



RESEARCH ARTICLE

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Key Points:

- Large iceberg from Antarctica influenced the ocean noise near equator
- Annual cycle of iceberg volume off Antarctica modulates the noise levels
- Ambient noise levels are affected by climate-induced iceberg volume variations

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Antarctic icebergs: A significant natural ocean sound source in the Southern Hemisphere

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Abstract In late 2007, two massive icebergs, C19a and B15a, drifted into open water and slowly disintegrated in the southernmost Pacific Ocean. Archived acoustic records show that the high-intensity underwater sounds accompanying this breakup increased ocean noise levels at mid-to-equatorial latitudes over a period of ~1.5 years. More typically, seasonal variations in ocean noise, which are characterized by austral summer-highs and winter-lows, appear to be modulated by the annual cycle of Antarctic iceberg drift and subsequent disintegration. This seasonal pattern is observed in all three Oceans of the Southern Hemisphere. The life cycle of Antarctic icebergs affects not only marine ecosystem but also the sound environment in far-reaching areas and must be accounted for in any effort to isolate anthropogenic or climate-induced noise contributions to the ocean soundscape.

1. Introduction

Archived acoustic recordings of the northern Pacific Ocean indicate an increase in ambient noise of ~10–12 dB in the 25–50 Hz frequency range since the 1960s [e.g., Frisk, 2012; Hildebrand, 2009; Chapman and Price, 2011; Andrew *et al.*, 2011; McDonald *et al.*, 2006]. The potential impacts of increased ocean noise on marine animals' reproduction [Lillis *et al.*, 2013], feeding [Simpson, 2005], communication [Edds-Walton, 1997], and physiology [Rolland *et al.*, 2012] have raised concerns about ecosystem health. Studies have shown that the distance to major ports and shipping lanes, changes in shipping routes, as well as economies and regulatory policies, may affect low-frequency noise levels [Miksis-Olds *et al.*, 2013; McKenna *et al.*, 2012]. Other studies suggest that the oceans may become more transparent to sound waves (noisier) in response to ocean acidification resulting from increased atmospheric carbon dioxide [Hester *et al.*, 2008; Wilcock *et al.*, 2014]. However, recent measurements off the North American coast indicate that noise trends have been level or even slightly decreasing since the mid 1990s despite the fact that the number and size of ships is still increasing [Andrew *et al.*, 2011; Wilcock *et al.*, 2014] and CO₂ levels in the atmosphere are rising [Wootton *et al.*, 2008]. This raises questions regarding how well we understand the major noise inputs into, and influences on, the global soundscape.

In the Southern Hemisphere, the natural sounds associated with the breakup of icebergs represent an important and potentially underappreciated acoustic noise source. Annually tens of thousands of icebergs drift out from Antarctica into the open waters of the Southern Ocean, creating a ubiquitous natural source of sound as they disintegrate [Silva *et al.*, 2006]. The paths of individual icebergs >5–6 km in length can be tracked using satellite-based imagery, and radar altimeters now provide an estimate of the distribution of smaller (100–2800 m) icebergs in sea-ice free areas. It is estimated that the calving of icebergs >18.5 km in length can account for nearly half of the annual ice loss from Antarctica (~1089 + 300 Gt) [Silva *et al.*, 2006]. Altimeter-based measurements report an additional mean annual volume of ~400 Gt, with icebergs exhibiting a mean length of ~750 m in the austral summer and ~450 m in the winter [Tournadre *et al.*, 2012], and an average half-life of ~200 days [Jacka and Giles, 2007]. In comparison, in the Northern Hemisphere, the mean annual iceberg flux from Greenland is estimated to be only 170–270 Gt [Bigg, 1999].

Antarctic icebergs are known to generate two types of sounds: one is a long-duration harmonic tremor and the other is a broadband burst [Talandier *et al.*, 2006; Chapp *et al.*, 2005; MacAyeal *et al.*, 2008]. Harmonics

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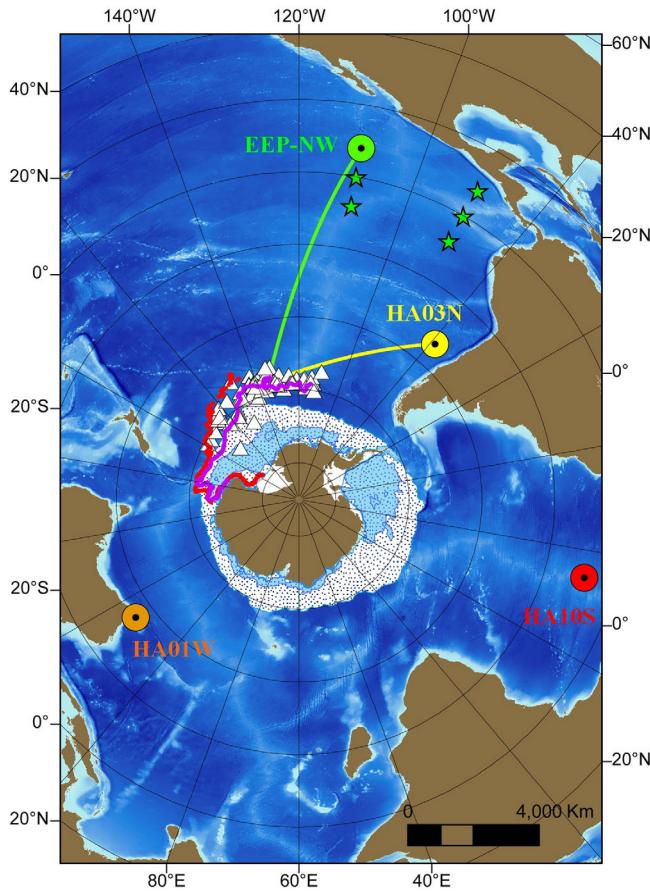


