AN ABSTRACT OF THE DISSERTATION OF

Samara M. Haver for the degree of Doctor of Philosophy in Wildlife Science presented on January 12, 2021.

Title: Long Term Trends and Sources of Sound in United States Waters.

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Passive acoustic monitoring is a valuable tool for observing the status of marine environments. Comparisons of underwater soundscapes over temporal and spatial scales can provide data to inform marine conservation efforts, including protection of threatened and endangered species. This dissertation utilizes passive acoustic data collected via a broadly spaced array of autonomous hydrophones, the National Oceanic and Atmospheric Administration and National Park Service Noise Reference Station Network. The Noise Reference Station Network is the first effort to continuously sample widespread ocean areas across the United States using identically calibrated passive acoustic instrumentation. Using these data, I measure and compare diverse acoustic environments and management contexts of marine soundscapes in all major regions of United States waters.

The chapters of this dissertation quantify the levels and drivers of ambient sound in marine protected and biologically important areas at different scales. Chapter 2 compares the sound levels and trends at five widespread deep-water (>500 m depth) sites (Alaskan Arctic, Olympic Coast National Marine Sanctuary, Channel Islands National Marine Sanctuary, Gulf of

Mexico, and Northeast Canyons and Monuments National Monument). Chapter 3 evaluates the acoustic environments of four shallow (<100 m depth) marine protected areas (Stellwagen Bank National Marine Sanctuary, National Park of American Samoa, Buck Island Reef National Monument, and Glacier Bay National Park and Preserve). Chapter 4 is a two-year-long case-study at a single deep-water site (550 m depth) in Cordell Bank National Marine Sanctuary. Chapter 5 links international acoustic pressure indicators for commercial shipping activity to vessel movement records at five deep-water (>500 m depth) sites (Gulf of Mexico, Cordell Bank National Marine Sanctuary, Hawaii, Northeast Canyons and Monuments National Monument, and Alaskan Arctic). The results of the four manuscripts included in this dissertation provide decision-making information for regulatory agencies to manage acoustically sensitive ecological areas.

Long Term Trends and Sources of Sound in United States Waters

by
Samara M. Haver

A DISSERTATION

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APPROVED:

Major Professor, representing Wildlife Science

Head of the Department of Fisheries and Wildlife

Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Samara M. Haver, Author

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CONTRIBUTION OF AUTHORS

Chapter 2. Samara M. Haver designed the study, analyzed the data, prepared the figures, and drafted the manuscript. Jason Gedamke, Leila Hatch, Robert P. Dziak, Sofie Van Parijs, Megan McKenna, Jay Barlow, Catherine Berchok, Eva DiDonato, Brad Hanson, Joseph Haxel, Marla Holt, Danielle Lipski, Haru Matsumoto, Christian Meinig, David K. Mellinger, Sue Moore, Erin Oleson, Melissa Soldevilla, and Holger Klinck conceived and designed the Noise Reference Station Network. Holger Klinck provided initial critical revisions. All authors edited manuscript. This manuscript was published in Marine Policy in 2018.

Chapter 3. Samara M. Haver designed the study, prepared the figures, and drafted the manuscript. Robert P. Dziak, Jason Gedamke, Leila T. Hatch, Joseph Haxel, Megan F. McKenna, David K. Mellinger, Sofie M. Van Parijs conceived and designed the Noise Reference Station Network and contributed data from Stellwagen, American Samoa, and Virgin Islands. Michelle E. H. Fournet and Christine Gabriele contributed data from Glacier Bay. Samara M. Haver and Michelle E. H. Fournet processed and analyzed the data with support from Christine Gabriele, Leila T. Hatch, Joseph Haxel, Megan F. McKenna, David K. Mellinger, Sofie M. Van Parijs, and Scott A. Heppell. Michelle E. H. Fournet, Sofie M. Van Parijs, Megan F. McKenna, Leila T. Hatch, Christine Gabriele provided initial critical revisions. All authors edited manuscript. This manuscript was published in Frontiers in Marine Science in 2019.

Chapter 4. Samara M. Haver designed the study, prepared the figures, and drafted the manuscript. Leila T. Hatch, Danielle Lipski, Robert P. Dziak, Jason Gedamke, Joseph Haxel, Megan F. McKenna, David K. Mellinger, Sofie M. Van Parijs conceived and designed the Noise Reference Station Network and contributed data from Cordell Bank National Marine Sanctuary. Lauren Roche build hydrophone and coordinated all field operations with Danielle Lipski and others. Jaime Jahncke contributed visual marine mammal abundance data. Samara M. Haver processed the acoustic data and conducted all sound level analyses. Samara M. Haver and Zoe Rand analyzed the data for the presence of humpback whales. William K. Oestreich and John Ryan analyzed the data for the presence of blue and fin whales. Samara M. Haver analyzed the data for the presence of gray whales. All authors edited manuscript. This manuscript was published in the Journal of the Acoustical Society of America in 2020.

Chapter 5. Leila T. Hatch, Sofie M. Van Parijs, Robert P. Dziak, Joseph Haxel, Megan F. McKenna, David K. Mellinger, Jason Gedamke conceived and designed the Noise Reference Station Network and contributed passive acoustic data. Jeffrey D. Adams contributed Automatic Information System vessel data for all sites. Samara M. Haver designed the current study with Jeffrey D. Adams, Jason Gedamke, Leila T. Hatch, Sofie M. Van Parijs. Samara M. Haver analyzed and synthesized the data with support from Jeffrey D. Adams, Leila T. Hatch, Sofie M. Van Parijs, Scott A. Heppell, Jason Gedamke. Samara M. Haver prepared the figures and drafted the manuscript. All authors edited manuscript. At the time this dissertation was submitted this manuscript was in preparation for submission to Frontiers in Marine Science.

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“Instructions for living a life:
Pay attention.
Be astonished.
Tell about it.”

-Mary Oliver, Sometimes

CHAPTER 1. GENERAL INTRODUCTION

BACKGROUND

Acoustic signals travel quickly and efficiently over long distances in the aquatic environment; thus, sound is the principal sensory modality used by many marine 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). These abilities have evolved in this widely distributed taxon 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.

The acoustic signals that animals produce, coupled with sounds generated from abiotic natural sources (e.g. surface winds), geophysical processes (e.g. earthquakes) and anthropogenic (e.g. vessel noise) sources, make up the soundscape (Pijanowski et al., 2011). Recordings of soundscapes can be analyzed to understand how animals use the acoustic environment as well as to indicate overall ecosystem health in a particular location or time (Miksis-Olds et al., 2015). For example, human-generated sounds that may impede an animal’s ability to hear environmental cues that are vital for survival (i.e., predator avoidance, foraging, navigation, and reproduction) are considered “anthropogenic noise” (Cato et al., 2015; Clark et al., 2009). Anthropogenic noise can negatively impact 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). Although cetaceans have been the primary focus of research efforts investigating the effects of noise, the behavior and physiology of many fishes and marine invertebrate species are similarly affected (Popper, 2003; Simpson et al., 2016).

Passive acoustic monitoring (PAM) is used to measure, monitor, and assess levels of and trends in ocean ambient sound; i.e. the soundscape. Long-term autonomous acoustic ecosystem monitoring can be used to answer questions about specific systems (e.g., NPS terrestrial soundscape database, Buxton et al., 2017) for informing noise management and mitigation decisions and strategies. Because anthropogenic noise may be detrimental to animals and ecosystems, reducing or eliminating the ecosystem services they provide (McLeod and Leslie, 2009), it is essential to monitor and manage noise pollution within natural soundscapes.

Comparisons 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 sea ice coverage or earthquakes. Synthesis of these data allow for description and comparison of levels of ocean sound to inform marine animal protection and ocean conservation efforts. In the past few decades a handful of studies have compared long-term ocean ambient sound levels (e.g., Andrew et al., 2002; Hatch et al., 2008; McDonald et al., 2008; Širović et al., 2016), but each of these efforts was limited by the lack of a comprehensive and comparable data set collected throughout U.S. waters. My dissertation aims to start filling this knowledge gap to quantify ocean ambient sound conditions by using a broadly spaced array of hydrophones located throughout the U.S. Exclusive Economic Zone (EEZ), including in national parks (NPS) and national marine sanctuaries (NMS) and monuments.

By measuring ocean ambient sound levels and temporal trends of the diverse acoustic environments within U.S. ocean soundscapes, these results provide valuable information that regulatory agencies can use manage acoustically sensitive ecological areas.

INTRODUCTION TO THE NOAA/NPS OCEAN NOISE REFERENCE STATION NETWORK

A partnership between NOAA and the NPS was established in which the Ocean Noise Reference Station (NRS) Network, comprising 12 identical autonomous passive acoustic instruments, was first deployed between June 2014 and November 2016 to document baseline levels and multi-year trends in ocean ambient sound within and near to the U.S. EEZ. Monitoring marine ambient sound using standardized methods supports assessments of ocean sound levels across widespread ecosystems. The manuscripts included in this dissertation quantify differences among these coastal and deep-water marine soundscapes in the Atlantic, Pacific, and Arctic oceans.

Implementation of the NRS Network advances the capabilities of NOAA and the NPS to address national issues dealing with monitoring protected areas and living marine resources (marine mammals, fish, invertebrates), and the contribution of anthropogenic sources to ambient sound associated with energy production (e.g., oil and gas exploration, renewable energy development) and socioeconomic activity (e.g., container shipping, commercial fisheries, and recreation/tourism). Broadly, temporal and cross-network comparisons of NRS data provide information on the relative presence of biological, geophysical, and anthropogenic sounds, supporting marine planning and policy development by providing quantitative measures to understand and manage the scope of anthropogenic noise sources in sensitive marine environments. These analyses also define ambient sound level baselines to evaluate changes over time, including the presence of anthropogenic activities, and the efficacy of management approaches addressing both protected areas and species.

CHAPTER SUMMARIES

In Chapter 2, I introduce the NRS project and examine data from the first calibrated recordings to present initial comparative sound levels among separate ocean areas of the U.S. EEZ. To facilitate future analyses of NRS data, this study establishes comparable baselines of the ocean ambient sound levels at five NRS sites and describes quantitative methods for assessment of cross-network comparisons of ambient sound levels.

Chapter 3 assesses differences in shallow water NRS soundscapes across four geographic regions. This analysis compares management schemas and habitat types at marine protected areas within U.S. waters to explore how soundscape analysis can inform management. Using humpback whale (*megaptera novaeangliae*) song as a proxy for soniferous and acoustically sensitive species in these soundscapes, I evaluate how song detections may change in relation to variable ambient noise conditions in these shallow and protected park waters.

Chapter 4 is a case study of Cordell Bank National Marine Sanctuary, prepared to specifically support sanctuaries management in addition to the NOAA Ocean Noise Strategy. This manuscript describes the establishment of a passive acoustic monitoring mooring (a Noise Reference Station) and provides the first description of the underwater soundscape. In the paper I quantify baseline sound levels and describe the contributions of baleen whales and vessel activity to the low-frequency soundscape (10 Hz - 2 kHz). I also compare passive acoustic and visual baleen whale detections to evaluate the utility of passive acoustic monitoring for endangered species and marine protected area conservation.

The culminating data chapter of this dissertation is a broad comparison of data sampled from multiple Noise Reference Stations to compare acoustic conditions across broad regions of the U.S. Exclusive Economic Zone. In this paper I combine vessel movement records from Automatic Information Systems (AIS) with internationally standardized analytical methods to measure noise from commercial shipping traffic to evaluate the efficacy of the aforementioned methods in U.S. waters. These results facilitate U.S.-wide and international comparisons of the acoustic impact of vessel activity in a variety of environments, including different management contexts of marine protected areas.

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CHAPTER 2. MONITORING LONG-TERM SOUNDSCAPE TRENDS IN U.S. WATERS: THE NOAA/NPS OCEAN NOISE REFERENCE STATION NETWORK

Samara M. Haver, Jason Gedamke, Leila Hatch, Robert P. Dziak, Sofie Van Parijs, Megan McKenna, Jay Barlow, Catherine Berchok, Eva DiDonato, Brad Hanson, Joseph Haxel, Marla Holt, Danielle Lipski, Haru Matsumoto, Christian Meinig, David K. Mellinger, Sue Moore, Erin Oleson, Melissa Soldevilla, Holger Klinck

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ABSTRACT

The National Oceanic and Atmospheric Administration (NOAA)/National Park Service (NPS) Ocean Noise Reference Station (NRS) Network is an array of currently twelve calibrated autonomous passive acoustic recorders. The first NRS was deployed in June 2014, and eleven additional stations were added to the network during the following two years. The twelve stations record data that can be used to quantify baseline levels and multi-year trends in ocean ambient sound across the continental United States, Alaska, Hawaii, and island territories within and near to the United States Exclusive Economic Zone (U.S. EEZ). The network provides multi-year, continuous observations of low-frequency underwater sound between 10 Hz and 2,000 Hz to capture anthropogenic, biological, and geophysical contributions to the marine soundscape at each location. Comparisons over time and among recording sites will provide information on the presence of calling animals and the prevalence of abiotic and anthropogenic activities that contribute to each soundscape. Implementation of the NRS Network advances broad-scale passive acoustic sensing capabilities within NOAA and the NPS and is an important tool for monitoring protected areas and marine species and assessing potential environmental impacts of anthropogenic noise sources. This analysis focuses on the first year of recordings and captures the wide variability of low-frequency sound levels among and within individual NRS sites over time. Continued data collection will provide information on long-term, low-frequency sound level trends within or near the U.S. EEZ and will be used to explore the value of using soundscape analysis to inform management and mitigation strategies.

INTRODUCTION

Many marine animals have evolved sensory systems to exploit the efficiency of underwater sound propagation. These organisms rely on sound as their primary sensory modality to communicate, detect predators and prey, and navigate (Richardson et al., 1995). The acoustic cues that animals produce, coupled with sounds emanating from abiotic geophysical factors (e.g., weather and geologic processes) and anthropogenic (i.e., human-generated) sources, make up the soundscape (Pijanowski et al., 2011). Broadly, soundscape analysis can be 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 broadly accepted standards for analyzing or reporting soundscape conditions, including ambient (background) sound (Cato et al., 2015; Erbe et al., 2016).

Within a soundscape, human-generated sounds that may impede an animal's ability to hear environmental cues that are vital for survival (i.e., predator avoidance, foraging, 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 anthropogenic noise has been shown to affect marine animals in numerous ways, including 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 cetaceans have been the primary focus of research efforts investigating the effects of noise, the behavior and physiology of many fishes and marine invertebrate species are similarly affected (Popper, 2003; Simpson et al., 2016).

Sources of anthropogenic noise in the ocean (e.g., commercial and recreational vessel traffic, naval activities, and fossil fuel exploration/extraction) commonly emit low-frequency signals that propagate over long distances (Munk, 1994; Wilcock et al., 2014). Thus, a source of anthropogenic noise does not need to be in close physical proximity to an animal to potentially interfere with biological signals (Nieukirk et al., 2004). In this study, ocean ambient noise is considered to encompass persistent or long-term "chronic" sources of anthropogenic noise in a marine soundscape (Erbe et al., 2016a). While transient natural sources of sound in the ocean (e.g., seaquakes) are among the loudest sounds on Earth, chronic anthropogenic noise may be more threatening to animal communication due to its persistence and acoustic properties. Further, rapidly changing marine soundscapes are particularly detrimental to marine animals given the relatively short time necessary to adapt abilities developed over millennia for the historical underwater acoustic environment (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 effects of 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 statutes, anthropogenic activities can be regulated and restricted for animal and habitat conservation. However, current U.S. policies are tailored toward discrete incidences of noise exposure instead of the cumulative effects of chronic noise. This emphasis is now changing, as can be seen by the establishment of U.S. National Oceanic and Atmospheric Administration's Ocean Noise Strategy (ONS; Gedamke et al., 2016). The ONS focuses on the research and management of the impacts of noise, both acute and chronic, on marine species. 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[1] acoustic monitoring capabilities across those offices.

The ONS was developed in support of the goals of the U.S. National Ocean Policy (National Ocean Policy, 2010), and reasons that existing baseline conditions (e.g., ocean ambient sound levels) must be measured to better protect animals and understand the threats they are exposed to. 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 (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 marine and terrestrial wildlife, and that understanding conditions of the acoustic environment over space and time is essential for informing management and evaluating the impacts to wildlife and visitors (Barber et al., 2010; Buxton et al., 2017; Lynch et al., 2011; Shannon et al., 2016). Chronic anthropogenic noise is an

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[1] "Passive" in an acoustic context means listening only, without any active generation of sounds.

international issue as the habitats of especially highly migratory marine species span national boundaries; thus, to achieve its goals, the U.S. must join the global community in an international effort to monitor and manage ocean ambient noise (Dekeling et al., 2015).

Long-term acoustic ecosystem monitoring can be used to answer questions about specific systems (e.g., NPS terrestrial soundscape database, Buxton et al., 2017) for informing noise management and mitigation decisions and strategies. Because chronic noise may be detrimental to animals and ecosystems and therefore reduce or eliminate the ecosystem services they provide to human stakeholders (McLeod and Leslie, 2009), 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 the values to wildlife and human visitors (National Park Service and U.S. Department of the Interior, 2006). By managing acoustic environments as a resource 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. (National Ocean Policy, 2010).

To date, there have been a handful of studies that monitored long-term ocean ambient sound (e.g., Andrew et al., 2002; Hatch et al., 2008; McDonald et al., 2008; Širović et al., 2016), but there is no comprehensive and comparable data set collected throughout U.S. waters. This study aims to fill this knowledge gap by measuring ocean ambient sound and identifying the contributions of anthropogenic, geophysical, and biological sounds to the environment in order to determine baseline levels throughout and adjacent to the U.S. Exclusive Economic Zone (EEZ), including national parks and national marine sanctuaries and monuments. By comparing ocean ambient sound levels and establishing long-term monitoring of acoustic environments across diverse regions within U.S. waters, this study provides tools for managers and stakeholders to prioritize the needs of sensitive acoustic ecosystems and time periods.

To address this knowledge gap, a partnership between NOAA and the NPS was established in which the Ocean Noise Reference Station (NRS) Network, comprising 12 identical autonomous passive acoustic instruments, was first deployed between June 2014 and November 2016 to document baseline levels and multi-year trends in ocean ambient sound within and near to the U.S. EEZ. The NRS Network was established as a flagship project of the ONS, which aims to characterize acoustic habitats and manage the impacts of anthropogenic noise exposure on the places and species in NOAA's trust (Gedamke et al., 2016). The NRS Network represents the first concerted effort to combine cross-agency capabilities to compare ocean ambient sound levels across regions and leverage them towards the collective management vision and goals of the ONS.

Implementation of the NRS Network advances the capabilities of NOAA and the NPS to address national issues dealing with monitoring living marine resources (marine mammals, fish, invertebrates), and the effects of human noise sources associated with energy production (e.g., oil and gas exploration, renewable energy development) and socioeconomic activity (e.g., container shipping, commercial fisheries, and recreation/tourism). Temporal and cross-network comparisons of NRS data will provide information on the relative presence of biological, geophysical, and anthropogenic sounds, supporting marine planning and policy development personnel by providing 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 collection of calibrated data collection to present initial comparative sound levels among separate ocean areas of the U.S. EEZ. To facilitate future analyses of NRS data, this study establishes comparable baselines of the ocean ambient sound levels at five NRS sites and describes quantitative methods for assessment of cross-network comparisons of ambient sound levels. Future analyses will identify the relative contributions of anthropogenic, geophysical, and biological sounds to ocean ambient sound levels.

METHODS

Instrumentation

The NRS Network is composed of nine deep-water and three shallow-water moorings designed and constructed by NOAA's Pacific Marine Environmental Laboratory (PMEL) (Figures 1 and 2). 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 nominal sensitivity of -192 dB re 1V/µPa and a flat frequency response (-/+ 1 dB) between 10 Hz and 2,000 Hz. Signals incoming to the AUH are conditioned by a pre-amplifier and pre-whitening filter to maximize the dynamic range of the 16-bit 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 deep sound channel (Urick, 1983) at depths of 500-900 m. Deep-water NRSs are anchored to the ocean floor and are equipped with swivel links and low-stretch and low-drag mooring line to reduce self-noise from current-related strumming (Figure 2), as well as an acoustic release that, upon command, detaches the mooring from the anchor so that it may be recovered at the surface. The AUHs for the three shallow-water (<100 m) NRSs were calibrated to the same specifications as the deep-water sites, but instead were 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 sample rate of 5 kHz (2 kHz low-pass cutoff), enabling data collection up to two years in duration between servicing of the moorings.

Deployment locations for the NRS Network are presented in Table 1 and Figure 1. The first NRS was deployed in June 2014, and over the following 27 months 11 other stations were also deployed. Deep-water NRSs are deployed for up to two years before recovery. Due to the potential for biofouling on the hydrophone of the shallow-water NRS, those moorings are recovered for cleaning and service annually. Recording effort for the NRS Network from June 2014 through December 2016 is presented in Figure 4. Due to equipment failure and deployment vessel availability, some data gaps exist.

Quantitative Approaches

This analysis of NRS data compares ocean ambient sound levels at the five deep-water NRS that were operational in 2014-2015: NRS01 (Alaskan Arctic), NRS03 (Olympic Coast National Marine Sanctuary), NRS05 (Channel Islands National Marine Sanctuary), NRS06 (Gulf of Mexico), and NRS08 (NE US) (Figure 4). Several of the NRS deployed in 2014-2015 were omitted from initial analysis due to an instrument failure. Original data files (.DAT format) were converted to WAVE audio file format (.wav) using custom Matlab™ routines and then manually reviewed in Raven Pro interactive sound analysis software (Charif et al., 2010) to assess recording success and data quality. To quantify ocean ambient sound levels, long-term spectral average (LTSA) plots (10–2,000 Hz range) from each NRS were calculated in Matlab with 1 Hz and 1 second resolution. The 1 Hz binned spectrum levels were averaged over 1 hour windows and calibrated according to overall system sensitivity (hydrophone sensitivity and pre-amplifier gain curve) to determine sound levels (dB *re* 1 μPa^2/Hz) from raw .DAT files.

Median (50th percentile, hereafter L50) monthly spectrum levels (dB *re* 1 μPa^2/Hz) at each NRS were calculated using custom Matlab code. The 10th (L90) and 90th (L10) percentiles of spectrum levels at each NRS were also calculated from monthly sound levels. Only full months of data collection were included in monthly L50 calculations, and values were indexed according to the Julian calendar for the corresponding year of deployment (2014/2015).

November 2014, February 2015, and May 2015 were selected for monthly cross-system sound level comparison based on overlapping data-collection effort among the five sites (Figure 4). Continuous temporal comparison of sound levels within sites was also performed November 2014 – June 2015 at the Alaskan Arctic, Olympic Coast National Marine Sanctuary, Channel Islands National Marine Sanctuary, and Gulf of Mexico NRS sites (Figure 4). To estimate seasonal variability in sound levels at these sites, the difference between the monthly L10 and L90 for each frequency in the 10-2,000 Hz band was calculated for each site. These differences were aggregated into histograms and smoothed with a nonparametric kernel distribution to show how frequently a given sound level difference occurred. Higher differences indicate higher sound level variability at a site from November 2014 to June 2015.

RESULTS & DISCUSSION

The initial investigation of data collected by the NRS Network demonstrates temporal and geographic variability of 10 Hz to 2,000 Hz ocean ambient sound levels in five NRS soundscapes over an 8-month time-period. As evident in time-aligned LTSA plots, sound levels recorded at each NRS vary by time of year, as well as across the network (Figure 5). Variations of monthly L50 spectrum levels at each NRS are generally greater across sites than within each NRS site (Figure 6). These preliminary analyses begin to demonstrate the extent of spatial and temporal sound level variability within and near to the U.S. EEZ, and establish existing conditions, given current anthropogenic contributions to noise, that may be applied to future assessments. Overall, the NRSs in the Alaskan Arctic and Gulf of Mexico recorded the greatest variabilities in monthly L50s over the 8-month time period selected for cross-network comparison. Additionally, the Alaskan Arctic NRS recorded the overall lowest monthly L50, while the highest monthly L50s were recorded at the NRS in the Gulf of Mexico.

Documenting sound levels within and near to the U.S. EEZ establishes baselines of existing ambient sound levels for future long-term temporal comparisons. Drivers such as climate, tectonics, ocean processes, and policy affect the presence and intensity of sound sources (e.g., weather, anthropogenic activity, and animal calling activity), which translates to measurable disparities across soundscapes. For example, the federally managed areas of national marine sanctuaries and monuments and national parks, where some NRSs are located, impose specific regulations of some anthropogenic activities. Thus, in tandem with additional drivers of soundscape variability (e.g., climate, seafloor processes, and tectonics), biological and anthropogenic sound sources and levels across the NRS Network are highly variable across locations and time.

Patterns of ambient sound levels at NRS sites likely reflect the proximity to densely populated port cities and local shipping lanes, as well as the sound propagation features of the site (e.g., shallow vs deep); these factors increase susceptibility to higher anthropogenic noise levels (Halpern et al., 2015; Hildebrand, 2009). Specifically, anthropogenic sources likely increase sound levels at NRS sites closer to densely populated port cities, such as the Olympic Coast National Marine Sanctuary (NMS), Channel Islands NMS, Gulf of Mexico, and NE US, compared to relatively remote areas (e.g., Alaskan Arctic) (Figure 7). For example, thousands of large container ships travel annually across the Pacific to ports along the U.S West Coast, and likely increase sound levels in the Channel Islands and Olympic Coast NMSs as their acoustic footprint extends into sanctuary waters (Megan F McKenna et al., 2012; Redfern et al., 2017). A similar impact may be observed in the NE US (NRS08) as vessels travel from Europe, Africa, and other points in the North Atlantic to Boston, New York City, and other major Northeast U.S. port cities (Clark et al., 2009). In areas rich in energy resources, such as the Gulf of Mexico, seismic airguns are also often a significant source of low-frequency anthropogenic noise (Estabrook et al., 2016; Jasny et al., 2005; Wiggins et al., 2016). Seismic airgun use in the Atlantic (e.g., Eastern Canada) may also increase sound levels in the NE US (Nieukirk et al., 2012).

Marine animals are important contributors to ambient sound levels and soundscapes across the U.S. EEZ. For example, observed peaks in sound levels at ~18 Hz at Olympic Coast NMS, Channel Islands NMS, and NE US are likely indicative of fin whale (*Balaenoptera physalus*) or blue whale (*Balaenoptera musculus*) calling (Figure 6, Watkins, 1981; Watkins et al., 1987). While marine mammals are a ubiquitous contributor to ambient sound worldwide, fish and invertebrates may also influence sound levels in particular locations; for example, snapping shrimp significantly contribute to ambient sound levels in shallow temperate and tropical waters

(Staaterman et al., 2013), and are likely part of the soundscape at National Park of American Samoa (NRS10, Figure 1). 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. 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), far above the upper frequency limit of the NRS hydrophones. Species acoustic presence and behavior may differ by location and time for multiple reasons (e.g., prey availability, reproduction, or weather impeding area access), and likely affects the consistency of sound levels across soundscapes in the U.S. EEZ.

The NRS Network is dispersed over a broad range of climate zones and it is anticipated that regional differences in weather conditions influenced median sound levels at each station. Weather can influence a soundscape via wind, rain, ice, or other physical phenomena and also by impeding the presence of anthropogenic or biological sound sources (Hildebrand, 2009; Klinck et al., 2012; Nystuen, 1986; Urick, 1983). Specifically, the seasonality of sound levels observed in the Alaskan Arctic at NRS01 is likely related to the acoustic contrast of sea ice states over time (Figure 6; Roth et al., 2012). The largest range of monthly L50 values across all measured frequencies was recorded in the Alaskan Arctic, where the maximum monthly L50 values were recorded in January 2015 and were ~12 dB higher across most frequencies than the monthly L50 recorded in June 2015. Artic sea ice coverage 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 (e.g. January 2015), as well as by damping sounds at the air-sea barrier when fully formed (e.g., June 2015) (Makris and Dyer, 1991; Matsumoto et al., 2014; Menze et al., 2017; Milne and Ganton, 1964; Urick, 1971).

