Natural and anthropogenic events influence the soundscapes of four bays on Hawaii Island

Heenehan, Heather L.*[a,b,c], Van Parijs, Sofie M [c], Bejder, Lars [d,a], Tyne, Julian A. [d], Southall, Brandon L. [e,f], Southall, Hugh [f], Johnston, David W. [a,d]

a Duke University Marine Laboratory, Nicholas School of the Environment, 135 Duke Marine Lab Road, Beaufort, NC, USA
b Integrated Statistics, 16 Sumner Street, Woods Hole, MA 02543
c Northeast Fisheries Science Center, National Marine Fisheries Service, NOAA, 166 Water Street, Woods Hole, MA, USA
d Cetacean Research Unit, School of Veterinary and Life Sciences, Murdoch University, South Street, Murdoch WA 6150
e Institute of Marine Sciences, Long Marine Laboratory, University of California at Santa Cruz, 115 McAllister Way, Santa Cruz, CA
f SEA, Inc. 9099 Soquel Drive, Suite 8, Aptos, CA;
* corresponding author, a: main affiliation address, c: present address hheenehan@gmail.com,

Abstract

The soundscapes of four bays along the Kona Coast of Hawaii Island were monitored between January 2011 and March 2013. Equivalent, unweighted sound pressure levels within standard 1/3rd-octave bands (dB re: 1μPa) were calculated for each recording. Sound levels increased at night and were lowest during the daytime when spinner dolphins use the bays to rest. A tsunami provided an opportunity to monitor the soundscape with little anthropogenic component. We detected a decrease in sound levels and variability in one of the busiest bays. During the daytime in the 3.15 kHz 1/3rd octave band, we detected 92 loud outliers from vessels, aquaculture, and military mid-frequency active sonar. During one military mid-frequency active sonar event sound levels reached 45.8 dB above median ambient noise levels. The differences found in the bays ilustrates the importance of understanding soundscapes to effectively manage noise pollution in marine ecosystems.

Keywords: soundscape, Hawaii, Marine mammals, acoustics, coral reef, spinner dolphin

Introduction

The sounds from living organisms, geological features and processes, and human activities, sometimes referred to as the biophony, geophony, and anthrophony respectively, during a specified time period form the acoustic environment, or the soundscape (Krause and Gage 2003, Dumyahn and Pijanowski 2011). Since sound travels efficiently underwater, marine animals rely heavily on sound, and their soundscape, for critical life functions (e.g. Cato et al. 2005). However, we also know that ocean noise levels have been increasing over the past decades (see Frisk (2012)) posing a risk to marine animals (Williams et al. 2014). Given the importance of sound for marine animals, it is critical to monitor the soundscape of marine ecosystems and understand the natural and anthropogenic factors that influence it.

Soundscape ecology, compared to the "species centered" field of bioacoustics (Towsey et al. 2014), is a more holistic approach to understanding sound (Dumyahn and Pijanowski 2011). A growing body of marine soundscape literature has established important baseline data to monitor change and assess how natural and anthropogenic events transform the acoustic environment (for examples see Staaterman et al. (2013), Merchant et al. (2014), Kaplan and Mooney (2015), Nedelec et al. (2015), Sánchez-Gendriz and Padovese (2016)). However, McWilliam and Hawkins (2014) acknowledged that there are still "large gaps" in our understanding of marine soundscapes in this growing field. Staaterman et al. (2014) published the first study to compare more than a year's worth of recordings at multiple coral reef environments. Only in the last few years have studies explicitly characterized the acoustic environment of marine mammals (Rice et al. 2014, Clark et al. 2015, Guan et al. 2015). For reasons related to the focal species, several studies focus on frequencies below 2 kHz (Staaterman et al. 2014) or even lower frequencies for fish (Kaplan and Mooney 2015). Consequently, there is a paucity of knowledge on a large and essential component of the soundscape for most marine mammals. There is also a need to understand intra-site temporal and seasonal variability and inter-site variability (Dumyahn and Pijanowski 2011) across "ecologically significant" areas (Rice et al. 2014). Moreover, to contextualize the current soundscape, there is a need to characterize "pristine" areas, or to otherwise determine a baseline soundscape (Chapman and Price 2011, Au et al. 2012, Rodriguez et al. 2014).

Anthropogenic sounds are an increasingly prominent component of many marine soundscapes (Gage and Axel 2014). Thus, it is essential to quantify how humans affect this important aspect of the ecosystem. In many marine soundscapes, the 10 to 500 Hz frequency range (as characterized by Hildebrand (2009)), is dominated by human-made sounds, especially those from commercial shipping. An important component of the band between 500 Hz and 25 kHz in shallow areas are the sounds from small vessels with a majority of the sound energy between 1 and 5 kHz (Hildebrand 2009) extending to 10 kHz (Lobel 2009). Military mid-frequency active (MFA) sonars also contribute to this range of frequencies in areas where testing and training occurs (Hildebrand 2009).

Environmental sounds are present in low frequencies between 1 and 50 Hz in the form of volcanic activity (Au and Hastings 2008) and sounds from wind in frequencies less than 100 Hz (Tricas and Boyle 2014). The sounds of breaking waves and rainfall also contribute to sound between 500 Hz and 25 kHz (Hildebrand 2009).

In this study, we monitored the soundscape of four shallow bays with popular coral reefs and recreational areas on the Kona Coast of Hawaii Island for 20 to 27 months between January 2011 and March 2013. These bays are economically important for many recreational and commercial uses (Heenehan et al. 2014). They also serve as important resting habitats for Hawaiian spinner dolphins (*Stenella longirostris*) (Tyne et al, 2015). Due to the predictable presence of spinner dolphins in these areas, they are frequented by a large year-round dolphin-focused tourism industry (O'Connor et al. 2009). Since the bays are easily accessible and popular destinations, we expected a wide range of sounds produced by human activities. As foundation species (Altieri and van de Koppel 2014), corals support some of the most diverse marine habitats (Côté and Knowlton 2014). Thus, due to the combination of coral reef habitat, the winter breeding of humpback whales and the importance of coastal areas to Hawaiian spinner dolphins (Tyne et al. 2015) we also expected a diverse range of biological sounds contributing to the soundscape in the bays.

Biological sounds in these areas span most frequencies (Hildebrand 2009). Spinner dolphins use the bays year-round to rest during the day with peak rest occurring in the late morning and early afternoon (Tyne et al. 2015, Tyne et al. 2017). Their sounds, including whistles, clicks and burst pulses range from 2 to 140 kHz and aid in navigation, foraging and conspecific communication (Brownlee and

Norris 1994, Lammers et al. 2003, Bazúa-Durán and Au 2004, Lammers et al. 2004, Benoit-Bird and Au 2009). Between mid-February and mid-March, humpback whale song is a major feature of the soundscape with peak frequencies between 200 Hz and 2 kHz (Au et al. 2012). Snapping shrimp, a major component of any shallow inshore soundscape, produce loud snapping sounds to stun prey and defend territory (Au and Banks 1998, Versluis et al. 2000) at a broad range of frequencies with peak frequencies in at 2.5 kHz (Au et al. 2012) but also contain energy to 200 kHz (Au and Banks 1998). Another important component of the soundscape are fish sounds (Hildebrand 2009). Many coastal fish species of the Hawaiian Islands use sound for "agonistic interactions and resource defense, reproduction, nest defense, feeding and vigilance" and dominate the frequencies between 100 and 300 Hz extending up to 6 kHz (Randall 2007, Tricas and Boyle 2014).

In this study we aimed to help fill some of the gaps in the marine soundscape literature by comparing more than a year's worth of recordings at multiple coral reef environments, explicitly characterizing the soundscape of important marine mammal habitat, exploring inter and intra-site variability for our four sites, and determining a baseline soundscape for these areas. This study describes the ambient noise in four bays focusing on large changes to the soundscape documented in each of the four bays. To achieve these goals this paper is organized into three sections in which we: 1) characterized the overall hourly soundscape in each of the four bays; 2) focused on the soundscape during the tsunami event of March 2011 to approximate a natural or baseline soundscape; 3) focused on the daytime hours to determine who or what is creating the loudest soundscape perturbations and quantify those perturbations.