Figure 1. Iceberg sound sources (white triangles) located by the hydrophones in the Pacific (green and yellow circles). Satellite tracks of B15a (red) and C19a (maroon) are overlaid (data from <http://www.scp.byu.edu/data/iceberg/QuickSCAT/>). The IMS HA03N hydrophone on the north side of Juan Fernandez Islands (33.441°S , 78.911°W) is shown by a yellow mark and the EEP-NW hydrophone (8.0°N , 110.0°W) by a green mark. Brown circle is the IMS HA01W hydrophone (34.892°S , 114.153°E) off Cape Leeuwin in the South Indian Ocean. Red circle in the Atlantic Ocean is the IMS HA10S hydrophones (8.941°S , 14.648°W) off the Ascension Island. All sensors are moored within the deep ocean sound channel, at depths of 800–1000 m. White and blue stippled areas around Antarctica delineate the maximum (winter) and minimum (summer) sea-ice extent in 2008 (<https://climatedataguide.ucar.edu/climate-data/sea-ice-concentration-data-nasa-goddard-and-nsidc-based-bootstrap-algorithm>). Solid lines mark the acoustic paths to HA03N (~4800 km) and EEP-NW (~7500 km) from iceberg C19a (58.5°S , 132.5°W) on 14 September 2008, when the recorded ambient noise was near its highest at HA03N. Also shown are two IMS hydrophones; HA01W (34.892°S , 114.153°E) on Western Australia facing the South Indian Ocean and HA10S (8.941°S , 14.648°W) off the Ascension Island in the South Atlantic Oceans.

of $\sim 11,000 \text{ km}^2$), calved off the Ross Ice Shelf and broke into several smaller smaller icebergs; the largest of which was B15a (Figure 1). As B15a drifted out into the open waters of the South Pacific (N of 63°S) in December 2007, its disintegration hastened. By July 2008, its estimated size was $\sim 1400 \text{ km}^2$ [Feldman and McClain, 2014]. In 2002, C19, the second largest tabular iceberg on record ($\sim 6300 \text{ km}^2$), broke off from the Ross Sea Ice Shelf. Its largest piece, C19a ($\sim 5500 \text{ km}^2$), also drifted out of the sea-ice covered area and into the open South Pacific Ocean in late 2007. By April–May 2009, B15a and C19a had disintegrated to pieces too small to be tracked individually.

Here we examine the sounds generated by the disintegration of C19a and B15a recorded by two hydrophone stations in the Pacific [Matsumoto et al., 2013] including an autonomous hydrophone (AUH) array in the eastern equatorial Pacific (EEP) and International Monitoring System (IMS) hydrophone array north of the Juan Fernandez Islands (HA03N, 33.441°S , 78.911°W). The EEP-AUH array (Figure 1) was maintained by the National Oceanic Atmospheric Administration/Oregon State University from May 1996 to

tremors are generated when the icebergs shoal or collide with other icebergs, whereas short-duration bursts, which are much more common [Talandier et al., 2006], are generally associated with iceberg breakup in the open sea and probably caused by “edge wasting” and “rapid disintegration” processes [Scambos et al., 2008]. By monitoring these sounds with a deep-water hydrophone array, iceberg locations and source levels can be estimated. Chapp et al. [2005] acoustically located iceberg B15d ($\sim 215 \text{ km}^2$) within the Indian Ocean in 2005 and estimated a maximum source level of 245 dB-rms re $1\mu\text{Pa}$ @ 1 m for its tremor signals. Dziak et al. [2013] estimated an average source level of 220 dB-rms re $1\mu\text{Pa}$ @ 1 m for iceberg A53a drifted in the Scotia Sea in the South Atlantic in 2008. The transient acoustic signals generated by icebergs last typically from a few tens of seconds to up to ~ 20 min with spectral contents exceeding 400 Hz [Dziak et al., 2013]. With tens of thousands of icebergs disintegrating annually, collectively these sounds have the potential to raise the noise levels thousands of kilometers away even considering the propagation losses.

In 2000, B15, the largest tabular iceberg on record (original size

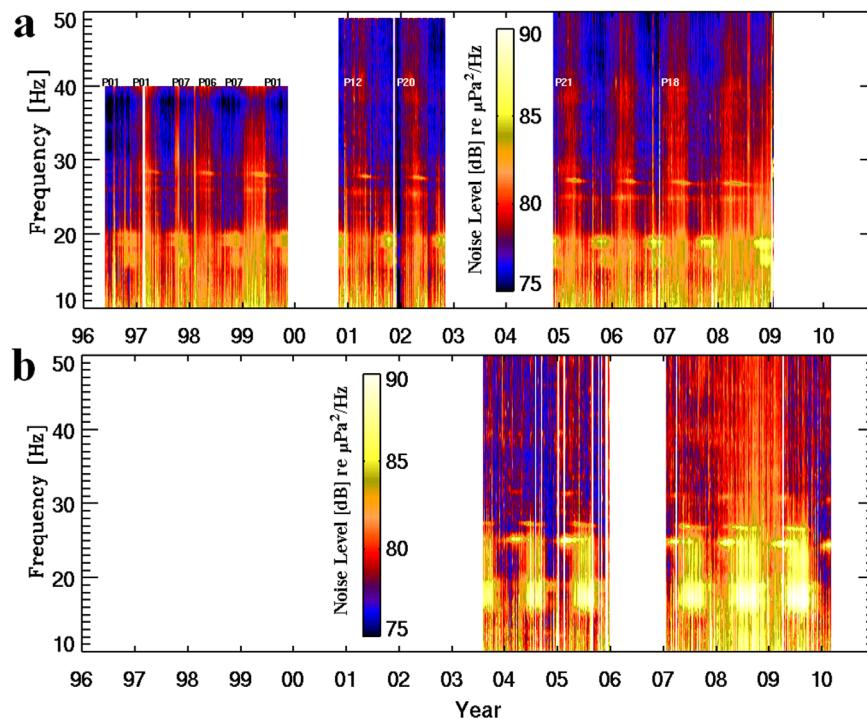


Figure 2. Daily noise spectrograms of deep-ocean sound in the Pacific. (a) EEP-NW (8°N , 110°W) noise spectrogram between May 1996 and December 2008, which shows a faint seasonal pattern of wideband noise with an austral summer-high and winter-low pattern. Two long data disruptions in the EEP-NW time series are the result of instrument failure and mooring loss. From December 2001 through January 2002, right after the regular service, there is an unusually low-noise period. It is unclear if this reflects a physical phenomenon or a problem with the instrument electronics; however, the system continued logging and the data appears normal throughout the remainder of the 1 year deployment period. (b) HA03N (33.441°S , 78.911°W) spectrogram between July 2003 and February 2010. The station went offline on 27 February 2010, when it was struck by a tsunami generated by the Mw 8.8 Chile earthquake. In both records, wideband iceberg noise increased in late 2007 and was sustained through 2008 and early 2009.

