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Low-frequency sound level in the Southern Indian Ocean

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This study presents long-term statistics on the ambient sound in the Southern Indian Ocean basin based on 2 years of data collected on six widely distributed autonomous hydrophones from 47°S to 4°S and 53°E to 83°E. Daily mean power spectra (10–100 Hz) were analyzed in order to identify the main sound sources and their space and time variability. Periodic signals are principally associated with the seasonal presence of three types of blue whales and fin whales whose signatures are easily identified at specific frequencies. In the low frequencies, occurrence of winter lows and summer highs in the ambient noise levels are well correlated with iceberg volume variations at the southern latitudes, suggesting that icebergs are a major sound source, seasonally contributing to the ambient noise, even at tropical latitudes (26°S). The anthropogenic contribution to the noise spectrum is limited. Shipping sounds are only present north and west of the study area in the vicinity of major traffic lanes. Acoustic recordings from the southern sites may thus be representative of the pristine ambient noise in the Indian Ocean. *© 2015 Acoustical Society of America*.
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I. INTRODUCTION

Investigating the variability of ambient sound in the oceans is the key for understanding many oceanic processes, such as surface wave interactions, wind, and climate change, as well as monitoring for seismic events and marine life. Oceanic ambient noise can be defined as a composite noise originating from all sound sources in the ocean (Kibblewhite and Jones, 1976) and ocean-bottom processes too. Because of the diversity of sources and their variable nature, ocean ambient noise can be difficult to assess without fully understanding their respective contributions (Wilcock *et al.*, 2014; Hawkins *et al.*, 2014). In the low frequency band (10–100 Hz), natural sources in the open-ocean are mainly marine mammals, seismic events, ice, and sea-state (Wenz, 1962; Wilcock *et al.*, 2014). In this frequency range, anthropogenic noise is generally produced by commercial shipping or seismic exploration (Hildebrand, 2009). In the Northern Hemisphere oceans, distant shipping is the dominant sound source (Wenz, 1962; McKenna *et al.*, 2012) and the overall development of shipping for the past four decades has been a concern for acoustic monitoring (Andrew *et al.*, 2002).

Ambient noise studies mostly focus on the North Pacific (Curtis *et al.*, 1999; Andrew *et al.*, 2002; Chapman and Price, 2011) and the Atlantic oceans (Perrone, 1969; Nieukirk *et al.*, 2004). Previous studies in the Indian Ocean have focused on the Northwest (Wagstaff, 2005) and the tropical Indian Ocean (Hawkins *et al.*, 2014). Based on data from the International Monitoring System near Diego Garcia Island (7°S), Miksis-Olds *et al.* (2013) showed that the increasing ship traffic correlates with an overall increase of the ambient noise level. Furthermore, Tournadre (2014) recently demonstrated that, during the last decade, the largest ship traffic increase occurred in the Indian Ocean. In the Southern Ocean, a recent study highlighted the predominant role of icebergs in the Southern Hemisphere soundscape (Matsumoto *et al.*, 2014). These acoustic studies, however, rely on data collected at sparse and isolated sites in the Central (Diego Garcia) and easternmost part of the Southern (Cape Leeuwin) Indian Ocean.

In an attempt to enrich the understanding of the global oceanic soundscape, particularly in the remote southern latitudes, this paper presents an analysis of long-term hydroacoustic time series collected in the Southern Indian Ocean by a network of autonomous hydrophones covering an area of about $3000 \times 4800\,\mathrm{km}^2$ between sub-tropical and southern latitudes. This network, initially designed for monitoring the low-level seismic as well as marine mammal activities in the Indian Ocean, provides an overall picture of the low-frequency (10–100 Hz) ambient noise distribution and its variability in time and space at a regional scale. The temporal variations appear to be mainly triggered by natural sources such as marine life and cryogenic events. The spatial variations at basin scale reveal that shipping is a dominant source to the north and that natural sources control the soundscape to the south.

II. DATA ACQUISITION AND PROCESSING

From February 2012 to March 2014, eight autonomous hydrophones were deployed at six sites in the Southern Indian Ocean (Table I and Fig. 1) and constitute the OHASISBIO experiment. The study area spans latitudes from 47°S (WKER) to 4°S (RAMA) and longitudes from 53°E (NCRO3) to 83°E (NEAMS). The instruments were moored in the axis of the sound fixing and ranging (SOFAR) channel, from 500 to 1300 m below sea surface. Data were recovered every year during the annual voyages of the RV Marion Dufresne to the French islands in the Southern

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TABLE I. OHASISBIO autonomous hydrophone (AUH) network.

