then drifted eastward in the South Pacific Ocean below 63°S. Most icebergs from the Ross Sea drift along the Antarctica coast westward driven by the Coriolis force; it is unusual for icebergs of this size to drift out far north and then move eastward in the South Pacific [13] and disintegrate there. In the South Pacific, the concentration of tabular icebergs is significantly lower than in the South Indian and South

Atlantic oceans [[14]]. It was, therefore, a rare event that two unusually large tabular icebergs appeared in the lower latitude of the Pacific Ocean. For the next 1.5 years, the two icebergs melted and broke apart continuously in the sea-ice free open water between 50°S and 60°S, losing volume by a process called “edge wasting” and “rapid disintegration” [15]. By early 2009, both icebergs had completely disintegrated to sizes too small to be tracked by satellite.

Figure 1a and 1b show a thinning process of B15a from 018, 2008 to 339, 2008. The surface area was reduced from $\sim 1,700 \text{ km}^2$ to $\sim 550 \text{ km}^2$ in 321 days, while keeping the original shape roughly the same. Figure 1c and 1d show the same thinning process of C19a. Figure 1b and 1c show edge wasting and rapid disintegration processes occurring at the same time.

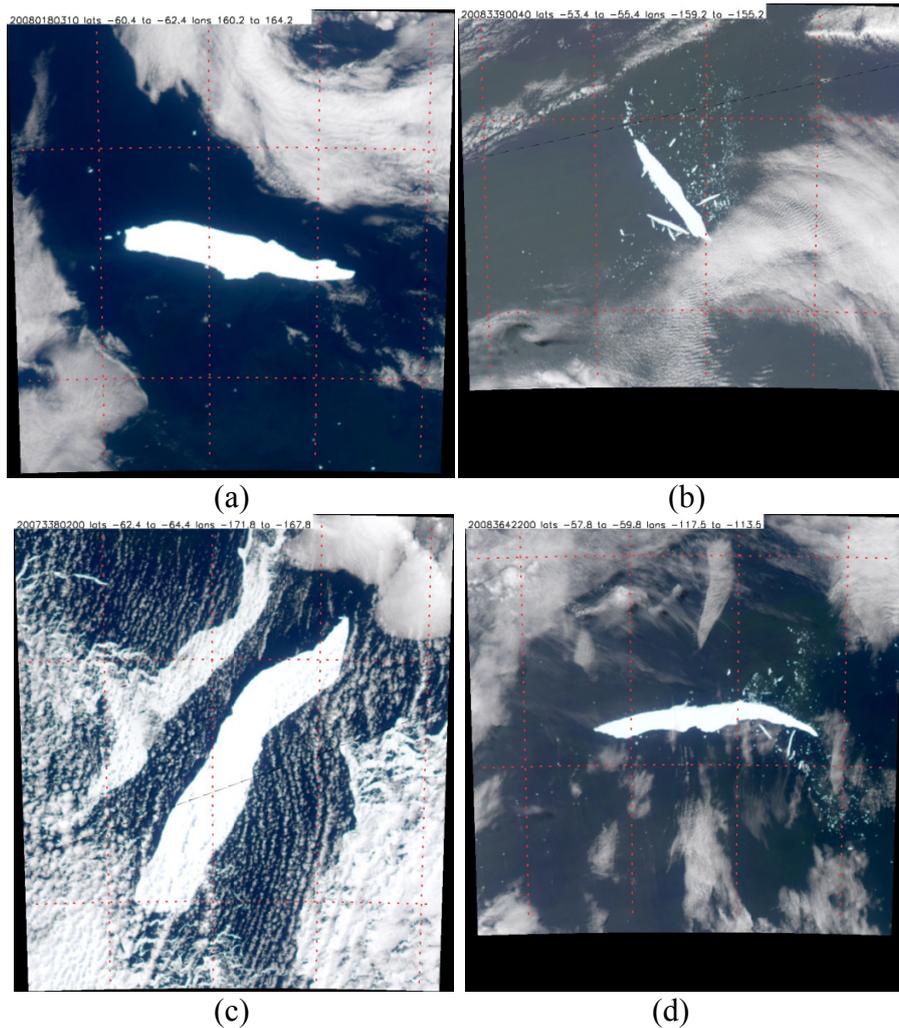


Fig. 1. (a) Satellite picture of B15a on JD 018, 2008 at 61.4°S, 162.2°E near the Ross Sea area. Area estimate $\sim 1,700 \text{ km}^2$. (b) B15a on 339, 2008 at 54.4°S, 157.2°W, $\sim 2,700 \text{ km}$ southwest from Christchurch, New Zealand. Area size $\sim 