December 2008, with a service interval of every 1–2 years [Fox *et al.*, 2001]. Among the EEP hydrophones, EEP-NW at 8.0°N , 110.0°W was examined because it was the farthest from the seismically active Middle America Trench, East Pacific Rise, and Galapagos Ridges [Fox *et al.*, 2001]. It was also one of the least affected by baleen whale calls [Stafford *et al.*, 1999]. We also examine the long-term noise levels and trends at two other IMS stations: Cape Leeuwin hydrophone (HA01W, 34.892°S , 114.153°E) in the South Indian Ocean and Ascension Island (HA10S, 8.941°S , 14.648°W) in the South Atlantic Ocean. Narrow-frequency-range noise levels at 10–13 Hz and 30–36 Hz are compared with the time series of iceberg volume estimated by the satellite altimeter-derived [Tournadre *et al.*, 2012] time-latitude Hovmöller diagrams in these respective regions.

2. Impacts by B15a and C19 Icebergs in the Pacific

At a latitude higher than 60°S , the acoustic energy radiated near the surface propagates efficiently through the surface sound channel duct, crosses the Antarctic Convergence Zone, and then becomes trapped within the deep sound channel at midlatitudes [Chapp *et al.*, 2005; de Groot-Hedlin *et al.*, 2009]. Taking advantage of long baselines between OSU/NOAA EPP and IMS HA03N arrays in the Pacific of approximately 5600 km, iceberg locations (Figure 1) were estimated from the acoustic time series using an iterative nonlinear least square method [Fox *et al.*, 2001]. Despite the long source-to-receiver distance (maximum of ~ 9600 km), the acoustically tracked positions of C19a and B15a are consistent with the satellite-derived tracks. Scatter in the acoustically derived locations results from signal dispersion, uncertainty in the sound velocity model, and the array geometry. It is also likely that some of the iceberg sounds were generated within the many unnamed daughter icebergs sourced from C19a and B15a [Tournadre *et al.*, 2012].

The sound pressure level spectrograms of EEP-NW (1996–2008) and of the IMS-HA03N (2003–2010) are shown in Figures 2a and 2b, respectively. To construct these long-term spectrograms, a daily power