Site	Geographic coordinates	Period of recording	Water depth (m)	AUH depth (m)
RAMA	3.83°S, 80.50°E	05/05/12–12/09/13	5000	1200
MAD	26.08°S, 58.14°E	03/10/12–02/16/14	5200	1300
NEAMS	31.59°S, 83.25°E	03/05/12–02/10/14	3800	1000
NCRO3	41.25°S, 53.10°E	01/30/12–01/10/14	3300	1100
SWAMS	42.99°S, 74.60°E	03/01/12–02/06/14	3400	1000
WKER1	46.64°S, 60.13°E	02/04/12–01/14/14	4510	500
WKER2	46.59°S, 60.58°E	02/05/12–10/23/13	4550	500
WKER3	46.83°S, 60.40°E	02/04/12–01/16/14	4400	500

Indian Ocean (French Southern and Antarctic Territories). The instrument at RAMA was moored in the Central Indian Basin for a year in 2012–2013. Instruments consist of a microphone connected to an acquisition and storage system developed by the Laboratoire Domaines Oceaniques (Brest, France). The acoustic data are digitized at a sampling rate of 240 Hz using a 24-bit analog-to-digital conversion. The hydrophone sensitivity is known to be around −163.5 dB re. 1 V/μPa including preamplifier gain. Raw data are corrected from the instrument response curve provided by the manufacturer, which has a flat spectrum in the frequency band between 1 and 110 Hz.

Power spectral density of the signal was estimated using a Welch's averaged modified periodogram method of spectral estimation. Data were divided by day into non-overlapping 200 s segments. In each segment, a fast Fourier transform algorithm (DFT) was applied to 240 samples in a Hann window, so the resolution of the one-sided spectrum is 1 Hz. A smoothed periodogram was then obtained by averaging all segments spectra. As an example, the 2-year long spectrograms at WKER1 and SWAMS sites are shown in Fig. 2. Daily spectral averages were then used to derive percentiles in the distribution of low-frequency noise levels. Different percentiles were computed at 1%, 10%, 50%, 90%, and 99% in order to investigate extreme and median conditions in the ambient noise.

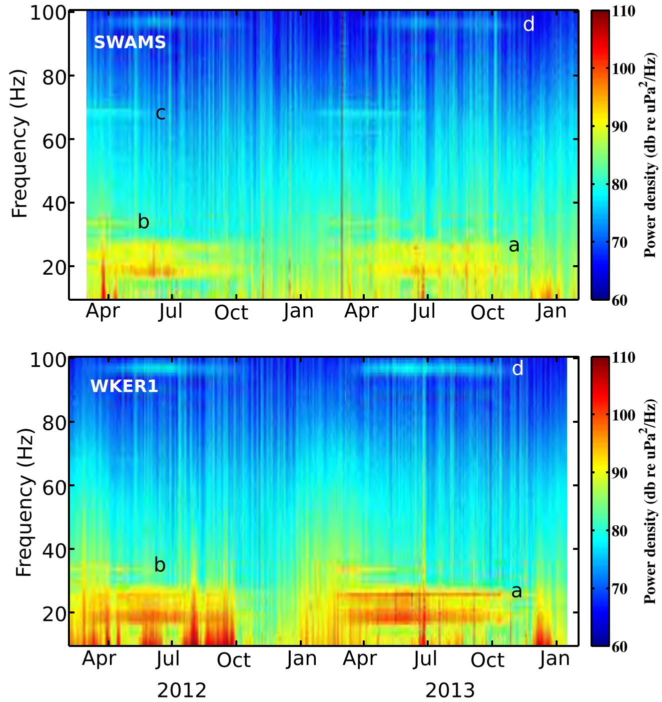

FIG. 2. (Color online) Spectrograms of the acoustic data collected at the WKER1 and SWAMS sites from March 2012 to January 2014. Each bin in the spectrograms corresponds to smooth Welch's periodogram averaged over 24 h with a spectral resolution of 1 Hz. The sound level is higher for WKER1 than SWAMS but displays similar patterns like in April 2012 and December 2013. Horizontal lines of higher energy outline the presence of several species of whales: (a) Antarctic blue whale, (b) Madagascar-type pygmy blue whale, (c) Australia-type pygmy blue whale, and (d) fin whale.

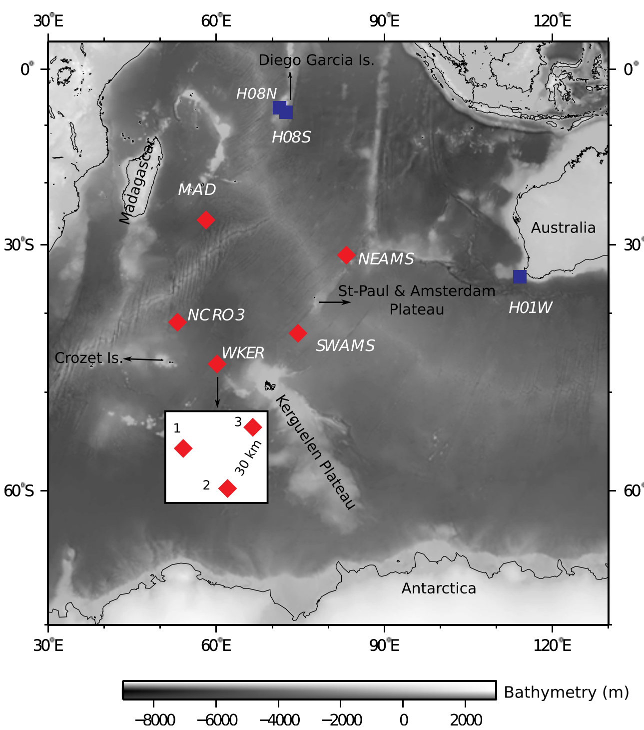

FIG. 1. (Color online) Hydrophone locations of the OHASISBIO network in the Indian Ocean (diamonds). The distance between the WKER hydrophones is 30 km. Squares indicate the permanent hydroacoustic stations of the International Monitoring System, labeled as H01W (Cape Leeuwin), H08N (Diego Garcia North), and H08S (Diego Garcia South).