Methods

General Methods

We deployed passive acoustic recorders to study the long-term soundscapes of four bays along the Kona Coast of Hawaii Island: Makako (Bay 1), Kealakekua (Bay 2) Honaunau (Bay 3) and Kauhako (Bay 4) (Figure 1, between 19 55° 37'N, 155 53° 45'W and 19 99 21° 40'N, 155 53° 31'W). Each logger was deployed in a sandy area of the bay (Supplemental Appendix B more information on logger location and bottom type). We made calibrated 30-second recordings every four minutes between January 8, 2011 and March 30, 2013 at a sampling rate of 80 kHz with DSG-Ocean Acoustic Loggers (Loggerhead Instruments, Sarasota, FL, USA) outfitted with HTI-96-Min/3V hydrophones (hydrophone sensitivity: within 1 dB of -186.6 dBV μPa^{-1}, calibrated by High Tech Inc., Gulfport, MS, USA) and a 16-bit computer board. All four bays were recorded between January 8, 2011 and August 30, 2012 with the Bay 2 logger continuing to record for an additional seven months through March 30, 2013. Certified scientific divers deployed the acoustic loggers in depths between 15.8 and 24.6 meters (Supplemental Appendix B more information). Approximately every two weeks we recovered, serviced and returned the loggers to the bottom of the bay in the same location. Each recording day was initially processed and marked as successfully recorded or not. We excluded malfunctions and logger servicing days from this analysis (for more details see Heenehan et al. (2016)).

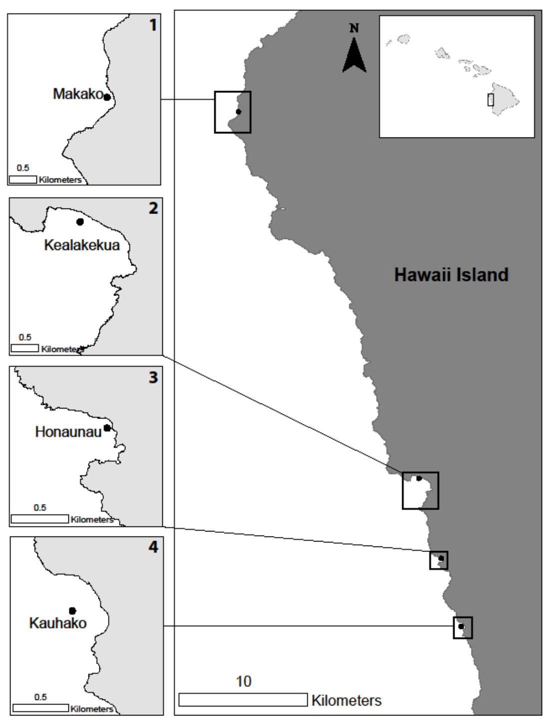


Figure 1: Map of the four study sites on the west Kona coast of Hawaii Island, the biggest of the main Hawaiian Islands between 19 55° 37′N, 155 53° 45′W and 19 99 21° 40′N, 155 53° 31′W. From North to South the four bays are Makako Bay 1, Kealakekua Bay 2, Honaunau Bay 3 and Kauhako Bay 4. Each is important marine animal habitat. For example, for marine mammals, each bay is a spinner dolphin resting area and is frequented by humpback whales during breeding season. These bays also have important benthic habitat for marine animals, including coral reefs in Bay 1, Bay 2 and Bay 3 and therefore home to numerous fish and invertebrate species.

For each of the acoustic sound files, we calculated the equivalent, unweighted ambient noise level (Leq) in standard 1/3rd-octave frequency bands (Table 1) with center frequencies from 16 Hz to 20 kHz (more detail Appendix A Table 3) using custom-written scripts in MATLAB (The Mathworks Inc., Natick MA; Version 2014a). Equivalent, unweighted ambient noise level, Leq, is used extensively in the literature for measuring ambient noise and translates an unsteady sound level in each sound recording to a constant level with equal energy (Ware et al. 2015). The equivalent noise level (King and Davis 2003, Griefahn et al. 2006) and the maximum noise level (Carter 1996, Marks et al. 2008) have both been utilized and are supported by the literature on the effects of nocturnal noise on sleep and the effects of noise on wildlife. In addition to the Leq, we also calculated the broadband ambient noise level for each 30-second recording (Table 1).

Table 1: Description of the soundscape metrics used. Leq was calculated for each 30-second recording and summarized with percentile statistics on various time scales (hourly by day, hourly overall, daily and monthly). rms dB was also calculated for each 30-second recording. TOTS and SNR were used for calculations and characterization of the sonar signal. Time segmented Leq (TOTS) was calculated the same way as the Leq metric just on smaller time segments (ten 3-second segments) within these 30-second files. The Signal to Noise Ratio was calculated using the maximum TOTS value and an L50 calculated from the July and August 2011 and 2012 files (with the sonar time period August 8-11 removed).

Metric	Description	Units	Data Used	Time	Frequency Bin	Calculation Method
Leq	equivalent unweighted ambient noise level in 1/3rd-octave bands	dB re 1 μPa	All 30-sec files	30-sec	In 1/3rd-octave bands from 16 Hz to 20 kHz center frequency	Equivalent pressure level in a 1/3rd-octave bands, unweighted
rms dB	broadband ambient noise level	dB re 1 μPa	All 30-sec files	30-sec	broadband	Root mean square pressure level across the entire frequency range
TOTS	Time segmented Leq	dB re 1 μPa	Select 30-sec files in sonar period	3-sec segments of 30-sec file (10 3-sec time segments)	In the 3.15 and 4 kHz 1/3rd-octave bands	Same as Leq in 10 3-sec time segments
SNR	Signal to noise ratio	dB re 1 μPa	Select 30-sec files in sonar period	3-sec segments of 30-sec file (10 3-sec time segments)	In the 3.15 and 4 kHz 1/3rd-octave bands	Max value TOTS calculation minus L50

To describe and characterize the soundscape over time, we calculated percentile statistics for the full Leq time series for each bay over multiple time scales (hourly by day, hourly overall and daily). The 10th, 50th and 90th percentile levels for each 1/3rd-octave band were calculated in R (R Core Team, R Foundation for Statistical Computing, Vienna, Austria; Version 3.1.0), hereafter referred to as the L10 (90th percentile), L50 (50th percentile) and L90 (10th percentile) (statistics were ordered to reflect the same process as in Hatch and Fristrup (2009)). Percentile statistics can be interpreted in the following manner: 10% of values are greater than the L10, 50% of the values are greater than the L50 and 90% of values are greater than the L90. Additionally we used minimum and maximum values to describe certain aspects of the soundscape.

An initial evaluation and principal components analysis (PCA) of the Leq in the 30-second recordings in all bands was also completed in R (R Core Team, R Foundation for Statistical Computing, Vienna, Austria; Version 3.1.0 using the markdown, rmarkdown, knitr, car, FactoMineR and ggplot2 libraries). This analysis showed that for all four bays, the 1/3rd-octave bands between 2.5 and 20 kHz were all highly correlated (See supplemental information for more detail). Therefore, in this manuscript we focused on the 3.15 kHz 1/3rd-octave band since it allowed us to represent the variability with one band, covered a large proportion of the relevant marine animal frequencies as well as both narrow, and broadband sound events of interest.

Section 1: Broad Soundscape Analysis

We broadly characterized the 24-hour soundscape of each bay for those files recorded between January 8, 2011 and August 30, 2012, using the overall hourly L10, L50 and L90 described above. The recordings from August 8, 9, 10 and 11, 2011 were removed from this initial analysis due to an extended sonar event (see Section 3). We calculated the differences (Δ) between the minimum daytime (06:00 to 18:00) and maximum nighttime (18:00 to 06:00) L50 for each bay in the 1/3rd-octave bands with center frequencies between 2.5 kHz and 20 kHz to quantify diel patterns. This frequency range spanned the bands identified by the PCA as highly correlated as well as the frequency range of spinner dolphins, humpback whales and snapping shrimp. Visualizations of the 3.15 kHz 1/3rd-octave band were made in Oriana (Kovach Computing Services, Version 4).

Section 2: Identifying the natural soundscape

In March 2011, a major earthquake off Japan caused a tsunami to descend upon the Hawaiian Islands. The earthquake registered at 19:46 HST on March 10, 2011 and at 2:59 HST on March 11 the first signs that the tsunami had reached the Hawaiian Islands were observed. The tsunami warnings ended at 11:29 HST on March 11, 2011. Given this timing, we expected to see a quieter acoustic environment due to the reduced human activity at sea (e.g.. reduced recreational and commercial boating activity) and attempts were made to quantify a natural soundscape in each bay during this natural event. We examined the hourly by day metrics for three days before and one to three days after the tsunami event in the 3.15 kHz 1/3rd-octave band and plotted these values in JMP Pro 11.

Section 3: Daytime soundscape analysis

In this part of the analysis, we used the (255) files recorded in the hours between 06:00 and 18:00 (hereafter referred to as daytime). Median daily L10, L50 and L90 in broadband ambient noise and the 3.15 kHz 1/3rd-octave band were included in a summary table to help interpret the results of this analysis. We also included information from Heenehan et al. (2016) and (2017) about the presence of dolphins in the different bays, the level of vessel activity, the vessel contribution to the soundscape and the distance to Honokohau Harbor to help interpret the results of this analysis.

