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THESIS

INFLUENCE OF STORMS ON MARINE MAMMAL VOCALIZATION

by

Brandon Anthony

June 2021

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Passive acoustic data collected from four sites in the Monterey Bay National Marine Sanctuary were analyzed to compare the vocalizations of three baleen whale species to the incidence of four storm events. Periods of rainfall were identified using a combination of radar reflectivity data, utilized by weather services around the world, and analysis of the 16 kHz octave level. By utilizing trained human analysis, changes in vocalization patterns were identified for blue whales and humpback whales. Fin whale calls were calculated by analyzing power differences between 12, 20, and 30 Hz frequency bands. Blue whales had the most marked response to the storm events, with rainfall showing the biggest impact. Fin whales also changed their behavior, but only in response to larger amount of rainfall. Humpback whales only responded to the strongest storm event. Although these findings indicate that whales alter their behavior when confronted by weather events, they do not indicate that whales depart an area. These changes in patterns alter the overall soundscape, and this understanding can increase the ability to manage resources for conservation and naval operations.

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INFLUENCE OF STORMS ON MARINE MAMMAL VOCALIZATION

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requirements for the degree of

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ABSTRACT

Passive acoustic data collected from four sites in the Monterey Bay National Marine Sanctuary were analyzed to compare the vocalizations of three baleen whale species to the incidence of four storm events. Periods of rainfall were identified using a combination of radar reflectivity data, utilized by weather services around the world, and analysis of the 16 kHz octave level. By utilizing trained human analysis, changes in vocalization patterns were identified for blue whales and humpback whales. Fin whale calls were calculated by analyzing power differences between 12, 20, and 30 Hz frequency bands. Blue whales had the most marked response to the storm events, with rainfall showing the biggest impact. Fin whales also changed their behavior, but only in response to larger amount of rainfall. Humpback whales only responded to the strongest storm event. Although these findings indicate that whales alter their behavior when confronted by weather events, they do not indicate that whales depart an area. These changes in patterns alter the overall soundscape, and this understanding can increase the ability to manage resources for conservation and naval operations.

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LIST OF ACRONYMS AND ABBREVIATIONS

GIS	geographic information system
HARP	High-frequency Acoustic Recording Package
LTSA	long-term spectral average
MARS	Monterey Accelerated Research System
MBARI	Monterey Bay Aquarium Research Institute
MBNMS	Monterey Bay National Marine Sanctuary
NCEI	National Center for Environmental Information
NEXRAD	next-generation radar
NOAA	National Oceanic and Atmospheric Administration
NPS	Naval Postgraduate School
OL	octave level
PAM	passive acoustic monitoring
SanctSound	Sanctuary Soundscape Monitoring Project
SCUBA	self-contained underwater breathing apparatus
SPL	sound pressure level
TOL	third octave level

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I. INTRODUCTION

The marine soundscape is an extremely complicated combination of acoustic signals that permeates the underwater environment. These signals are products of biologic, geologic, and anthropogenic sources (Pijanowski et al. 2011). Biologic sources include any organism that emits a sound while it moves, hunts, or communicates. Whale songs and fish choruses are examples of these biological sounds. Geophony, or the acoustics produced by non-living processes such as earthquakes, winds, waves, and precipitation (Erbe et al. 2015). Meteorological events, although they occur in the atmosphere above the ocean, can influence the characteristics of the ocean to significant depths. Winds, waves, and rainfall not only cause mixing and variability in temperature and salinity but induce sounds that can be heard a great distance away from the source. Anthropogenic sources include any sound created by humans, such as machinery or sonar. The way these various components blend together can have a dramatic impact on the behavior of the many different species found under the sea.

Monterey Bay National Marine Sanctuary (MBNMS) comprises over 4,000 square nautical miles of ocean, stretching along the California coast from San Francisco to Cambria (National Marine Sanctuary Program Regulations 2008). Monterey Bay is home to a wide variety of marine fishes, mammals, and other wildlife, which creates a rich and diverse acoustic environment (Michel 2019). Marine mammals show significant seasonal variability, with gray whales appearing in winter and humpbacks and blue whales present during the summer and fall. Additionally, this vast ecosystem provides economic opportunities in the form of fishing and tourism via whale watching vessels and SCUBA diving (Michel 2019). Although Monterey Bay has a sizeable record of marine mammal sightings, largely due to whale watching vessels, the passive acoustic systems deployed by Naval Postgraduate School (NPS), Monterey Bay Aquarium Research Institute (MBARI), and other agencies provides opportunities to observe and record the soundscape in all conditions (Erbe et al. 2015).

Passive acoustic monitoring (PAM) can provide many benefits to understanding the soundscape of a given area. It can be difficult to effectively monitor the presence, absence, or behavior of various animals when it is difficult to see them under water (Simard et al. 2015). Some species are driven away by unfamiliar sounds in their environment, such as vessels or other anthropogenic Sources related to survey operations. There are several instances of a species being considered rare due to a lack of sightings that have been identified in passive acoustic data such as the beaked and sperm whales (Hildebrand et al. 2015; Hildebrand et al. 2019). Furthermore, PAM systems record around the clock, so they avoid biases based on work cycles that can be found on some survey vessels (Bittencourt et al. 2018). Due to the ability for continuous collection, PAM systems generate a large amount of data when deployed and can be difficult to analyze without special visualization software (Sánchez-Gendriz and Padovese 2017). Although analysis of some parameters can utilize auto-detection software, they frequently require experience human-in-the-loop verification to reduce errors (Lewis and Širović 2018; Baumgartner et al. 2020).

Simply having soundscape acoustic data is not enough. Changes in recorded vocalization patterns can be due to a wide variety of reasons as ambient noise levels change (Cholewiak et al. 2018). Some cetacean species have been found to increase the intensity of their vocalizations in response to ambient noise, also known as the Lombard effect (Holt et al. 2009). For a decrease in vocalizations, the simplest possibility is that the animals in question have either changed their emission patterns or have left the area entirely (Dunlop et al. 2010). Increasingly complex options include effects such as masking or changes in sound propagation that decrease the signal to noise ratio to prevent detection of vocalization signals among the background noise. Finally, it is even possible for significantly powerful sounds to physiologically harm the animals, either temporarily or even permanently. Significant analysis of the soundscape is required to identify the possible sources of behavioral changes and may require additional efforts to physically locate and examine individual animals.

Understanding the factors that influence the soundscape and, by extension, the entire underwater ecosystem, is of great importance to naval forces, government planners, and conservationists. The Navy heavily relies upon acoustic data while conducting operations in a variety of ways, from contact detection to mapping the ocean bottom. In recent years, some of these operations have faced wide-spread criticism for their impacts on the marine ecosystem, with extra concern regarding marine mammals (Erbe 2012). Due to these concerns, naval vessels frequently restrict their use of sonar equipment to reduce possible harm done to nearby wildlife (Office of the Chief of Naval Operations [CNO] 2019). Fully understanding how these creatures react to other changes in the soundscape is essential to implementing effective protections while simultaneously maximizing operational capabilities. For non-military purposes, understanding the environment is critical to effectively managing conservation efforts to protect any areas of interest (Davis et al. 2017; Haver et al. 2019). Even businesses that rely upon the ecosystem can benefit from this understanding. If an animal changes its behavior due to environmental factors, that can have a significant impact on how a variety of businesses conduct their daily operations, such as whale watchers or fishermen operating in poor locations (Aspillaga et al. 2016).

It has been demonstrated by many studies that severe storms have a significant impact on underwater ecosystems, but many of these studies focus on hurricanes and their impacts on shallower waters than those found in the Monterey Canyon (Baring et al. 2014). Some of these studies have determined that storms can significantly affect the distribution of fishes due to fluctuations in temperature and light levels (Munks et al. 2015). Others have seen no significant changes in phytoplankton distributions, despite changes in nutrient availability (Grémare et al. 2003).

With the use of satellites, meteorological conditions can be determined practically anywhere around the world. By comparing this meteorological data to an area with significant underwater monitoring resources, such as Monterey Bay, it may be possible to predict the behavior of undersea wildlife in areas that may not have a robust underwater management capability. Before that step can be reached, we must first form the analyses to begin comparisons. This study is one such analysis, to show that some marine mammals, specifically blue whales and fin whales change their vocalization behavior when a meteorological event is encountered.

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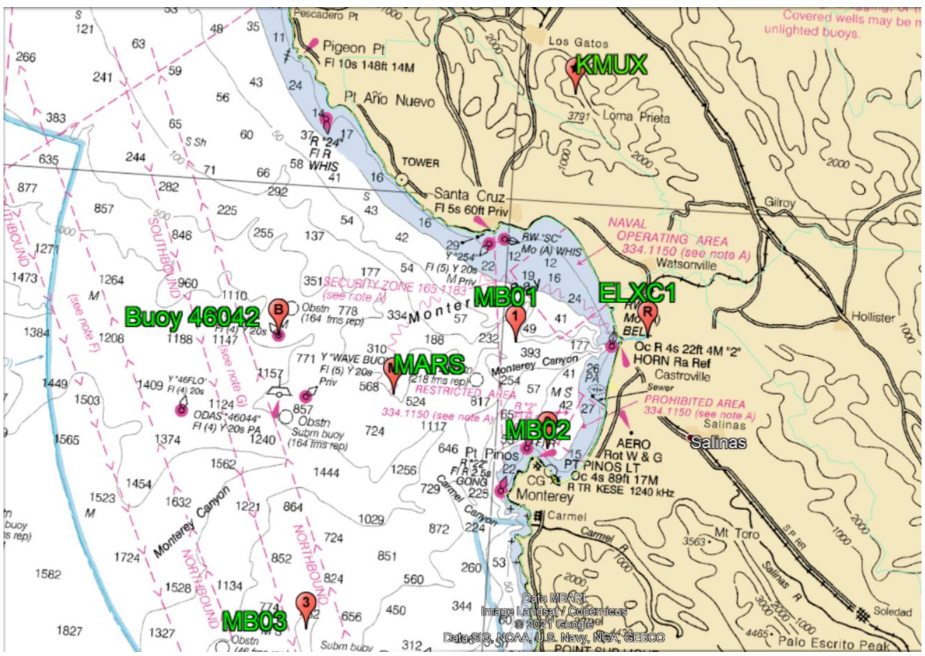
II. DATA

Data used in this experiment was retrieved from several sources collected during observations utilized for other projects. These data were collected, quality controlled, organized and stored in a wide variety of methods and locations. The locations of all sensors are depicted in Figure 1.



Nautical chart showing locations of data collection sites (red markers), shoreline, Monterey Bay National Marine Sanctuary waters (blue arc), and shipping lanes (dashed lines). Adapted from NOAA (2020).

Figure 1. Map of Monterey Bay Data Collection Sites

A. ACOUSTIC DATA

The acoustic data utilized in this study came from a variety of sources that are all participants in the NOAA Navy Sanctuary Soundscape Monitoring (SanctSound) Project, a four-year collaboration that includes the Naval Postgraduate School (NPS), National Oceanic and Atmospheric Administration (NOAA), Monterey Bay Aquarium Research Institute (MBARI), Moss Landing Marine Labs, and many other agencies and universities.

