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The not-so-silent world: Measuring Arctic, Equatorial, and Antarctic soundscapes in the Atlantic Ocean

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A R T I C L E I N F O

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A B S T R A C T

Anthropogenic noise in the ocean has been shown, under certain conditions, to influence the behavior and health of marine mammals. Noise from human activities may interfere with the low-frequency acoustic communication of many Mysticete species, including blue (*Balaenoptera musculus*) and fin whales (*B. physalus*). This study analyzed three soundscapes in the Atlantic Ocean, from the Arctic to the Antarctic, to document ambient sound. For 16 months beginning in August 2009, acoustic data (15–100 Hz) were collected in the Fram Strait (79°N, 5.5°E), near Ascension Island (8°S, 14.4°W) and in the Bransfield Strait (62°S, 55.5°W). Results indicate (1) the highest overall sound levels were measured in the equatorial Atlantic, in association with high levels of seismic oil and gas exploration, (2) compared to the tropics, ambient sound levels in polar regions are more seasonally variable, and (3) individual elements beget the seasonal and annual variability of ambient sound levels in high latitudes. Understanding how the variability of natural and man-made contributors to sound may elicit differences in ocean soundscapes is essential to developing strategies to manage and conserve marine ecosystems and animals.

1. Introduction

The ocean is a noisy place. In the six decades since Jacques Cousteau popularized the "Silent World" of life in the sea (Cousteau, 1956), mechanized anthropogenic activities such as shipping, oil and gas exploration, renewable energy development, and fishing have threatened marine ecosystems by acoustically intruding on the habitats of marine species (Davidson et al., 2012; Halpern et al., 2007; Kappel, 2005; Read, 2008; Rolland et al., 2012). Chronic noise generated by anthropogenic activities can be especially harmful to marine mammals that rely on low-frequency communication space to send and receive acoustic signals (Clark et al., 2009). Increased sound levels from anthropogenic activities influence marine mammals by hindering communication (Hatch et al., 2012), altering communication behavior (Parks et al., 2012), altering locomotive behavior (Pirotta et al., 2012), and inducing stress (Rolland et al., 2012). Higher sound levels can also damage animal hearing (Southall et al., 2016) and reduce an animal's ability to hear environmental cues that are vital for survival, e.g., avoiding predators, finding food, and navigation (Clark et al., 2009; Hatch et al., 2012).

Collectively, the acoustic signals present in a particular location and time are the "soundscape" (Pijanowski et al., 2011). A soundscape is comprised of three "components" of sound: geophysical, anthropogenic, and biological (Fig. 1). Individual sources of sound, or "elements", can be grouped into one of the three soundscape components. The relative contribution of an element to one of the three soundscape components is influenced by drivers such as ocean processes, tectonics, climate, or policies (e.g. marine protected areas). Soundscape components can also directly influence other components; for instance, ice is a geophysical element of sound that can also limit the physical accessibility of an area to both animals and vessels. Compartmentalizing elements of sound into broader soundscape components facilitates comparisons of sound levels over time and among different regions, providing insight to the status of an ocean ecosystem.

As it is more difficult to monitor across widely separated sounds-

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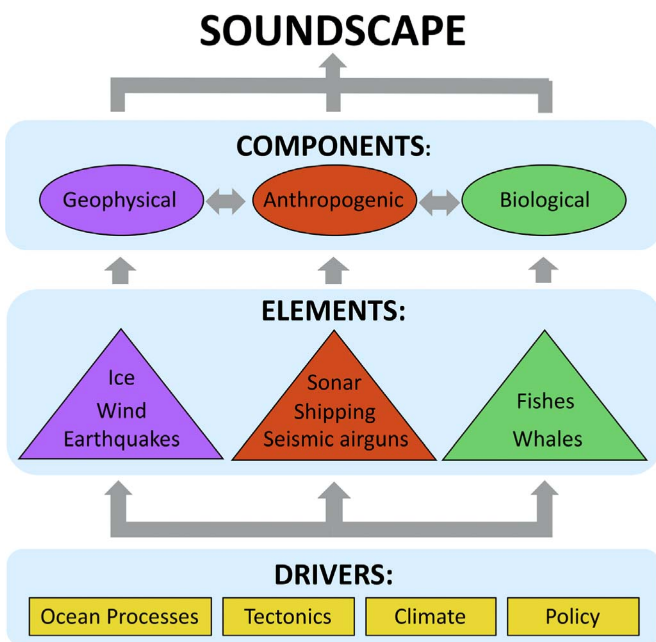

Fig. 1. Flowchart of soundscape composition. A soundscape is composed of three components, geophysical, anthropogenic, and biological, which are comprised of elements that are influenced by broad drivers.

capes than discrete, smaller areas, few research efforts have attempted to compare ambient sound levels across ocean basins. However, for marine animal conservation, ocean sound is a global concern; it is just as important to monitor ocean ambient sound on a broad scale as it is to focus on discrete areas because many species migrate over extended distances or maintain widespread seasonal habitats that transcend national boundaries. Garnering information about an area from its soundscape is a non-invasive, low-cost strategy that can frame a comprehensive assessment of ecosystem dynamics as well as human influence. Passive acoustic technology is commonly used to monitor and determine the contributions of sound sources to the ambient sound field (Gedamke et al., 2016; Van Parijs et al., 2015). Archival or real-time recordings are analyzed for the frequency and intensity of natural and man-made sounds. By identifying how elements of sound may affect soundscape components over temporal and spatial scales, soundscape monitoring is essential for understanding how patterns and trends of ocean ambient sound may impact marine animals (Hatch et al., 2016).

The purpose of this study was to investigate and compare baseline and seasonal changes in low-frequency (15–100 Hz) sound levels among Arctic, Equatorial, and Antarctic soundscapes in the Atlantic Ocean. This manuscript describes how these changes are related to the variability of the anthropogenic and biological elements in each soundscape, and serves as an example of why increasing ocean sound levels are of global concern. Deciphering the relationships among the elements and components of low-frequency ambient sound throughout the Atlantic basin is integral to developing targeted strategies to manage ocean noise that may be harmful to marine animals and ecosystems.

2. Background: soundscape elements in the Atlantic Ocean

The three target soundscapes for this study were selected for a diversity of exposure to anthropogenic activity, animal presence, and climate. The varied tectonics, climate, and ocean processes of each site drive the elements that are present in the different soundscapes over time. The following components and elements of a soundscape were considered when investigating sound levels in our study areas.