Strong and seasonal oceanic currents and perhaps storms near Crozet Islands create non-negligible strumming effects on the mooring line at NCRO3. This results in a high-energy mechanical noise contaminating a wide range of frequency (up to 30–40 Hz). This noise is particularly important during the southern summer and autumn, while in spring and winter the strum is at its minimum. The greater occurrence of storms in the latter seasons suggests that they have little effect on the noise at these frequencies; furthermore, at this site, the hydrophone is moored 1100 meters below the sea-surface (Table I). High mechanical noise is not surprising in the dynamic environment of Crozet Islands, governed by the circulation of the sub-Antarctic front and the Agulhas return current (Park and Gamberoni, 1997) as well as strong internal tides. A different configuration of the mooring line was tested in 2013, but did not remove the strumming effects. For that reason, only the data from July 2012 to January 2013 are considered in this study.

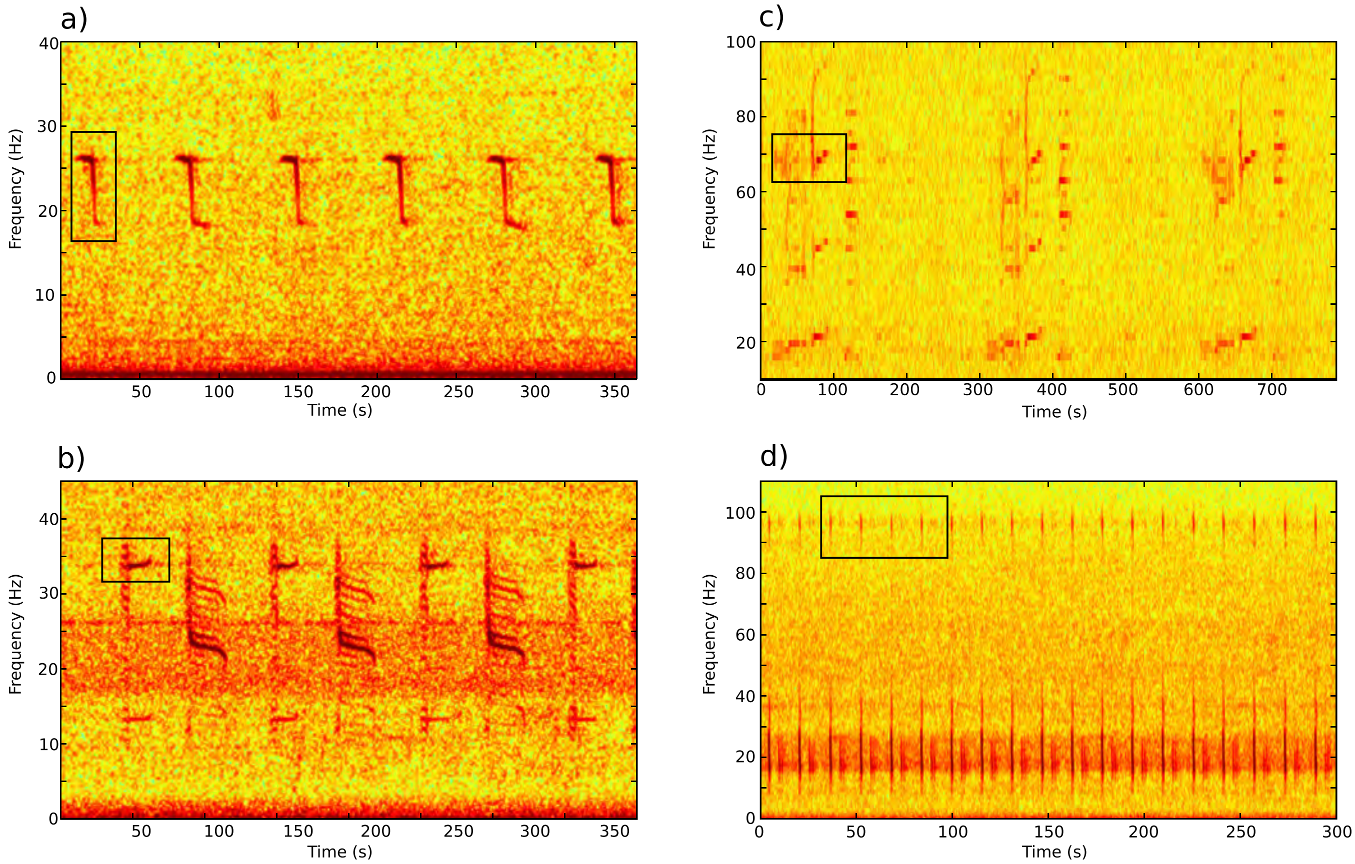

FIG. 3. (Color online) Typical spectrograms of recorded calls from (a) Antarctic blue whales, (b) Madagascar-type pygmy blue whales, (c) Australia-type pygmy blue whales, and (d) fin whales. Boxes outline the part of the call clearly visible in the long-term spectrograms of Fig. 2.