This project, started in 2018, aims to conduct long-term acoustic monitoring in seven national marine sanctuaries and one national marine monument across the United States.

The first sources of acoustic data were a pair of SoundTrap ST500 recording systems deployed as part of the SanctSound project (Figure 2). MB01 is an offshore sensor deployed at the head of the Monterey Canyon, 8.5 nautical miles from shore at position 36.798°N, 121.976°W in 119 meters of water. MB02 is much closer to shore, located 1.19 nautical miles from shore at 36.6496°N, 121.908°W at a depth of 70 meters. These hydrophones are deployed for a period of several months and replaced before the collected data is brought back to shore for analysis. Frequency band and sample rate (Fs) information is depicted in Table 1. The sample rate was adjusted following the first deployment to provide longer periods of measurement and reduce strain placed on assets required for redeployment of the sensors. Hydrophones have been deployed at both MB01 and MB02 locations since November 15, 2018.

Table 1. SoundTrap Characteristics

Deployment Number	Collection Fs	Original Range	Decimation Factor	Decimated Fs	Decimated Range
1	96 kHz	10 Hz- 48 kHz	48	2 kHz	10-1000 Hz
2 & 3	48 kHz	10 Hz- 24 kHz	48	1 kHz	10-500 Hz

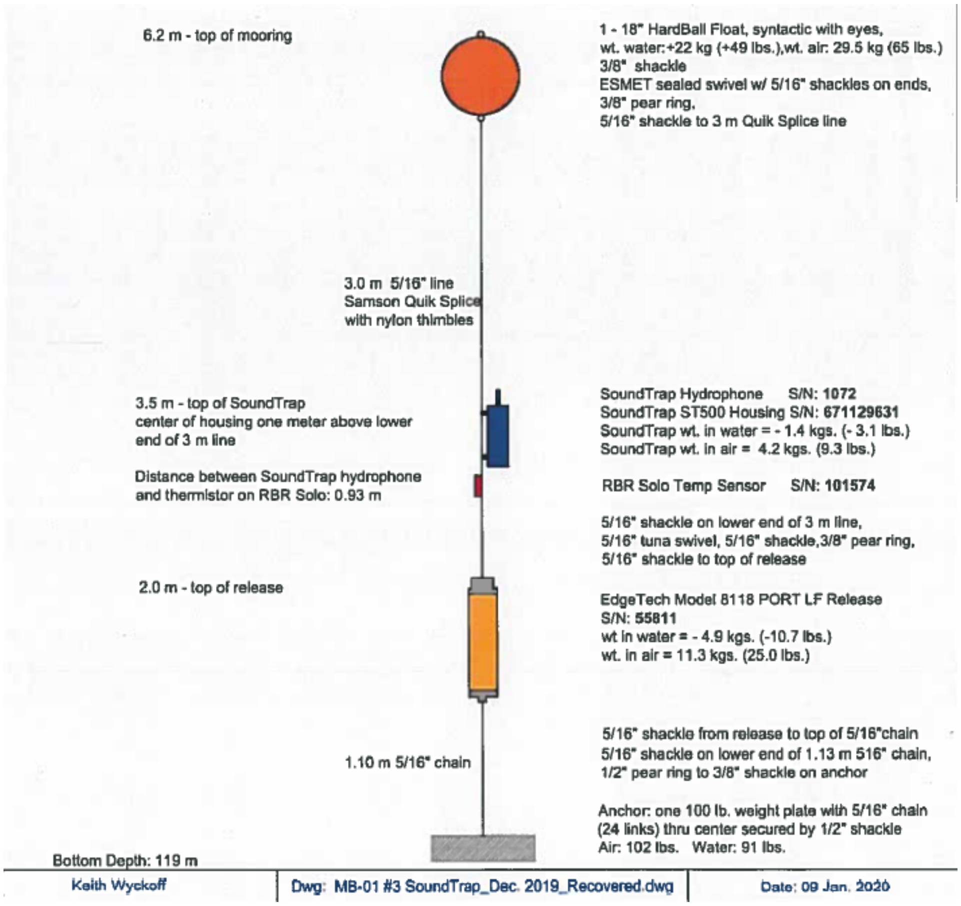


Figure 2. Diagram of MB01 ST500 instrumentation. Source: Wyckoff (2020).

The second source of acoustic data was a High-frequency Acoustic Recording Package (HARP) also deployed as part of the SanctSound project (Figure 3). This recording system is deployed to a fixed position along Big Sur Ridge, at 36.3703°N, 122.315°W at a depth of 845 meters. This hydrophone is located outside of the main portion of Monterey Bay, and is located between the busy northbound and southbound shipping lanes that lie along the coast of California. Similar to the SoundTraps, the HARP must be recovered and redeployed in order to obtain the data for analysis and has also been deployed since November 13, 2018. The HARP system records with a sample rate of 200 kHz to collect data from 10 Hz to 100 kHz.

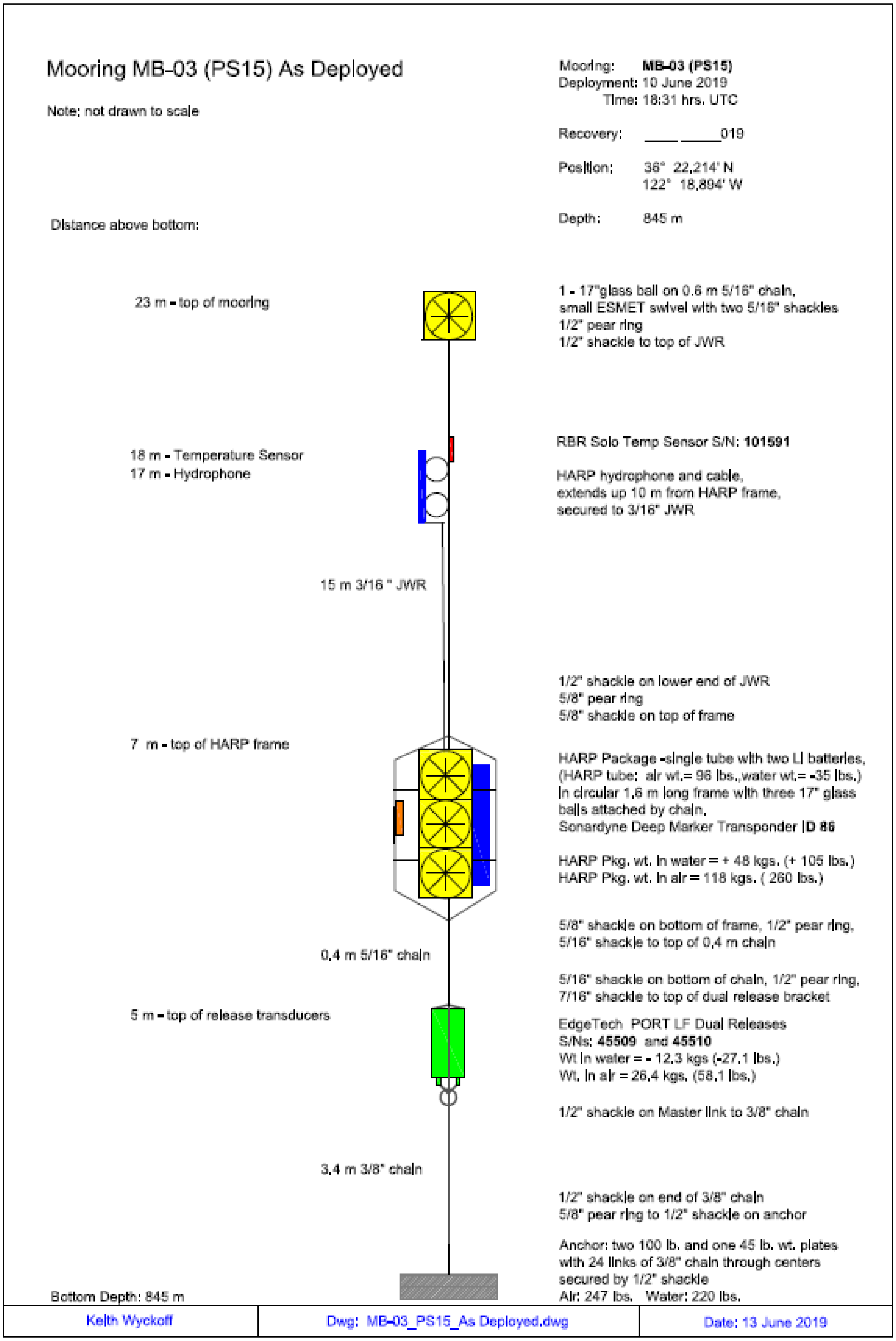


Figure 3. High-Frequency Acoustic Recording Package (HARP) diagram. Source: Wyckoff (2019).

The third source of acoustic data was an omnidirectional hydrophone on the Monterey Accelerated Research System (MARS) cabled observatory operated by MBARI, as illustrated in Figure 4. The MARS observatory is located at 36.7125°N, 122.187°W, in 891 meters of water. Its modular sensors continuously collect data for a wide variety of research initiatives, which is then immediately transmitted via cable to a shore-based location (Ryan et al. 2016). Specifically, data from the observatory's passive fixed audio recorder, capable of collecting acoustic frequencies from 10 Hz to 100 kHz with a sampling frequency of 200 kHz, was utilized. Due to a focus on the 0–1000 Hz band, only MARS data that had been decimated by a factor of 100, with a new sample frequency of 2 kHz was analyzed.

