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Title: The Soundcheck of the Sea: Comparing Marine Soundscapes on a Continental Scale

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Monitoring marine ambient sound using standardized methods supports assessments of ocean sound levels across widespread ecosystems. This thesis quantifies differences among coastal and deep-water marine soundscapes in the Atlantic and Pacific oceans. The sources of sound in a soundscape are compartmentalized into three components and compared over time and among different areas to give insight into the status of ocean ecosystems, revealing the presence of vocalizing animals, anthropogenic activity, and environmental changes such as weather (e.g., wind, rain) and ice coverage. Assessment of acoustic differences across discrete soundscapes supports the work of policy and planning leaders to address issues dealing with monitoring protected areas and marine species (marine mammals, fish), and the contribution of anthropogenic sources to ambient sound associated with energy production (oil exploration, renewable energy development) and socioeconomic activity (container shipping, commercial fisheries, and sport watercraft). These data also define a baseline to evaluate changes over time, including the presence of anthropogenic activities, and the efficacy of management approaches addressing both protected areas and species.

The Soundcheck of the Sea: Comparing Marine Soundscapes on a Continental Scale

by
Samara M. Haver

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Samara M. Haver, Author

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Slowly at first, and then in a rush, more people came to settle here and brought with them new ways and new sounds, some very beautiful and some less so. But everyone was so busy with the things that had to be done that they scarcely had time to listen at all. And, as you know, a sound which is not heard disappears forever and is not to be found again. People laughed less and grumbled more, sang less and shouted more, and the sounds they made grew louder and uglier. It became difficult to hear even the birds or the breeze, and soon everyone stopped listening for them. The Soundkeeper grew worried and disconsolate. Each day there were fewer sounds to be collected, and most of those were hardly worth keeping. Many people thought it was the weather, and others blamed the moon, but the general consensus of opinion held that the trouble began at the time that Rhyme and Reason were banished. But, no matter what the cause, no one knew what to do.

— *Norton Juster, "The Phantom Tollbooth"*

CHAPTER 1: GENERAL INTRODUCTION

BACKGROUND

Marine Animals and Sound

The ocean is dark and vast, limiting the effective transmission of visual signals. By comparison, acoustic signals travel quickly and efficiently over long distances in the aquatic environment; thus, sound has become the principal sensory modality used by many marine animal species. This is particularly true for acoustically oriented marine mammals that rely on sound to communicate with conspecifics, perceive their environment, detect and avoid predators, forage for food, and navigate (Richardson et al., 1995).

While sound generally plays a significant role in the ecology marine mammals, the use of sound for communication and signal detection is not identical among species. Marine mammals produce sounds that span acoustic frequencies ranging from infrasonic low-frequency calls of blue whales (*Balaenoptera musculus*) to ultrasonic high-frequency echolocation clicks of harbor porpoises (*Phocoena phocoena)* (Richardson et al., 1995). The approximately 70 species of marine mammals protected by the National Oceanic and Atmospheric Administration (NOAA) within U.S. waters (NOAA Fisheries, 2017) have a combined vocal range of ~10 Hz to 200 kHz (National Research Council, 2003), making these taxa one of the most vocally diverse on the planet (Tyack, 1986).

Baleen whales (suborder mysticeti), including some of the most critically endangered marine mammal species, are especially well adapted to use low-frequency sound for long-range communication. Mysticete cetaceans produce sounds in the frequency range of ~10 Hz – 2 kHz in order to maintain contact with conspecifics (i.e. fin whales, *Balaenoptera physalus*), attract mates (i.e. humpback whales, *Megaptera novaeangliae*), and glean information about environmental features (i.e. bowhead whales, *Balaena mysticetus*) (Richardson et al., 1995; Weilgart, 2007). Some of these low frequency vocalizations – including those of blue whales – are capable of travelling hundreds of kilometers through the ocean (Weilgart, 2007). These abilities have evolved in this widely distributed taxa as a response to the need to maintain communication in the marine realm across great distances, and enable communication between individuals that would otherwise be unlikely to encounter each other. However, these abilities arose in an ocean devoid of anthropogenic influences.

In the contemporary ocean, many low- and mid-frequency vocalizations that support critical life functions in baleen whales inhabit the same frequency band as human produced vessel noise. This overlap results in a substantial "masking" risk. Masking can be defined as the process by which an acoustic signal is overshadowed by a louder more prominent signal in a shared frequency band, meaning that louder anthropogenic noises can overshadow or "mask" relatively quieter biologically important sounds (Clark et al., 2009; Wenz, 1962). Animals located near densely populated ports are especially susceptible to masking from anthropogenic activity (Halpern et al., 2015). For example, the endangered North Atlantic right whale (*Eubalaena glacialis)* is among the most threatened species in the U.S. waters (National Marine Fisheries Service, 2016) and forages along the heavily trafficked New England seaboard. North Atlantic right whales rely on a suite of low to mid-frequency calls (primarily 50 – 400 Hz), all of which fall within the frequency range of large vessel noise, to communicate with conspecifics on their foraging grounds (Parks et al., 2011).

Several behavioral responses to anthropogenic noise have been observed in cetaceans. North Atlantic right whales have demonstrated some ability to adapt to increased noise by increasing the duration and frequency of their calls; however, this comes at the cost of reduced vocalization rates (Parks et al., 2007). Killer whales (*Orcinus orca*) have been observed increasing their call amplitude proportionally in response to vessel noise (Holt et al., 2012, 2009). Similarly, humpback whales have been observed lengthening the duration of their song in response to sonar exposures (Miller et al., 2000).

When cetaceans must change their acoustic behavior to accommodate anthropogenic noise, the repercussions may be physiologically expensive. Vocalizing at louder volume or outside of the animal's normal frequency range is energetically taxing, and animals may need to compensate by reducing calling rates or increasing energy consumption in order for the behavior to be sustainable (Pick, 1989; Tyack, 2008). Noise from vessels and other sources has also been documented to increase stress hormones (Rolland et al., 2012), alter locomotive behavior (Pirotta et al., 2012), and damage animal hearing (Southall et al., 2016); all of these activities may result in reduced individual fitness. Despite this, vessel transport remains the primary shipping method for 90% of the world's trade (IMO Maritime Knowledge Centre, 2012). Furthermore, vessel technology continues to advance, including developments to allow for increased speeds (e.g., larger engines) that have been associated with elevated vessel noise (Wright et al., 2007). In light of these anticipated changes in anthropogenic activities, it is likely that marine animals that rely on low-frequency communication may be severely limited in the distance over which they are able to send and receive acoustic signals.

In the U.S. marine mammals are protected from harassment by the Marine Mammal Protection Act and the Endangered Species Act. Harassment is categorized into either type A or B, and defined to either, "[have] the potential to injure (Level A) [or] to disturb (Level B) a marine mammal or marine mammal stock in the wild by causing disruption of natural behavioral patterns" (U.S. Fish & Wildlife Service, 1973; U.S. Secretary of the Interior and U.S. Secretary of Commerce, 2007). Any activity, including sound exposure, that may "harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage" is classified as either Type A or B harassment depending on the dB level and exposure type (e.g., continuous, transient) of the sound (NOAA, 2013). These regulatory restrictions are intended to protect animals from harassment, and are one strategy to mitigate the effects of noise.

As an alternative to governmentally mandated management, voluntary guidelines have also been proposed to mitigate negative interactions between marine animals and human activities. The port of Vancouver, British Columbia, Canada implemented an optional program for vessels to earn reduced port fees in exchange for adoption of vessel quieting technologies. The "EcoAction" program is the first in the world to incentivize vessel-based noise reduction (Vancouver Fraser Port Authority, 2017). EcoAction sets an example for a future of balancing human use of marine systems with animal conservation. This concept, which addresses humans and the natural world as a coupled system, provides a foundation to actively manage ocean sound; in the absence of this coupling any proposed regulatory scheme may falter.

Beyond shipping ports, marine ecosystems also provide for humans via goods and jobs (e.g., fishing, tourism), cultural services (e.g., recreation, aesthetics, spirituality), and biological and biogeochemical services (e.g., biological diversity, nutrient cycling, photosynthesis, carbon extraction) (McLeod and Leslie, 2009; Roman et al., 2014). As anthropogenic noise is a marine pollutant, it requires management at the ecosystem level (Dekeling et al., 2015). Ecosystem-based management (EBM) acknowledges the range of benefits provided by an ecosystem and promotes a holistic approach to balancing the use and conservation of natural resources (McLeod and Leslie, 2009). Beyond promoting sustainability by managing anthropogenic impacts, the goal of EBM is to support the long-term capacity of a system to deliver services by approaching conservation in context and connection with the evolving ecological and social needs of an environment (Rosenberg and McLeod, 2005). EBM acknowledges that human well-being is connected to ecosystems via ecosystem services, and promotes the long-term sustainable delivery of the ecosystem services that humans want and need.

Monitoring Ocean Noise

Passive acoustic monitoring (PAM) is used to measure, monitor, and assess levels and trends of ocean ambient sound in underwater ecosystems. Using autonomous recorders, researchers can efficiently listen to an environment to assess all acoustic signals present in a particular location and time (including biotic and abiotic signals), collectively defined as the "soundscape". A soundscape is comprised of three generalized groups of sounds: biological, geophysical, and anthropogenic (Pijanowski et al., 2011). All of the individual sources of sound in a soundscape environment can be characterized into only one of these three groupings. For example, many elements of weather can influence a soundscape. Wind and rain are prominent sources of sound in marine environments, contributing substantially to ambient sound levels in frequencies above 300 Hz (Klinck et al., 2012; Nystuen, 1986; Vagle et al., 1990). Sea ice contributes to ambient sound levels via formation, cracking, and calving, as well as dampens sounds at the air sea barrier when fully formed (Makris and Dyer, 1991; Matsumoto et al., 2014; Menze et al., 2017; Milne and Ganton, 1964; Urick, 1971). Sound from wind, rain, and ice are grouped together with earthquakes and active volcanoes as the geophysical component of a soundscape, while the biological component contains all sound emitted from living elements such as whales and fish, and the anthropogenic component is all sound from elements of human interaction with the ocean (e.g., vessel activity) (Pijanowski et al., 2011).

Drivers, such as climate and tectonics but also policies, influence the presence and levels of these sources of sound within a particular soundscape. For example, biological elements of sound may also vary within a soundscape as a consequence of prey availability; that is, without food resources a species may not persist at a given location. Many areas of the U.S. Exclusive Economic Zone (EEZ) are rich foraging areas for various species, including marine mammals that vocalize over a broad range of frequencies. Thus, seasonality of sound levels in those soundscapes are likely related to animal migratory patterns as species move in and out of each area to feed, though this has not yet been quantified at any appreciable scale.