The intersection of anthropogenic activity, bioacoustic signaling, and geophysical sounds in each NRS soundscape determines the sound levels. While it is impossible to assess the impact of anthropogenic noise without a detailed analysis of specific sound sources, temporal cross-network analyses allow characterization of each NRS Network soundscape to 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 NMS, Channel Islands NMS, and Gulf of Mexico, between November 2014 and June 2015, the difference in the L10 and L90 spectrum levels was largest in the Alaskan Arctic, with a mode of 14 dB. This contrast is likely related to seasonal variation of sea ice damping and/or physically blocking sound sources when fully formed versus the contrast of noisy formation and movement (Makris and Dyer, 1991; Matsumoto et al., 2014; Menze et al., 2017; Milne and Ganton, 1964; Urick, 1971). In comparison, the variability of sound levels among all frequencies in the Olympic Coast, Channel Islands, and Gulf of Mexico was much smaller, with modes of 9.2 dB, 7.7 dB, and 9.3 dB, respectively (Figure 8), suggesting more consistent noise from either local or distant human activity. Combined, these seasonality assessments reveal differences across sites, and measuring differences on various temporal scales (e.g., daily, multi-year) can also provide clues to identify drivers of seasonal changes.

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. Without overlapping data from all seasons, at this point, it is difficult to comprehensively assess how geophysical, biological, 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, and indices; Erbe et al., 2016; Parks et al., 2014) to tease apart individual contributors and investigate long-term trends across the entire network.

FUTURE DIRECTIONS

The establishment of the NRS Network is critical to fill 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 its Ocean Noise Strategy Roadmap (Gedamke et al., 2016), NOAA recognizes 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 (Callender et al., 2017; National Oceanic and Atmospheric Administration, 2017) and reiterated by the NPS (Fristrup et al., 2010). As ocean health conditions change due to shifts in climate and industrial human use patterns, it is essential to monitor evolving anthropogenic activity in biologically sensitive areas such as increased vessel traffic in the Arctic due to decreased ice coverage, and energy extraction in the Gulf of Mexico and along the U.S. East Coast.

The addition of forthcoming data from NRS that were first deployed between 2015 and 2016 will supplement existing cross-network sound level comparisons in deep water and permit them in shallow water (see Figure 4). 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 and the occurrence of the events. Such knowledge will establish sound level baselines across all sampled frequencies and inform models to predict future changes within soundscapes, as well as hindcasting to predict historical noise levels with less or no anthropogenic input, giving managers and policymakers tangible tools to assess program effectiveness over a decadal time scale and ensure that the needs of all ecosystem user groups are met in a sustainable way.

The NRS Network is dispersed across the different management contexts of national parks, marine sanctuaries, and the U.S. EEZ. Continuous soundscape monitoring is necessary to ensure the impact of human use is appropriate and sustainable for each managed area. Specifically, it is important to consider acoustic habitats in determining the sustainable levels of industry use in each area, including fishing, energy extraction from both renewable and non-renewable sources, and shipping. By estimating contributions of distinct sources to ambient sound levels, long-term continuous NRS recordings will help fulfill NOAA’s mandates to monitor and conserve marine animals and their habitats, and help safeguard resources necessary to sustain healthy marine ecosystems.

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FIGURES

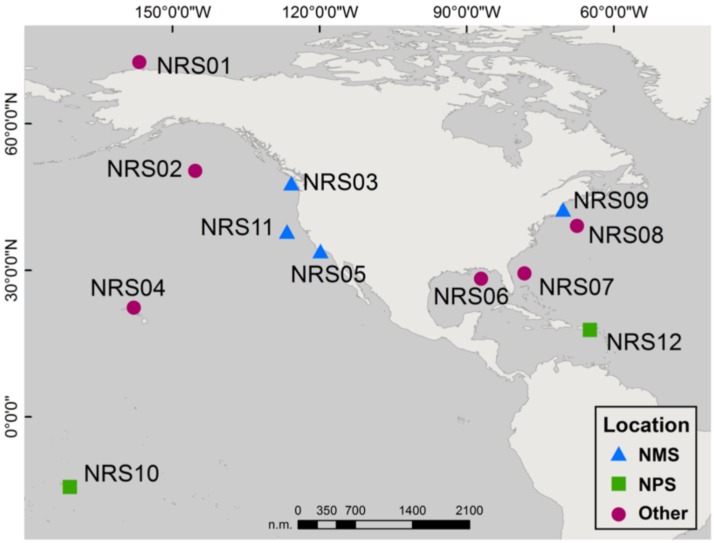

Figure 2.1. Locations of NRS moorings colored by site type (National Marine Sanctuary sites are marked with blue triangles, National Park Service sites are marked with green squares, and other NRS sites are identified by purple circles).

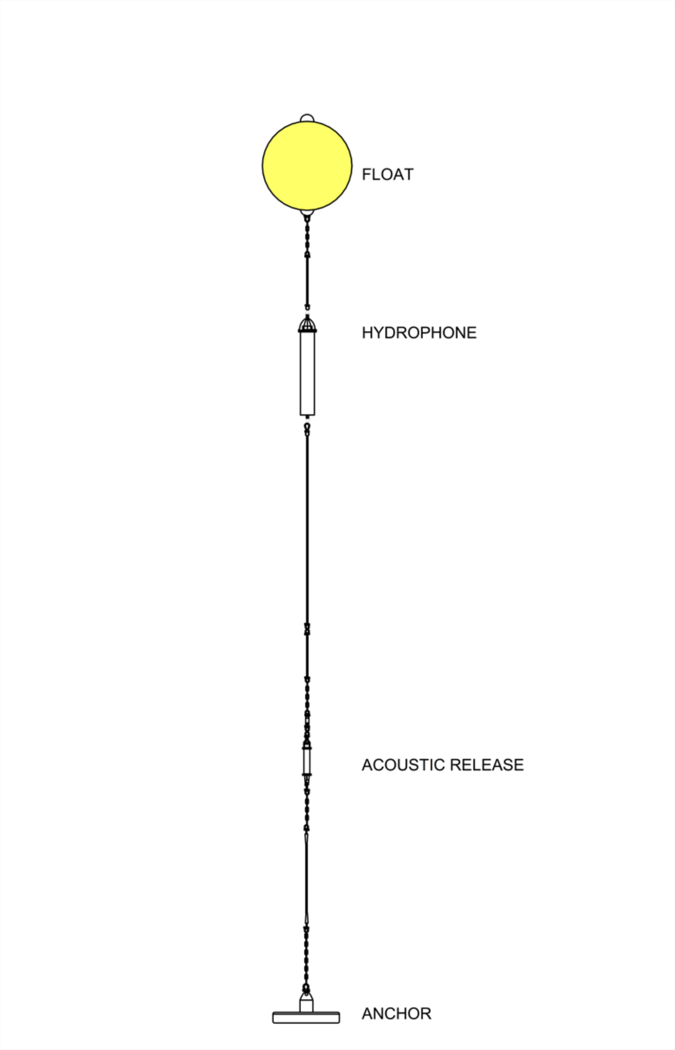

Figure 2.2. Example mooring diagram of NRS05 in the Channel Islands National Marine Sanctuary. All deep-water NRS hydrophones are similarly suspended in the water column between a syntactic foam float and a bottom-mounted acoustic release (Diagram: Michael Craig, NOAA PMEL). Depending on mooring location, the hydrophone may be suspended at a different depth.

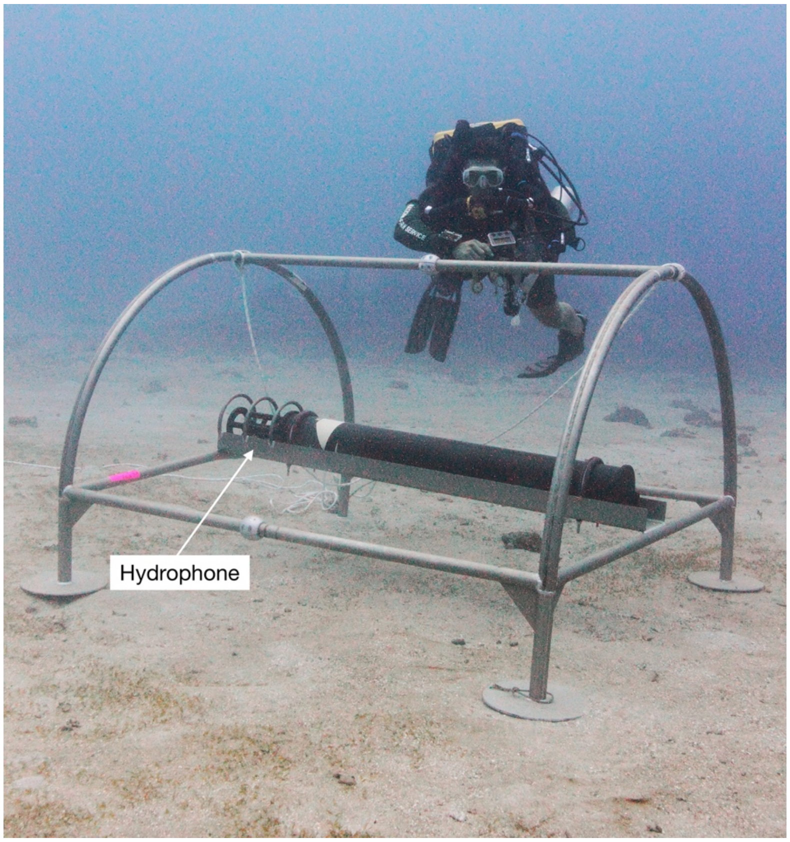

Figure 2.3. A shallow-water NRS deployed off the coast of Tutuila Island in the National Park of American Samoa. All shallow water NRS are bottom-mounted on similar hollow metal landers. (Photograph: NPS, National Park of American Samoa, 11 June 2015).

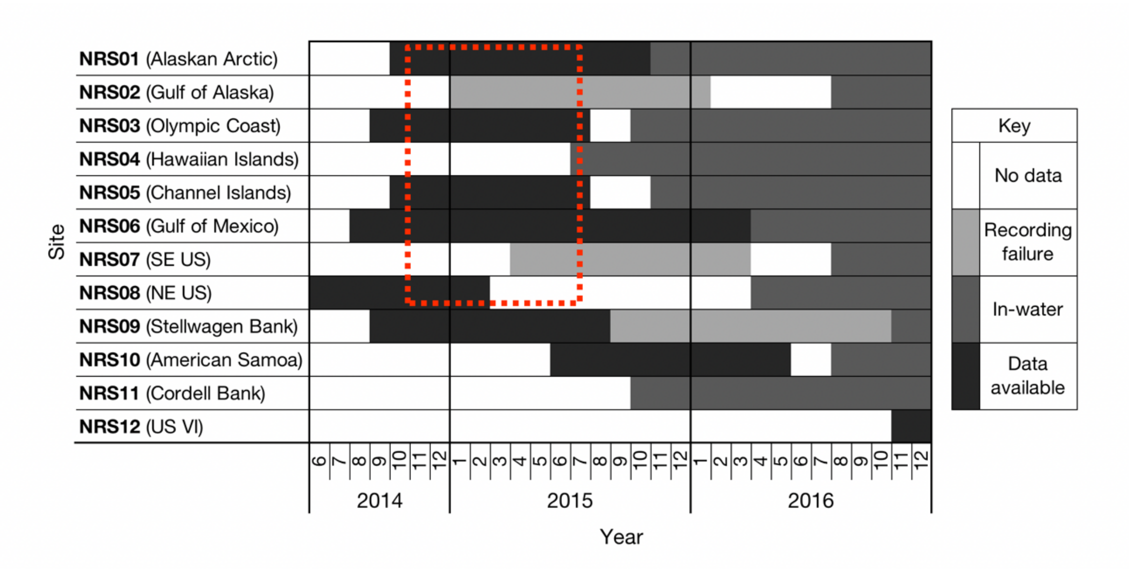

Figure 2.4. Initial NRS acoustic data collection effort by site and month. Shading indicates the recording success (i.e., data collection) during a given month. The dashed red box highlights the temporally overlapping data selected for initial deep-water cross-network analysis here. NRS09 (Stellwagen Bank National Marine Sanctuary) and NRS10 (National Park of American Samoa) are shallow stations and were not included in 2014-2015 cross-network sound level comparisons because the initial analysis was focused on deep-water soundscapes. Effort through December 2016 is included to show the establishment of the entire network and quantity of data that will be available for future analyses.

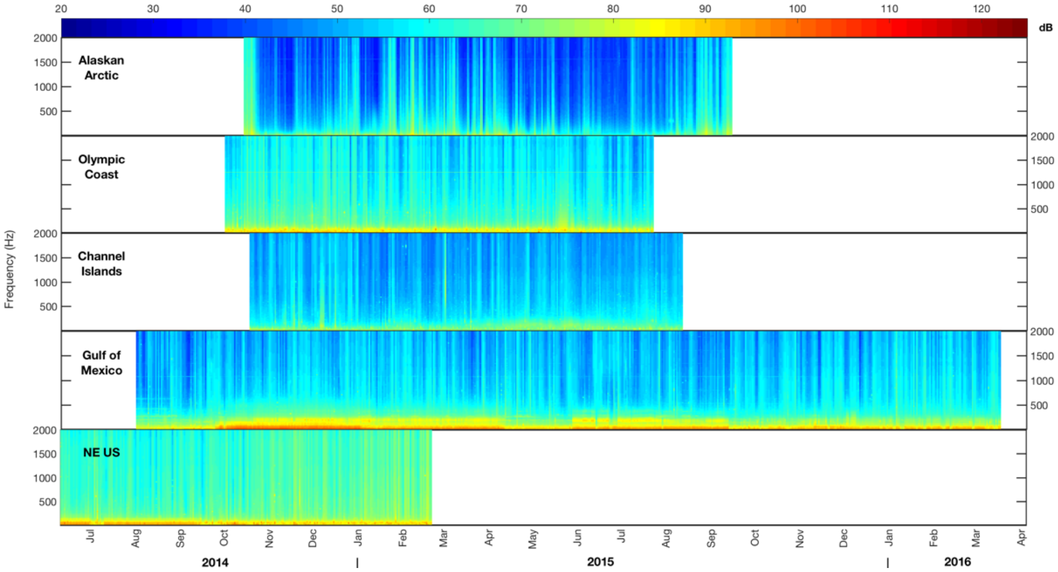

Figure 2.5. Time-aligned long term spectral averages (LTSA) of the first year (2014-2015) of acoustic data from five deep-water NRS (Alaskan Arctic, Olympic Coast National Marine Sanctuary, Channel Islands National Marine Sanctuary, Gulf of Mexico, and NE US). Increasing intensity of sound (dB *re* 1 μPa^2/Hz) is indicated on the blue to red scale.

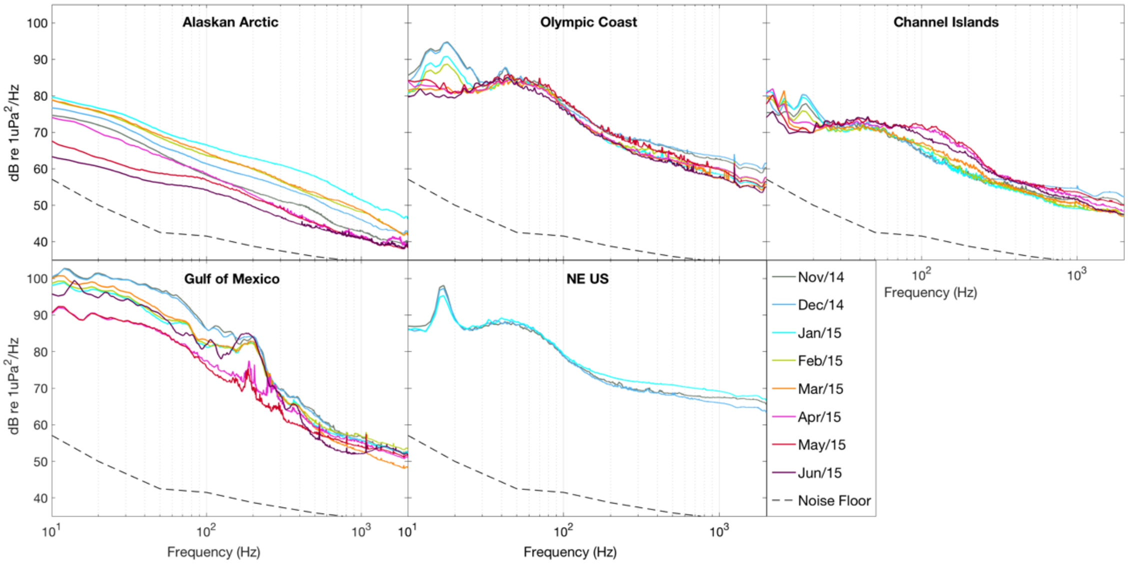

Figure 2.6. Within-site comparison: Monthly median spectrum levels (L50) at five deep-water NRSs calculated for all available months between November 2014 and June 2015 plotted by site. Data recorded prior to November 2014 or after June 2015 were excluded to control for temporal inconsistencies. The dashed line in each plot indicates the system noise floor. These data depict relatively stable monthly L50 from November 2014 through June 2015 in the initial deployment period at the NRSs in the Olympic Coast and Channel Islands National Marine Sanctuaries, with the exception of the increased sound levels around 18 Hz during winter months due to seasonal calling of fin whales (*Balaenoptera physalus*). Monthly L50 at the NRS in the North Atlantic were also affected by fin whale calling. Compared to the other three sites, the monthly L50 at the NRSs in the Alaskan Arctic and the Gulf of Mexico were more seasonally variable across all frequencies.

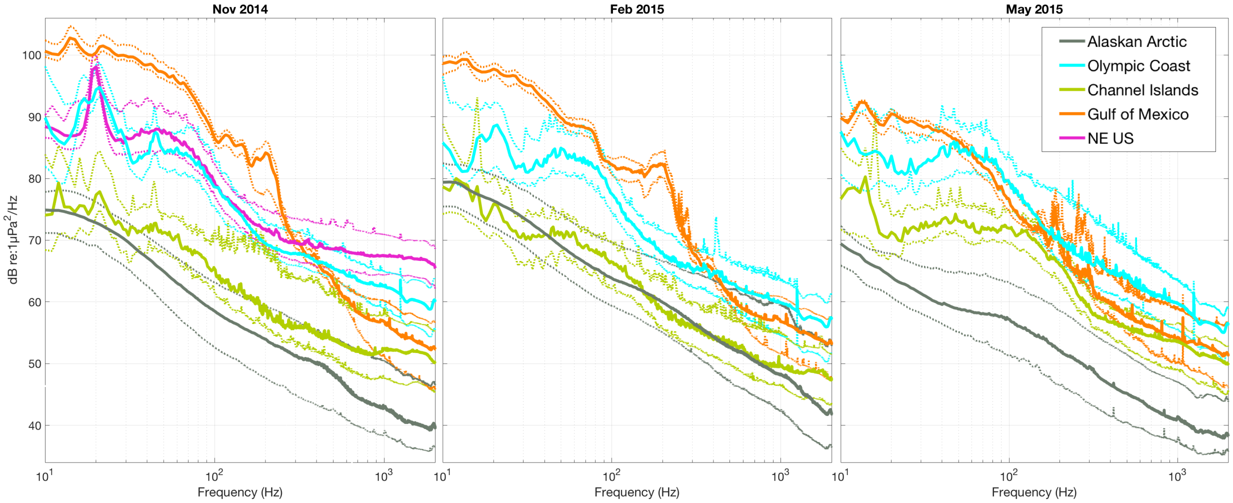

Figure 2.7. Cross-site comparison: Median monthly spectrum levels (monthly L50) at each NRS calculated in 1 Hz bins for November 2014, February 2015, and May 2015. Each NRS site is indicated by a single color solid line (Alaskan Arctic, grey; Olympic Coast National Marine Sanctuary, cyan; Channel Islands National Marine Sanctuary, light green; Gulf of Mexico, orange; NE US, pink). Thinner dotted lines indicate the L90 (lower) and L10 (upper) percentiles of monthly sound levels at each NRS.

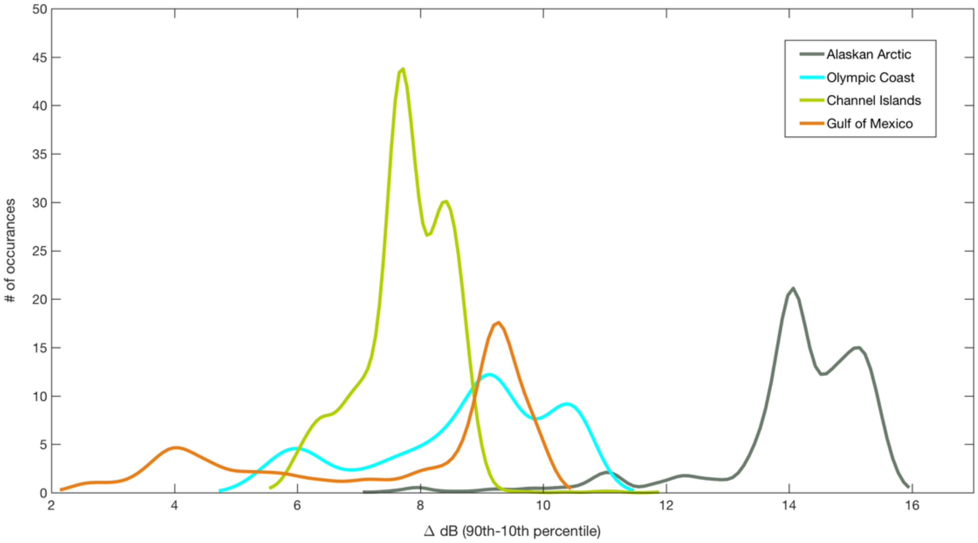

Figure 2.8. Distribution (nonparametric kernel-smoothed, width parameter of 500) of the median decibel difference (Δ dB) between the monthly L10 and L90 for each 1 Hz frequency bin from Nov 2014- June 2015 within the Alaskan Arctic, Olympic Coast National Marine Sanctuary, Channel Islands National Marine Sanctuary, and Gulf of Mexico NRS sites. Comparatively smaller differences in Δ dB in the Channel Islands, with a mode of 7.7 dB, reflect little variation of sound levels across the investigated frequency band throughout late fall through winter to late spring. Differences in dB level between percentiles at Alaskan Arctic, Olympic Coast, and Gulf of Mexico were long-tailed towards smaller Δ dB levels. This negative skewedness (broader spread to the right of the mean) is likely related to seasonal changes in marine mammal calling, local weather, and anthropogenic activity (e.g., shipping, seismic airguns). The frequent occurrence of a Δ dB of 14 in the Alaskan Arctic suggests that sound levels increase and decrease seasonally (i.e., between November-June) due to ice coverage. The negative skewedness of the Alaskan Arctic histogram occurs because of the less frequent occurrence of more consistent 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 2.1. NRS deployment site information.

CHAPTER 3. COMPARING THE UNDERWATER SOUNDSCAPES OF FOUR U.S. NATIONAL PARKS AND MARINE SANCTUARIES

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ABSTRACT

Passive acoustic sensors provide a cost-effective tool for monitoring marine environments. Documenting acoustic conditions among habitats can provide insights into temporal changes in ecosystem composition and anthropogenic impacts. Agencies tasked with safeguarding marine protected areas, such as the U.S. National Park Service and U.S. National Oceanic and Atmospheric Administration’s Office of National Marine Sanctuaries, are increasingly interested in using long-term monitoring of underwater sounds as a means of tracking species diversity and ecosystem health. In this study, low-frequency passive acoustic recordings were collected fall 2014 - spring 2018, using standardized instrumentation, from four marine protected areas across geographically disparate regions of the U.S. Economic Exclusive Zone: Northwest Atlantic, Northeast Pacific, South Pacific, and Caribbean. Recordings were analyzed for differences in seasonal conditions and to identify acoustic metrics useful for resource assessment across all sites. In addition to comparing ambient sound levels, a species common to all four sites, the humpback whale (*Megaptera novaeangliae*), was used to compare biological sound detection. Ambient sound levels varied across the sites and were driven by differences in animal vocalization rates, anthropogenic activity, and weather. The highest sound levels ($\mathrm{dB}_{\mathrm{RMS}\ (50\ \mathrm{Hz}\text{-}1.5\ \mathrm{kHz})}$ re 1 μPa) were recorded in the Northwest Atlantic in Stellwagen Bank National Marine Sanctuary (Stellwagen) during the boreal winter-spring resulting from bioacoustic activity, vessel traffic, and high wind speeds. The lowest sound levels ($\mathrm{dB}_{\mathrm{RMS}\ (50\ \mathrm{Hz}\text{-}1.5\ \mathrm{kHz})}$ re 1 μPa) were recorded in the Northeast Pacific adjacent to a vessel-restricted area of Glacier Bay National Park and Preserve (Glacier Bay) during the boreal summer. Humpback whales were detected seasonally in the southern latitude sites, and throughout the deployment periods in

the northern latitude sites. Temporal trends in band and spectrum sound levels in Glacier Bay and the National Park of American Samoa were primarily driven by biological sound sources, while trends in Stellwagen and the Buck Island Reef National Monument were primarily driven by anthropogenic sources. These results highlight the variability of ambient sound conditions in marine protected areas in U.S. waters, and the utility of long-term soundscape monitoring for condition assessment in support of resource management.

INTRODUCTION

Sound is a critical component of the marine environment. Most, if not all, marine species use sound as a means of interacting with and interpreting their environment (Knowlton et al., 2016). Across taxa, acoustic cues are used in the marine environment to facilitate biological and ecological processes such as breeding, predator-prey interactions, navigation and habitat selection. For example, soniferous fish chorus during spawning seasons (Rowe and Hutchings, 2006), spiny lobsters emit 'rasps' when confronted with predators (Patek et al., 2009), echolocating whales and dolphins use ultrasonic sounds to find and capture prey (Richardson et al., 1995), and larval reef species use acoustic cues to determine adequate settlement locations (Montgomery et al., 2006). Combined, these activities contribute to the acoustic diversity of a given marine environment, with animals creating and relying on unique acoustic signatures which can be compared within and between habitats. Characterizing these acoustic signals, as well as the ambient conditions that contain other sound components, is relevant for understanding an acoustic environment and for long-term assessment and management of ecosystem health in the marine environment.

The sources and acoustic characteristics of all biotic and abiotic ambient sounds present in a particular location and time are collectively defined as the "soundscape" (ISO, 2017; Pijanowski et al., 2011). Natural drivers such as climate and tectonics, as well as anthropogenic drivers such as economics and management, influence the presence and levels of sound sources within a soundscape (Krause and Farina, 2016; M. F. McKenna et al., 2012). Establishing baselines that document acoustic conditions over time and among different areas will facilitate ecosystem heath assessments by revealing the presence of vocalizing animals, anthropogenic activities, and environmental changes. Synthesis of these data allow for description and comparison of acoustic conditions that can be used to evaluate and adapt resource management strategies.

The value of passive acoustics for long-term monitoring was recently recognized within the Global Ocean Observing System (GOOS) committee, with the designation of "ocean sound" as an Essential Ocean Variable (EOV) (Tyack, 2018, 2017), as well as by the European Marine Strategy Framework Directive (European Union, 2008; Tasker et al., 2010). The U.S.'s Ocean Noise Reference Station (NRS) network, including sites presented in this study, was provided within EOV documentation as an example of a passive acoustic array that supports many of the global "ocean sound" observing objectives (Tyack, 2018). The NRS network was established in 2014 by the U.S.'s National Oceanic and Atmospheric Administration (NOAA) and National Parks Service (NPS) to document baseline low-frequency (10 Hz – 2 kHz) sound levels and multi-year trends in ocean ambient sound within and near to the U.S. Exclusive Economic Zone (Haver et al., 2018). Composed of 12 identical calibrated autonomous passive acoustic instruments, the NRS Network includes placement of sensors within sanctuaries and national parks. The long-term acoustic data collected via the NRS network meet the GOOS steering committee's call for comparable measurements of ocean sound levels and sources over time to define the effects of changes on individuals, populations, and ecosystems.