550 \text{ km}^2$. (c) C19a on 338, 2007 at 63.6°S, 168.4°W. Area size $\sim 4,500 \text{ km}^2$. (d) C19a on 364, 2008 at 58.8°S, 115.5°W. Area size $\sim 1,200 \text{ km}^2$. Images are from Brigham Young University, Center for Remote Sensing.

C19a and B15a generated wideband acoustic noises (Fig. 2a) that were tracked by two hydroacoustic stations: one operated by the CTBTO since 2003 and located on the north side of Chile’s Juan Fernández Islands (yellow mark in Fig. 2b), and the other the NOAA/OSU EPP-NW (red mark in Fig. 2b). Wide station separation of $\sim 5,600 \text{ km}$ helped to improve the

array's angular resolution. White triangles in Fig. 2b are the acoustic locations of iceberg sound sources (one per week) in 2008. Green and red lines are satellite tracks of B15a and C19a, respectively. Despite the long distances, $\sim 10,000$ km from sound sources to the receivers, the source location estimates matched reasonably well with the satellite tracks. The spectrogram and time series show a wideband and short-burst nature of the iceberg sound generated by edge wasting and rapid disintegration processes. The CTBTO and the NOAA/OSU hydrophone signals were sampled at 250 Hz and with 100-Hz anti-aliasing filter. Dziak *et al.* (2013) found bandwidth of another tabular iceberg's (A53a) sound that exceeded 500 Hz [11], which was recorded in the Scotia Sea by a data logger with a 1-kHz sampling rate. The average source level of A53a was ~ 220 dB_{rms} re $1\mu\text{Pa}^2/\text{Hz}$ @ 1 m. It is expected that C19a and B15a's source level is similar.