Soundscape components can also be influenced by other components; for instance, geophysical elements such as ice can limit the physical accessibility of an area to both animals and vessels, thus decreasing the amount of sound each can introduce in a given area and eliciting seasonal differences in ambient sound (Hildebrand, 2009; Klinck et al., 2012; Nystuen, 1986; Urick, 1983). Therefore, broad acoustic comparison of soundscape components over time and among different areas gives insight into the status of an ocean ecosystem, revealing the presence of vocalizing animals, anthropogenic activity, and environmental changes such as seismic activity and ice coverage. Synthesis of these data allow for description and comparison of levels of ocean sound to inform marine animal protection and ocean conservation efforts.

By identifying baseline sound levels, long-term soundscape monitoring efforts, such as the experiments described in this thesis, are integral to the conservation and effective management of marine species. Using passive acoustics, this thesis presents two research efforts to document the differences among discrete soundscapes in the deep Atlantic Ocean and around the United States EEZ.

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CHAPTER 2: THE NOT-SO-SILENT WORLD: MEASURING ARCTIC, EQUATORIAL, AND ANTARCTIC SOUNDSCAPES IN THE ATLANTIC OCEAN

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ABSTRACT

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.

I. 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 (Figure 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 soundscapes 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.

II. 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.

II.A. Geophysical Elements

II.A.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).

II.A.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).

II.A.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 5-15 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).

II.B. 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

[1] Between August 2009 and December 2010, 25 earthquakes (> 2.5 magnitude) occurred along the mid-Atlantic ridge within 500 nm 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).

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).

II.B.1. 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 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 (1m source levels) than commercial shipping (Goold and Coates, 2006; Hatch and Wright, 2007; Richardson et al., 1995).

II.B.2. 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* 1μPa at a frequency of 2-188 Hz at 1m) 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 seconds (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.

II.C. Biological

Acoustic recordings were also analyzed for biological sources of sound. Vocalizations of endangered blue (*Balaenoptera musculus*) and fin (*B. physalus*) whales (ICUN, 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 to 40 Hz range, but the principal (low-frequency) call type varies by species (Figure 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).

III. METHODS

III.A. 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) (Figure 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 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 8-100 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 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.

III.B. Data Analysis

III.B.1. Overall Sound Levels

Long-term term spectral averages (LTSA) of 15-100 Hz data were calculated (1 Hz, 200s 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.

III.B.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).

III.B.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.

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

IV. RESULTS

The levels and seasonality of ambient sound varied among the three study sites (Figure 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 (Figure 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 (Figure 6) and spectral probability density (SPD) plots (Figure 7). The curves in Figure 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 (Figure 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 (Figure 8). Peak calling occurred during the austral winter months (March to 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 to 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 (Figure 10). Seismic airgun signals were detected seasonally (primarily during the summer months) in the Fram Strait for a total of over 4,000 hours. The Bransfield Strait exhibited very little airgun activity (a total of 171 hours).

V. 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 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 (Figure 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 (Figure 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 (Figure 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.

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 (Figure 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 *u*Pa^^{2}/Hz) was 7 dB higher than the same measurement at the Bransfield Strait (83 dB re 1 *u*Pa^^{2}/Hz), and 3 dB higher than the Fram Strait (87 dB re 1 *u*Pa^^{2}/Hz) (Figure 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 *u*Pa^^{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 (Figure 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 hours 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 hours of the entire recording period, a relatively small amount that is likely related to scientific research (Figure 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 (Figures 5, 8, 9, and 10). Consequently, daily median broadband sound levels in the Fram Strait were highest in August and September (Figure 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 Fram Strait (Figure 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 (Figure 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. (Figures 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 (Figure 8) (Reilly et al., 2008a).

Among all three sites, fin whale calls were detected year-round in the Atlantic (Figure 8); Specifically, calling activity in the Fram Strait was loud enough to increase median sound levels (Figure 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 (Figure 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 (Figure 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.

VI. 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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FIGURES

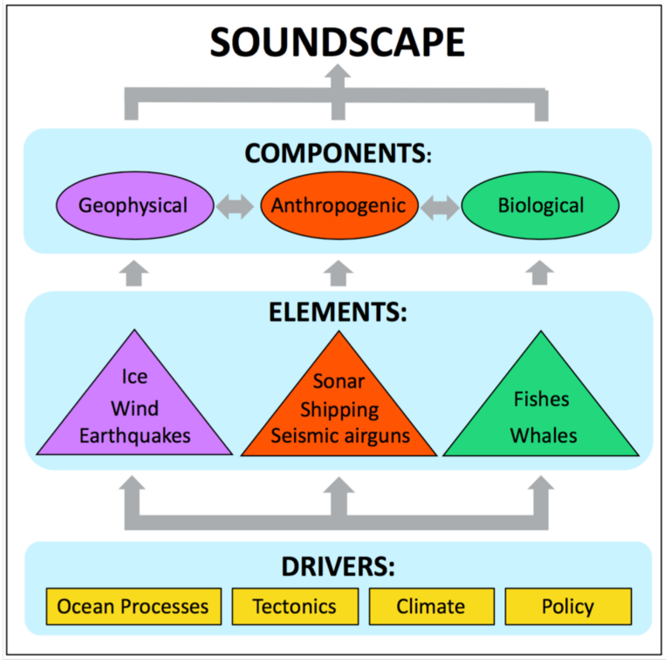

Figure 2.1 Flowchart of soundscape composition. A soundscape is defined by three components, biological, geophysical, and anthropogenic, which are comprised of elements that are influenced by broad drivers.

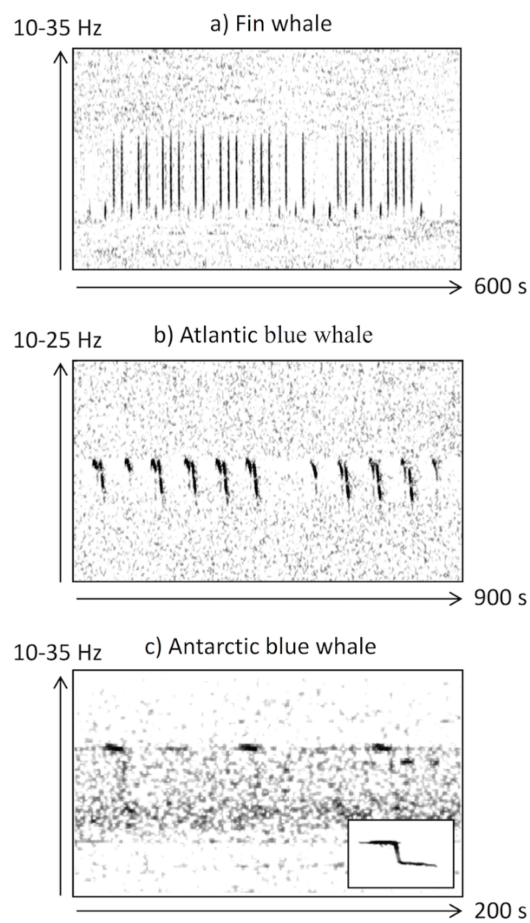

Figure 2.2 Spectrograms (Hann window) of fin whale 20-Hz calls (FFT 1024, 50% overlap), and Atlantic (FFT 256, 25% overlap) and Antarctic-type (FFT 1024, 90% overlap) blue whale calls, recorded in 2009 at Ascension Island (fin, Atlantic blue) and the Bransfield Strait (Antarctic blue) in the Atlantic Ocean.

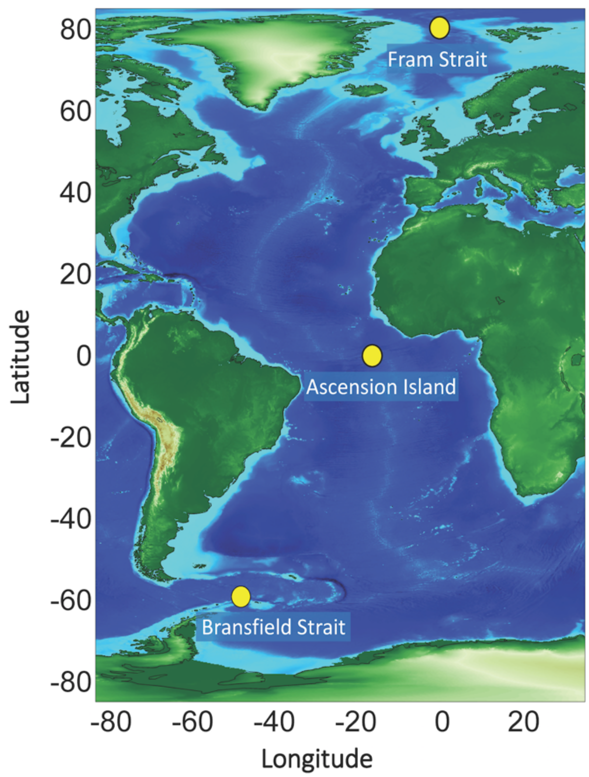

Figure 2.3 Map of the locations of the three hydrophone mooring sites analyzed in this study. From North to South: Fram Strait, Ascension Island, and Bransfield Strait.

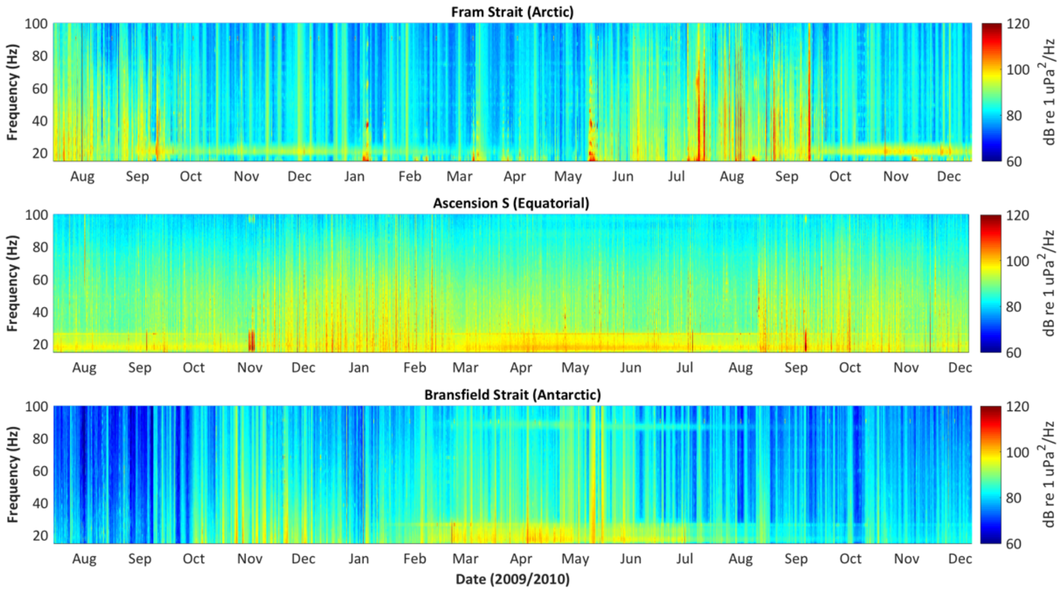

Figure 2.4 Long term spectral averages calculated in 1 Hz, 200 s bins from August 2009 through December 2010. Intensity of sound is indicated by the range of color (navy to red).