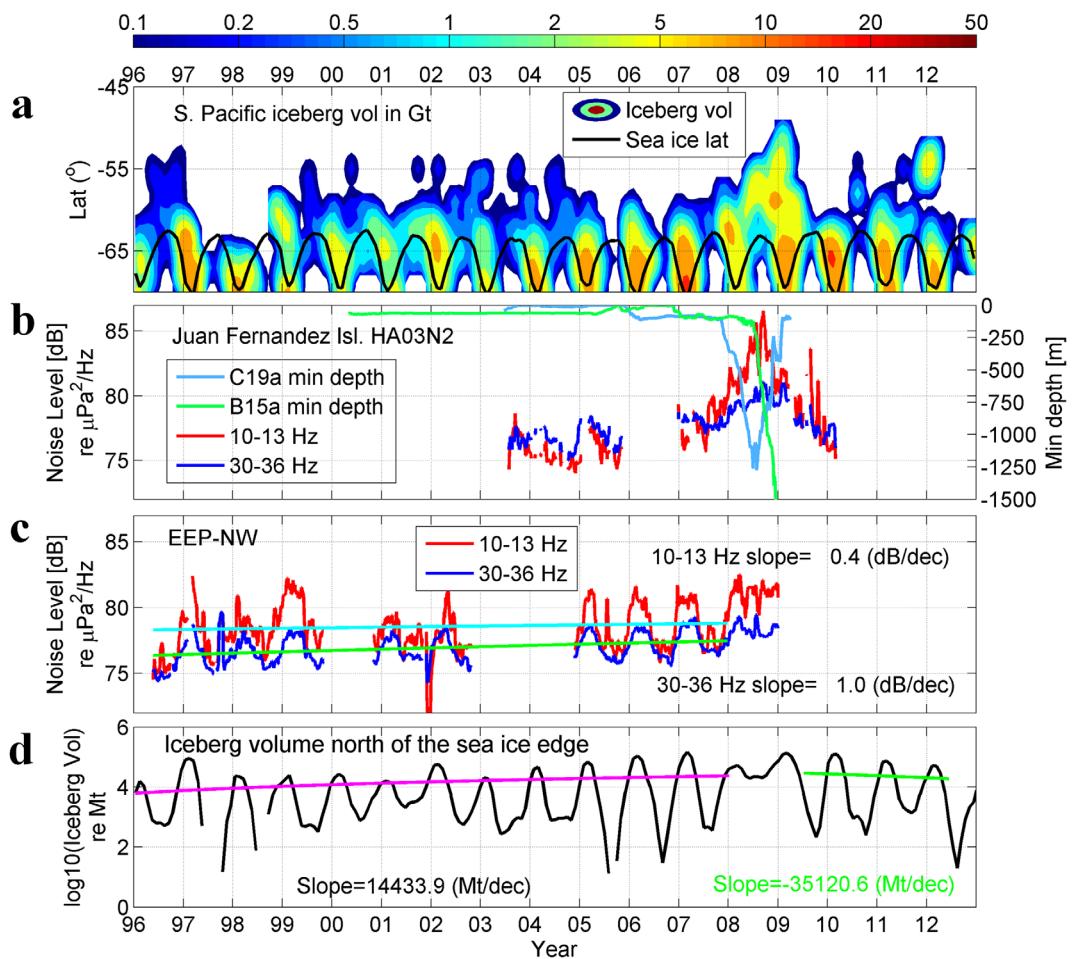


Figure 3. Satellite-derived iceberg volume and acoustic noise levels in the Pacific. (a) Time-latitude Hovmöller diagram of the ALTIBERG monthly iceberg volume (in Gt) in the South Pacific region between 150°E and 70°W, made from a 1°-latitude, 2°-longitude grid [Tournadre et al., 2013]. The monthly iceberg volume data were smoothed using a 5 × 5 2-D Gaussian filter. Sea-ice edge advance and retreat over the South Pacific region is identified with the solid black. (b) Noise level at Juan Fernandez Islands station HA03N between 10–13 Hz (red) and 30–36 Hz (blue) from 2003 to 2010. Also shown are the minimum bathymetric depth along the acoustic paths to HA03N from C19a (light blue) and B15a (green). The sounds originating from these massive icebergs were largely blocked by the Juan Fernandez Islands, except for the period between late 2007 through early 2009. (c) Noise levels at EEP-NW between 10–13 Hz (red) and 30–36 Hz (blue) from 1996 through 2008. A consistent austral summer-high and winter-low seasonal pattern is observed from 1996 through 2007 until 2008. The noise anomaly in 2008 is caused by the break up of C19a and B15a. The linear trends from 1996 through 2007 is +0.4 dB/decade in the 10–13 Hz and +1.0 dB/decade in the 30–36 Hz band. (d) Logarithm of altimeter-derived volume of icebergs in megaton north of the sea-ice edge in the Pacific-Antarctic waters, which shows a ~14 Gt/decade increase from 1996 through 2008.

spectrum was estimated by averaging the squared magnitudes of 432 discrete Fast Fourier Transforms calculated from a series of 200 s duration nonoverlapping data segments. In both spectrograms, baleen whale calls appear seasonally between 15 and 28 Hz. The sample rate of the EEP hydrophones was 100 Hz from 1996 to 1999, and it was increased to 250 Hz in 2000 through 2008. The IMS hydrophone signals, by comparison, have been sampled consistently at 250 Hz [Prior et al., 2011]. To be consistent, only the frequency ranges of 10–50 Hz are displayed in Figure 2. The same AUHs have been used continually at the same locations since the EEP array's inception in May 1996. In late 2007 through early 2009, a wideband noise, which we attribute to iceberg sound, becomes prominent in the HA03N spectrogram and also appears (more faintly) in the EEP-NW spectrogram. The EEP-NW spectrogram also exhibits a subtle seasonality, with an austral summer-high and winter-low pattern apparent in the wideband noise.

To minimize the influence of ubiquitous baleen whale calls [Stafford et al., 1999; McDonald et al., 2009], the spectral density in 10–13 Hz and 30–36 Hz frequency ranges were evaluated at HA03N (Figure 3b) and EEP-NW (Figure 3c). A 21 point median filter was then used to reduce abrupt spikes associated with episodic seismic/tectonic events [Fox et al., 2001]. The narrow-frequency-range noise levels are compared with the

satellite altimeter-derived time-latitude Hovmöller diagram of the ALTIBERG monthly iceberg volume (in Gt) in the South Pacific region between 150°E and 70°W, made from a 1° latitude, 2° longitude grid [Tournadre *et al.*, 2013] (Figure 3a). The gridded diagram represents monthly volumes of small icebergs (100–2800 m) in Gt. The diagram was then integrated in latitude between 40°S and the sea-ice edge. This produces a time series of the total iceberg volume north of the sea-ice edge (Figure 3d), where warm waters and wave action are expected accelerated iceberg breakup and increase sound production. The increase in iceberg volume at more northern latitudes in late 2007 and subsequent decrease in early 2009 track the northward drift of C19a and B15a (Figure 3a). Timing of the sound level increases at both HA03N and EEP-NW (Figures 3b and 3c) correspond well to the accelerated release of acoustic energy as these massive tabular icebergs breakup in 2008.

The location of HA03N on the north side of the Fernandez Islands results in bathymetric shielding of sound from the C19a and B15a by the islands, except during a ~1.5 year period from late 2007 to early 2009. Figure 3b shows the minimum bathymetric depth that sound from C19a and B15a would have encountered approaching the hydrophone station. The noise maximum on HA03N occurs on 14 September 2008, reaching levels ~12 dB (10–13 Hz) and ~6.0 dB (30–36 Hz) higher than the previous September baseline. This noise maximum corresponds to the time at which both C19a and B15a obtained an acoustic line-of-sight to HA03N (back-azimuths of ~210–230°) and the iceberg volume reached its northern maximum.

Due to blockage from most southern azimuths, iceberg-generated signals normally are not a dominant noise source at HA03N—except for this time window when large icebergs C19a and B15a are optimally positioned. Consequently, other noise sources typically disrupt any seasonal pattern related to ice, and the temporal and spectral noise characteristics observed at HA03N therefore do not match those observed in open waters at EEP-NW (Figures 3b and 3c). For example, at EEP-NW sound energy was consistently higher in the 10–13 Hz range than in the 30–36 Hz range (Figure 3c), in keeping with the spectra of ice-generated noise [e.g., Dziak *et al.*, 2013, Talandier *et al.*, 2006]. Whereas, at HA03N, prior to the arrival of C19a and B15a, noise in the 30–36 Hz range was typically higher than in the 10–13 Hz range. This pattern becomes reversed in 2008 as the signals from these large icebergs arrive at HA03N (Figure 3b).

In 2008, as C19a and B15a moved northward and broke up, the noise level at EEP-NW also rose by ~6.0 dB in the 10–13 Hz and by ~2.5 dB in the 30–36 Hz ranges (Figure 3c). The smaller increase at EEP-NW, relative to HA03N, results from a larger propagation loss over approximately twice the range. Since there was no significant bathymetric blockage of acoustic energy to the EEP-NW station for sounds originating along the C19a and B15a paths, an elevated noise level was sustained for a longer period of time and the sound pressure time series better mirror the iceberg volume record (Figure 3d). The acoustic signals associated with the breakup of these massive icebergs effectively masks the seasonality observed at EEP-NW in the years before 2008 (Figures 3a, 3c, and 3d).