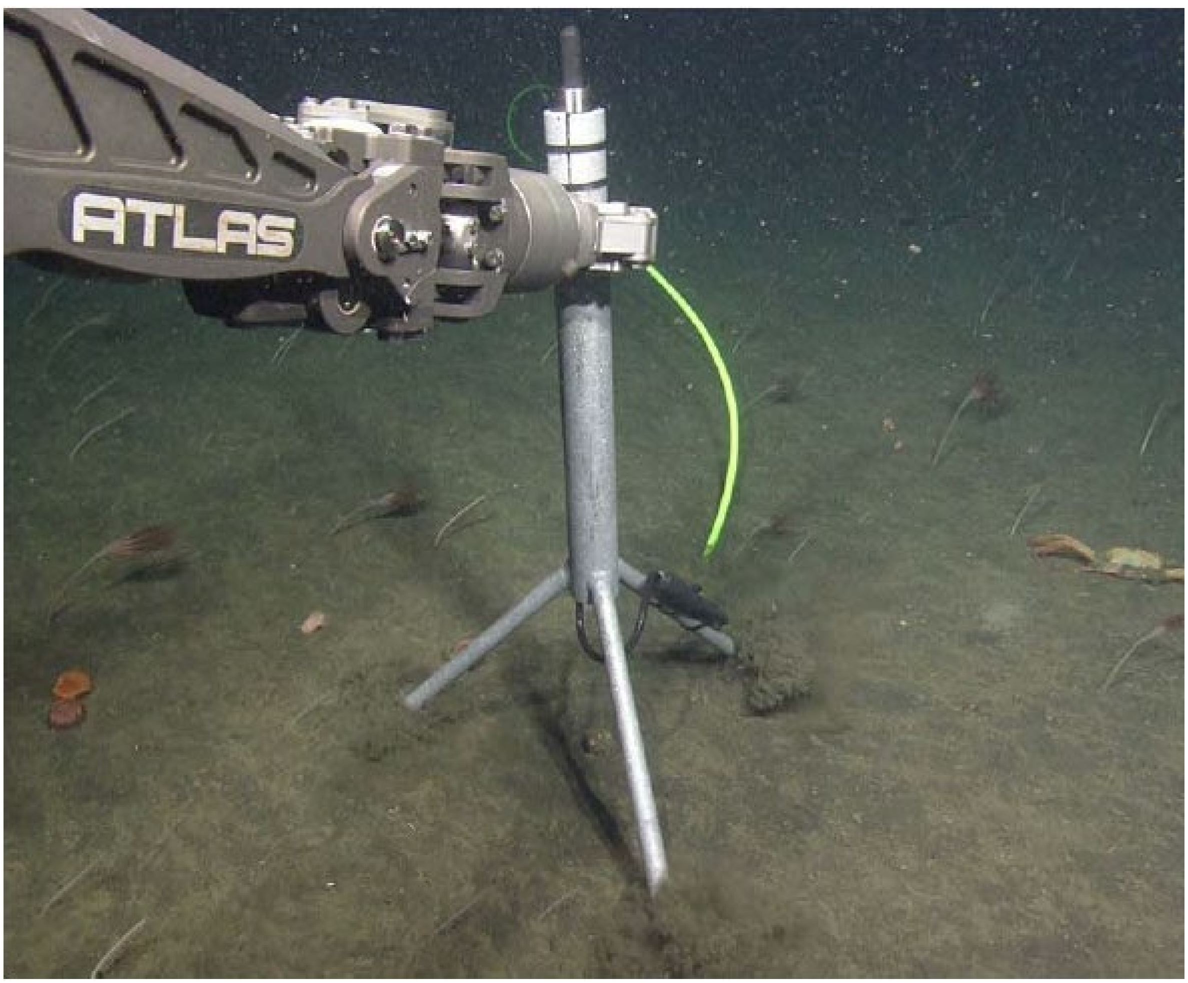


Figure 4. MARS hydrophone deployment. Source: Ryan et al. (2016).

B. ATMOSPHERIC DATA

All atmospheric data were collected from online databases that are available to the public. The first source of atmospheric data was NOAA buoy 46042, located at 36.785°N, 122.398°W, approximately 27 nautical miles west of Monterey (Figure 5). This buoy currently carries a Self-Contained Ocean Observations Payload (SCOOP), that provides measurements of wind direction, wind speed, gust speed, wave height, dominant wave period, average wave period, mean wave direction, atmospheric pressure, atmospheric temperature, and water temperature. From the initial time of SanctSound hydrophone deployments in November 2018, until November 10, 2019, all data were recorded every hour at the 50-minute mark. After November 10, 2019, atmospheric measurements were recorded every 10 minutes, while the wave data were collected every hour at the 40-minute mark.

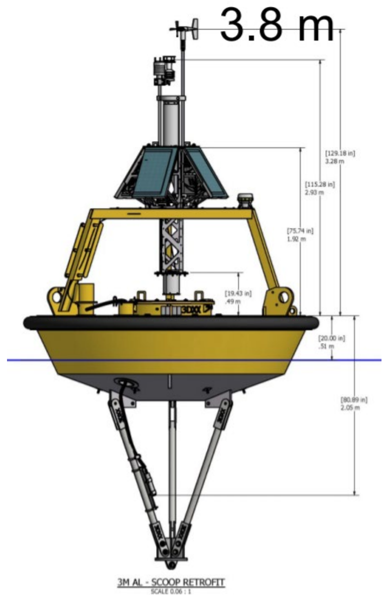


Diagram of the SCOOP payload currently deployed on NOAA buoy 46402. Source: Bouchard et al. (2017).

Figure 5. Weather Buoy Schematic

The second source of atmospheric data was the National Estuarine Research Reserve System's (NERR) Caspian Weather Station, identifier ELXC1, located in Elkhorn Slough at 36.815°N, 121.738°W (Figure 6). This station provided measurements of wind speed and direction, air pressure, air temperature, and precipitation recorded every 15 minutes. This data was accessed via the MESOWest project at the University of Utah.

Figure 6. Weather Station ELXC1. Source: U.S. Department of Commerce (2021).

The third and final source of atmospheric data was the NOAA National Center for Environmental Information (NCEI) online Radar Data Map. This radar data was a composite of data collected from WSR-88D Next-Generation Radar (NEXRAD) stations KMUX located in San Francisco, KDAX in Sacramento, and KHNX in the San Joaquin Valley. This data was provided in the form of display of composite reflectivity mosaic displayed on a basic online GIS interface in 5-minute increments A digital overlay was created to mimic the physical overlay to ease future comparison (Figure 7).

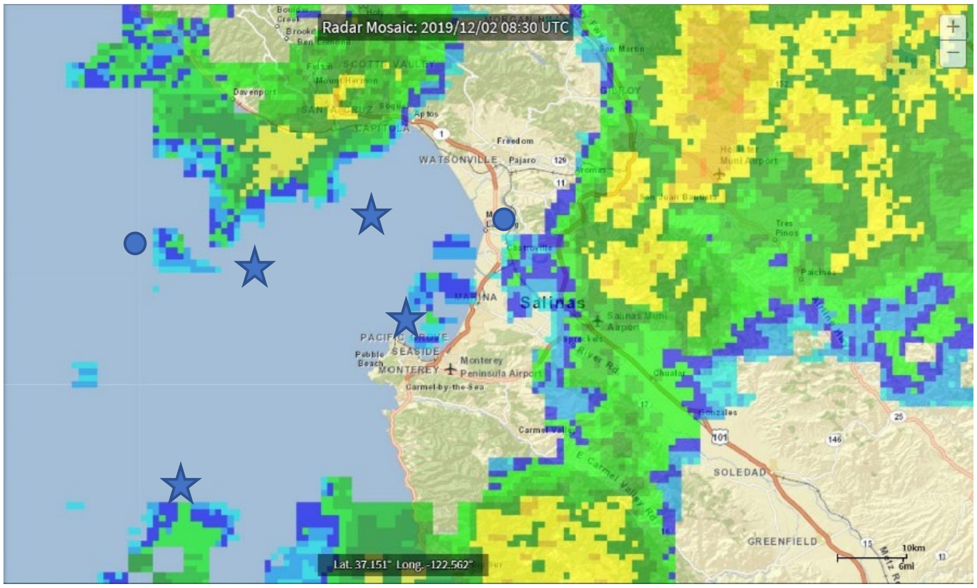
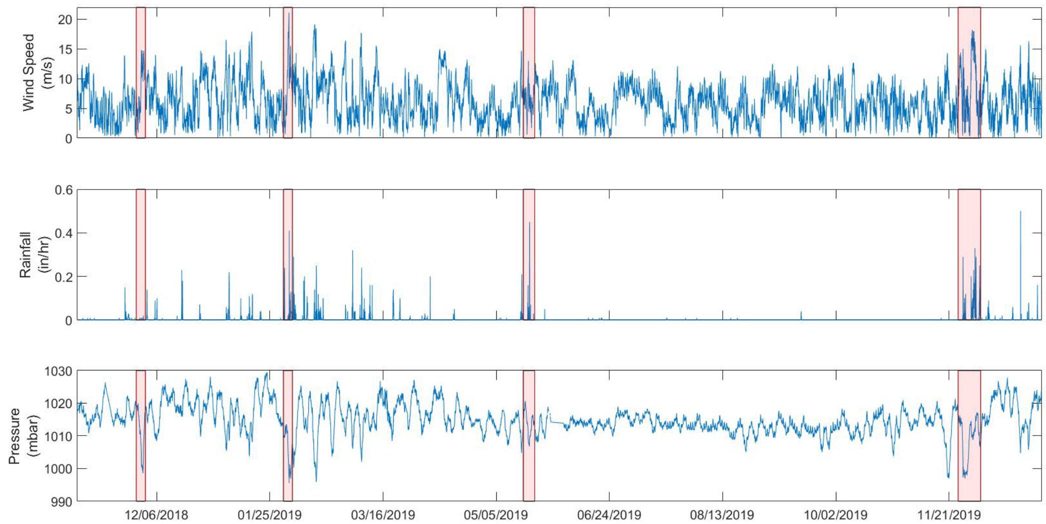


Figure 7. Radar Mosaic with Digital Overlay. Adapted from NCEI (2021).

III. METHODS

A. DETERMINING WHALE VOCALIZATION PATTERNS

In order to determine the time frames to consider for analysis of available passive acoustic data, available recordings of wind speed, wind direction, wave height, wave direction, rainfall, and atmospheric pressure were retrieved. Based on these parameters, four storm events were identified (Figure 8). The two days preceding and following the peak of the meteorological event were included in the analysis to establish comparisons of before and after the storm event. The first event occurred from November 27 to December 01, 2018, and featured a low pressure of 998 mb, no rainfall, and moderate wind speeds of 8 m/s. The second event occurred from January 31 to February 04, 2019, and presented a low pressure of 995 mb, 0.41 inches per hour (in/hr) of rainfall, and high winds of 11 m/s. The third event occurred from May 17 to 22, 2019, and exhibited a pressure of only 1006 mb, a rainfall of 0.45 in/hr, and moderate winds of 7 m/s. The final event considered actually consisted of two events separated by 24 hours, so they were considered as one long event that occurred from November 25 to December 05, 2019, this event had a low pressure of 998 mb, rainfall of 0.48 in/hr, and wind speeds of 10 m/s.



Windspeed, rainfall, and pressure measurements used to identify periods of interest. Red boxes indicate dates chosen for detailed analysis.

Figure 8. Windspeed, Rainfall, and Pressure Data

Once the meteorological events were identified, passive acoustic data were retrieved from databases containing collections. All data were decimated utilizing the Triton software package (https://github.com/MarineBioAcousticsRC/Triton/wiki) for MATLAB to focus on the 10–500 Hz band (Table 2). Once decimation was complete, the individual files for each hydrophone during each meteorological event were stitched together to create a single long-term spectral average (LTSA) file using a time bin of 5 seconds, and a frequency bin of 1 Hz.