To determine who or what was producing the loudest sounds in the bays we used outliers in the daily daytime Max and daily daytime L10 metrics. The Max metric was used to identify acute perturbations, namely loud files. The Max metric reflects the loudest file of the 255 recorded that day between 06:00 and 18:00. The L10 metric was used to identify more chronic perturbations, namely loud days, since the L10 is a summary metric calculated across that day's recordings. We calculated these two metrics across all recordings for each bay in the 3.15 kHz 1/3rd-octave band. These two outputs were plotted as outlier boxplots for each bay by month in JMP Pro 11 to manually identify the days with these loud 'outlier' events (i.e. loud files via the Max outliers and loud days via the L10 outliers) in each bay. Spectrograms of the days with 'outliers' were visually and aurally inspected in Raven Pro (Bioacoustics Research Program, The Cornell Lab of Ornithology, Ithaca, NY; Version 1.5) using a 512-

point DFT, 50% overlap, and a 512 point (6.4 ms) Hann window. Where possible, the sources of the sound were identified and marked with different colors on the plot. The breakdown of these outliers was also added to the summary table described above. More information on the outliers can be found in the Appendix. We also examined specific outliers in more detail by plotting finer (hourly by day) scale metrics in days before, during and after the outlier.

A military mid-frequency active (MFA) sonar exercise was recorded in all four bays for multiple periods between August 8 and 11 2011. We examined all the sound files recorded in each bay during this time and noted the presence of sonar signals in each of the four bays. Once identified, we noted that individual signals were relatively short in duration (~1.5 seconds), regularly repeated, did not persist for the full 30-second recordings, and were more limited in their frequency range compared to other anthropogenic signals. As a result, we made additional calculations of daytime sonar signals.

Initially we calculated the 3.15 kHz 1/3rd-octave band L10, L50 and L90 for each bay from the daytime (06:00 – 18:00) July and August recordings from 2011 and 2012. The MFA sonar period (August 8-11, 2011) was removed from this calculation to create a baseline against which to compare the sonar event. Next, we located all 30-second daytime files recorded during the August 8-11, 2011 sonar period for which Leq values were greater than the July/August L10 for each bay. Because the duration of individual sonar signals was much shorter than the full 30-second file, Leq was calculated again over a smaller time scale to more adequately quantify the received MFA sonar levels. All recordings identified as greater than the July/August L10, including those without the MFA sonar, were segregated into ten contiguous 3-second time segments. Leq was quantified in each time segment using custom-written MATLAB scripts. This metric was called the Third Octave Time Segment (TOTS) (Table 1). To put these sounds into context, we calculated the signal to noise ratio (SNR) using the maximum TOTS value for each file (i.e. the maximum value from the ten smaller time segments) and the July/August L50 for the respective bay. These values were plotted in JMP Pro 11 and summarized in a table. Since the energy in the mid-frequency active sonar signal spanned the 3.15 and 4 kHz 1/3rd-octave bands the same process was repeated for the 4 kHz band and the results are presented in the Appendix (Figure 16 and Table 10).

Results

Section 1: Overall Soundscape Patterns

This analysis included recordings made between January 8, 2011 and August 30, 2012. 181,124 files were recorded in Bay 1 (Makako), 159,442 files from Bay 2 (Kealakekua), 183,906 from Bay 3 (Honaunau) and 176,974 files from Bay 4 (Kauhako). The L10, L50, and L90 for all 1/3rd-octave bands between 2.5 and 20 kHz were greater between 18:00 and 06:00 (nighttime) than 06:00 and 18:00 (daytime). They generally displayed a U-shape pattern with transitions around 06:00 (from louder to quieter) and 18:00 (from quieter to louder) in all four bays (see example in the left panel of Figure 2 for the 3.15 kHz 1/3rd-octave band in Bay 1). The difference between the maximum nighttime hourly L50 and the minimum daytime hourly L50 (Δ, see left panel of Figure 2), ranged from 4.3 to 9.5 dB (Appendix A Table 4). The lowest sound levels in the bays in these bands were recorded between 13:00 and 15:00.

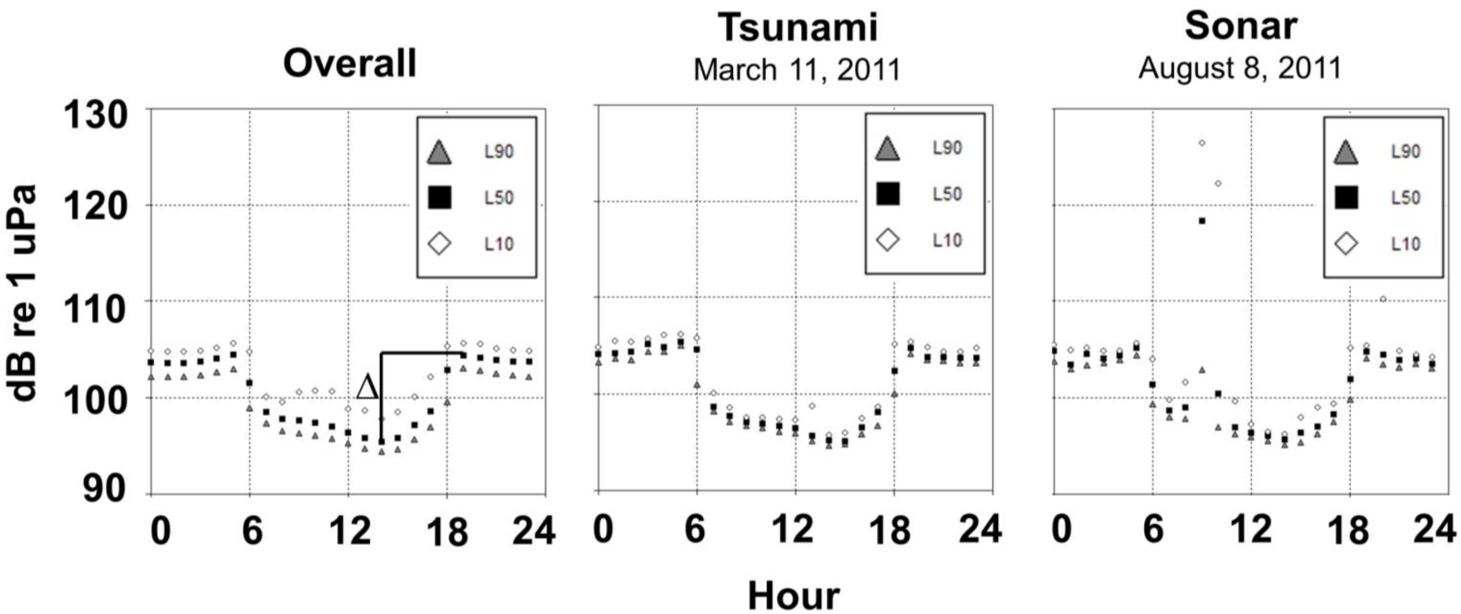


Figure 2: Visualization of the L10 (90th percentile, white diamonds), L50 (50th percentile, black squares) and L90 (10th percentile, gray triangles) in the 3.15 kHz 1/3rd-octave band Bay 1 overall (left), on March 11, 2011 (tsunami, middle) and on August 8, 2011 (sonar, right). Visualization of Δ (the difference between the maximum hourly nighttime L50 and the minimum hourly daytime L50) is also shown