2.1. Geophysical elements

2.1.1. Sea ice

Sea ice may act as a physical barrier to vessels and marine mammals in addition to acoustically contributing to the geophysical component of a soundscape (e.g. via melting (Urick, 1971), internal cracking (Milne and Ganton, 1964), and calving (Matsumoto et al., 2014)). Sea ice cover can also limit propagation of abiotic sources of sound (e.g., wind, waves) through the upper surface layer (Menze et al., 2017).

2.1.2. Wind

Weather contributes substantially to soundscapes, but because the most common weather elements, wind and rainfall, produce signals that are best detected above the upper frequency limit of the hydrophone systems used (100 Hz) (Klinck et al., 2012; Nystuen, 1986; Vagle et al., 1990), these sources were not analyzed for individual contributions to the ambient sound field in this study. Sound from wind can only be correlated with frequency levels below 100 Hz in areas unaffected by anthropogenic or biological sources of sound below 100 Hz (Burgess and Kewley, 1983; Cato, 1976). Pervasive sounds from anthropogenic or biological sources were expected to affect all experiment soundscapes, preventing quantification of the contribution of wind to ambient sound levels (Wilcock et al., 2014).

2.1.3. Natural seismicity

Undersea earthquakes can influence sound levels in a soundscape (Wilcock et al., 2014). However sounds from earthquakes were not expected to significantly influence this soundscape investigation because peak energy of natural seismic events is typically between 5 and 15 Hz (Simao et al., 2010; Webb, 1998; Wilcock et al., 2014), below the lower limit of the frequency range of our data. Additionally, the hydrophones were each deployed in similar deep-ocean tectonic environments (i.e., seafloor spreading centers), and a preliminary investigation of geophysical activity in the three areas revealed that each site was subjected to similarly low levels of stochastic background earthquake activity (mean of <2 per month[1]) (USGS Earthquake Hazards Program, 2016).

2.2. Anthropogenic elements

The ocean propagates low-frequency sound efficiently and allows such signals to travel over long distances (Munk, 1994; Wilcock et al., 2014). Thus, low-frequency noise created by the high level of anthropogenic activity in the northern and southern hemispheres of the Atlantic Ocean can not only travel across the entire basin to both coastlines, but also latitudinally from each hemisphere to the equator (Munk, 1994; Nieukirk et al., 2012). Compared to the Pacific, the Atlantic ocean has more overall shipping traffic, a higher (coastal) population density, and is home to large oil reserves (Kaluza et al., 2010; Shirley, 2005). Collectively, these growing sources of anthropogenic sound may contribute to increases of ambient noise levels over time (McDonald et al., 2008, 2006; Miksis-Olds and Nichols, 2016).

2.3. Shipping

The soundscapes analyzed in this study were not located near ($<$ 500 nm) major shipping lanes (Arctic Council, 2009; Dziak et al., 2015; Miksis-Olds and Nichols, 2016), thus, vessel sounds associated with regular shipping routes could not be precisely detected. Tonal sounds

[1] Between August 2009 and December 2010, 25 earthquakes (>2.5 magnitude) occurred along the mid-Atlantic ridge within 500nm of Ascension Island, 44 earthquakes occurred north of Iceland along the mid-Atlantic ridge near the Fram Strait, and 19 events were recorded within 900nm of the Bransfield Strait (USGS Earthquake Hazards Program, 2016).

from distant shipping are easily masked by other elements of sound, inhibiting the ability of an experienced analyst or software detector to consistently and accurately estimate the impact of vessel sounds on a soundscape. Specifically, the sites selected for this experiment were directly impacted by more proximate seismic airgun signals which are comparatively louder (1 m source levels) than commercial shipping (Goold and Coates, 2006; Hatch and Wright, 2007; Richardson et al., 1995).

2.4. Seismic airguns

Seismic airguns, used in exploration for fossil fuels under the seabed, are one of the predominant elements of anthropogenic sound below 100 Hz (Tolstoy et al., 2004). Organized in multi-unit arrays, each airgun expands and contracts releasing pressurized air underwater and creating a loud transient signal (< 0.1 s, 235–260 dB *re* 1 μ Pa at a frequency of 2–188 Hz at 1 m) that penetrates the ocean floor to reflect off subsurface features in the exploration for gas and oil reserves (Caldwell and Dragoset, 2000; Hatch and Wright, 2007). Industrial seismic airgun surveys typically continue over weeks or months, with shots being discharged at intervals of 10–15 s (not including reverberation) depending on the survey (Caldwell and Dragoset, 2000). Seismic airgun activity has been shown to affect over 37 marine species, inducing behavioral changes such as decreasing vocalization rates and avoiding areas in range of seismic airgun surveys (Stone and Tasker, 2006; Weilgart, 2014). Given that seismic airgun signals are easily identified and measured in acoustic data, these signals were analyzed in this study as the representative element of anthropogenic sound in each soundscape. Typically, the frequency range of airgun pulses does not differ widely between equipment and location (Caldwell and Dragoset, 2000), permitting a comparison of airgun acoustic presence among soundscapes.

2.4.1. Biological

Acoustic recordings were also analyzed for biological sources of sound. Vocalizations of endangered blue (*Balaenoptera musculus*) and fin (*B. physalus*) whales (IUCN, 2016) were selected to represent the biological component of each soundscape; both species are acoustically active in all three study locations, and their low-frequency calls (typically less than 100 Hz) are reliably recorded by the hydrophones. The most common fin whale call, the "20 Hz pulse", is a highly stereotyped short pulse signal in the 18–25 Hz frequency band (Watkins, 1981; Watkins et al., 1987), and is present in recordings at all three sites. Two species of blue whale vocalizations were present in the recordings: Atlantic (*Balaenoptera musculus musculus*) and Antarctic (*B. m. intermedia*). Both Atlantic and Antarctic blue whales produce low-frequency vocalizations in the 10–40 Hz range, but the principal (low-frequency) call type varies by species (Fig. 2). Antarctic blue whale calls differ from Atlantic blue whale calls in shape and duration, and the initial energy of the Antarctic blue whale signal is concentrated at a higher frequency, 27 Hz compared to 19 Hz (Ljungblad et al., 1998; Mellinger and Clark, 2003; Stafford et al., 2004).