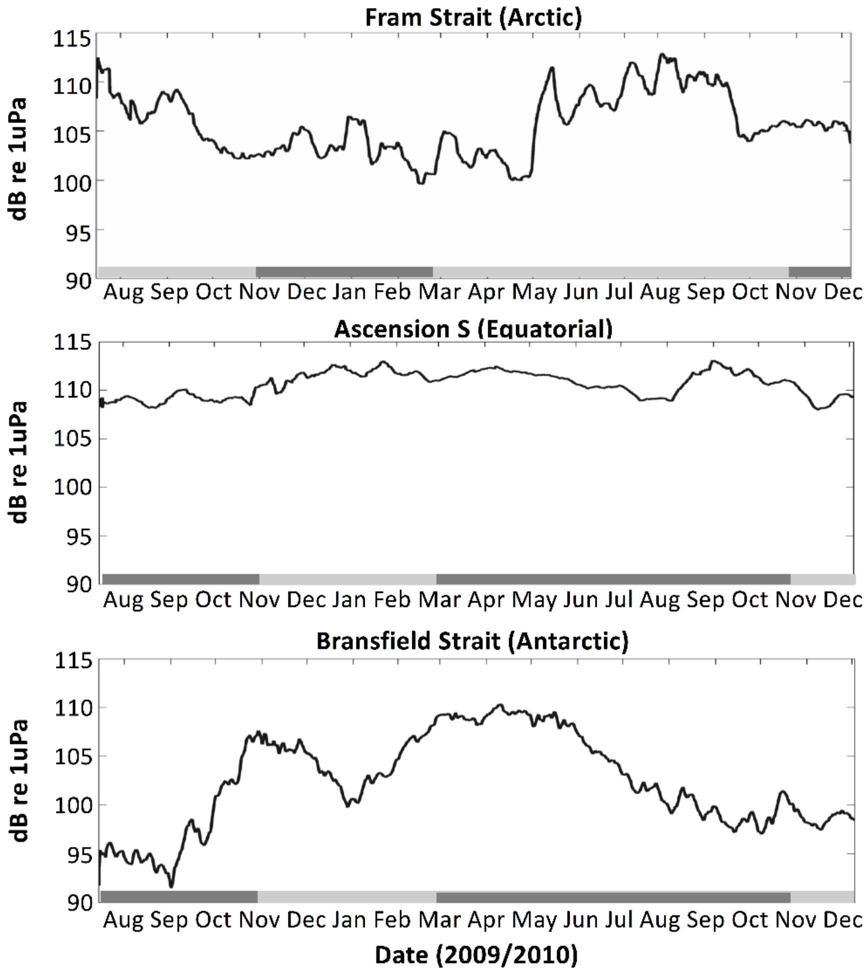

Figure 2.5 Daily median (50^{th} percentile) sound levels (15-100 Hz) at each study site. The shading (dark for winter and light for summer) above the x-axis indicates boreal and austral seasons. Note the difference in winter and summer months between the Fram Strait, which is high-latitude northern 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.

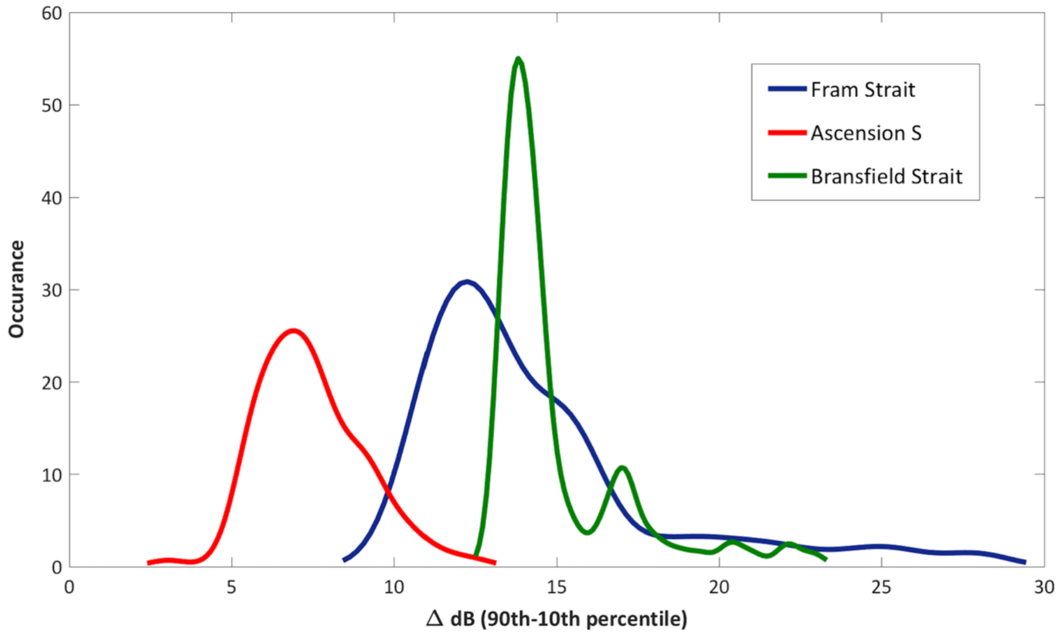

Figure 2.6 Kernel smoothed histograms (bin width 10) of the occurrences of the difference in decibel (dB) level between the 90th and 10th percentiles of 15-100 Hz sound at the Fram Strait (blue), Ascension S (Red), and the Bransfield Strait (green) from August 2009 – December 2010. Comparatively smaller 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.

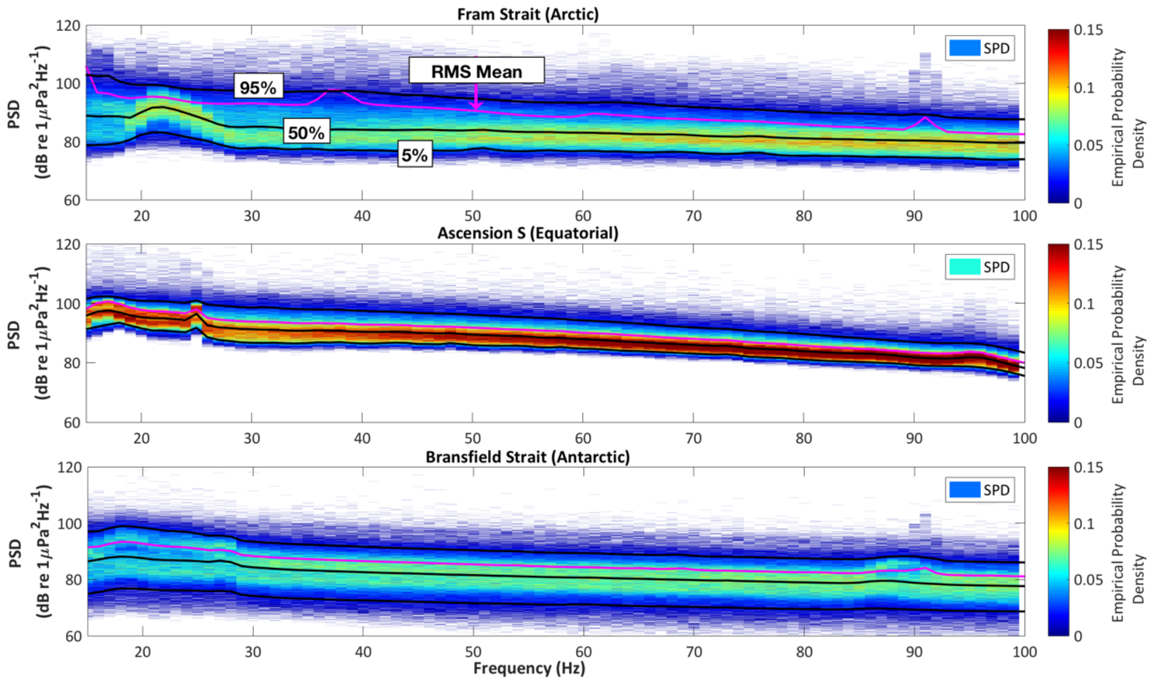

Figure 2.7 Root-mean-square (RMS), percentiles (95%, 50%, 5%), and spectral probability densities (SPD; Merchant et al., 2013) showing differences in 15 Hz – 100 Hz sound level distribution at each site. The SPD indicates the empirical probability density of sound levels in each frequency band between August 2009 and December 2010. An overall SPD is also calculated for each site.

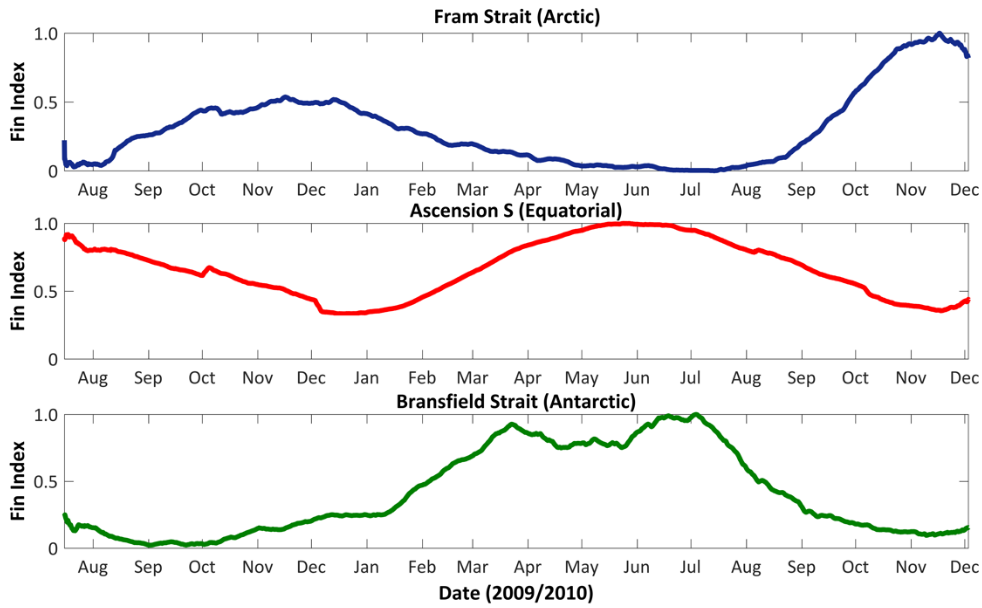

Figure 2.8 Seasonality of fin whale calling activity from August 2009 – December 2010 derived from an energy metric.