The NPS has used passive acoustic monitoring (PAM) to inform management of noise in terrestrial parks for many years, and more recently has extended monitoring efforts to underwater environments. Soundscapes within U.S. National Parks are considered to be resources based on intrinsic value as well as the values to wildlife and human visitors (National Park Service and

U.S. Department of the Interior, 2006). Monitoring sources and levels of underwater ambient sound in parks is critical for identifying noise sources inappropriate to a park setting and understanding how noise interferes with visitor experience and affects a variety of marine wildlife. Similarly, NOAA's Office of National Marine Sanctuaries (ONMS) implements place-based efforts to conserve designated marine areas. NOAA's Ocean Noise Strategy (Gedamke et al., 2016) highlighted the importance of protecting the acoustic conditions of key marine habitats within NOAA's jurisdiction, including within US National Marine Sanctuaries (Hatch et al. 2016). However, NOAA does not directly manage noise sources or levels within sanctuaries (Hatch and Fristrup, 2009).

The long-term monitoring focus of the NRS facilitates standardized assessments of acoustic status and trends within a low-frequency band (10 Hz – 2 kHz) that contains both considerable biological activity and a main contributor to chronic background noise in many marine environments, namely vessels (Southall et al., 2017). The frequency overlap between the acoustic signature of vessels and vocalizations that support critical life functions in marine mammals (particularly baleen whales), sonic fishes, and marine invertebrates can result in "masking", when the perception of one sound by an animal is affected by the presence of another sound (Clark et al., 2009; Richardson et al., 1995). Loss or reduction in efficiency of information transfer due to masking can have consequences for marine animals that rely on sound to carry out basic life functions (e.g., foraging, navigation, communication with conspecifics) (Erbe et al., 2016b). Masking is not the only potential effect of increased noise; individual- and population-level effects such as stress (Rolland et al., 2012) and displacement (Small et al., 2017) can also occur.

In this study, we use data from the NRS network to provide baseline information on soundscapes in the relatively shallow waters (33-79 m) of three marine protected areas managed by the NPS (Glacier Bay National Park and Preserve, National Park of American Samoa, Buck Island Reef National Monument), and one U.S. National Marine Sanctuary (Stellwagen Bank). We extracted standardized acoustic metrics from the long-term data to understand biological activity, natural physical events, and anthropogenic activities across these locations. Specifically, we examined hypotheses that ambient sound levels within each site would differ by location (latitude and longitude) in accordance with season, vessel management schema (e.g., restrictions), physical environment of the site, and relative human population size in the nearest port (i.e., urban or remote) as a proxy for vessel traffic. We also identified a species common to all sites, the humpback whale (*Megaptera novaeangliae*), and analyzed recordings for occurrence of humpback whale vocalizations (i.e., song and non-song calls) as a proxy to assess low-frequency soniferous wildlife between diverse sites. Collectively, these metrics that describe each soundscape establish current baseline conditions and inform the management of these protected places.

METHODS

Site Selection

Here we compare low-frequency (10 Hz – 2 kHz) sound levels in shallow water (33-79 m) soundscapes within four sites managed by either the U.S. NPS or ONMS. The presence of biological and anthropogenic activity and weather events all contribute to the measured sound levels at each site, and in some cases one source may dominate the soundscape. Further, the oceanographic conditions of each deployment site (including depth, temperature profile, complex bathymetry, and bottom type) affect how sound propagates to the monitoring site. Sites in secluded regions are only exposed to local sources, whereas exposed sites receive sound from both local and regional sources. The comparisons of the four soundscapes presented in this manuscript are based on data collected at a single hydrophone per area. Each deployment site was selected to be generally representative of each region. These analyses also aim to highlight how environmental differences are relevant to and may require attention in soundscape management.

Each site was chosen to capture conditions across a diversity of biological, anthropogenic, and oceanographic conditions (Table 1 and Fig. 1). The Stellwagen Bank National Marine Sanctuary (Stellwagen), managed by ONMS, is located in the temperate Northwest Atlantic, offshore of the urban port of Boston, MA. This monitoring site at a depth of 79 m is located near the mid-latitude eastern border of Stellwagen on a gravel bottom. Stellwagen is a biologically rich area that is an important feeding ground for many species of marine mammals as well as some of the largest commercial fisheries in the U.S. (Hatch et al., 2008; Hatch and Wright, 2007). The National Park of American Samoa (American Samoa), managed by NPS, is located in the remote, equatorial South Pacific region, with little commercial vessel traffic present. The monitoring site is located in a sandy bottom habitat at a depth of 33 m near offshore reefs. Baleen whales migrate through the region (Robbins et al., 2011; Storlazzi et al., 2017). The Buck Island Reef National Monument (Virgin Islands) is located within the U.S. Virgin Islands in the tropical Southwest Atlantic in close proximity to many other Caribbean port cities and popular tourist destinations. The monitoring site is located along a steep shelf edge in 40 m of water on a sandy bottom (Fig. 2), acoustically exposing the site to regional shipping traffic and migrating whales as well as local vessel traffic and soniferous fish. The Beardslee Island complex within Glacier Bay National Park and Preserve (Glacier Bay) is within a remote area of Southeast Alaska. Seasonally managed cruise ships, tour boats, and other small vessels transit the bay near the monitoring site, which is at a depth of 62 m (National Park Service, 2006), but the park is acoustically isolated from regional vessel traffic. Glacier Bay is a glacially carved estuary with one of the highest deglaciation and sedimentation rates in the world, resulting in a dynamic and relatively young ecosystem (Etherington et al., 2007). The region supports high marine biological diversity including species of birds, marine mammals, fishes, and invertebrates.

The distinct biological, physical, and human activity patterns, as well as the environments of these protected areas drive the differences between the soundscapes. Across sites, we expected the lowest sound levels would be recorded during the boreal summer in Glacier Bay, a remote location where the number of vessels is regulated by daily (maximum of two cruise ships, three tour vessels, and thirty-one smaller vessels) and seasonal quotas, and the course and speed (13-20 kt depending on time of year) of vessels is often regulated in areas important to marine mammals (McKenna et al., 2017). We predicted biological sources would likely be the primary contributors to the Glacier Bay soundscape. Similarly, American Samoa, a remote site, was also predicted to be dominated by biological sources. We expected the highest sound levels would be recorded during the winter in the most urban site (Stellwagen) when wind, vessels, and biological sources would all likely contribute to the soundscape. Given that the Virgin Islands site is exposed to unmanaged local and regional vessel traffic and is in a biologically rich environment, we predicted that this site would experience relatively higher sound levels with contributions from both anthropogenic and biological sources. Further, this region is exposed to seasonal hurricanes which have the potential to significantly elevate sound levels during transient storm events.

Time periods sampled at each site varied within a three-and-a-half-year span (Table 1). The shortest recording was four and a half months in Glacier Bay (boreal summer season), while the longest was a full continuous year in Virgin Islands. In both Stellwagen and American Samoa ten months of continuously recorded data were available for analysis (Fig. 3). Although the temporal sampling periods of the sites were not entirely concurrent, simultaneous recordings were not necessary for the baseline measurements determined in this study.

Instrumentation

Each Noise Reference Station (NRS) instrument contains a single passive model ITC-1032 (International Transducer Corp., Santa Barbara, CA) acoustic archival autonomous underwater hydrophone (AUH) (Fox et al., 2001) with a sensitivity of −192 dB re 1 V/µ Pa and a flat frequency response (-/+ 1 dB) between 10 Hz and 2 kHz. Signals incoming to the AUH are conditioned by a pre-amplifier and a pre-whitening filter to maximize the dynamic range of the 16-bit acoustic data logging system. Each AUH was programmed to record acoustic data continuously at a sample rate of 5 kHz with a (2 kHz low-pass cutoff) frequency (Haver et al., 2018). The AUH is designed such that there is no gap between the end of one recorded sound file and the start of the next.

Sounds at frequencies below 10 Hz were excluded to decrease the likelihood that the differences in bottom material and mooring depths of each hydrophone would limit sound propagation, as well as to avoid possible low-frequency current-generated flow noise on the mooring that might otherwise be difficult to distinguish from other sounds of interest and fall outside the flat frequency response of the hydrophone. Recordings were also manually reviewed for diurnal tidal flow noise contamination above 10 Hz, but such noise was not determined to be a strong driver of ambient sound levels.

Sound Level Metrics

To quantify ocean ambient sound levels at all sites, long-term spectral averages (LTSAs) of 10 Hz – 2 kHz data were calculated from original data files (.DAT binary format) with custom Matlab™ (version 2018b, Mathworks, Inc.) software and results were summarized in 1 Hz/5 minute bins. The 50 Hz – 1.5 kHz band and 500 Hz frequency were selected for band sound level measurements ($\mathrm{dB_{RMS}}$ re 1 μPa) to assess temporal trends in ambient sound in the overlapping frequency range of humpback whale vocalizations, vessel noise, and environmental sounds (Fournet et al., 2018a; Hildebrand, 2009). Deployment-long variations in the band levels were investigated with percentile values (10th, 50th, and 90th percentile values). The 10th percentile sound level is the value at which sound is quieter than this level 10% of the time, so it represents a value close to the noise floor; the 50th percentile is the median sound level; and the 90th percentile is the value at which sound exceeds this level 10% of the time, so it represents a typical high-noise condition.

In addition to the band measurements, spectral probability density plots (SPD; Merchant et al., 2013) were calculated to identify the empirical probability density (EPD) of the occurrence of power spectral density (PSD) sound levels in 1 Hz/5 minute spectral bins (dB re 1 $\mu\mathrm{Pa}^2/\mathrm{Hz}$) at each site over the duration of the deployment. EPD values provide insight on how likely a sound level will occur within each frequency bin; rare events will have lower EPD and more commonly occurring sound levels will have a higher EPD. These metrics reveal the variation of sound levels within a specific frequency band and can highlight particular sources, and can also indicate the presence and temporal variation of the potential biological, natural physical, and anthropogenic drivers at the site.

Relationship of Physical Environment to Ambient Sound Levels

Wind is an important component of a soundscape (Wenz, 1962). To assess the extent to which wind speed conditions affect sound levels, wind speed measurements in Stellwagen (lighted buoy 44013) were retrieved from the NOAA National Data Buoy Center database (National Data Buoy Center, 1971), divided into 10 cm/s bins, and correlated with time-aligned sound levels. Wind speed measurements for American Samoa and Virgin Islands were sought, but ultimately not obtained due to lack of proximate data and/or insufficient temporal density. Records of major hurricanes and tropical storm events that occured during the acoustic recording time period were obtained from the database maintained by the NOAA National Hurricane Center (Landsea and Franklin, 2013). Wind speed data were available for Glacier Bay, but were not included because analysis spanned only the boreal summer months (May – September) during which winds speeds contributed to ambient sound levels in only a minor way (Fournet et al., 2018a).

Contributions of Humpback Whale Vocalizations to Ambient Sound Levels

To assess spatio-temporal presence of low-frequency soniferous wildlife between diverse sites, we identified a common species, the humpback whale (Megaptera novaeangliae), and analyzed recordings for occurrence of humpback whale vocalizations. Humpback whales are an ideal proxy for the study of soniferous and acoustically sensitive species as they are predictably present at all study sites, their vocal behavior in these regions is relatively well described, and the lower frequencies of their vocal range overlaps with important sonic species in each environment (e.g., sonic fishes, marine invertebrates, pinnipeds, and other cetaceans) which may also be affected by changes in ambient sound (Au et al., 2006; Cerchio et al., 2001; Cholewiak et al., 2018; M. E. H. Fournet et al., 2015; Fournet et al., 2018a; Gabriele et al., 2018; Stimpert et al., 2011).

Humpback whales are acoustically active throughout their somewhat predictable migratory range. Humpback whales migrate between high latitude foraging grounds, including two of our monitoring sites (Glacier Bay, Stellwagen), in spring, summer, and fall months to low-latitude breeding grounds, including our other two sites (American Samoa, Virgin Islands), in winter months. Humpback whales across age and sex classes produce a suite of low-frequency vocalizations (50-5,000 Hz) known as non-song calls or simply “calls” (Dunlop et al., 2007; M. E. H. Fournet et al., 2015) throughout the migratory corridor. Song, a longer more highly structured sequence of vocalizations that are hierarchically organized and produced only by male humpback whales, is produced predominantly on breeding grounds, but can also be detected throughout the migratory range (Gabriele and Frankel, 2002a, 2002b; Stimpert et al., 2012). Migratory consistencies coupled with well-described acoustic behavior for all age-sex classes of humpback whales may permit us to extrapolate success rates in detecting humpback whale vocalizations to other biological sound sources in a given region and season.

To assess presence or absence of humpback whale vocalizations (songs or calls), original data files (.DAT binary format) were converted to WAVE audio file format (.wav) using custom Matlab™ routines. An automated detector, the generalized automated detection and classification system (DCS; Baumgartner and Mussoline, 2011), was used to identify humpback whale vocalizations via a multivariate discrimination analysis (comparing pitch tracks drawn through high energy tonal sounds) for acoustic data in Stellwagen, Virgin Islands, and American Samoa. A daily time scale was selected to tally presence or absence, and all DCS results were manually verified at a daily resolution to remove any false positives. To evaluate possible missed detections in DCS, entire days without any detected humpback whale vocalizations that occurred between entire days with positive detections were manually checked with Raven Pro 1.5 (Cornell Lab of Ornithology) interactive sound analysis software. For Glacier Bay, one hour of acoustic data per day was randomly subset and manually reviewed with Raven Pro 1.5 by an experienced observer (MF) for the presence of humpback whale calls. If calls were not identified on the initially selected recording, additional hours from the same day were randomly selected and reviewed until either a call was identified or all hours in a day were reviewed. As part of ongoing collaborative work in Glacier Bay, the annotation of daily humpback whale acoustic presence or absence was underway prior to the inception of this study, and obviated the need for automated detection.

RESULTS

Variation in Ambient Sound Levels

We found unique seasonal, diel, and spectral ambient sound level patterns across the four sites. The variability in band sound levels ($dB_{RMS\ (50\ Hz\text{-}1.5\ kHz)}$ re 1 μPa) revealed how each environment was influenced by biological, environmental, and anthropogenic sound sources (Fig. 3). Band sound levels were lower in Stellwagen during the summer months (June-August) compared to November-May, probably due to lower winds during the summer. There were no deployment-long diel trends in band sound levels recorded in Stellwagen, though there were numerous high-level transient events likely due to vessel passages (Fig. 3). Compared to the variability of band sound levels in Stellwagen, band sound levels were relatively stable in Glacier Bay (boreal summer), American Samoa, and Virgin Islands, with source-driven daily-weekly changes (Fig. 3). In Glacier Bay, bioacoustic signaling is the source of increased band sound levels from late June to late July. A diel pattern is evident in the summer data from Glacier Bay (summer). Band sound levels increased twice per day, in the morning around 0600-0800 and in the afternoon around 1500, primarily due to timing of day-trip tourism vessels entering and exiting park waters. The seasonal band sound level variations observed in American Samoa (August-November) are related to humpback whale vocalizations, while the short-term band sound level increase in February is due to an isolated weather event. A distinct diel pattern of band sound levels was also observed in American Samoa throughout the recording time period; band sound levels were lower during daylight hours (compared to nighttime), with the highest daily levels recorded during crepuscular time periods. This diel pattern is likely due to bioacoustic signaling (e.g., urchins, shrimp, fish). A 29-day lunar cycle in sound levels (Kaplan et al., 2018) is also evident in American Samoa, with quieter periods throughout the day near full moons. Similar to patterns observed in American Samoa, seasonal band sound level variations observed in Virgin Islands were likely related to humpback whale vocalizations in February-March and short-term weather events in September. There were no deployment-long diel trends in band sound levels recorded in Virgin Islands.

Variability in sound spectrum levels across frequencies was investigated by calculating spectral probability density (SPD) plots (Fig. 4). These metrics reveal distinct peaks in acoustic energy as well as the variation within a specific frequency band, and provide further insight into the biological, natural physical, and anthropogenic drivers at the site. In addition to frequency-specific SPD values, an overall SPD is calculated for each site to represent the overall probability of sound level consistency over time. Between the four sites, Stellwagen had the lowest overall SPD meaning it experiences the highest level of variability in sound levels across the measured frequency band, while the American Samoa site had the highest SPD meaning it has comparably stable acoustic conditions (Fig 4., upper-right corner of each panel).

In Stellwagen, the site in the North Atlantic, the 90th, 50th (median), and 10th percentiles of power spectral density (PSD, dB re 1 $\mu Pa^2/Hz$) sound levels all peaked at ~20 Hz. The range of intensities of recorded PSD sound levels, ~70 dB to ~105 dB re 1 $\mu Pa^2/Hz$, indicates higher energy levels within the 20 Hz frequency band, relative to other frequencies. In Glacier Bay, the site in Southeast Alaska, the highest PSD levels (90th percentile) were recorded between ~90-150 Hz, likely due to the seasonal breeding roars of male harbor seals. The empirical probability density indicates that this peak is related to a short-term increase of sound energy within that frequency band as PSD levels were less likely to be above ~70 dB re 1 $\mu Pa^2/Hz$ and more likely (median and below) to be between ~60-70 dB re 1 $\mu Pa^2/Hz$ (Fig. 4, Glacier Bay). PSD levels were less variable across all measured frequencies in American Samoa (the south Pacific site) and Virgin Islands (the Caribbean site), in comparison to Glacier Bay and Stellwagen, indicating fewer spatio-temporal differences in sound levels throughout the data collection time periods. Further, these two sites did not show any distinct spectral peaks in acoustic energy. Across all sites, the highest PSD sound levels were recorded in Stellwagen at ~20 Hz and in American

Samoa between 10-20 Hz, and the lowest PSD sound levels were recorded at frequencies >1 kHz in Glacier Bay (Fig. 4).

Natural Physical Drivers of Ambient Sound Levels

Wind noise and surface agitation during high-wind events (e.g., hurricanes, storms) increased ambient sound levels in Stellwagen, Virgin Islands, and American Samoa. In Stellwagen, these events occurred regularly throughout the winter and spring, and an increase in hourly mean wind speed was highly correlated (R2=.956, df=206, p=<.05) with an increase in hourly mean 500 Hz sound levels. In Virgin Islands, two category 5 hurricane events, Hurricanes Irma and Maria, traveled through the U.S. Virgin Islands and brought unusually high wind conditions to St. Croix on September 6th and 20th (respectively) 2017. In American Samoa, a category 5 tropical cyclone, Winston, traveled through the South Pacific in February 2016, increasing RMS sound levels (Fig. 3). Wind speed measurements for Virgin Islands and American Samoa (NOAA water level observation network stations CHSV3 and NSTP6) were not available for correlation with sound levels due to system malfunctions during and immediately after these high-wind events. High wind speed weather events are rare in Glacier Bay during the boreal summer when acoustic data were collected and thus likely had a negligible effect on ambient sound levels (Fournet et al., 2018a).

Humpback Whale Acoustic Presence

Humpback whale acoustic activity was observed throughout the entire deployment period in Glacier Bay (Fig. 5), with calls detected every day (April 30th – September 22nd). In Stellwagen, vocalizations were detected on all weeks except for the time period from January 31st – March 24th. Humpback whale vocalizations were observed seasonally in American Samoa and Virgin Islands. In American Samoa vocalizations were detected during the austral spring months (July-November), and in Virgin Islands vocalizations were detected during boreal winter months (January-April) (Fig. 5).

Daily median 500 Hz sound levels (Fig. 6) were compared to the verified daily presence and absence of humpback whale vocalizations to determine if there was a relationship between the measured sound levels and the presence/absence of humpback whale vocalizations. In Stellwagen, Virgin Islands, and American Samoa, daily median 500 Hz sound levels (dB re 1 μPa2/Hz) were distributed across lower intensities on days with true positive detections of humpback whale vocalizations, indicating that other sound sources likely contribute to the higher measured sound levels. The mean difference between the means of all daily median 500 Hz sound levels in the absence and presence conditions of humpback whale vocalizations was largest in Stellwagen (difference of 3.57 dB) followed by Virgin Islands (1.15 dB) (i.e., mean sound levels were higher on days humpback whales were not acoustically detected). In contrast, in American Samoa the mean of the daily median 500 Hz sound levels was 0.83 dB higher on days when humpback whale vocalizations were present compared to days that humpback whale vocalizations were not detected. Differences could not be evaluated for Glacier Bay because humpback whale calls were present throughout the recording time period.

DISCUSSION

Here we compare the low frequency soundscapes of four U.S. marine protected areas to document seasonal and daily variations in ambient underwater sound levels as well as daily presence of humpback whale vocalizations during the recorded periods. As predicted, sound levels were not consistent across the four sites; observed variability of both band levels (dB_{RMS}

$_{(50\ \mathrm{Hz}\text{-}1.5\ \mathrm{kHz})}$ re 1 μPa) and PSD (dB re 1 $\mu\mathrm{Pa}^2$/Hz) among and within the sites was driven by differences in biological activity, weather, and proximate anthropogenic activity, primarily vessel traffic. The contributions of these various sound sources to each soundscape varied widely across the four areas due to distinctions among soundscape drivers (e.g., management, climate, species richness). The most persistent and loudest sound sources were different at each site, and as a result, sound levels and trends were different across the four sites.

Sound Levels Reveal Dominant Sources

The metrics for evaluating the soundscapes identified in this study are not only relevant to tracking conditions over time and across sites, but also indicate biotic and abiotic low-frequency sound sources that distinguish each unique soundscape. The Beardslee Island Complex within Glacier Bay, the northernmost site in this comparison, is located in a high-latitude temperate area of the Pacific Ocean. Glacier Bay is a seasonal (boreal summer) feeding ground for humpback whales, where the whales produce an assortment of calls that are comparatively quieter than song (Fournet et al., 2018b). In the area monitored in Glacier Bay, boreal summer RMS sound levels showed a short seasonal trend, increasing during late June through late July, which was attributed to the seasonal breeding roars of male harbor seals (*Phoca vitulina;* Fournet et al., 2018a; Matthews et al., 2017; McKenna et al., 2017) (Figs. 3 and 4). A diel pattern was also evident in the data recorded in Glacier Bay resulting from daylight-driven vessel passages. Glacier Bay is a fjord that terminates at the face of several tidewater glaciers. As a result, ships must enter and exit from the mouth of the bay. During the boreal summer data collection period, the acoustic signatures of these vessel passages (i.e., into the bay each morning traveling towards the glaciers, and looping back out each afternoon to exit the bay) are clearly reflected in the band sound levels (Fig. 3). Moreover, the hydrophone site is in a protected interior environment sheltered from the open ocean. The highly managed vessel activity and isolated hydrophone location is unusual across the protected sites in this comparison and is reflected in the lower overall band sound levels recorded during months with mild weather conditions.

American Samoa is located in a low-latitude remote location in the South Pacific Ocean (Fig. 1) where the weather is relatively consistent year-round. Although fully exposed to the open ocean, American Samoa is thousands of miles away from any major shipping port (i.e., in Eastern Australia, Northern New Zealand, or Hawai'i), limiting the influence of large vessel noise on sound levels. In American Samoa, minimal seasonal ambient sound level variation was observed across the low-frequencies measured in this analysis (Figs. 3 and 4). However, 10-20 Hz PSD sound levels at this site were among the highest recorded PSD sound levels across all sites, likely due to an abundance of biological sound sources near the receiver. In American Samoa, a clear diel trend of low-frequency sound levels is evident in the recordings; band sound levels ($dB_{RMS\ (50\ Hz\text{-}1.5\ kHz)}$ re 1 μPa) are lowest during the day and peak at dawn and dusk. This difference is likely related to the activities of reef animals, such as the crepuscular feeding behavior of sea urchins, a ubiquitous species in tropical reef environments (Castle and Kibblewhite, 1975; Radford et al., 2008b). Sea urchins feed by scraping algea via a ventral beak-like mouth, and the skeleton of each sea urchin acts as a Helmholtz resonator, magnifying the scraping sounds from each individual (800 Hz – 2 kHz, depending on body size) into a "reef chorus" that may also include sounds from other animals such as fish or shrimp (Radford et al., 2008a). Whilst a low frequency limit is applied in this study (<2 kHz), this frequency band captures the lower end of the dominant frequencies (120 Hz – 4 kHz, Richardson et al., 1995) of humpback whale song components. Ambient sound levels at American Samoa were among the highest recorded, and humpback whale vocalizations were detected daily throughout the expected seasonal time period for Southern Hemisphere humpback whales (Robbins et al., 2011). On days with humpback whale vocalizations present, the mean of the daily median 500 Hz sound levels was 0.83 dB re higher compared to days that humpback whale vocalizations were not detected (Fig. 6). Thus, peaks in band sound levels in August until November were likely driven, at least partially, by presence of humpback whale vocalizations (Fig. 3).

In Virgin Islands and Stellwagen, the two sites located in the Atlantic, no diel pattern of band sound levels was observed (Fig. 3). This is likely related to the high amount of continuous anthropogenic activity in the North Atlantic (Kaluza et al., 2010); both Virgin Islands and Stellwagen were exposed to year-round adjacent and regional vessel noise. However, ambient sound levels in Virgin Islands were lower and less variable compared to Stellwagen (Fig. 4). An illustrative example of this difference is that humpback whale vocalizations are visible in the band sound level plots of Virgin Islands, but not in Stellwagen (Fig. 3), although humpback whale vocalizations were detected and known to occur in both areas (Heenehan et al., 2019; Stanistreet et al., 2013). This inconsistency suggests that ambient sound levels, combined with other influencing factors (e.g., distance between conspecifics, number of individuals), are likely a contributing factor in the success or failure in detecting humpback whale vocalizations and other biological sources in a given region and season. Further, in both Stellwagen and Virgin Islands, the mean of daily median 500 Hz sound levels was higher when humpback whale vocalizations were *not* detected than when they were, and the difference is larger in Stellwagen compared to Virgin Islands (~3.5 dB and ~1.1 dB, respectively) (Fig. 6). Different local weather also explains the lower sound levels in Virgin Islands compared to Stellwagen. Specifically, Virgin Islands is located in a low-latitude Caribbean climate zone with warm temperatures year-round. Hurricanes were the only major ephemeral weather event to increase ambient sound levels in Virgin Islands. Short-term wind-speed increases during hurricane events are reflected in increased band sound levels (Fig. 3).

In Stellwagen, ambient sound levels during June-August were lower than levels observed during November-May (September-October had no data). Stellwagen is the only site located near the continental U.S., and is the closest site to a major U.S. port (Boston, MA). Consequently, various classes of vessels transit the sanctuary year-round (in fluctuating seasonal numbers by class) contributing to low-frequency sound levels (Hatch et al., 2008). Additionally, from late fall through early spring, mixing of cold Arctic air and warm jet stream water creates powerful storms along the northeast coast of the continental U.S., bringing high wind speeds to Stellwagen. Surface winds increase sea state which is positively correlated with ambient sound levels (Wenz, 1962). Sound levels in the 500 Hz frequency band were strongly correlated with windspeed; This finding is consistent with other studies of shallow water acoustic habitats (Haxel et al., 2013). The combination of seasonal weather patterns and vessel passages in Stellwagen likely increased ambient sound levels.

Vessel Noise

The duration and density of vessel traffic that contributes to the soundscape of each site is determined by factors such as the size of the nearest port, the management schema of vessel traffic in park or sanctuary waters, and the physical environment around the site. Sound generated from sources outside the borderlines of U.S. national marine sanctuaries and parks can propagate into protected waters. For example, while a protected area, Stellwagen has a soundscape that includes regional Massachusetts Bay traffic as well as ocean-going vessels transiting the shipping lane through the sanctuary to and from the Port of Boston, MA (See Supplementary Figure 3.7 for map). In comparison, Virgin Islands does not contain major local shipping lanes and the closest port city is over ten times smaller than Boston, MA; however, regionally this area has vessel traffic in many directions transiting in the Caribbean Sea and to and from the Panama Canal (NOAA Office for Coastal Management, 2017, 2015). Though a correlation of vessel density and sound levels throughout the listening time periods was beyond the scope of this study, annual U.S. government-compiled vessel density datasets such as MarineCadstre.gov (BOEM and NOAA 2019) may be valuable to future multi-year comparisons of localized changes in levels of sound and vessel activity in highly trafficked regions. MarineCadastre vessel density data are not currently available for the Pacific Islands region or Alaskan waters.