Table 2. Decimation Factors

Source	Original Frequency	Decimation Factor	New Frequency
MB01	10 Hz-48 kHz	48	10-1000 Hz
	10 Hz-24 kHz		10-500 Hz
MB02	10 Hz-48 kHz	48	10-1000 Hz
	10 Hz-24 kHz		10-500 Hz
MB03	10 Hz-100 kHz	100	10-1000 Hz

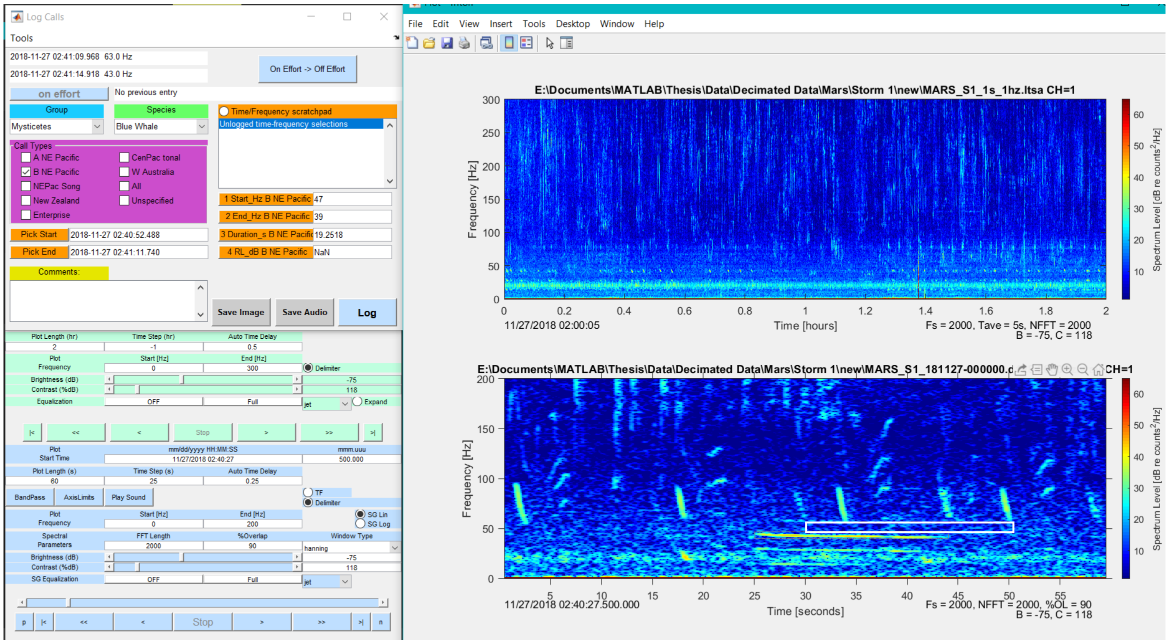
MARS data was not decimated further from what was received.

Each LTSA file was analyzed by visually comparing low-frequency signals present to previously identified blue whale A and B calls. To ensure equivalent viewing, the settings that were changed to view the expanded spectrogram are listed in Table 3 Additionally, LTSA plot length was kept at 2 hours, with a frequency range of 0–300 Hz. The higher resolution view of the .WAV files were kept at 60 second length, with frequency range of 0–200 Hz, and utilizing a Hanning window with 90% overlap.

Table 3. Triton Viewing Parameters

		LTSA		WAV File		
Data set		Brightness	Contrast	FFT	Brightness	Contrast
ST500	Storm 1–2	40	250	2000	40	250
	Storm 3–4			1000		
HARP		1	100	2000	-5	150
MARS		-75	118	2000	-75	118

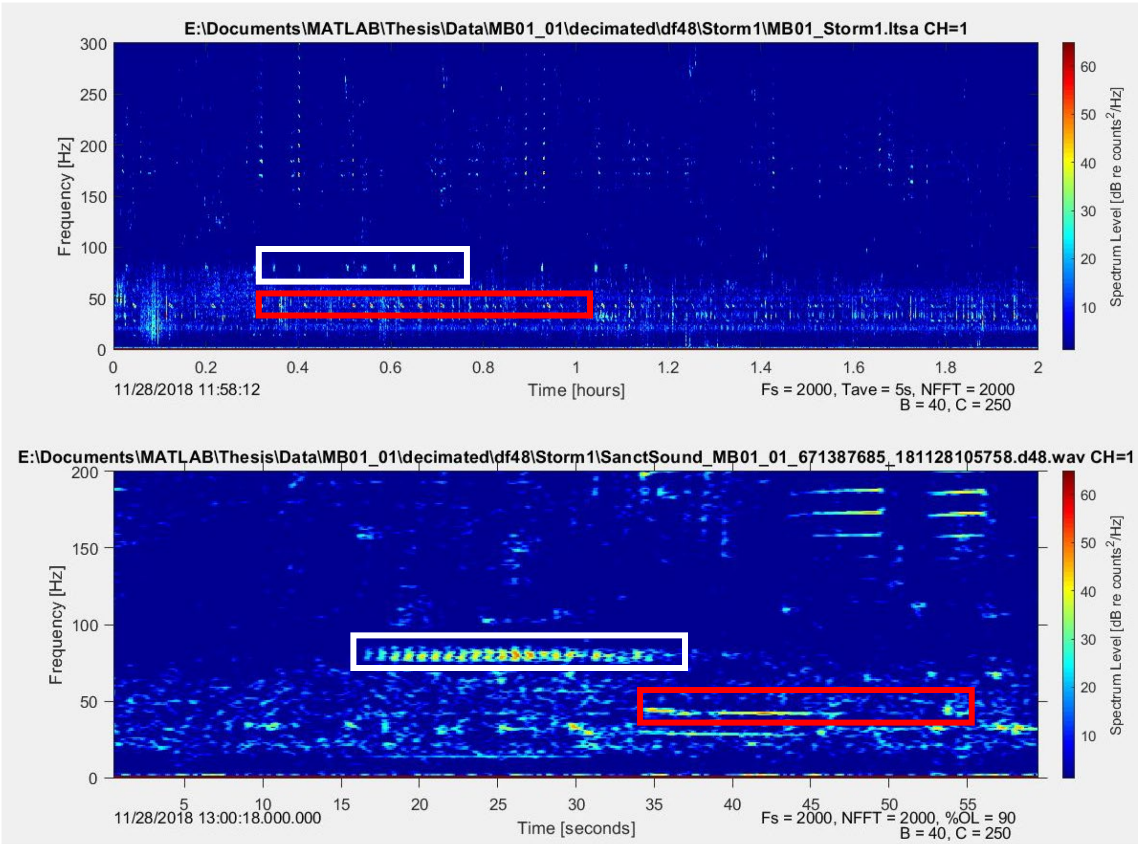
Individual calls were identified using a "click and drag" technique available within the logger remora in Triton utilizing the top left and bottom right corners of a signal (Figure 9). This method allowed simple recording of start and end times, upper and lower frequency limits, duration, and signal frequency width within the logger remora. The initial analysis of the first data set was conducted by simply clicking on the upper left corner of a signal, recording the initial data, and then clicking on the lower right to record the end of signal data. After reconducting the analysis of this data set utilizing the click and drag method, the initial data was kept to compare the impact of different recording methods and experience. Due to occurrence outside normal blue whale migration patterns in the Monterey area, LTSA files for storm periods 2 and 3 were scanned to verify absence of either A or B Calls (Burtenshaw et al. 2004).



White box is indicative of box drawn over spectrogram in Triton. Actual box is a dotted selection box common to Microsoft Windows applications.

Figure 9. Illustration of Call Recording Technique in the Triton Graphical User Interface

A calls were identified as pulses occurring roughly between 70–90 Hz, and a "gated" appearance as demonstrated in Figure 10. Signals that appeared indistinct or blurred in this frequency range, but between 5 and 20 seconds long were considered as A calls. B calls were identified primarily utilizing the third harmonic signal occurring between 40–50 Hz. Signals classified as B calls required a slight decrease in frequency over the duration of the call, or downsweeping (Figure 10). This was determined by comparing the progression of the signal to the straight line comprising the top of the box created by utilizing the click and drag technique. If the signal demonstrated downsweeping and persisted for a period between 10 and 25 seconds, it was classified as a B call. If a lower frequency harmonic was visible meeting these same parameters, then it was still classified as a B call if there was signal noise along the 40–50 Hz bands.



White boxes indicate A calls in both LTSA (top) and higher resolution WAV spectrogram (bottom), while red boxes indicate B calls.

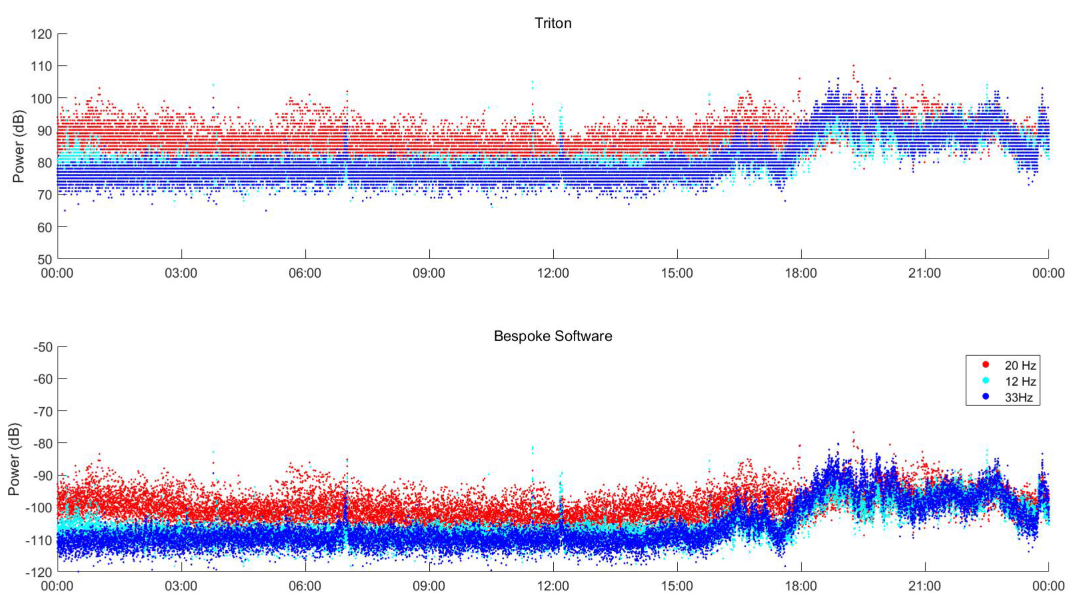
Figure 10. Examples of Blue Whale Calls

Once all storms were analyzed, the data was reviewed to correct any mis-labeled calls by examining the call type and frequency band recorded. Due to the utilization of the click and drag methods ability to instantly record all signal variables, the frequency recordings were given higher credibility than the call type identifiers. Any calls recorded as a B call, but located above 60 Hz were changed to A calls. Similarly, any A calls occurring below 60 Hz were changed to B calls. Duplicate call recordings were also identified and removed. To be considered duplicate, both calls were required to have the same start and end times +/- 1 second, and be in the same frequency range, +/- 5 Hz.