3. Iceberg Volume Versus Acoustic Noise Levels in the Pacific

Fitting a linear trend to the EEP-NW noise data from 1996 to 2007, a year before the C19a-B15a anomaly in 2008, shows the noise level appears to increase at rates of ~1.0 dB/decade in the 30–36 Hz and ~0.4 dB/decade in the 10–13 Hz frequency ranges. Although there is no evidence that the number of icebergs in the entire Southern Ocean has been increasing [Long *et al.*, 2002], the altimeter-derived small iceberg volume north of the sea ice in the region to the south of these hydrophone arrays has increased from 1996 through 2007 at a rate of ~14 Gt/decade (Figure 3d). However, the noise level increase is subtle, and it is not clear if it can be attributed to the change in iceberg volume. The mean noise levels from 1996 through 2007 in 10–13 Hz and 30–36 Hz ranges were 78.6 dB and 77.0 dB re 1 $\mu\text{Pa}^2/\text{Hz}$, respectively (Table 1). Interestingly, since mid-2009, iceberg volume has been decreasing at rate of ~35 Gt/decade; unfortunately, we have no acoustic records for comparison. To best represent changes in peak volumes during the austral summers, decadal iceberg volume trends were estimated using a linear, instead of logarithmic, scale. Iceberg volume is analogous to the amount of “fuel” for the noise generation, and the distribution of icebergs is clearly dynamic, with an excursion of significant ice mass farther to the north accompanying the aforementioned movement of C19a and B15a in late 2007 through 2009 (Figure 3a).

Narrow-frequency-range noise spectra for the EEP-NW hydrophone (Figure 3c) highlights a seasonal pattern, whereby the ambient sound level is observed to rise and fall in concert with the seasonal change of iceberg volume (Figure 3d). The seasonal noise pattern at EEP-NW and the noise level rise at the EEP and

Table 1. Noise Levels in Three Oceans, Trends, and Iceberg Volumes^a

	Pacific Ocean EEP-NW (8°N, 110°W)		Indian Ocean HA01W (34.9°S, 114.2°E)		Atlantic Ocean HA10S (8.9°S, 14.6°W)	
	1996–2007	2009–2012	1996–2003	2004–2012	1996–2004	2005–2012
Noise level (10–13Hz)	Mean (dB)	78.6	NA	NA	89.0	NA
	Trend (dB/dec)	+0.4	NA	NA	-2.9	NA
	NL \otimes IV	0.76	NA	NA	0.92	NA
Noise level (30–36 Hz)	Mean (dB)	77.0	NA	NA	84.7	NA
	Trend (dB/decade)	+1.0	NA	NA	-2.4	NA
	NL \otimes IV	0.82	NA	NA	0.86	NA
Iceberg volume	Trend (Gt/decade)	+14	-35	+13	-24	+43
Distance from 60°S (km)		~7500		~2800		~5500

^aMeans and trends of narrow-frequency range noise levels in 10–13 Hz and 30–36 Hz re $\mu\text{Pa}^2/\text{Hz}$. Noise levels in the Pacific are at the EEP-NW. Indian Ocean noise levels are at IMS-HA01W. Atlantic Ocean noise levels are at IMS-HA10S. NL \otimes IV is the correlation value between the noise level and the iceberg volume time series of respective Ocean.

HA03N from late 2007 to 2009 match well with the iceberg volume time series. The interannual daily noise level at the EEP-NW (Figure 4) shows a persistent seasonality of maximum levels in March and minimum levels in late August to September with a dynamic range of 3.9 dB in the 10–13 Hz and 2.5 dB in 30–36 Hz frequency. Short rises of noise levels occur in mid-October through November. A similar low-frequency noise seasonality, but with much larger dynamic ranges, was found in the southern Indian Ocean ~7 dB in 8–16 Hz [Hanson and Bowman, 2006] and Bransfield Strait ~20 dB in 50–110 Hz [Matsumoto et al., 2007], where iceberg noise sources were at much closer ranges to the hydrophones. Interestingly, along the North American West Coast, Andrew et al. [2011] show the same low-frequency noise seasonality with a few decibel of dynamic range and a wideband spectrum consistent with the characteristics of ice-generated noise observed at high southern latitudes [e.g., Dziak et al., 2013].

Considering EEP-NW hydrophone data from the time window before 2008, when the sound generated by C19a and B15a became prominent, there is a strong correlation of 0.76 and 0.82 between the iceberg volume time series and the 10–13 Hz and 30–36 Hz noise levels, respectively (Figure 5a). These high correlation values suggest that, despite the distances, there is a direct relationship between the ocean acoustic noise levels near the equator and iceberg volume off Antarctica. The noise time series, however, lag the iceberg volume data by ~18 days in the Pacific, suggesting that noise generation is not purely a function of iceberg volume (Figure 5c).

Instead, the acoustic output reflects the rate of iceberg disintegration and, therefore, likely depends on the seawater and air temperatures where icebergs are located, as well as wind and wave action [Scambos et al., 2008]. This is shown by the “hysteresis loop” of iceberg volume versus noise levels that the same volume of icebergs produces higher noise energy during the austral

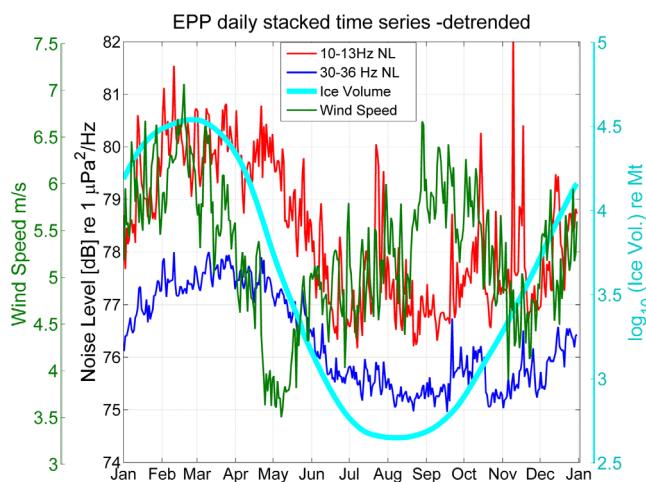


Figure 4. Interannual average of daily acoustic noise, wind speed at EEP-NW and iceberg volume in the South Pacific. Noise spectral density in the 10–13 Hz frequency range is plotted in red and in the 30–36 Hz range in blue. The seasonal noise maximum occurs in March and the minimum in August to September, with a dynamic range of 3.9 dB in 10–13 Hz and 2.5 dB in 30–36 dB frequency bands. Overlaid are the interannual iceberg volume time series data (thick cyan line) and wind speed data (green) taken from Tropical Atmosphere Ocean project climate buoys in the eastern equatorial Pacific region (data available from http://www.pmel.noaa.gov/tao/data_deliv/deliv.html). For all time series, the period from May 1996 through December 2007, before the large-scale breakup of C19a-B15a, is considered.