Both American Samoa and Glacier Bay are remote from any major shipping routes and port cities; however, the soundscapes of these two marine protected areas are not identical. Differences in the geographically isolated soundscapes of American Samoa and Glacier Bay can be partially attributed to environment (American Samoa is exposed to remote open ocean, while the Beardslee Island Complex within Glacier Bay is sheltered interior waters) and management (Glacier Bay actively manages vessel traffic transiting within the Beardslee Island complex area while American Samoa has no such management) (Gabriele et al., 2018). Large, distant vessel traffic results in a chronic source of sound in Stellwagen and Virgin Islands and transient, closer sources in American Samoa and Glacier Bay. While the higher populations in the nearest port city are likely related to increased anthropogenic noise levels in a soundscape, the environment (e.g., bathymetry, pressure, temperature; see Urick, 1983) can also facilitate propagation of low-frequency sound energy from more distant sources.

Assessing Acoustic Habitat Conditions Using Passive Acoustic Monitoring

Understanding the past, current and potential future conditions of a habitat is required to ensure appropriate and effective conservation and management efforts. Previously, methods aimed at documenting underwater species presence and diversity have relied on visual surveys (e.g., via remote platforms or direct underwater observation) or invasive methods (e.g., traps, trawls) (Costello et al., 2017). While these methods can cover relatively large spatial areas, they are resource-intensive, making it difficult to capture long-term seasonal changes in key protected areas, particularly during inclement weather or in remote regions. By deploying fixed passive acoustic monitoring (PAM) recorders in ecosystems of interest, researchers maximize temporal data collection that would otherwise be logistically impractical (Merchant et al., 2015). For instance, during and immediately following hurricanes Irma and Maria in the Caribbean, PAM, as undertaken during the current study, allowed for ecosystem monitoring in Virgin Islands that would not have been possible otherwise. PAM can add value to visual surveys by providing cost-effective long-term data collection encompassing a wide range of species, weather events, and human activities (Sousa-Lima, 2013a). Furthermore, continuing advances in data processing and interpretation constantly improve upon the efficiency of PAM to provide useful information. The future applications for PAM are vast, and researchers are constantly evolving PAM tools to collect and process data more efficiently. For example, the introduction of cabled systems allows for real-time monitoring capabilities which could expedite regulatory action when biologically important metrics are exceeded (Gabriele et al., 2018; Ryan et al., 2016).

We measured almost a year of humpback whale vocal activity in one foraging ground (Stellwagen) and an entire summer foraging season in another (Glacier Bay), as well as almost a year in two lower-latitude environments (American Samoa, Virgin Islands) where humpback whales are presumed to be engaged in breeding or migratory activity (Fig. 5). Bioacoustic activity from other soniferous species were detected within these long-term datasets, and future studies could examine these and additional PAM data to further investigate and monitor these bioacoustic sources. For example, to our knowledge, very little is known about the composition and sensitivity to sound of the species that make up the reef chorus in American Samoa. These data highlight times of high acoustic activity to direct potential future habitat monitoring and investigations of other bioacoustic contributors to the soundscape (e.g., fish, shrimp).

There are limitations to PAM; it is impossible to determine the presence of a silent or masked animal. Higher levels of ambient sound from any source may interfere with animal communication space and mask vocalizations. For example, measuring the highest sound levels on days with no humpback whale vocalizations detected and comparing them to levels on days with humpback whale vocalizations detections may indicate possible masking impacts to animals (Fig. 6). Not only does noise from vessels and other anthropogenic sources overlap with the frequency range of humpback whale vocalizations (Clark et al., 2009; Gabriele et al., 2018), but many weather-related sounds also fall into this range (e.g., wind, rain; Wenz, 1962). These chronic sources of broadband abiotic sound may limit the capacity of a humpback whale to exercise resilience against ambient noise (e.g., modulating the pitch, duration, or intensity of vocalizations). Ongoing and future research efforts may benefit from coupling soundscape monitoring with other methods (e.g., visual surveys) to identify potential places and times to quantify possible effects. Further, advanced analytical techniques many be able to parse the components of a soundscape more effectively (T.-H. Lin et al., 2017; T. H. Lin et al., 2017; Seger et al., 2018) and quantify the degree to which signals may be masked in different ambient conditions (Helble et al., 2013).

CONCLUSION

This study contributes to a growing body of knowledge documenting ambient conditions in underwater soundscapes (Erbe et al., 2016a). Soundscape monitoring can eventually lead to more informed and efficient management of marine protected areas by documenting current (and potentially changing) conditions. For example, identifying the times and locations in which soniferous species (e.g., humpback whales) overlap with anthropogenic sources and other abiotic sounds can inform decision makers regarding when, where, and how acoustic conditions in marine habitats necessitate further protection (Hatch et al., 2016; Hatch and Fristrup, 2009; Merchant et al., 2018).

To understand how best to protect ecosystems and maintain diversity, it is essential to establish baseline soundscape conditions and associated metrics that adequately capture the conditions at a site. A soundscape may include a richness of sonic animals, heavy human use, dynamic environmental conditions, or numerous combinations therein. Each of the aforementioned sources creates a significantly different acoustic habitat, and, depending on the use and conservation priorities of an area, may need customized acoustic management (e.g., Erbe et al., 2012; Williams et al., 2015). For example, at sites where human uses are relatively quiet and marine animals dominate the soundscape (e.g., American Samoa), management needs may differ from sites where resident or seasonally predictable acoustically active animals are central to the ecosystem, but anthropogenic sources dominate the soundscape (e.g., Stellwagen). The management of vessel transits by the National Park Service in Glacier Bay National Park and Preserve provide an example of how policies to mitigate anthropogenic sound can be successfully incorporated into regulatory planning for a marine protected area (McKenna et al., 2017). Furthermore, soundscapes within marine protected areas may also be influenced by sources beyond their boundaries, some of which may have propagated from great distances (Hatch and Fristrup, 2009). Documenting the status and trends of animal and human use, as well as weather and environmental conditions, can inform the need for and balance of management plans to protect acoustic habitats within soundscapes, as well as provide a basis for evaluating changes over time.

Comparing the acoustic conditions of geographically diverse ocean environments is complicated. By utilizing calibrated instruments deployed within a three-and-a-half-year time period, we have established baseline levels and metrics for monitoring the soundscapes of four widespread marine protected areas. Together with methods to document other essential ocean variables (e.g., water sampling, remote sensing), continued soundscape monitoring will facilitate detection of changes over time (including anthropogenic sources), recommendations of potential management priorities, and evaluations of the efficacy of actions aimed at either protecting an individual species, suite of species, or soundscape as a stand-alone resource of intrinsic value.

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FIGURES

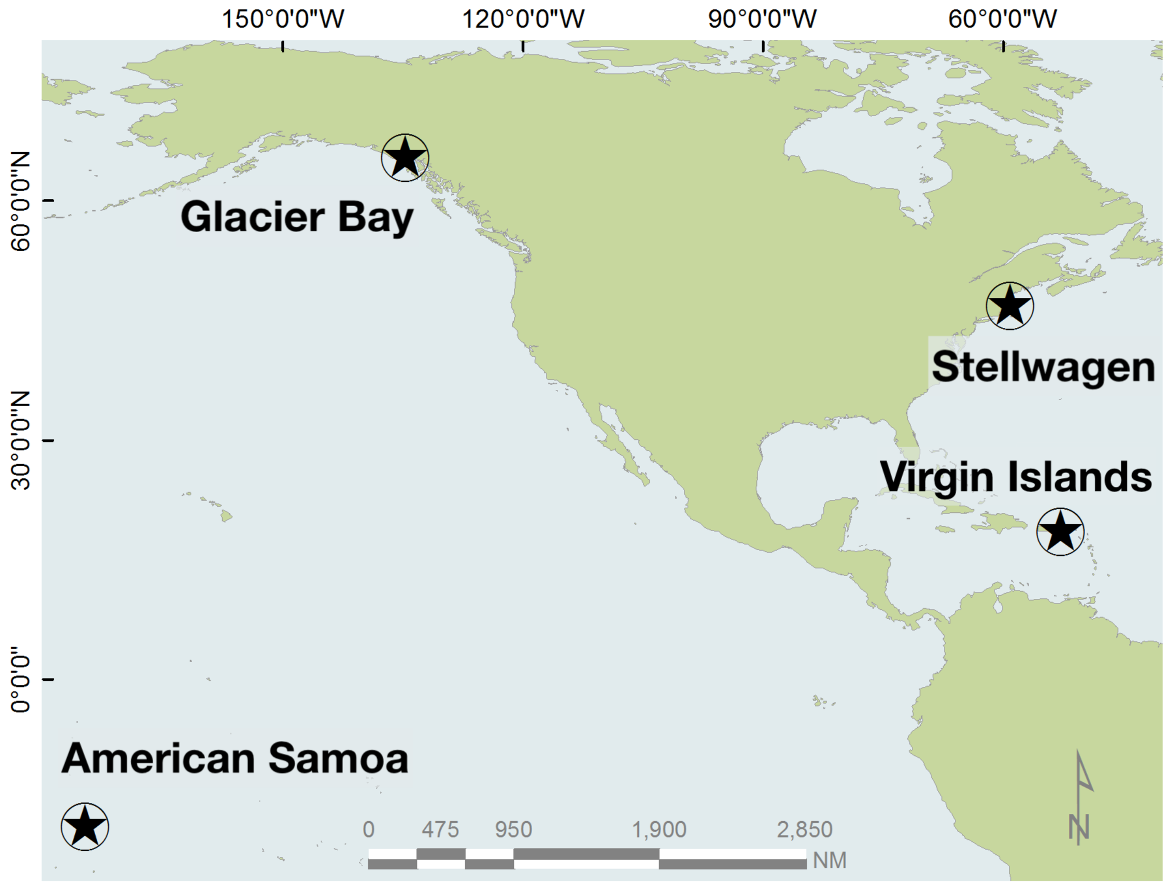

Figure 3.1. Map of recording sites: National Park of American Samoa (American Samoa), Glacier Bay National Park (Glacier Bay), Stellwagen Bank National Marine Sanctuary (Stellwagen), Buck Island Reef National Monument (Virgin Islands).

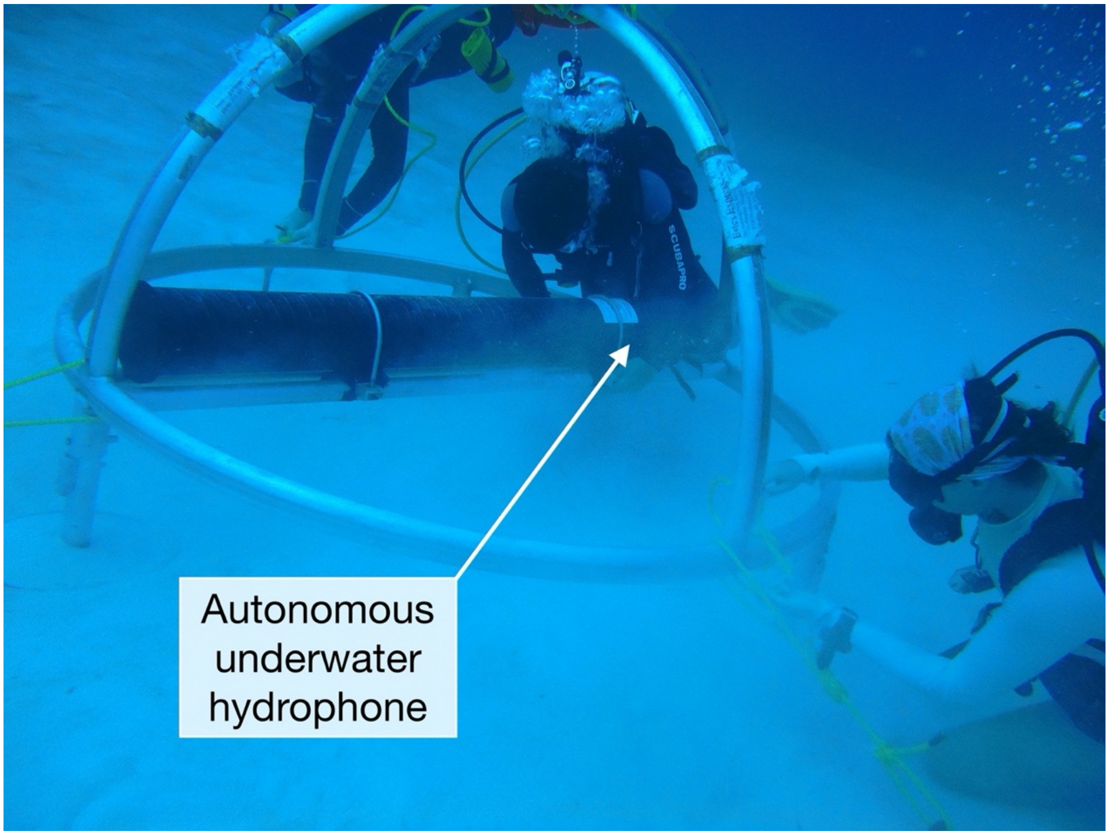

Figure 3.2. Divers deploying the Virgin Islands instrument. The instruments for all of the NRS moorings used here consist of an acoustic data logging system housed in a composite pressure case and secured to a bottom-mounted metal frame. (Photograph: Clayton Pollock/NPS, Virgin Islands)

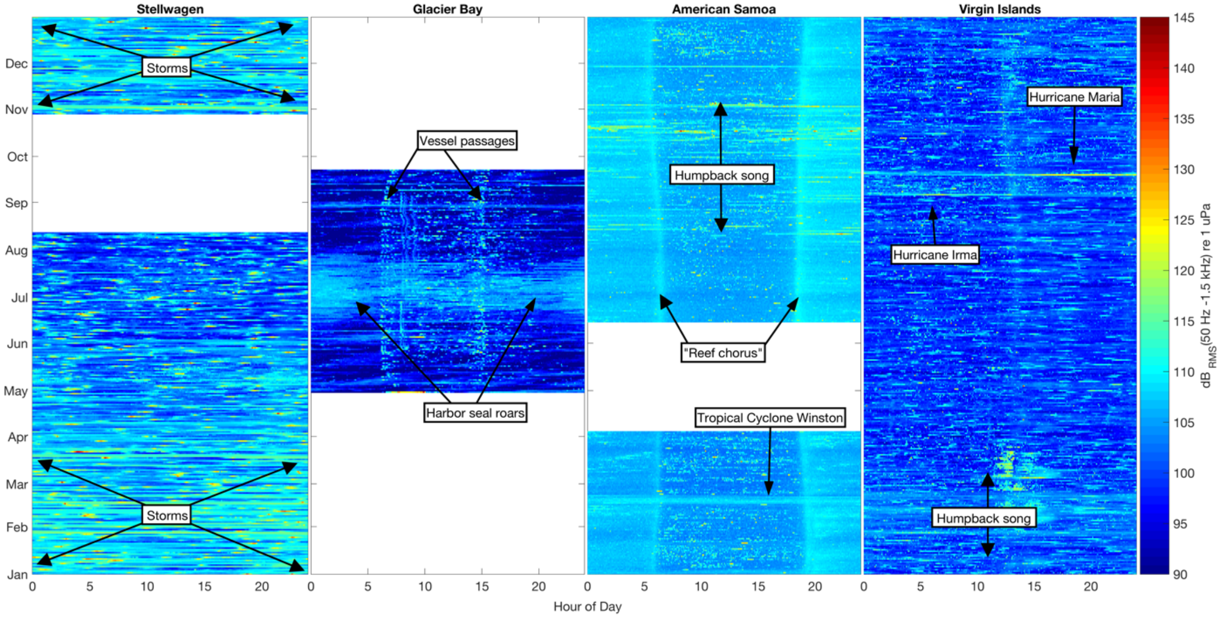

Figure 3.3. Sound levels in the 50 Hz-1.5 kHz band (dB$_{\mathrm{RMS}}$ re 1 μPa) at four shallow-water mooring sites calculated in 5-minute bins for all available data. Color (blue-yellow-red) indicates sound level intensity in each bin, with the lowest levels (90 dB) dark blue and the highest (145 dB) bright red. Each NRS site is plotted by month (Jan – Dec) and hour of day (0-24).

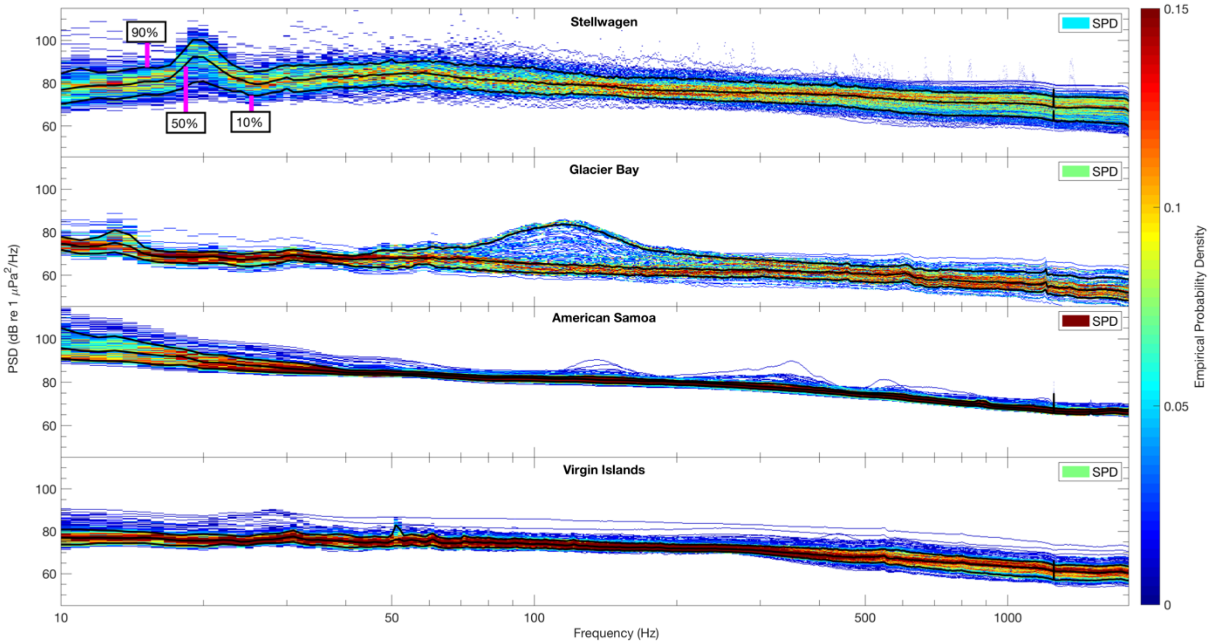

Figure 3.4. Spectral probability density (SPD; Merchant et al., 2013) plots of the distribution of sound levels (10 Hz – 2 kHz) across sites for all available data (see Table 1). Solid black lines indicate percentile levels (90th, 50th (median), 10th) of power spectral densities (PSD, dB re 1 μPa2/Hz). PSD sound levels of each frequency band determine the empirical probability density (EPD), indicated by z-axis color bar range of blue (lower probability) to red (higher probability). An overall SPD is also calculated for each site (upper right corner of each panel) indicating the overall probability of temporal sound level constancy.

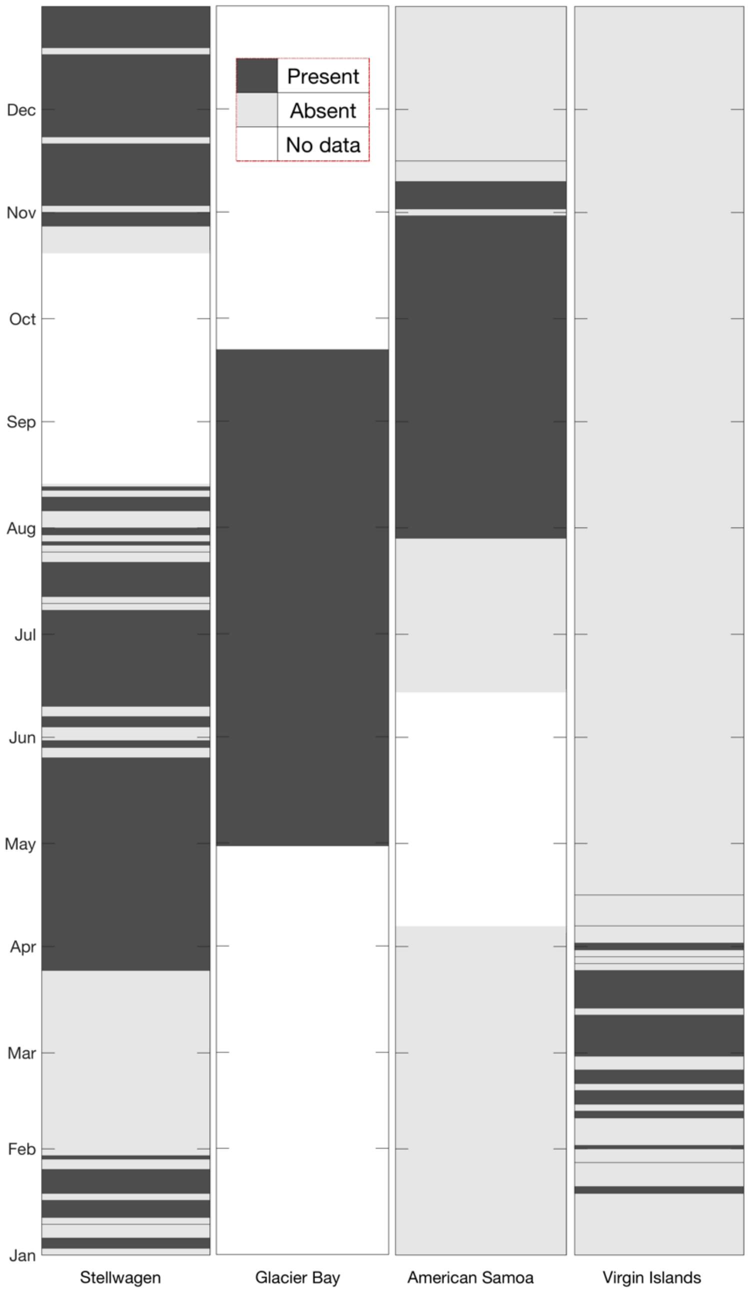

Figure 3.5. Site-by-site comparison of monthly presence (dark grey shading) or absence (light grey shading) of humpback whale vocalizations. All available data were analyzed for the presence/absence of humpback whale vocalizations. White sections indicate data gaps at each site.

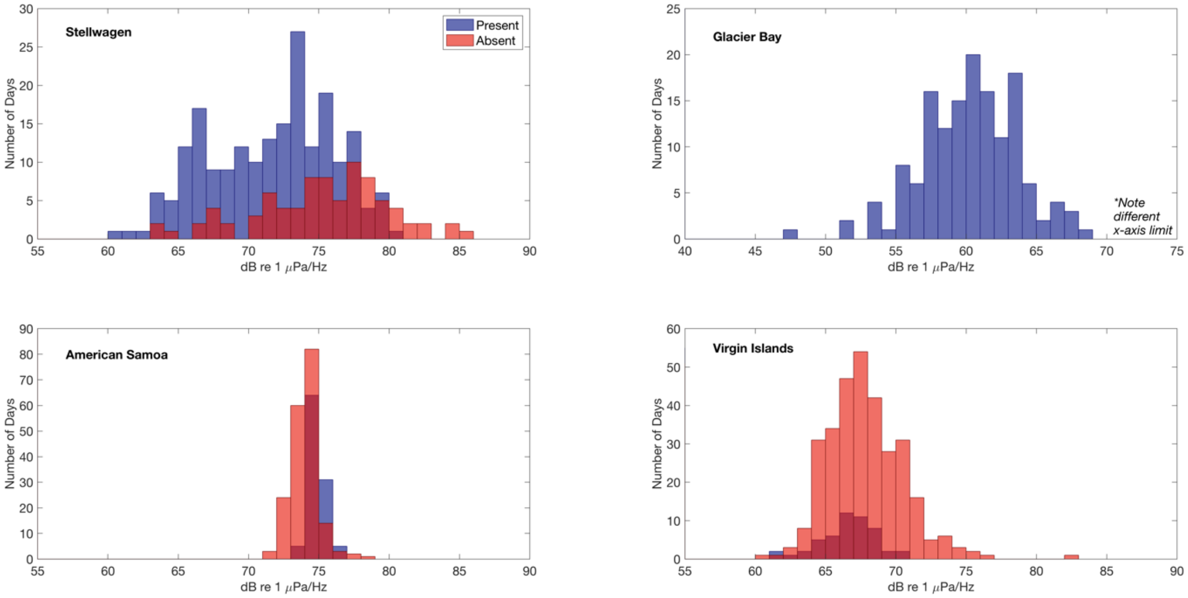

Figure 3.6. Relationship between the distribution of daily median 500 Hz power spectral density sound levels (dB re 1 μPa^2/Hz) and detection of humpback whale vocalizations at each site. Histograms of sound levels (1 dB bin width) are plotted for two conditions, when humpback whale vocalizations are present (blue) or absent (red). In Glacier Bay, humpback whale vocalizations were detected on all days and thus no absent (red) condition is plotted.

TABLES

Site	*Partners*	*Latitude*	*Longitude*	*Hydrophone Depth (m)*	*Deployment Length (months)*
Stellwagen Bank National Marine Sanctuary	NOAA/Stellwagen	42.40	−70.13	79	10 (Oct 2014 - Aug 2015)
Glacier Bay National Park and Preserve	NOAA & NPS/Glacier Bay	58.51	−135.96	62	4.5 (May - Sep 2016)
Tutuila Island, National Park of American Samoa	NOAA & NPS/American Samoa	−14.27	−170.72	33	10 (Jun 2015 - Apr 2016)
Buck Island Reef National Monument, U.S. Virgin Islands	NOAA & NPS/Buck Island Reef	17.79	−64.65	40	12 (May 2017 - May 2018

Table 3.1. Hydrophone deployment site details.

SUPPLEMENTARY MATERIAL

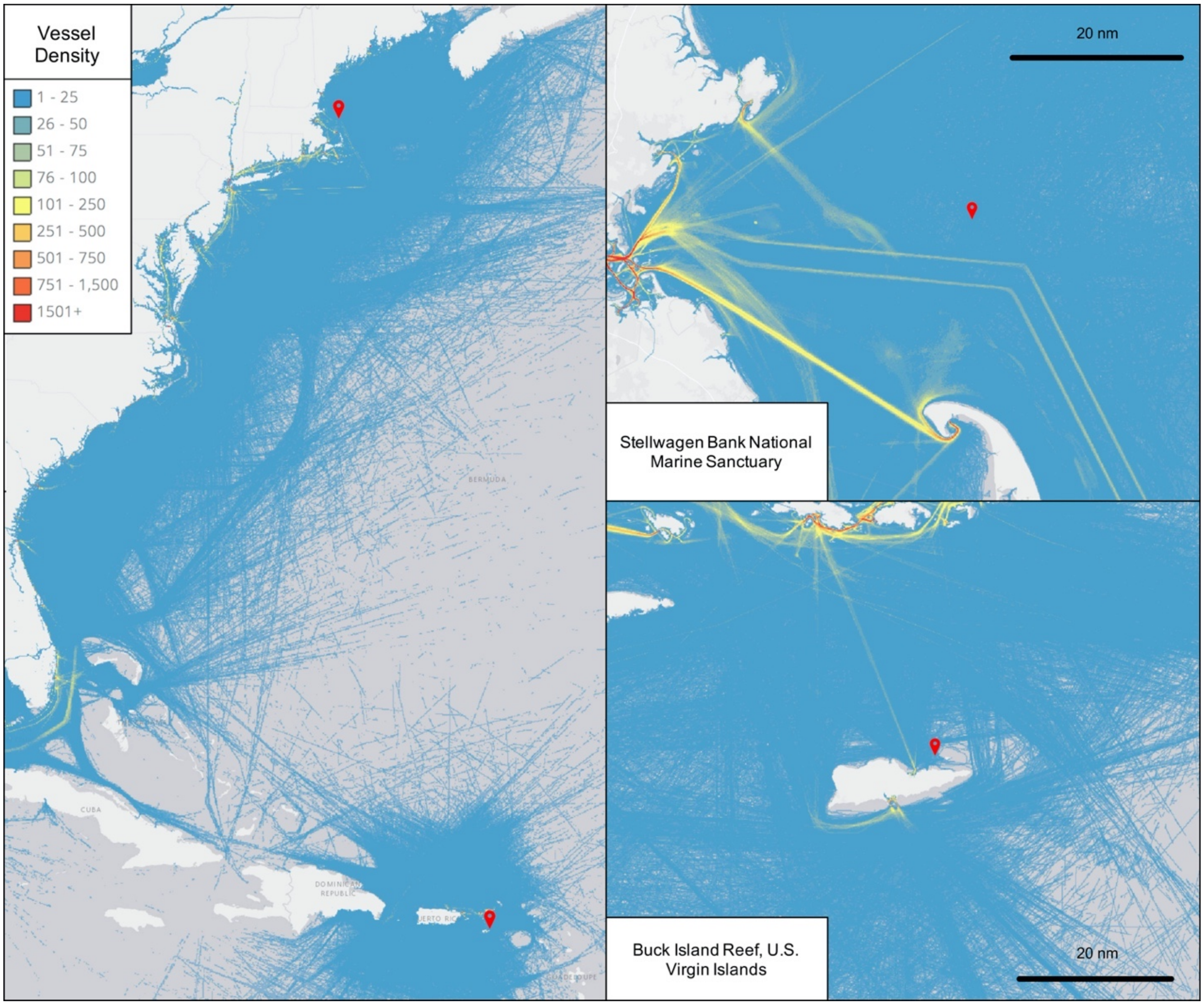

Figure 3.7. Density maps of Automatic Identification System (AIS) vessel track lines of all vessel types (100 m grid cell resolution) in 2015-2017 in the Atlantic Ocean compiled with the MarineCadastre.gov National Viewer (BOEM and NOAA). Detail maps show vessel activity near the hydrophones (red markers indicate location) in Stellwagen Bank National Marine Sanctuary and Buck Island Reef National Monument. AIS data are not currently available via the Marine Cadastre for the Pacific Islands region or Alaskan waters.

