Running Head: Underwater Soundscapes of US National Marine Sanctuaries

Monitoring spatial and temporal underwater soundscape features within four US National Marine Sanctuaries

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Abstract

National Oceanic and Atmospheric Administration's National Marine Sanctuaries Program serves a network of underwater parks encompassing more than 2,000,000 km^2 of marine waters. These US National Marine Sanctuaries (NMS) maintain areas of the marine environment needing unique protection due to ecological, historical, archeological, scientific, and/or recreations qualities. Due to the large variability of attributes among NMS, monitoring these sites to achieve the best resource protection can be challenging. Underwater soundscape monitoring programs are growing in popularity as a tool for supporting marine protection management and mandates. Acoustics provide invaluable autonomous information regarding habitat associations, identifying species spatial and temporal use, and patterns in conditions that are otherwise difficult to survey, while providing metrics that can aid protective efforts. Using standardized equipment and analysis methods, the current study aimed to derive measurements to investigate temporal changes in sound pressure levels and power spectral density, identify presence of select species of importance and support within and among site comparison of ambient underwater sound among eight sites within four US NMS. Broadband sound pressure levels of ambient sound (10 – 24,000 Hz) varied markedly among the sites, sanctuaries and seasons, from 100 to 124 dB re 1μPa. Signals biotic in origin, such as snapping shrimp snaps and vocalizations of fishes, exhibited distinct diel and seasonal patterns and showed variation among sites. Presence of anthropogenic signals, such as vessel passage, also varied substantially among sites, ranging from on average 1.6 h to 21.8 h per day. The current study identified measurements that most effectively summarized and communicated baseline soundscape attributes and prioritized future opportunities for integrating non-acoustic and acoustic variables in order to inform area-specific management questions within four fairly shallow, yet ecologically varying US National Marine Sanctuaries.

Keywords

Underwater soundscapes, passive acoustic monitoring, fish and marine mammal vocalizations, bioacoustics, US National Marine Sanctuaries

1. Introduction

Over the past decade the field of 'soundscape ecology' has matured into a research discipline of its own, e.g., Pijanowski et al. 2011a, 2011b, Truax & Barret. 2011, Farina 20144, Gasc et al. 2016. Terrestrial ecologists initially took the lead in describing and quantifying soundscapes, defining the term as the relationship between a landscape and the composition of its sound (Pijanowski et al. 2011b). Soundscapes are comprised of contributions from the organisms utilizing the space (biotic sound), human activities in and around the space (anthropogenic sound) and environmental processes occurring in the space (abiotic/geophysical sound) (e.g. Pijanowski et al. 2011a). These three components together determine the distinct sound signature at any given place, which depending on the source, can show recognizable spatio-temporal patterns at differing time scales, reflective of changes in biotic, anthropogenic or even abiotic activities (Matsinos et al. 2008, Farina et al. 2011, Pijanowski et al. 2011b, Staaterman et al. 2014, Buscaino et al. 2016). As recording effort continues to grow internationally, the field is challenged to develop analytical techniques and tools that both accurately describe and characterize this variation in soundscapes and from these data isolate relevant ecological indicators that relate to targets of interest for marine science and management, such as biological diversity and ecosystem health.

Marine soundscape ecology is a relatively recent field, with most studies focused descriptively on improving understanding of the acoustic characteristics of different marine environments, and isolating contributions to their trends and status. Underwater acoustic monitoring has been successful in identifying species presence/absence, habitat associations, migration timing and pathways, spawning patterns and locations, environmental conditions, and largescale differences among underwater habitats e.g. McCauley & Cato 2000, Parsons et al. 2009, Bertucci et al. 2015, Erbe et al. 2015, Davis et al. 2017, Putland et al. 2017a, Rowell et al. 2017) . However, understanding in how to effectively translate and employ the results derived from quantitative soundscape data is an area still under development. The application of terrestrially derived approaches, measurements and metrics to marine soundscapes initially appeared straightforward. However, due to a combination of factors such as the greater efficiencies of sound propagation underwater, contributing to significant biological and anthropogenic signal of interest, among other complications, applying these methods to the marine environment has proven to be largely unsuccessful and do not appear to translate consistently across the marine realm, requiring scientists to rethink existing approaches and develop new methodologies for characterizing marine habitats (Freeman and Freeman 2016, Harris et al. 2016, Staaterman 2017, Bohnenstiehl et al. 2018, Mooney et al. 2020). Despite the demand for new methods, terrestrial soundscape management can provide invaluable examples for how to apply an improved understanding of soundscapes to drive new management approaches and support mandates within protected areas, parks and sanctuaries.

Acoustics provide invaluable autonomous information regarding spatial and temporal use patterns in conditions that are otherwise difficult to survey, providing metrics of use within protected areas that aid protective efforts (Mooney et al. 2020). Terrestrial scientists and managers have made significant head way in using the science derived from soundscape research to inform management of anthropogenic noise conditions within protected areas (Buxton et al. 2017). For example, some US National Parks have identified thresholds to guide visitor and wildlife noise exposure within park areas, leading to management techniques such as the use of shuttle buses to reduce car traffic and alignment of overflight patterns with roads to concentrate peak noise conditions. A study examining similarities and differences in noise pollution controls in a US National Park and a US National Marine Sanctuary, highlighted a common need for long term quantitative data and developing criteria designed to effectively manage sounds in natural areas (Hatch et al. 2009).

Soundscape monitoring programs are growing as a tool for supporting marine protective management and management. In Europe, the Baltic Sea Information on the Acoustic Soundscape (BIAS project) produced seasonal soundscape maps for the demersal, pelagic and surface zones, serving as a baseline for the development of monitoring and assessment of ambient noise in the Baltic Sea (Nikolopoulos et al. 2016). In the US, large-scale comparative soundscape monitoring capacities have been steadily growing under support from multiple federal agencies (NOAA & U.S. Navy Sound Monitoring - https://sanctuaries.noaa.gov/science/monitoring/sound/, Gedamke et al. 2016, Haver et al. 2018). While, in the southern hemisphere, Parks Australia are utilizing acoustic recordings to monitor anthropogenic activity and understand vessel presence within National Park Zones prohibiting fishing and other commercial activities to gain information on when best to focus compliance efforts (Kline et al. 2020).

Using passive acoustic recording, the current study investigates the underwater soundscapes within four US National Marine Sanctuaries: spanning latitudes from 42° to 24° (Figure 1). The northern-most sanctuary, Stellwagen Bank National Marine Sanctuary (SBNMS), has a highly seasonal ecology with spring upwelling driving high summer productivity that attracts a variety of invertebrate schooling and predatory fish and high concentrations of feeding marine mammals. The mid-latitude site, Gray's Reef National Marine Sanctuary (GRNMS), is a temperate hard-bottom reef located off the coast of Georgia, with complex "live-bottom" and rocky ledges providing habitat for a wide range of invertebrates, fishes and turtles, as well as transient marine mammals. The southern-most locations, within Florida Keys National Marine Sanctuary (FKNMS), were placed within different zones of fishing and recreational use within the range of the coral reef habitat contained within this protected area. Finally, the locations within western Gulf of Mexico's Flower Garden Banks National Marine Sanctuary (FGBNMS) monitored two protected coral reef caps that sit atop disparately placed salt domes and host diverse communities of invertebrates, fish and turtles, as well as transient mammals. At all eight sites in the four sanctuaries, recordings were gathered coincidentally over two years. Measurements were derived to investigate temporal changes in sound pressure levels and power spectral density, identify presence of select species of importance and support within and among site comparison of ambient underwater sound among sanctuaries. This standardized method enabled the study to identify measurements that most effectively summarized and communicated soundscape attributes both among and within these sites and prioritized future opportunities for integrating non-acoustic and acoustic variables in order to inform area-specific management questions of interest.

2. Materials and Methods

2.1 Study sites and deployment schedule

The four sanctuaries that were monitored in this study are all relatively small (57 to 9947 km^2), shallow to very shallow (14.5 – 68 m recording depths) and are positioned offshore on the US continental shelf (4.8 – 185 km from shore, with the exception of FKNMS).

The eight passive acoustic listening stations included: Stellwagen Bank National Marine Sanctuary (SBNMS); Site 27 (Site 1) and Site 33 (Site 2), Gray's Reef National Marine Sanctuary (GRNMS); FS15 (Site 3) and Station 20 (Site 4), Florida Keys National Marine

Sanctuary (FKNMS); Western Dry Rocks (Site 5) and Eastern Sambo (Site 6), and Flower Garden Banks National Marine Sanctuary (FGBNMS); Stetson Bank (Site 7) and East Flower Garden Bank (Site 8) (Figure 1, Table S1). Within each sanctuary, using available data, sites were chosen to reflect areas likely to be exposed to variable acoustic influence from sound-producing species and human activities. Given the relatively localized sound propagation field around shallower sites, it was understood that two recording locations would not sufficiently describe soundscape conditions throughout the sanctuaries. Thus, emphasis was placed on locations where other information sources were available (including past acoustic information, diver surveys, other oceanographic sampling), where acoustic signals of interest would likely be present (whether biotic or anthropogenic or both), and where overall acoustic signatures might differ when compared.

Deployments were planned to occur concurrently at all sites for at least one lunar phase during each season in 2016/17. However, due to the inaccessibility of some locations this was not always achieved, therefore, seasons were defined among sites as follows; Summer: 28th June – 13th September 2016, Fall: 19th October – 29th December 2016, Winter: 22 February – 13th April 2017, Spring: 26th April – 15th July 2017. Due to the nature of concurrent sampling at multiple distant locations we aimed for at least one complete lunar phase during each season during years 2016/17 (Table 1).

Table 1. Duration of acoustic recordings (days) per site per season. Number of days vary due to timing on ability to retrieve (R) reaching memory capacity (M) or battery malfunction (B) (all units had same memory capacity (128 GB) except FGBNMS in the spring (256 GB). NB. asterisk denotes times with issues identified, therefore data removed from analysis.

Sanctuary	Site Name	Site ID	Summer (June – Sep)	Fall (Oct – Dec)	Winter Feb – April)	Spring (April – July)	Total
Stellwagen Bank National Marine Sanctuary	Site 27	1	36 (R)	51 (R)	53 (R)	34 (R)	174
	Site 33	2	36 (R)	51 (R)	53 (R)	34 (R)	174
Gray's Reef National Marine Sanctuary	FS15	3	29 (M)	33 (M)	0 (R)	31 (M)	93
	Station 20	4	35 (R)	44 (M)	0 (R)	39 (M)	118
Florida Keys National Marine Sanctuary	Western Dry Rocks	5	37 (M)	*	*	*	37
	Eastern Sambo	6	36 (M)	38 (M)	11 (B)	36 (R)	121
Flower Garden Banks National Marine Sanctuary	Stetson Bank	7	31 (M)	26 (M)	36 (M)	62 (M)	155
	East Flower Garden Bank	8	31 (M)	23 (M)	0 (R)	69 (M)	123

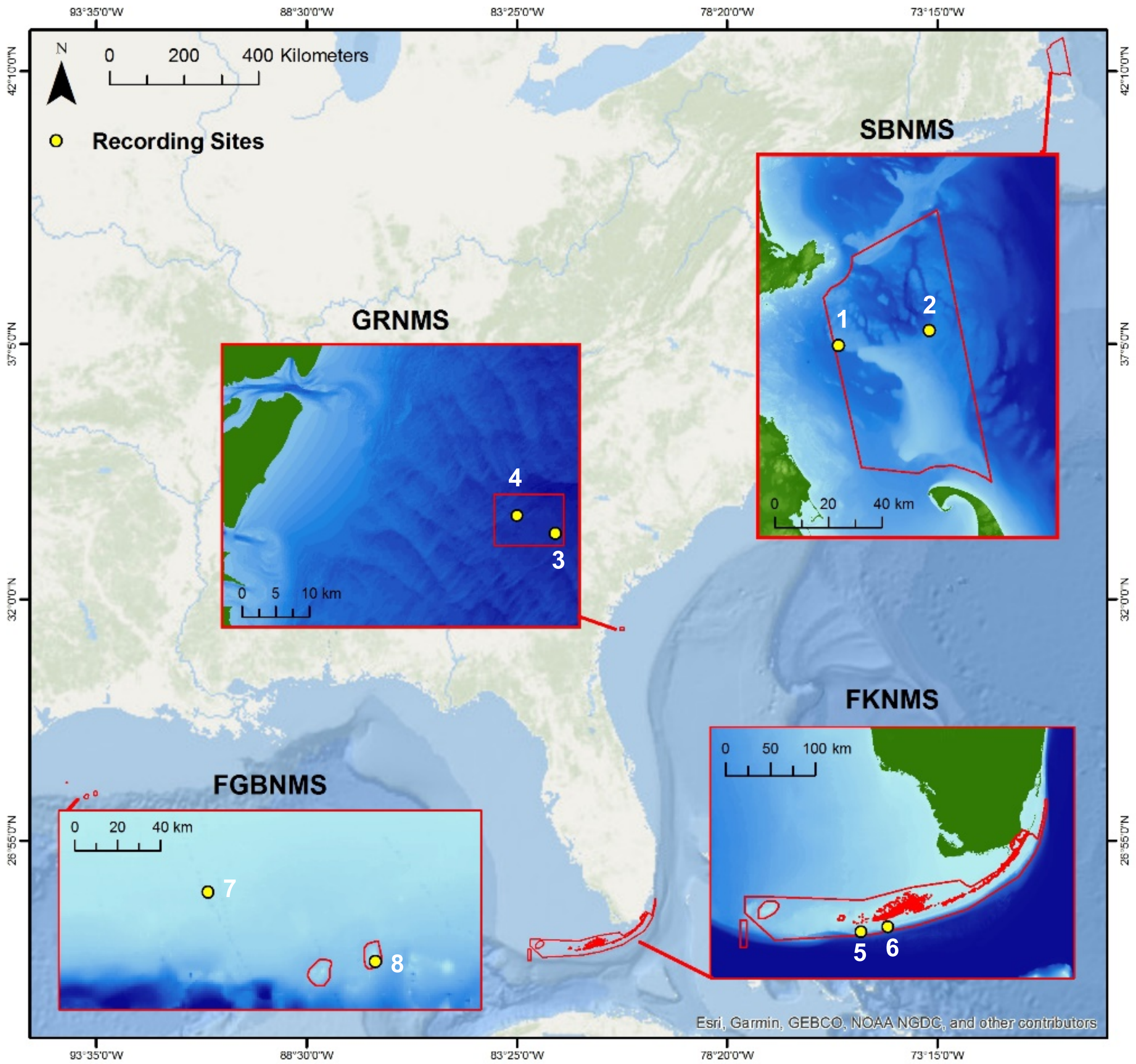

Figure 1. Map showing recording sites within each sampled National Marine Sanctuary. Stellwagen Bank National Marine Sanctuary (SBNMS); Site 27 – Site 1, Site 33 – Site 2, Gray's Reef National Marine Sanctuary (GRNMS); FS15 – Site 3, Station 20 – Site 4, Florida Keys National Marine Sanctuary (FKNMS); Western Dry Rocks – Site 5, Eastern Sambo –Site 6, Flower Garden Banks National Marine Sanctuary (FGBNMS); Stetson Bank – Site 7, East Flower Garden Bank – Site 8.