Out of the three instruments deployed west of Kerguelen Islands, only the data from the WKER1 site is used in this study, since at the scale of the triad (30 km; Fig. 1) all oceanic/climatic conditions can be considered the same. The oceanic dynamics around Kerguelen Islands (Park *et al.*, 2008) might also produce strong local current triggering strum on the mooring line (Fig. 2), mostly occurring in winter and spring and in a weaker way than at the NCRO3 site.

III. RESULTS

The spectral sound levels were computed for each hydrophone in the study area at five different percentiles of the distribution (Figs. 4 and 5). The overall median sound level in the 10–100 Hz differs from north to south and the energy spectrum varies significantly between sites and frequency ranges. Sound levels at RAMA and MAD slope from 78 dB at 10 Hz to 67 dB at 100 Hz and from 73 to 60 dB, respectively. Unlike the other sites in the study area, sound level in the 30–50 Hz band is dominated by distant shipping noise and appears flat. Daily variations in the sound pressure level are in the order of 20 dB at 10 Hz and 15 dB at 50 Hz and are associated with tectonic and shipping noise, respectively. Fluctuations in the 99th percentile of the distribution may indicate the presence of ships. Similar patterns in the sound spectrum are observed at the SWAMS, NEAMS, and WKER1 sites. Sound levels at SWAMS and NEAMS slope from 86 dB at 10 Hz to 66 dB at 100 Hz. High median sound levels are observed at WKER1 below 15 Hz and are mainly generated by a mechanical noise due to strumming on the mooring line but also by ice movements. Daily variations in the ambient noise at WKER1 are of 10–15 dB and reach up to 30 dB at 10 Hz due to tectonic activity, energetic ice movements and possible mechanical noise. Exception to that is the NEAMS site where the 99th percentile of the distribution exhibits highly fluctuating sound levels that could be explained by nearby or local shipping.

A clear difference is observed between the northernmost site RAMA and the five other sites in the study area, which display different patterns from north to south, depending on the frequency range (Fig. 6). In the 10–30 Hz frequency band, the sound level is the lowest at MAD, at all seasons. The sound levels tend to increase toward the southern latitudes, except at NCRO3 in the spring. Sound levels at SWAMS and WKER1 are higher than at RAMA, probably because of the greater contribution of whale calls to the southern soundscape. Latitudinal variations in sound levels have similar trends in the 40–60 Hz and 80–100 Hz frequency bands. Sound levels at RAMA are always higher than at the other sites, at all seasons. North to south variations in the sound level are in the order of 10 dB at 40–60 Hz and 8 dB at 80–100 Hz. When excluding the RAMA site, sound level differences do not exceed 4 dB from MAD to WKER1. In the 80–100 Hz frequency band the sound levels at NEAMS are lower than at the MAD site, reflecting the contribution of distant shipping to the MAD site, which is the closest to major traffic lanes in the Southern Indian Ocean.