3. Methods

3.1. Data collection

Acoustic recordings from August 2009 through December 2010 were obtained from a Comprehensive Nuclear-Test-Ban Treaty Organization International Monitoring System (CTBTO IMS) hydrophone cabled sensor at Ascension Island (8°S, 14.4°W) (Fig. 3). The CTBTO IMS is a network of coordinated moorings established in the Pacific, Indian, and Atlantic Oceans established to listen for and locate nuclear explosions. The CTBTO IMS site location at Ascension Island consisted of two arrays of three omni-directional hydrophones that

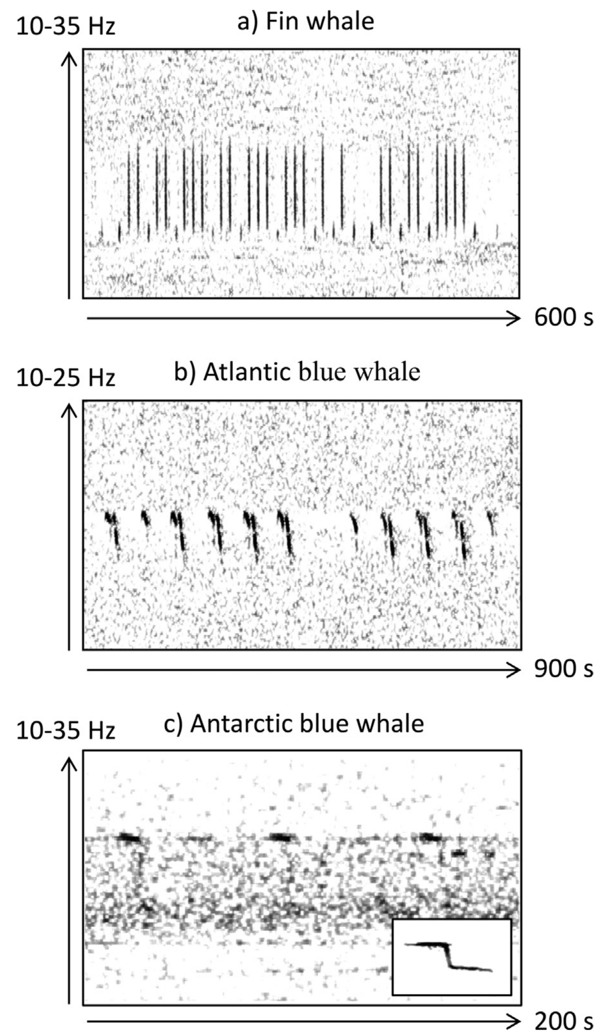

Fig. 2. Spectrograms (Hann window) of fin whale 20-Hz calls (FFT 1024, 50% overlap), and Atlantic (FFT 256, 25% overlap) and Antarctic-type (FFT 1024, 90% overlap) blue whale calls, recorded in 2009 at Ascension Island (fin, Atlantic blue) and the Bransfield Strait (Antarctic blue) in the Atlantic Ocean.

record continuous low-frequency sound at a 250 Hz sampling rate. One array was deployed on the north of Ascension Island; the other was deployed south of the island. The hydrophones were calibrated individually prior to initial deployment in January 2002 and re-calibrated while at-sea in 2011. All hydrophones had a flat (3 dB) frequency response from 8 to 100 Hz. Information from individual hydrophone response curves was applied to the data to obtain absolute values over the experiment frequency spectrum (15–100 Hz). Furthermore, each hydrophone is suspended in the Sound Fixing and Ranging (SOFAR) channel to maximize the spatial coverage of the observations (Urick, 1983). Archived recordings from the southern Ascension Island hydrophone (Ascensions S) were selected for this analysis, and the hydrophone depth at this location was 865 m (seafloor depth ~3442 m) (Miksis-Olds and Nichols, 2016).

Simultaneously, two additional calibrated Autonomous Underwater Hydrophones (AUHs) (Dziak et al., 2010; Klinck et al., 2012) were deployed in the SOFAR channel at a depth of ~ 500 m in the Fram Strait (79°N, 5.5°E) and the Bransfield Strait (62°S, 55.5°W). The seafloor depths were approximately 2645 m and 1852 m, respectively. The systems used ITC-1032 hydrophones (International Transducer Corp., Santa Barbara, CA, USA). Each AUH was equipped with a custom-built pre-amplifier with pre-whitening gain curve for a typical deep ocean ambient noise which amplified the incoming hydrophone signal (Klinck et al., 2012). The inverse pre-amplifier curve for each

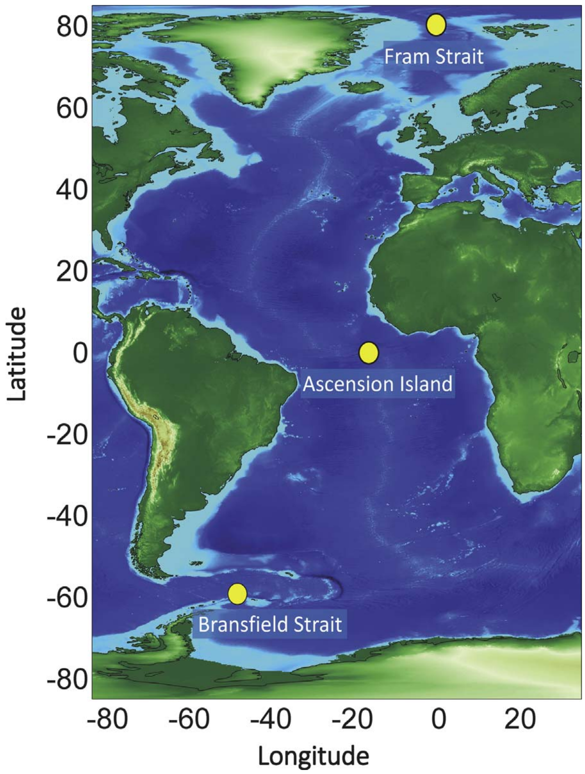

Fig. 3. Map of the locations of the three hydrophone mooring sites analyzed in this study. From North to South: Fram Strait, Ascension Island, and Bransfield Strait.

AUH was applied to the data to obtain absolute sound levels over the frequency spectrum. The Fram Strait AUH recorded acoustic data continuously at 2 kHz sample rate, while the Bransfield instrument continuously recorded data at a 1 kHz sample rate. However, to account for differences among the three hydrophone systems, the analysis was limited to the frequency range 15–100 Hz.

Remotely sensed monthly sea ice concentrations at the two polar sites were retrieved from the Global Monitoring for Environment and Security (GMES) Polar View project database (Spreen et al., 2008), and visually assessed to determine the extent of seasonal ice coverage at the deployment site of each AUH.

3.2. Data analysis

3.2.1. Overall sound levels

Long-term term spectral averages (LTSA) of 15–100 Hz data were calculated (1 Hz, 200 s window) for all sites for August 2009 through December 2010 using custom Matlab™ code. Seasonal patterns in the acoustic data were investigated by analyzing daily median band levels in the 15–100 Hz range. Spectral probability density plots (SPD; Merchant et al., 2013) were calculated to identify the probability density of sound levels in 1 Hz spectral bins at each site.