2.2 Instrumentation

2.2.1 Autonomous underwater acoustic recorders

All acoustic recordings were made using SoundTrap ST300's and external battery packs (Self-noise less than sea-state 0 at 100 Hz – 2 kHz and <34 dB re 1µPa above 2 kHz, Ocean Instruments Inc., Auckland, New Zealand). At all recording sites, the SoundTraps continuously sampled at a rate of 48000 Hz with a flat full-scale frequency response between 20 – 60 kHz (± 3 dB). The same individual acoustic recorders were used at the same site for the duration of the data collection, except for FGBNMS in the winter season. Each individual SoundTrap at each site was calibrated by the manufacture directly before deployment and each had unique end-to-end response sensitivity. Digitized recordings (.wav files) were directly downloaded to a computer using the SoundTrap host software.

2.2.2 Mooring configuration

At all sites with water depths of less than 30 m (GRNMS, FKNMS and FGBNMS) the acoustic recorders were deployed and retrieved by divers. In these instances, recorders were dived to the benthos at each site and fixed securely to a rigid and weighted benthic stand, with no surface or subsurface mooring lines or floats. The hydrophone element in these situations were approximately 1 m from the seafloor. We found this depth to be the optimal balance between reducing flow noise across the hydrophone element which can be heightened in the water column and reducing the noise created from sediment moving across the hydrophone element. At sites with water depths greater than 31 m (sites at SBNMS) the acoustic recorders were suspended approximately two meters off the seafloor via an acoustic release and held to the substrate by two 18 kg biodegradable sandbags. The acoustic release was a VEMCO VR2AR acoustic release and acoustic telemetry receiver (logs and decodes all VEMCO 69 kHz transmitters), with the ID transmitting disabled to reduce unnecessary signals in the immediate area. Acoustic telemetry information was opportunistic to the project and was not used in any analyses, except for verification that Atlantic cod *(Gadus morhua*) was physically present in the vicinity of an acoustic recorder in SBNMS while detecting vocalizations. There was no significant range testing carried out on the telemetry receivers as this was outside of the scope of the project. Both mooring types were specifically designed and engineered to reduce any extraneous noise from the moorings themselves.

2.3 Acoustic Analyses

2.3.1 Soundscape quantification

All acoustic data were analyzed using MATLAB software (version 2017b) and statistical tests were run in RStudio (version 1.1.456, R version 3.5.1). Sound files (.wav) were separated into 15 min files for ease during analysis. The sound files were manually high pass filtered at 10 Hz to partially remove potential low frequency surface motion noise or low frequency interference, 10

Hz and not 50 Hz (usual standard) was used to retain some portion of the energy from fin whale pulses as these signals may be of acoustic significance to the sites. SoundTraps have a built-in high pass filter set at 20 Hz to reduce any potential noise from mooring vibration and flow noise, therefore, there is a drop in sensitivity/response which would cause an approximate attenuation of 13 dB at 10 Hz. All times are standardized for local standard time at each site (daylight savings offset removed).

To quantify ambient sound levels at each recording site and variation with frequency and time scale, power spectral densities (PSD) and broadband (10 – 24,000 Hz) RMS, median and percentile sound pressure levels (BB SPLs) were obtained for all recordings. Power spectral densities were calculated using a discrete Fourier transformation with a Hann window resulting in 1 Hz, 60 s resolution with 50 % overlap. Spectrograms were produced with DFT length of 48000, using a Hanning window with 50% overlap for a 24-hour period ('sample day') at one site within each sanctuary to illustrate and identify peak daily patterns (specifically of intense acoustic biological or anthropogenic activity) for that season and day.

To determine if season effected the broadband ambient sound recorded at each recording site, broadband RMS SPLs were averaged in 60s and 60min lengths, to determine the robustness of the relationship at different sampling resolutions. Kruskal-Wallis or Mann-Whitney U statistical tests were subsequently used to test for differences. If such tests provided significant results, a Dunn's pairwise multiple comparison, with Bonferroni correction, was then used to isolate further differences. Non-parametric statistical methods were used to test for differences among seasons as the data had unequal variance among treatments and data had a non-normal distribution (Zar 1999). Broadband SPLs were also averaged, in 5 min bins, across each recording season, within each site, to produce an average diel trend plot for each site over each season.

Sound pressure levels (RMS) were also calculated in fractional 1/3 octave bands with a 60 s resolution for all recordings. Diel trends in select 1/3 octave frequency bands, centered on 125, 251, 501, 630, and 1258 Hz, were plotted for three days around each moon phase captured in the recordings for all site over all seasons to illustrate the variation among those selected frequency bands, and to demonstrate which bands most influenced broad band levels. A period of three days was selected to depict daily patterns while recognizing anomalies such as human activities i.e., vessel passages. Aural and visual inspection were used during these periods to identify signals and sources.

2.3.2 Vessel presence and contribution to the soundscape

During the Summer recording period one site within each sanctuary (SBNMS – Site 1, GRNMS – Site 4, FKNMS – Site 6, FGBNMS – Site 8) was visually and aurally inspected for vessel presence during the three days surrounding each lunar phase, totaling twelve days for each site. Using Raven Pro 1.5, times with both audible and visible vessels were tagged so to be separated from periods without the presence of vessel signals. Ninety-six 15-minute sound files were loaded into Raven in 90-second pages for each day and viewed as a spectrogram using a fast Fourier transform (FFT) value of 4096. After the vessel signals were identified, the hours of vessel noise/day were recorded. Sound Pressure Level in 1/3 octave frequency bands were analyzed for both times where vessel noise was present and absent at each site. The median and 90th percentile levels were plotted for each lunar phase separately as well as across the entire month at each site. These plots were then used to compare the power spectral density levels for presence and absence of vessel signal to determine the influence of vessel presence on the soundscape.

2.3.3 Detection and classification of vocalizers

Snapping shrimp

Data from all Sanctuaries with temperate and tropical reef conditions (GR, FK and FGBNMSs), were analyzed using a snap detection algorithm to quantify the acoustic activity of snapping shrimp, using methods and rationale for amplitude thresholds for detection from Bohnenstiehl, Lillis & Eggleston, 2016. Snap rates (number of snaps per 60s) were determined for the first 60 s of each 15 min sound file for the duration of the recording period at each site. The number of snaps that were detected during Dawn (site specific sunrise ± 90 min), Noon (noon ± 90 min), Dusk (site specific sunset ± 90 min) and Midnight (midnight ± 90 min) were also compared by calculating snap rate for these periods over a standardized segment of time, for each sampling day at each site during each recording season. Differences among snap rates were tested for statistical significance using the Friedman Test as data had a non-normal distribution. Following a significant Friedman test result, post-hoc multiple group comparisons were conducted using Tukey Tests. Simple linear regression methods were used to test if snap rate could be used to predict the values of SPL in the 2000 – 20,000 Hz during the different recording seasons. This method was used despite the fact there was a slight deviation from a normal distribution in the data. However, the sample size was large enough to be assumed to not impact results, and transformations of the data may lead to more severe bias (Schmidt and Finan 2018).

Atlantic cod

As the distribution of Atlantic cod (*Gadus morhua)* along the North American coast is from Cape Hatteras to Ungava Bay, identification of their calls was restricted to recordings from SBNMS. Acoustic data were processed using the Atlantic cod detection algorithm (Urazghildiiev and Van Parijs 2016) and all detections were manually verified visually and aurally for true calls (Stanley et al. 2017).

Low frequency vocalizing whales

Acoustic data from all recording sites were processed using the Low Frequency Detection and Classification System (LFDCS) (Baumgartner and Mussoline 2011) using methods from Davis *et al.,* 2017, utilizing all detections from fin (*Balaenoptera physalus*), sei (*B. borealis*), blue (*B. musculus*) and Northern Atlantic right (NARW) (*Eubalaena glacialis*) whales. For continuous data, a given day was marked as having a species present if certain criteria were met, with each species having different criteria due to the performance of the detectors. The criteria were as follows; for NARW, if three or more true upcalls detections were found, for fin whales if one true pulse detection was found with at least 4 subsequent pulses in a 2 min window, for sei whales if one true down sweep doublets or triplets were found, and for blue whales if one true call with at least 3 song units present in a two-minute window were found. These criteria were used in order to be conservative and confident in stating these species presence. Detector evaluation/missed detection rate was quantified using the same methods as Davis *et al.,* 2017.

2.4 Wind and Wave Data

Hourly wind speed and wave height data was collected from the nearest NOAA weather station to the recorders within each sanctuary (SBNMS: Station 44029, GRNMS: 41008, FKNMS: SANF1 and FGBNMS: TABS V) (https://www.ndbc.noaa.gov/). Wave height was not available for the sites in FKNMS and FGBNMS. A Pearson Correlation test was performed to assess the relationship between hourly broadband SPL and hourly wind speed (m/s) and separately wave height (m) within all sites to assess the contribution wind has on the broadband SPL metric.

3. Results

3.1 Stellwagen Bank National Marine Sanctuary

3.1.1 Patterns in broadband sound pressure levels

Broadband (10 – 24000 Hz) SPLs (both median and RMS values) varied by as much as 10 dB among recording sites and recording seasons within SBNMS, (100.5 – 110 dB re 1µPa, Table 2), with both sites reflecting the same overall seasonal patterns. The highest median broadband SPLs occurred during the Winter recording period, followed by Fall, Spring and with lowest levels recorded in the Summer recording period for both sites. Season significantly affected broadband SPL at both sites when using 60 sec averaging (Kruskal-Wallis; $P = <0.001$, Mann-Whitney; $P = <0.001$, Table 2 and S2). Conversely, when using 60 min averaging not all seasons showed significant differences (Table S2), with SBNMS, Site 1 showing no significant differences between Summer and Spring recording periods (Dunn's; $Z = 1.73$, $P = <0.51$).

Diel seasonal averages of broadband SPL (BB SPL) varied among recording sites within SBNMS (Figure 2). While Site 1 tended to show an increase in BB SPL towards midday during the Summer and Spring recordings periods, Site 2 did not show this increase during any seasonal recording period. However, at Site 2 during the Winter period there was an increase in BB SPL during the nighttime hours (~6 dB increase), with the transition occurring around sunrise and sunset (Figure 2). There was no strong linear relationship ($r > -0.5$ or 0.5) between BB (10 – 24000 Hz) SPL and wind speed (m/s) or wave height (m) at either recording sites within SBNMS during any seasonal recording period. Winter and Spring recording periods had the highest correlation among these variables; however, this was found to be a relatively weak to moderate relationship, with r values in the 0.257 – 0.425 range for wind speed and BB SPL, and 0.205 – 0.394 for wave height and SPL.

Table 2. **Broadband (BB) sound pressure level (dB re 1 µPa) statistics, using 60 s bins, for each recording site during each recording season.** NB. Shaded cells indicate the sampling season with highest median (blue) and Root Mean Squared (RMS) (grey) broadband SPL (per site). Stellwagen Bank National Marine Sanctuary (SBNMS), Gray's Reef National Marine Sanctuary (GRNMS), Florida Keys National Marine Sanctuary (FKNMS), Flower Garden Banks National Marine Sanctuary (FGBNMS).