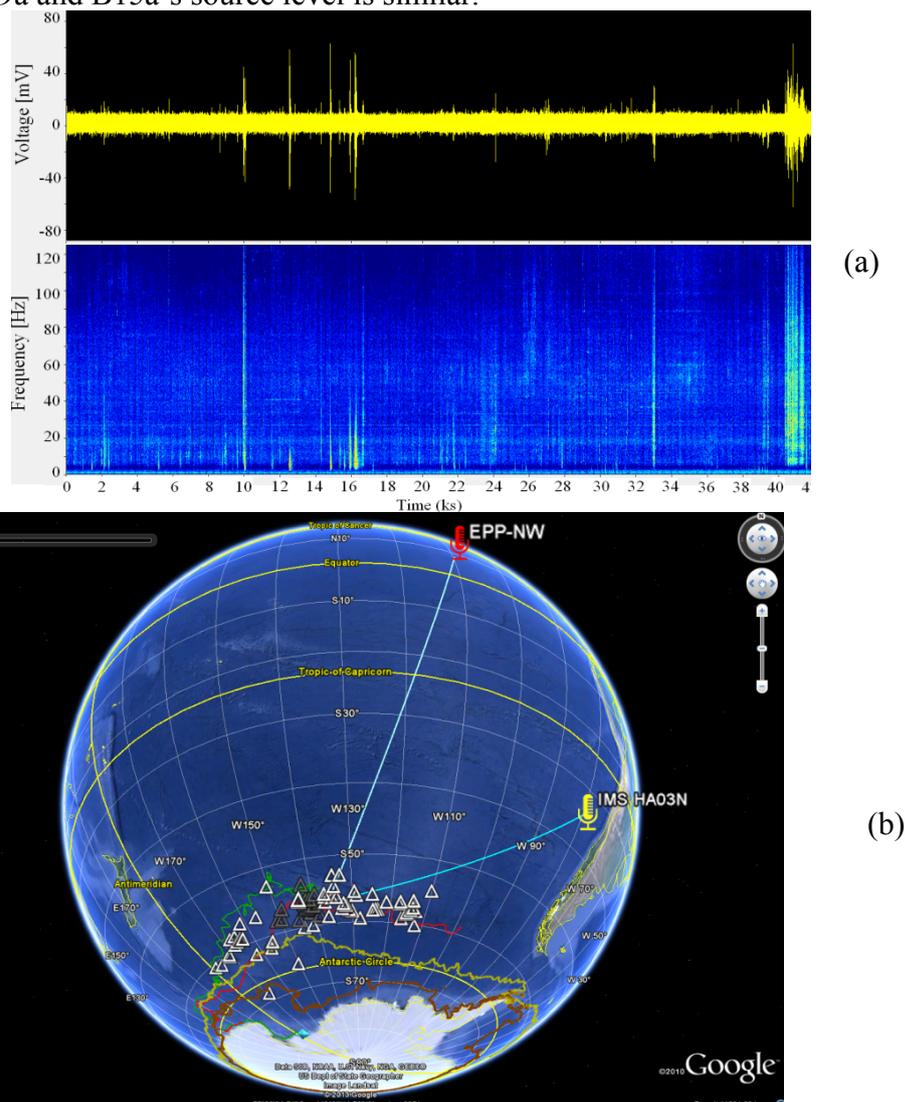


Fig. 2 (a) An 11-hour long acoustic record (top) and spectrogram (bottom) at EEP-NW on Julian day 169, 2008. A sequence of wideband iceberg noises arriving at the end of record. (b) Iceberg location estimates (white triangles) derived acoustically using the IMS-HA03N and EEP-NW arrays. Green and yellow lines are satellite tracks of B15a and C19a, respectively. Yellow and brown lines are the sea ice edge in the austral winter and summer, respectively. Blue lines are the great circle paths in September 2008 from iceberg C19a to IMS-HA03N ($\sim 4,500$ km) and to EEP-NW ($\sim 9,600$ km).

ICEBERG SOUND AFFECTING SOUNDSCAPES ACROSS THE OCEAN BASIN

Figure 3a shows the contour of the monthly volume of ice distribution (in Gt) from small icebergs (<2 km in length) as a function of time and latitude (Hovmüller diagram) in the South Pacific region (150°E to 70°W) (reproduced from Tournadre *et al.* (2013) [16]). It shows that, in 2008, a large volume of ice departed the Antarctic coast, drifted northward, and reached ~50°S in early 2009. This increase of the volume of ice corresponds to C19a and B15a's drift to the South Pacific region in late 2007 and subsequent disintegrations through 2008 and early 2009. It also shows that iceberg volume fluctuation is consistently austral-summer-high-winter-low. The black line is the sea-ice edge averaged over the South Pacific region, which also shows the same austral-summer-low-winter-high seasonality.

