Marine Policy 90 (2018) 6–13

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

Monitoring long-term soundscape trends in U.S. Waters: The NOAA/NPS Ocean Noise Reference Station Network

Samara M. Haver[a,*], Jason Gedamke[b], Leila T. Hatch[c], Robert P. Dziak[d], Sofie Van Parijs[e], Megan F. McKenna[f], Jay Barlow[g], Catherine Berchok[h], Eva DiDonato[i], Brad Hanson[j], Joseph Haxel[a], Marla Holt[j], Danielle Lipski[k], Haru Matsumoto[a], Christian Meinig[k], David K. Mellinger[a], Sue E. Moore[l], Erin M. Oleson[m], Melissa S. Soldevilla[n], Holger Klinck[o]

[a] *Cooperative Institute for Marine Resources Studies, NOAA Pacific Marine Environmental Laboratory and Oregon State University, Hatfield Marine Science Center, 2030 SE Marine Science Drive, Newport, OR 97365, USA*
[b] *Office of Science and Technology, NOAA Fisheries, 1315 East West Highway, Silver Spring, MD 20910, USA*
[c] *Gerry E. Studds Stellwagen Bank National Marine Sanctuary, NOAA Office of National Marine Sanctuaries, 175 Edward Foster Road, Scituate, MA 02066, USA*
[d] *NOAA Pacific Marine Environmental Laboratory, Hatfield Marine Science Center, 2115 Marine Science Drive, Newport, OR 97365, USA*
[e] *NOAA Northeast Fisheries Science Center, 166 Water Street, Woods Hole, MA 02543, USA*
[f] *National Park Service Natural Sounds and Night Skies Division, 1201 Oakridge Drive, Suite 100, Fort Collins, CO 80525, USA*
[g] *NOAA Southwest Fisheries Science Center, 8901 La Jolla Shores Drive, La Jolla, CA 92037, USA*
[h] *NOAA Alaska Fisheries Science Center, 7600 Sand Point Way NE, Seattle, WA 98115, USA*
[i] *National Park Service Water Resource Division, 1201 Oakridge Drive, Suite 250, Fort Collins, CO 80525, USA*
[j] *Conservation Biology Division, NOAA Northwest Fisheries Science Center, 2725 Montlake Boulevard East, Seattle, WA 98112, USA*
[k] *Cordell Bank National Marine Sanctuary, 1 Bear Valley Road, Point Reyes Station, CA 94956, USA*
[l] *NOAA NMFS/Office of Science and Technology, 7600 Sand Point Way NE, Seattle, WA 98115, USA*
[m] *NOAA Pacific Islands Fisheries Science Center, 1845 Wasp Boulevard, Honolulu, HI 96818, USA*
[n] *NOAA Southeast Fisheries Science Center, 75 Virginia Beach Drive, Miami, FL 33149, USA*
[o] *Bioacoustics Research Program, Cornell Lab of Ornithology, Cornell University, 159 Sapsucker Woods Road, Ithaca, NY 14850, USA*

ARTICLE INFO

Keywords:
Acoustic monitoring
Ocean noise management
Ocean conservation

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 2000 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.

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* Corresponding author.
E-mail address: samara.haver@noaa.gov (S.M. Haver).

https://doi.org/10.1016/j.marpol.2018.01.023
Received 22 September 2017; Received in revised form 14 November 2017; Accepted 20 January 2018

1. 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 [51]. 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 [47]. 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 [33]. However, currently there are no widely accepted standards for analyzing or reporting soundscape conditions, including ambient (background) sound [11,6].

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” [6,8]. Anthropogenic noise can negatively impact the ecological processes of acoustically sensitive marine animals, including their ability to communicate with conspecifics and detect threats [17,52,54,9]. Increased anthropogenic noise has been shown to affect marine animals in numerous ways, including hindering communication [19], altering communication behavior [45], altering locomotive behavior [48], and inducing stress [52]. 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 [49,55].

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 [35,65]. Thus, a source of anthropogenic noise does not need to be in close physical proximity to an animal to potentially interfere with biological signals [42]. In this study, ocean ambient noise is considered to encompass persistent or long-term “chronic” sources of anthropogenic noise in a marine soundscape [11]. 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 [19,39,8].