Sanctuary	SBNMS		GRNMS		FKNMS		FGBNMS	
Site ID	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
Summer: June – September								
BB Median	100.5	100.2	117.0	119.8	109.4	109.5	118.9	110.5
10th percentile	93.6	94.8	114.0	117.9	108.3	108.3	116.6	108.8
90th percentile	108.0	107.6	119.6	121.9	111.1	111.0	121.9	113.7
BB RMS	107.8	114.3	123.9	121.5	112.0	109.5	120.3	118.0
Fall: October – December								
BB Median	104.5	106.3	113.3	116.4	-	108.9	116.8	110.4
10th percentile	98.8	100.9	110.6	114.5		107.7	114.4	110.4
90th percentile	110.4	112.3	115.2	118.1		110.4	119.4	112.1
BB RMS	109.4	111.5	117.8	117.5		113.4	117.5	111.5
Winter: February – April								
BB Median	105.2	110	-	-	-	107.8	116.5	-
10th percentile	100.35	103.6				106.6	114.3	
90th percentile	110.3	113.9				109.5	118.8	
BB RMS	108.6	111.6				111	117.2	
Spring: April – July								
BB Median	100.9	101.4	115.6	118.6	-	109.6	117.3	111.2
10th percentile	94.6	96.4	113.0	116.9		108.4	115.6	109.7
90th percentile	108.1	96.4	118.5	120.3		111.0	119.2	113.7
BB RMS	107.8	106.8	118.2	121.1		111.6	117.9	113.9

3.1.2 Seasonal and lunar spectral composition

In relation to spectral composition, the two recording sites within SBNMS were relatively complex due to a variety of acoustic contributors, both sites had similar overall frequency contributions with shared biotic and anthropogenic signals (Figure 4, Panels 1 & 2).

At both SBNMS recording sites there was a general trend of higher SPLs at low frequencies (<200 Hz) (Figure 3a), decreasing into the higher frequencies throughout the recording seasons. This was largely due to the presence of large commercial ships (see below). There were also large peaks in the spectra at both Site 1 and Site 2 centered around 20 Hz due to the pulse vocalization of fin whales (*Balaenoptera physalus*). This was most pronounced during the Fall and Winter recording periods, with a rise of up to 20 dB re 1 $\mu Pa^2 Hz^{-1}$, less so in the Summer and very little to none during the Spring recording period (Figure 4). Particularly at Site 2 there were also narrowband spikes in the spectra from 8 – 12 kHz during all seasons except Winter, due to the signals from acoustic devices used on commercial fishing nets to deter porpoises. These devices increased these frequency-specific sound levels at this site during those time periods by as much as 12 dB re 1$\mu Pa^2 Hz^{-1}$ (Figure 4).

Sites within SBNMS showed a large amount of variation in SPLs within the 125 Hz 1/3 octave band (Figure S2). During the Summer recording period Site 1 had an increase (12 – 31 dB re 1µPa RMS) in several 1/3 octave bands (centered on 125, 251, 501, 630 Hz) which peaked around midday, and likewise in the spring, although to a lesser extent (10 – 16 dB re 1µPa RMS). This diel trend was not seen during other seasons or at Site 2. The Winter recording period was more consistent, however, episodic peaks (≤ 14 dB re 1µPa RMS) in SPL still occurring, although not in consistent diel trend.

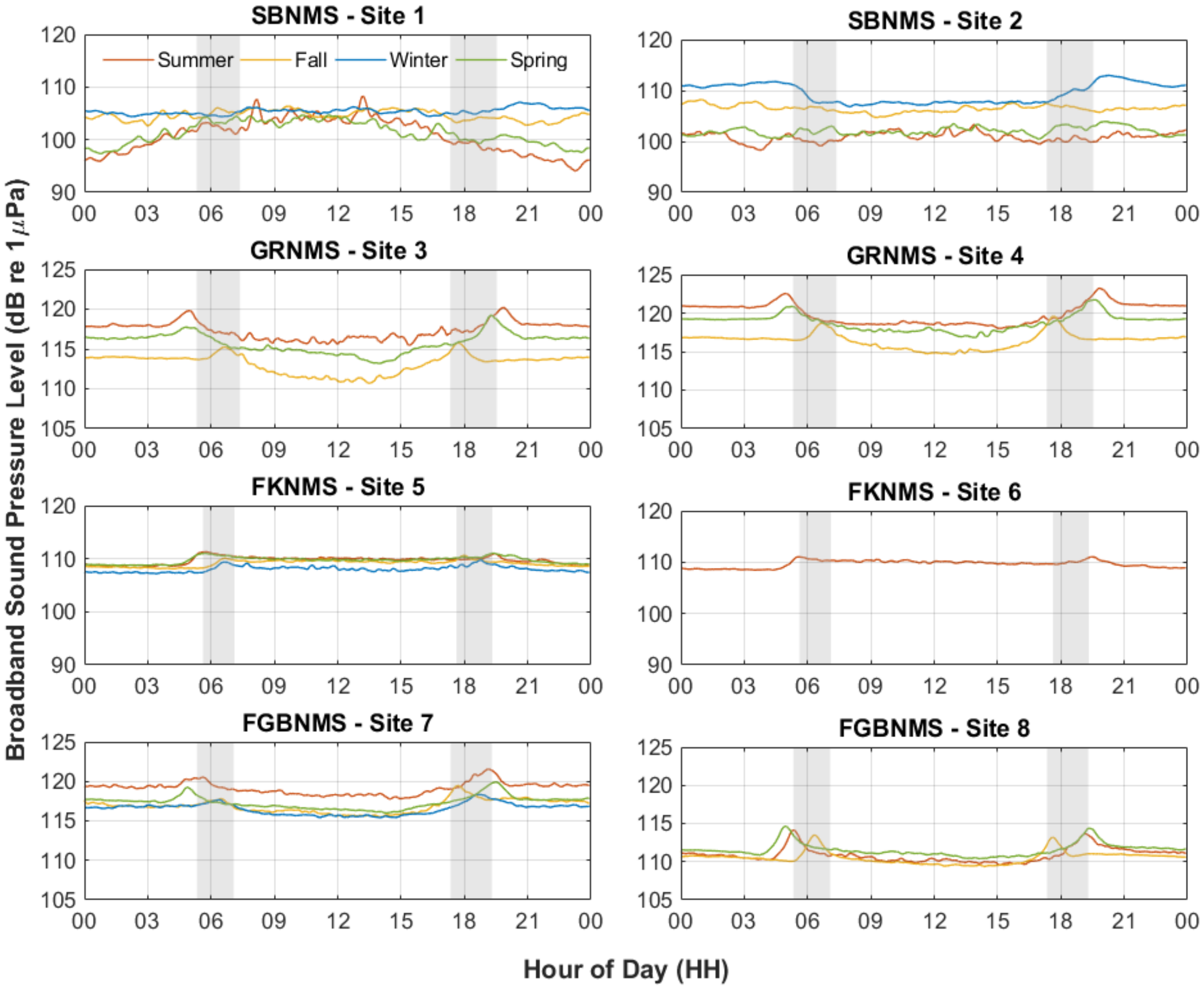

Figure 2. Diel time series plots showing seasonal averages (5 min averaging bins) of broadband sound

standard time). Stellwagen Bank National Marine Sanctuary (SBNMS), Gray's Reef National Marine Sanctuary

standardized for local standard time at each site.

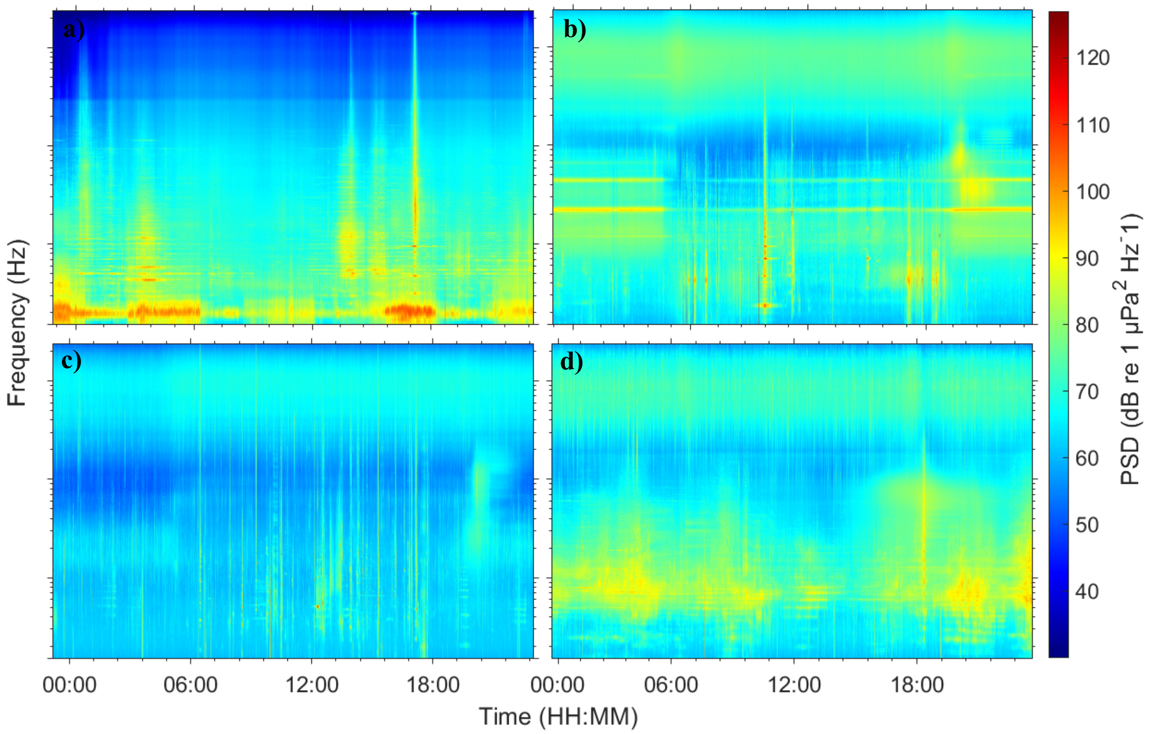

Figure 3. Spectrogram showing 24 h sample. a) Site 2 in SBNMS (Fall, full moon), b) Site 4

identical in each spectrogram.

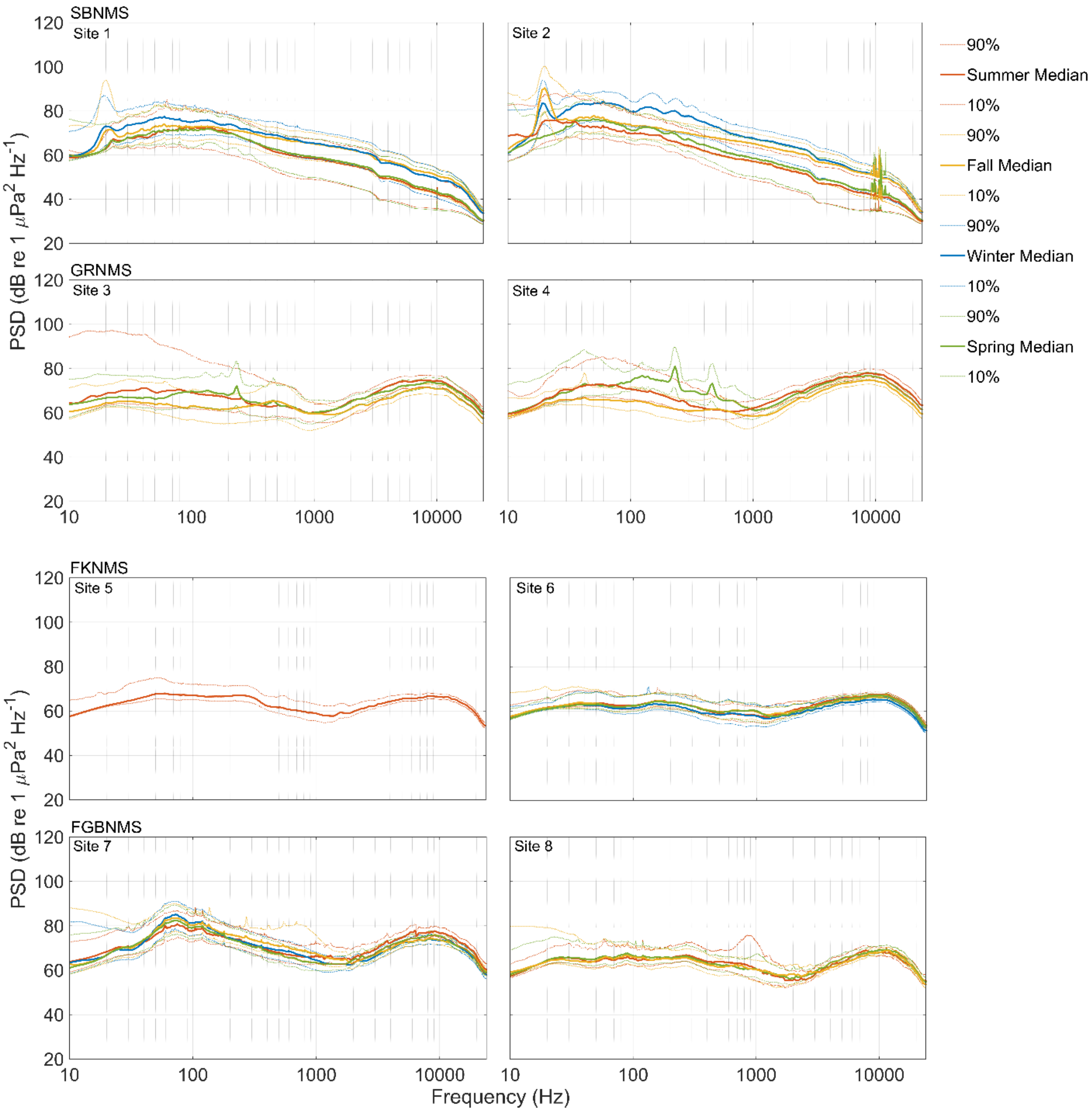

Figure 4. Seasonal power spectral density levels for each recording site, including median, 10th

3.1.3 Vessel presence and contribution to the soundscape

At Site 1 within SBNMS, over the three days per summer moon phases manually examined for vessel presence, there was the highest vessel occurrence within this study, with 90.6 % of the hours analyzed including vessel sound (261 of 288 h), and a daily average of 21.75 ± 0.4 h of presence per day (Table S5). Due to the high proportion of total hours with vessel presence, SBNMS was excluded from the further detailed vessel analysis as there were too few hours available to compare times with vs. without vessel presence.