3.2.2. Seismic airgun sounds

To identify all hours with airgun pulses, acoustic recordings were first screened using an energy sum detector in Ishmael interactive sound analysis software (Mellinger, 2002) and then each hour containing detections was manually verified in Raven interactive sound analysis software (Charif et al., 2010).

3.2.3. Fin whale sounds

Fin whale presence was calculated using the “fin index” to identify occurrence of fin whale calls. The fin index is custom Matlab™ code designed to detect the presence of fin whales by quantifying energy in the 20 Hz frequency band (Klinck et al., 2012; Nieukirk et al., 2012; Širovic et al., 2015). The fin index normalizes and excludes broadband signals to calculate the daily relative animal acoustic presence.

3.2.4. Blue whale sounds

Blue whale calls were identified in the data via a template detector (frame size 1024 samples, 75% overlap, Hamming window) in Ishmael (Mellinger, 2002). A low threshold was used to minimize the number of missed calls, and acoustic presence of Atlantic blue whales was tallied in hours per day at the Fram Strait and Ascension Island. A similar detector for Antarctic blue whale calls was used to analyze recordings from the Bransfield Strait and Ascension Island. When acoustically active, blue whales typically call in long repetitive sequences and thus

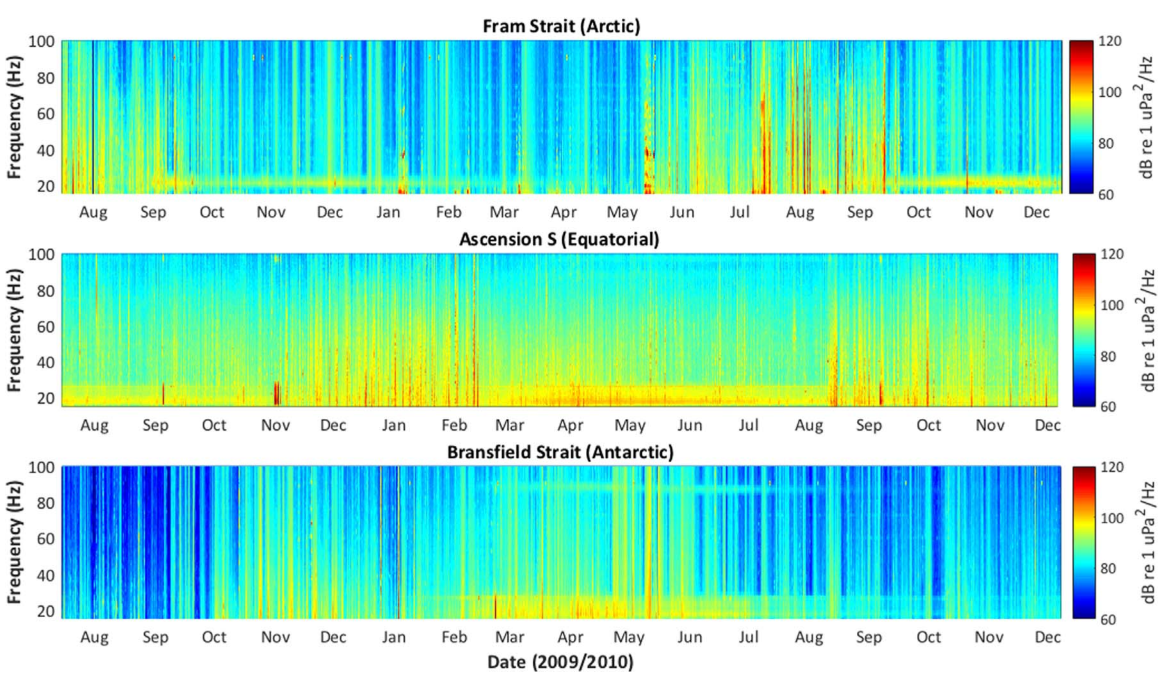

Fig. 4. Long term spectral averages calculated in 1 Hz, 200 s bins from August 2009 through December 2010. Intensity of sound is indicated by the range of color (navy to red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

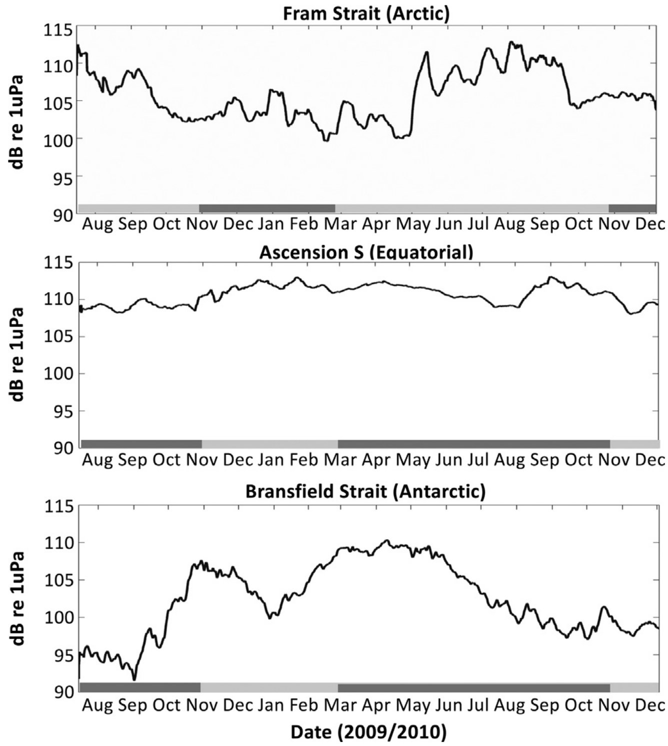

Fig. 5. Daily median (50th percentile) sound levels (15–100 Hz) at each study site. The shading (dark for winter and light for summer) above the x-axis indicates boreal and austral seasons. Note the difference in winter and summer months between the Fram Strait, which is high-latitude northern hemisphere, and the two study sites in the southern hemisphere (Ascension S and Bransfield Strait). The poles experience higher seasonality of sound levels compared to the equatorial site.