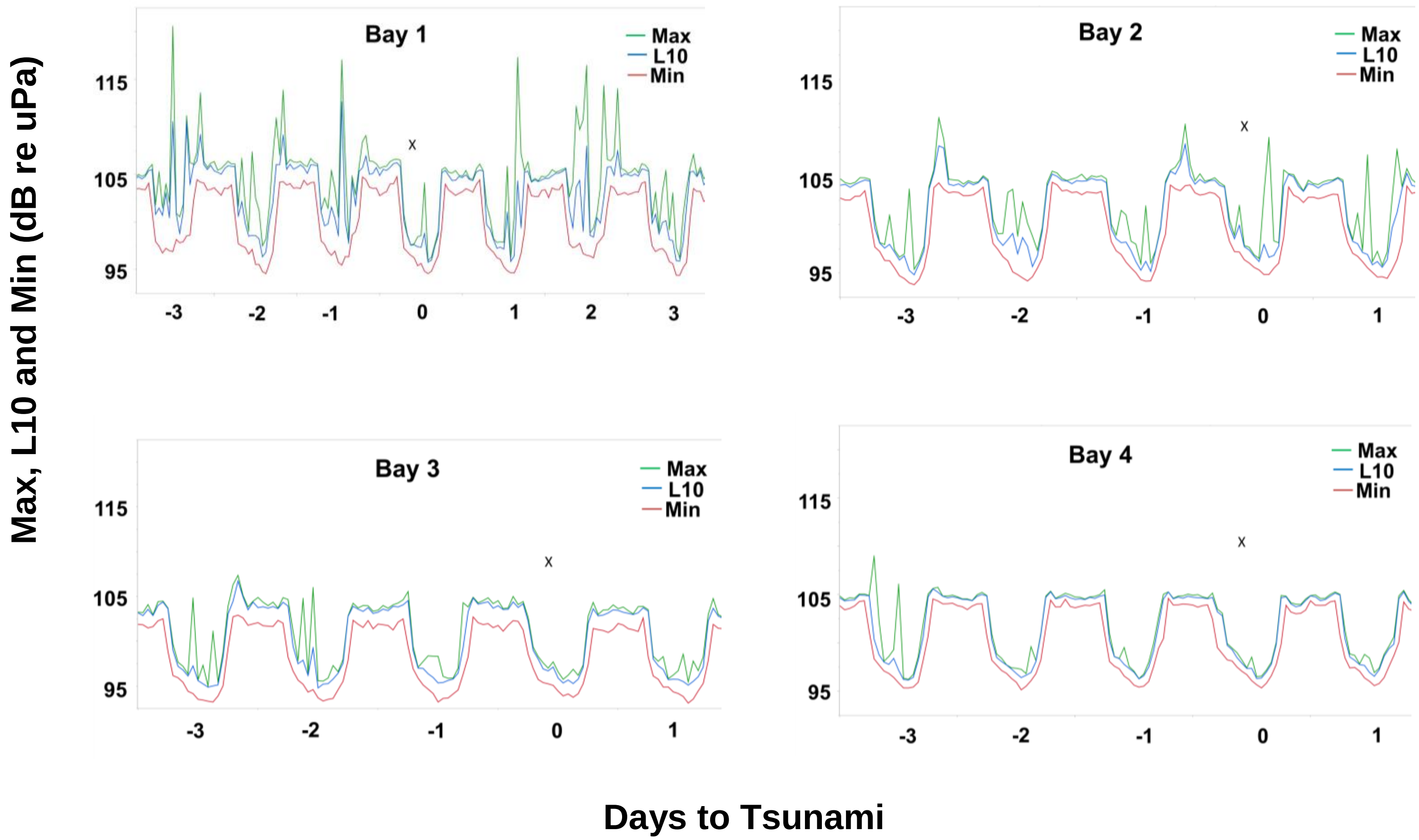


Figure 3: Hourly max (green), L10 (blue) and Min (red) soundscape metrics in the days before, during and after the tsunami in each bay A) Bay 1 3/8/11-3/14/11, B) Bay 2 3/9/11-3/12/11, C) Bay 3 3/9/11-3/12/11, D) Bay 4 3/9/11-3/12/11. The day the tsunami wave encountered the Kona coast is marked with an X for each bay. The Max and L10 values for Bay 1 are the most striking on the tsunami day as compared to the days before and after the event. Bay 3 and Bay 4 were also relatively quiet on this day. Bay 2 had something hitting the logger for much of the day resulting in elevated noise levels.

Section 2: Identifying the natural soundscape

We initially examined and compared the hourly maximum, L10 and minimum soundscape metrics in the days before, during (March 11) and after the tsunami in each bay in the 3.15 kHz 1/3rd-octave band (Figure 3). The specific number of days per bay was limited by the deployment schedule and servicing the devices. In Bay 1, we examined three days before and after the tsunami and noted a decrease in the L10 and Maximum metrics on March 11. The spike in the 13:00 hour L10 and Max in Bay 1 is reflective of the only vessel sound recorded that day (Figure 3). In Bay 2, 3 and 4 we examined three days before and one day after the tsunami. In Bay 2, we found an increase in maximum sound levels on March 11 and upon visual and aural inspection confirmed that these elevated sound levels were created by something hitting the hydrophone. In Bay 3, we found slightly lower Max and L10 levels on March 11 and no difference in Bay 4 sound levels. In all four bays, we noted no decrease in minimum recorded sound levels. There were no outliers in the minimum, L10 or maximum values around the time of the tsunami in Bay 1, Bay 3 or Bay 4. However, March 11, 2011 was a Max outlier in Bay 2 (see above for explanation of this outlier).

Given the largest change in Bay 1, we compared the overall hourly L10, L50 and L90 from Section 1 with the hourly L10, L50 and L90 from those files recorded on March 11 (Figure 2, left and middle panels). The overall hourly L90 values compared to the March 11, 2011 hourly L90 values were very similar with no further reduction in the L90 on March 11, 2011. The loudest hourly L10 value between 08:00 and 17:00 on March 11, 2011, was 98.8 dB re 1 uPa at 13:00 when the one and only vessel passed by; otherwise, the L90, L50 and L10 were close to overlapping on March 11, 2011.

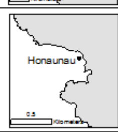
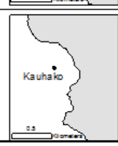
Section 3: Daytime Soundscape Analysis

This analysis focused on daytime (06:00 to 18:00) hours only. In Bays 1, 3 and 4 this analysis spanned between January 8, 2011 to August 30, 2012 resulting in 507 recording days (182,204 30-second files) in Bay 1, 497 days (178,146 30-second files) in Bay 3, and 490 days (175,718 30-second files) in Bay

4. In Bay 2, this analysis spanned from January 8, 2011 to March 30, 2013 resulting in 575 days (206,500 30-second files) of recordings.

To help put the results into context and describe different levels of anthropogenic activity across the four bays, Table 2 includes information about the level of dolphin presence (the target of dolphin tour activity from Heenehan et al. (2016)), general vessel activity based on mean values from hourly vessel scans (from Heenehan et al. (2016)), and the level of contribution of vessel noise to the soundscape (from Heenehan et al. (2017)) with darker colors indicating higher levels. For more information about these values and human use of the bays see Heenehan et al. (2014), (2016) and (2107). The median values for the daily broadband rms dB L10, L50, and L90, and the 3.15 kHz 1/3rd-octave band L10, L50 and L90 (Table 2) were included to help summarize broad patterns in ambient noise in each bay. Each soundscape metric was color-coded to display the rank from white (the quietest) to dark gray (the loudest). Bay 1 had the highest values for all sound metrics except the L90 in the 3.15 kHz 1/3rd-octave band while Bay 3 had the lowest values for all sound metrics.

Table 2: Summary of key resting bay characteristics and broad soundscape results for Bay 1, Bay 2, Bay 3 and Bay 4 (Makako, Kealakekua, Honaunau and Kauhako). A scaled map, distance to Honokohau Harbor and levels of dolphin presence, vessel activity, and motorized vessel based dolphin tours are included for each bay. These cells are colored light to dark based on human pressure. The darkest cells are those with the highest levels of vessel activity, highest levels of motorized vessel based dolphin tours, and closest distance to Honokohau Harbor. The L10, L50 and L90 for broadband rms and the 3.15 kHz 1/3rd-octave band are also shaded light to dark with darker cells representing louder decibel (dB re 1 uPa) values.