3.1.4 Detection and classification of biological vocalizers

Atlantic cod

The number of cod vocalizations varied greatly between the two sites in SBNMS and among seasonal recording periods. Winter and Spring periods had the fewest numbers of detected calls, with seven and one vocalization(s) respectively. During the Spring recording period the only vocalization was detected at Site 1 (Figure 5). The Summer period had an intermediate number of vocalizations detected at both Site 1 and Site 2, with 32 and 29 vocalizations respectively. The Fall recording period had the largest number of vocalizations detected, with a substantially higher number of calls at Site 1 compared to Site 2 (4903 and 32 respectively). The peak of the vocalizations was recorded on the 24th of November 2016, with 715 true calls, three days after the third quarter moon phase.

Low frequency vocalizing whales

True detections of vocalizations from fin, sei and North Atlantic right whales were identified in all seasonal recording periods. Fin whale vocalizations had the highest daily presence, these were present every day during the Summer, Fall and Winter recording seasons at Site 2 (Figure S1). These were also high in daily presence at Site 1 occurring in 62.2 %, 90 % and 90.2 % of days during the Summer, Fall and Winter recording periods respectively. There were no fin whale vocalizations detected at either site during the Spring recording period (Figure S1). Sei whale vocalizations were present at both sites during all seasonal recording periods. Vocalizations were present at Site 1 for 8.1 %, 20 %, 54.9 % and 44.1 % and at Site 33 for 29.7 %, 24 %, 74 % and 91.2 % of days in the Summer, Fall, Winter and Spring recording periods respectively. Vocalizations from North Atlantic right whales were present during all recording periods at Site 2 (Summer: 2.7 %, Fall: 20 %, Winter: 21.6 % and Spring: 29.4 %) and all with the exception of the Summer period for Site 27 (Fall: 4 %, Winter: 49 % and Spring: 11.8 %).

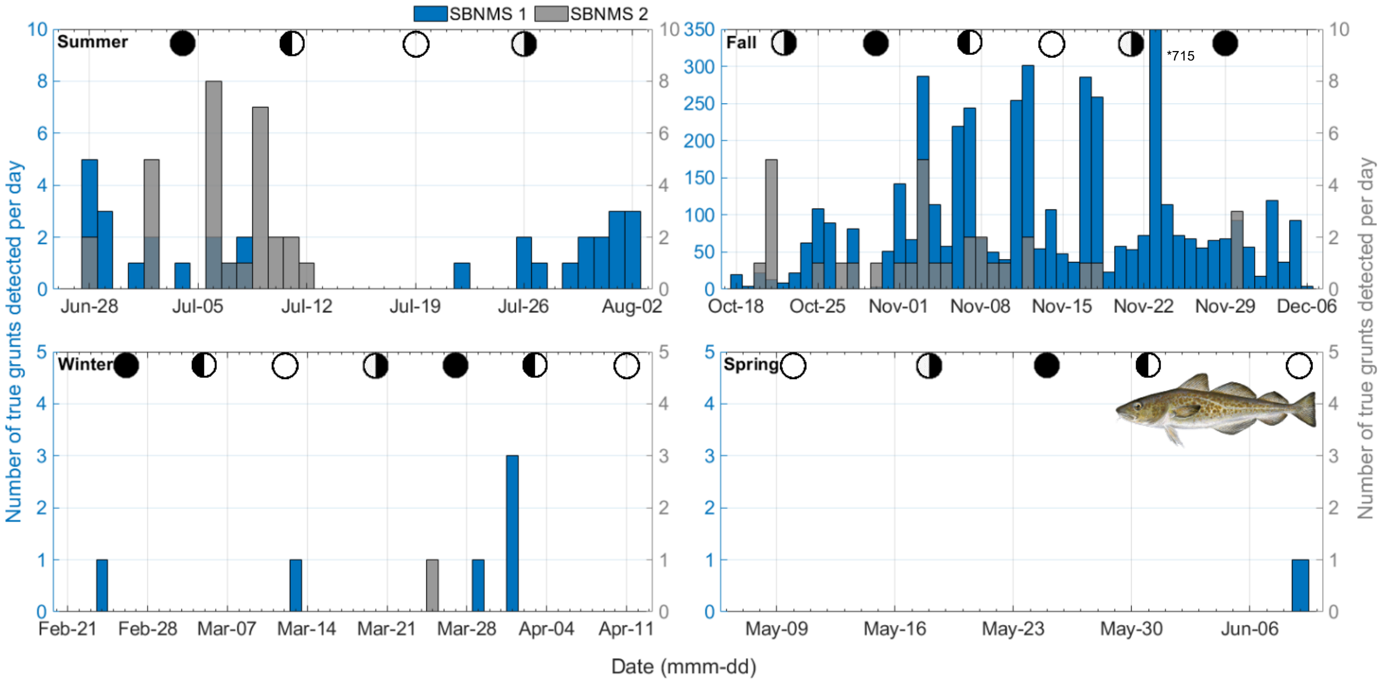

Figure 5. Daily number of true cod grunts detected during the seasonal recording periods at Site 1 & 2 in

3.2 Gray's Reef National Marine Sanctuary

3.2.1 Patterns in broadband sound pressure levels

Broadband (10 – 24000 Hz) SPLs (both median and RMS values) varied by as much as 10 dB among recording sites and seasons within GRNMS (110.6 – 123.9 dB re 1µPa, Table 2). Season significantly affected BB SPL at both sites when using both 60 s and 60 min averaging (Kruskal-Wallis; $P = <0.001$, Mann-Whitney; $P = <0.001$, Table 2 & S2). The highest median BB SPLs occurred during the Summer recording period for both sites within GRNMS, followed by Spring and lastly the Fall recording period for both sites. No data was available for the Winter period. On average, Site 4 had consistently higher BB SPLs than Site 3 during all seasonal recording periods.

Diel seasonal averages of BB SPL were relatively consistent between recording sites (Figure 2). Both sites showed a consistent rise in BB SPL around dawn and dusk, which followed temporal and seasonal patterns in sunrise and sunset times (length of day). Both sites within GRNMS tended to peak around sunrise and sunset for approximately 1.5 hours, with daytime hours (defined as post-dawn peak to pre-dusk peak) being lower than nighttime hours (defined as post-dusk peak to pre-dawn peak).

There were no strong linear relationships ($r > -0.5$ or 0.5) between BB SPL and wind speed (m/s) or wave height (m) at either site within GRNMS. Sites had weak to moderate correlations, with the Summer period exhibiting the strongest of all seasons (wind; $r = 0.24$ & 0.39, wave; $r = 0.200$ & 0.181 at Site 4 and Site 5 respectively) (Table S3).

3.2.2 Seasonal and lunar spectral composition

In terms of spectral composition, both sites within GRNMS had similar overall shapes/frequency contributions with shared biotic signals such as snapping shrimp and toadfish (Figure 4, panels 3 & 4).

Both sites were largely dominated by the acoustic signals of snapping shrimp, these snaps produced a broadband rise in the spectra at both sites between ~2 – 15 kHz. which was consistent through all recording seasons sampled (Figure 4, Figure S1c & d). As the two sites within GRNMS were relatively shallow (~ 20 m ± 1 m), there was also low frequency signal (10 – 500 Hz) associated with the wind and waves acting on the water surface (Figure 4). Periods of high winds, at times, caused an increase in broadband SPL, however, these factors were only mildly statistically correlated at Site 4 during the Summer recording period (Pearson correlation; r (682)

= 0.39, P = <0.001) (see above section). There were two large spectral peaks in the mid frequencies (~230 Hz and again at ~460 Hz), which were most pronounced during the Spring recording periods, at both sites but with Site 4 being most evident (Figure 3 & 4, Figure S1c & d). These peaks were the fundamental and harmonics of the calls produced by a toadfish species, thought to be the oyster toadfish (*Opsanus tau*), and raised the 258 Hz 1/3 octave band by as much as 15 dB re 1 μPa^2 during the spring.

Sites within GNMS showed stable broadband SPLs and were generally most influenced by the increase in snaps from snapping shrimp at dawn and dusk. This increased broadband SPLs by as much as 6 dB re 1μPa at both sites during the Summer, and 8 dB and 6 dB re 1μPa at Site 4 and Site 3 respectively during the Spring recording period (Figure 6 & S2A). Infrequent and close vessel passage (Figure 6d ~12:20 – 13:30), SCUBA diving activity (Figure S2d ~12:00 25th, 26th & 27th July, Site 3), intense periods of fish chorusing, contact with the hydrophone stand, and times of heavy rain and/or thunder (Figure S2d ~09:00 18th July, Site 3) were also found to raise the broadband SPLs and were also seen to influence all 1/3 octave band measured (251, 501, 630, and 1258 Hz). During the Spring recording period 1/3 octave band sound pressure levels showed strong diel patterns, with Site 3 showing a distinctive peak around dusk in all select octave bands. This resulted in a 33 and 28 dB re 1μPa increase in the 501 & 630 Hz band respectively for around 4.5 hours, which was more pronounced around the full moon phase (Figure S2). At Site 4, these peaks were not limited to dusk and SPLs in 251 and 501 Hz bands would peak around dusk and remain elevated through the dark hours and then drop off around dawn (approximately 10 hours). This pattern was most pronounced around the 1st quarter and full moon. These two bands would also rise from dawn till around noon and then drop until dusk (Figure 6).

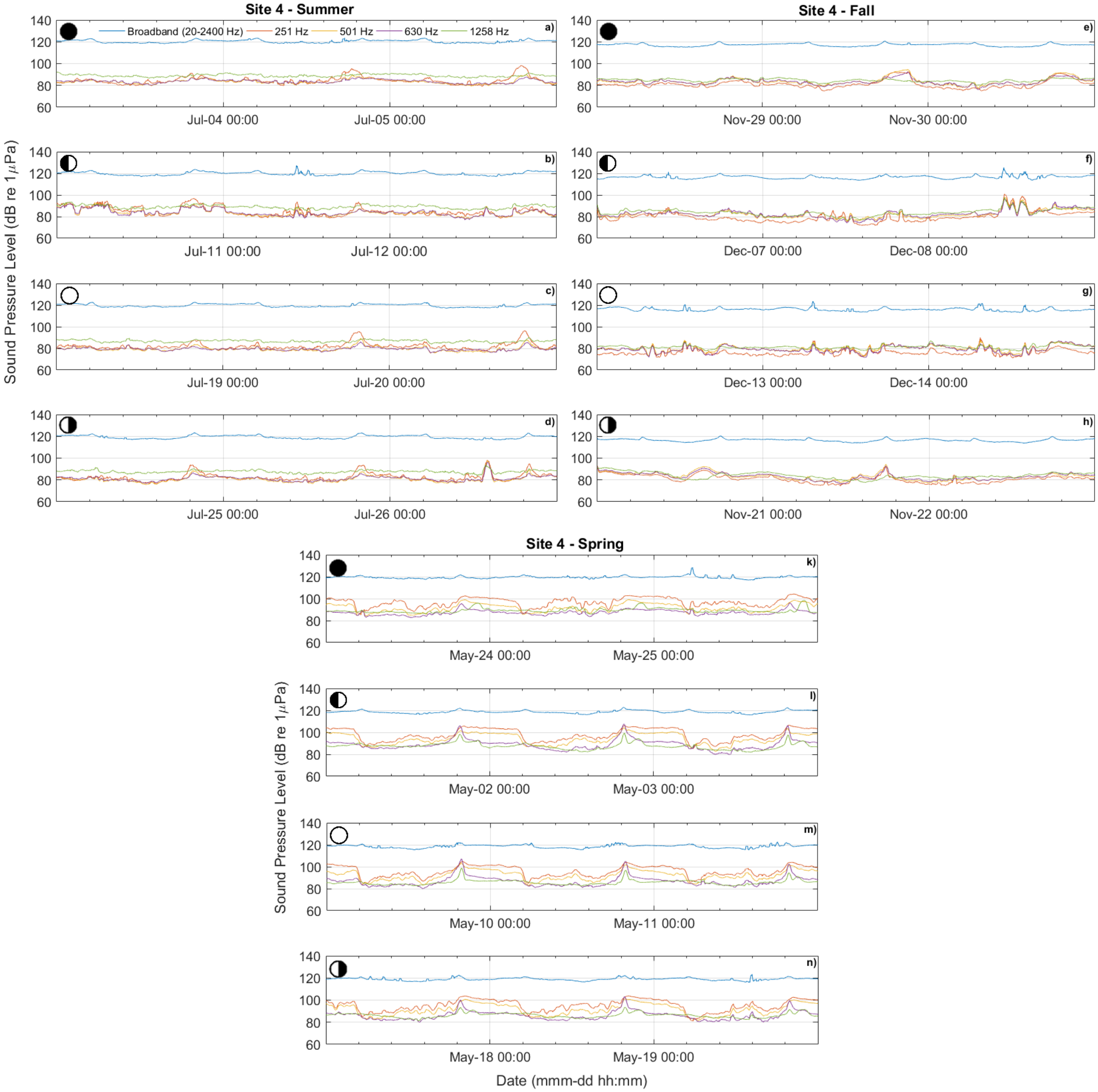

Figure 6. Sound pressure levels in 1/3 octave bands centered on 251 Hz, 501 Hz, 630 Hz, 1258 Hz,

open, closed, and left half open circles indicate new, first quarter, full and third quarter moons

3.2.3 Vessel presence and contribution to the soundscape

At Site 3 within GRNMS, over the three days per summer moon phases manually examined for vessel presence, there was a low occurrence of vessel presence in the recordings (6.6 % or 18.9 of 288 h). This site had a daily average of 1.58 ± 0.5 h of vessel presence per day (Table S5) and was the lowest occurrences of the study.