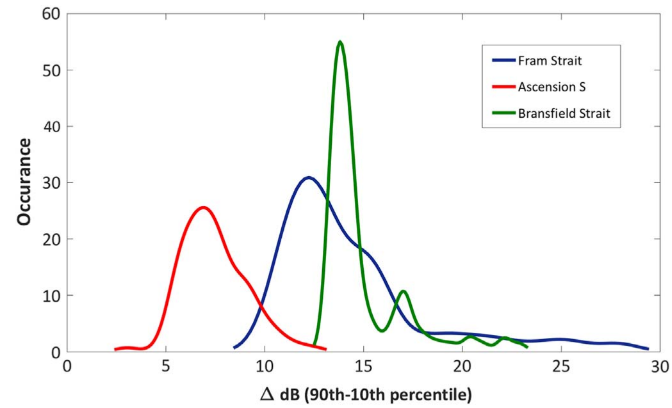

Fig. 6. Kernel smoothed histograms (bin width 10) of the occurrences of the difference in decibel (dB) level between the 90th and 10th percentiles of 15–100 Hz sound at the Fram Strait (blue), Ascension S (Red), and the Bransfield Strait (green) from August 2009 to December 2010. Comparatively smaller differences in the change of dB between percentile levels at Ascension S reflect little variation of sound levels across the investigated frequency band throughout the year. Differences in dB level between percentiles at the Fram Strait were long-tailed towards larger dB level changes, signifying that at some frequencies the spread between the 90th and 10th percentiles of sound was larger than 25 dB. This positive skewedness (broader spread to the right of the mean) is related to seasonal changes in marine mammal calling and seismic airgun activity. The high occurrence of a ~14 dB difference between the 90th and 10th percentiles of sound at the Bransfield Strait indicates that there is a wide range of sound levels throughout the year. Slight positive skewedness is related to seasonality of marine mammal calling and interannual differences in ice coverage over the strait.

any calling within an hour can be a proxy for counting individual calls (Širović et al., 2004, 2015). Detector results for each call type were manually verified in Triton (600 s window, 0–75 Hz, FFT 1024, 90% overlap) (Wiggins et al., 2010).

4. Results

The levels and seasonality of ambient sound varied among the three study sites (Fig. 4). Daily median (50th percentile) broadband (15–100 Hz) sound levels exceeded 100 dB (*re* 1 µPa throughout unless otherwise stated) for most of the 16-month recording period (Fig. 5). Sound levels remained above 100 dB year-round at Ascension Island with very little seasonal variability (~5 dB). Daily median sound levels did not exceed 115 dB at any location. In addition, sound levels at the polar sites were generally lower than the equatorial site; lowest levels (~92 dB) were recorded in the Antarctic in September 2009. Seasonal variability was more pronounced in the Fram Strait than the Bransfield Strait. The data also revealed interannual variability of sound in the Bransfield Strait, where sound levels during the late austral winter (August and September) in 2009 were 5–10 dB lower than sound levels in 2010.

Spectral variability was investigated by calculating kernel smoothed histograms (Fig. 6) and spectral probability density (SPD) plots (Fig. 7). The curves in Fig. 6 indicate the highest variability of change in broadband median sound levels in the Bransfield Strait (median ~14 dB) followed by the Fram Strait (median ~12 dB) and Ascension Island (median ~7 dB).

During the deployment period, sea ice coverage was only detected over the Bransfield Strait, not the Fram Strait. In the Bransfield Strait, sea ice covered the location of the AUH in the winter of 2009, but not during 2010.

Variability in band and spectrum levels was primarily determined by anthropogenic and biological sources. For example, in the Ascension Island data, a clear peak in sound levels at 27 Hz (Fig. 7) is associated with Antarctic blue whale calling activity, while in the Fram Strait elevated sound levels in the 20–24 Hz band are due to fin whale vocal activity.

Blue (both species) and fin whale calling activity was observed year-round at the Ascension Island site (Fig. 8). Peak calling occurred during the austral winter months (March–July). Blue and fin whale calls were recorded seasonally at the polar sites. In the Fram Strait, blue whales were predominately recorded during late summer through early fall (August–October). Fin whale calling typically occurred later in the year, from September to January. In the Bransfield Strait, no blue whale calls were recorded between August and December 2009. However, constant blue whale calling activity was noted for the 2010 observation period with a peak in March through May. A similar pattern was found for fin whales.

Airgun sounds, our indicator of anthropogenic activity, were most prominent at the equatorial site. At Ascension Island, seismic airgun signals were audible in almost every hour of the entire recording period (Fig. 10). Seismic airgun signals were detected seasonally (primarily during the summer months) in the Fram Strait for a total of over 4000 h. The Bransfield Strait exhibited very little airgun activity (a total of 171 h).

5. Discussion

This research effort compared the soundscapes of three widespread locations in the Atlantic Ocean to document elements of and changes in ambient sound levels over a 16-month period. Understanding how individual elements influence the presence and proportion of the components of sound within each soundscape reveals how increasing ocean sound levels must be managed on a basin-wide scale to preserve acoustic environments. Results from the 2009–2010 recording periods show that low-frequency ambient sound is not consistent in intensity and frequency among Arctic, Equatorial, and Antarctic marine soundscapes. Variance of natural and man-made elements of sound elicited differences in the soundscapes throughout the year.

The temporal variability of blue and fin whale calls observed in this study illustrates how variation of marine mammal calling (biological