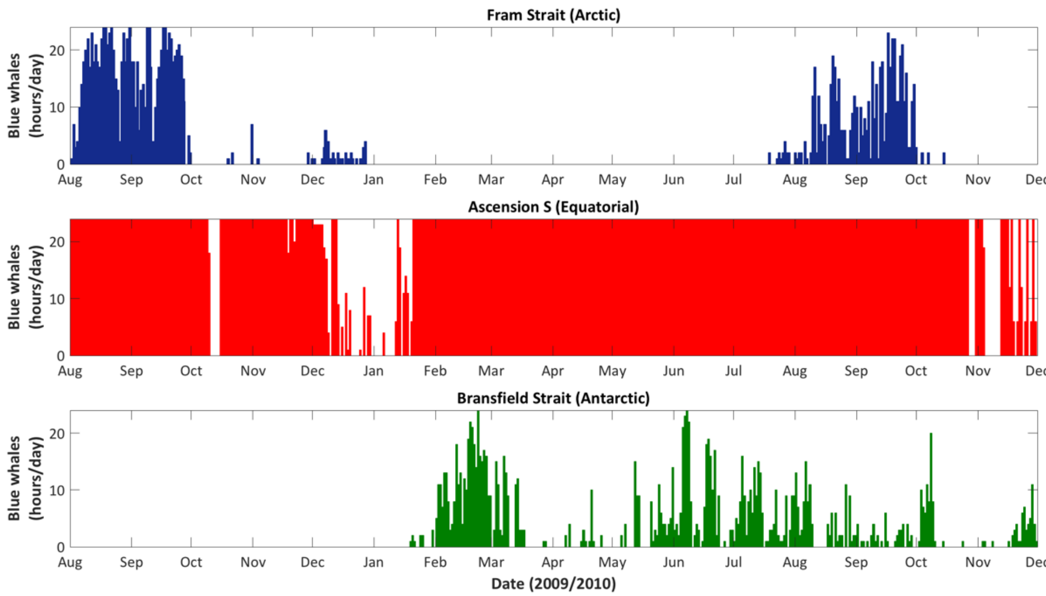

Figure 2.9 Seasonality of blue whale calling activity from August 2009 – December 2010 in hours detected per day (24-hour period).

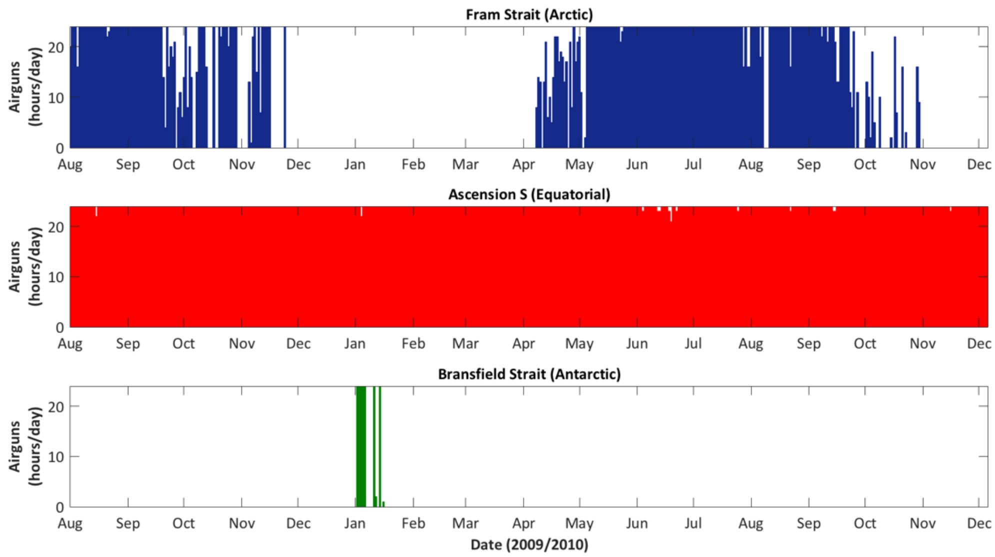

Figure 2.10 Histograms showing the occurrence (hours per day) of seismic airgun acoustic signals from August 2009 to December 2010.

CHAPTER 3: MONITORING LONG-TERM SOUNDSCAPE TRENDS IN U.S. WATERS: THE NOAA/NPS OCEAN NOISE REFERENCE STATION NETWORK

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ABSTRACT

The NOAA/NPS Ocean Noise Reference Station (NRS) Network is an array of currently 12 calibrated autonomous passive acoustic recorders that are maintained by the U.S. National Oceanic and Atmospheric Administration (NOAA) and the National Park Service (NPS). The first NRS was deployed in June 2014, and 11 additional stations were added to the network during the following two years. The 12 NRS continue to document baseline levels and multi-year trends in ocean ambient sound across the continental United States, Alaska, Hawaii, and island territories within the United States exclusive economic zone (U.S. EEZ). The multi-year network records low-frequency underwater sound between 10 to 2,000 Hz to capture anthropogenic, biological, and environmental contributions to each marine soundscape. Comparisons over time as well as between recording sites will provide information on the relative presence of calling animals and the prevalence of abiotic and anthropogenic activities that contribute to each soundscape. Implementation of the NRS significantly advances passive acoustic sensing capabilities within NOAA and NPS in order to address national issues dealing with monitoring protected areas and marine species, the impacts of chronic anthropogenic noise sources associated with energy production, naval operations, and socioeconomic activity (such as shipping). Preliminary analysis focused on the first year of recordings and captures the wide variability of low-frequency sound levels both between and within each NRS site. Continued data collection efforts will provide information on long-term low-frequency sound level trends within the U.S. EEZ and explore the value of using soundscape ecology to inform management and mitigation strategies.

I. INTRODUCTION

In the marine environment light attenuates rapidly, while sound propagates very efficiently. Thus, many marine animals have evolved sensory systems to exploit the efficiency of sound. These organisms rely on sound as their primary sensory modality to communicate, detect predators, navigate, and socialize (Richardson et al., 1995).

The acoustic cues that these animals produce, coupled with sounds emanating from abiotic environmental factors (e.g., weather and geology) and anthropogenic (i.e., human-generated) sources, make up the soundscape (Pijanowski et al., 2011). Broadly, soundscape analysis is used to understand how animals use sound in their environment as well as to indicate overall ecosystem health in a particular location or time (Miksis-Olds et al., 2015). However, currently there are no standards for analyzing or reporting soundscape conditions, including ambient (background) sound (Cato et al., 2015; Erbe et al., 2016).

Within a soundscape, “man-made” sounds that may impede an animal’s healthy biological function via the ability to hear environmental cues that are vital for survival (i.e., avoiding predators, finding food, navigation, and reproduction) are considered “anthropogenic noise” (Cato et al., 2015; Clark et al., 2009). Anthropogenic noise can negatively impact the ecological processes of acoustically sensitive marine animals, including their ability to communicate with conspecifics and detect threats (Davidson et al., 2012; Halpern et al., 2015; Rolland et al., 2012; Shannon et al., 2016). Increased ambient anthropogenic noise may affect marine animals 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). Although marine mammals have been the primary focus of research efforts investigating the effects of noise, the behavior and physiology of fish and marine invertebrate species are similarly effected (Popper, 2003; Simpson et al., 2016).

Sources of ambient anthropogenic noise in the ocean (e.g., commercial and recreational vessel traffic, naval activities, and energy exploration/extraction) commonly emit low-frequency signals that propagate over long distances similar to animal vocalizations (Munk, 1994; Wilcock et al., 2014). Thus, a source of anthropogenic noise does not need to be in close physical proximity of an animal to potentially interfere with biological signals (Nieukirk et al., 2004). In this experiment, ocean ambient noise is considered to encompass these persistent or long-term “chronic” sources of noise in a marine soundscape (Erbe et al., 2016). While natural sources of noise in the ocean (e.g., volcanic eruptions) are among the loudest sounds on earth, chronic anthropogenic noise may be more threating to animal communication due to its persistence and acoustic properties. Further, the relatively short adaptation time afforded to marine animals subjected to rapidly changing ocean soundscapes is particularly threatening (Clark et al., 2009; Hatch et al., 2012; National Research Council, 2003).

Following research chronicling the negative effects of anthropogenic noise (National Research Council, 2003), the United States (U.S.) government has established protocols to protect marine animals from deleterious noise exposure (Jasny et al., 2005; National Research Council of the U.S., 2005). In particular, marine mammals are protected in the U.S. by the Marine Mammal Protection Act and the Endangered Species Act (U.S. Fish & Wildlife Service, 1973; U.S. Secretary of the Interior and U.S. Secretary of Commerce, 2007). Under these statues, anthropogenic activities are restricted to guidelines of animal conservation. However, current U.S. policies are tailored towards discrete incidences of noise exposure, instead of the additive effects of chronic noise. This mind set is now changing as can be seen by the establishment of U.S. National Oceanic and Atmospheric Administration's Ocean Noise Strategy Roadmap (ONS, Gedamke et al., 2016), which focuses on the research and management of the impacts of noise (including ambient) on marine species.

The ONS was developed in support of the goals of the U.S. National Ocean Policy (Exceutive Order 13547, 2010), and argues that to better protect animals and understand the threats they are exposed to, baseline conditions (e.g., ambient sound levels) must be determined. The ONS joins the U.S. with the European Union (Marine Strategy Framework Directive, European Union, 2008), Canada (Heise and Alidina, 2012), and the 23 member countries of the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic area (Resolution 6.17, ACCOBAMS, 2016) in an international effort to monitor and manage ocean ambient noise. Additionally, the National Park Service (NPS) acknowledges that chronic anthropogenic noise is threatening to both marine and terrestrial species, and asserts that future research must evolve to assess the impacts of chronic anthropogenic noise over time and in areas that are important to sensitive species (Buxton et al., 2017; Shannon et al., 2016). As outlined by the United Nations (UN), the U.S. must coordinate with other UN member states to address the threat of ocean noise among global ecosystems (United Nations General Assembly, 2016).