Removing times with vessel presence reduced the median SPL in the lower 1/3 octave frequency bands (bands centered on 251.2 Hz and below) by up to 4 dB and up to 12.5 dB re 1µPa in the 90th percentile (Figure 7). However, the 1/3 octave bands centered on 316 Hz and above, the median and 90th percentile SPL slightly increased by up to 2.8 dB re 1µPa ± 0.1, as it removed biologically significant times of the day increase SPL in these bands.

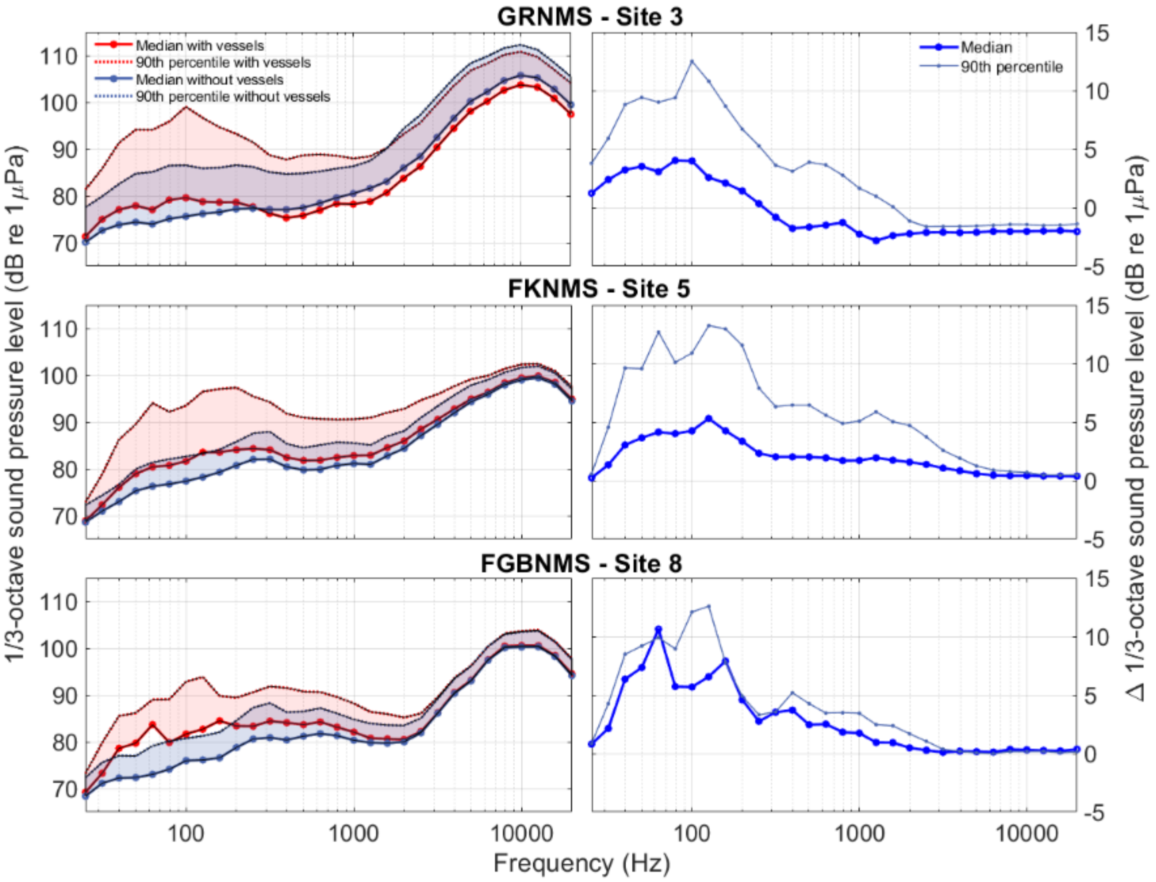

Figure 7. Median and 90th percentile in 1/3 octave sound pressure levels (left panels) and median and

presence.

3.2.4 Detection and classification of biological vocalizers

Snapping shrimp

Sound from the snaps of snapping shrimp were present in all recordings at both sites within GRNMS. Snap signals were quantified in terms of both snap detection rate (per 60 seconds) and the SPLs of the snap associated frequency band (2000 – 20,000 Hz) during the three recording seasons. In general, Site 4 had higher overall snap rates than Site 3 for every seasonal recording period within GRNMS (Table 3, Figure 8). The Spring recording periods had the highest seasonal snap rates at Site 3 and Spring and Summer were equally high at Site 4.

At a 24-hour time scale, both sites within GRNMS exhibited typical, strong diel patterns in snap rate, with an increase around dawn, dusk and midnight time segments compared to noon rates (Table 3, Figure 8). There were significant differences in snap rate among the time segments (Dawn, Noon, Dusk & Midnight) within each site in GRNMS (Friedman Test; $P = <0.001$), with the Noon time segment consistently lower snap rates that the other three segments. During the Summer both sites exhibited significantly higher snap rates during Dawn and Midnight (Table 3). During the Fall and Spring recording periods Site 3 showed significantly higher rates during Dawn, Dusk and Midnight, compared to Noon, whereas at Site 4 during the Fall and Spring, Dusk and Midnight were significantly higher compared to Dawn and then Noon (Table 3).

Low frequency vocalizing whales

There were no validated detections of vocalizations from either fin, sei or North Atlantic right whales in any seasonal recording periods.

Table 3. Median snap rate per season (bold) and Median snap rate within Dawn, Noon, Dusk and Midnight time segments of the seasonal recording periods. Asterisks indicate significant difference detected among snap rates for the different time segments within a site and season, and lower-case letters indicate differences among seasons or time periods within a site (Friedman Test and subsequent Tukey Test). Gray's Reef National Marine Sanctuary (GRNMS), Florida Keys National Marine Sanctuary (FKNMS), Flower Garden Banks National Marine Sanctuary (FGBNMS). Seasons: Summer (June - Sept), Fall (Oct – Dec), Winter (Feb – April), Spring (May – July).

NB. Shaded cells signify the sampling season (grey) and time segment (blue) with highest snap rate per site.

Sanctuary	**GRNMS**		**FKNMS**		**FGBNMS**	
Site	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
Summer	**675 b**	**864 a**	**361**	**362 b**	**377 b**	**306 b**
Dawn	904 a	1006 a	340 b	341 b	318 b	253
Noon	461 c	665 c	335 b	340 b	384 a	284
Dusk	670 b	838 b	378 a	356 a	381 a	307
Midnight	855 a	997 a	297 c	292 c	355 b	296
Sig	*	*	*	*	*	
χ^2	68	68	61	58	22	5
P	<0.001	<0.001	<0.001	<0.001	<0.001	0.2
Fall	**452 c**	**639 b**		**296 c**	**300 c**	**189 c**
Dawn	457 a	672 b		285 a	274 b	205 a
Noon	231 b	398 c		275 b	244 c	139 b
Dusk	495 a	725 a		311 a	317 a	228 a
Midnight	479 a	703 a	-	252 b	280 b	196 a
Sig	*	*		*	*	*
χ^2	78	62		66	50	76
P	<0.001	<0.001		<0.001	<0.001	<0.001
Winter				**237 d**	**294 c**	
Dawn				258 a	286 a	
Noon				201 b	232 b	
Dusk				263 a	226 b	
Midnight	-	-	-	208 b	291 a	-
Sig				*	*	
χ^2				22	45	
P				<0.001	<0.001	
Spring	**685 a**	**869 a**		**614 a**	**446 a**	**335 a**
Dawn	783 a	970 a		555 b	373 b	308 b
Noon	491 b	622 c		546 b	384 b	291 c
Dusk	722 a	885 b		638 a	410 a	327 a
Midnight	726 a	916 a	-	533 b	423 a	314 b
Sig	*	*		*	*	*
χ^2	72	64		53	37	51
P	<0.001	<0.001		<0.001	<0.001	<0.001

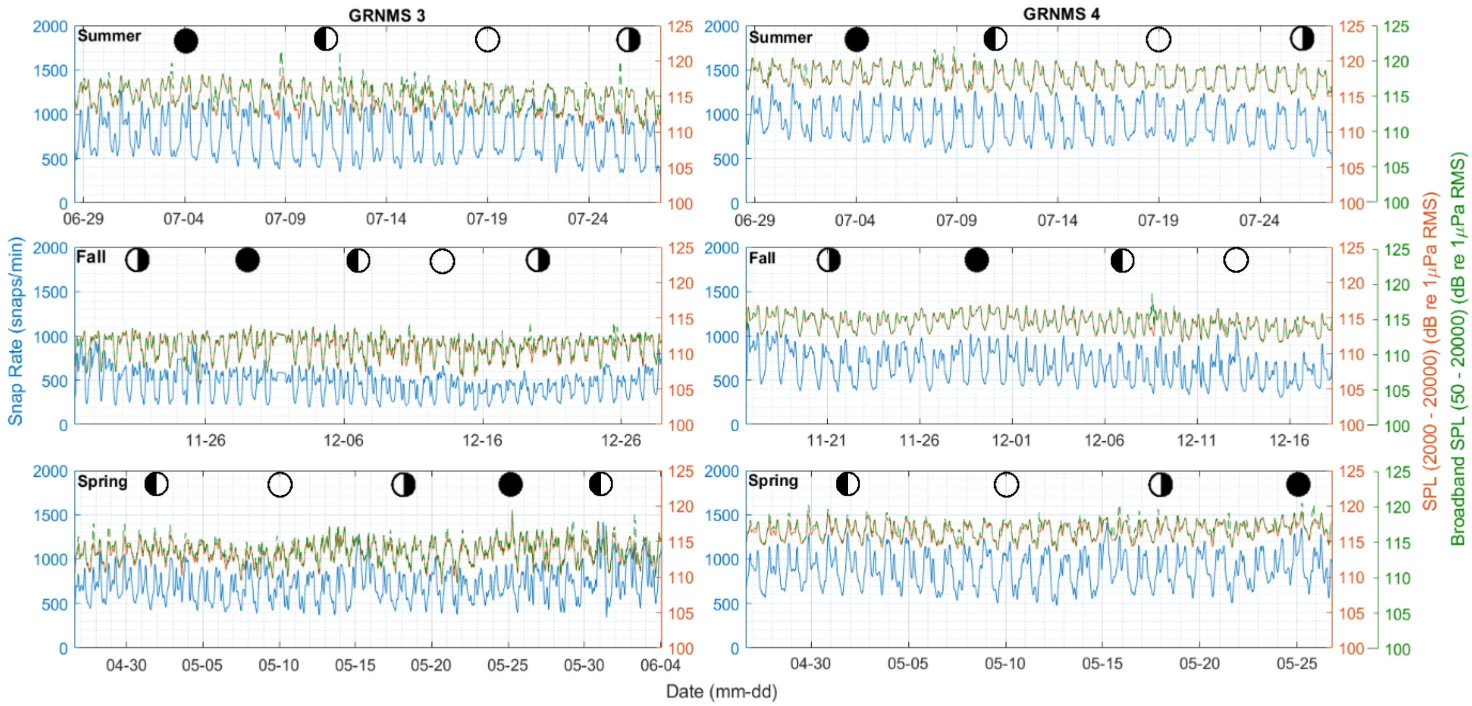

Figure 8. Patterns in snap rate of snapping shrimp over entire deployment duration for each seasonal displaying snap rates per minute (blue line), sound pressure levels (SPL) in the snap associated frequency band (2000 – 20000 Hz dB re 1 µPa RMS) (orange line) and broadband sound pressure levels (50 – 20000 Hz dB re 1 µPa RMS) moons respectively. NB. Gray shaded bars indicate time of recording loss.

3.3 Florida Keys National Marine Sanctuary

3.3.1 Patterns in broadband sound pressure levels

Broadband (10 – 24000 Hz) SPL (both median and RMS values) in FKNMS had a high degree of seasonal consistency, only varying by as much as 1.9 dB (107.8 to 109.6 dB re 1 uPa Winter and Spring respectively, Table 2). Seasonal comparisons were only available at Site 6 as Site 5 only had useable data from the Summer recording period. Season statistically affected broadband SPL at Site 6 when using 60 s averaging (Kruskal-Wallis; *P* = <0.001, Table 2), However, when using 60 min averaging there was no significant difference between Summer and Spring recording periods (Table S2). At Site 6 the Spring recording period had the highest median broadband SPL, followed by Summer, Fall and then Winter, but these differences among seasons (within 1.8 dB re 1 µPa, Table 2) were much lower than those observed at other sanctuaries.

Diel seasonal averages of broadband SPL were also extremely stable among seasons and recording sites within FKNMS. Both sites exhibited a rise in SPL around dawn and dusk, which followed temporal and seasonal patterns in sunrise and sunset times. The SPL at both sites within FKNMS peaked approximately 45 m before sunrise and post-dawn levels remained higher than pre-dawn levels. Sound pressure levels remained constant during daylight hours (Figure 2).

There were no strong linear relationships ($r > -0.5$ or 0.5) between broadband SPL and wind speed (m/s) or wave height (m) at either site within FKNMS. Site 5 had no significant linear relationship between broadband SPL and wind speed (m/s) and Site 6 had a weak correlation in the Fall, Winter and Spring recording periods (wind; $r = 0.13$, 0.27, 0.01 respectively).