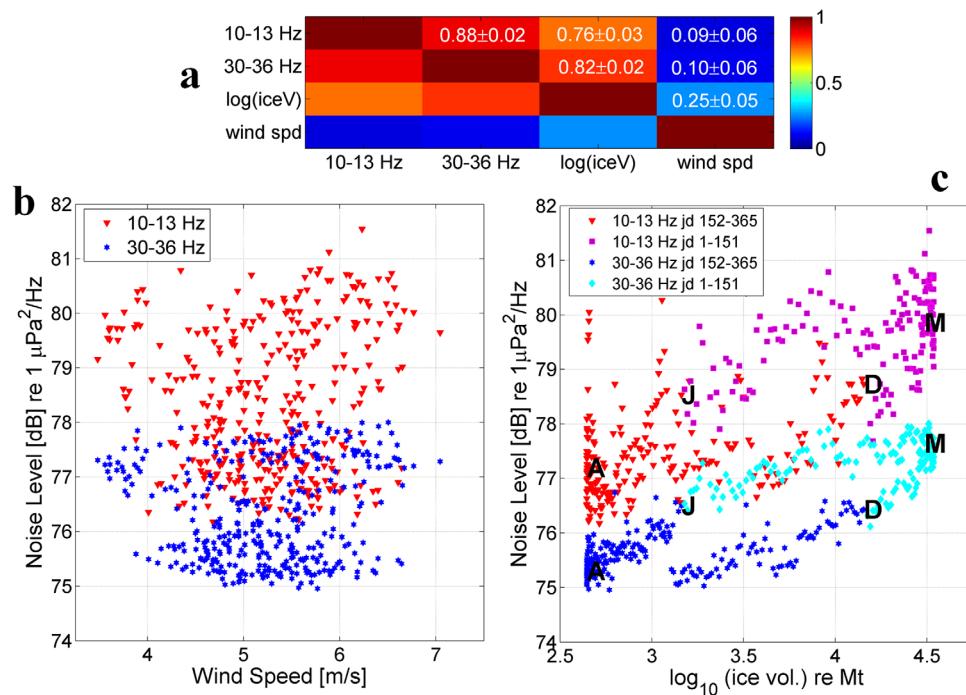


Figure 5. Correlations between acoustic noise levels, wind speed, and iceberg volume. (a) Correlation matrix shows that iceberg volume has a strong correlation of 0.76 and 0.82 with trend-removed acoustic noise levels in the 10–13 Hz and 30–36 Hz frequency ranges. Local wind speed at EEP and noise levels had low correlations of less than 0.16. (b) Scatter plot of acoustic noise levels at EEP-NW versus local wind speed. (c) Scatter plot of acoustic noise levels at EEP-NW and iceberg volume off Antarctica, showing a clear relationship between the iceberg volume and acoustic noise at the EEP, displaying a “hysteresis loop,” whereby the same volume of icebergs produces higher noise level during the austral summer-fall than the winter-spring. Data are color-coded by two seasons: summer and winter. For 10–13 Hz noise levels–ice volumes, red “inverted triangle” represent Julian days 152–365 and maroon “square” are days 1–151. For 30–36 Hz, blue “circle” represent Julian days 152–365 and light blue “diamond” are days 1–151. “A” is 15 August, “J” is 1 June, “D” is 31 December, and “M” is 15 March.

summer-fall than the winter-spring (Figure 5c). The potential influence of local wind speed at the EEP-NW is also examined using meteorological time series data from nearby climate buoys. Figures 4a and 5a, however, indicate that there is little (<0.16) correlation between the interannual daily wind speed data and noise levels. No relationship was found between the deep-water noise levels and wind within this wind speed range (0–7 m/s).

4. Iceberg Volume Versus Acoustic Noise Levels in the South Indian Ocean

At Cape Leeuwin IMS hydrophone station (HA01W) in the South Indian Ocean, similar to the Pacific EEP-NW case, narrow-frequency range noise levels repeat the seasonal pattern of austral summer-highs and winter-lows (Figure 6c). This is consistent to the monthly latitude Hovmöller diagram (Figure 6a) and iceberg volume (Figure 6b) in the Indian-Antarctic region between 30°E and 150°E . Noise maximum occurred also in March and minimum in late August to October with dynamic range of 7.5 dB in 10–13 Hz and 4.5 dB in 30–36 Hz. Correlations between the 10–13 Hz and 30–36 Hz sound levels and the total iceberg volume time series are 0.92 and 0.86, respectively (Table 1). The iceberg volume influence appears stronger at Cape Leeuwin than the Pacific because the distance from the HA01W hydrophone (34.892°S) to the Antarctic coast is ~ 3500 km, which is less than half of the $\sim 10,000$ km distance between EEP-NW (8°N) and Antarctica.

The mean noise levels at HA01W from 2004 through 2012 in 10–13 Hz and 30–36 Hz ranges were 89.0 dB and 84.7 dB re $1 \mu\text{Pa}^2/\text{Hz}$, respectively (Table 1), significantly higher than the EEP-NW levels in the Pacific. The iceberg volume in the Indian Ocean exhibited a decreasing trend from 2004 through 2012, at rate of 24 Gt/decade. During the same time window, noise levels in 10–13 Hz and 30–36 Hz ranges also decrease at a rate of -2.9 and -2.4 dB/decade, respectively. The high correlation values and agreement of the long-term