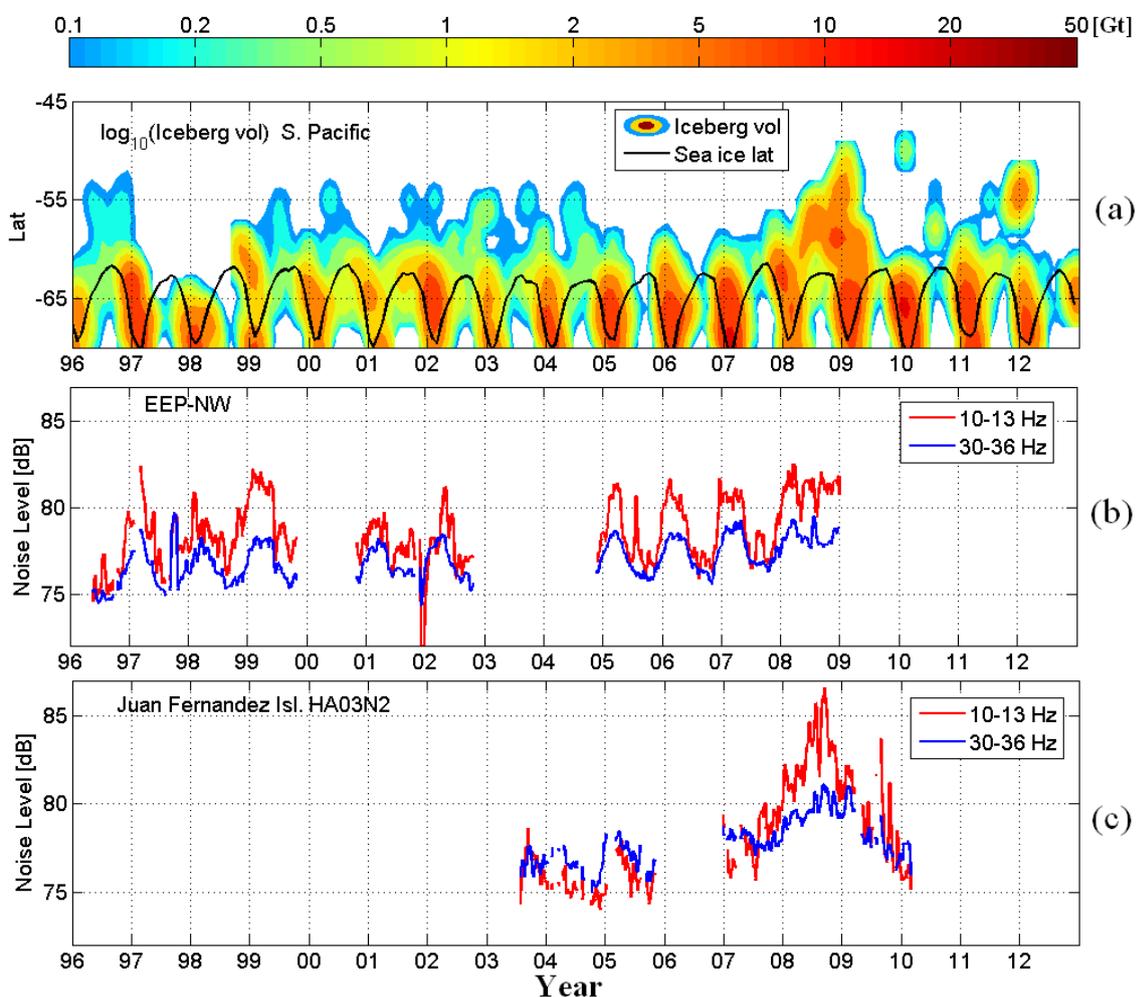


Fig. 3. (a) Logarithm of monthly volume of ice distribution (in Gt) of small icebergs in the Pacific as a function of time and latitude in the Pacific region. Black line is the sea-ice edge averaged over the Pacific. (b) Noise levels (in dB) relative to $\mu\text{Pa}^2/\text{Hz}$ at EEP-NW (8°N, 110°W). (c) Noise levels (in dB) relative to $\mu\text{Pa}^2/\text{Hz}$ at IMS-HA03N off the Juan Fernández Islands.