3.3.2 Seasonal and lunar spectral composition

In terms of spectral composition, both recording sites within FKNMS were again the most consistent/stable among seasons (Figure 4, Table 3). Both sites had similar overall shapes/frequency contributions, with common biotic signals such as snapping shrimp and multi-species fish vocalizations present, the low frequency signals abiotic signals of wind and waves at the surface, and low to medium frequency signals of small vessels (anthropogenic) (Figure 4, panels 5 & 6).

The acoustic signals of snapping shrimp produced a relatively broadband rise in the spectra between ~3 – 15 kHz, which was consistent through all recording seasons. As the two sites within FKNMS were shallow (~ 15 & 13 m), there was also low frequency signals (10 – 500 Hz) associated with the wind and waves acting on the water surface (Figure 3 & 4). Periods of high winds, at times, caused an increase in broadband SPL, however, these factors were only mildly statistically correlated at Site 6 during the Fall, Winter and Spring recording period (see above section).

Additional to the ubiquitous peaks at dawn and dusk due to the patterns in snapping shrimp activity there were also additional episodic peaks in FKNMS recordings that did not appear to occur in any defined pattern or time of day. During the Summer recording period at Site 5 the 1/3 octave band centered on 251 Hz exhibited a diel trend in which SPL would rise (5 – 8 dB re 1 μPa depending on the moon phase) around dusk, drop by ~2 dB during the dark hours, rise back up to dusk levels at dawn, and then drop back down to daytime levels during after dawn (Figure S2). This pattern was most pronounced during the third quarter and full moon. This pattern was not observed at Site 6, except during the first quarter moon and the increase in SPL in the dark hours was less pronounced (~3 dB). Nonetheless, the dusk peaks were still present in the 501, 630 and 1258 Hz bands and would increase by as much as 15 dB around the full moon. This pattern of increase in the octave bands at dusk also continued during the Fall, Winter and Spring recording periods. Frequent episodic spikes in SPLs caused by vessel traffic were common in all season but most pronounced around noon in the Fall and Winter periods (Figure S2).

3.3.4 Vessel presence and contribution to the soundscape

At Site 5 within FKNMS, over the three days per summer moon phases manually examined for vessel presence, there was a low occurrence of vessel presence in the recordings (12.6 % or 36.6 h of 288 h, and a daily average of 3.1 ± 0.37 h of vessel presence per day) (Table S5).

Removing times with vessel presence reduced the median SPL in the lower 1/3 octave frequency bands (bands centered on 251.2 Hz and below) by up to 5.3 dB and the 90th percentile by up to 13.24 dB re 1µPa, Figure 7a & b). The 1/3 octave bands centered on 316 Hz and above decreased the 90th percentile by up to 5.9 dB re 1µPa, however, this decrease in SPL dropped to as low as 0.46 dB re 1µPa in the 5012 Hz bands and above (Figure 7b).

3.3.5 Detection and classification of biological vocalizers

Snapping shrimp

Sound from the snaps of snapping shrimp were present in all recordings at both sites within FKNMS. During the Summer recording period both sites had very similar average snap rates (361 and 362 snap/60 s) (Table 3, Figure S3a). At Site 6, there were significant differences in snap rate among seasons (Kruskal-Wallis; H = 6585, P = <0.001). Spring had the highest snap rate (614 snaps/60 s), followed by Summer (362), Fall (296), and then the Winter recording period with the lowest (237).

Over a 24-hour time scale, both sites within FKNMS exhibited a diel pattern in snap rate, with an increase around dawn, dusk time segments compared to noon and midnight (Table 3, Figure S3a). There were significant differences in snap rate among time segments (Dawn, Noon, Dusk & Midnight) within both sites in FKNMS (Friedman Test; P = <0.001), generally with Dusk and Dawn exhibiting consistently higher snap rates that the other time segments (Table 3, Figure S3a). In both sites during the Summer recording period, Dusk significantly had the highest snap rate, followed by Dawn and Noon, and with Midnight having the lowest. During the Fall and Winter periods (Site 6), both Dusk and Dawn had significantly higher snap rates to Noon and

Midnight and the Spring having significantly highest rates at Dusk compared to Dawn Noon and Midnight (Table 3).

Low frequency vocalizing whales

There were no true detections of vocalizations from either fin, sei or North Atlantic right whales in any seasonal recording periods at both sites within FKNMS.

3.4 Flower Garden Banks National Marine Sanctuary

3.4.1 Patterns in broadband sound pressure levels

Broadband (10 – 24000 Hz) SPL (both median and RMS values) varied by as much as 12 dB among recording sites and seasons within FGBNMS (108.8 – 121.9 dB re 1µPa, Table 3). Site 7 had significantly higher SPL than Site 8 over all seasons. Season significantly affected broadband SPL at both sites when using both 60 sec and 6 min averaging (Kruskal-Wallis; $P = <0.001$) (Table 2 & S2). The Summer and Spring recording periods at both sites within FGBNMS exhibited the highest broadband median and RMS SPL, followed by Fall and then Winter.

Diel seasonal averages of broadband SPLs showed similar overall patterns at both FGBNMS sites (Figure 2). Both sites exhibited a consistent peak around dawn and dusk, which followed temporal and seasonal patterns in sunrise and sunset times (length of day), for approximately 1.5 hours, with daytime hours (defined as post-dawn peak to pre-dusk peak) being lower than nighttime hours (defined as post-dusk peak to pre-dawn peak). On average, Site 7 had consistently higher broadband SPLs than Site 8 during all seasonal recording periods.

There was no strong linear relationship ($r > -0.5$ or 0.5) between broadband (10 – 24000 Hz) SPL and wind speed (m/s) at either site within FGBNMS (Tables S3), although, Site 8 showed a weak correlation in the Fall season (Pearson Test; $r = 0.18$).

3.4.2 Seasonal and lunar spectral composition

Both sites within FGBNMS exhibited a broadband rise in the spectra between ~2 – 15 kHz, and this rise was consistent through all recording seasons. Site 7 was dominated by low frequencies (40 – 150 Hz), due to long periods of stationary vessel activity close to the recording location and additional distant human activity sources (e.g., vessels and seismic sources used in oil and gas exploration). This peak was not observed at Site 8, though did exhibit a distinctive peak in the spectra at ~600 – 1500 Hz, only present in the 90th percentile. Extensive low frequency biological signals associated with the vocalizations from fishes were apparent at both sites in FGBNMS. However, due to the high proportion of overlap with the low frequency anthropogenic signals, particularly at Site 7, with anthropogenic signals, especially at Site 7, the presence of any periodicity in these biological signals was not apparent within any of the average spectral level measurements during any of the recording seasons (Figure 3 & 4).

In FGBNMS, the largest spectral features were peaks around dawn and dusk (~3 – 4 dB re 1µPa), which were seen in 1/3 octave bands centered on 251, 501, 630 and 1258 Hz. Broadband and 1/3 octave band SPLs at Site 7 were on average 6 – 9 dB re 1µPa higher than Site 8, depending on the season (Table 2 & Figure S2), and dawn and dusk maxima were less prominent due lower frequency dominance. During all seasonal recording periods except for Fall, there were episodic peaks (≤ 16 dB re 1µPa RMS) in the selected 1/3 octave band SPLs, although they did not occur in a consistent diel or other trend that could be determined. During the Fall recording period there was a substantial rise in SPLs (16 – 18 dB re 1µPa) in the 251, 501 and 639 Hz 1/3 octave bands, beginning around dusk and returning to ambient levels around midnight or just after midnight depending on the moon phase. These peaks were highest over the full and third quarter moon phases. Site 7 had a high occurrence of continuous distant anthropogenic sound, i.e., stationary and moving vessels and seismic surveying (Figure 3 & 4). The increase in SPL the lower frequencies often appeared to remove the influence of the peak in snapping shrimp acoustic activity, however, it was also found that patterns in snap rate varied from the typical dawn and dusk increase as seem in the other two sanctuaries (see snapping shrimp section below).

3.4.3 Vessel presence and contribution to the soundscape

At Site 5 within FGBNMS, over the three days per summer moon phases manually examined for vessel presence, there was a moderate occurrence of vessel presence in the recordings (27.3 % or 78.6 h of 288 h, and a daily average of 7.1 ± 0.99 h of vessel presence per day) (Table S5). Removing times with vessel presence produced a notable reduction in median SPL in the lower 1/3 octave frequency bands (bands centered on 251.2 Hz and below) reduced by as much as 10.63 dB and the 90th percentile by up to 12.58 dB re 1µPa, Figure 7e & f). Octave bands centered on 316 Hz and above decreased the 90th percentile by up to 5.2 dB re 1µPa, but above 2512 Hz the differences were negligible (< 0.28 dB) (Figure 7f).

3.4.5 Detection and classification of biological vocalizers

Snapping shrimp

Sound from the snaps of snapping shrimp were present in all files recorded at both sites within FGBNMS though Site 7 had higher overall snap rates than Site 8 for all seasonal recording periods (Table 3, Figure S3b). At Site 7, there were significant differences among seasons in snap rates (Kruskal-Wallis; H = 8861, $P = < 0.001$). Spring had the highest average snap rate (446 snaps/60 s), followed by Summer (377), and Fall and Winter (300 & 294 respectively). This pattern was also consistent at Site 8 (Kruskal-Wallis; H = 6339, $P = < 0.001$) with Spring (335) having the highest, followed by Summer (306) and then Fall (189) with the lowest.

At a 24-hour time scale both sites exhibited highly variable diel patterns in snap rate that varied among seasons. (Table 4, Figure S3b). There were significant differences in snap rate among diel time segments (dawn, noon, dusk & midnight) within both sites in FGBNMS during all recording seasons (Friedman Test; $P = <0.001$), with the exception of the Summer at Site 8. Site 7 was the most variable of all sites in, however, Dusk most often had the highest snap rate.

During the Summer recording period at Site 7, Noon and Dusk had a significantly higher snap rate than Midnight and Dawn, where as Site 8 had no significant differences. During the Fall periods Site 7 and 8, had differing patterns in snap rate, with Site 7 showing significantly highest rates during the Dusk time segment, followed by Midnight and Dawn, and then Noon. Whereas Site 8 exhibited significantly higher rates at Dusk, Dawn and Midnight segments, compared to Noon segments. During the Winter recording period Site 7 had significantly higher snap rates in the Dawn and Midnight time segments compared to Noon and Dusk. Again, in the Spring period both sites had different patterns in snap rate with Site 7 showing significantly higher rate in the Midnight and Dusk segments than Noon and Dawn. At Site 8, Dusk was significantly higher than Midnight and Dawn, with Noon being the lowest (Table 3).

Low frequency vocalizing whales

There were no true detections of vocalizations from either fin, sei or North Atlantic right whales in any seasonal recording periods at both sites within FGBNMS.

3.5 Inter-Sanctuary Comparisons

3.5.1 Patterns in broadband sound pressure

Broadband SPLs (both median and RMS values) varied substantially among sanctuaries ranging from 100.2 – 124 dB re 1µPa (Table 2). GRNMS had the highest broadband RMS SPLs across all seasonal recording periods sampled, with maximum levels recorded in the summer and fall and highest median levels in the summer and spring. The highest broadband RMS levels recorded in the winter were within FGBNMS which also showed the highest median SPLs in the fall and winter (Table 3).

Diel trends in broadband SPL also varied among sanctuaries. Seasonal average diel SPL showed similar temporal patterns among the three reef-based sanctuaries (GRNMS, FKNMS and FGBNMS), generally with a rise around dawn and dusk, and following temporal and seasonal patterns in sunrise and sunset times (length of day) due to biological signaling. SBNMS showed a dissimilar pattern in average diel SPLs from the other sanctuaries, which varied among seasons (Figure 2). Broadband (10 – 24000 Hz) SPL (both median and RMS values) in FKNMS showed the highest consistency among recording sites and seasons, and SBNMS exhibited the most variation.

3.5.2 Seasonal spectral composition

Among sanctuaries, seasonal frequency power spectra varied in overall appearance, due to differing biotic, abiotic and anthropogenic signals contributions. Sites within GRNMS, FKNMS and FGBNMS exhibited a similar broadband rise in the spectra between ~2 – 15 kHz, and this rise was consistent through all recording seasons. Sites within GRNMS displayed the greatest variability in the mid-range frequencies (100 – 10000) among seasons. Again, FKNMS showed the highest consistency in both PSD and frequency distribution among sites and seasons, and SBNMS exhibited the most variation. See individual Sanctuary sections for further detail.

3.5.3 Vessel presence and contribution to the soundscape

In total, 48 days were manually examined for vessel presence, three days over each moon phase (12 days in total) during the Summer recording period for one site in each sanctuary. SBNMS had the highest occurrence of vessel presence in recordings (261 of 288 h) and an average of 21.75 hours of vessel presence per day. The lowest vessel presence was in GRNMS (18.9 of 288 h), with vessel presence in FKNMS and FGBNMS sanctuaries more moderate (36.6

h of 288 and 36.6 h of 288 h respectively). Overall, vessel presence contributed the largest amount of energy to low frequency 1/3 octave bands between 31.6 and 398.1 Hz, with 63 to 125 Hz bands being the most influenced at all sites. Only GR, FK and FGBNMs had enough variance in vessel presence to support comparison of levels between periods without vs. with vessels. Of these sanctuaries, FGBNMS had the greatest increase in median SPL due to the contribution of vessels when times with less versus more vessels were compared.