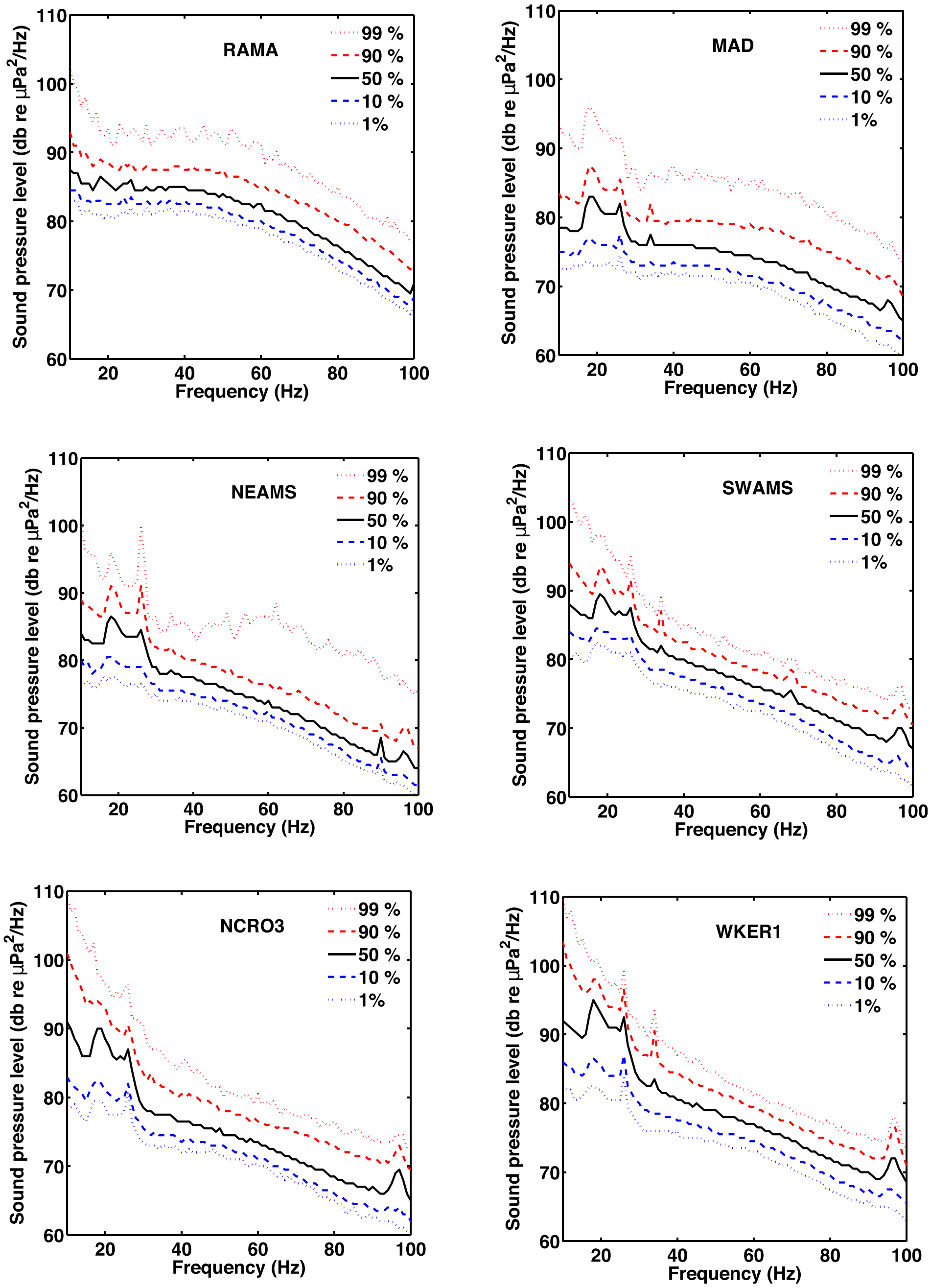

FIG. 4. (Color online) Noise distribution at different percentiles for each hydrophone of the OHASISBIO experiment, from north to south, averaged over 2012 and 2013. The NCRO3 plot is only based on 7 months of recording due to periods of high strumming noise that biases the frequency distribution.

A. Biological sounds

Whale vocalizations inside the study area are the dominant seasonal acoustic sources and produce the highest sound levels. A total of four (sub-)species of cetaceans are identified in this part of the Southern Ocean (Samaran *et al.*, 2013): the Antarctic blue whale (*balaneoptera musculus intermedia*), two sub-species of pygmy blue whale (Australian and Madagascar types, *b. m. brevicauda*), and fin whale (*b. physalus*). Antarctic blue whales (Fig. 3) are present year-round in the study area, with highest levels between April and June. Their signal is clearly identified as the highest sound level peaks at 18–28 Hz for all stations (Figs. 2, 4, and 5). A second peak at 34 Hz is associated with the Madagascar-type pygmy blue whale, which is recorded at every site from February to June with a maximum visibility in May (Figs. 2 and 5). Fin whale calls are recorded at every station with similar levels at 96 and 20 Hz (Fig. 3) and are present all year long with highest levels between May and July. Australia-type pygmy blue whales are only recorded at SWAMS with a dominant frequency at 23 Hz and a harmonic around 68 Hz, which does not appear at other locations. At RAMA site, only fin whales can be recognized from the spectrogram around 20 Hz. Antarctic blue whales are not expected to be detected at this latitude, since they would unlikely migrate further north than sub-tropical to tropical latitudes (Stafford *et al.*, 1999).

B. Cryogenic sounds

Aside from baleen-whale calls at specific frequencies, most temporal variations occur below 15 Hz and are likely due to climatic effects, since shipping traffic is very limited in the Southern Ocean. For instance, ice tremors and iceberg cracking can produce energetic signals in this very low frequency range