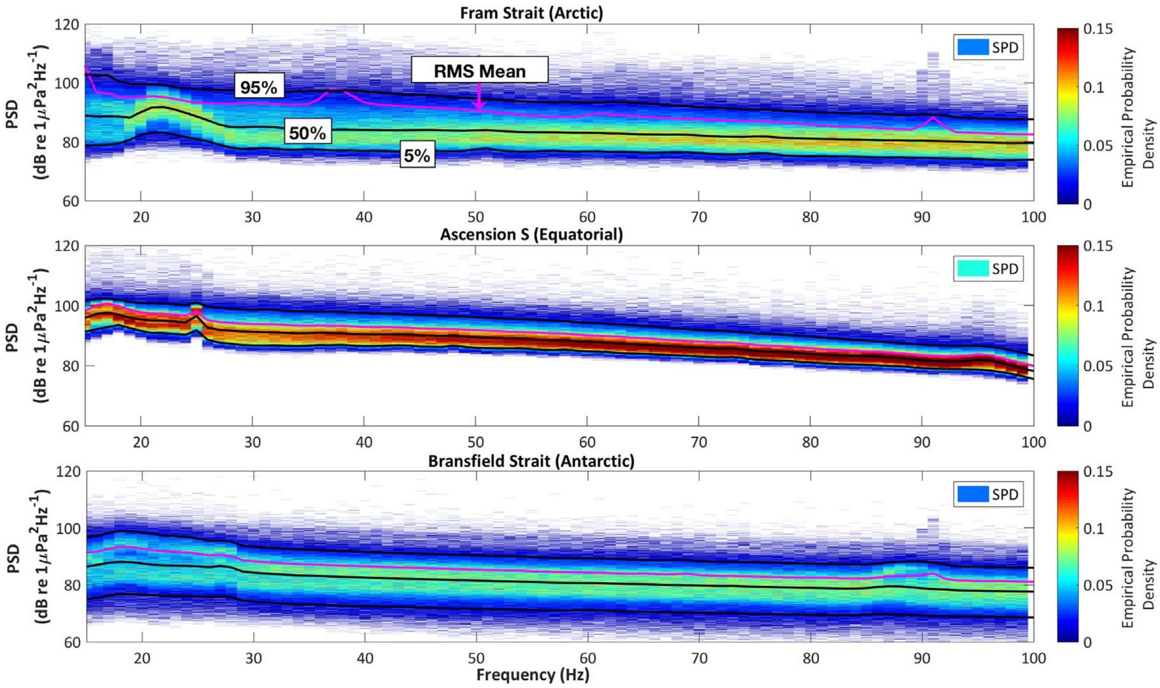

Fig. 7. Root-mean-square (RMS), percentiles (95%, 50%, 5%), and spectral probability densities (SPD; Merchant et al., 2013) showing differences in 15–100 Hz sound level distribution at each site. The SPD indicates the empirical probability density of sound levels in each frequency band between August 2009 and December 2010. An overall SPD is also calculated for each site. (For interpretation of the color in this figure legend, the reader is referred to the web version of the article).

elements of sound) affects sound levels at specific soundscape frequencies. In the Fram Strait, Atlantic blue whale vocal activity was relatively low, which was reflected by the lack of a clear signal at 19 Hz in the spectral density plot (Fig. 7). This finding is not surprising, as this population of blue whales is thought to be small (hundreds of animals; Vacquié-garcia et al., 2017). In the late summer and fall, calls were detected in more hours, which fits the calling pattern that is expected for summer resident Atlantic blue whales migrating to winter breeding areas. Furthermore, consistent with the findings of Moore et al. (2012) and Klinck et al. (2012), there are more fin whale calls in the Fram Strait relative to Atlantic blue whale calls and acoustic data reveal this difference via elevated sound levels at ~20 Hz (Fig. 7). At Ascension, fin and blue whales were recorded year-round. Particularly, calls from both Atlantic and Antarctic blue whales were detected in 13 months of the 16-month recording period, and are reflected in the higher sound levels observed at frequencies below ~27 Hz (Fig. 7). In the Bransfield Strait, Antarctic blue whale calls are typically detected more often than fin whale calls, although both species are only present seasonally (Širović et al., 2004). The seasonality of both fin and Antarctic blue whale calling activity was not identical between 2009 and 2010. Detections of blue whale vocalizations are assumed to be positively correlated with the number of individuals, and consistent with the observations reported by Sirović et al. (2013) and Dziak et al. (2015). Interannual variability of blue whale migration could be explained by specific drivers such as timing of sea ice formation and prey availability.

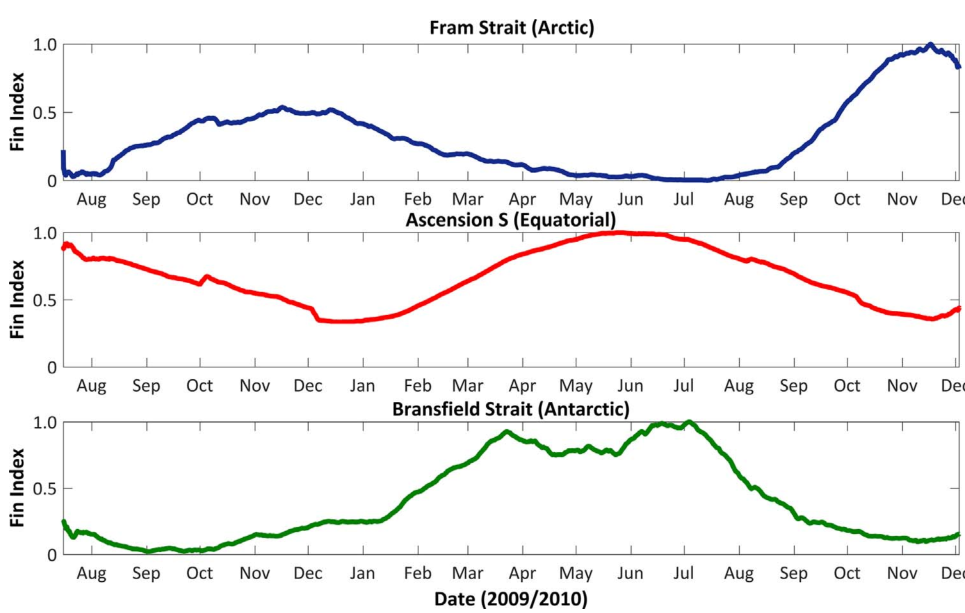

Fig. 8. Seasonality of fin whale calling activity from August 2009 to December 2010 derived from an energy metric.

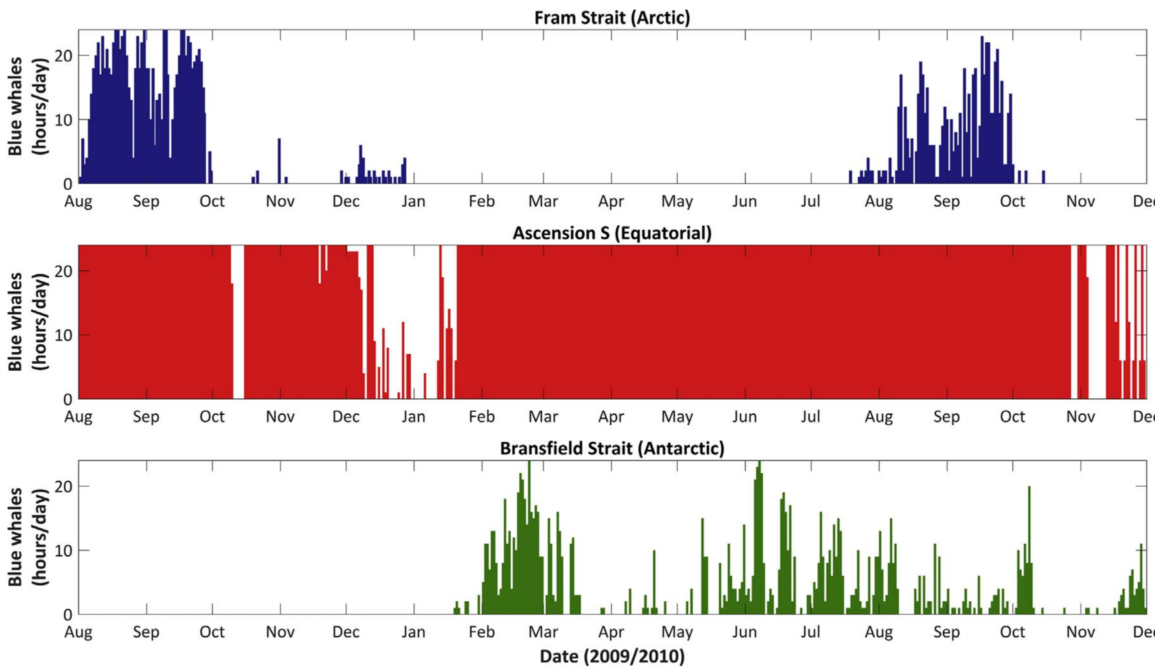

Fig. 9. Seasonality of blue whale calling activity from August 2009 to December 2010 in hours detected per day (24-h period).