3.5.4 Detection and classification of biological vocalizers

Due to the geographically disparate locations of the sanctuaries, most vocalizing species were sanctuary specific and their presence could not be compared among sites. However, the snaps from snapping shrimp were detected at sites within GRNMS, FKNMS and FGBNMS. At a 24-hour time scale all three sanctuaries exhibited strong diel patterns in snap rate, with an increase around dawn and dusk, however, rates during the daytime and nighttime periods differed among sanctuary. Both sites within GRNMS and FGBNMS generally exhibited higher snap rates during the Midnight time segments than Noon segments (Table 4). This was not the case at sites within FKNMS, as Midnight segments were more similar to Noon segments.

Sites within GRNMS had the highest snap rates among all sanctuaries and seasonal recording periods (no sampling in winter). Specifically, during the Summer recording period both sites within GRNMS had higher snap rates than all other sites (Kruskal-Wallis; H = 10792, $P =$ <0.001) and East Flower Garden Bank exhibiting the lowest. For the Fall, snap rates at sites within GRNMS were the highest, followed by FKNMS and FGBNMS. Between the two sites available for analysis during the Winter recording season, Site 7 (FGBNMS) had a significantly higher snap rate than Site 6 (FKNMS). During the Spring period, after sites within GRNMS, Site 6 (FKNMS) had the highest median snap rate followed by Site 7 and then Site 8, both within FGBNMS (Table 3).

Sound pressure levels in the 2000 – 20,000 Hz analysis band was a significant predictor of snap rate at several sites during several seasons. At both sites within GRNMS $\mathrm{SPL}_{(\text{snap band})}$ was a significant predictor of snap rate during all seasons with the exception of Spring at Site 3. This model was stronger at Site 4 than Site 3 (Site 4: Summer – $\mathrm{SPL}_{(\text{snap band})} = 111.8 + (0.00666 * \text{snap rate})$, $R^2 = 0.87$), Fall – $\mathrm{SPL}_{(\text{snap band})} = 110.3 + (0.00625 * \text{snap rate})$, $R^2 \geq 0.87$), Spring – $\mathrm{SPL}_{(\text{snap band})} = 111.5 + (0.00558 * \text{snap rate})$, $R^2 \geq 0.87$) and Site 3: Summer – $\mathrm{SPL}_{(\text{snap band})} =$

109.5 + (0.00703 * snap rate), $R^2 = 0.75$), Fall – $\mathrm{SPL}_{(\text{snap band})} = 107.1 + (0.00839 * \text{snap rate})$, $R^2 \geq 0.62$), Spring – $\mathrm{SPL}_{(\text{snap band})} = 109.4 + (0.00579 * \text{snap rate})$, $R^2 \geq 0.31$).

At sites within FKNMS SPL did not show this same predictor strength as GRNMS, with both sites having a weak to no predictor value of SPL (2000 – 20,000 Hz) to snap rate during all seasons ($R^2 \leq 0.27$). FGBNMS was more similar to FKNMS than GRNMS with both sites also having a weak to no predictor value of SPL to snap rate during all seasons ($R^2 \leq 0.28$), with the exception of Site 8 in the Fall – $\mathrm{SPL}_{(\text{snap band})} = 104.4 + (0.0193 * \text{snap rate})$, $R^2 \geq 0.62$).

4. Discussion

The current study provides baseline acoustic characterization information exploring the contributors and drivers of daily and seasonal patterns and identified the abiotic complexities of the underwater soundscape within four fairly shallow, yet ecologically varying US National Marine Sanctuaries.

Studies investigating marine underwater soundscapes have primarily focused on temporal trends or variations within a single habitat (Curtis et al. 1999, Radford et al. 2008, Haxel et al. 2013, Staaterman et al. 2013, Staaterman et al. 2014). This effort can be very important when gaining baseline information and continued monitoring of a site or habitat to better understand changes in biological contributors, anthropogenic activities, and/or some degree of habitat ‘health’ or regime shifts (Rossi et al. 2017). However, the focus is beginning to shift to studies which focus on exploring the spatial variation within and among several underwater habitats (McWilliam and Hawkins 2013, Putland et al. 2017a, Haver et al. 2018, Haver et al. 2019). These studies improve our knowledge of soundscapes in a larger number of underwater habitats and regions, and together with temporal datasets, allows for future long-term comparisons and improved spatial management of underwater acoustic environments.

When undertaking acoustic monitoring efforts in geographically separated and biologically and physically dissimilar systems, a standardized approach towards both data collection and analyses is necessary for comparisons and long-term monitoring. The standardized equipment, field design and analyses in this study assisted in identifying measurements that most effectively summarized soundscape attributes at sites both within and among sanctuaries. Some factors remain difficult to standardize when recording among different systems but are important for data interpretation.

Due to the distinct environmental features of individual sites (e.g., differences in depth, substrate type, temperature, complexity) over wide ranging monitoring projects, direct quantitative comparisons among sites should note the possible influence in varying acoustic propagation characteristics.

In this study, the most prominent example of this is the moderately deeper (50-68 meter) locations of the recording sites in SBNMS, relative to the more similar shallow conditions of the remaining recorders (~20 meters). Depth can play a major role in how signals propagate from the source to the recorder, as the cutoff frequency increases at decreasing depths (according to normal-mode theory). Modes near the cutoff frequency are strongly attenuated and therefore the shallower the site the greater the low frequencies may be affected (Tindle et al. 1978, Tindle 1982, Putland et al. 2017a). Due to more efficient propagation of low frequencies in deeper waters, sound levels over a larger area in the vicinity of SBNMS recording sites may have contributed to levels at these sites, more than what was possible at the other recording locations. Therefore, care needs to be taken when considering SPLs among sites, especially at low frequencies. Despite this, differences in propagation characteristics cannot account for many sources of variation in soundscape parameters studied here.

Spectral composition and identification of contributors

All four US National Marine Sanctuaries were found to have differences in broadband sound pressure level (10 – 24,000), one third octave band levels and distinct spectral compositions, each with unique characteristics due to differences in biology, human use patterns, propagation properties, and climate. Unsurprisingly, there was less variation in the measured soundscape parameters within a sanctuary, compared to among sanctuaries. In three out of the four sanctuaries monitored, variation in sound levels over the course of the project among sampled locations in the same sanctuary was relatively low. However, variance among sampled locations in Flower Garden Bank National Marine Sanctuary (FGBNMS) was relatively high. The difference underscores the role that pilot projects such as this one can play in determining sampling needs for longer-duration efforts, as well as highlighting that even small protected areas can still demand higher sampling levels. Small changes in physical habitat, biological and oceanographic processes and/or human use can lead to very distinct changes in the soundscape even within a relatively short distance (Radford et al. 2010, Stanley et al. 2012, Radford et al. 2014).

In general, SBNMS soundscapes were most dissimilar to the sites within GRNMS, FKNMS and FGBNMS, with the polarizing feature being the frequency of the dominant signals within the soundscape. The frequency composition of the two sites within SBNMS were largely dominated by low frequency signals (10 – 100 Hz) with a median PSD found to be between approximately 58 – 101 dB re 1μPa^2 Hz^{-1}. This was largely due to the near constant presence of the signal created by large vessels travelling to and from Boston Harbor (Hatch et al. 2008, Hildebrand 2009). The more trafficked site in FGBNMS showed the most similarity to this pattern among the other sanctuaries. There was also a substantial peak in SBNMS recordings (up to 22 dB re 1μPa^2 Hz^{-1}) in the spectra at approximately 15 – 25 Hz during all seasonal recording periods, except for the Spring, due to the presence of the fin whale (*Balaenoptera* physalus) pulse vocalizations, which was also consistent with detection output from the Low Frequency Detection and Classification and System (LFDCS) (Baumgartner and Mussoline 2011, Morano et al. 2012). In the western North Atlantic, fin whales regularly occur within Massachusetts Bay and SBNMS (Hain et al. 1992) and have been reported to sing from approximately September through June (Clark and Gagnon 2002). In a study by Moreno *et al*, (2012) they reported fin whales vocalizations received at an acoustic listening station, very close to one of the SBNMS sites in the current study, in 814 of 817 days analyzed from October 2007 to March 2010. This differs to some extent to the results seen here at the comparable site in 2016/17, where the 20 Hz vocalizations were present in LFDSC output everyday sampled within the Summer, Fall and Winter, however, not present in LFSDS output, nor the indicative 20 Hz peak in the power spectra during the Spring Sampling Period. Fin whale vocalizations, and subsequently this peak in the spectra, were not observed in any of the other sanctuaries.

Sound levels at higher frequencies, 2 – 24 kHz, were much lower at the sites within SBNMS compared to the other sites, likely due to the absence of reef dwelling snapping shrimp. SBNMS is thought to be beyond their northern distribution (McClure 1995). However, during all the seasonal recording periods there were narrowband impulsive signals present centered around 10 kHz (9 – 12 kHz) due to the presence of signals from acoustic deterrent devices. These devices are attached to pelagic or bottom gillnets in attempt to reduce cetacean and pinniped bycatch (Mate and Harvey 1986, Coram et al. 2014).

At the reef sites within GRNMS, FKNMS and Site 8 within FGBNMS, signals at low frequencies (< 50 Hz) were largely due to abiotic factors such and wind and waves acting at the water surface (Knudsen et al. 1948) and sporadic vessel activity. Site 7 within FGBNMS was the exception to this, as it was also dominated by the lower frequency bands (40 – 150 Hz) with a peak centered around 70 Hz during all seasons with a median and 90th percentile PSD between approximately 72 – 85 dB and 87 – 91 dB re 1μPa^2 Hz^{-1} respectively. This low frequency contribution was identified to be in part due to near continuous heavy commercial shipping and to a lesser extent, distant seismic exploration (National Oceanic and Atmospheric Administration and Office of National Marine Sanctuaries 2012, Bureau of Ocean Energy Management & National Oceanic and Atmospheric Administration 2018). The northwest Gulf of Mexico is one of the most active areas of oil and gas exploration and development in the world, with approximately 150 oil and gas platforms located within 40 km of the boundaries of FGBNM (National Oceanic and Atmospheric Administration and Office of National Marine Sanctuaries 2012). These anthropogenic activities have also been documented in other areas of the Gulf of Mexico, with seismic survey sources dominating (Estabrook et al. 2016, Wiggins et al. 2016). Site 8 within FGBNMS had a similar spectral shape to Site 7 from 10 – 30 and 300 – 24,000 Hz, however it lacked this low frequency peak centered on 70 Hz. These differences observed between Site 7 and Site 8 are likely due to differences in anthropogenic activity and the distance between the two sites being outside of the propagation limits of these signals to be present in both soundscapes.

Sites within FGBNMS were the most geographically separated of all sites occurring within the same sanctuary, with Site 7 located on the mid-shelf and Site 8 located near the outer edge of the continental shelf, separated by approximately 74 kilometers, which is over double the distance of any of the other sanctuaries. Site 7 also had a heavily used shipping fareway within 10 km from the site, where as Site 8 and had less used shipping fareway at a greater distance during the recording periods (Bureau of Ocean Energy Management & National Oceanic and Atmospheric Administration 2018).

Where the low frequencies dominated in SBNMS and FGBNMS (Site 7), the shallower sites within GRNMS, FKNMS and FGBNMS (Site 8), were largely dominated by the mid- to high-frequencies (200 – 20,000 Hz). This was consistent during all seasonal recording periods, and by large, all driven by a common signal in the 2000 – 20,000 Hz frequency range and produced by various species of snapping shrimp (member of the *Alpheus* and *Synalpheus* genera) (Au and Banks 1997, Versluis et al. 2000). These sites exhibited the highest median and percentile values of PSD in this 'snap band' frequency, with a median at the peak of the band found to be between 67 – 78 dB re 1μPa^2 Hz^{-1} during the Summer and Spring recording periods. All three sanctuaries that contained snapping shrimp exhibited clear spatial differences in snap rate and generally exhibited strong seasonal and diel patterns, increasing around dawn and/or dusk, a pattern which has been previously observed in many different locations and habitats around the world (Radford et al. 2010, Ricci et al. 2016, Lillis and Mooney 2018). However, in support of the observed trend by Lillis & Mooney, 2018, not all sites showed the typically reported increased rate during dark periods compared with light periods. For example, sites within the FKNMS showed a peak in snaps at dusk and exhibited higher snap rates during the day compared to night (light and dark periods respectively). Understanding of these spatial variations in snap rate and pattern is not well understood and could be at times be due to small bathymetric and depth differences in the sound propagation and reflections. However, these inter-sanctuary variations could also be indicative of ecological differences such as species composition and the diversity of hosts (Lillis and Mooney 2018).

There were also various distinct spectral peaks in the mid-frequencies (101 – 1000 Hz) depending on the season and site. At times, these peaks were due to the vocalizations of a large number of various fish species. Most perceptible was the pulse repetition rate or fundamental frequency and 1st harmonic (peak 231 & 462 Hz respectively) of the boat-whistle calls produced by the toadfish, thought to be *Opsanus tau*, seen within GRNMS during the Spring. As water temperatures rise in the spring sexually mature males of the species establish nests and produce advertisement signals or boat-whistles for the females (Maruska and Mensinger 2009, Van Wert and Mensinger 2019). These signals also presented a peak in the spectra during the Summer recording period however to a much lesser degree due to diminishing mating season, and the fundamental frequency and 1st harmonic were higher in frequency (270 & 540 Hz respectively) due to the increase in water temperature (Fine 1978). During certain seasons fish vocalizations would constitute a traditionally defined chorus, whereby the sound from many individuals is continuously above ambient background levels for an extended period using an averaging time of 1 sec., and several distinct types of choruses were present together, however, they held their own aural or temporal niche within the soundscape. For example, at Sites 3 & 4 within GRNMS during the Spring recording period, most observable during the new moon phase, there were up to four distinctive fish choruses occupying the same time but residing in different frequency bands. During the dark hours these choruses would often peak together around dusk with two choruses subsequently dropping to ambient levels, one staying elevated during the night and dropping sharply after dawn, and one chorus exhibiting a peak around dusk and again approximately 2 hours later before dropping again. Interestingly, these choruses during the dark hours were most often frequency partitioned (peak frequency), although they also exhibited some temporal partitioning in the peak of the energy. In contrast, the vocalizations occurring during light hours were often overlapping and would not usually constitute a 'chorus' by the traditional definition. This observation gives evidence for environmental constraints (dark vs. light) and the use of different acoustic strategies to avoid masking or misinterpretation by the targeted receiver during these time periods, supporting the acoustic niche hypothesis (Krause 1993). Partitioning of the acoustic environment with temporal or frequency separation has been demonstrated in a wide variety of animal groups, including insects, birds and mammals (Wilkins et al. 2013), however, partitioning of the acoustic space in the marine environment, and especially in fishes, is not well documented (Ruppe et al. 2015, Desiderà et al. 2019).