Chronic anthropogenic noise is an international issue as the habitats of many marine species cross national boundaries, thus it is imperative that the U.S. join the global community in an international effort to monitor and manage ocean ambient noise (Dekeling et al., 2015).

Long-term ecosystem monitoring can be used to answer questions about specific systems (e.g., NPS terrestrial soundscape database, Buxton et al., 2017) to inform management and noise regulations. Because chronic noise may harm animals and ecosystems, and therefore reduce or eliminate the ecosystem services they provide to human stakeholders, it is essential to monitor and manage noise within soundscapes. In the U.S., the NPS considers acoustic environments to be manageable resources based on intrinsic value as well as extrinsic value to wildlife and human visitors (National Park Service and U.S. Department of the Interior, 2006). By managing acoustic environments as an ecosystem service in need of protection, the NPS sets an example for the integrative management approach recommended by the U.S. National Ocean Policy to support healthy aquatic ecosystems across the U.S. (Exceutive Order 13547, 2010).

To date there have been a handful of studies to monitor long term ocean ambient noise (Hatch et al., 2008; McDonald et al., 2008) but there is no comprehensive and comparable data collected throughout the U.S. Exclusive Economic Zone (EEZ). This experiment aims to fill this knowledge gap by measuring ocean ambient sound to establish levels throughout the U.S. EEZ, including national parks and marine sanctuaries. By determining comparable sound level baselines and establishing long-term monitoring across acoustic environments within the U.S. waters, this study provides tools for managers and stakeholders to prioritize the needs of sensitive acoustic ecosystems and time periods.

Through a partnership between NOAA and the NPS, 12 identical autonomous passive acoustic hydrophone moorings, the NOAA Ocean Noise Reference Station Network (NRS), were first deployed between June 2014 and November 2016 to document baseline levels and multi-year trends in ocean ambient sound within the U.S. EEZ. Temporal and cross-network comparisons of these baselines will provide information on the relative presence of biological, environmental and anthropogenic sounds.

The NRS was established as a flagship project of the ONS, which aims to characterize acoustic habitats and manage the impacts of anthropogenic sound exposure on the places and species in NOAA's trust (Gedamke et al., 2016). The ONS is an agency wide initiative to identify common scientific and management goals among NOAA line offices (Oceanic and Atmospheric Research, National Marine Fisheries Service, and the National Ocean Service), and identifies a common need for long-term passive acoustic monitoring capabilities across those offices. The NRS represents the first concerted effort to combine cross-agency capabilities to compare ambient sound levels across ecosystems and leverage them towards the collective management vision and goals of the ONS.

Implementation of the NRS advances the capabilities of NOAA and the NPS to address national issues dealing with monitoring living marine resources (marine mammals, fish), the effects of human sound sources associated with energy production (oil exploration, renewable energy development), and socioeconomic activity (container shipping, commercial fisheries, and sport watercraft). Data from the NRS will support marine planning and policy enforcement personnel with quantitative measures to understand and manage the scope of anthropogenic noise sources in sensitive marine environments.

This manuscript introduces the NRS project and examines data from the first year of calibrated data collection to present preliminary comparative sound levels among separate ocean areas of the U.S. EEZ. To facilitate future analysis of NRS data, this initial study establishes scientific baselines of the underwater ambient sound fields at five NRS sites and describes quantitative methods for preliminary assessment of cross-network sound levels.

II. METHODS

II.A. Instrumentation

The NRS is comprised of nine deep and three shallow-water moorings designed and constructed by NOAA Pacific Marine Environmental Laboratory (PMEL) (Figure 1). Each NRS mooring contains a single passive acoustic archival autonomous underwater hydrophone (AUH) (Fox et al., 2001; Haxel et al., 2013). The hydrophones are model ITC-1032 (International Transducer Corp., Santa Barbara, CA) with a sensitivity of -192 dB re 1V/μPa and a flat frequency response (-/+ 1 dB). Incoming signals to the AUH were augmented by a pre-amplifier and pre-whitener in order to utilize the entire 16-bit range of the acoustic data logging system.

The AUHs for the nine deep-water NRS moorings consist of an acoustic data logging system housed in a titanium pressure case and suspended within the SOFAR channel between 500 - 900 m deep. Deep-water NRS are anchored to the ocean floor and are equipped with swivel links and low stretch mooring line to reduce self-noise from mooring movement or current-related strumming (Figure 3). The AUHs for the three shallow water (<100 m) NRS were calibrated to the same specifications as the deep-water sites, but instead housed in a composite pressure case and secured to a bottom mounted metal frame (Figure 3). Each NRS AUH was programmed to record acoustic data continuously at a 5 kHz, enabling on-going data collection over two years duration.

Deployment locations for each NRS are presented in Table 1 and Figure 1. The first NRS was deployed in June 2014 and over the following 27 months 11 other sites were also deployed.

Deep-water NRS are deployed for up to two-years before recovery. The instrument at each NRS is typically a "hot-swap" and the mooring is re-deployed within hours of recovery. Due to the potential for biofouling on the hydrophone of the shallow-water NRS, those moorings are recovered for cleaning and service on an annual basis. Recording effort for the NRS is presented in Figure 4. Due to equipment failure and deployment vessel availability, some initial data gaps exist.

II.B. Quantitative Approaches

Preliminary analysis of NRS data compared the five deep-water NRS that were operational in 2014-2015: 01 (Alaskan Arctic), 02 (Gulf of Alaska), 03 (Olympic Coast), 05 (Channel Islands), and 08 (NE US) (Figure 4). Several of the NRS deployed in 2014-2015 were omitted from initial analysis due to a data gap. Original data files (.DAT format) were converted to wav audio file format (WAV) using custom Matlab™ code and then manually reviewed in Raven interactive sound analysis software (Charif et al., 2010) to assess recording success and data quality. Long-term spectral average (LTSA) plots (10 Hz–2 kHz range) from each NRS were calculated in Matlab with 1 Hz and 1 sec resolution and the sum energy pressure was averaged over 1 Hz, 1 hour windows to determine spectrum levels (dB *re* 1 $\mu Pa^2/Hz$) from raw .DAT files.

Median (50th percentile, L50) monthly spectral levels (dB *re* 1 $\mu Pa^2/Hz$) at each NRS were calculated in 1 Hz bins using custom Matlab code. 10th and 90th percentiles of spectral levels were also calculated for each NRS from monthly sound levels using the statistics package for Matlab. Only full months of data collection were included in monthly L50 calculations and values were calculated according to the Julian calendar for the corresponding year of deployment (2014 or 2015).

November 2014, February 2015, and May 2015 were selected for cross-system sound level comparison based on overlapping data-collection effort among the 5 sites (see Figure 4). The maximum temporal comparison of sound levels was November 2014 – May 2015 at the Alaskan Arctic, Olympic Coast, and Channel Islands NRS sites (Figure 4). Spectral variability across these three sites was also measured using kernel smoothed histograms to compare of the number of occurrences of the difference in decibels (dB) between the 90^{th} and 10^{th} percentiles of 10 Hz – 2 kHz sound.

III. RESULTS & DISCUSSION

Documenting sound levels within the U.S. EEZ establishes baseline sound levels for temporal comparison. Drivers such as climate, tectonics, ocean processes, and policy affect the presence and intensity of sound sources (e.g., weather, anthropogenic activity, and animal habitats), which translates to measurable disparities across soundscapes (Haver et al., 2017). For example, the federally managed areas of National Marine Sanctuaries and the NPS where some NRS are located impose specific regulations of some anthropogenic activities. Thus, in tandem with additional drivers of soundscape variability, soundscapes across the NRS vary. Specifically, variation of frequency (Hz) and intensity (dB *re* 1 $\mu Pa^2/Hz$) of monthly L50 spectral levels at each NRS was generally greater across sites compared to seasonally within each NRS site (Figure 5).

This initial investigation of data collected by the NRS network observed temporal and geographic variability of low-frequency (10 Hz - 2 kHz) ocean ambient sound levels in five individual NRS soundscapes over a 6-month time-period. With few exceptions, monthly median sound levels (L50, measured in dB *re* 1 $\mu Pa^2/Hz$) at each site increased and decreased in intensity throughout the year. Overall, within-site monthly L50 differences were comparatively smaller than the variation measured across sites (Figure 6). These preliminary analyses begin to demonstrate the extent of spatial and temporal sound level variability within the U.S. EEZ, establishing current baselines that may be applied to future assessments. Overall, the NRS in the Alaskan Arctic recorded not only the largest seasonally variable monthly L50s, but also the lowest monthly L50. The highest and least seasonally variable monthly L50s were recorded at the NE US NRS in the northwest Atlantic Ocean.

Marine animals are important contributors to ambient sound and soundscapes across the U.S. EEZ. Marine mammals are a ubiquitous contributor to ambient sound worldwide, but fish and invertebrates may also influence sound levels in particular locations; for example, snapping shrimp significantly contribute to ambient sound levels in the shallow temperate and tropical waters (Staaterman et al., 2013). At all sites, animal chorusing (i.e. groups of animals calling at the same time over multiple hours) may increase sound levels within the specific frequency range of the calling species. For example, observed peaks in sound levels at ~20 Hz at Olympic Coast, Channel Islands, and NE US are likely indicative of fin whale (*Balaenoptera physalus*) calling (Figure 6, Watkins, 1981; Watkins et al., 1987). Approximately 70 species of marine mammals are protected by NOAA within the U.S. EEZ (NOAA Fisheries, 2017) and have a combined vocal range of ~10 Hz to 200 kHz (National Research Council, 2003), above the upper sampling limit of the NRS hydrophones. Species presence may differ by location and time for multiple reasons (e.g., prey availability or weather impeding area access), and likely affects the consistency of sound levels across soundscapes in the U.S. EEZ.