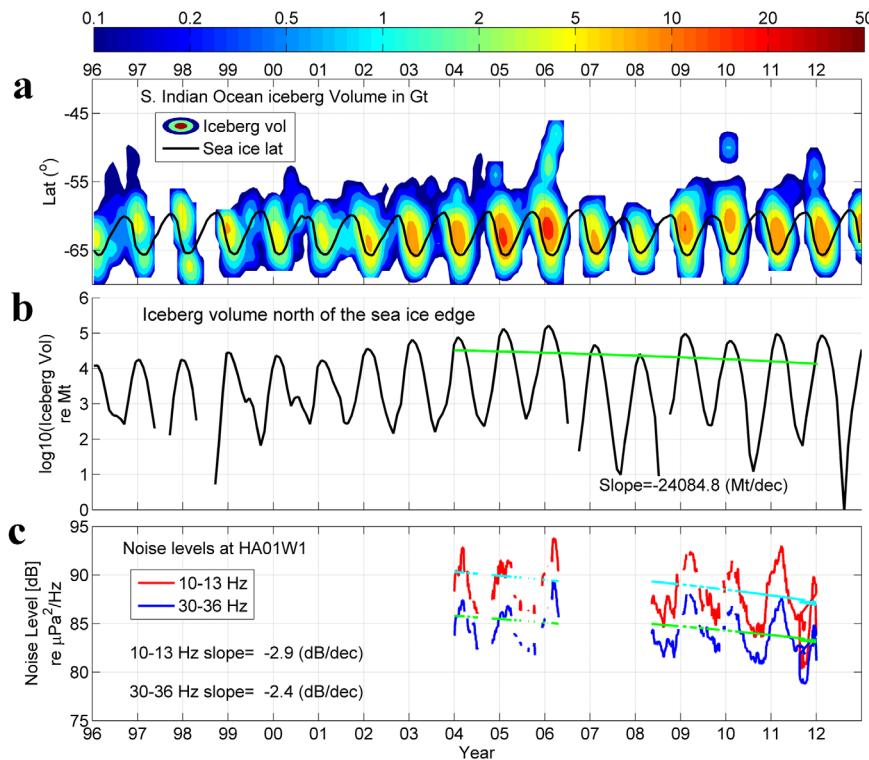


Figure 6. Iceberg volume and acoustic noise levels in the South Indian Ocean. (a) Time-latitude Hovmöller diagram of the monthly iceberg volume (in Gt) in the South Indian region between 30°E and 150°E from 1996 through 2012. Solid black line is the sea-ice edge. (b) Logarithm of altimeter-derived volume of icebergs in megaton north of the sea-ice edge in the Indian-Antarctic waters, which shows a ~24 Gt/decade decrease from 2004 through 2012. (c) Noise levels at Cape Leeuwin station HA01W1 between 10–13 Hz (red) and 30–36 Hz (blue) from 2004 through 2012. The linear trend from 2004 through 2012 is −2.9 dB/decade in the 10–13 Hz and −2.4 dB/decade in the 30–36 Hz band.

noise and iceberg volume trends suggest that the cause of the noise seasonality and long-trend is likely the iceberg volume of Indian-Antarctica region.

5. Iceberg Volume Versus Acoustic Noise Levels in the South Atlantic Ocean

From 2005 through 2012, in the Atlantic Ocean, Ascension Island hydrophone HA10S (Figure 1) show a seasonal pattern of austral summer-highs and winter-lows that matches that observed on the Pacific and the Indian Ocean records. The noise maximum also occurred in March with a minimum in August to October, and a dynamic range of 4.2 dB in the 10–13 Hz and 2.7dB in 30–36 Hz ranges. The monthly latitude Hovmöller diagram (Figure 7a) and total iceberg volume (Figure 7b) in the South Atlantic Ocean (70°W–30°E) are both in concert with the daily variations of noise levels (Figure 6c). Seismic air-gun shots, used primarily for oil exploration, are among the most pervasive anthropogenic noise sources in the Atlantic Ocean [Nieuwirk et al., 2004]. Despite the airgun noise in the Atlantic Ocean, correlation coefficients between the sound levels and the total iceberg volume are 0.88 and 0.84 in the 10–13 and 30–36 Hz ranges, respectively (Table 1). The iceberg influence is slightly stronger at HA10S than at EEP-NW in the Pacific. In the Atlantic icebergs drift out to as far north as ~45°S (Figure 7), whereas in the Pacific and Indian Oceans the lowest latitude is ~55°S. The distance from the HA10S Ascension Island station to the Antarctic coast is ~7000 km which is approximately twice the distance of Cape Leeuwin (HA01W) to Antarctica. The larger propagation loss and possible influence of air-gun noises could explain why in the Atlantic correlations are slightly lower than the values of the South Indian Ocean.

The mean noise levels at HA10S (8.9°S) from 2005 through 2012 in the 10–13 Hz and 30–36 Hz ranges were 86.6 dB and 83.1 dB re 1 $\mu\text{Pa}^2/\text{Hz}$, respectively (Table 1), significantly higher than at a similar latitude in the Pacific (EEP-NW, 8.0°N) but slightly lower than in the South Indian Ocean (HA01W, 34.9° S). The total iceberg