Following research chronicling the negative effects of anthropogenic noise [39], the United States (U.S.) government has established protocols to protect marine animals from deleterious effects of noise exposure [24,40]. In particular, marine mammals are protected in the U.S. by the Marine Mammal Protection Act and the Endangered Species Act [58,59]. 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; [16]). 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 [36], 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, [13]), Canada [22], and the 23 member countries of the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic area [1] 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 [26,3,4,54]. Chronic anthropogenic noise is an 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 [10].

Long-term acoustic ecosystem monitoring can be used to answer questions about specific systems (e.g., NPS terrestrial soundscape database, [4]) 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 [31], 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 [38]. 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. [36].

To date, there have been a handful of studies that monitored long-term ocean ambient sound (e.g., [2,18,29,56]), 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 [16]. 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 socio-economic 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

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

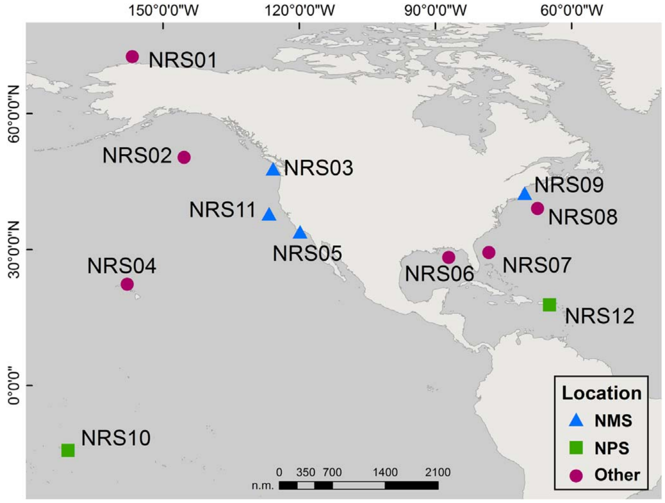

Fig. 1. Locations of NRS moorings colored by site type (National Marine Sanctuary sites are marked with blue triangles, National Park Service sites are marked with green squares, and other NRS sites are identified by purple circles). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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.

2. Methods

2.1. 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) (Figs. 1 and 2). Each NRS mooring contains a single passive acoustic archival autonomous underwater hydrophone (AUH) [14,21]. The hydrophones are model ITC-1032 (International Transducer Corp., Santa Barbara, CA) with a nominal sensitivity of −192 dB re 1 V/μ Pa and a flat frequency response (-/+ 1 dB) between 10 Hz and 2000 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 [60] 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 (Fig. 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 (Fig. 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 Fig. 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 Fig. 4. Due to equipment failure and deployment vessel availability, some data gaps exist.

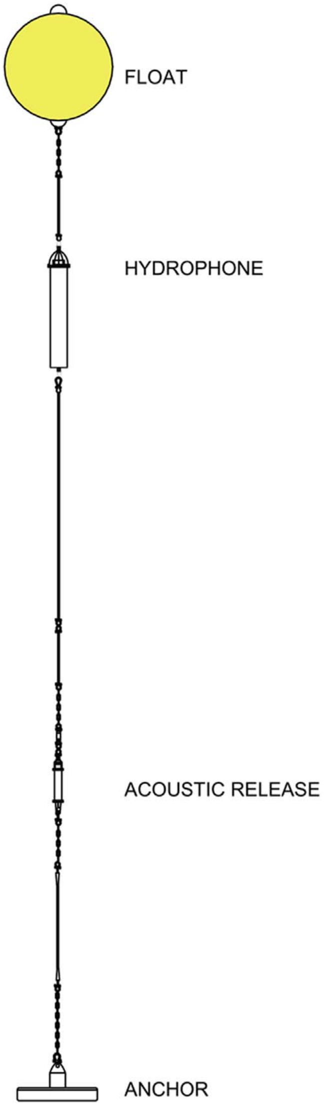

Fig. 2. Example mooring diagram of NRS05 in the Channel Islands National Marine Sanctuary. All deep-water NRS hydrophones are similarly suspended in the water column between a syntactic foam float and a bottom-mounted acoustic release (Diagram: Michael Craig, NOAA PMEL). Depending on mooring location, the hydrophone may be suspended at a different depth.