The NRS is dispersed over a broad range of climate zones and it is likely that regional discrepancies of weather influenced sound levels at all stations. Weather can influence a soundscape not only via wind, rain, ice, or other atmospheric phenomena but also by impeding the presence of anthropogenic or biological sound sources (Hildebrand, 2009; Klinck et al., 2012; Nystuen, 1986; Urick, 1983). For example, the seasonality of sound levels observed in the Alaskan Arctic at NRS01 is likely related to sea ice (Figure 6). Specifically, the largest range of monthly L50 across all measured frequencies was recorded in the Alaskan Arctic where the maximum monthly L50 were recorded in January 2015 and (across most frequencies) were ~10 dB higher than the monthly L50 recorded in June 2015. Artic sea ice volume is seasonally variable (Zhang and Rothrock, 2003; 2014-2015 PIOMAS predictions from: https://sites.google.com/site/arctischepinguin/home/piomas) and contributes to ambient sound levels via formation, cracking, and calving, as well as dampens sounds at the air sea barrier when fully formed (Makris and Dyer, 1991; Matsumoto et al., 2014; Menze et al., 2017; Milne and Ganton, 1964; Urick, 1971).

The U.S. EEZ extends 200 nm out from U.S. soil, and patterns of sound levels at NRS sites are likely reflective of the proximity of the NRS to shore within that boundary. Anthropogenic sources likely increase sound levels at NRS sites closer to shore, such as the Olympic Coast, Channel Islands, and NE US, compared to relatively remote sites (e.g., Alaskan Arctic and Gulf of Alaska) (Figure 7). For example, monthly L50 recorded in the Gulf of Alaska did not surpass 63 dB at any frequency between 10 Hz-2 kHz, whereas the lowest monthly L50 recorded in the NE US exceeded 63 dB in every frequency between 10 Hz-2 kHz (Figure 6).

Furthermore, soundscapes located off-shore of densely populated port cities are especially susceptible to noise from anthropogenic activity (Halpern et al., 2015). For example, in the Channel Islands National Marine Sanctuary, thousands of ships travel annually across the Pacific to ports along the California coast (including San Francisco, one of the most densely populated port cities in the U.S.), increasing sound levels as their acoustic footprint extends into the Sanctuary (Clark et al., 2009; McKenna et al., 2012). A similar impact may be observed in the NE US as vessels traveling from Europe, Africa, and other points in the North Atlantic to Boston, New York City, and other major Northeast U.S. port cities. In areas rich in energy resources, seismic airguns are also often a significant source of low-frequency anthropogenic noise (Nieukirk et al., 2012; Wiggins et al., 2016); seismic airguns likely increased sound levels in the NE US (Nieukirk et al., 2012).

The intersection of animal habitats, weather, and anthropogenic activity in each NRS soundscape determine the ambient sound levels. While it is impossible to assess the impact of anthropogenic noise in a soundscape without a targeted analysis of all sound sources, cross-network sound level comparisons can identify times and areas of elevated sound levels for further analysis. For example, comparing the difference between percentiles of sound levels can reveal the magnitude of seasonal changes in a soundscape (Figure 8, Haver et al., 2017). Among the soundscapes of the Alaskan Arctic, Olympic Coast, and Channel Islands between November 2014 and May 2015, the difference in dB between the 90^{th} and 10^{th} percentiles of sound at all frequencies (10 Hz - 2 kHz) was largest in the Alaskan Arctic (mode ~17 dB *re* 1 μPa). In comparison, the variability of intensity of sound among all frequencies in the Olympic Coast and Channel Islands was much smaller (modes of ~9.5 dB and ~7.5 dB *re* 1 μPa, respectively, Figure 8). Not only can these seasonality assessments can reveal differences across sites, but also measuring differences on various temporal scales (e.g., daily, multi-year) can provide clues to identify drivers of change.

Marine ecosystems are dynamic environments, and the ambient sound levels recorded within each discrete NRS soundscape are likely related to the variability of sound sources across the U.S. EEZ. But without overlapping data from all seasons, it is difficult to comprehensively assess how weather, animals, and anthropogenic activity may intersect to shape each NRS soundscape and to assess noise versus sound. While this study did not determine individual contributors to each NRS soundscape, as additional years of data are collected future work will apply soundscape analysis metrics (e.g., detectors, manual and automatic classification algorithms; Erbe et al., 2016) to tease apart individual contributors and investigate long-term trends across the entire network.

IV. FUTURE DIRECTIONS

The establishment of the NRS is critical to filling relevant data gaps for understanding temporal and spatial patterns in ocean noise. The ongoing goal of this monitoring effort is to maintain the continuous recording of ambient sound throughout the U.S. and expand temporal and spatial sound level measurement products to understand the specific sources that contribute to soundscapes and how these sources may vary. These data products may be guided by the needs of resource managers to inform strategies for understanding changing soundscapes and monitoring ocean noise on local scales as well as more broadly across the U.S. EEZ.

In the Ocean Noise Strategy Roadmap (ONS), NOAA assesses a need to document and monitor underwater sound levels throughout the U.S. This need is also specifically cited by the NOAA National Marine Sanctuary system's scientific needs assessment for monitoring noise in sensitive marine ecosystems, and reiterated by the NPS (Callender et al., 2017; Fristrup et al., 2010; National Oceanic and Atmospheric Administration, 2017). In changing ocean health conditions due to shifts in climate and industrial human use patterns, it is essential to monitor evolving anthropogenic activity in biologically sensitive areas (e.g., increased vessel traffic in the Arctic due to decreased ice coverage, energy extraction along the U.S. East Coast and in the Gulf of Mexico).

The addition of forthcoming data from NRS that were first deployed between 2015 and 2016 will supplement existing deep-water (and permit shallow-water) cross-network sound level comparisons. Future analysis of data collected by the entire network will establish efficient methods to quantify sound levels by type (i.e., biological, geophysical, or anthropogenic). Classification of sounds will elucidate the contribution of different sources to marine soundscapes. Such knowledge will establish sound level baselines across all sampled frequencies and inform models to predict future changes within soundscapes, giving managers and policymakers tangible tools to assess program effectiveness over a long-term decadal scale and ensure that the needs of all ecosystem user groups are met in a sustainable way.

The NRS in national parks, marine sanctuaries, and the U.S. EEZ represent different management contexts. Continuous soundscape monitoring is necessary to ensure human usage is appropriate for each managed area. Specifically, it is important to consider acoustic habitats in determining the sustainable limit of industry use in each area (e.g., fishing, renewable energy, and shipping). By determining contributions of distinct sources to sound levels, long-term continuous NRS recordings will help fulfill NOAA's mandates to monitor and conserve marine animals, and help safeguard resources necessary to sustain healthy marine ecosystems.

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FIGURES

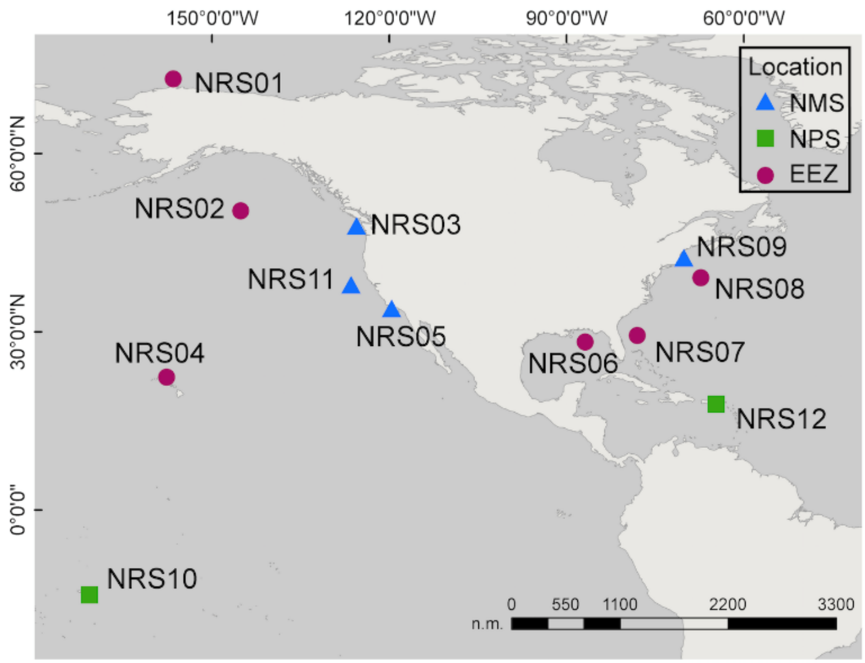

Figure 3.1 Locations of NRS moorings throughout the U.S. EEZ colored by site type (National Marine Sanctuary sites are marked with blue triangles, National Park Service sites are marked with green squares, and the locations of all other NRS sites are identified by yellow circles).