Bay	Level of Dolphin Presence (rank 1-4, lowest to highest, from Heenehan et al. 2016 and 2017)	Level of Vessel Activity (rank 1-4, lowest to highest based on mean # boats from Heenehan et al. 2016)	Vessel contribution to the soundscape (rank 1-4, lowest to highest from Heenehan et al. 2017)	Distance to Honokohau Harbor (rank 1-4, farthest to closest)	Broadband (rms dB re 1 uPa) L10	Broadband L50	Broadband L90	3.15 kHz 1/3rd-octave band (dB re 1 uPa) L10	3.15 kHz L50	3.15 kHz L90	Max Outliers Vessel	Max Outliers Sonar	Max Outliers Other	Max Outliers Total	L10 Outliers Aqua	L10 Outliers Vessel	L10 Outliers Sonar	L10 Outliers Other	L10 Outliers Total
Bay 1 	4	3	4	4	120	117	116	101	97	96	2	1		3	18	3	1		22
Bay 2 	3	4	3	3	117	115	114	100	97	95	21	2	2	25		2	1	1	4
Bay 3 	1	1	0	2	117	115	114	98	96	94	1			1		3	1	2	6
Bay 4 	2	2	0	1	118	115	115	100	97	96	26	1		27		1	2	1	4

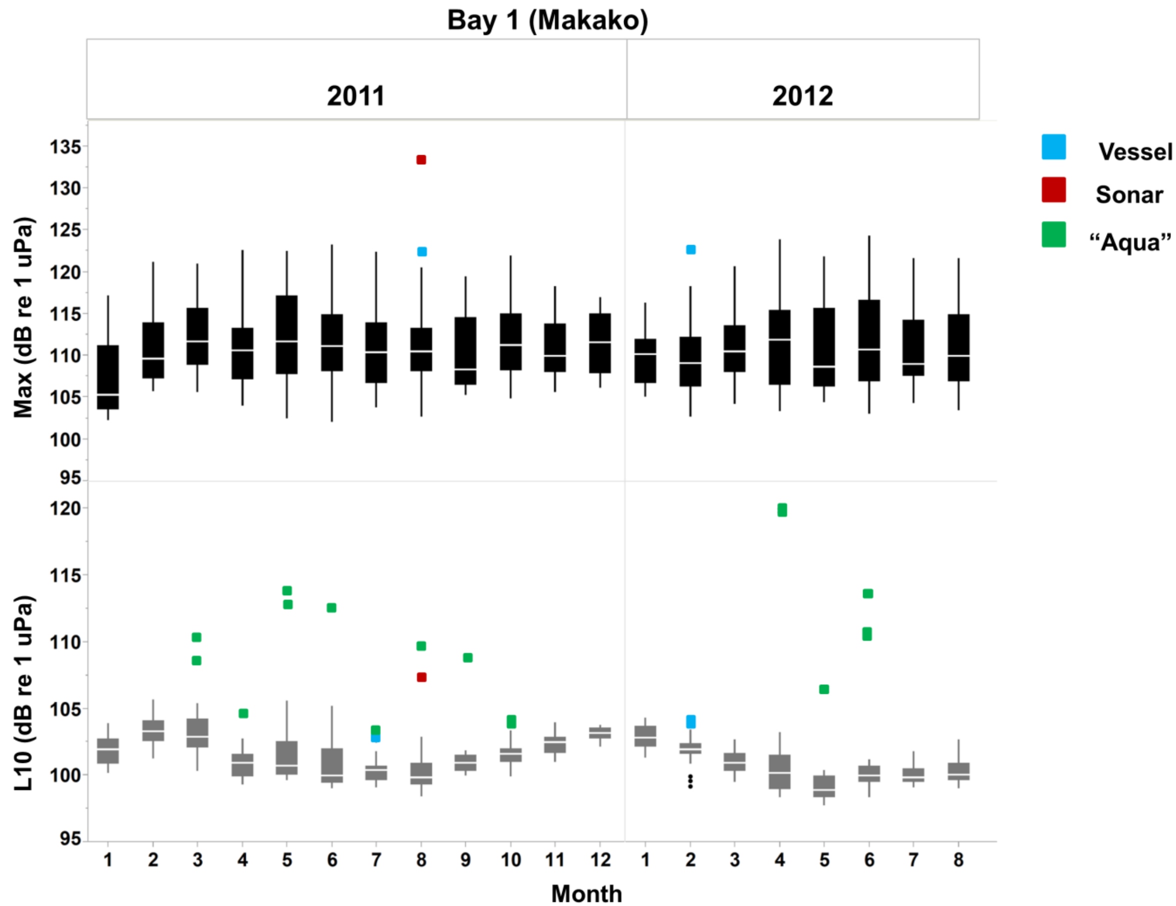


Figure 4: Bay 1, Makako Bay Max and L10 outliers colored by source of the sound. Box plots are made using daily max and L10 values binned by month. Outliers are colored blue for vessels, red for sonar and green for "Aqua" or aquaculture sound, specifically the sound of pressure washing the fish pens.

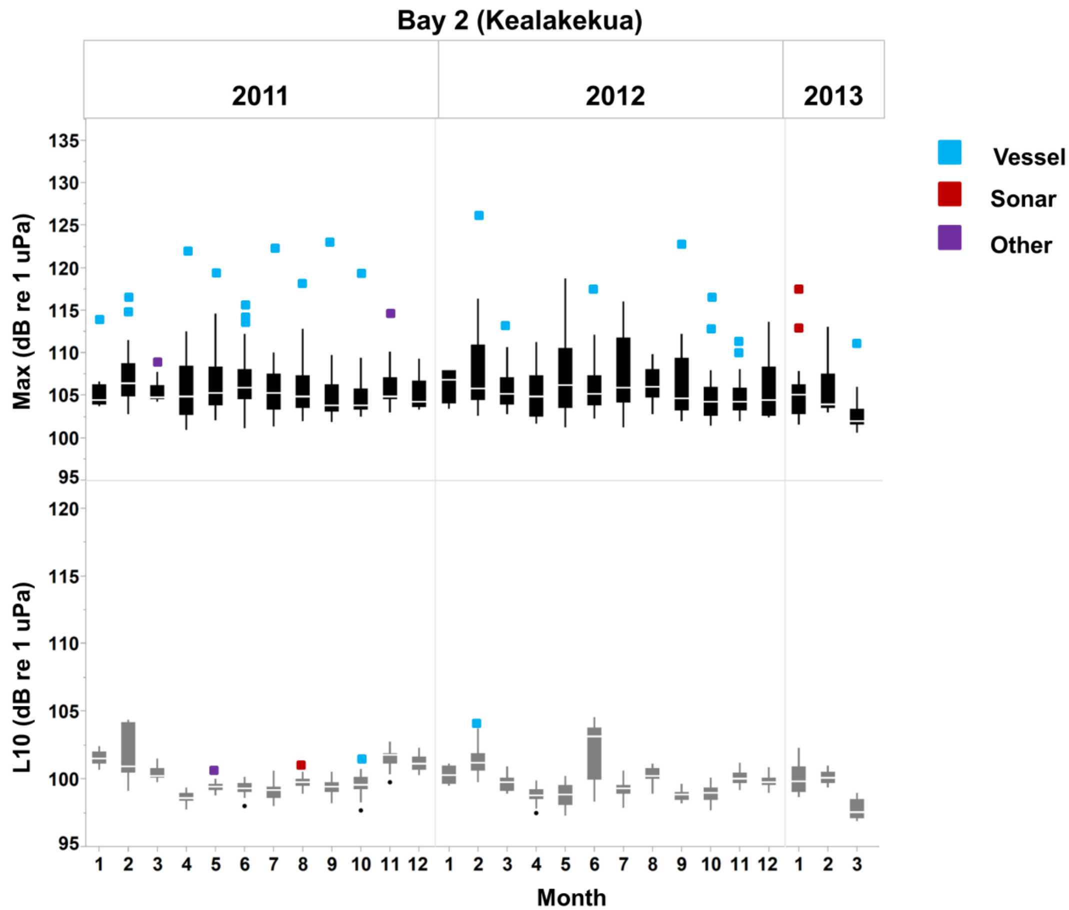


Figure 5: Bay 2, Kealakekua Bay Max and L10 outliers colored by source of the sound. Box plots are made using daily max and L10 values binned by month. Outliers are colored blue for vessels, red for sonar and purple for "other" sounds. The sources of these "other" sounds are identified in the Appendix supplemental information (Table 5 and 6). There were no aquaculture sounds in Bay 2.