CHAPTER 4. SEASONAL TRENDS AND PRIMARY CONTRIBUTORS TO THE LOW-FREQUENCY SOUNDSCAPE OF THE CORDELL BANK NATIONAL MARINE SANCTUARY

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ABSTRACT

Passive acoustic monitoring of ocean soundscapes can provide information on ecosystem status for those tasked with protecting marine resources. In 2015, the National Oceanic and Atmospheric Administration (NOAA) established a long-term, continuous, low-frequency (10 Hz – 2 kHz) passive acoustic monitoring site in the Cordell Bank National Marine Sanctuary (CBNMS) located offshore of the central U.S. west coast, near San Francisco. The California Current flows southward along the coast in this area, supporting a diverse community of marine animals, including several baleen whale species. Acoustic data analysis revealed that both large vessels and vocalizing baleen whales contribute to the ambient soundscape of CBNMS. Sound levels fluctuated by month, with the highest levels in the fall and lowest levels in the summer. Throughout the year, very low-frequency (10 Hz – 100 Hz) sound levels were most variable. Vessels and whales overlap in their contributions to ambient sound levels within this range, though vessel contributions were more omnipresent, while seasonal peaks were associated with vocalizing whales. This characterization of low-frequency ambient sound levels in CBNMS establishes initial baselines for an important component of this site's underwater soundscape. Standardized monitoring of soundscapes directly supports NOAA's ability to evaluate and report on conditions within national marine sanctuaries.

Keywords: passive acoustic monitoring; ambient soundscape; marine mammals; management

INTRODUCTION

The soundscape of an underwater environment is composed of acoustic contributions from biotic and abiotic natural sources, and often also includes sounds generated by anthropogenic activities; these latter sources may be harmful to sound-sensitive species (Erbe et al., 2019; Popper and Hawkins, 2019; R. Williams et al., 2015). Passive acoustic monitoring is a non-invasive and relatively economical method for observing a soundscape over extended durations (Sousa-Lima, 2013b). Data collected through long-term passive acoustic monitoring efforts can provide critical information about the status of an ecosystem and help record changes over time to inform those tasked with protecting marine resources (Buxton et al., 2019; Hatch et al., 2016; S.M. Van Parijs et al., 2015).

In the United States of America (U.S.), the National Oceanic and Atmospheric Administration (NOAA) manages 14 national marine sanctuaries and two national marine monuments located throughout the U.S. Exclusive Economic Zone, which extends 200 nautical miles from the coast. The guiding legislation for the NOAA Office of National Marine Sanctuaries is the National Marine Sanctuary Act which mandates, among other things, "comprehensive and coordinated conservation and management of these marine areas, and activities affecting them…" and that the sanctuaries are to "maintain the natural biological communities in the national marine sanctuaries, and to protect, and, where appropriate, restore and enhance natural habitats, populations, and ecological processes" (National Oceanic and Atmospheric Administration (NOAA), 2000).

Cordell Bank National Marine Sanctuary (CBNMS; Fig. 1) is one of five national marine sanctuaries in the northeast Pacific along the west coast of the contiguous U.S. CBNMS borders the central-western boundary of the Greater Farallones National Marine Sanctuary, which is adjacent to Monterey Bay National Marine Sanctuary to the south. CBNMS is located on the continental shelf and slope and is geographically exposed to deep-open ocean (Fig. 1). Within CBNMS, Cordell Bank (42 sq mi) rises to 35 m beneath the surface and is surrounded by soft sediment on the shelf and a steep drop to the west (NOAA, 2014). Cordell Bank comprises approximately one-third of the total area of CBNMS. The prevailing California Current flows southward along the coast in this area, and the annual upwelling of nutrient-rich deep ocean water supports the sanctuary's rich biological community of fishes, invertebrates, sea birds, and marine mammals (Office of National Marine Sanctuaries, 2009). Many of the marine species in CBNMS can detect and utilize sound for communication; however, marine mammals are of particular interest because of their known soniferous behavior (and thus detectability via passive acoustic monitoring), because their frequency range overlaps with anthropogenic sound sources, and because they are the target of conservation efforts within many sanctuaries (Gedamke et al., 2016; Hatch and Fristrup, 2009). CBNMS provides habitat for endangered populations of blue (*Balaenoptera musculus*) and fin (*B. physalus*) whales and federally protected humpback whales (*Megaptera novaeangliae*) (Gill et al., 2007; Scales et al., 2017). Gray whales (*Eschrichtius robustus*) are also common in the region (Guazzo et al., 2017). These soniferous cetaceans rely on low-frequency sound for basic life functions of feeding, navigation, and reproduction.

Broadly, large cetaceans are threatened by anthropogenic activity in the form of ship strikes, entanglement, and increased noise (Frankel and Gabriele, 2017). Anthropogenic noise can impact whales in a number of ways, including hearing loss, masking, and behavioral changes (Blair et al., 2016; Castellote et al., 2012; Clark et al., 2009; Fournet et al., 2018a; Melcón et al., 2012; Parks et al., 2016; Richardson et al., 1995). San Francisco Bay is home to large global shipping ports, including the ports of Oakland and San Francisco (Moore et al., 2018), which are accessed by shipping lanes that pass through all three National Marine Sanctuaries in the area. Therefore, noise from the ships that use these ports likely impact cetaceans in all three sanctuaries. A traffic separation scheme has been in place in the San Francisco Bay Area since 1973 and was modified in 2013, primarily to increase mariner safety but also to reduce the overlap of known whale hot spots and ship traffic; however, this reduced overlap between vessels and marine mammals in CBNMS still poses a threat to marine mammals (NOAA, 2014). CBNMS is exposed to noise radiated not only from the San Francisco traffic separation scheme shipping lanes, but also from regional offshore traffic transiting in deeper waters along the U.S. west coast.

Under certain environmental conditions, the sound velocity structure of the water column can create conditions favorable for the efficient propagation of low-frequency vessel sounds to areas outside of the traffic separation scheme, potentially degrading whale habitat in other areas of the sanctuaries. Historical underwater recordings from this area have been compared to more recent data showing that sound levels have increased in the North Pacific since the 1960's (Andrew et al., 2010; Chapman and Price, 2011). These increases in low-frequency ambient sound levels may be positively correlated with economic growth via the expansion of commercial shipping (Frisk, 2012; M. F. McKenna et al., 2012) as an increasing number of larger and faster ships have been linked to increased ambient noise levels (Mark A. McDonald et al., 2006a). The commercial shipping lanes in and around CBNMS experience minimal seasonal and diel variability in traffic density (Jensen et al., 2015). Although many previous studies have documented ambient and vessel-related noise near the port of Los Angeles (Mark A McDonald et al., 2006; McDonald et al., 2008; Megan F McKenna et al., 2012; Redfern et al., 2017), no studies have specifically sought to document sound levels in CBNMS.

Baseline monitoring of underwater sound levels in CBNMS supports the ability of marine sanctuary managers to characterize and track long term changes in the soundscape. Monitoring underwater soundscapes across biologically important areas in U.S. waters is a priority for NOAA, including priority acoustic habitats within National Marine Sanctuaries that are affected by noise, such as CBNMS (Ferguson et al., 2015; Gedamke et al., 2016; Hatch et al., 2016). Additionally, acoustic monitoring and soundscape research are specifically identified as priority activities in the CBNMS management plan (NOAA, 2014). Current CBNMS objectives related to sound include acoustic monitoring of ambient sound in the sanctuary, assessing the sources and effects of anthropogenic activities on marine organisms and ecosystem health, and developing management activities to conserve sanctuary resources. To support these management priorities, it is necessary to understand the relative inputs to the sanctuary soundscape and any spatial or temporal patterns of sounds. Additionally, the potential effects of these sounds on species of concern must be assessed (Cordell Bank National Marine Sanctuary, 2014).

Soundscape monitoring in CBNMS is achieved through one of the 12 stations included in the NOAA/National Park Service Noise Reference Station (NRS) network. The NRS network was established in 2014 in an effort to document current baseline levels and sources of ambient sound in U.S. waters using calibrated autonomous underwater hydrophone moorings (Haver et al., 2018). The NRS in CBNMS is the first effort to document soundscape conditions in the sanctuary, and data collected support the NOAA Office of National Marine Sanctuaries goal of NMS system-wide comparative measurements. Continued passive acoustic monitoring in CBNMS provides data to support NOAA efforts to characterize the soundscape, including the relative presence of animals and activities that make sounds, and to assess the overall status of ambient noise as a stressor affecting the condition of the sanctuary as prescribed in the CBNMS management plan (NOAA, 2014).

Guided by the scientific needs of NOAA Office of National Marine Sanctuaries managers of protected marine resources, here we document the underwater soundscape of CBNMS during the first deployment of the NRS hydrophone mooring between October 2015 and October 2017. Specifically, we quantify baseline measurements of ambient sound levels, assess seasonal sound level differences, and document the temporal variation of four highly vocal marine mammal species.

METHODS

Instrumentation

The Noise Reference Station (NRS) mooring was deployed in Cordell Bank National Marine Sanctuary at 37.8° N 123.4° W, at a water depth of 550 meters (Fig. 1). The single passive acoustic archival hydrophone (Fox et al., 2001) is housed in a titanium pressure case and suspended within the deep sound channel at 500 m (sound speed profile verified via GOSSPL; Barlow, 2019). The model ITC-1032 (International Transducer Corp., Santa Barbara, CA) hydrophone has a sensitivity of −192 dB re 1 V/µPa and a flat frequency response (-/+ 1 dB) between 10 Hz and 2 kHz. The instrument was programmed to record continuously from October 2015 to October 2017 at a sample rate of 5 kHz with a 2 kHz low-pass cutoff frequency.

Incoming signals were conditioned by a pre-amplifier and pre-whitening filter to maximize the dynamic range of the 16-bit acoustic data logging system (see Haver et al., 2018 for additional details). In all analyses, the effect of the pre-whitening filter was removed to restore actual spectral levels.

Sound level measurements

Spectrum levels were calculated from raw binary files in 1 s spectral averages at a 1 Hz frequency resolution (10 Hz – 2 kHz), and then averaged in hourly windows before conversion to decibels for efficient data analysis of the two-year-long continuous data set. Median (50th percentile), first, fifth, 10th, and 90th percentiles of 10 Hz – 2 kHz power spectral densities (re 1 $\mu Pa^2/Hz$) were computed in decibels. Percentiles (also known as statistical noise levels) are computed to evaluate sound level fluctuations from both chronic and intermittent sources; for example, the 5th percentile is the sound level exceeded 95% of the time, and thus is a measure of background sound levels, while the 90th percentile is the level exceeded 10% of the time, indicating sporadic peaks in sound levels. The 1st percentile power spectral density sound levels were calculated as a measure of the system noise floor. Two-year mean monthly narrow-band sound levels were calculated from monthly median power spectral densities.

Historical weather records

Weather, specifically wind and rain in this climate zone, can influence the ambient soundscape (Wenz, 1962). To assess the extent to which wind speed conditions affected sound levels, wind speed measurements in CBNMS from NOAA buoy Station 46013, located approximately 40 kilometers from the NRS (Fig. 1), were retrieved from the NOAA National Data Buoy Center database (National Data Buoy Center, 1971), divided into 10 cm/s bins, and correlated with hourly time-aligned 500 Hz sound levels. Daily rainfall measurements were obtained from the Bodega Ocean Observing Node at the U.C. Davis Bodega Marine Laboratory (http://boon.ucdavis.edu/data_rain_fall.html).

Whale presence/absence visual analysis

Large whale surveys were conducted daily from the lighthouse on the Southeast Farallon Islands (SEFI) at an elevation of 90 m (Pyle and Gilbert, 1996), located approximately 45 kilometers from the NRS (Fig. 1). All observations were recorded and identified down to species using 10X and 25X binoculars. Observations of surrounding waters were conducted for one hour per day (15 minutes per quadrant) when visibility was greater than 11.2 km, no low hanging fog was present, the Beaufort wind force was less than or equal to 4, and swells were less than 3 m. The daily total numbers of humpback, gray, blue, and fin whales observed in all quadrants were summed and used for analysis. Additionally, at-sea marine mammal surveys were also conducted in CBNMS during Applied California Current Ecosystem Studies (ACCESS) cruises in May, July, and September of 2016 and 2017 from the survey vessel's flying bridge. Standardized line transect methods were used to count whales from both sides of the vessel while "on effort" in the sanctuary, which was defined as daylight hours while the vessel was underway at 10 knots (see Jahncke et al., 2008 for more details on methodology). Each cruise was six to ten days in duration and the survey area included CBNMS and most of the offshore regions of Greater Farallones NMS. Results from SEFI and ACCESS visual observation efforts were compiled into a single database including all effort spanning October 2015 to October 2017 (hereafter, ACCESS/SEFI data). Results were separated by platform and species monitored.

Whale acoustic analysis

Humpback whales

Using the ACCESS/SEFI data, all days of NRS acoustic sampling that corresponded with ACCESS/SEFI effort (322 days, which includes days with no positive visual detections of humpback whales) were manually reviewed for the presence of humpback whale vocalizations by a trained analyst using Raven Pro software (Cornell Bioacoustics Research Program). Comparisons of visual and acoustic detections included only visual on-effort survey days so as not to bias results towards continuous acoustic monitoring. The analyst reviewed data for both song and non-song vocalizations, including feeding-type calls between 200-600 Hz (M. E. Fournet et al., 2015; Stimpert et al., 2011). Data were reviewed chronologically by day starting in 2015 until vocalizations were identified or the entire day elapsed (see Fig. 2 for example vocalizations). If humpback whale vocalizations were identified in the data, the time and date of the vocalizations were logged, and the observer moved ahead to the next day corresponding to visual effort. If no vocalizations were identified in a day, an absence was recorded.

Gray whales

Migrating eastern North Pacific gray whales have been detected visually and acoustically near CBNMS (Guazzo et al., 2017; Lagerquist et al., 2019; Pyle and Gilbert, 1996). The M3 call is the most common gray whale migratory call type and has been successfully used to localize migrating gray whales via passive acoustic monitoring. The M3 call has a source level of 156.9 dB re 1 μPa at 1 m in the 20 Hz - 100 Hz bandwidth of the call and a peak frequency of 38.1 Hz (Guazzo et al., 2017). The ACCESS/SEFI data were used to identify days and times of visual observations of gray whales, and the days with the highest number of gray whales sighted (>15 individuals) were reviewed first for the presence of M3 calls in order to try and increase the likelihood of detecting their vocalizations. Days with <15 individuals sighted were randomly subsampled in hourly bins to reduce processing time. All manual analysis was completed using Raven Pro. Although an automated detector was developed to identify gray whale M3 calls in nearby Monterey Bay (as described in Guazzo et al., 2017; Helble et al., 2012), our application of the algorithm to facilitate and expedite detection of M3 calls in all available acoustic data from CBNMS was unsuccessful.

Blue and fin whales

Blue and fin whales in the California Current are often detected acoustically via the most prominent components of their songs – B-calls and 20 Hz "pulse" calls, respectively (Mark A. McDonald et al., 2006b; William A. Watkins et al., 1987). While these call types are often used to quantify acoustic presence due to their relative abundance, this abundance can create significant overlaps between individual calls, creating a "chorusing" effect (see Fig. 2 for example vocalizations). This chorusing effect, previously documented for both blue and fin whales in the California Current (Redfern et al., 2017; Širović et al., 2015), was present in the acoustic data collected in the present study. As a result, acoustic detection of blue and fin whales was determined via calculation of "call index" values for blue whale B-calls and fin whale 20 Hz pulses rather than individual call detection.

Building upon acoustic power methods introduced by Mellinger et al. (2009), Širović et al. (2009), Širović et al. (2015), and Oestreich et al. (*unpublished*) for fin and blue whales, both call indices were calculated as a signal to noise ratio between peak and background frequencies in calibrated long-term spectral averages (LTSAs). For the blue whale B-call index, peak values were calculated as the mean across 43-44 Hz; background values were calculated as the mean of values at 37 and 50 Hz. For the fin whale pulse call index, peak values were calculated as the mean across 20-21 Hz; background values were calculated as the mean of values at 12 and 34 Hz. Call indices were calculated on both daily and monthly LTSAs in order to present results at multiple temporal scales. For determination of acoustic presence at a daily scale, the number of days with blue whale B and fin whale pulse call index exceeding a conservative estimate of background call index values (1.1) was recorded.

Vessel noise propagation

To estimate the range at which vessel noise would be detectable above ambient levels, we followed the methods of Širović et al. (2013) to compute the passive sonar equation and calculated average (mean and median rounded to whole number) power spectral density ambient sound levels between 10 Hz and 100 Hz. We assumed a vessel source level of 177 dB re 1 μPa at 1 m at 41 Hz (Gassmann et al. 2017), which was measured from vessels in Southern California following the current American National Standards Institute protocol for measurement of underwater sound from ships (ANSI/ASA, 2009). Transmission loss was calculated using the Phased Array System Toolbox™ in Matlab (The MathWorks Inc., Natick, MA) for four ranges between the NRS mooring: center of each western entry/exit point into the traffic separation scheme (north, middle, south) and the entry/exit to the San Francisco bay (see Fig. 1).

Automatic Information System vessel tracking

Automatic Information System (AIS) large vessel movement tracks in the traffic separation scheme shipping lanes near the NRS hydrophone in CBNMS from 2015-2017 were obtained from the U.S. Coast Guard National AIS (https://www.dcms.uscg.mil/Our-Organization/Assistant-Commandant-for-Acquisitions-CG-9/Programs/C4ISR-

Programs/NAIS/). Daily AIS tracks were imported and plotted in QGIS (Version 3.4, www.qgis.org), and the TimeManager plugin was utilized to quantify the daily sum of vessels transiting in the traffic separation scheme corresponding to each day of acoustic data from 2015-2017. Daily sum totals were exported to Matlab for comparison with acoustic data.

RESULTS

Sound level trends

Sound levels in CBNMS varied in both the frequency and time domains throughout the year. Over the two-year recording time period, the largest difference between the 10th and 90th percentiles of sound levels across the whole recording period (88.0 dB vs 105.3 dB for a difference of 17.3 dB at 45 Hz) and the highest monthly median sound level (November 2016; 105.9 dB at 44 Hz) were observed below 50 Hz, which was likely driven by blue whale song (B-call harmonics).

Between 50 Hz and 2 kHz, sound level variations were generally broadband. The exceptions to this consistency were the increased sound levels observed at ~60 Hz and ~80 Hz from September-December, which were likely driven by blue whale vocalizations (B-call harmonics and A-calls, respectively), as well as between 200 Hz – 500 Hz from November-January which were driven by humpback whale song (Figs. 2 and 3). Across all frequencies between 50 Hz and 2 kHz, the lowest monthly median sound levels were recorded in August. Because blue whales began vocalizing (B-calls) in August, the lowest monthly median sound levels between 10 Hz and 50 Hz were recorded in either June, July, or August depending on the frequency (Fig. 3).

Monthly trends

Sound levels varied in an apparent seasonal pattern, with the highest levels recorded in the fall/winter and the lowest in the summer months. The highest monthly median power spectral density sound levels were recorded in October and November at approximately 15 Hz, 30 Hz, and 45 Hz, which are the fundamental frequency and harmonics of the blue whale B-call (Fig. 3). Sound levels between ~15 Hz - ~30 Hz were highly variable by month throughout the year (Fig. 3). The lowest monthly median power spectral density sound levels were recorded in August at frequencies above 100 Hz (Fig. 3).

Differences between the 10th and 90th percentiles of 10 Hz – 2 kHz power spectral densities were largest at frequencies below 100 Hz that are associated with blue and fin whale vocalizations (Fig. 3). At three frequencies associated with blue whale vocalizations (15 Hz, 30 Hz, and 45 Hz), the 90th percentile sound levels were ~15 dB higher than the 10th percentile sound levels (15.3, 14.5, and 17.2 dB, respectively). At 22 Hz, a frequency associated with fin whale vocalizations, the 90th percentile sound levels were 12 dB higher than the 10th percentile sound levels. At all frequencies between 500 Hz and 2 kHz, the 90th percentile sound levels were a minimum of 14 dB higher than the 10th percentile sound levels, likely driven by fluctuations of wind and humpback whale vocalizations.

Weather increases ambient sound levels in some conditions

Wind noise and surface agitation increased ambient sound levels in CBNMS. The highest measured wind speeds were in the winter (January-March; three-month mean 4.8 m/s, maximum hourly mean 9.9 m/s) and wind speeds were lowest in the summer (June-August; three-month mean 3.4 m/s, maximum hourly mean 7 m/s). At wind speeds greater than 4 m/s (~50% of all hours sampled), hourly mean wind speed was highly correlated (R^2=0.86) with an increase in hourly mean 500 Hz sound levels. Rainfall (collected by the Bodega Ocean Observing Node) was not found to be correlated with sound levels recorded in CBNMS. Typically, bubble-induced rainfall sounds contribute to ambient sound in the 4-20 kHz range; however, heavy rainfall (i.e., larger bubbles) can influence ambient sound at frequencies below 2 kHz (Nystuen, 1996). It is likely that the light amounts of rainfall near CBMNS between October 2015 – October 2017 did not influence ambient sound levels below 2 kHz.

Comparison of visual and passive acoustic detections of whales

Detections of vocalizations of humpback, gray, blue, and fin whales in passive acoustic data were compared to visual observations of the same species collected during SEFI field station effort and ACCESS cruises.

Humpback whales

Humpback whales were detected in all months between October 2015 and October 2017 in the passive acoustic data (93% of days with corresponding visual effort), and in all months except December 2015 by visual observation efforts (visual detections on 51% of on effort days, Fig. 4). In all months except July 2017, humpback whales were detected acoustically on more days than they were detected via visual observation. On only one day in July 2017, visual survey efforts detected humpback whales that were not detected in the acoustic data.

Gray whales

Although gray whale M3 migratory calls were anticipated to be detected in the acoustic data on the same days visual observers identified gray whales, no M3 calls were detected in the acoustic data. The ACCESS/SEFI data were used to identify days and times of visual observations of gray whales, and those days and times were reviewed in acoustic data for the presence of M3 calls; however, no M3 calls were positively identified at any of the acoustic day/time correlates. Gray whales were primarily observed by SEFI visual observer effort in the winter and early spring (Fig. 4).

Blue whales

Acoustic detections of blue whale B-call song vocalizations were temporally offset from visual sightings of the animals during the ACCESS cruises or at the SEFI field site. B-call vocalizations were detected in a continuous time period that began in July or August and ended in December or January, depending on the year (Fig. 5). Each year, the highest B-call index was observed in a successively earlier month (i.e., in 2015, November; in 2016, October; in 2017, September). However, due to the deployment and retrieval operations taking place in October 2015 and 2017, the full B-call season was captured only in 2016.

Fin whales

Although fin whales were rarely observed in and nearby CBNMS by ACCESS/SEFI effort, the 20 Hz fin whale pulse sound was recorded consistently throughout the fall and winter. In all years, peak fin whale call index values were observed in the early fall and gradually decreased until March (Fig. 5). Background-level call index values suggest that no calls were detected in the late spring and early summer.

Low-frequency vessel noise propagation

Average (mean and median power spectral density rounded to whole number) ambient sound levels were 88 dB re 1 $\mu Pa^2/Hz$ between 10 Hz and 100 Hz. Range dependent transmission loss calculations revealed that low-frequency noise emanating from vessels transiting within the traffic separation scheme shipping lanes and into the San Francisco bay would exceed average ambient sound levels by 15-20 dB depending on vessel characteristics (vessel source levels calculated by Gassmann et al., 2017). This range of signal excess would increase for larger or faster ships, such as super tankers (180 dB at 50 Hz; Carey and Evans, 2011), and would persist above ambient levels for slower or quieter ships with source levels above ~164 dB re 1 μPa at 1 m at 40 Hz (signal excess calculated in Matlab for a 40 Hz signal propagating up to 100 km to a hydrophone at 500 m deep). Quantifying actual physical loss is complex and varies with oceanographic conditions, (e.g. temperature, salinity). Instead of providing absolute measures of vessel noise contributions, our estimates demonstrate that vessel noise originating within the traffic separation scheme shipping lanes and at points further off-shore up to at least 100 km away, will increase sound levels at the NRS mooring location within CBNMS and therefore vessel noise contributes to the soundscape at this site.

Automatic Information System vessel tracking

Review of AIS vessel tracks between 2015 and 2017 revealed nearly daily presence of vessels accessing the San Francisco traffic separation scheme near the NRS hydrophone in CBNMS (daily mean 21; Fig. 6). The acoustic impact of vessel traffic in the traffic separation scheme to ambient sound levels was estimated with the fifth percentile of daily sound level measurements in the 40 Hz to 100 Hz band in weekly bins. Although many sound sources, including whales, drive 40 Hz – 100 Hz sound levels, calculating the fifth percentile (i.e., the sound level exceeded 95% of the time) excludes some of the variability associated with episodic sound sources within those frequencies to reveal ambient sound levels driven by chronic sources. Additionally, by limiting the bandwidth to 40 Hz – 100 Hz, biological (e.g., fin and blue whale song fundamental frequencies and many components of humpback whale song) and physical sound sources (e.g. wind) outside of this range are excluded from the calculation. Although the fifth percentile of weekly 40 Hz to 100 Hz sound levels was not significantly correlated with the number of vessels accessing the traffic separation scheme, it was not as variable as the frequencies associated with animal vocalizations, signifying that chronic low-frequency sound sources like vessels are contributors to the sanctuary soundscape (Fig. 6).

DISCUSSION

Analysis of long-term continuous passive acoustic monitoring data collected in the CBNMS revealed that whale vocalizations and vessel traffic are primary drivers of low-frequency (<2 kHz) sound levels, and that wind (or other natural abiotic sources) may increase sound levels during specific times. Temporal (monthly) variability was most apparent in the lowest end of recorded frequencies (10 Hz - 100 Hz), related to seasonal patterns of whale acoustic behavior. Ships accessing the ports of Oakland and San Francisco were present year-round in AIS data and likely increased ambient sound levels throughout sanctuary due to the physical environment of CBNMS.

Environmental features influence the ambient soundscape

The physical environment of CBNMS is an underlying driver of the soundscape. Combined, the oceanography (e.g. California Current upwelling), density profile, bathymetry (e.g. Bodega canyon, Cordell Bank), and bottom substrate directly influence the soundscape by facilitating sound transmission from coastal and offshore sound sources. Furthermore, upwelling also bolsters biological productivity which makes central California a prime feeding habitat for whales that may vocalize in the environment.