2.2. Quantitative analysis

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) (Fig. 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 [7] to assess recording success and data quality. To quantify ocean ambient sound levels, long-term spectral average (LTSA) plots (10–2000 Hz

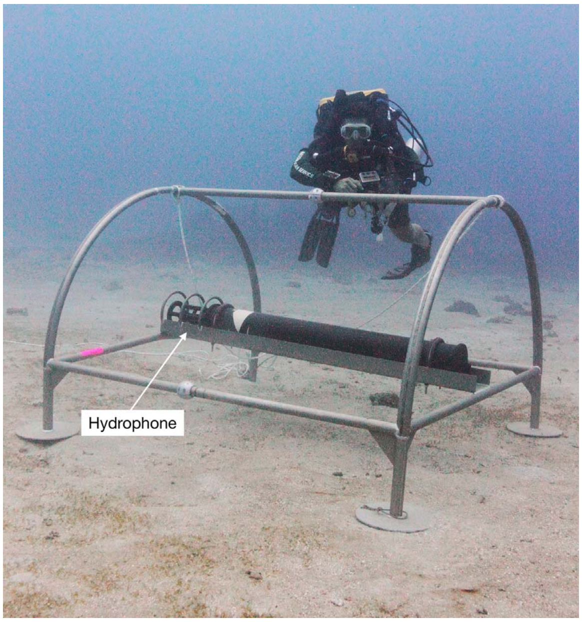

Fig. 3. A shallow-water NRS deployed off the coast of Tutuila Island in the National Park of American Samoa. All shallow water NRS are bottom-mounted on similar hollow metal landers. (Photograph: NPS, National Park of American Samoa, 11 June 2015).

range) from each NRS were calculated in Matlab with 1 Hz and 1 s resolution. The 1 Hz binned spectrum levels were averaged over 1 h 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 (Fig. 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 (Fig. 4). To estimate seasonal variability in sound levels at these sites, the difference between the monthly L10 and L90 for each frequency in the 10–2000 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.

3. Results & discussion

The initial investigation of data collected by the NRS Network demonstrates temporal and geographic variability of 10 Hz to 2000 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 (Fig. 5). Variations of monthly L50 spectrum levels at each NRS are generally greater across sites than within each NRS site (Fig. 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 [17,23]. 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) (Fig. 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 [30,50]. 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 [8]. In areas rich in energy resources, such as the Gulf of

Table 1
NRS deployment site information. See also Fig. 1.

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/CINMS & 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, National Park of 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 National Monument, U.S. Virgin Islands (US VI)	NOAA & NPS	17.79	−64.65	40	40

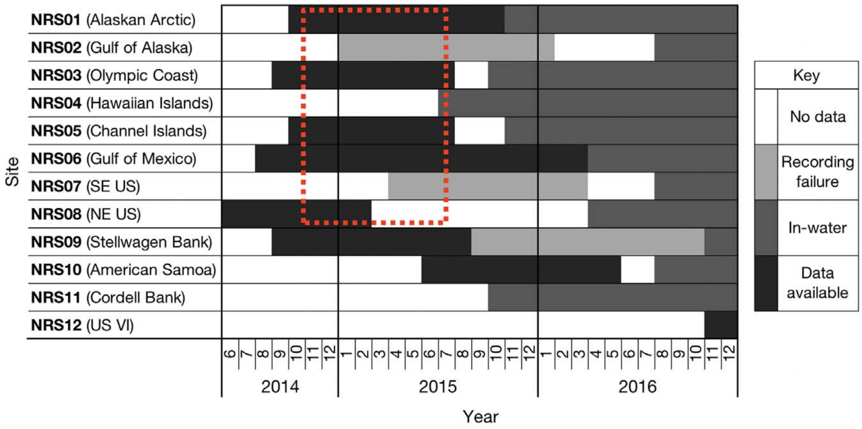

Fig. 4. Initial NRS acoustic data collection effort by site and month. Shading indicates the recording success (i.e., data collection) during a given month. The dashed box highlights the temporally overlapping data selected for initial deep-water cross-network analysis here. NRS09 (Stellwagen Bank National 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.