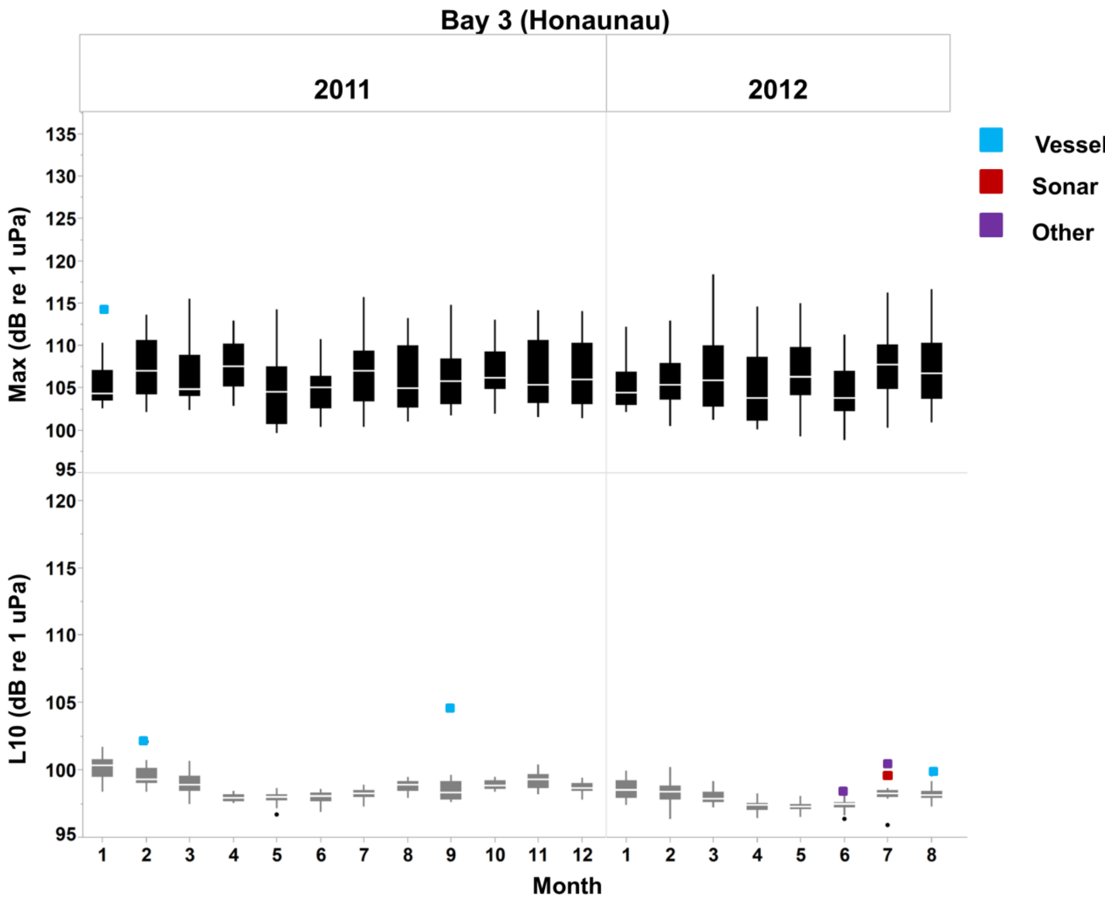


Figure 6: Bay 3, Honaunau Bay Max and L10 outliers colored by source of the sound. Box plots are made using daily max and L10 values binned by month. Outliers are colored blue for vessels, red for sonar and purple for "other" sounds. The sources of these "other" sounds are identified in the Appendix supplemental information (Table 5 and 6). There were no aquaculture sounds in Bay 3.

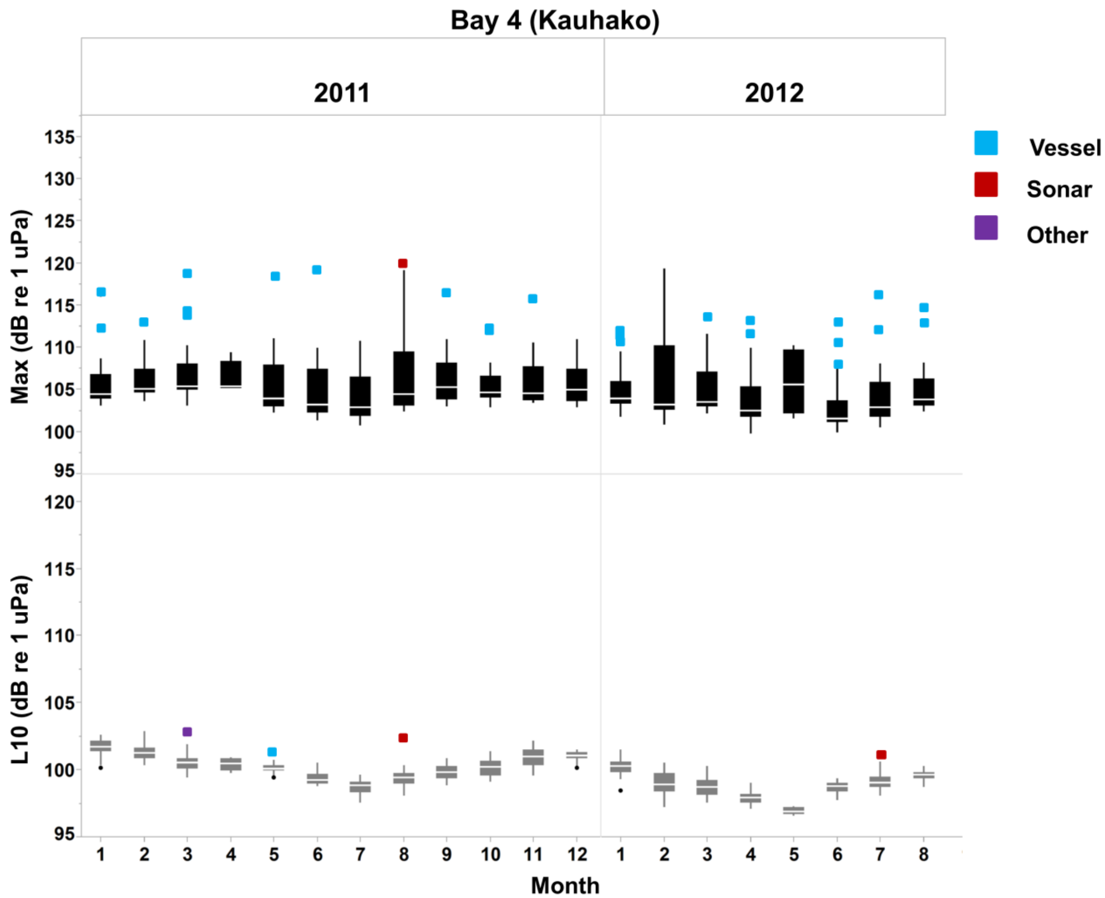


Figure 7: Bay 4, Kauhako Bay Max and L10 outliers colored by source of the sound. Box plots are made using daily max and L10 values binned by month. Outliers are colored blue for vessels, red for sonar and purple for "other" sounds. The sources of these "other" sounds are identified in the Appendix supplemental information (Table 5 and 6). There were no aquaculture sounds in Bay 4.

Using the daily 3.15 kHz 1/3rd-octave band L10 metric as a measure, the loudest months we recorded were February and March 2011 in Bay 1 (Figure 4) and February 2011, February 2012 and June 2012 in Bay 2 (Figure 5). Bay 3 and Bay 4 were much less variable than Bay 1 and Bay 2, but Bay 3 was the loudest in January 2011 (Figure 6) and Bay 4 the loudest in January 2011 and November 2011 (Figure 7).

Analysis of daily Max and L10 'outliers'

The outlier analysis identified 56 Max and 36 L10 outliers across all four bays (Table 2, Figure 4, Figure 5, Figure 6, and Figure 7). It was possible to identify the sound source for all instances of Max outliers and most of the L10 outliers through visual and aural inspection of the spectrograms. These outliers fell into three major categories of sound sources and were color-coded by source on the boxplots. "Aquaculture" sound was coded green, vessel sounds blue, sonar sound red and other sources of unidentifiable and non-specific sound were color-coded purple (see Appendix Table 7 for spectrogram examples and descriptions). Other than a few instances of sound produced by scuba divers, the three color-coded sources, vessels, sonar and aquaculture sound were the three major sources of human-generated noise in the bays.

Vessels and sonar were sources of outliers in each bay. Vessel sounds accounted for 52 of the 56 total 3.15 kHz 1/3rd-octave band Max outliers across the four bays (Table 2). All Max outliers for each bay (top Figure 4, Figure 5, Figure 6, Figure 7, and summarized in Table 2) came from anthropogenic sources including vessels, sonar and other human-made sounds (more detail in Appendix A Table 5). The L10 outliers for each bay (bottom Figure 4, Figure 5, Figure 6, Figure 7, and summarized in Table 2) came from aquaculture sound, vessels, sonar and other sounds (More detail in Appendix A Table 6). Since the L10 could not be linked to a single file, these outliers were more broadly characterized. The L10 outliers for Bay 1 were all anthropogenic.

Bay 2 (25 outliers, Figure 5) and Bay 4 (27 outliers, Figure 7) had the most Max outliers, primarily from vessel sound (Table 2). Bay 1 was generally the loudest, with the most L10 outliers, primarily from “Aquaculture.” “Aquaculture” or “Aqua” (Figure 4) was exclusively found in Bay 1 on sixteen of the twenty-one 3.15 kHz 1/3rd-octave band L10 outliers. After contacting local businesses and officials, this sound was confirmed from pressure washing the Blue Ocean Mariculture fish pens, located approximately 1 km offshore from our acoustic logger, by cross-referencing a list of days with the sound against the company’s activity logs and checking additional dates and times (See Appendix A Figure 15 and Table 8 for more information). Upon investigation of the days surrounding the March 27, 2011 and March 29, 2011 outliers other instances of the aquaculture sound were found that were not originally identified (See Appendix A Figure 15 and Table 8 for more information). Therefore, not all days with aquaculture sound were captured by the L10 outliers and the elevated sound levels in Bay 1 during March 2011 can be attributed to increased sound produced by aquaculture maintenance.