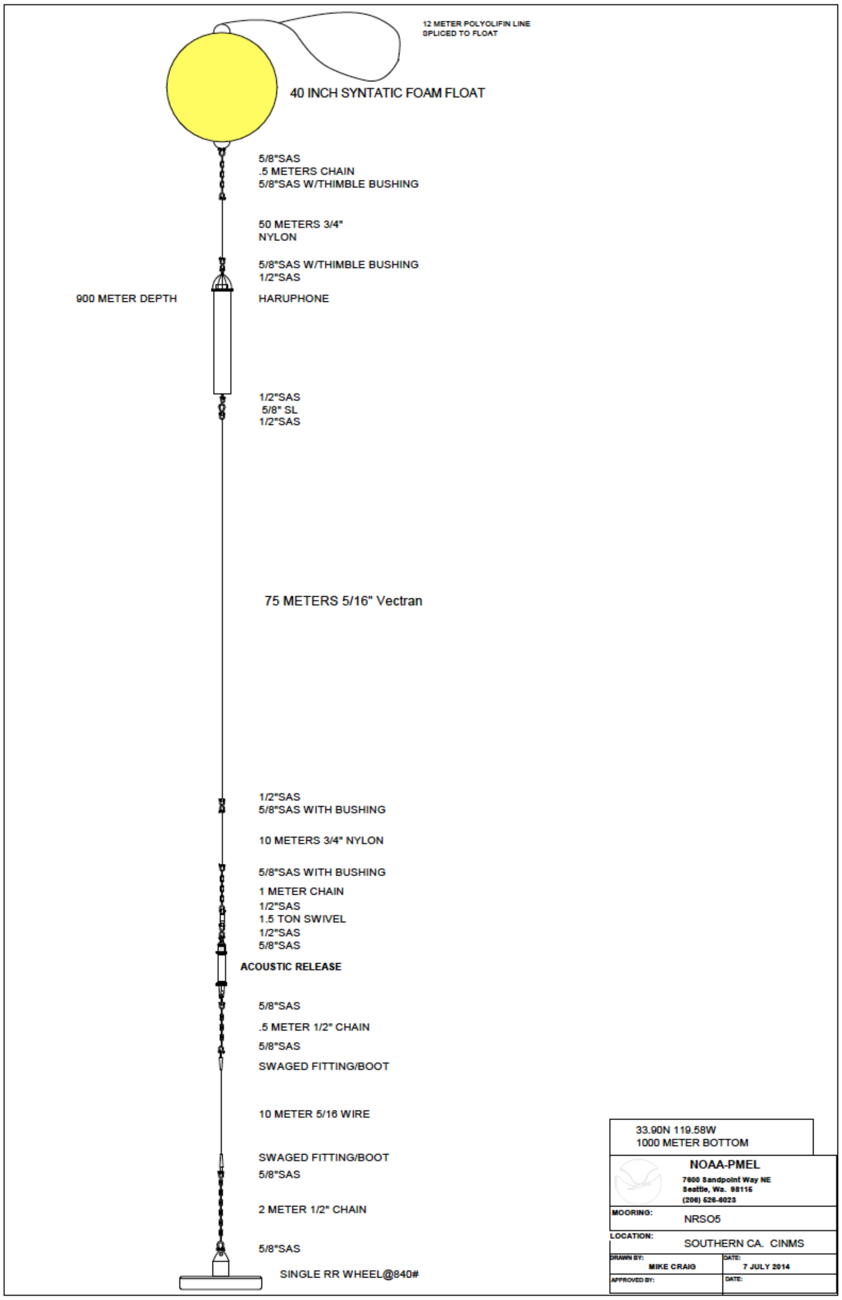

Figure 3.2 Example mooring diagram of NRS05 in the Channel Islands National Marine Sanctuary. All deep-water NRS hydrophones are similarly suspended in the water column between a syntactic foam float and a bottom-mounted acoustic release (Diagram: Michael Craig, NOAA PMEL).

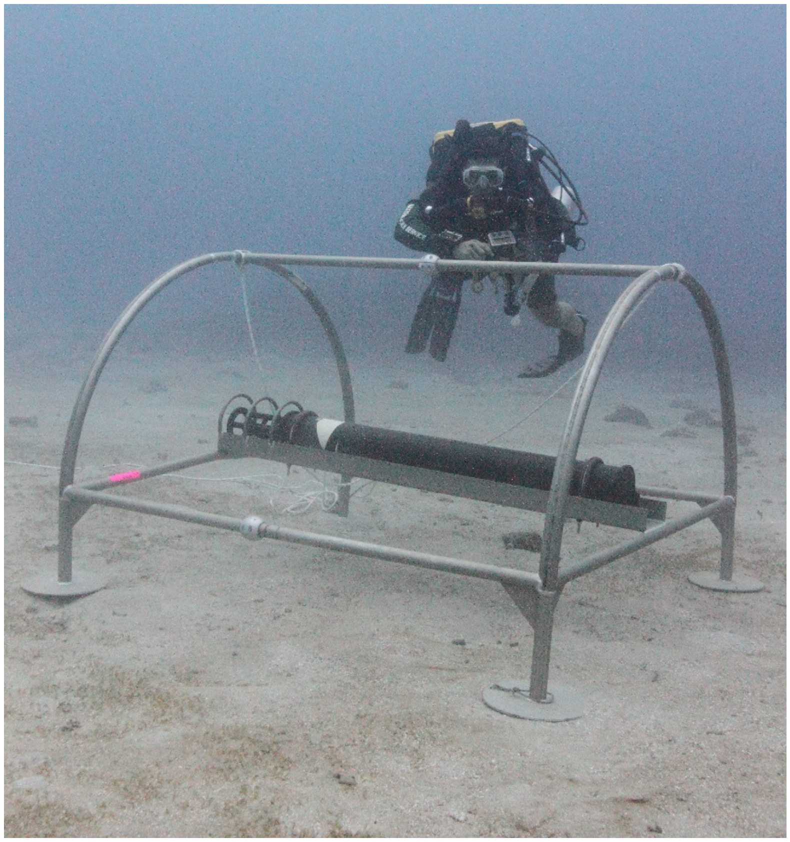

Figure 3.3 A shallow water NRS deployed off the coast of Tutuila Island in the National Park of American Samoa. All shallow water NRS are bottom mounted on similar hollow metal landers. Each lander is appropriately weighted to the seafloor according to substrate and location to ensure the NRS remains stationary. (Photograph: NPS, National Park of American Samoa, 11 June 2015).

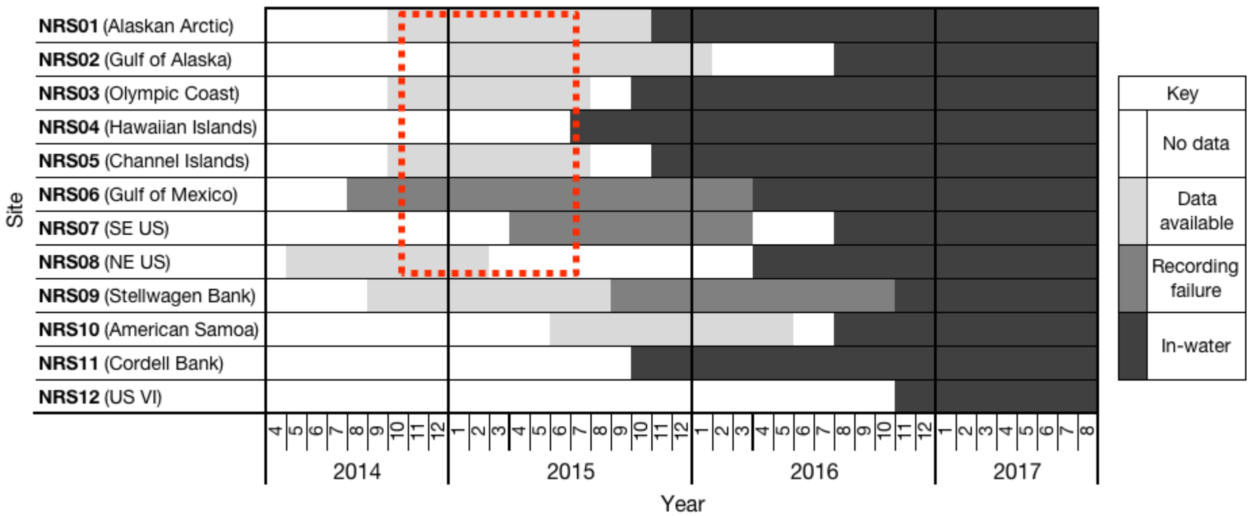

Figure 3.4 Initial NRS acoustic data collection effort by site and month. Shading indicates the recording success (i.e., data collection) during a given month. The dashed selection box highlights the temporally overlapping data selected for preliminary deep-water cross-network analysis here. NRS09 (Stellwagen Bank National Marine Sanctuary) and NRS10 (American Samoa) are shallow stations and were not included in 2014-2015 cross-network sound level comparisons because initial analysis was focused on deep-water soundscapes.

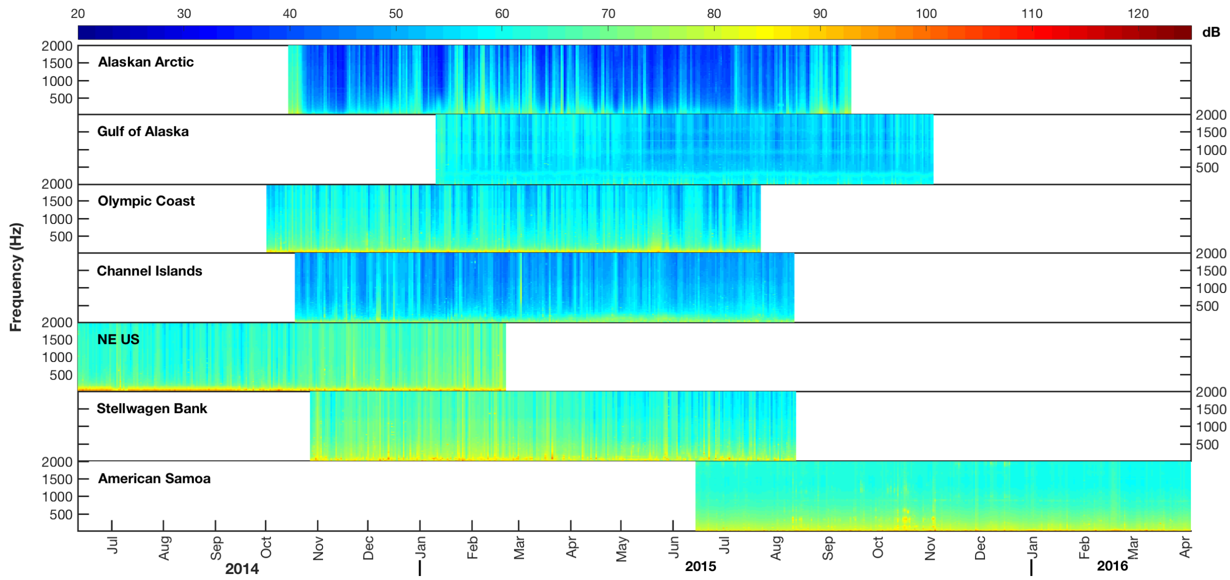

Figure 3.5 Time aligned long term spectral averages (LTSA) of the first year (2014-2015) of acoustic data from five deep-water NRS (Alaskan Arctic, Gulf of Alaska, Olympic Coast, Channel Islands, and NE US) and two shallow-water NRS (Stellwagen Bank, American Samoa). Intensity of sound (dB *re* 1 $\mu Pa^2/Hz$) is indicated by blue-red variation.