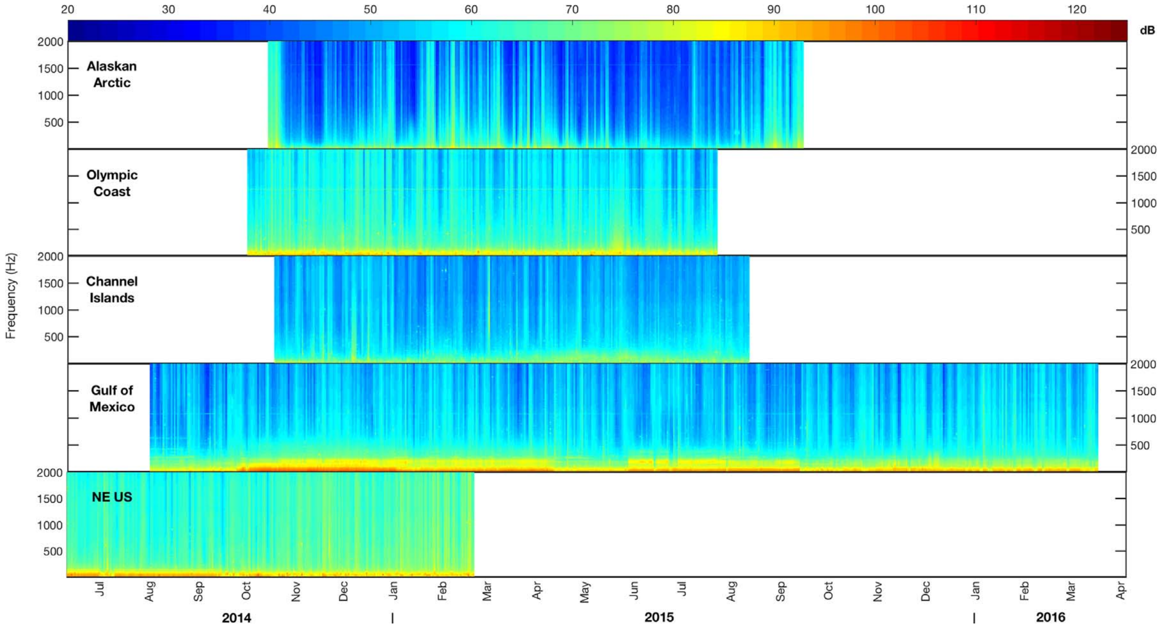

Fig. 5. Time-aligned long term spectral averages (LTSA) of the first year (2014–2015) of acoustic data from five deep-water NRS (Alaskan Arctic, Olympic Coast National Marine Sanctuary, Channel Islands National Marine Sanctuary, Gulf of Mexico, and NE US). Increasing intensity of sound (dB *re* 1 μPa^2/Hz) is indicated on the blue to red scale.

Mexico, seismic airguns are also often a significant source of low-frequency anthropogenic noise [12,24,64]. Seismic airgun use in the Atlantic (e.g., Eastern Canada) may also increase sound levels in the NE US [41].

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 (Fig. 6, [62,63]). 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 [57], and are likely part of the soundscape at National Park of American Samoa (NRS10, Fig. 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 [43] and have a combined vocal range of ~10 Hz to ~200 kHz [39], 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 [23,25,44,60]. 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 (Fig. 6; [53]). 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 ([66]; 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) [27,28,32,34,61].