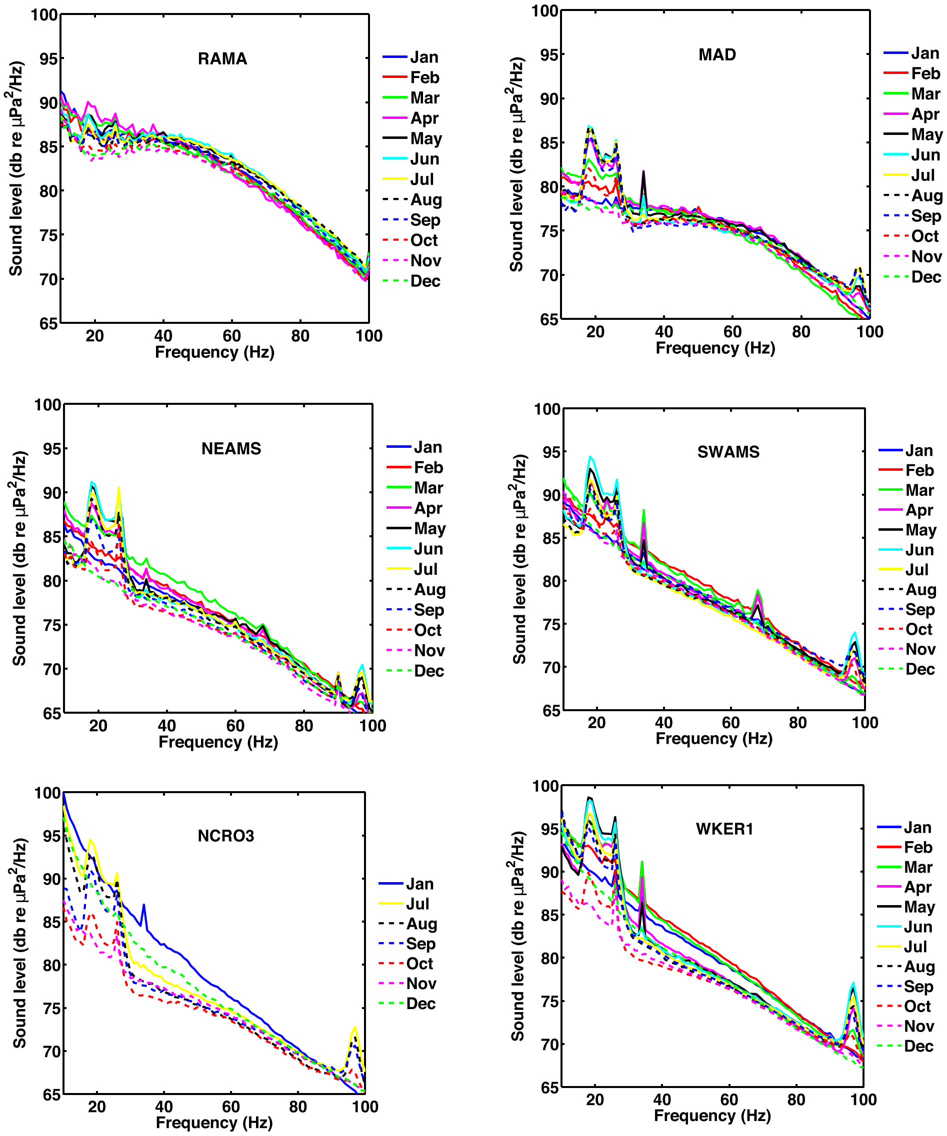

FIG. 5. (Color online) Monthly median sound levels as a function of frequency for each site of the OHASISBIO network (average over 2012 and 2013). The NCRO3 plot only shows 7 months of recording in 2012 with no or limited strumming noise.

(Chapp *et al.*, 2005; Talandier *et al.*, 2006; Matsumoto *et al.*, 2014; Royer *et al.*, 2015) but also at higher frequencies up to 400 Hz (Dziak *et al.*, 2013). In order to test this hypothesis, the ice volume at high latitudes is compared to the sound level in the southern Indian Ocean. The monthly iceberg volume (in Gt) from January 2012 to December 2013 was extracted from the satellite-derived ALTIBERG database (Tournadre *et al.*, 2008) between 30°E to 130°E. The total volume of icebergs per month was obtained by adding the contribution from all the grid cells from the Antarctica up to 50°S (Fig. 7). Sound level time series were extracted in the narrow 10–13 Hz frequency band following Matsumoto *et al.* (2014). The 30–36 Hz band was excluded here due to the presence of the Madagascar-type pygmy blue whale that could bias the comparison. In 2012 and 2013, sound levels show a seasonal pattern with summer highs and winter lows that matches the variations in the iceberg volume. High correlation coefficients (0.74 for MAD and NEAMS, 0.84 for SWAMS) between the ice volume and the sound level at 10–13 Hz suggest that the presence of icebergs is a major driver for changes in ambient noise levels, even as far north as site MAD (26°S).

Moreover, a large number of cryogenic events were identified in the acoustic records, even at the remote site MAD (Royer *et al.*, 2015). Most of these events have been located by triangulation from the arrival times on several hydrophones. In 2012, the number of events recorded per week is well correlated to the variations in ice volume and support the hypothesis that icebergs are a dominant sound source in the low frequency band (Fig. 7). Sound levels observed in the north are, however, lower than in the south, which is consistent with increasing distances of the hydrophones from the ice front. The WKER1 site, the closest to the Antarctic latitudes, displays broad peaks up to 94 and 100 dB in the noise level, nearly at all seasons, which probably combines a large cryogenic component and mechanical noise; some of these peaks are probably solely due to this current-induced noise. So the correlation is not as obvious as for the sites less affected by strumming noises. But if MAD and NEAMS, the furthest away from the ice front, record ice-related noises, it is very unlikely that the southernmost site of the network would not do so, given its overall high sound level.