Dynamic climates can drive seasonal and annual variability of biological sound. In September 2010, fin and blue whale acoustic activity was observed in the Bransfield Strait that was not detected in 2009. This difference is likely correlated with abundance of sea ice cover (Miksis-Olds et al., 2013), as fin and blue whales avoid ice covered areas (Meredith and Campbell, 1988; Širović et al., 2004). The lack of physical sea ice coverage over the strait in 2010 (GMES database, Spreen et al., 2008) permitted calling fin and blue whales (biological elements of sound) to move into the area and influence the soundscape, increasing sound levels in the frequencies associated with each call type. Thus, lower sound levels were detected during the ice covered month of September 2009 compared to the relatively ice-free month of September 2010 (Fig. 5). This difference exemplifies the need for continuous multi-year data sets to define baseline sound levels and natural variability, and to monitor long-term changes in soundscape environments.

In addition to biological elements, anthropogenic elements contributed to each soundscape. Specifically, the impact of seismic airgun signals is abundantly obvious in the Equatorial Atlantic at Ascension. Due to the efficient transmission of acoustic signals through water, seismic airgun signals from both the Northern and Southern hemispheres may be heard at the equator (Munk, 1994; Nieukirk et al., 2012). The lower-latitudes of the equatorial Atlantic are a high density area for oil and gas reserves, and the warm climate permits year-round vessel access for resource exploration off the coasts of Brazil and West Africa (Nieukirk et al., 2004). The combination of local and widespread anthropogenic activity elicited consistently high sound levels in the equatorial Atlantic.

The prevalence of anthropogenic activity contributed to the observed overall increases in low-frequency Atlantic Ocean ambient sound, particularly between the 40 and 60 Hz frequency bands (Miksis-Olds and Nichols, 2016; Nieukirk et al., 2012); specifically, the 50 Hz frequency band has been positively correlated with seismic airgun signals (Klinck et al., 2012). Comparison of the average 50 Hz spectrum level at each site revealed that Ascension (90 dB re 1 μPa^^{2}/Hz) was 7 dB higher than the same measurement at the Bransfield Strait (83 dB re 1 μPa^^{2}/Hz), and 3 dB higher than the Fram Strait (87 dB re 1 μPa^^{2}/Hz) (Fig. 7). Not only does this difference exemplify the disparity in 50 Hz sound levels among the three study sites, but also provides baseline approximations from which comparisons can be made to other ocean locations. For example, in the central and western tropical and subtropical Pacific, where seismic airgun activity is less prevalent, monthly average 50 Hz spectral levels recorded between 2009 and 2011 ranged between 67 and 76 dB re 1 μPa^^{2}/Hz (Sirović et al., 2013).

Although shipping could not be quantified in this experiment, ship noise may also affect sound levels between 40 and 60 Hz (McKenna et al., 2012; Miksis-Olds and Nichols, 2016) and likely contributed to differences in sound levels across the three study sites. The Fram and Bransfield Strait locations are far from major shipping lanes, so the contribution of ship noise to sound levels was likely minor. In contrast, the high density of anthropogenic activities and stressors in the lower latitudes of the southern hemisphere (Halpern et al., 2015) means that vessel activity likely influenced overall ambient sound levels at Ascension. However, tonal sounds from distant shipping are easily masked by airguns, which were a continual and dominant source of sound at Ascension Island (Fig. 10).

Compared to the year-round recordings of seismic airgun signals at Ascension, seismic airguns were only detected at the Fram Strait for 10 out of 16 months of recording. During those 10 months with seismic airgun signals, pulses were detected, on average, 17 h per day. To determine the contribution of airgun signals to the soundscape of the Fram Strait, the seasonal variability of sound in the Fram Strait was compared to the seasonal variability of sound levels in the Bransfield Strait. The Bransfield Strait has a similar climate to the Fram Strait but only recorded airgun signals during 171 h of the entire recording period, a relatively small amount that is likely related to scientific research (Fig. 10). In the Fram Strait, neither seismic airgun signals, blue whales, nor fin whales were detected year-round, but the presence of all three elements overlapped in August and September (Figs. 5, 8, 9, and 10). Consequently, daily median broadband sound levels in the Fram Strait were highest in August and September (Fig. 5). During all other months of the year, the presence of either anthropogenic activity or whale calling maintained elevated sound levels. In contrast, in the Bransfield Strait, the similar seasonal calling patterns of blue and fin whales and lack of seismic airgun activity allowed for relatively quiet months.

Differences between the 90th and 10th percentiles of sound levels were generally larger in the Bransfield compared to the Fram Strait, but the absolute largest differences (up to 28 dB) were observed in the

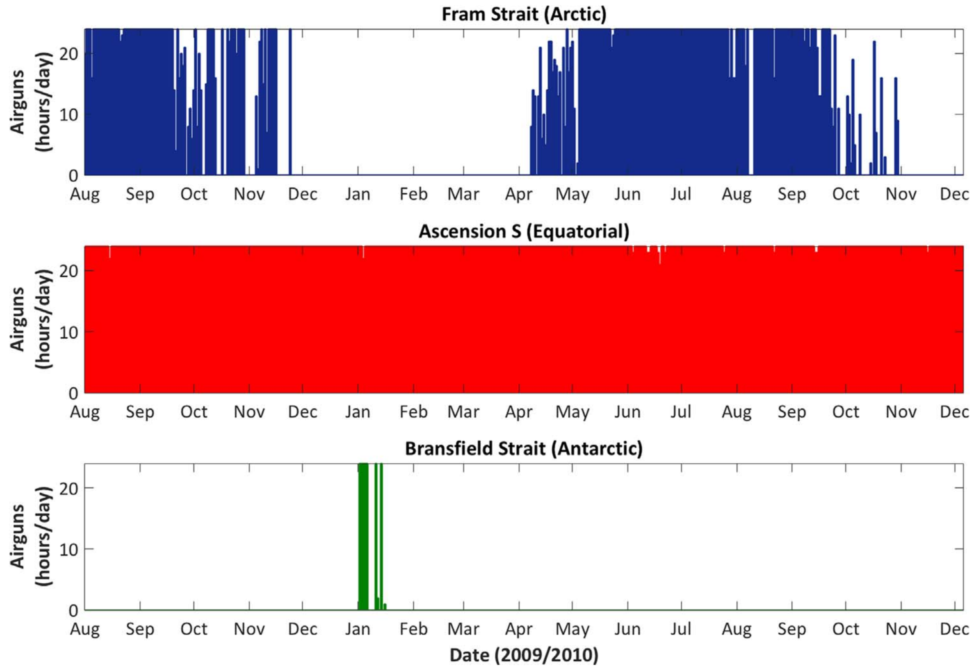

Fig. 10. Histograms showing the occurrence (hours per day) of seismic airgun acoustic signals from August 2009 to December 2010.