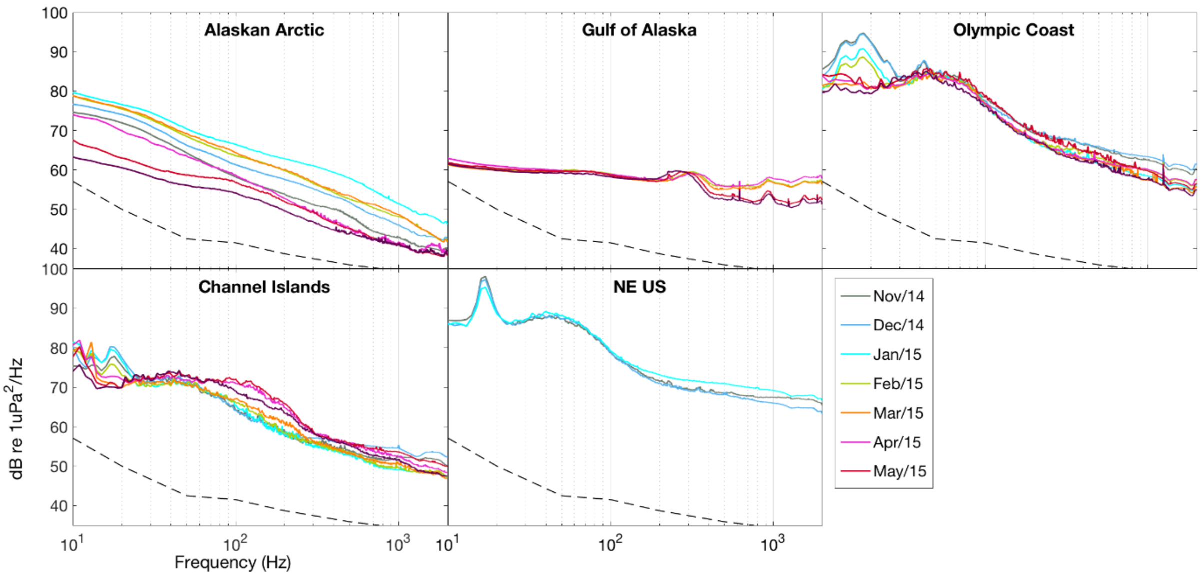

Figure 3.6 Monthly median sound levels (L50) at five deep-water NRS calculated in 1 Hz bins for all available months between November 2014 and May 2015 and plotted by site. The dashed line in each plot indicates the system noise floor. These data depict relatively stable monthly L50 between November 2014 and 2015 in the initial deployment period at each NRS location, with the exception of the Alaskan Arctic (NRS01). Data recorded prior to November 2014 or after May 2015 were excluded to control for temporal inconsistencies.

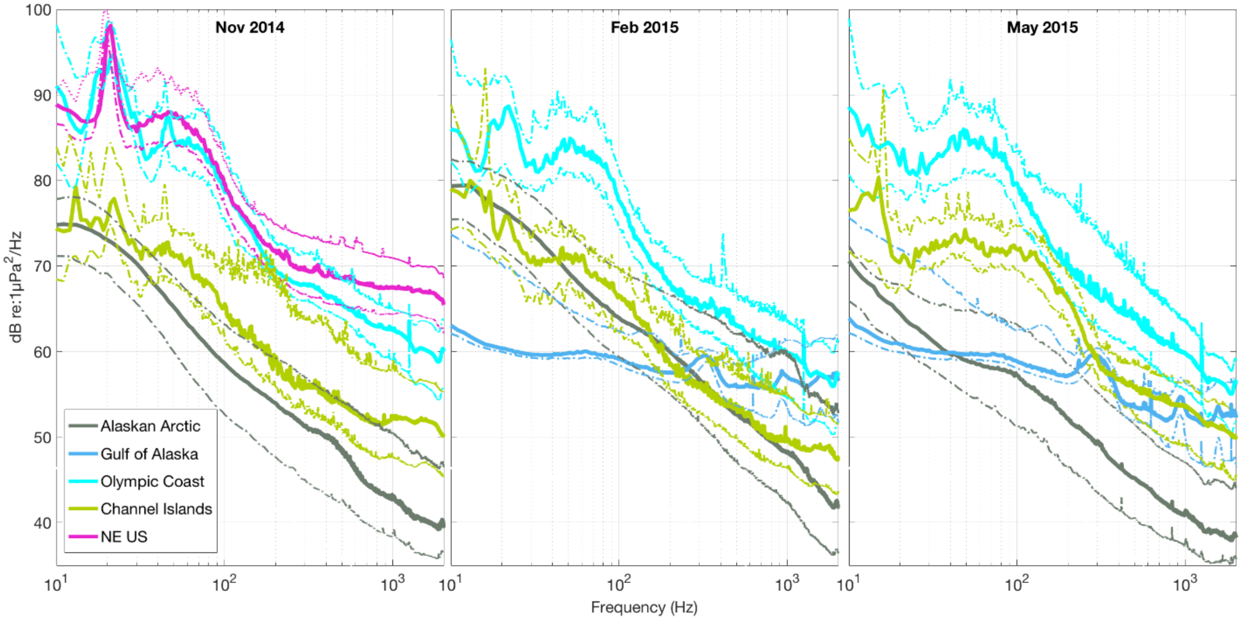

Figure 3.7 Monthly median sound levels (monthly L50) at each NRS calculated in 1 Hz bins for November 2014, February 2015, and May 2015. Each NRS site is indicated by a single color (Alaskan Arctic, grey; Gulf of Alaska, light blue; Olympic Coast, cyan; Channel Islands, light green; NE US, pink). Thinner dashed lines indicate the 10th (lower) and 90th (upper) percentiles of monthly sound levels at each NRS.

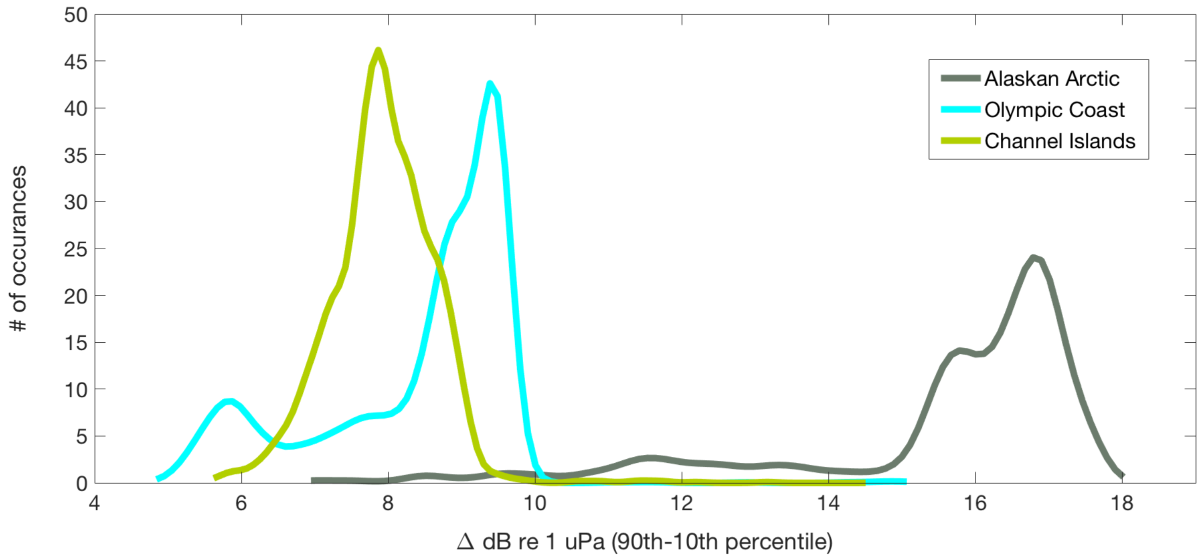

Figure 3.8. Kernel smoothed histograms (bin width 500) of the number of occurrences of the difference in decibels (dB) between the 90th and 10th percentiles of 10 Hz – 2 kHz sound in the Alaskan Arctic, Olympic Coast, and Channel Islands from November 2014 – May 2015. Comparatively smaller differences in the change of dB between percentile levels in the Channel Islands reflect little variation of sound levels across the investigated frequency band throughout seasonal changes of late fall through winter to late spring. Differences in dB level between percentiles at Olympic Coast and Channel Islands were long-tailed towards larger dB level changes at some frequencies, indicating that the spread between the 90th and 10th percentiles of sound was up to ~15 dB at both locations. This positive skewedness (broader spread to the right of the mean) is related to seasonal changes in marine mammal calling, local weather, and vessel activity. The high occurrence of a ~17 dB difference between the 90th and 10th percentiles of sound in the Alaskan Arctic indicates that sound levels increase and decrease seasonally due to ice coverage. This negative skewedness is related to less frequent small changes in noise levels, likely due to marine mammal calling and storms.

TABLES

Station	Location	Partners	Latitude	Longitude	Water depth [m]	AUH depth [m]
NRS01	Alaskan Arctic	NOAA/AFSC	72.44	-156.55	1,000	500
NRS02	Gulf of Alaska	NOAA/PMEL	50.25	-145.13	4,250	500
NRS03	Olympic Coast National Marine Sanctuary	NOAA/NWFSC & NOAA/OCNMS	47.77	-125.52	936	488
NRS04	Hawaiian Islands	NOAA/PIFSC	22.33	-157.67	~4,900	900
NRS05	Channel Islands National Marine Sanctuary	NOAA/SWFSC	33.90	-119.58	1,000	900
NRS06	Gulf of Mexico	NOAA/SEFSC	28.25	-86.83	1,230	900
NRS07	Southeastern continental U.S. (SE US)	NOAA/SEFSC	29.33	-77.99	870	900
NRS08	Northeastern continental U.S. (NE US)	NOAA/NEFSC	39.01	-67.27	~3,550	900
NRS09	Stellwagen Bank National Marine Sanctuary	NOAA/SBNMS	42.40	-70.13	79	79
NRS10	Tutuila Island, American Samoa	NPS/NPAS	-14.27	-170.72	33	33
NRS11	Cordell Bank Coast National Marine Sanctuary	NOAA/CBNMS	37.88	-126.44	534	500
NRS12	Buck Island Reef, U.S. Virgin Islands (US VI)	NOAA/NPS	17.79	-64.65	40	40

Table 3.1. NRS deployment site number, location, collaborator(s), latitude/longitude, and water and hydrophone depths.

CHAPTER 4: GENERAL CONCLUSIONS AND FUTURE DIRECTIONS

The scope of this research is widespread; by reviewing soundscapes in different oceans we start to understand the difference and variability between marine ecosystems at ecologically relevant scales. There is a high demand and demonstrated need for monitoring anthropogenic noise, as it is ineffiecient to establish policies for noise pollution without a baseline.

Future comparisons of Ocean Noise Reference Station Network soundscapes—over time within sites, among shallow and deep water habitats, and among National Marine Sanctuaries, National Parks, and the greater U.S. Exclusive Economic Zone—will reveal how natural and anthropogenic contributors to ocean ambient sound vary by location and time, and identify long-term trends across the entire network. These data improve condition monitoring of some of NOAA's most valued marine areas, which will support management planning and policy development. The key to reducing anthropogenic noise and preserving acoustic habitats is to inform the public and scientific community about how human activities may negatively and directly influence marine environments. This thesis contributes to an evolving understanding of how human activity may affect soundscapes on a continental scale.

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