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

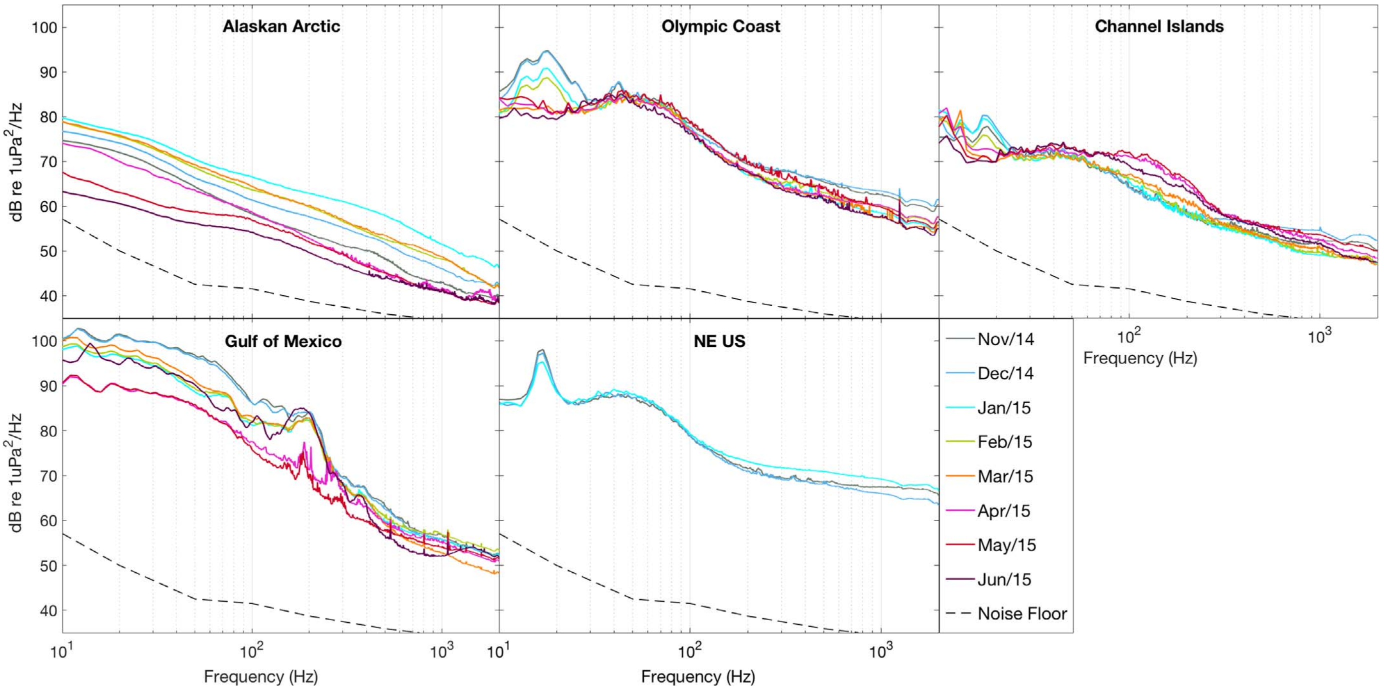

Fig. 6. Within-site comparison: Monthly median spectrum levels (L50) at five deep-water NRSs calculated for all available months between November 2014 and June 2015 plotted by site. Data recorded prior to November 2014 or after June 2015 were excluded to control for temporal inconsistencies. The dashed 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.

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 (Fig. 8, [20]). 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 [27,28,32,34,61]. 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 (Fig. 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.,