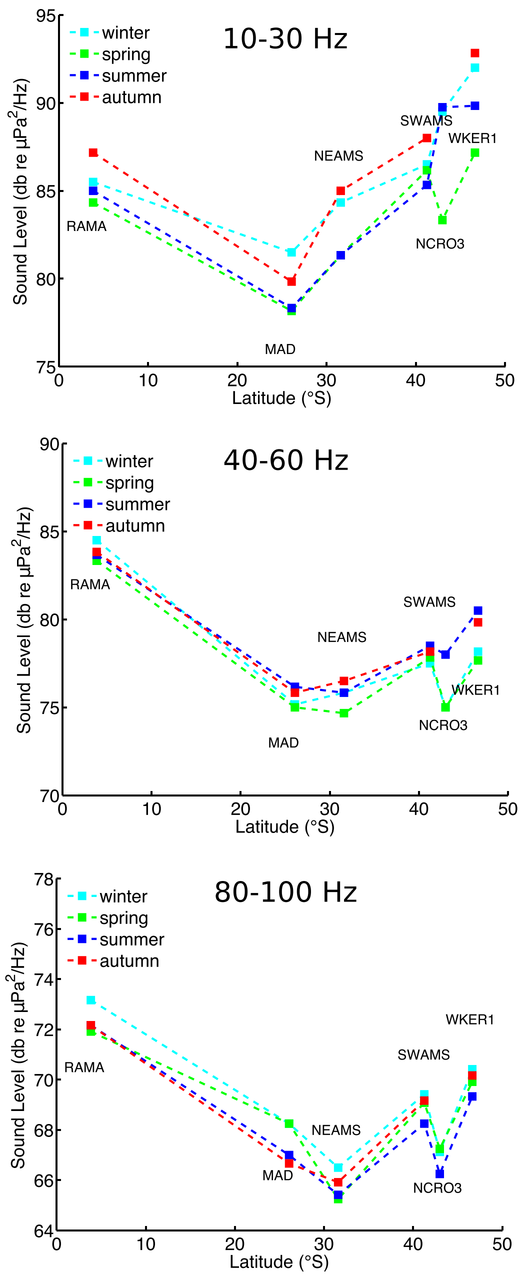

FIG. 6. (Color online) Variations in the sound levels as a function of latitude at different seasons and frequency bands: (top) 10–30 Hz, (middle) 40–60 Hz, and (bottom) 80–100 Hz. The NCRO3 sound level in autumn are not shown due to strong strumming effects on the mooring line. Median sound levels are averaged over 2 years, except at NCRO3, where only 2012 is considered.

IV. DISCUSSION

A great variability in the sound level is observed in the Indian Ocean, and spatial and temporal variations reflect the contribution of local and distant sources at different ranges of frequency. There is a clear difference between the northernmost RAMA site and the other sites. The ambient sound level is globally higher at RAMA, except in the very low-frequency 10–30 Hz band, where the southernmost sites exhibit similar or higher sound levels, likely due to the greater contribution of whale calls in this frequency band. At higher frequencies, dominated by shipping noise and distant shipping, the sound levels at RAMA are always higher than

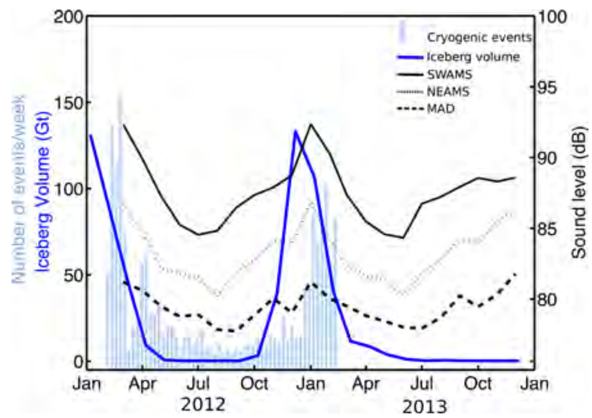

FIG. 7. (Color online) Comparison of the total iceberg volume in the Indian Ocean per month from January 2012 to December 2013 and average monthly sound level in the 10–13 Hz frequency band at different sites. Three sites are not shown: sound levels in this bandwidth at NCRO3 (2012) and WKER1 (2012–2013) sites are dominated by mechanical noises, which obscure the cryogenic component; the RAMA site is located more than 50° north and away from Antarctica. The histogram shows the number of cryogenic events located during the year 2012 from their arrival times at three or more hydrophones.

at the other sites in the study area, revealing the major contribution of traffic to the ambient noise. At the other locations, different patterns are observed, showing that the acoustic dynamics is clearly different to the north and to the south. Sound levels decrease linearly with increasing frequency at the southern sites, while it is not the case at RAMA and MAD. Furthermore, from MAD to WKER1, sound levels generally increase, independently of the time period or frequency band. Because the distribution of sound levels is very similar from one site to another, this might indicate that the natural sound sources are the same across the basin and prevail in the southern part of the study area.

Median ambient noise levels at 50 Hz range from 85 dB at RAMA site to 75 dB near the Madagascar Basin (MAD) or the St-Paul and Amsterdam Plateau (SWAMS and NEAMS). The overall higher sound levels recorded at RAMA are within the same range than those reported by Miksis-Olds *et al.* (2013) at Diego Garcia South (7°S), roughly 1000 km away. Similar sound levels are observed off the California coast (Andrew *et al.*, 2002; McDonald *et al.*, 2006), revealing the contribution of shipping noise to the overall ambient noise. Sound levels are also higher above 50 Hz at RAMA reaching 73 dB at 100 Hz while it is only 66–68 dB at other sites. The significant increase in ship number observed near coastal region in the Central Indian Ocean (Miksis-Olds *et al.*, 2013; Tournadre, 2014) is thus also observed in deep and remote ocean areas like at RAMA site, where sound levels are loud in the 10–100 Hz range. This shows that shipping noise can be the dominant sound source, even at deep-sea sites. At the other locations sound levels are lower with values ranging from 75–80 dB at 50 Hz to 66–68 dB at 100 Hz. This result is consistent with the ambient noise predicted in a context of remote and light shipping (Ross, 1976), commercial routes being limited in the Southern Indian Ocean. The measured levels are slightly higher than those reported in the subtropical Pacific (Sirovic *et al.*, 2013) or off Southern California (McDonald *et al.*, 2008), which are typical regions of light shipping. This higher noise-level is thus likely due to the contribution of ice (Dziak *et al.*, 2013) and possibly sea-state related noise. Currents also trigger a high-energy mechanical noise at the southernmost NCRO3 and WKER1 sites. The median distribution of the noise level in the southern sites (NEAMS, SWAMS, NCRO3, WKER1) may thus be representative of the pristine sound level in the Indian Ocean.