All data were then loaded into MATLAB and plotted against rainfall, pressure, and windspeed values. Due to the number of calls recorded, call data were plotted as number of calls occurring in a ten-minute period. Data were further analyzed by comparing the intervals between calls.

Humpback whale presence was determined by manually scanning LTSAs in Triton. For humpback whale determinations, the data were decimated to 4 kHz sample rate. LTSAs were created utilizing temporal bins of 5 seconds, and frequency bins of 1 Hz. The LTSA was scanned by a trained analyst in hourly bins for visual evidence of humpback vocalizations, including both song and non-song vocalizations. Possible humpback vocalizations were aurally confirmed to be humpbacks before logging a positive detection in the Triton Logger Remora to determine the hourly presence on humpback vocalizations. Analysis of humpback data was conducted by Jack Barkowski of Moss Landing Marine Labs.

Fin whale presence was determined by utilizing a scatterplot comparison method. Because Triton software only utilizes integers for calculating power information to use in LTSA creation, a bespoke program set based on modified Triton routines, was utilized for more precise measurements (Figure 11).



Top panel shows scatterplot created using Triton data (calculated by using integers), while bottom plot is bespoke software utilizing full calculated values.

Figure 11. Triton versus Bespoke Software

After the new power data was retrieved, three frequency bands were created for comparison. The primary band of interest was 19–21 Hz, as fin whales primarily vocalize at 20 Hz (Aulich et al. 2019). Two frequency bands near 20 Hz were selected for comparison because they should not include fin whale activity, while still expressing influences from other sources on the environment. An "upper" frequency band was created around 33 Hz, from 29–37 Hz, and a "lower" frequency band around 12 Hz, from 8–16 Hz. All frequency bands were averaged to capture a representation of variability within them. Presence of fin whale vocalizations was determined by comparing the average values to each other. If the 20 Hz band was more than 3 dB above both the 33 Hz and 12 Hz bands, then it was determined as a fin whale call. Once the calls were determined, the calls were compared to the same environmental factors as blue whales.

B. STORM INCIDENCE

Pressure data collected at both stations were compared to determine a temporal offset caused by the distance between the two stations to align precipitation data with passage over the hydrophones in Monterey Bay. Although exact radar measurements were unavailable, a physical overlay was created to place over a screen to identify the locations of the sensors used to collect data compared to predominant geography on the NCEI online Radar Data map. By comparing the radar reflectivity to the rainfall records collected at ELXC1, an estimate was made of the time that rainfall occurred at the individual hydrophone sites. This estimate was used to reduce uncertainty in determining the incidence of the actual storm event in the acoustic data. To verify storm occurrence, the sound pressure level (SPL) at all available octave level (OL) was calculated to compare against the wind, wave, and rain data. Octave and 1/3-octave sound pressure levels (SPLs) were calculated within the SanctSound project as median over 1 hr/1Hz bins for standard octave and 1/3-octave frequency bands. Pressure was not considered as it has no direct mechanism to influence acoustic behavior.

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IV. RESULTS

A. STORM VERIFICATION

Utilizing the occurrence of peak radar reflectivity, Table 4 displays the estimated time of precipitation arrival at each hydrophone during the time periods in question. Since storms were defined by a combination of wind, rain, and pressure events, there were frequently multiple rainfall events during each storm period that did not necessarily occur during the selected peak of the storm. When possible, multiple rainfall events were utilized to capture as much variety as possible.

Table 4. Time of Occurrence Compared to Recorded Rainfall at ELXC1

Measured	Radar	Radar	Radar	Radar
ELXC1	MARS	MB01	MB02	MB03
11/30/18 0245	11/30/18 0215	11/30/18 0215	11/30/18 0240	11/30/18 0240
12/01/18 2000	12/01/18 1945	12/01/18 2020	10/01/18 1950	12/01/18 2015
1/31 /19 0900 (1030)	1/31 /19 0800 (0845)	1/31 /19 0850 (1000)	1/31 /19 0850 (0945)	1/31 /19 0730 (0815)
02/02 /19 1245	02/02 /19 1145	02/02 /19 1200	02/02 /19 1215	02/02 /19 1115
02/04 /19 0815 (1045)	02/04 /19 0730 (N/A)	02/04 /19 0745 (1000)	02/04 /19 0745 (1000)	02/04 /19 0730 (N/A)
05/19 /19 1545	05/19 /19 1430	05/19 /19 1430	05/19 /19 1515	05/19 1445
05/19 /19 1730	05/19 /19 1630	05/19 /19 1630	05/19 /19 1715	05/19 /19 N/A
11/27 /19 0415 (0500)	11/27 /19 0325 (0425)	11/27 /19 0315 (0430)	11/27 /19 0345 (0450)	11/27 /19 0400 (0450)
12/02 /19 0945 (1100)	N/A	12/02 /19 1030 (1040)	12/02 /19 1015 (1040)	12/02 /19 0900 (1010)
12/04 /19 2145 (2215)	12/04 /19 2000 (2035)	12/04 /19 2050 (2130)	12/04 /19 2000 (2045)	N/A

Times in parentheses indicate time of peak rainfall. All times are UTC. N/A indicates that there was no significant radar reflectivity over the sight to indicate significant rainfall.

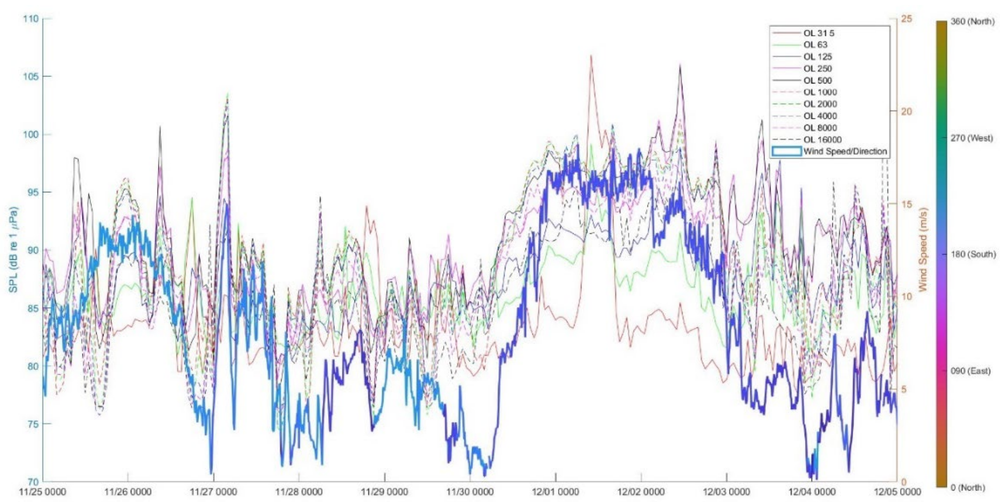
Once all of the occurrence times were recorded, an offset was estimated to apply to the rainfall times in precipitation plots (Table 5).

Table 5. Offsets

Offsets	MARS	MB01	MB02	MB03
Storm 1	30	30	30	5
Storm 2	60	45	45	90
Storm 3	60	75	15	60
Storm 4	90	30	30	45

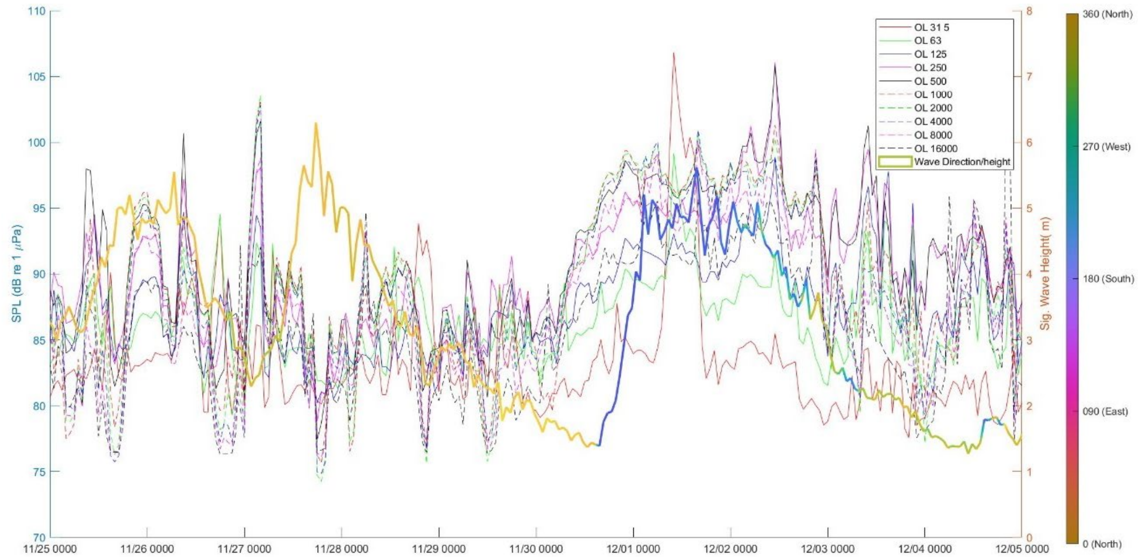
Offsets applied to rain data. Time, in minutes, used to adjust rainfall times recorded at ELXC1 to match occurrence at each station.

Once offsets were calculated, the new precipitation times were plotted against the standard octave levels (OLs) calculated for each data set to determine accuracy of each offset. Ten Ols, identified by its central frequency, were plotted against each atmospheric factor for each storm at each site (Figures 12–14). Based on these figures, it was apparent that the 250 Hz OL matched well with windspeed, while the 16 kHz OL matched rainfall. Waves did not appear to correlate to any specific OL in any of the data sets.



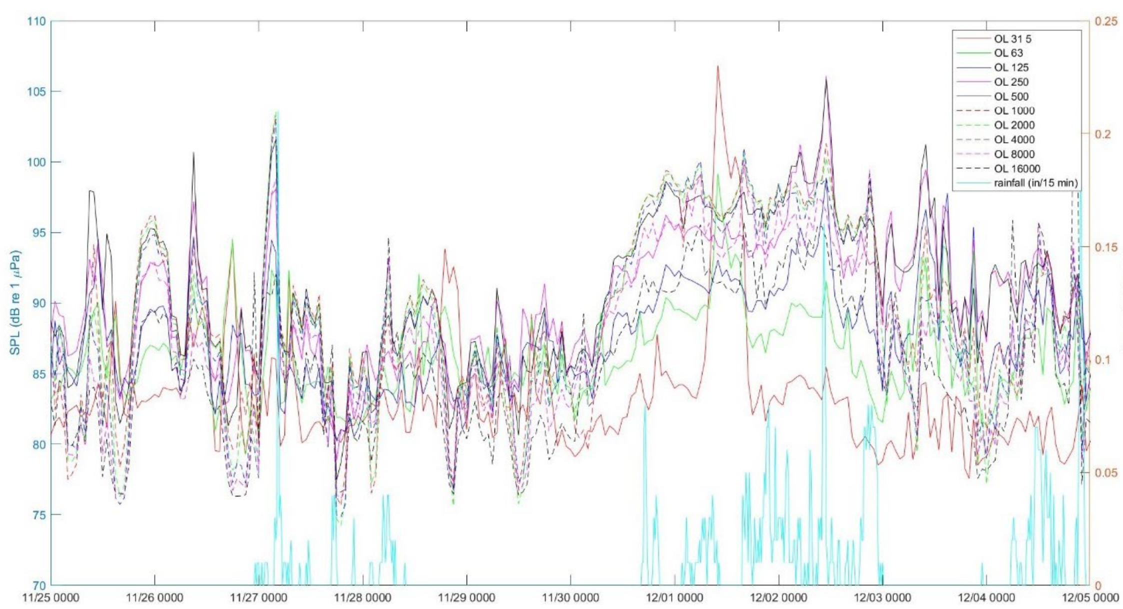
Thicker line, wind speed, is colored to represent mean wind direction as reflected by the colorbar. Solid lines are lower frequencies, dashed lines are high frequencies. Data are from MB01 Storm 4

Figure 12. Example Wind versus OLs



Thicker line, significant wave height, is colored to represent mean wind direction as reflected by the colorbar. Solid lines are lower frequencies, dashed lines are high frequencies. Data are from MB01 Storm 4.