Weather is a significant source of sound in any soundscape, even in the relatively mild and temperate region of Central California. In CBNMS, the primary source of natural abiotic sound is wind. Wind speeds as low as 4 m/s (or Beaufort force 3) are highly correlated with an increase in ambient sound levels (at lower speeds, other sound sources may mask more subtle acoustic contributions from wind). In CBNMS, wind speeds at 4 m/s or higher were recorded at the sea surface during approximately half of the year. Although wind speeds were highly positively correlated with sound levels in the 500 Hz frequency band ($R^2=0.86$), high wind speeds are likely related to a broadband increase of sound levels at frequencies greater than 200 Hz (Širović et al., 2013). However, in acoustic environments where many sound sources overlap in the time and frequency domains (e.g., wind, animals, and vessels) it can be difficult to extract subtle impacts of each source in the overlapping frequency ranges.

Rainfall can also be a significant contributor to underwater sound levels, but the absence of an in-situ udometer and minimal rainfall levels recorded at a nearby shore station (Bodega Ocean Observing Node) did not provide evidence to support a relationship between rainfall and ambient sound levels below 2 kHz in CBNMS.

Broader climate patterns may drive long-term temporal acoustic variability. For example, inter-annual or decadal shifts in ocean temperatures (e.g., warm water anomalies, El Niño-Southern Oscillation, the Pacific Decadal Oscillation, etc.) may affect the physical properties of underwater sound propagation or change biological features that affect the ecology of migratory and resident soniferous species in the sanctuary. Additional long-term acoustic and environmental data can be compared to these observations and used to evaluate or model the potential effects of environmental changes to the soundscape.

Finally, the central Pacific region is geologically active area, well known for high levels of seismic activity. The United States Geological Survey earthquake monitoring database (https://earthquake.usgs.gov/) revealed that seismic events recorded between October 2015 and October 2017 in the immediate vicinity of the hydrophone in the San Francisco Bay Area (including terrestrial areas) were minor (<4.0 magnitude). Although events of this size may influence sound levels at frequencies as high as 50 Hz, because earthquake activity is a stochastic process, seismic energy doesn't consistently contribute to the soundscape, and thus is likely not expressed in the monthly median power spectral density levels.

Whales are drivers of the temporal variability of low-frequency sound levels

Multiple species of baleen whales contribute to the CBNMS soundscape across a range of frequencies and time periods. Acoustic data were analyzed for vocalizations of humpback, gray, blue, and fin whales. Results of contemporaneous visual marine mammal surveys and passive acoustic data were not equivalent, with substantial differences across the four species selected for analysis. These differences highlight the ability of passive acoustic technologies to facilitate endangered and protected species monitoring and research in varying conditions. For example, when visual observers are not on effort or when conditions may preclude detection of animals at the surface, passive acoustic monitoring can provide data about the potential presence of species-specific vocalizations. The life history of each species drives the usefulness of each sampling technique at different times (e.g., seasonality of feeding-type versus reproductive function vocalizations). As observed here, humpback whales were often detected by visual and acoustic sampling simultaneously, while acoustic detections of blue whales extended into fall and winter months beyond the time period when visual observers recorded their presence within CBNMS. It is difficult to draw conclusions about gray and fin whales because gray whales were not detected acoustically, and fin whales were only seen on six days compared to the >300 days when they were heard (Figs. 5 and 6). However, the abundant acoustic detections of fin whales compared to few visual sightings further highlights the usefulness of passive acoustic monitoring for whale species that occur far offshore (see Calambokidis et al., 2015; Scales et al., 2017).

Humpback whales were acoustically detected year-round, and visually in all months but one. Humpback whale vocalizations are distributed across the frequencies sampled in this study, and often overlap with frequencies associated with vessel noise and weather. Thus, humpback whale vocalizations were less evident in the monthly sound level plots in comparison to the high energy narrower-band vocalizations of blue and fin whales. The central California coast region, including CBNMS, is the largest “Biologically Important Area” for humpback whales and they have been observed year-round in the region, although their primary seasonal occurrence is considered to be from July to November (Calambokidis et al., 2015; Ferguson et al., 2015). The observed year-round presence of humpback whale vocalizations implies high use, and may increase the likelihood of whale and vessel interactions, a resource protection priority for CBNMS (see Strategy RP-2, NOAA, 2014).

Most of the temporal variability detected in the 10-100 Hz range was due to seasonal patterns of blue and fin whale vocalizations. Consistent with previous studies of fin and blue whale song seasonality in Southern California, blue whale B-calls (song) were detected between late summer and early winter, peaking in late fall, and fin whale 20-Hz vocalizations were detected throughout the fall and winter (Lewis et al., 2018; Širović et al., 2015; Wiggins et al., 2005). However, the acoustic detections of these species are not consistent with the SEFI and

ACCESS visual observation results. Specifically, blue whales were detected by visual observers primarily in the spring and summer, while fin whales were rarely seen at all. This difference can possibly be attributed to environmental factors that may affect visual detection range, such as low-visibility and increased sea state, as well as whale behavior, including physical distance from shore, foraging vs. transiting vs. migratory behavior, and change in calling activity or type by season or behavior (e.g. social feeding-type D-calls compared to reproductive function B-calls). For example, blue whale B-call detections represent male singing behavior (reproductive function) and thus have a seasonal pattern that is offset from feeding behavior and D-calls (which is likely what was visually observed in the spring and summer)(Oleson et al., 2007; Szesciorka et al., 2020). It is also possible that the first B-call singers in the late spring or summer months were masked by other ambient sounds.

The lack of blue whale sightings in the fall and winter may be related to seasonally specific behaviors in addition to potentially lower visibility and increased sea state. Specifically, following spring and summer feeding periods, blue whales may maintain a larger geographic distance from shore with less frequent and predictable surfacing intervals, which presumably makes them more difficult for visual observers to detect but still places them within acoustic detection range (Burtenshaw et al., 2004; Irvine et al., 2019). Although a comprehensive analysis of all blue whale vocalization behavior was beyond the scope of this paper, additional comparative studies may provide further evidence to link specific behaviors (e.g., feeding, migrating) to seasons and call types in and near CBNMS.

Similarly, although gray whales were visually detected throughout the winter, spring, and summer, no migratory vocalizations (i.e., M3 calls) were detected in the acoustic data. Gray whales migrate through central California between northern feeding grounds and southern breeding grounds, usually close to shore. The M3 call has been repeatedly detected nearby in Monterey Bay (Guazzo et al., 2017) and although the hydrophone was deployed offshore, we expected that M3 calls would propagate to the hydrophone location and be detected during quiet ambient noise condition periods. While it is possible that a small number of calls were recorded in the dataset, none were positively identified on days with the highest number of visually detected gray whales. With passive acoustic monitoring, it is impossible to determine whether an animal is not detected due to behavior (not calling) or masking (calls are quieter than ambient sound). Although it was not possible to measure the propagation range of whale vocalizations in this study due to the dynamic nature of the CBNMS environment and the limitation of data collection via a single instrument, we can make assumptions based on known characteristics of the call and whale behavior. For example, the relatively low source level of the gray whale M3 call (156.9 dB re 1 μPa at 1m; Guazzo et al., 2017) likely limits the audible propagation range in this environment, and the large amount of nearby vessel traffic could more easily mask the lower frequency and source level calls. Also, gray whales can exhibit a behavioral response to exposure to vessels or other sounds associated with predators, including avoidance, change of behavior state, and change in vocalizations (Burnham and Duffus, 2019a; Dahlheim and Castellote, 2016; Malme et al., 1984; Sullivan and Torres, 2018; Tyack and Thomas, 2019). Thus, we cannot definitively determine a reason for the lack of M3 calls in the CBNMS dataset.

Understanding the seasonality of whale presence in CBNMS is important for the CBNMS mission, as it can directly inform management efforts to reduce ship strikes and entanglement. For example, since 2015 a voluntary vessel speed reduction program for the San Francisco traffic separation scheme shipping lanes (Fig. 1) has been implemented annually from May 1 through November 15, a date range that is based on historic visual observation data of higher whale abundances during that time period. Our results show that multiple species of endangered or threatened large whales are present throughout the winter well beyond that time period, which could inform future adaptive management efforts related to this topic.

Differences in acoustic detection of vocalizations across the four species of whales analyzed in this dataset provide species-specific baseline information for future studies. California is home to some of the largest shipping ports in the world, and the anthropogenic stressors of vessel presence and noise may influence the behavior of these large migratory whale species. Future integration of data that documents each species' behavioral response to noise may provide information that resource managers and policy makers can use to make decisions about species-specific conservation actions.

Vessel noise propagates into CBNMS

CBNMS does not provide refuge from vessel noise for marine mammals. The physical environment of a habitat is an important driver of the potential effects of anthropogenic noise, particularly low-frequency vessel noise (Redfern et al., 2017). Specifically, CBNMS is small relative to other west coast national marine sanctuaries, close to densely trafficked shipping lanes, and exposed to deep-ocean areas where low-frequency sound may travel from hundreds to thousands of kilometers away.

Mean and median band sound levels at 50 Hz and 100 Hz in CBNMS were extracted to compare with predicted levels in Southern California whale habitats, including the Channel Islands National Marine Sanctuary. In CBNMS, both mean and median 50 Hz sound levels were

1 dB higher (89 dB vs. 88 dB), and 100 Hz sound levels were 4 dB higher (81 dB vs. 77 dB) than the levels predicted for Southern California whale habitat (Redfern et al., 2017). In both regions, these sound levels correspond with "heavy traffic" conditions (National Research Council, 2003; Wenz, 1962), which is consistent with the high vessel activity documented in the San Francisco Bay Area (Moore et al., 2018). However, due to the physical location and environment of CBNMS, restricting vessel traffic within the sanctuary for any reason would not necessarily decrease vessel-related noise there because low-frequency sound easily propagates into the sanctuary from sources outside of the boundary.

Although there are no current regulatory statutes to limit chronic noise exposure to protected species, establishing current sound level baselines facilitates assessments of potential regulatory actions that may affect ambient noise levels within CBNMS. For example, actions to reduce ship speed may have a quieting effect on the soundscape because slower vessels are generally quieter (McKenna et al., 2013), and cooperation with NOAA's request for voluntary seasonal vessel speed reduction in the San Francisco traffic separation scheme has increased from 28% of nautical miles traveled by large ships in 2015 to 45% in 2018. Additionally, since 2018, California national marine sanctuaries, local air quality management districts in coastal California, and other partners have conducted an incentive-based program to further encourage cooperation with the slow-down request in order to improve air quality and reduce lethal ship strikes (Mobley et al., 2018). Meanwhile, other policies may increase vessel-generated sound in CBNMS; for example, the Ocean-Going Vessel Fuel Rule resulted in some carriers approaching the San Francisco Bay Area from offshore instead of using coastal routes (Jensen et al., 2015; Moore et al., 2018). Continued acoustic monitoring in CBNMS is necessary to assess changes to the ambient soundscape over time, and will provide data to facilitate regulatory efforts to balance commercial needs with the conservation of protected species and environments.

CONCLUSION

Establishing a long-term passive acoustic monitoring program in CBNMS helps meet CBNMS science goals as well as broader NOAA Office of National Marine Sanctuaries conservation research and the NOAA Ocean Noise Strategy (Gedamke et al., 2016). Specifically, continuous underwater ambient sound monitoring collects data that can be analyzed to provide assessments of biological resources and anthropogenic impacts not available through existing research and monitoring programs, as well as facilitating site goals of integrating acoustic research with additional data streams (e.g., AIS vessel tracking, Essential Ocean Variables, animal behavior studies). With these data collected in CBNMS, as well as from the two other Noise Reference Stations deployed in national marine sanctuaries along the West Coast of the U.S. (Channel Islands NMS and Olympic Coast NMS), future studies can compare the three soundscapes to assess how the similarly managed marine protected areas may be unequally affected by anthropogenic, physical, and biological sound sources, and how they may change over time and in response to management actions. For example, overlapping temporal coverage of data from the Channel Islands and Olympic Coast National Marine Sanctuaries will enable comparisons of the acoustic impact of events that may affect ocean soundscapes along the entirety of the west coast such as climate fluctuations (e.g. Pacific Decadal Oscillation, El Niño-Southern Oscillation), significant seismic or volcanic activity, and the U.S. economy (M. F. McKenna et al., 2012). Cross-sanctuary comparisons will also be possible with the Monterey Bay Aquarium Research Institute cabled MARS hydrophone in Monterey Bay National Marine

Sanctuary (Ryan et al., 2016). By investigating the sources and factors that account for the variability in these soundscapes over time and space, it may be possible to determine how place-based factors may affect each sanctuary and drive differences, as well as identify the ability of passive acoustic monitoring to detect changes in animal use, weather, and anthropogenic stress in these areas.

This first documentation of the underwater soundscape of CBNMS establishes current baseline measurements of ambient sound, monthly sound level differences, and the temporal variation of three highly vocal marine mammal species. Collecting and analyzing data from a calibrated U.S. network of passive acoustic hydrophone moorings supports broader NOAA goals of standardized soundscape monitoring over time and compared to other protected sites, and directly supports NOAA's ability to assess habitat quality, evaluate trends, and report on conditions within national marine sanctuaries.

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FIGURES

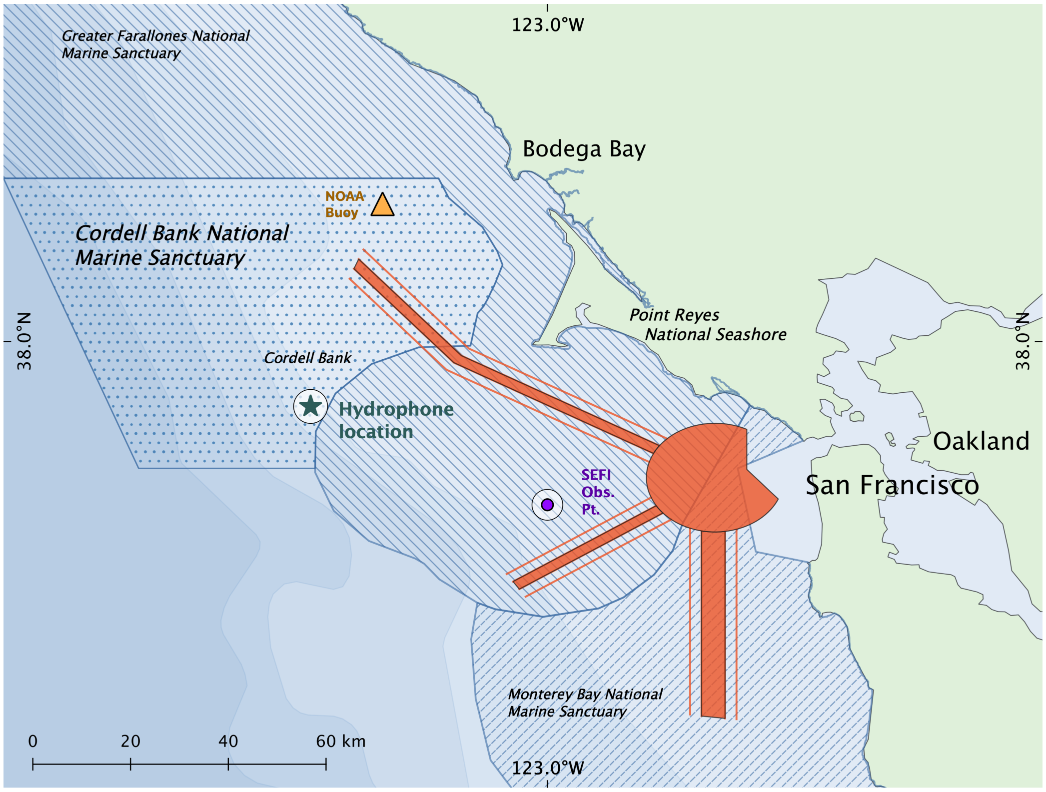

Figure 4.1. Map of hydrophone location (star) within the Cordell Bank National Marine Sanctuary (dot filled outline) and surrounding area including San Francisco Bay Area traffic separation scheme shipping lanes (opaque orange circle and lines), the Greater Farallones National Marine Sanctuary (solid diagonal line fill), and the Monterey Bay National Marine Sanctuary (dashed diagonal line fill). The Southeast Farallon Island (SEFI) land-based surveys were conducted from an island lighthouse marked by the purple dot. Wind data were collected by NOAA Station 46013 (filled triangle). Gradient shading in water (light to dark) indicates bathymetric contours at 200 m, 1000 m, 2000 m, 3000 m, and 4000 m.

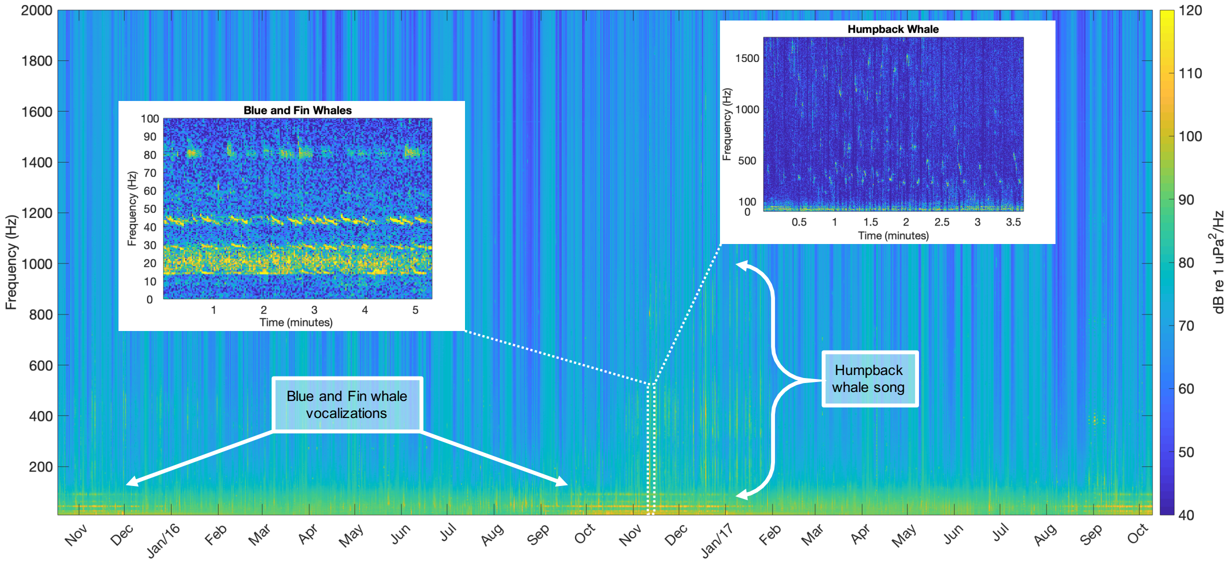

Figure 4.2. Long-term spectral average of passive acoustic data recorded in Cordell Bank National Marine Sanctuary between October 2015 and October 2017. Color (blue to yellow) indicates increasing intensity of sound (dB re 1 μPa2/Hz). Magnified spectrogram clips (inset) shows example detail of blue/fin whale (left), and humpback whale (right) vocalizations represented in the time periods indicated in the long-term spectral average.

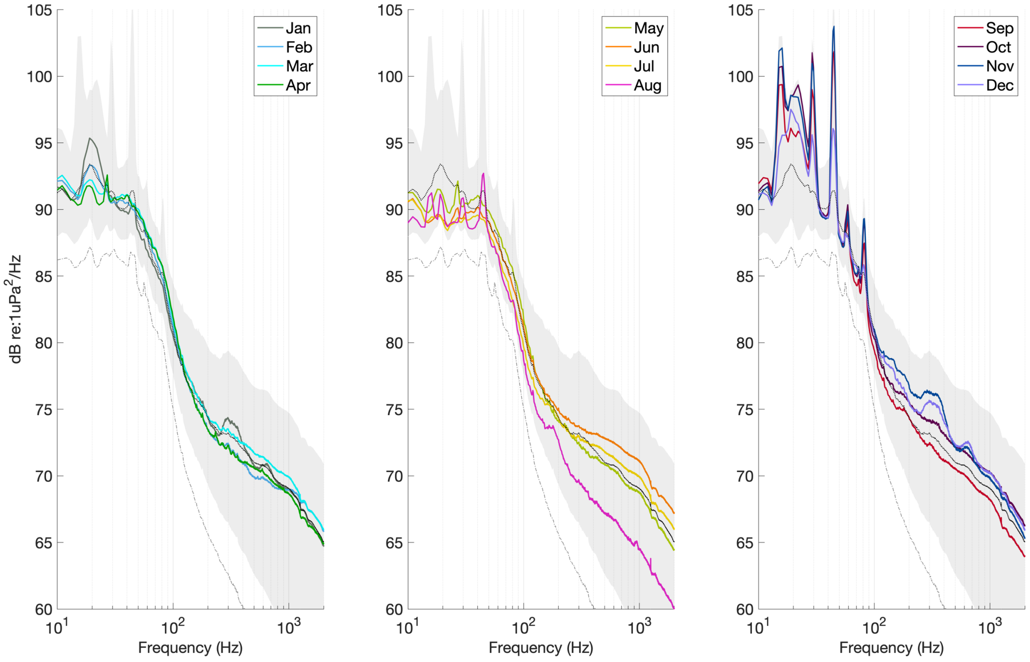

Figure 4.3. Monthly median power spectral density sound levels (mean of two-year recording) between 10 Hz – 2 kHz colored by month and plotted by season (Jan-Apr, May-Aug, Sept-Dec). In each panel, the light grey background shading shows 90th and 10th percentile power spectral density sound levels, while the central grey dashed line shows the median over the entire two-year recording. The system noise floor (1st percentile power spectral density sound levels) is indicated by the dash-dot line.

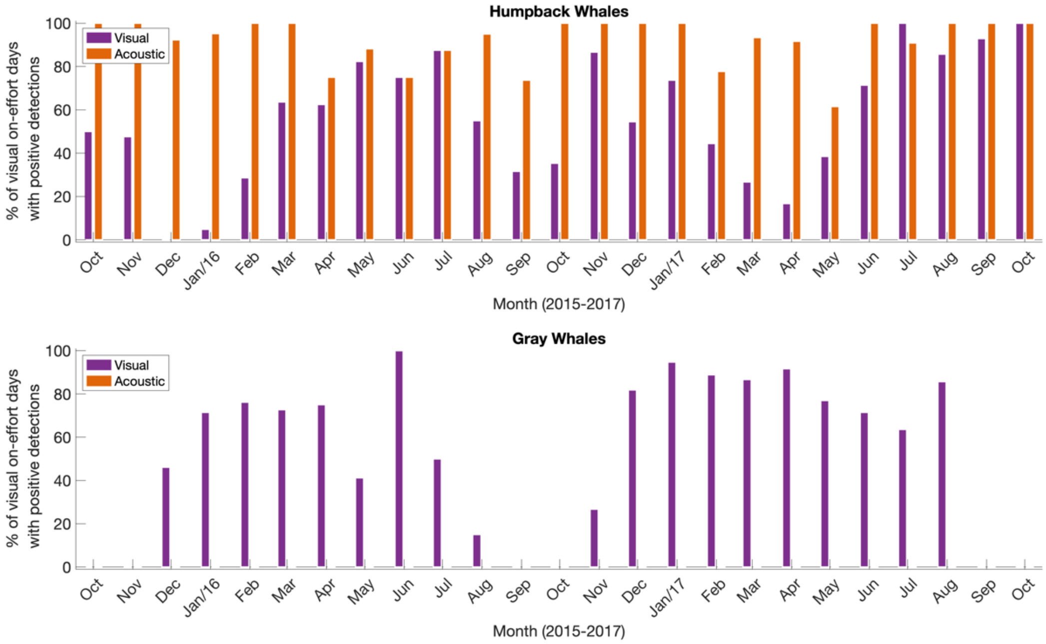

Figure 4.4. Monthly percentage of positive detections of humpback (top) and gray whale (bottom) presence via visual (purple) and acoustic (orange) methods during all on-effort visual survey days between October 2015 and October 2017. Note that there were no acoustic detections of gray whales.

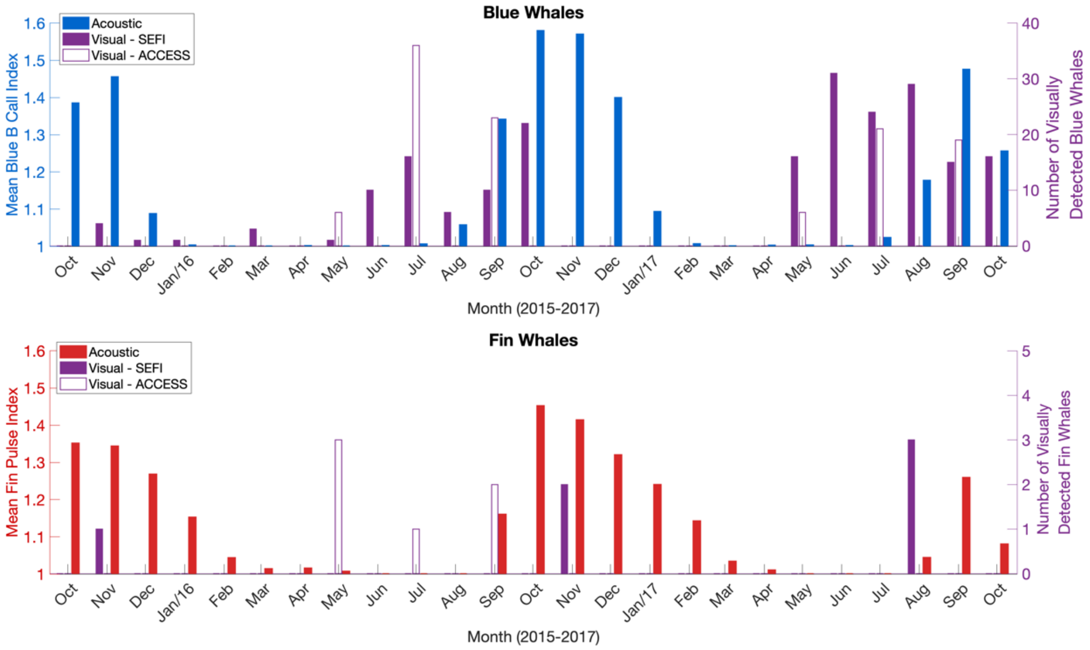

Figure 4.5. Monthly acoustic vocalization indexes (left axis) for blue whale B-call (blue bars, top) and fin whale 20 Hz pulse (red bars, bottom) alongside the monthly sum of visually detected blue and fin whales during on effort time periods (right axis) from October 2015 to October 2017. Filled purple bars represent visual observations at the SEFI field site (year-round), and open purple bars are sightings during ACCESS cruises (May, July, September only).