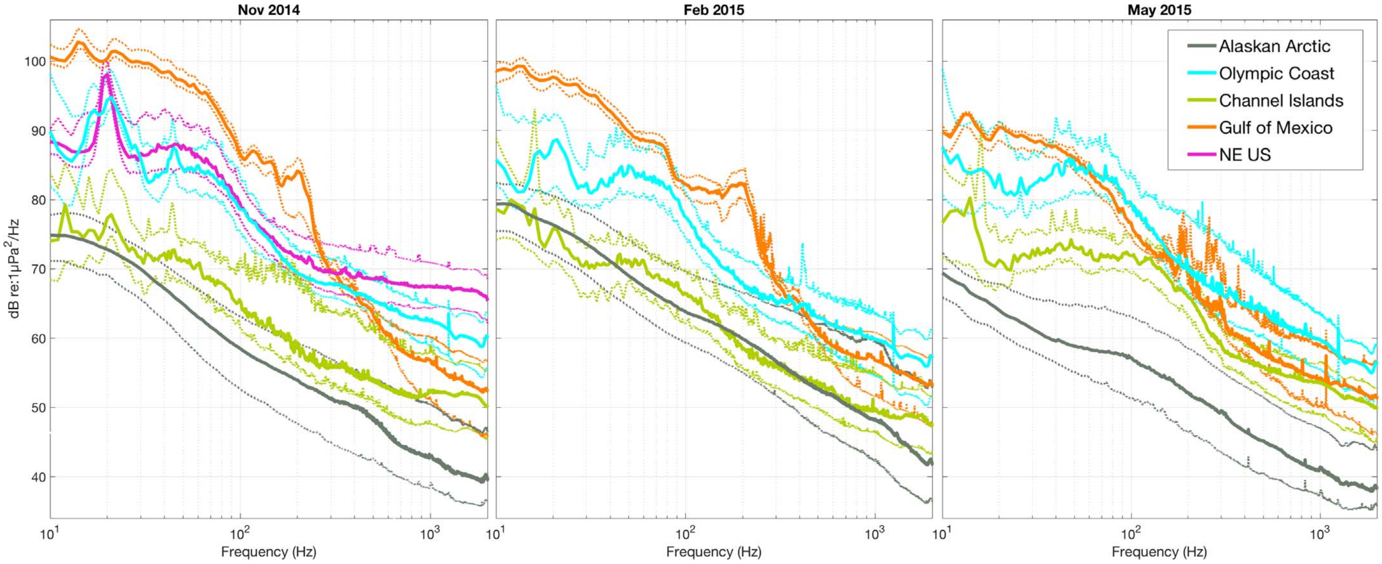

Fig. 7. Cross-site comparison: Median monthly spectrum levels (monthly L50) at each NRS calculated in 1 Hz bins for November 2014, February 2015, and May 2015. Each NRS site is indicated by a single color solid line (Alaskan Arctic, grey; Olympic Coast National Marine Sanctuary, cyan; Channel Islands 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. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

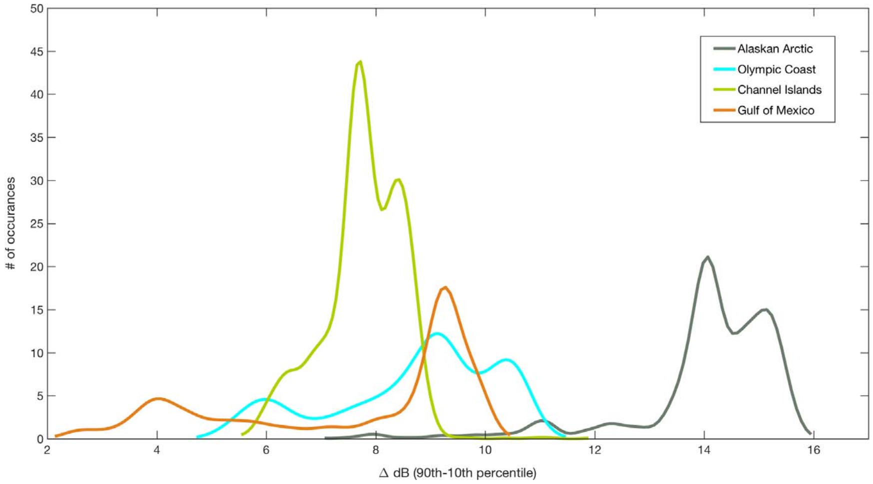

Fig. 8. Distribution (nonparametric kernel-smoothed, width parameter of 500) of the median decibel difference (Δ dB) between the monthly L10 and L90 for each 1 Hz frequency bin from Nov 2014- June 2015 within the Alaskan Arctic, Olympic Coast National Marine Sanctuary, Channel Islands National Marine 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.

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; [11,46]) to tease apart individual contributors and investigate long-term trends across the entire network.

4. 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 [16], 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 [37,5] and reiterated by the NPS [15]. 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 Fig. 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.

Acknowledgements

This work was supported by the NOAA Office of Oceanic and Atmospheric Research, Pacific Marine Environmental Laboratory, National Marine Fisheries Service, Office of National Marine Sanctuaries, Dr. Nancy Foster Scholarship Program (SH), and the National Park Service. Additional resources were provided by Oregon State University and the Hatfield Marine Science Center. Publication of this paper was supported, in part, by the Henry Mastin Graduate Student Fund. The authors thank their collaborators: Danielle Cholewiak, Michael Craig, TK Andy Lau, and Sharon Nieukirk, as well as Charles Anderson, Timothy Clark, Jordan Colmenero, Genevieve Davis, Matt Fowler, Burt Fuiava, Zandy Hillis-Starr, Brian Kahn, Anthony Martinez, Eric Matzen, Ian Moffitt, Clayton Pollock, Lauren Roche, Jenni Stanley, Alex Turpin, Carrie Wall, and Tracy Ziegler for field and data support. This is NOAA/PMEL contribution #4695.

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