Fram Strait (Fig. 6). Specifically, these large differences in the Fram Strait represent the acoustic contrast between the loudest months of August and September, when both biological and anthropogenic elements contributed to the soundscape, and the quietest months in which no seismic airgun, blue, or fin whale signals were detected. Variation in the size and shape of the three curves in the kernel smoothed histograms also reveal how differences in sound levels are not uniform among the sites (Fig. 6). The narrower and taller curve representing sound levels in the Bransfield Strait reflect that most dB level changes are a similar value (~14 dB). This consistency is likely related to uniform seasonal changes in animal calling and weather patterns. In contrast, the wider and higher distributions of the curves from sound levels in the Fram Strait and Ascension reveal inconsistent changes that are likely due to anthropogenic activity overlapping with other soundscape elements.

Due to the frequency, intensity, and prevalence of seismic acoustic signals, broadband energy may continue to permeate an area after the operations vessel moves away (National Research Council, 2003; Richardson et al., 1995). Cetacean species have been shown to respond to seismic signals by changing behavior and vocalization rates to avoid noise from seismic airguns (Stone and Tasker, 2006). Specifically, the species analyzed in this study, blue and fin whales, have both been observed to alter calling behavior in response to seismic airgun exposure (Di Iorio and Clark, 2010; McDonald et al., 1995). This observation is likely due to the low- and mid-frequency range overlap of many baleen whale vocalizations with seismic airgun signals and other forms of sound from vessels. In addition, the loud anthropogenic sounds can mask (especially if reverberation is present) the relatively quieter biological sounds, and observations of higher anthropogenic sound levels may be coupled with a change in observed animal acoustic activity (Clark et al., 2009; McDonald et al., 2006; Parks et al., 2014; Wenz, 1962). For example, fin whales in the North Atlantic vocalize year-round throughout their latitudinal range of Southeast continental United States up to the Arctic Ocean (Clark, 1995; Reilly et al., 2008a). Therefore, observed dips in detections of fin whale calling activity concurrent with detections of seismic airgun signals in the Fram Strait are likely due to either masking or altered calling behavior (i.e., reducing or ceasing to call) in response to the elevated sound levels. (Figs. 8 and 10). Comparatively, in the Bransfield Strait, where negligible seismic airgun activity was detected, fin whale calling activity peaks aligned with the species' expected austral winter presence in the upper-middle latitudes of the Southern hemisphere (Fig. 8) (Reilly et al., 2008a).

Among all three sites, fin whale calls were detected year-round in the Atlantic (Fig. 8); Specifically, calling activity in the Fram Strait was loud enough to increase median sound levels (Fig. 7). Given the acoustic properties of fin whale calls, the fin index at Ascension may reflect calling from fin whales located closer to the Fram Strait; however, the fin index calculations for Ascension do not reflect this, and instead suggest decreases in calling activity during the peak calling months at the Fram Strait (Fig. 8). These decreases in fin whale detections may be due to masking from strong seismic airgun signals in the lower and middle latitudes of the Atlantic Ocean.

Individual seasonal distribution of Atlantic and Antarctic blue whale subspecies are poorly understood—but as an entire species blue whales are known to inhabit waters from Norway to Antarctica (Reilly et al., 2008b). Thus, similar to patterns observed in fin whale calling, the gaps in blue whale calling activity at Ascension are likely related to the temporal overlap of seismic airgun signals or altered vocal behavior (Fig. 9). For example, seismic airgun signals recorded at Ascension in January 2010 were so loud that neither Atlantic nor Antarctic blue whale calls (or 40 Hz (McKenna et al., 2012) tonal shipping sounds) could be picked out of the raw data. Without the use of animal borne acoustic tags it is impossible to confirm if observed decreases in animals calling are due to true masking, or if the animals altered their calling behavior or left the area.

Successful acoustic communication between marine mammals requires that sound propagate through the environment from sender to receiver; if this communication is interrupted by other signals the cost may be a missed opportunity for locating food or mates, or increased predation risk if the signal was a warning. Consequently, it is important to continue to monitor the soundscape of ocean areas to evaluate how different elements contribute to overall sound levels and if changes occur over time. By establishing long-term acoustic monitoring of soundscapes to determine baseline sound levels and track changes over time, it may be possible to ascertain how and why ocean sound ambient levels change. Future studies can also take advantage of recent technological advances such as satellite Automatic Identification

Systems (AIS) ship data, which collect information that can quantify nearby vessel activity and supplement acoustic data. AIS data can provide a way to approximate sound level impacts from anthropogenic sources like shipping, which produce tonal sounds that can be challenging to quantify. In doing so, it is also possible to investigate how anthropogenic activity may influence the behavior of marine animals, providing results to inform and guide regulatory agencies in protecting the critical habitats of endangered species and developing strategies to manage increasing ocean noise levels.

6. Conclusion

The National Park Service and the National Oceanic and Atmospheric Administration (NOAA) have recognized the escalating threat of anthropogenic noise to marine mammals in the NOAA Ocean Noise Strategy Roadmap, which outlines NOAA's current plans to address and manage manmade sources of noise in the ocean (Gedamke et al., 2016). Monitoring ocean sound across an ocean basin is not only essential to marine mammal protection, but also to ocean conservation as a whole, as determining ocean sound level baselines informs future studies of the impact of climate change on soundscapes at varied latitudes. It is not possible to establish policies for acoustic pollution without a baseline, thus the continued examination of soundscapes in the Atlantic Ocean and worldwide is critical to conservation and management efforts. The results of this study are the first steps towards documenting the variability of sound levels between soundscapes in the Atlantic Ocean ocean basin and documenting the issue of increasing global ocean noise levels.

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