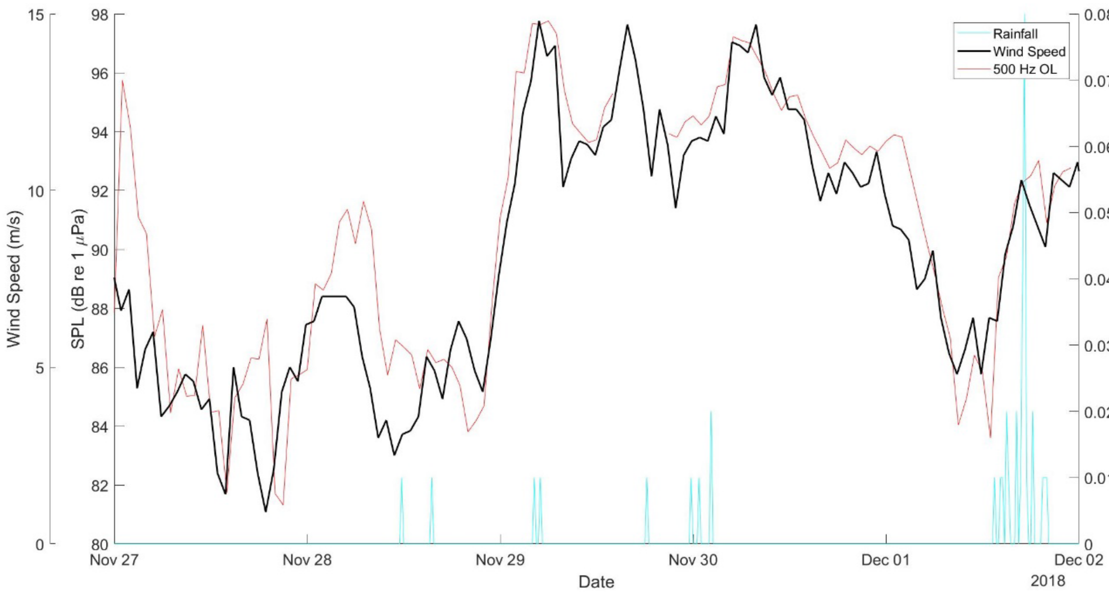
Figure 13. Example Waves versus OLs



Solid lines are lower frequencies, dashed lines are high frequencies. Data are from MB01 Storm 4.

Figure 14. Example Rainfall versus OLs

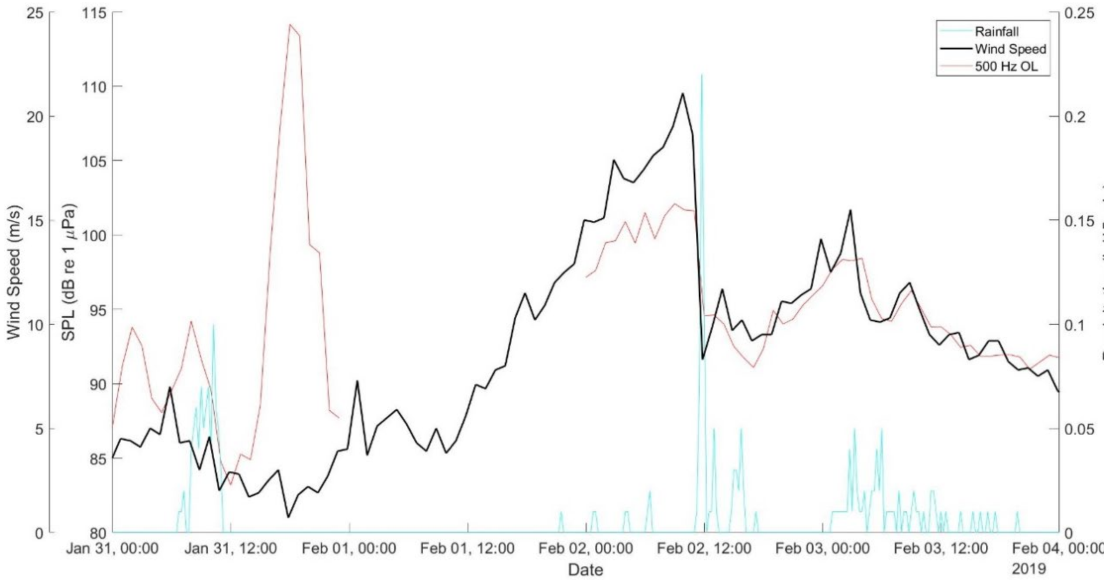
MARS data was harder to verify due to a lack of high-frequency data, so the 500 Hz OL was used instead of the 16 kHz used elsewhere. Figure 15 shows a good relationship between the 500 Hz OLs on November 29, but the offset appears to slightly lag behind the OL data for the peaks occurring on November 28, while slightly leading the OL peaks on November 30 and December 1. These differences may also stem from the influence of wind noise on the lower OLs.



500 Hz OL line is indicative of wind speed (black line). Due to lack of high frequency data, 500 Hz OL is maximum OL available for MARS data.

Figure 15. MARS Storm 1 OLs versus Wind Speed and Precipitation

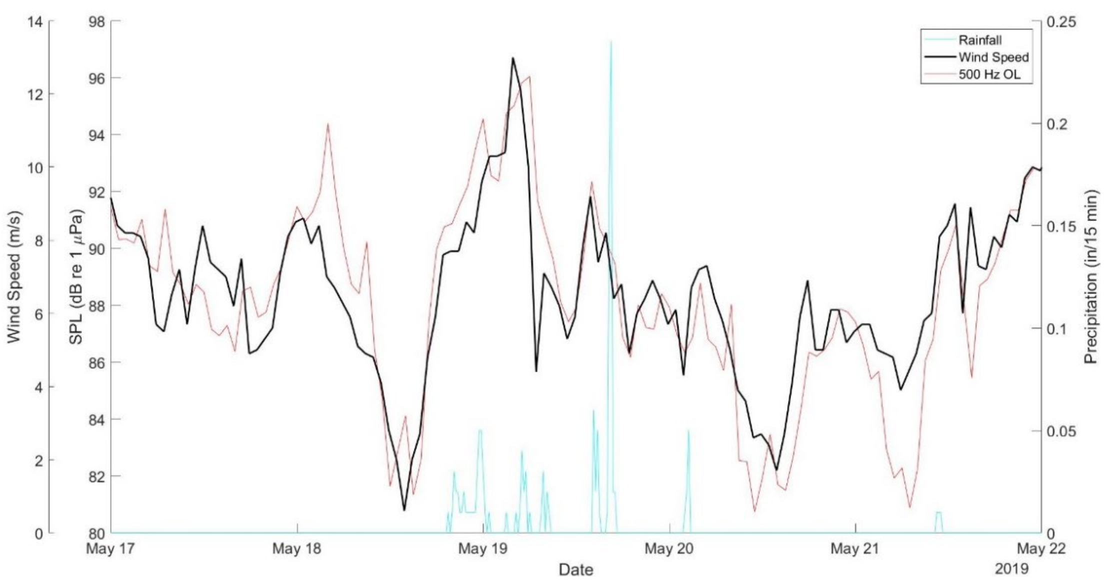
The storm 2 offset for MARS appears to have had more success with peaks in the OLs and rainfall occurrences matching more closely (Figure 16). There is a peak of unknown origin in the 500 Hz OL on the afternoon of January 31, but this appears to be due to anthropogenic work in the area of the sensor.



500 Hz OL line is indicative of wind speed (black line). Due to lack of high frequency data, 500 Hz OL is maximum OL available for MARS data.

Figure 16. MARS Storm 2 OLs versus Wind Speed and Precipitation

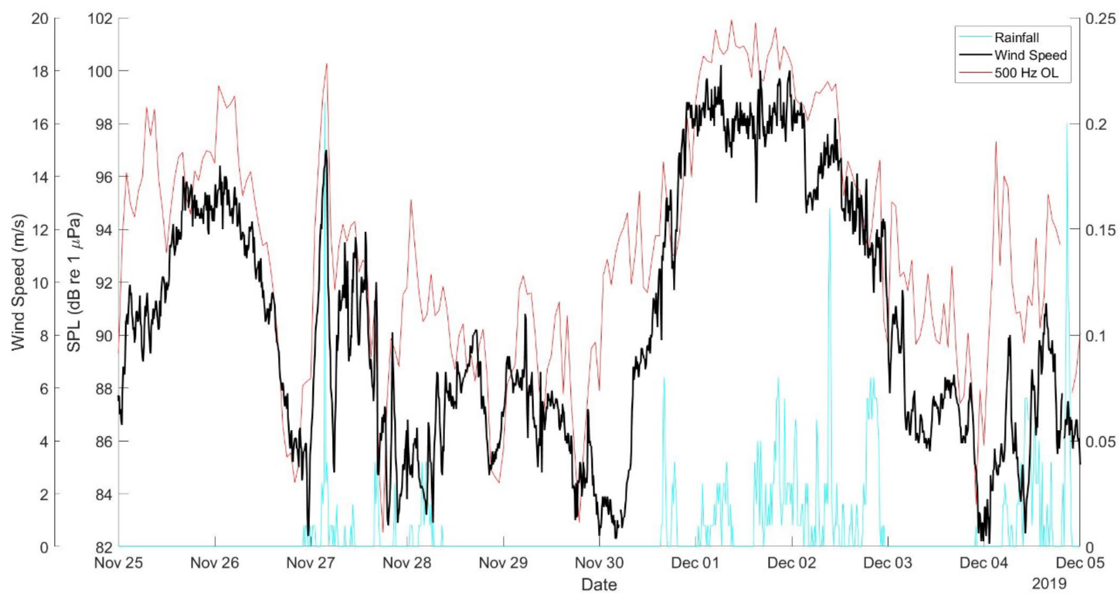
The storm 3 offset for MARS is less conclusive, but the rainfall peaks appear to match peaks in the 500 Hz OL around the morning of May 19 (Figure 17).