Biological sounds are an important component of the ambient noise and largely contribute to its seasonal pattern at specific frequencies. Antarctic blue whales are detected year-round across the study area, as fin whales, with maximum call amplitude during austral winters (Figs. 2 and 5). Blue whales are believed to feed off Antarctica during southern summer and to migrate north during winter. While their location of wintering is still debated, Stafford *et al.* (2004) suggest that Antarctic blue whales winter in different places and spread north in the Pacific and Indian oceans. Although calls are detected near Diego Garcia Island during the southern autumn (Stafford *et al.*, 2004), the paucity of calls and previous observations (Mackintosh, 1972) suggest that Antarctic blue whales do not migrate much above sub-tropical latitudes as confirmed by the recordings at RAMA (Figs. 4 and 5). Based on a similar hydrophone experiment in 2007, Samaran *et al.* (2013) demonstrated that a part of the Antarctic blue whale population is likely to winter in sub-tropical and temperate latitudes. The data presented here are consistent with their observation. Although the number of calls or the number of individuals cannot be derived directly from spectral averages, sound levels show seasonal peaks matching with peaks in the number of detected calls, suggesting that the average sound level could be indicative of the abundance of marine mammals. Similar observations are made for the Madagascar pygmy blue whales, whose sound level peaks in autumn. As suggested by Stafford *et al.* (2011) and Samaran *et al.* (2013), Madagascar- and Australia-type pygmy blue whales seem to be geographically distributed between west and east longitudes, although the actual limit of their territories is quite uncertain. The absence of a clear peak on WKER1 and NCRO3 spectrum suggests that only few Australia-type whales migrate further west of 75°E. These results demonstrate the relevance of wide hydroacoustic networks for regional scale studies of whale behavior and migration patterns.

Sound levels below 15 Hz are generally higher to the south and present seasonal variations with winter highs and summer lows revealing that climate is presumably the principal driver of ambient noise changes, as suggested by Matsumoto *et al.* (2014). Sound levels at these frequencies near Kerguelen are within the same range as those reported by Matsumoto *et al.* (2014) at H01W (Fig. 1) and two other IMS stations in the southern ocean. However stations NEAMS and SWAMS, located north and south of the St-Paul and Amsterdam Plateau, respectively, display 3–5 dB lower levels. The total iceberg volume in the Southern Indian Ocean exhibits a temporal pattern that matches the changes in the sound level at each site even at the remote MAD station, located at a sub-tropical latitude (26°S). High correlation coefficients suggest that ice generated noise dominates the ambient noise level in the low frequency band but also above 15 Hz. Matsumoto *et al.* (2014) showed a similar good agreement between ice volume and noise level time series in the 30–36 Hz narrow band, showing that high energy ice signals can propagate over long distances even at higher frequencies. Exception to that are the NCRO3 and WKER1 sites, where strumming on the mooring line due to local oceanic currents produce a high-amplitude mechanical noise that obscures any trend. This noise is seasonal and is particularly important in autumn at NCRO3 and WKER1. Such mechanical noise is not recorded by the hydrophones at lower latitudes. The recording and location of numerous cryogenic events during the year 2012, however, exhibit a similar seasonal pattern. This support the idea that icebergs, and most presumably ice, are important drivers of noise in the southern oceans, but also at higher latitudes. During austral winter, in the absence of drifting and disintegrating icebergs, sound levels decrease by 6–7 dB on average and low-frequency noise is mainly dominated by transient tectonic events.

V. CONCLUSION

This analysis shows that natural sources are dominant in the Southern Indian Ocean soundscape. North to south variations and seasonal patterns in the ambient noise level indicate that ice is the main source of noise below 15 Hz and that an increase in iceberg volume triggers a basin-wide increase in the ambient noise level. To fully characterize the ambient noise in the Southern Hemisphere, collecting additional data from South Pacific and South Atlantic oceans would help quantify the overall contribution of ice to ambient noise changes. Sound levels observed at tropical and sub-tropical latitudes are consistent with a general increase in ship traffic at these latitudes although more observation sites are needed for a better estimation of long-term trends. The contribution of distant shipping does not extend south of the Madagascar Basin. The southernmost sites of the study area are located in a region with little or no shipping, they might thus be representative of the pristine ambient noise in the Indian Ocean. In this respect, the recordings at the OHASISBIO southern sites may be used as a reference to evaluate the acoustic impact of anthropogenic noise on marine life and baleen whales in particular. The OHASISBIO experiment started in 2010 and will continue several more years. Only 2 years have yet been analyzed. Long-term deployments of hydrophone in remote areas of the world ocean and at a basin scale is a demanding enterprise, but remains the only way to describe the complexity of the ocean soundscape and to monitor its evolution due to global environmental changes and human activities.

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