In this study, broadband SPLs and the diel plots were used to illustrate the diel patterns and differences among sanctuaries and seasons. The use of broadband sound pressure levels illustrates the ability of certain identifiable signals to raise ambient background levels irrespective of their frequency. Various other unidentified fish, invertebrate, and marine mammal species were also regularly contributing to the monitored soundscapes, however, their acoustic intensity were either not high enough or they were not calling in significant numbers to raise the ambient background levels for detection when examining the PSD (seasonal) or averaged SPLs (60 s). For example, Atlantic cod and haddock are present and producing low frequency spawning vocalizations (40 – 400 Hz peak in energy) within SBNMS during the spring and winter seasons. However, these signals are not raising the ambient background levels over any extended duration as they are completely dominated by the higher amplitude signals of large vessels. This overlap could also be resulting in periods of acoustic masking and a reduction in the communication spaces of these animals during critical life history periods (Putland et al. 2017b, Stanley et al. 2017).

In the last decade it has become apparent that the signals produced by large vessels are increasing rapidly in many ocean regions (Hildebrand 2009). Scientists and policy makers are viewing it as a major concern as it has many implications for the populations of acoustic signalers, from behavioral changes to reduction in communication spaces during critical biological periods (Erbe 2002, Jensen et al. 2009, Halliday et al. 2017, Putland et al. 2017b, Stanley et al. 2017). In the current study, the signals from various vessel types raised the ambient sound level by up to 13.2 dB in the 251.2 Hz 1/3 octave band and below in the sites analyzed. However, at Site 1 within SBNMS where analyses were unable to be run due to the lack of time samples where the ambient soundscape did not include vessel signal, it was noted that an individual vessel transit past the hydrophone could raise ambient sound pressure levels by up 60 dB re 1 μPa between 50–2500 Hz. This frequency bandwidth overlaps with a large majority of biological sources in these sanctuaries soundscapes, potentially causing energetic masking in species who use acoustic communication during vital life history events e.g., Atlantic cod and haddock (Clark et al. 2009, Putland et al. 2017b, Stanley et al. 2017). Site 1 within SBNMS had the highest amount of vessel presence in the recordings analyzed (90.6 % of h per day), corresponding to close proximity to the Boston Traffic Separation Scheme which is utilized by large oceangoing cargo ships, tankers and cruise ships (Hatch et al. 2008). Despite this, sites within SBNMS did not exhibit the greatest median broadband sound pressure levels during any seasonal recording period and was found to be between 10.3 – 18.7 dB re 1μPa lower than the greatest site. This is likely due to the relative absence of biological contributions in the higher frequency range (> 1000 Hz), especially seasons relevant to onshore fishes spawning cycles and snapping shrimp peaks. Care must be taken when using and reporting broadband SPL metrics, as it does not reflect the frequency contributions that make up the level and is not necessarily an appropriate metric when referring to comparable levels encountered by biological receivers at different locations.

Within the shallower sanctuaries, occurrence of vessels in the recordings was much reduced (< 7.09 h/day average) and was composed of smaller vessel types. Despite this, during the times when vessels were present, they could significantly raise the SPL within the 50 – 10,000 Hz frequency band. When comparing periods of time with and without vessels, and its modification of the frequency spectra, care needs to be taken especially when removing times with vessels present. For example, this study highlighted that often high energy biological contributions can be greatly time dependent, therefore if the duration of a vessel presence spans a long enough time window, particularly at a biologically significant time of day, removing it could be also be removing time that is greatly influenced by peaks biological activity.

Teasing apart the contribution of human activities vs. abiotic sources (e.g., wind & waves) to the ambient soundscape can also be difficult, especially if there is no reliable wind speed or wave height data available in close proximity to the recording site. Site 2 (SBNMS) had the highest broadband SPLs of any site during the Winter recording period, and it also had significantly higher winds speeds during this time when compared to the other seasonal recording periods. However, when testing for a relationship in broadband SPL and wind speed and wave height there was only a moderate and weak association respectively. Site 7 (FGBNMS) had the highest wind speeds during the Fall and Winter recording periods, but again had no significant relationship between broadband SPL and wind speed. Rather than investigating the relationship between wind speed and broadband SPL, many studies have examined the relationship between windspeed and various low 1/3 octave bands (125, 160, 251, 501 Hz) and larger bandwidth low frequency bands (Erbe et al. 2015, Ceraulo et al. 2018). These 1/3 octave bands were also examined in both SBNMS and FGBNMS with only a slight increase in statistical relationship in the 501 and 1000 Hz octave bands.

Future directions

As passive acoustic monitoring capacity has increased, a variety of challenges arise from these progressively longer-term and larger-scale programs. They are producing terabytes of data over multiple years and consequently demanding storage and analysis methods that can efficiently ingest high volumes of data, identify signals of interest and effectively summarize attributes of descriptive value. Techniques such as signal recognition software or computer learning techniques and automated and semi-automated acoustic detectors seek to enable the eventual unsupervised detection, and in some cases, classification of vessels, impulsive signals, baleen whale, fishes, and invertebrates (Baumgartner and Mussoline 2011, Bohnenstiehl et al.

2016, Girdhar et al. 2016, Urazghildiiev and Van Parijs 2016, Ranjard et al. 2017, Ricci et al. 2017, Lin et al. 2018, Rice et al. 2019). While output from detectors designed to identify specific sounds of interest remain important, peak performance is often constrained to a relatively small number of target sounds (biological and anthropogenic) and specific contexts or geographic regions. Methods that necessitate significant human oversight are less feasible to apply to such large and wide-ranging datasets, and transitions to more automation often require significant training and ground-truthing with additional information sources. For example, the current study utilized a time intensive method of vessel identification by hand browsing subsampled data. While this method was accurate and sufficient for the current use, it is not sustainable for application to the entire data set. This confirmed data set, however, is useful for ground-truthing more automated approaches.

There has been significant interest by both scientists and managers in metrics that can summarize the full range of acoustical energy a soundscape of interest and extract information on the local habitats biodiversity, state and/or health (Sueur et al. 2014). However, several marine based studies and research working groups have identified the challenges and complexities in applying terrestrially derived metrics (e.g. Acoustic Richness, Acoustic Entropy Index, Acoustic Complexity Index, Acoustic Diversity Index) to marine acoustic environments. For example, a few loud or omnipresent but varying sound sources (e.g. snapping shrimp, seismic air guns, large vessels) can strongly modulate these metrics, masking other biologically important characteristics. Unlike terrestrial environments in which species are often partitioned in acoustic space, marine species tend to overlap in both frequency and temporal space (Parks et al. 2014, Staaterman et al. 2017, Bohnenstiehl et al. 2018). However, it's also important to note that the characteristics of biological signals and the health/biodiversity of a habitat may not always be directly related, therefore, applying a single metric or method is not going to necessarily represent the multitude of factors that determine this (Mooney et al. 2020). It is important that we understand these dynamic and address the biases and limitations they can potentially produce when conducting soundscape measurements.

Answering questions of management interest often requires the ability to compare both contemporary and time-series soundscape measurements among wide-ranging (regional, international) projects. Such comparisons must be able to account for or at least acknowledge the variation introduced by differences in recording location and habitat, recording hardware and/or analytics and a standardized approach towards both data collection and analysis is necessary for valuable results (Erbe et al. 2016). Increased standardization both within and among projects is therefore a subject of keen interest within the soundscape monitoring community (see International Quiet Ocean Experiment – Standardization and Marine Bioacoustical Standardization, ISO-terminology, Consortium for Ocean Leadership report—https://adeon.unh.edu/standards, https://www.iso.org/standard/62406.html, http://oceanleadership.org/understanding/u-s-quiet-ocean-project/). Within US National Marine Sanctuaries, levels of anthropogenic input of sound are not directly managed, but instead are the subject of interagency dialog and recommendations as part of NOAA's mandate to reduce or eliminate likely injury to resources within these sites (Hatch and Fristrup 2009). Understanding the relative contributions of noise from proposed new activities in relation to previous baseline conditions can be essential to site assessments of potential impacts, as well as supporting the design of mitigating recommendations. Additionally, NOAA is required to report on conditions within sanctuaries, and to update these reports over time. A standardized system-wide passive acoustic monitoring network, such as the one piloted in this study, allows for the extraction of several measures of condition "state", both contemporarily and showing trends over time, including the presence of sound producing marine wildlife, the presence of human activities, and, as developed, metrics that correspond with biological diversity (e.g., Freeman and Freeman 2016). In addition, metrics can be further developed to address reported conditions on "pressure" to the "states", including impacts associated with levels of noise produced by human activities, further defined within sanctuaries to frequencies, time periods and areas within particular biological importance. This study indicated a need for more continuous sampling early in site evaluations to quantify base sampling needs required to capture indicators of interest. With insights from this pilot as well as current work with enhanced longevity at many of these sites (https://sanctuaries.noaa.gov/science/monitoring/sound/), NOAA will be in a better position to match available resources with priority information needs. Such decisions will also benefit from continuing development and reduction in equipment cost with longer recording life.

Ongoing work is also focusing on integration of acoustic measures used together with complimentary data types and sources (e.g., environmental information, Automatic Identification System (AIS) vessel tracking, acoustic telemetry, and underwater visual surveying, as well as additional development of automated techniques) can provide more complete measures and wider understanding of ecosystem health and species interactions and potential impacts of specific sound-producing human activities (Erbe et al. 2015, Kaplan et al. 2015, Putland et al. 2017c, Staaterman et al. 2017, Stanley et al. 2017, Rafter et al. 2018, Solsona Berga 2018, Zemeckis et al. 2019). With this data integration and ground-truthing, such metrics have been used to rapidly assess large areas of coral reef habitat and assist in detection and characterization of ecological changes (Freeman and Freeman 2016). Further identification of vocalizing and chorusing species will also continue to inform studies of biological acoustic partitioning and aid in long-term monitoring of visitation patterns and acoustic ecology within these protected areas (Erbe et al. 2015).

Conclusions

The current study investigated the underwater soundscapes over a broad frequency range among four US National Marine Sanctuaries. Each sanctuary revealed a complex soundscape that was composed of some relatively rare events, such as seasonal fish chorusing or thunderstorms, and relatively common events, such as large vessel transits and shimming shrimp snaps. The variability in geographic location, physical habitat and biological inhabitants found among sanctuaries led to distinct sound signatures that varied in time, e.g., day, moon phase and season. It was found that there were different acoustic dominants among the sanctuaries, ranging from a more anthropogenically driven SBNMS to more biologically driven GRNMS and FKNMS, and with FGBNMS including a combination of both more anthropogenically and more biologically driven locations. These dominant drivers were the foremost cause of the observed seasonal fluctuations in the acoustic measurements recorded, except for strong weather events in some sanctuaries during some seasons. Among all the acoustic signals occurring, the signals from both small and large vessels stood out as the most ubiquitous and chronic soundscape influencers. The collected data begins to report on conditions in ambient sound levels and associated drivers at each sanctuary and support the generation of capacity in sanctuaries for longer-term temporal comparisons to better understand and monitor changes across the systems. The current study identified challenges to monitoring and comparing acoustic conditions in geographically and biologically dissimilar systems. It is hoped that identifying a common framework in terms of field design, equipment, and simple acoustic measurements, will encourage further compatibility and comparisons among future monitoring and management effort.

In a time of increased human use and environmental change in the world oceans it is essential to understand how to protect ecosystems and the species inhabiting them. To do this we need to establish 'baseline' understanding of the conditions of these ecosystems and define measurements that allow us to evaluate important changes in human impacts and the status of ecosystems (Staaterman et al. 2017, Ceraulo et al. 2018, Lindseth and Lobel 2018). Underwater soundscape monitoring together with other methods to document critical environmental and biological parameters can facilitate the procurement of this knowledge, monitor change and evaluate the effectiveness of management actions to either a single species, species assemblage, habitat, or ecosystem.

Acknowledgements

The authors would like to sincerely thank all of the staff at the four National Marine Sanctuaries involved in this project (Stellwagen Bank, Gray's Reef, Florida Keys and Flower Garden Banks), with special thanks to Kimberly Roberson, Lonny Anderson, Mike Buckman, Emma Hickerson, and Marissa Nuttall for their endless help with deployments, retrievals and troubleshooting throughout the project, without their tireless effort this project would not have been possible. We would also like to thank Dr. Ashlee Lillis for her assistance with methods in snap counting in these datasets, and the Passive Acoustics Group in the Protected Species Branch of Northeast Fisheries Science Center (NOAA) for LFDCS review.

Financial support was provided by National Oceanic and Atmospheric Administration's Office of National Marine Sanctuaries and National Marine Fisheries Service's Ocean Acoustics Program.

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