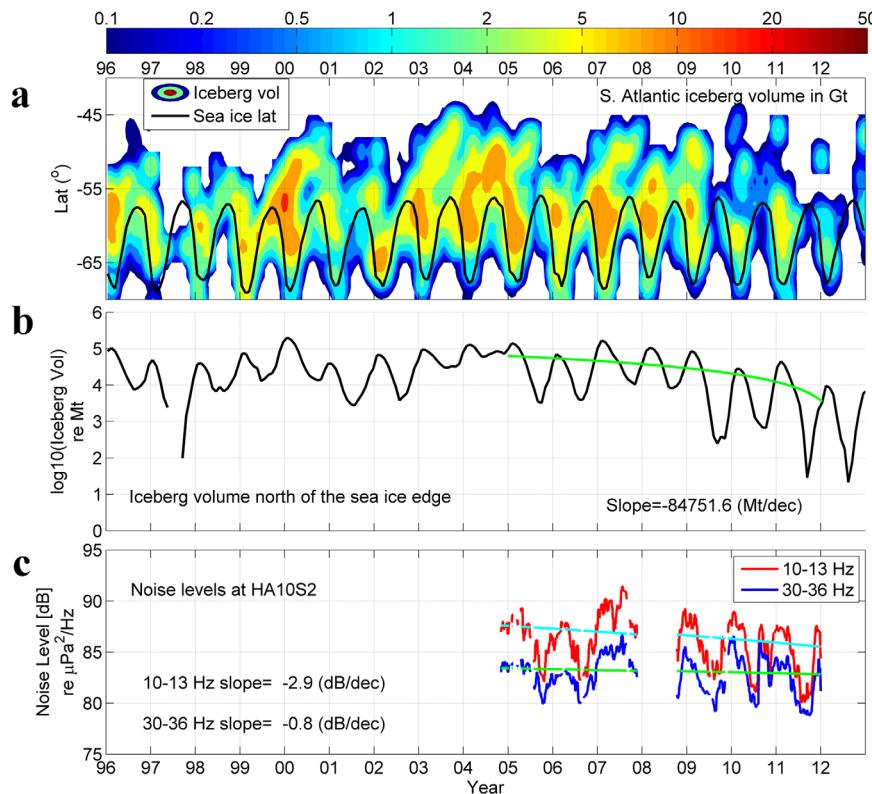


Figure 7. Iceberg volume and acoustic noise levels in the South Atlantic Ocean. (a) Time-latitude Hovmöller diagram of monthly iceberg volume (in Gt) in the South Atlantic region between 70°W and 30°E from 1996 through 2012. Solid black line is the sea-ice edge. (b) Logarithm of altimeter-derived volume of icebergs in megaton north of the sea-ice edge in the Indian-Antarctic waters, which shows a ~85 Gt/decade decrease from 2005 through 2012. (c) Noise levels at IMS Ascension Island station HA10S between 10–13 Hz (red) and 30–36 Hz (blue) from 2004 through 2012. The linear trend from 2004 through 2012 is –2.9 dB/decade in the 10–13 Hz and –0.8 dB/decade in the 30–36 Hz band.

volume in the South Atlantic exhibited a decreasing trend from 2005 through 2012 at rate of ~85 Gt/decade. During the same period, noise level trends in the 10–13 Hz and 30–36 Hz ranges also decreased at rates of –2.9 and –0.8 dB/decade, respectively.

6. Discussion

Our analysis demonstrates that within the most remote areas of all three Oceans in the Southern Hemisphere, including the equatorial eastern Pacific, the South Indian and the equatorial Atlantic Oceans, the seasonal drift and breakup of icebergs from Antarctica can generate sufficient acoustic energy to modulate distant sound levels. This effect is observed in the low-frequency ranges that are of likely ecological importance to many marine species [Stafford *et al.*, 1999]. In all three Oceans, the austral-summer-high and winter-low seasonality in low-frequency noise corresponds to changes in regional iceberg volume to the north of the Antarctic sea ice edge. Correlation values between the iceberg volume and narrow-frequency noise levels in the Pacific at EEP-NW in the 10–13 Hz and 30–36 Hz ranges are 0.76 and 0.82, respectively. In the South Indian Ocean at Cape Leeuwin, HA01W, correlations were 0.88 and 0.84 in the 10–13 Hz and 30–36 Hz ranges, respectively. In the Atlantic to the south of Ascension Island, HA10S, they were 0.76 and 0.82 in 10–13 Hz and 30–36 Hz ranges, respectively. Sound generation by icebergs, however, is not only a function of their volume. Rather, as icebergs drift to lower latitudes, the rate of disintegration can be accelerated by warm seawater and air as well as currents and wind [Scambos *et al.*, 2008]. This is evident by the small lag between the interannual iceberg volume and pressure time series, and the fact that the same volume of icebergs corresponds to a slightly higher noise level during the austral summer-fall than during the winter-spring.

In the case of the Pacific at EEP-NW (8°N, 110°W), this seasonal acoustic pattern was disrupted beginning in late 2007 through early 2009, when two massive icebergs, C19a and B15a, moved northeastward and

disintegrated through calving within the South Pacific Ocean. Our observations suggest that their breakup likely increased low-frequency ocean noise levels throughout the southern Pacific including HA03N (33.4°S , 78.9°W) over a period of 1.5 years. Prior to this event, long-term noise levels in the Pacific (EEP-NW) and the regional iceberg volume were both increasing, but the trends are too subtle to determine a robust relationship between the two time series. It is not clear if the iceberg volume in the Pacific-Antarctic region would have contributed to the noise leveling or decreasing as recently observed in the midlatitude of North American West Coast [Andrew *et al.*, 2011], where shipping and local seasonal winds are considered to be the dominant low-frequency noise sources. The distance from $\sim 60^{\circ}\text{S}$ to the North American West Coast hydrophones is only $\sim 15\%$ larger than the distance to the EEP-NW. Therefore, it seems possible that iceberg life cycle and volume trend in the Southern Ocean influence soundscape of relatively quiet waters in the midlatitude of northern hemisphere. Further studies are needed to confirm this.

The maximum concentration of icebergs is found in the South Atlantic followed by the Indian Ocean, and the least in the South Pacific [Tournadre *et al.*, 2012]. Considering the distances to each hydrophone station (Table 1), the order of iceberg volumes correlates to the mean noise levels in each Ocean. In all three Oceans, the iceberg sound energy contribution to the ocean soundscape is stronger in the 10–13 Hz than 30–36 Hz range, probably as a result of the fracture mechanism of the tabular icebergs, which is similar to earthquakes [Dziak *et al.*, 2013].

In the South Indian Ocean at Cape Leeuwin, and at lower latitudes in the Atlantic Ocean at Ascension Island, the trends in low-frequency noise levels and iceberg volume both decreased from 2004 through 2012. In the Pacific, ice volume begins decreasing in 2009, after the disintegration of C19a and B15a. Regional and temporal differences in iceberg volume, and sound level reflect the local distribution and stability of the ice sheets, iceberg drift paths, and sea-surface temperature anomalies [e.g., Maheshwari *et al.*, 2013]. Romanov *et al.* [2014] found possible links between El Niño events and iceberg concentration in the east Pacific and in the west Atlantic sectors of Southern Ocean but the results were still inconclusive. It is still premature to link the climate influence to the ocean sound environment in the Southern Hemisphere.

Our results indicate that icebergs are a dominant noise source in the Southern Hemisphere. The spatial and temporal distribution of iceberg volume therefore must be considered in any effort to understand recent changes in the global soundscape. Furthermore, these findings suggest that any significant increase in iceberg volume in the future could have far-reaching acoustic impacts on marine ecosystems.

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