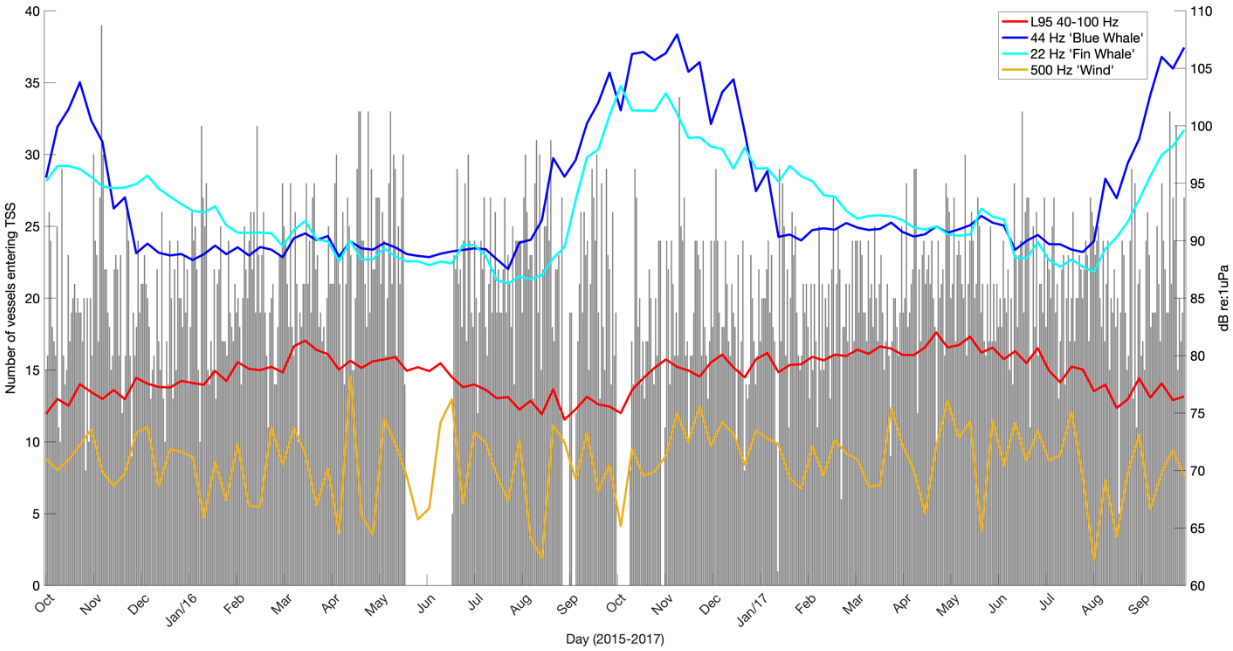

Figure 4.6. Daily sum of vessel transits (tallied by start time; gray bars, left scale). Weekly sound level measurements associated with ambient vessel noise (5th percentile of 40-100 Hz spectrum levels, dB re 1 µPa), blue whale (44 Hz, dB re 1 µPa2/Hz), fin whale (22 Hz, dB re 1 µPa2/Hz), and wind (500 Hz, dB re 1 µPa2/Hz) (right scale) are superimposed. Note data gaps in vessel transit data in 2016: June 1-30, September 8-11, October 12-19, and November 10-11.

CHAPTER 5. LINKING LARGE VESSEL TO CHANGES IN LOW-FREQUENCY UNDERWATER ACOUSTIC INDICATOR BANDS IN UNITED STATES WATERS

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ABSTRACT

Chronic low-frequency noise from commercial shipping is a worldwide threat to marine animals that rely on sound for essential life functions. Although the U.S. National Oceanic and Atmospheric Administration recognizes the potential negative impacts of shipping noise in marine environments, there are currently no standard metrics to monitor and quantify shipping noise in U.S. marine waters. However, one-third octave band acoustic measurements centered at 63 Hz and 125 Hz are used as international (Marine Strategy Framework Directive) indicators for underwater ambient noise levels driven by shipping activity. We apply these metrics to passive acoustic monitoring data collected over 20 months in 2016-2017 at five dispersed sites throughout the U.S. Exclusive Economic Zone: Alaskan Arctic, Hawaii, Gulf of Mexico, Northeast Canyons and Seamounts Marine National Monument (Northwest Atlantic), and Cordell Bank National Marine Sanctuary (Northeast Pacific). To verify the relationship between shipping activity and underwater sound levels, vessel movement data from Automatic Identification Systems were paired to each passive acoustic monitoring site. Daily average sound levels were consistently near to or higher than 100 dB re 1 μPa^2 in both the 63 Hz and 125 Hz one-third octave bands at sites with high levels of shipping traffic (Gulf of Mexico, Northeast Canyons and Seamounts Marine National Monument, and Cordell Bank National Marine Sanctuary). Where cargo vessels were less common (the Arctic and Hawaii), daily average sound levels were up to two orders of magnitude lower. Specifically, sound levels were ~20 dB lower year-round in Hawaii and ~10-20 dB lower in the Alaskan Arctic, depending on the season. Although these band-level measurements can only generally differentiate sound sources, these results demonstrate that international acoustic indicators of commercial shipping can be applied

to data collected in U.S. waters to approximate the influence of shipping as a driver of ambient noise levels, provide critical information to managers and policy makers about the status of marine environments, and to identify places and times for more detailed investigation regarding environmental impacts.

INTRODUCTION

Underwater acoustic environments are composed of many complex sound sources, collectively defined as the soundscape. Within a soundscape, underwater sound sources can be grouped into three main components: biological (e.g., whales, fish), natural physical (e.g., wind, seismic activity) and anthropogenic (e.g., vessels, sonar). Sounds emanating from these biological, physical, and anthropogenic sources vary by intensity and duration as well as frequency content and temporal occurrence. As technological advances in underwater monitoring have facilitated the ease and duration with which we can record and analyze underwater sound, researchers and conservation-oriented organizations have recognized the importance and value of monitoring underwater soundscapes (Firestone and Jarvis, 2007; Gedamke et al., 2016; McKenna, 2020; Tyack, 2018). Combined with research focused on the effects of increasing underwater sound levels on marine species (including whales, fish, and invertebrates), monitoring and documenting underwater sound levels provides critical information about the status of marine environments to managers and policy makers.

In the United States of America (U.S.), increasing noise in underwater soundscapes is both a concern and a priority research topic for the National Oceanic and Atmospheric Administration (NOAA), the government agency responsible for managing and conserving marine ecosystems and resources (Gedamke et al., 2016). Within a soundscape, species that rely on sound for critical life functions (e.g., foraging, reproduction, navigation, predator avoidance) share acoustic space with other natural, physical, and anthropogenic sound sources. These species evolved to use sound as their primary sensory modality in the presence of natural physical sound sources, but only in the past century have they had to adapt to the presence of anthropogenic sound sources. Additionally, anthropogenic sounds are often both higher in intensity and longer in duration compared to pulsed disturbances from natural physical and other biological sound sources. Decades of research on the effects of noise on marine animals has established that exposure to anthropogenic noise such as shipping, seismic airguns, construction, and sonar, can be detrimental to acoustic habitats and have negative impacts on the life history of soniferous species (Richardson et al., 1995; Thomsen et al., 2020).

Over the past few decades, NOAA, the U.S. National Park Service, and conservation-focused non-governmental organizations have prioritized monitoring ocean noise and global soundscapes, guiding underwater acoustic research efforts towards quantifying long-term sound level trends. Numerous studies have focused on quantifying and comparing changing underwater ambient soundscape conditions, and while they have arrived at different conclusions regarding the current state of underwater noise (Andrew et al., 2002; Chapman and Price, 2011; McDonald et al., 2006; Miksis-Olds and Nichols, 2016), all agree that commercial shipping is a significant and growing global noise source .

The overwhelming majority of goods traded worldwide travel by ship at some point in the journey from origin to destination. There are very few areas of the ocean that are not affected by vessel traffic, but locations that are isolated from major ports and shipping lanes are typically quieter than those areas that are not (Haver et al., 2019). Cargo vessels in particular are bigger, louder, and faster than other vessels – and the global fleet is growing rapidly both in terms of vessel number and vessel size and power (Erbe et al., 2019; Frisk, 2012; UNCTAD, 2020). In fact, technological advances and consumer demand has led to larger vessel sizes across almost all vessel types. For example, over 100 years ago the passenger ship *RMS Titanic* was the largest vessel of its time, but now is dwarfed by modern commercial passenger ships and is only half the length of the largest cargo ships sailing today. Even compared to vessels constructed around the year 2000, container ships being built today are overall four times as large and new oil tankers are nine times bigger (UNCTAD, 2020).

Vessel noise contributes to underwater soundscapes from frequencies as low as 10 Hz to as high as 10 kHz, depending on vessel size and speed (National Research Council, 2003; Wenz, 1962). Cargo shipping is prevalent throughout the northern hemisphere (Pirotta et al., 2018), contributing chronic low-frequency noise (<1 kHz) near port cities and along shipping routes. In high-use areas of heavily trafficked shipping lanes near large port cities, cumulative energy from multiple vessels can chronically increase ambient sound levels over distances of tens to hundreds of kilometers depending on environmental variables (e.g., bathymetry, water temperature profile) that facilitate sound propagation efficiency (see Urick, 1983). Chronic presence of low-frequency shipping noise can interfere with the life history of marine animals that vocalize within the same range (e.g., whales, pinnipeds). Therefore, it is important to monitor underwater sound in areas that are both in close proximity to shipping lanes and large ports and important environments for the life history of protected species (e.g., marine protected (see: Hatch et al., 2016) and biologically important areas (see: Van Parijs et al., 2015)).

In 2020, abrupt economic fluctuations and disruptions to human activities related to the COVID-19 pandemic changed the natural world, including acoustic environments (Derryberry et al., 2020; Thomson and Barclay, 2020). This disruption provided soundscape researchers the unprecedented opportunity of a natural experiment to measure how ocean sound levels may have changed in tandem with a volatile economy and shifts in human activities. However, to quantify changes for managers and policy makers as well as facilitate international research collaboration, 2020 fluctuations must be evaluated with standardized metrics and baseline data of historical conditions.

Monitoring low-frequency shipping noise can be challenging due to coinciding sound sources (e.g., whales, seals), however energy detectors are an effective and adequate tool that can be applied to determine the approximate energy contributions from broadly defined biological, anthropogenic, and natural physical sound sources. There are currently no established U.S. standards for monitoring shipping noise in U.S. waters, though 40-60 Hz is a historically-used frequency range regularly selected as proxy for all shipping noise (see: McDonald et al., 2006b; McKenna et al., 2012b; Miksis-Olds et al., 2012; Širović et al., 2013). However, in the European Union, two one-third octave bands, centered at 63 Hz and 125 Hz, are used as sound pressure level indicators for underwater ambient noise levels driven by shipping activity (EC Decision 2017/848).

Here we calculate 63 Hz and 125 Hz one-third octave band sound levels across an array of marine soundscapes to evaluate whether they are indicative of commercial shipping activity in U.S. waters. Specifically, we follow the metrics outlined in the Marine Strategy Framework Directive (European Union, 2008; Tasker et al., 2010; Van der Graaf et al., 2012) to quantify sound levels during 20 months of temporally aligned calibrated acoustic data sampled from five locations across the U.S. Exclusive Economic Zone. To estimate if the 63 Hz and 125 Hz one-third octave bands are an accurate proxy for nearby shipping activity, we compare these octave band sound levels to Automatic Identification System (AIS) vessel tracking data collected from each monitoring location. Since 2015, the U.S. Coast Guard requires most commercial, towing, passenger, and fishing industry vessels to carry AIS transponders[2] which emit position and identification information that can be read by satellite and terrestrial receivers. These individual data points can be composed to provide records of individual vessel movement throughout the ocean. The five sites selected for comparison span all regions of the U.S. Exclusive Economic Zone in the North Atlantic, Gulf of Mexico, Western Arctic, Northeastern Pacific, and North Pacific, and include a National Marine Sanctuary and a National Marine Monument, and are all established monitoring sites included in the NOAA and National Park Service Noise Reference Station Network (Haver et al., 2018).

MATERIALS AND METHODS

Passive Acoustic Instrumentation

Temporally overlapping acoustic data were collected from 1 January 2016 through 31 August 2017 at five locations dispersed throughout the U.S. EEZ (Fig. 1): Beaufort Sea, Alaskan Arctic (72.44° N, 156.55° W), North of Oahu Island, Hawaii (22.33° N, 157.67° W), Gulf of Mexico (28.25° N, 86.83° W), Northeast Canyons and Seamounts Marine National Monument, North Atlantic (39.01° N, 67.27° W), and Cordell Bank National Marine Sanctuary (37.8° N, 123.4° W). Each site was selected for inclusion based on general conservation concerns for potential use conflicts between humans and endangered marine species, as well as site-specific management needs such as shifting seasonal sea-ice conditions in the Arctic due to climate change. The five sites are all part of a calibrated U.S.-wide system of autonomous underwater hydrophone (AUH) moorings, the NOAA/National Park Service Noise Reference Station Network (Haver et al., 2018). To maintain comparable datasets, a single calibrated AUH was

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[2] https://www.navcen.uscg.gov/?pageName=AISRequirementsRev. Last accessed 10/01/2020

deployed at each site. Each AUH was programmed to sample at 5 kHz and suspended from a bottom-mounted mooring in the deep sound channel (see Haver et al., 2018 for equipment details). During the 20-month data collection period, approximately 13 months of data gaps exist across three sites (Hawaii: 23 December 2016 – 31 August 2017, Gulf of Mexico: 14 March 2016 – 12 April 2016, and Northeast Canyons and Seamounts National Monument: 1 January 2016 – 25 April 2016). There were no data gaps in the data collected in the Beaufort Sea or Cordell Bank National Marine Sanctuary. In sum, 87 months of acoustic data were included in analysis.

Quantifying Sound Levels

To calculate 63 Hz and 125 Hz one-third octave band (TOB) sound levels, hourly averaged narrow-band (1 Hz) power spectral density levels were summed across the two TOBs of interest (56 Hz -71 Hz and 112 Hz – 141 Hz, respectively) and converted to decibels. Hourly TOB sound levels (dB re 1 μPa^2, hereafter dB) were averaged (mean) in 24-hour bins to obtain daily values. A 14-day running mean was calculated for each site from daily mean values.

Extracting AIS vessel tracking data

Buffer radius

Satellite and terrestrial-based AIS data records from January 2016 through August 2017 within a 20 km circular buffer around each AUH deployment location were queried for activity mirroring the timeline of acoustic data collection. As vessel noise is not directionally consistent, and also varies significantly with speed and tonnage (Urick, 1983; Wenz, 1962), we selected a conservative buffer radius to maximize the likelihood that a commercial shipping vessel tracked within the buffer via AIS would also increase the 63 Hz and 125 Hz TOB sound levels at a hydrophone site. Using the passive sonar equation with the assumption of simple cylindrical spreading, 20 km was determined to be the approximate range that noise from a typical commercial shipping vessel (see: Gassmann et al., 2017) would be received at the hydrophone in excess of ambient sound levels at all of the five unique acoustic environments. Although vessel movement from further afield could be detected above ambient sound under certain conditions at some locations (e.g., deep-water convergence zone could amplify vessel noise), limiting the standardized buffer to 20 km across all sites minimized probability of tracking vessel movement that may not impact the sound field at the hydrophone (Bassett et al., 2012).

Following initial data query, results of vessel movement within the Beaufort Sea buffer zone was determined to be misleading due to distance between the hydrophone and the majority of regional vessel activity occurring very close to shore. Therefore, a secondary buffer of 150 km (inclusive of the entire distance from Alaskan shoreline to the hydrophone site) was queried for the Beaufort Sea site. Using the passive sonar equation, we calculated that transmission loss of a signal in the study frequency bands would be ~75 dB over 150 km at the Beaufort Sea hydrophone depth of 500 m. Given the distinctive acoustic environment of the Beaufort Sea, inclusion of a second expanded buffer was determined to be important for capturing vessel presence at this site; however, the buffer size for other sites was not revised as 150 km is generally too large a radius to reliably detect vessel activity over ambient sound levels in more densely trafficked regions.

Vessel types

AIS records for all Type A and Type B[3] vessels (including ships > 300 gross tons and commercial passenger vessels) within each buffer zone were queried into unique transits defined by the start and end times for entering and exiting the buffer radius around each recording site. In addition to start and ends time, we collated the name, size (length, tonnage), and vessel type for each entry. The nineteen vessel types were grouped into nine categories for analysis according to NOAA Marine Cadastre codes[4]: tanker, fishing, cargo, towing (including tug vessels), pleasure (including sailing vessels), passenger, other (including vessel types: high-speed craft, search and rescue, military, law, dredging, Resol-18, spare, and reserved), and unknown. Vessel names for all entries with the vessel type "Unknown" were queried on in the Marine Traffic[5] database to identify the type and relabeled. In a few instances no vessel type was available, and those entries remain classified as "Unknown".

Monthly vessel activity summaries

The monthly sum of vessel transits within the buffer radius of each hydrophone site were identified by querying the AIS data for unique results of date, vessel name, trip segment, and start and end time. Entries were flagged and ultimately excluded if the transit time or speed indicated an AIS transponder malfunction (e.g., impossibly fast speed over ground or distanced traveled) or in the case of duplicate entries where both satellite and terrestrial AIS logged a vessel's movement. The total sum of vessel transits, distance traveled within the buffer (nautical

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[3] https://www.federalregister.gov/documents/2015/01/30/2015-01331/vessel-requirements-for-notices-of-arrival-and-departure-and-automatic-identification-system. Last accessed 10/01/2020.

[4] https://coast.noaa.gov/data/marinecadastre/ais/VesselTypeCodes2018.pdf. Last accessed 08/26/2020.

[5] https://www.marinetraffic.com. Last accessed 08/26/2020.

miles), and time spent within buffer zone (counted in cumulative days) were calculated for each site and categorized by vessel type.

Environmental Variables:

Sea Ice Coverage in the Beaufort Sea

Monthly records of sea ice extent at the Beaufort Sea site (72.443° W, 156.5517° N) from January 2016 through August 2017 were retrieved from the University of Alaska Historical Sea Ice Atlas (University of Alaska, 2020).

Wind Noise

Although wind can significantly increase sound levels in underwater soundscapes via surface agitating, the impact to ambient sound levels is primarily detected >500 Hz (though sometimes as low as 100 Hz) (Širović et al., 2013; Urick, 1983; Wenz, 1962). Because the 63 Hz and 125 Hz TOBs measured in this comparison are primarily below that threshold, we did not take extra steps to quantify the acoustic impact of wind in this comparison.

RESULTS

Sound Levels

Daily 63 Hz and 125 Hz one-third octave frequency band (TOB) sound levels measured in the Gulf of Mexico, Northeast Canyons, and Cordell Bank were of higher energy compared to Hawaii and the Beaufort Sea (Fig. 2). Biweekly running mean TOB sound levels for both 63 Hz and 125 Hz varied by ~5 dB throughout the 20-month time period at the Northeast Canyons and Hawaii sites, and by ~10 dB at the Cordell Bank site. In the Gulf of Mexico and Beaufort Sea, 63 Hz and 125 Hz TOBs had a range of ~15 dB across time periods. In the Gulf of Mexico, 63 Hz and 125 Hz TOB sound levels were highest between January-March 2017, and lowest in

January-March 2016 in the 63 Hz TOB and July-August 2017 in the 125 Hz TOB. Additionally, the highest sound levels measured in the Gulf of Mexico were also the highest sound levels observed across all sites. Across all sites, 63 Hz and 125 Hz TOB sound levels varied over the widest range of dB in the Beaufort Sea; at that site sound levels were highest in both boreal spring (March-April) and late summer to early fall (August-October), and lowest in early summer (June-July) and November in both 2016 and 2017. The lowest sound levels measured in the Beaufort Sea were also the lowest sound levels observed across all sites (Supplementary Table 1).

AIS Vessel Tracking

Monthly vessel activity at each site was summarized by the number of transits within a buffer, total nautical miles traveled within a buffer, and total time spent within a buffer (Figs. 3 and 4). The Gulf of Mexico site had the highest number of overall transits, more than double the number of cargo transits, and five times as many tanker transits as any other site (Figs. 3 and 4). The average number of monthly vessel transits in the Gulf of Mexico was 91, with a minimum of 59; eight months had over 100 transits each (Fig. 3). Cordell Bank had the second highest number of transits, averaging 41 transits per month, excluding an outlier of 166 transits observed in August 2017. Detailed review of AIS data revealed that half of the vessel transits detected in August 2017 were from three tug vessels transiting back and forth through the buffer repeatedly (83 transits). Monthly mean transits were comparatively much lower at the other three sites (Hawaii -14 transits/month, Northeast Canyons – 9.2 transits/month, Beaufort Sea - 0.5/month). With the increased 150 km buffer radius in the Beaufort Sea, the monthly mean number of transits increased to 34.5, still lower than the monthly mean number of transits in both the Gulf of Mexico and Cordell Bank.

Distance traveled and total time within each site's buffer radius, in additional to total number of transits, varied across the nine vessel types identified from the AIS data (Fig. 4). The Gulf of Mexico, Cordell Bank, and Northeast Canyons saw mostly cargo vessels in transit. However, at these three sites, cargo vessels did not travel the most miles, nor did they spend the most time within the buffer. In the Gulf of Mexico and Cordell Bank, tug vessels traveled farther and spent more time within the buffer, while at Northeast Canyons, tanker vessels traveled comparatively further and spent more time within the buffer compared to cargo vessels. In Hawaii, fishing vessels were the most common, traveling more miles and also spending the most time inside the buffer area. Tankers were the second most common vessel type detected in Hawaii across all three variables of total transits, miles traveled, and time spent. The eight vessels that were detected within the Beaufort Sea 20 km radius were either fishing (two vessels) or classified as other, including three military, one search and rescue, one research, and one icebreaker. Within the Beaufort Sea 150 km radius, tug vessels transited through the larger buffer more than other vessel types.

Environmental Variables: Sea Ice Coverage in the Beaufort Sea

The Beaufort Sea is the only study site affected by seasonal ice coverage, which drives presence of both biological and anthropogenic sound sources (Jones et al., 2014; Moore and Laidre, 2006; Roth et al., 2012; Southall et al., 2020), as well as contributing significantly to the soundscape during seasonal freeze-up and melting (Matsumoto et al., 2014; Menze et al., 2017; Milne and Ganton, 1964; Urick, 1971). Monthly sea ice conditions at the Beaufort Sea site

(72.443° W, 156.5517° N) varied seasonally, with peak ice coverage in the boreal winter and spring and open ocean in the late summer through early fall. Specifically, sea ice was compact/very close pack from January 2016 through May 2016, and December 2016 through May 2017. In June and July 2016, November 2016, and June 2017 sea ice was open drift/close pack. During July 2017 conditions were open water/very open drift, and from August 2016 through October 2016 and in August 2017 no sea ice coverage was detected (University of Alaska, 2020).

DISCUSSION

Our results suggest that internationally standardized sound level indicators for commercial shipping activity can be applied to acoustic recordings of U.S. marine environments to assess the relative contribution of shipping (primarily cargo, but also tanker) activity within the soundscapes. By separating vessel activity by vessel type, we were able to observe that 63 Hz and 125 Hz one-third octave frequency band (TOB) sound levels were higher at the sites with cargo vessel activity within the buffer radius compared to sites with much less or no cargo vessel activity ($R^2=0.6$, Supplemental Fig. 1). Furthermore, we found that at the sites with cargo vessel activity, the TOB sound levels measured were consistently near to or higher than the international 100 dB threshold for environmentally healthy levels of low-frequency continuous sound (Tasker et al., 2010). We found that the three sites with consistent cargo vessel activity met or exceeded this sound level threshold year-round, whereas sound levels were lower at sites with very limited or no cargo vessel activity.

Commercial Shipping Traffic Increases Indicator Sound Levels

The sum of vessel activity for all vessel types (i.e., transits, nautical miles traveled, and/or time spent) within the buffer did not necessarily predict sound levels. For example, at the Hawaii site, more vessel activity was observed compared to the Northeast Canyons site, yet the sound levels measured at the Northeast Canyons site were much higher than at the Hawaii site. This difference was driven by the type of vessel active at each of these sites, as the vessel activity within the Northeast Canyons buffer radius was nearly entirely shipping (cargo and tanker), whereas in Hawaii fishing vessels were the majority of tracked vessel activity; they were nearly 18 times more common than cargo vessels. The specific frequencies included in the 63 Hz and 125 Hz center frequency TOBs are better predictors of cargo vessel activity compared to other vessel types due to the average size and speed of cargo vessels. Cargo vessels (i.e., dry goods transport) are the largest vessel type transiting the ocean, followed closely by tankers, which only transport liquid goods. In general, larger vessels generate lower frequency sound and vessels moving at faster speeds generate more acoustic energy (i.e., higher sound levels) (Gassmann et al., 2017; Veirs et al., 2018). To apply a TOB measurement to predict movement of comparatively smaller vessels (e.g., pleasure, fishing vessels), higher frequencies need to be measured (ANSI/ASA, 2009).

Indicator Band Sound Levels Increase with Proximity to Commercial Shipping Lanes

The AIS records were limited to a standardized 20 km buffer radius around each hydrophone, however, it is likely that noise from very large and fast-moving vessels (and other high-energy sound sources) could propagate to the hydrophone from outside the buffer. The 20 km range was selected to ensure that all vessel sound within the radius would be detected even at the sites with highest ambient sound levels. In this comparison, the 63 Hz and 125 Hz TOB sound levels measured at the Northeast Canyons sites were higher than those measured at the Cordell Bank site, but more vessel movement was observed at the Cordell Bank site compared to the Northeast Canyons (Fig. 4). This difference can be at least partially attributed to the specific location of each site in relation to shipping lanes and major port cities; the Northeast Canyons site is in very deep water (~3500 m) in the North Atlantic, offshore of New York City, and the Cordell Bank site is on the continental shelf in the North Pacific, within approximately 100 km of the entrance to the San Francisco Bay. Because of the proximity of the Cordell Bank site to shore, more vessels traveled within the narrow buffer radius, but at a quieter, slower speed as they approached port. In comparison, the offshore location of the Northeast Canyons site is in listening range of many louder, faster-moving vessels that did not transit through the buffer radius. This listening range is also impacted by the immediate environment of the hydrophone site. For example, compared to the Cordell Bank site on the continental shelf, sound propagates more efficiently in the deep, shelf-adjacent environment of the Northeast Canyons site. Additionally, the precise location of the Northeast Canyons site between commercial shipping lanes may have created a convergence zone at the hydrophone. In this case, the hydrophone would sample concentrated acoustic energy from vessels, similar to if the vessel sound sources originated much closer to the hydrophone (Urick, 1983). While these variations of the immediate environments of each monitoring site complicate cross-site comparisons, there is minimal impact to our ability to track within site trends unless shipping routes change.

Seasonal and Location-Specific Non-Vessel Sound Sources May Increase Indicator Sound Levels at Specific Times

Seismic Airgun Activity

Vessels are not the only chronic, anthropogenic low-frequency contributors to underwater soundscapes. In addition to the higher amounts of shipping traffic likely transiting just outside of the buffer radius (but within acoustic detection range), nearly 250 hours of seismic airguns were detected in the North Atlantic near the Northeast Canyons site in 2016 alone, likely increasing sound levels recorded at the Northeast Canyons site (Van Parijs, unpublished data; see methods in Wiggins et al., 2016). Arrays of seismic airguns generate, for weeks or months at a time, intense and repetitive low-frequency sounds (via large air bubbles) that are utilized to locate oil and gas under the seafloor, and have been repeatedly linked to increased sound levels in the Atlantic and the Gulf of Mexico (Haver et al., 2017; Klinck et al., 2012; Nieukirk et al., 2012; Wiggins et al., 2016).

Across the sites included in this comparison, the highest sound levels were recorded in the Gulf of Mexico. Although we did not specifically analyze the data for the presence of seismic airguns, it is highly likely that seismic airguns contributed to the 63 Hz and 125 Hz TOB sound levels measured at the Gulf of Mexico site in addition to shipping vessel activity (Wiggins et al., 2016). In the Gulf of Mexico, sound levels were highest in both TOBs between January and March 2017, while the lowest levels in the 63 Hz TOB were observed between January and March 2016, and from July and August 2017 in the 125 Hz TOB. As the Gulf of Mexico is a high-use area for both shipping and seismic airguns, these seasonal differences are likely related to fluctuation of those activities. Although the Gulf of Mexico is home to many marine species, large whales that vocalize within the 63 Hz and 125 Hz TOBs are rare (Garrison and Aichinger

Dias, 2020; Sirovic et al., 2014). Additionally, hurricanes are common between late May and early November and have the potential to impact low-frequency soundscapes; however, no hurricanes overlapped with the times of elevated sound levels in the Gulf of Mexico (NOAA National Hurricane Center, 2017).