Military MFA sonar received levels

August 8, 2011 appeared as an outlier in at least one metric in each of the bays recording that day (Figure 4, Figure 5, and Figure 7). In Bay 1, this day contained the bay’s loudest outlier in the 3.15 kHz 1/3rd-octave band Max and the loudest Max outlier overall. This day was also an outlier in the Max metric in Bay 4, the loudest in that bay, and an outlier in the L10 metric in Bays 1, 2 and 4. Although the logger in Bay 3 was malfunctioning and therefore not included in these calculations, we could still confirm that we recorded sonar on August 8, 2011 in Bay 3, and therefore, all four bays.

We made additional calculations during this MFA sonar event to further characterize this signal and signal to noise ratio (Table 1). The 116 daytime files identified as having an Leq greater than the July/August L10 were manually coded 1) sonar no vessel, 2) sonar and vessel, 3) no sonar (Figure 8 and more information in Appendix A Table 9). The maximum TOTS value from Bay 1 for a code 1 file with sonar and no vessel sound was 143 dB re 1 uPa, 46 dB above the July/August L50. The maximum value for Bay 2 in a code 1 file was 122 dB re 1 uPa, 25 dB above the July/August L50. The maximum TOTS value from Bay 4 in a code 1 file was 130 dB re 1 uPa, 33 dB above the July/August L50. The maximum values for the other files greater than the July/August L10 with codes 2 or 3 did not achieve such high levels. The 4 kHz band (more detail in Appendix A Figure 16 and Table 10) displayed similar patterns.

The 3.15 kHz band metrics proved to be a useful tool to quantify the known August 2011 sonar event. This analysis also identified two additional sonar events in our recordings (red outliers in Figure 4, Figure 5, Figure 6, and Figure 7). Therefore, sonar was ultimately recorded and registered as an L10 or Max outlier on three separate occasions. The first known event, as described above was between August 8-11, 2011 in Bay 1, 2 and 4 (Bay 3 logger was malfunctioning) during an Undersea Warfare Training Exercise, confirmed by the Navy's 2012 monitoring report. The second was on July 23, 2012 captured in Bay 3 and 4. The third was between January 21-22, 2013 in Bay 2 (the only bay recording at the time) during an Undersea Warfare Training Exercise, confirmed by the Navy's 2014 monitoring report.

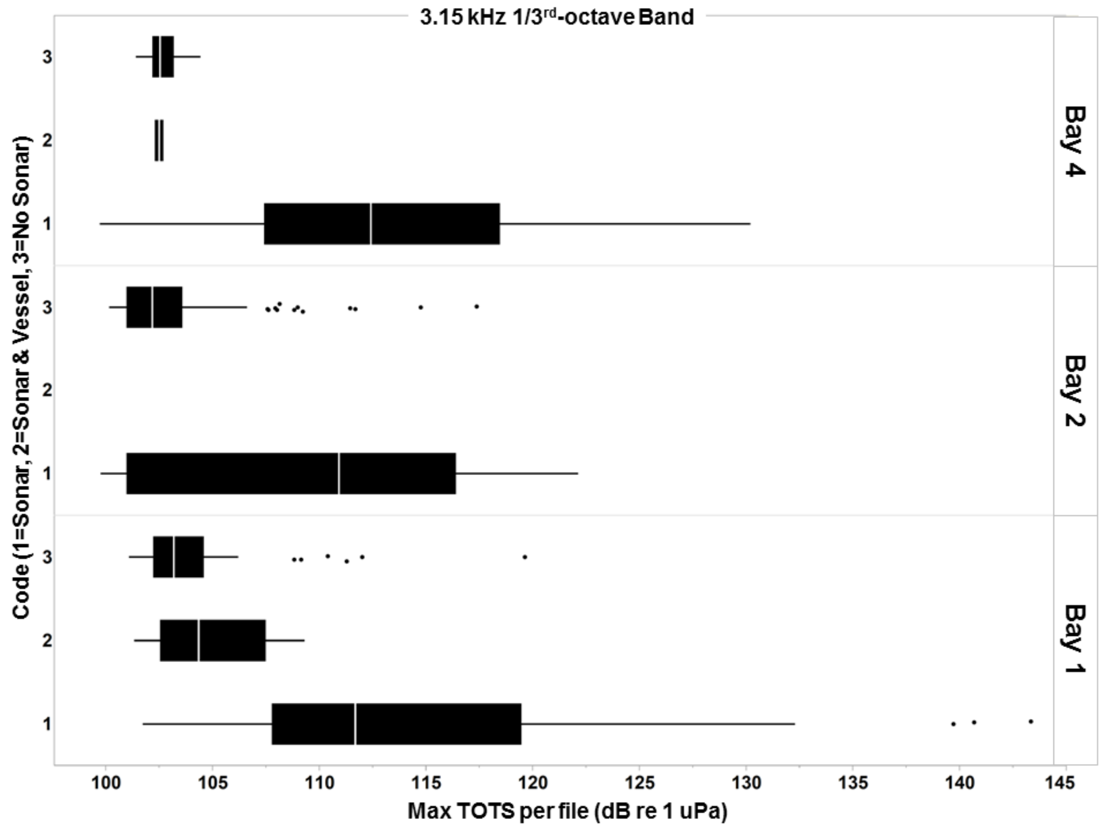


Figure 8: Maximum TOTS values for all files with Leq greater than the July/August 3.15 kHz 1/3rd-octave band L10 on August 8, 9, 10 or 11. TOTS values are TOTS values were calculated in ten 3-second segments over the 30-second recording. These are organized by the sound included in the file 1= sonar only, 2=sonar and vessels, Code 3= no sonar. Bay 1 achieves the highest values, reaching noise levels between 140 and 145 dB. The levels in files with sonar and vessels or no sonar sound at all are significantly quieter than these sonar only values.

Comparison between sonar and tsunami events

Finally, we compared the overall hourly values to the two discrete events observed during this study, the tsunami event on March 11, 2011 and the sonar event on August 8, 2011. In order to visualize the results we added the plot of the 3.15 kHz 1/3rd-octave band for August 8, 2011 to Figure 2 for Bay 1, the bay with the largest changes to the soundscape for both events. The L90 (grey triangles Figure 2) for both the tsunami and sonar time periods were similar between events except for the 09:00 hour on August 8, 2011, the hour with the loudest sonar signals recorded (Figure 2 right panel). The 09:00 L90 on August 8, 2011 was 102.9 dB, more than 6 dB greater than the 09:00 L90 during the tsunami (96.7 dB). The L10 values during the 09:00 and 10:00 hours were above 120 dB re 1 uPa compared to a 97.6 dB L10 on March 11, 2011.

Discussion

This multi-year and multi-site study, aimed to characterize the soundscapes in the four bays. To our knowledge, these are the first soundscape characterizations on Hawaii Island. In addition, we have explicitly characterized the acoustic environment in four shallow and ecologically significant areas critical to many marine animals including an estimated 524 and 801 spinner dolphins from Tyne et al. (2014) and Tyne et al. (2016). We also address both intra-site and inter-site variability, and used a tsunami event to determine the present natural state of the acoustic environment. This study showed consistent patterns of diel variation in the soundscape, with sound levels louder at night and quieter during the day likely due to the cacophony from snapping shrimp. The tsunami event resulted in a substantial change in the soundscape in Bay 1, a bay with normally high levels of vessel activity. We found that humans considerably alter the daytime soundscape in all four bays. In fact, humans (sonar, vessels, and aquaculture) generated the loudest sounds here called ‘outliers’ in each bay. The four bays differed in the amount of noise overall, with Bay 1 displaying the loudest sound levels as well as the loudest Max outlier from sonar activities. Sound levels in Bays 1, 2 and 4 during the August 8, 2011 sonar exposure were between 24.7 and 45.8 dB above median sound levels, achieving levels very rarely seen in these bays. Each bay had outliers from vessel sound and sonar, but only Bay 1 had outliers from aquaculture maintenance. The breakdown of the outliers showed that the presence of short loud sounds (e.g. vessel sound) versus persistent loud sounds (e.g. aquaculture) varied between each bay.