500 Hz OL line is indicative of wind speed (black line). Due to lack of high frequency data, 500 Hz OL is maximum OL available for MARS data.

Figure 17. MARS Storm 3 OLs versus Wind Speed and Precipitation

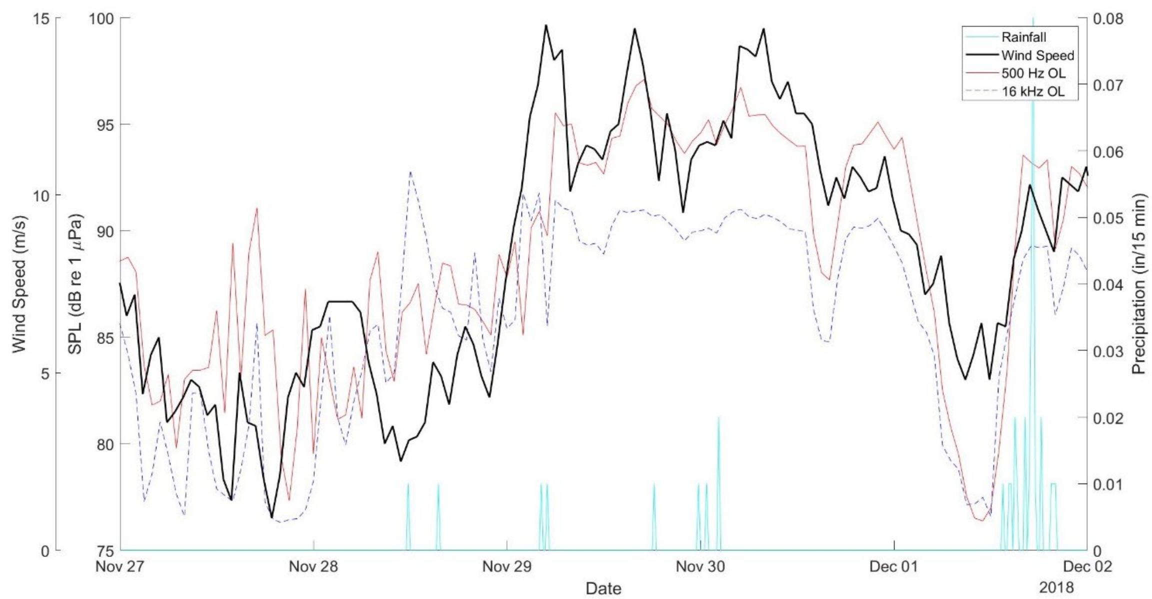
Although the storm 4 offsets appear to line up with some of the peaks in the 500 Hz OL, such as November 27 and December 2, there are also several peaks with no associated rainfall, such as those occurring throughout November 29 and 30 (Figure 18).



500 Hz OL line is indicative of wind speed (black line). Due to lack of high frequency data, 500 Hz OL is maximum OL available for MARS data.

Figure 18. MARS Storm 4 OLs versus Wind Speed and Precipitation

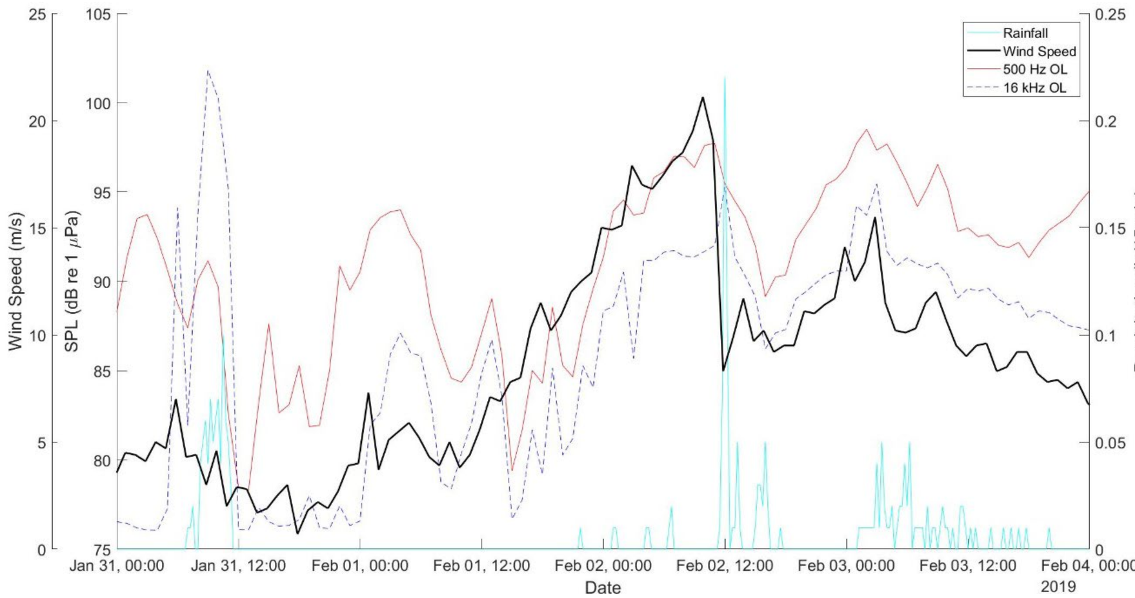
When a full frequency spectrum is considered, the offsets appear to match 8 kHz and 16 kHz quite well. Although storm 1 lacked a variety of rainfall events, the primary peak on 1 December 2018, as well as some of the smaller instances of rain, match peaks in the higher OLs at site MB01 (Figure 19). When compared to the wind speed values, the influence of rain in at higher OLs becomes more apparent.



500 Hz OL line is indicative of wind speed (black line). 16 kHz OL line is indicative of precipitation (cyan line).

Figure 19. MB01 Storm 1 OLs versus Wind Speed and Precipitation

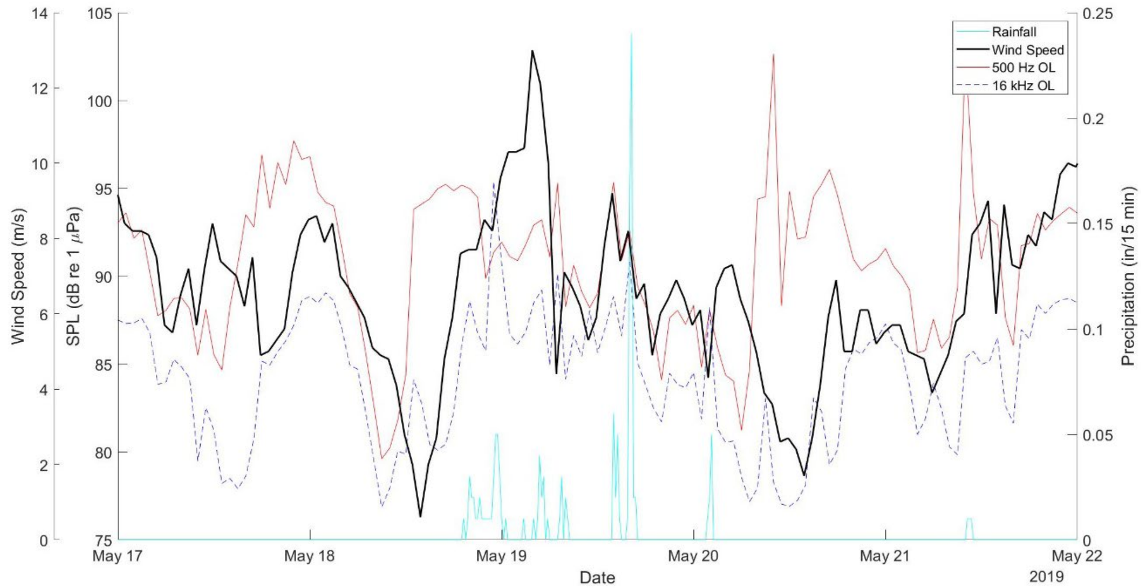
Storm 2 had more rain and shows a much better correlation on January 31 and February 2, but less success along the smaller peaks occurring throughout February 3 (Figure 20). In the instance of February 2, the peak of 8 kHz and 16 kHz correspond to a decrease in windspeed at the same time as increased rainfall.



500 Hz OL line is indicative of wind speed (black line). 16 kHz OL line is indicative of precipitation (cyan line).

Figure 20. MB01 Storm 2 OLs versus Wind Speed and Precipitation

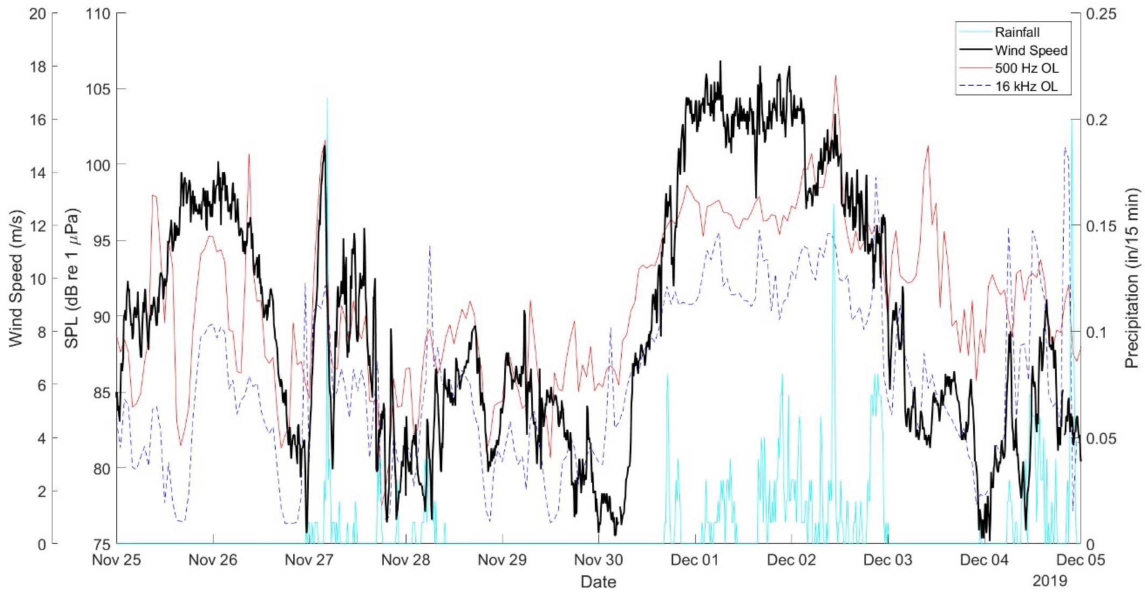
Storm 3 appears to show good correlation with the peak on May 19 and May 20, despite the appearance of more noise variations in the upper frequencies (Figure 20). Some of the variability is due to the wind, but some peaks, such as the one around 1200 on May 20 occur when the windspeed is decreasing.