Seasonal Impact of Whale Vocalizations

Mysticetes (baleen whales) contributed to sound levels within the 63 Hz and 125 Hz TOBs across the environments included in this study. Energy band measurements such as TOBs are often an efficient and reliable method of identifying and monitoring persistent sound sources; but the presence of multiple sound sources with overlapping frequency ranges (such as whales and vessels) can impede identification of individual sources at fine temporal scales and hinder the ability to detect what is driving differences over space and time. However, unlike shipping vessels, the highest-intensity whale vocalizations that overlap the frequencies of the 63 Hz and 125 Hz TOBs are seasonal rather than year-round contributors to the soundscape. For example, Northeast Pacific blue whale (*Balaenoptera musculus*) vocalizations (specifically A and B call types) overlap with the frequencies of commercial shipping noise and are the likely cause of the increased 63 Hz TOB sound levels we observed at the Cordell Bank site from October through December (Haver et al., 2020). Depending on the number and location of the whales and vessels, and the relative location of the hydrophone to the sound sources, the whales and vessels can overshadow each other. However, by nature the loudest reproductive-function vocalizations of migratory species like whales are a seasonal behavior. Therefore, it is often possible to discern when these biological sounds increase sound levels compared to vessel-generated sounds that are less likely to vary on the same predictable seasonal time scales unless extraordinary conditions occur such as a major storm or economically-related supply and demand disruptions (M. F. McKenna et al., 2012; Thomson and Barclay, 2020).

Vocalizations of other mysticetes that overlap with the frequencies of the 63 Hz and/or 125 Hz TOBs across the different sites in this comparison are either less intense than vessel sound (e.g., gray whales (*Eschrichtius robustus*); Burnham and Duffus, 2019), uncommon (e.g. Bryde's whale (*Balaenoptera edeni*); Garrison and Aichinger Dias, 2020), or distributed across a wider range of frequencies (e.g. humpback whales (*Megaptera novaeangliae*); Au et al., 2006) such that the energy within the shipping indicator bands is likely to be minimal. These species-specific differences contribute to the reliability of both shipping indicator band sound levels to measure vessel activity, as opposed to whale vocalizations. For example, the Hawaii site is near winter breeding habitat for humpback whales (*Megaptera novaeangliae*) (Palacios et al., 2019), where males display long, complex, and high-intensity vocalizations known as song (Payne and McVay, 1971). Yet, the acoustic properties of song are such that the energy is distributed across frequencies between ~50 Hz–1.5kHz (fundamental frequencies), so despite the repetitive vocalization behavior, the majority of singers did not impact averaged sound levels in the 63 Hz and 125 Hz TOBs. Finally, the location of the Hawaii site north of Oahu is separated from the highest density humpback whale wintering habitat by volcanic islands. While it is possible for sound to travel around these submerged masses, significant energy is lost during propagation from the humpback whale source to the spatially distant hydrophone receiver, such that the vocalizations would be less likely to increase sound levels above ambient.

Sea Ice and Arctic Climate

The Beaufort Sea site is located within the Arctic circle and is the only site in this comparison to be seasonally affected by sea ice coverage, which can significantly impact underwater sound levels by physically blocking vessels, as well as limiting wave and wind noise. Specifically, when sea ice is compact, it has a noise-damping effect at the air-sea barrier, compared to relatively noisier time periods of freeze up, melt, and open ocean. Changing sea ice conditions also drive presence of specific marine mammal species throughout the year (Southall et al., 2020). These non-anthropogenic sources likely contribute to sound levels within the 63 Hz and 125 Hz TOBs, affecting the reliability for isolating sound impacts from vessel activity (Blondel et al., 2020; Southall et al., 2020). Nevertheless, at this site we observed the highest sound levels within the 63 Hz and 125 Hz TOBs (over 100 dB) during August and September 2016, corresponding to the times that the highest number of vessel transits was detected in the area. In August 2017 the sound levels were slightly lower, matching a reduction in vessel transits compared to the previous year. The lowest sound levels were observed below 90 dB in January-February, May-July, and November corresponding with times of compact or close pack ice (University of Alaska, 2020). An increase in sound levels in March (~5 dB at peak) and April (~7 dB at peak) was likely driven by bearded seal (*Erignathus barbatus*) vocalizations, which fall within the frequency range of the 63 Hz and 125 Hz TOBs (Risch et al., 2007) and have been observed to peak during April (Jones et al., 2014). Bowhead whales (*Balaena mysticetus*) migrate to and from a wintering area in Bering Sea to a summer feeding area in the eastern Beaufort Sea in the spring and late fall when sea ice conditions are moderate to lightly packed (Moore and Laidre, 2006). Bowhead whale vocalizations are generally between 50 Hz – 200 Hz, and thus likely increased sound levels at this site during migration passages in April-May and

October-November (Clark and Johnson, 1984; Moore et al., 2010; Stafford et al., 2018), accounting for observed sound level increases during months with no vessel movement.

Conservation Concerns of Anthropogenic Noise in Marine Protected and Biological Areas of Interest

Commercial shipping noise and noise from other vessel types that generate high-intensity low-frequency sound is a high-priority conservation focus because of the frequency overlap between vessel noise and mysticete vocalizations. All of the sites included in this comparison are important animal habitats; two are designated as either Marine Protected Areas (Northeast Canyons and Seamounts Marine National Monument and Cordell Bank National Marine Sanctuary), and the other three are within habitats that are important to large whale vocal behavior (Gulf of Mexico, Hawaii, Beaufort Sea). Within U.S. waters, NOAA is responsible for managing marine environments to conserve, among other things, habitat for threatened and endangered species; increased ocean noise is a domestic and international marine pollution issue of high concern (Gedamke et al., 2016; MSFD Common Implementation Strategy Technical Group on Underwater Noise (TG-Noise), 2019).

For decades, passive acoustic monitoring tools have offered relatively economical and low-environmental impact means of documenting underwater sound levels and sources (Au and Hastings, 2008; National Research Council, 2003; Richardson et al., 1995). These technological developments complement decades of marine animal research that show anthropogenic noise can have dramatic behavioral and physiological impacts on mammals, fish, and invertebrates and we continue to learn more through numerous ongoing efforts across multiple scales and species. For example, determining species-specific impacts of noise is essential to defining the thresholds of problematic noise exposure. Simultaneously, it is critical to document current baselines of sound levels and drivers of these levels in a standardized way so that coordinated conservation efforts can be implemented as needs are revealed.

Unlike take regulations for short-duration, high-intensity sounds, currently the U.S. does not have specific conservation policies regarding chronic ocean noise. In part, this is because it is challenging to control for chronic noise in observational research to test for behavioral and/or physiological changes of protected marine mammals in response to exposure. Although scientists, managers, and policymakers agree that chronic noise is problematic for marine animals, specific impacts are difficult to isolate, and the scope and severity of the issue remains uncertain. Additionally, despite decades of research, many questions remain regarding the life history of marine mammals. For example, since we do not know the distances over which whales need to communicate, we cannot fully understand how increasing chronic background noise may affect sensory capacity. Working in tandem with research on the effects of noise on marine species, efforts to monitor underwater noise conditions and track potential changes over time supports mutual goals to protect marine mammals and their habitats.

Building on ecosystem-based management conservation strategies, monitoring acoustic pressure indictor bands as a proxy for commercial shipping traffic could be combined with established marine mammal monitoring programs. For example, acoustic vessel monitoring data streams can be evaluated in tandem with real-time marine mammal alert networks (e.g., Baumgartner et al., 2020) to provide managers with estimated likelihood of whale-vessel spatial and temporal overlap. Adaptive management of high animal- and anthropogenic-use areas could simultaneously maximize conservation and economic priorities. Similarly, coordination of vessel noise monitoring metrics at established cabled real-time ambient sound monitoring sites (e.g. Ryan et al., 2016; Vancouver Fraser Port Authority, 2017) can produce comparable results of long-term ambient sound level trends.

Passive Acoustic Monitoring is More Informative with Standardized Reporting

Coordinated long-term passive acoustic monitoring provides data on the status and trends of ambient sound levels, which can be compared to animal research to provide clues about how different species may respond to changes in their acoustic environments. The first step towards these research efforts is to establish monitoring sites and consistent data collection methods, as well as standardized metrics for comparison across spatial and temporal scales. The European Union standard pressure indicator frequency bands are an efficient and straightforward internationally accepted starting point for these comparisons. Additionally, widespread adoption of standardized metrics will simplify comparisons across different recording platforms and research projects and can provide managers with information that is necessary for making decisions about protecting acoustic habitats (for example, see: IQOE, 2019). Current international standards for ambient sound levels dictate that sound pressure in the indicator frequency bands should not exceed an average of 100 dB re 1µPa or the baseline levels within the indicator bands over a year (Tasker et al., 2010). Establishing baseline levels in U.S. waters is the first step towards implementing comparative methods for widespread monitoring of ambient noise associated with commercial shipping.

CONCLUSION

Although a perfect proxy for measuring the impacts of commercial shipping activities in soundscapes will likely never exist, the 63 Hz and 125 Hz TOB pressure indicator bands provide an initial step to identifying when and where to direct more thorough investigations. Coordinated metrics can facilitate comparisons across different monitoring platforms and research projects to compose a global picture of how human activities impact the ocean (Chou et al., 2021). Additionally, acoustic monitoring can be utilized to track the efficacy of vessel designs with quieter, more efficient propulsion technology, even as consumer demand continues to drive increases in fleet size and carrying capacity. The baselines we lay forth here are a starting point to demonstrate the application of international pressure indicators to approximate the acoustic impact of commercial shipping activity in U.S. territorial waters.

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FIGURES

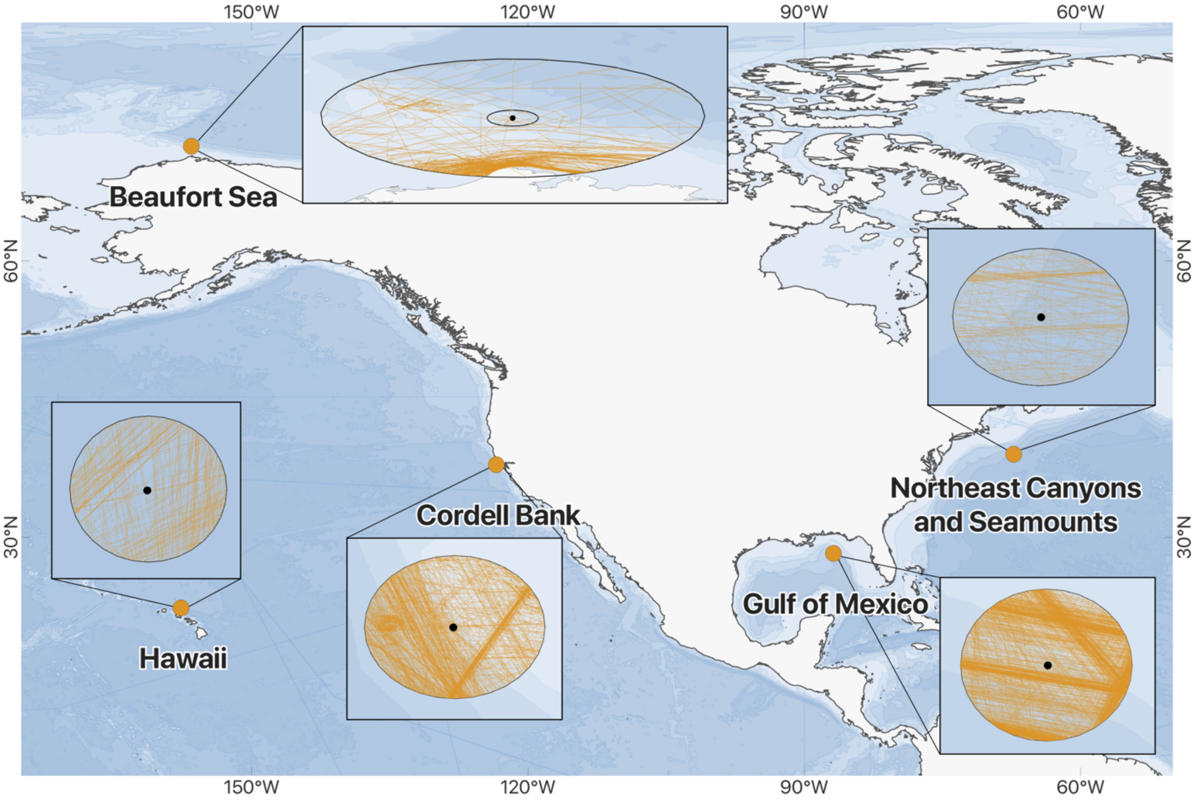

Figure 5.1. Locations of the five NOAA/NPS Noise Reference Station Network sites where passive acoustic and vessel transit data were sampled. A magnified image for each site shows AIS vessel track lines (orange) within each 20 km buffer radius, except at the Beaufort Sea site where both 20 km and 150 km buffer circles are shown (see methods). The small black dot within each buffer represents the location of the hydrophone. Note that the shape of each buffer varies due to map projection.

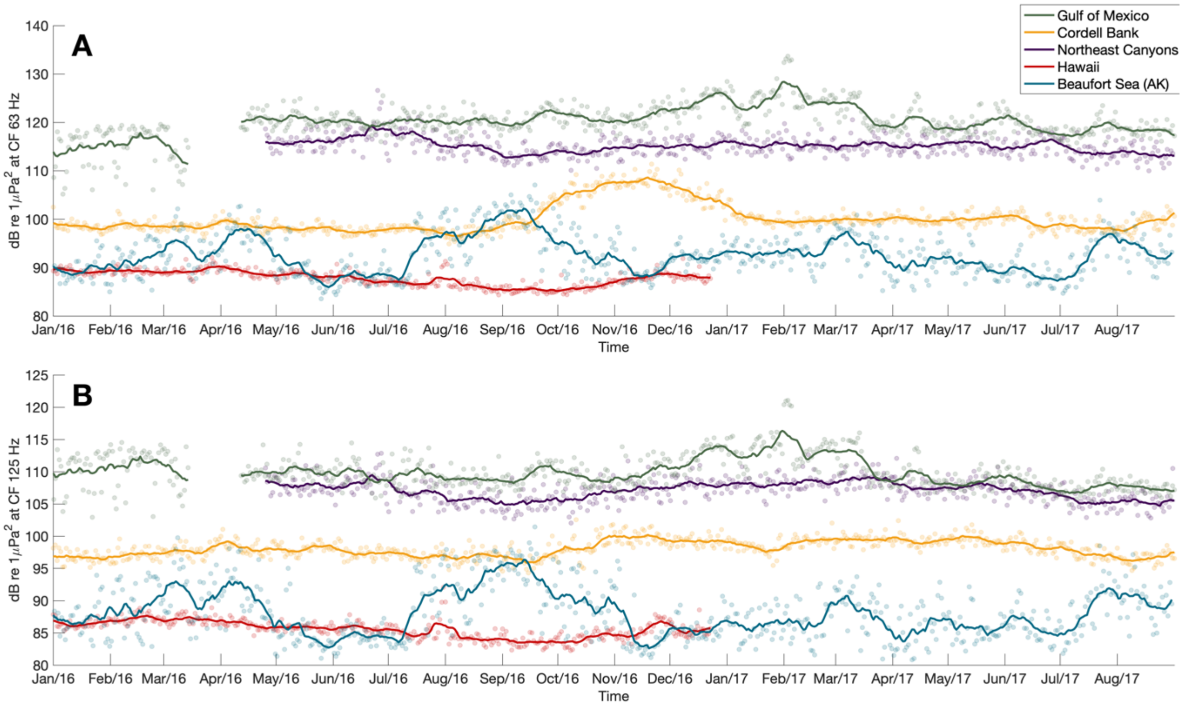

Figure 5.2. Daily one-third octave band sound pressure level measurements for 63 Hz (A) and 125 Hz (B) center frequencies (scatter plot) and overlaid biweekly moving average (mean) for five deep-water autonomous underwater hydrophone moorings from January 2016 through August 2017. Each mooring site is color-coded: Gulf of Mexico-green, Cordell Bank National Marine Sanctuary-yellow, Northeast Canyons and Seamounts National Monument-purple, Hawaii-red, Beaufort Sea Alaskan Arctic-blue.

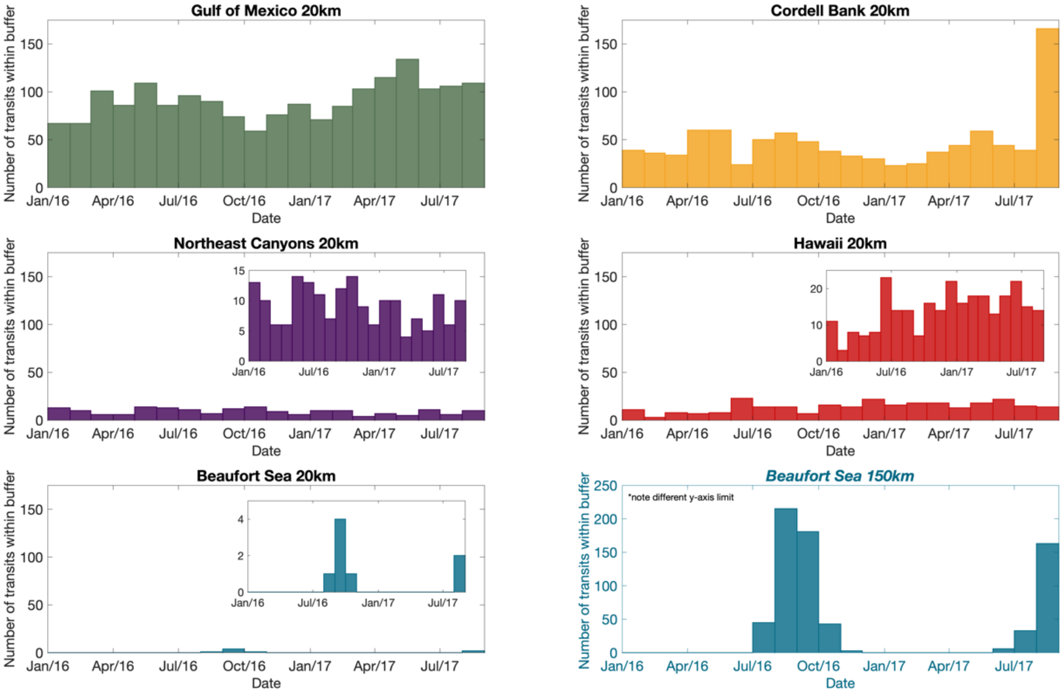

Figure 5.3. Site-specific histograms of the monthly sum of unique vessel transits within the buffer zone at each of the five deep-water autonomous underwater hydrophone moorings from January 2016 through August 2017. Inset histograms with lower y-axis limits show detail for the Northeast Canyons and Seamounts National Monument, Hawaii, and Beaufort Sea 20 km buffer zones. Results from the Beaufort Sea 150 km buffer zone are included in the bottom right panel histogram with blue axis and text.

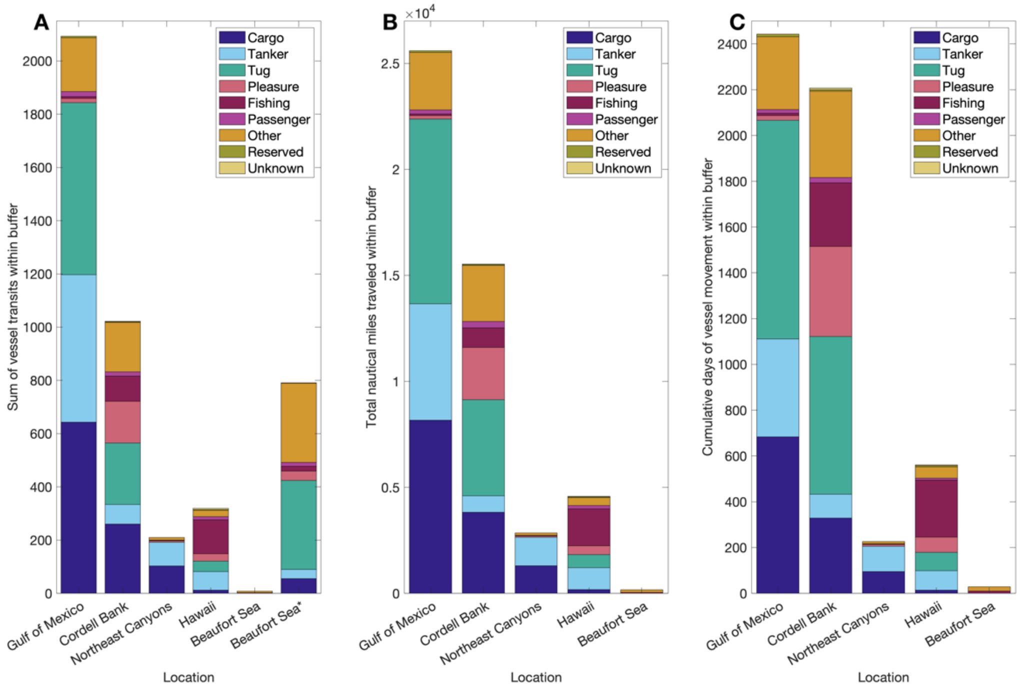

Figure 5.4. Site-specific histograms of the monthly sum of unique vessel transits (A), total distance traveled in nautical miles (B), and cumulative time measured in days (C) within the buffer zone at each of the five deep-water autonomous underwater hydrophone moorings from January 2016 through August 2017. Each vessel type is color-coded: cargo-indigo, tanker-cyan, tug-teal, pleasure-rose, fishing-wine, passenger-purple, other-ochre, reserved-olive, unknown-sand. Note that the Beaufort Sea 150km buffer zone is included in the plot of number of transits (A) denoted with asterisk, but not on the total distance (B) or sum of time plot (C) due to the unequal comparison of the amount time spent within 150km compared to 20km for the other sites.

SUPPLEMENTARY MATERIAL

Site	Median 63 Hz TOB	Median 125 Hz TOB	Max 63 Hz TOB	Max 125 Hz TOB	Min 63 Hz TOB	Min 125 Hz TOB
Gulf of Mexico	110.65 dB	119.96 dB	122.22 dB	133.65 dB	102.45 dB	105.17 dB
Cordell Bank	97.99 dB	99.46 dB	107.27 dB	111.55 dB	93.26 dB	94.86 dB
Northeast Canyons	107.35 dB	114.88 dB	113.89 dB	126.59 dB	101.82 dB	110.02 dB
Hawaii	85.62 dB	88.18 dB	92.06 dB	93.32 dB	82.25 dB	84.34 dB
Beaufort Sea	86.80 dB	91.24 dB	101.44 dB	107.07 dB	80.46 dB	82.24 dB

Supplemental Table 5.1. Median, maximum, and minimum daily sound pressure levels (dB re 1 μPa^2) for both 63 Hz and 125 Hz one-third octave bands at each of the five sites during the 2016-2017 sampling time period.

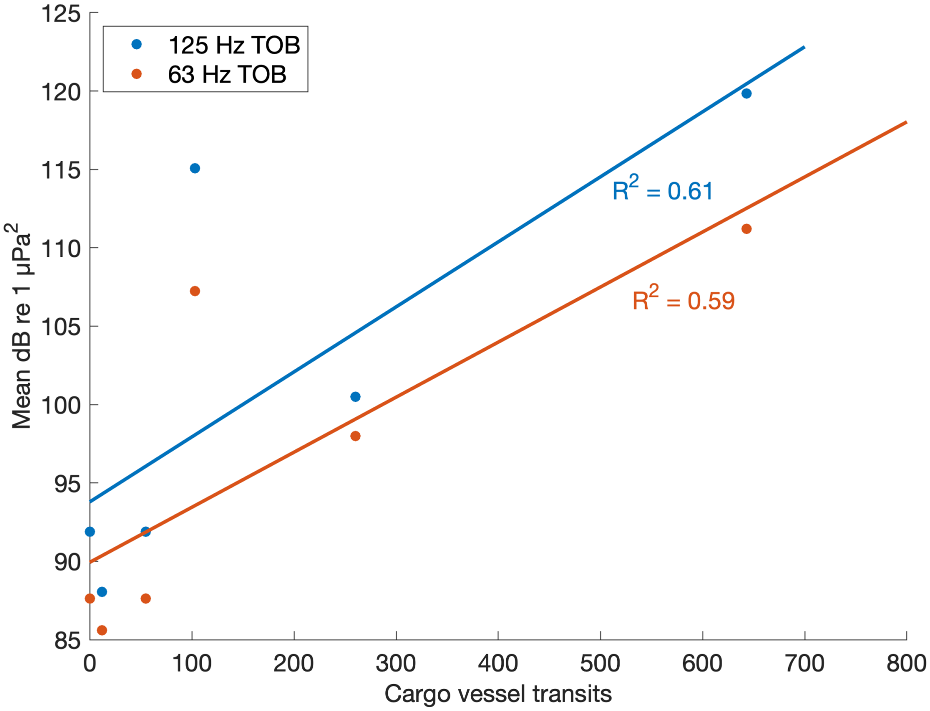

Figure 5.5. Scatter plot of both the 125 Hz (blue) and 63 Hz (orange) one-third octave frequency band (TOB) sound levels and the sum of cargo vessel transits from each of the five sites. Both 125 Hz and 63 Hz TOB sound levels were positively correlated with number of cargo vessel transits.

CHAPTER 6. GENERAL CONCLUSION

My research quantifies various qualities of long-term ocean ambient sound using data collected by a broadly spaced array of calibrated hydrophones located throughout United States (U.S.) waters. The acoustic sampling sites include marine protected areas within national parks and marine sanctuaries. The results of these analyses provide information to fill knowledge gaps and inform marine animal protection and ocean conservation efforts at ecologically relevant scales. By using calibrated technology to measure ocean ambient sound levels and temporal trends of diverse acoustic environments within U.S. waters, these studies meet the needs of U.S. regulatory agencies (e.g., NOAA, NPS) for standardized monitoring of soundscapes. The methods applied to describe acoustic conditions facilitate comparisons of a variety of environments, including different management contexts of marine protected and biologically important areas.

The overarching goal of my dissertation is to establish methodologies to document baseline soundscape conditions as well as compare levels and sources of sound across marine environments in U.S. waters. In Chapters 2 through 5, I present analyses to compare conditions at the twelve NOAA/NPS Noise Reference Station Network (NRS) hydrophone sites. In Chapter 2, I address the current need for calibrated, long-term underwater soundscape monitoring in U.S. waters and provide details about the NRS project instrumentation. In that section, I present the initial NRS data collection efforts that began in 2014, analyze the first available data from five of the deep-water (>500 m) hydrophone sites, and explore metrics to compare calibrated sound level measurements and discuss potential drivers and sources of sound that affected conditions over space and time. In Chapter 3, I investigate how management, climate, species richness, and physical environment affect soundscape conditions of four shallow water (<100 m) marine protected areas. That section analyzes differences in seasonal sound levels across the widespread site locations, with a specific focus on the presence of Humpback whale (*Megaptera novaeangliae*) vocalizations at each site. Chapter 4 establishes baseline soundscape conditions in Cordell Bank National Marine Sanctuary and integrates passive acoustic data with visual marine mammal observations to demonstrate the utility of passive acoustic monitoring for protected species monitoring. Finally, in Chapter 5, I return to cross-network deep-water comparisons in an evaluation of the acoustic impact of commercial shipping traffic on soundscapes in five important ocean regions within U.S. waters.

Collectively, these papers support the goals of the NOAA Ocean Noise Strategy, which calls for characterization of acoustic habitats and anthropogenic sound exposure to inform management of acoustically sensitive places and species in NOAA’s trust. I document sound levels and trends in important yet understudied soundscapes, and present novel comparisons across widespread areas to contextualize site-specific results. Additionally, in each chapter I discuss how climate, tectonics, ocean processes, and policy drive the presence and intensity of sound sources (e.g., weather, anthropogenic activity, and animal vocalizations) within soundscapes. Not only can passive acoustic soundscape monitoring reveal the sound sources within a marine environment, but ocean sound is also an essential observation variable in and of itself; comparable and consistent monitoring and synthesis of ocean sound conditions is essential to marine animal health and protection, and hereby to ocean conservation efforts. By utilizing standardized methods to describe baseline sound levels and comparing conditions across broad spatial and temporal scales, the research efforts described in this dissertation provide information to managers and policy makers to support effective and efficient conservation of valuable marine resources.

These projects also provide a foundation for future analysis of NRS data. Ongoing long-term passive acoustic data collection supports the ability of NOAA and the NPS to monitor protected marine environments, and evaluate changes over time and in response to natural (e.g. hurricanes) and human-generated (e.g. vessel traffic) events. Results of sustained NRS efforts will provide critical information about underwater soundscapes in U.S. waters and compliment data streams of other oceanographic monitoring variables to support U.S. efforts to conserve ocean ecosystems and resources.

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