While C19a and B15a were breaking up in the sea-ice free open ocean, several thousands of kilometers away at the hydroacoustic station off Chile, the noise levels in 10–13 Hz (in red) and 30–36 Hz (in blue) rose by a maximum of ~12 dB and ~6 dB in September 2008, respectively, relative to the baseline of the previous two years (Fig. 3b). Similarly the equatorial eastern Pacific noise levels in 10–13 Hz (red) and 30–36 Hz (blue) also went up by ~6 dB and ~2.5 dB, respectively (Fig. 3c). These two frequency ranges were chosen to avoid interference by the ubiquitous baleen whale calls in these areas [18]. The rise of noise levels at both sites corresponds to the period when large volumes of icebergs were moving out to the open waters at lower latitude.

ICEBERG DRIVING NOISE SEASONALITY ACROSS THE OCEAN BASIN

It appears that annual iceberg volume increase and decrease north of the sea-ice edge off Antarctica is influencing the seasonal variation in noise levels in the Southern Ocean, and appears to be extending across the equator up to 8°N. On average, approximately 400 Gt of icebergs are being transported annually to latitudes below 67°S and disintegrated annually [15] once exposed to by water temperatures above -1.8 °C and mechanical weathering forces due to current, wind, and waves [14]. At EEP-NW, the dynamic range of the annual average of noise levels showed clear seasonality, with austral summer highs and –winter lows of ~4.5 dB and 3 dB in 10–13 Hz and 30–36 Hz, respectively. Austral summer high and winter low seasonality at EEP-NW matched with the seasonality of iceberg volume north of the sea-ice edge. At EEP-NW, wind speed has a seasonality of austral winter high and summer high [http://www.pmel.noaa.gov/tao/data_deliv/deliv.html], which is the exact opposite of the noise seasonality. Since there is no seasonality in shipping, and whale calls interference in these frequency ranges is unlikely, it seems apparent that the seasonal iceberg volume off Antarctica is a driving force for noise as far north as the equatorial Pacific.

At both hydrophone sites, the 10–13 Hz noise energy was stronger than the 30–36 Hz when iceberg sound was not blocked by a land mass. At IMS-HA03N, although iceberg noise from the Antarctic coast was blocked by the islands, there was still the same seasonality as the EEP-NW apparent in the 2003 and 2005 data. This could be a result of diffraction around the islands, or acoustic to seismic wave conversion through the island, coming through as acoustic wave again on the north side of the islands [19].

Both the EEP and Juan Fernández Islands hydrophones are near seismically and tectonically active areas. As a result, noise spikes are seen in Fig. 3b and 3c. Some spikes in early deployment of the EEP hydrophones from 1996 through 1998 can be associated with particular seismic and volcanic events [20]. A series of spikes can be seen in the IMS-HA03N noise levels in late 2009 to early 2010. The magnitude 8.8 Chile earthquake occurred on 27 February 2010, and the IMS-HA03N array was destroyed by the tsunami that followed.

CONCLUSIONS

In late 2007, large icebergs C19a and B15a drifted out from the Antarctic coast to the sea-ice free waters of the South Pacific, and their subsequent disintegration generated high-level acoustic noise that influenced the ambient ocean noise levels off Chile, as well the eastern equatorial Pacific across the equator, for 1.5 years. At the eastern equatorial Pacific, noise level rose by ~6 dB in 10–13 Hz and 2.5 dB in 30–36 Hz. The iceberg sound also raised the noise levels off the Juan Fernández Islands by 12 dB in 10–13 Hz and 6 dB in 30–36 Hz,

respectively. In the Southern Hemisphere, tabular icebergs off Antarctica are the major noise contributors. The surface sound generated by iceberg break-up process propagates efficiently to the north through surface duct, the Antarctic Convergence Zone, and deep-sound channel. Seasonal changes of iceberg volume north of the sea-ice edge appeared to be driving the noise level seasonality of austral-summer-high and winter-low in the entire Southern Ocean. Iceberg noise also reached across the ocean basin as far north as 8°N in the Pacific, influencing the seasonality with dynamic ranges of 4.5 dB and 3 dB in 10–13 Hz and 30–36 Hz ranges, respectively.

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