Overall, these four bays are considerably quieter during the daytime. Minimum median daytime ambient noise in each bay ranged from 4.8 to 9 dB lower than maximum median values at night in the 1/3rd-octave bands between 2 and 20 kHz. This constitutes a substantial increase in ambient noise at night given that decibels are measured on a logarithmic scale. These differences are due in large part to the diurnal patterns in the sounds of snapping shrimp (Au and Banks 1998). This same pattern has been acknowledged in previous studies (Au et al. 2000, Au et al. 2012, Staaterman et al. 2013, Radford et al. 2014). Specifically in previous work on nearby Oahu, Hawaii, USA, Au et al. (2012) saw a 4 dB decrease in sound from snapping shrimp during the day while Lammers et al. (2008) found a 2 dB decrease.

Snapping shrimp were a dominant component of this portion of the soundscape. In lower frequencies (100 Hz – 2 kHz) in Hawaiian bays, fish sounds and choruses dominate the soundscape (Tricas and Boyle 2014) . In the 1/3rd-octave bands between 2 and 4 kHz we observed a 7.6 to 9 dB difference between nighttime and daytime levels compared to a 4.8 to 6.6 dB difference in the 5 to 20 kHz bands (Appendix A Table 4). The contribution of fish sounds to these lower frequencies, especially chorusing at dusk (e.g. McCauley (2012), Radford et al. (2014)), might account for this larger difference. Differences in the composition of the soniferous fish community in the four bays could account for between-bay differences (Kaplan et al. 2015).

Given the importance of sound to marine animals, including spinner dolphins, patterns in the local soundscape may have played an important part in dolphin decision-making. Previous investigations have identified key physical parameters for Hawaiian spinner dolphin resting areas including proximity to offshore feeding locations, depth, and rugosity (Thorne et al. 2012, Tyne et al. 2015). Soundscape parameters also provide an important indication of suitable habitat, as well as potential stressors in the case of introduced human noise. During the 24-hour recording period, the bays are the quietest during peak spinner dolphin resting time (10:00 – 14:00) (Tyne et al. 2015). This quiet environment would be conducive to communication and socialization by marine mammals including Hawaiian spinner dolphins and could aid in the detection of potential sound-producing mammalian predators. Environmental noise during rest is also a potential cause of disturbance and has been well studied in humans due to the important effects on health (Pirrera et al. 2010). The immediate and automatic physiological reactions to noise events during sleep (e.g. changes to sleep state, awakenings, and increased blood pressure) can have short (e.g. decreased alertness) or longer term (e.g. effects on cardiovascular health) effects on human health (Basner et al. 2010). Specific responses of marine mammals to noise include changes in communication, increased stress hormone levels, and changes in movement and spatial distribution (Shannon et al. 2015). As an example, when shipping noise decreased by 6 dB as a response to the events of September 11th, 2001, stress hormone levels also decreased in North Atlantic right whales (*Eubalaena glacialis)* (Rolland et al. 2012).

Given the contribution of sound from daytime human activities to the 3.15 kHz 1/3rd-octave band, we expected that if human activity in the bays decreased, then we would see a quieter soundscape. This is illustrated by the soundscape profile from Bay 1 on the day of the tsunami event (Figure 2 and Figure 3). When we compared the overall hourly soundscape profile to the March 11, 2011 recording profile in the 3.15 kHz band, we saw a difference in the L10 and L50 values but no difference in the L90 values. The fact that the L90 did not decrease any further on March 11, 2011 was not surprising given the pervasive presence of the cacophonous snapping shrimp, suggesting they were not affected by the event and are essentially the noise floor for the bays. Compared to the overall values, the space between the L10, L50 and L90 on March 11, 2011 in Bay 1 is minimal. The recordings during the tsunami and the established L90 levels for the bays are the closest we have to a characterization of the natural soundscape of these bays (i.e. one without humans).

All maximum outliers and many of the L10 outliers for each bay were from anthropogenic sounds and many of the L10 outliers were also human-generated. The aquaculture sound and vessel sounds were broadband, occupying more of the frequency band used by marine animals. Aquaculture sound was a chronic and pervasive sound exclusively found in Bay 1. Vessel sound was a source of both loud files (Max outliers) and loud days (L10 outliers). However, the loudest of the soundscape disruptions in the 3.15 kHz 1/3rd-octave band originated from the sonar signal on August 8, 2011 in Bay 1. The maximum daily levels recorded in Bay 1, Bay 2 and Bay 4 from sonar between August 8 and 11th were greater than values recorded in these bays 0.001 or 0.00001% of the time.

We chose to focus on the 3.15 kHz 1/3rd-octave band during the daytime to best capture anthropogenic sounds in the bays and consequently understand their potential effects on marine life. The 3.15 kHz 1/3rd-octave band is biologically relevant to spinner dolphins since it is within the fundamental frequency range of their whistles (Bazúa-Durán and Au 2004). It is also within the frequency range of humpback whale song (Au et al. 2012) and the range of snapping shrimp sound production (Au and Banks 1998). In our analysis we found diel changes in soundscape which we largely attribute to snapping shrimp. We also found seasonal changes in the soundscape. Seasonal soundscape variability has been attributed to sounds made by fish (e.g. McCauley (2012), Radford et al. (2014), Guan et al. (2015)), humpback whale song (e.g. Au et al. (2000)), weather and wind (e.g. Staaterman et al. (2014), Erbe et al. (2015)). Humpback whales are seasonally present inside and outside these bays with peak presence during February and March (Au et al. 2012) especially in the two northernmost bays (Bay 1 and Bay 2). In fact, Bay 1, lies within the boundaries of the Hawaiian Islands Humpback Whale National Marine Sanctuary. Therefore humpback whales are likely contributors to the loudest months recorded in these two bays (February and March 2011 in Bay 1 (Figure 4) and February 2011, February 2012 in Bay 2 (Figure 5)). As we saw from the outlier analysis, human activities also contribute heavily and likely account for some of the variation between bays in overall recorded sound levels. Although we cannot pinpoint the exact sources, all of these sources are likely contributors to seasonal soundscape variability.

We acknowledge the limitations of our recording equipment and focusing on the soundscape through the 20 kHz 1/3rd-octave band. For future work, placing multiple devices in a given bay and sampling at a higher rate would afford the opportunity to further characterize the soundscape. Placing devices closer to the reefs in Bay 1, Bay 2 and Bay 3 could offer additional opportunities to assess the health of these areas (Piercy et al. 2014, Nedelec et al. 2015).

There is discussion in the literature about the different effects of impulsive versus chronic sounds, which we argue are analogous to our Max and L10 outliers. Shannon et al. (2015) point to the high risk associated with chronic noise sources, like those identified by our L10 outliers, affecting important life functions especially if they overlap with the frequencies used by the animal. The maximum level of individual noise events, like that identified by our Max outliers, has been identified as the major cause of sleep disturbance in humans (Carter 1996, Basner et al. 2010) which is highly relevant to resting spinner dolphins. Carter (1996) supports the signal to noise ratio as another important characteristic affecting the level of disturbance, which relates to our calculations of the sonar signal. Therefore, we consider all of the outliers described here to be sources of potential disturbance, especially when considering the spinner dolphins during their critical resting period.

Since we found important differences in the sound sources and soundscape patterns in the four bays, it is important to make recordings across multiple sites especially if we are to make recommendations for minimizing acoustic disturbance to the animals that use these bays and managing the human contribution to the soundscape. Bay 1, the northernmost study site, was identified as the loudest, the closest to the harbor and having the most dolphin tour activity. It should be noted that the high presence of spinner dolphins in this, the loudest, bay should not be taken as the absence of an effect of these sounds on the animals (Francis and Barber 2013). Even when animals have the ability to understand the consequences of an action on their fitness, they do not always make the choices that reflect optimal pay-off (Jordan and Ryan 2015). In Bay 1, many of the persistent L10 outliers stemmed from pressure washing the fish pens. Blue Ocean Mariculture informed us that the pens would be replaced and the new pens would not need to be maintained in this manner. Therefore, this source of loud sound should be eliminated. To further reduce soundscape perturbations across each bay, since many of the outliers (52 out of 58 Max outliers) were from vessel sound, we would recommend a reduction in speed especially as the vessels enter and exit the bays (Au and Green 2000). More recommendations can be found in Heenehan et al. (2017).

Sound in the marine environment is an extremely important source of information for marine animals to sense their surroundings (Fay 2009). As anthropogenic noise in the ocean continues to increase, this degrades the soundscape and threatens the animals that depend on sound and the soundscape for important life functions (Fay 2009, Moore et al. 2012). The analysis described here is important for conservation and monitoring efforts for marine animals and should be included in studies of habitat quality. We aimed to establish a baseline for soundscape in four critically important areas, understand the normal variability within and across sites, and assess the effects of natural and anthropogenic events on the acoustic environment. These data can be used to monitor changes in the soundscape and assess how any future management efforts, anthropogenic or natural events change the soundscape.

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