500 Hz OL line is indicative of wind speed (black line). 16 kHz OL line is indicative of precipitation (cyan line).

Figure 21. MB01 Storm 3 OLs versus Wind Speed and Precipitation

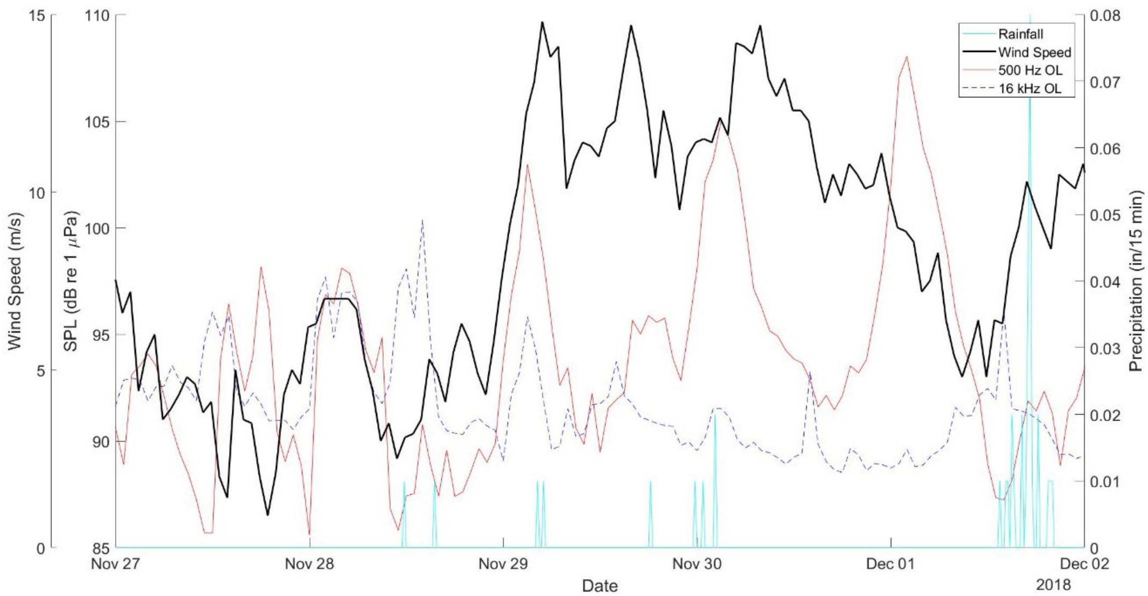
Due to the longer time period, there are many more rainfall events in storm 4, and they match peaks in upper OLs very well on November 27 and December 1 and 2 (Figure 22). The peak occurring late on December 2 occurs coincident with a rainfall peak and decreasing wind speeds.



500 Hz OL line is indicative of wind speed (black line). 16 kHz OL line is indicative of precipitation (cyan line).

Figure 22. MB01 Storm 4 OLs versus Wind Speed and Precipitation

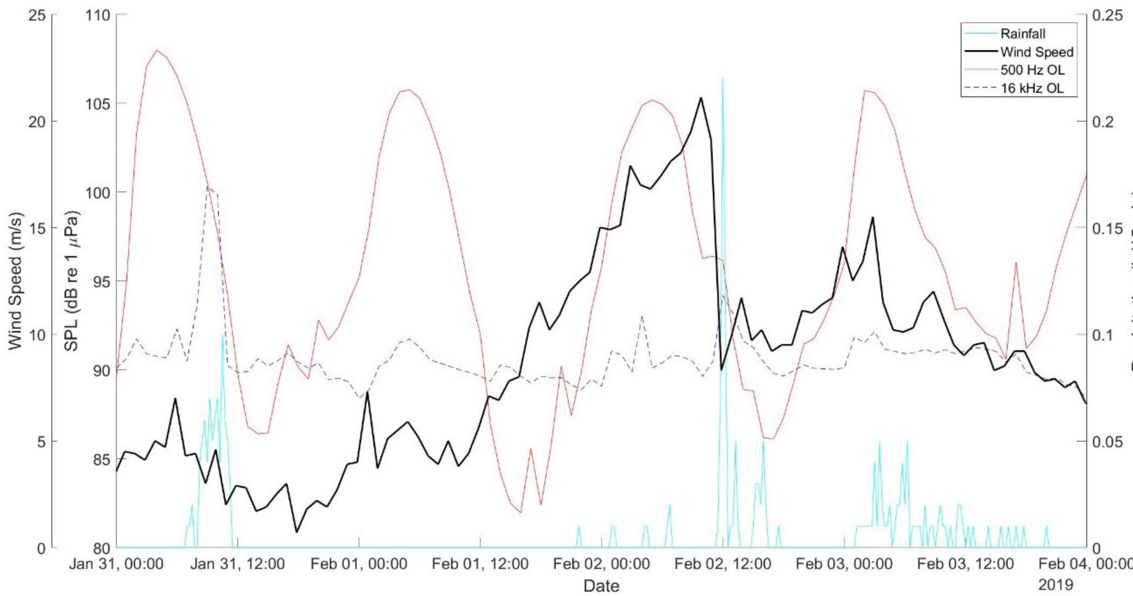
During storm 1 at MB02, the largest rain peak on December 1 lags a nearby peak in the 16 kHz OL, but this could be due to differences in rain drop size (Figure 23). The smaller peaks on November 28, 29, and 30 are reflected by peaks in the 16 kHz OL.



500 Hz OL line is indicative of wind speed (black line). 16 kHz OL line is indicative of precipitation (cyan line).

Figure 23. MB02 Storm 1 OLs versus Wind Speed and Precipitation

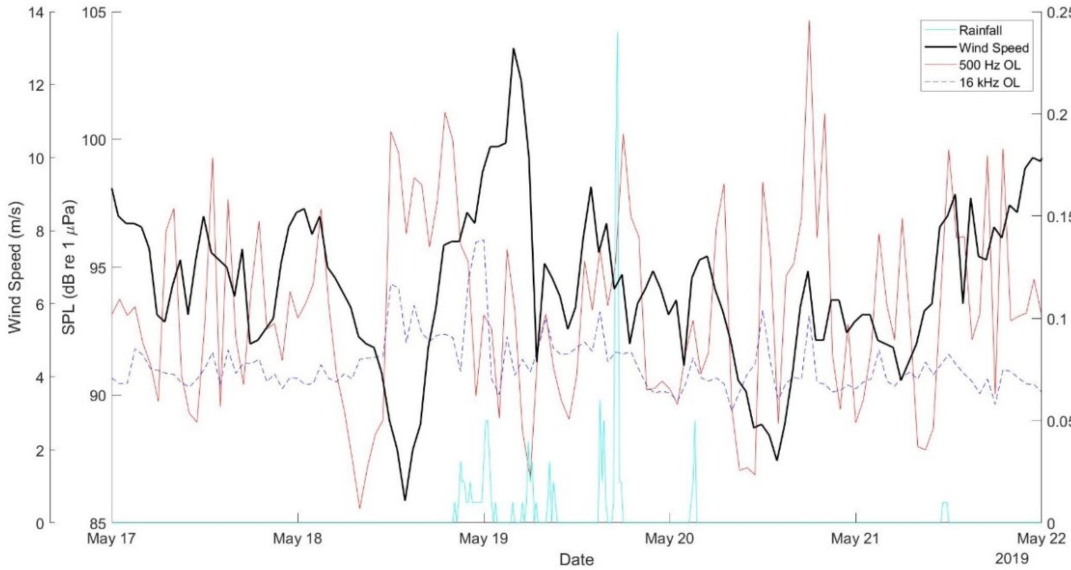
The two largest rainfall peaks of storm 2, on January 31 and February 2, match peaks in 16 kHz OLs (Figure 24). February 2 is particularly interesting because both the rainfall and 16 kHz peaks occur while wind speed and 500 Hz OL are both decreasing. The smaller peaks on February 3 slightly lag peaks in the 16 kHz OLs before the 16 kHz level smooths out.



500 Hz OL line is indicative of wind speed (black line). 16 kHz OL line is indicative of precipitation (cyan line).

Figure 24. MB02 Storm 2 OLs versus Wind Speed and Precipitation

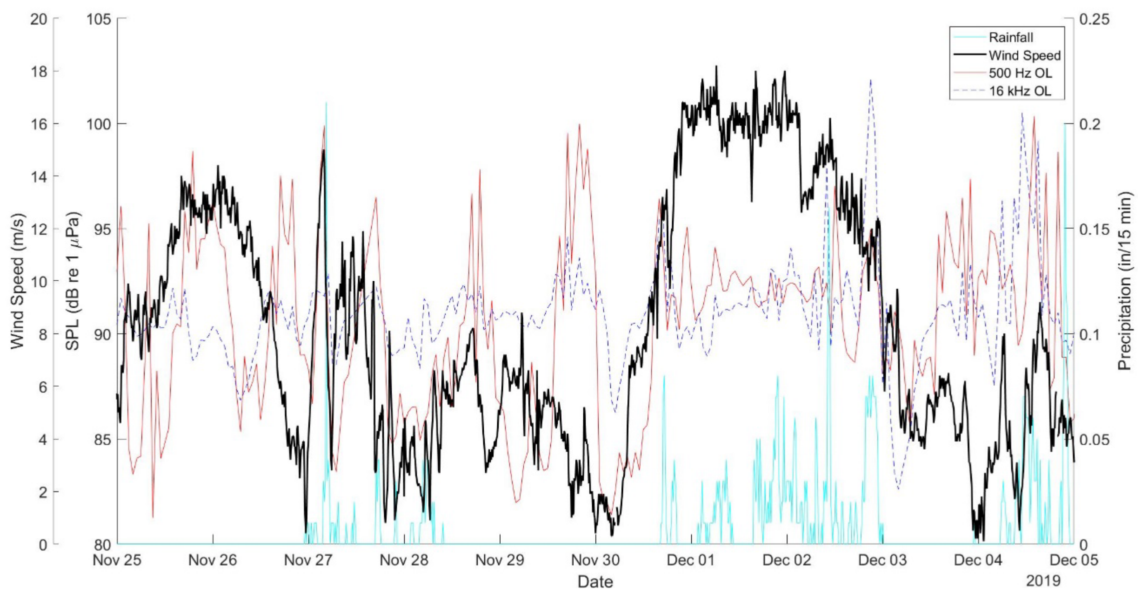
Although the peak May 19 rain event does not appear in the 16 kHz OL, there does appear to be correlation with the other, smaller rain events in the early morning of May 19 and 20 (Figure 25). In this case, the OL peaks surrounding the primary rain peak do not appear to be driven by either winds or waves.



500 Hz OL line is indicative of wind speed (black line). 16 kHz OL line is indicative of precipitation (cyan line).

Figure 25. MB02 Storm 3 OLs versus Wind Speed and Precipitation

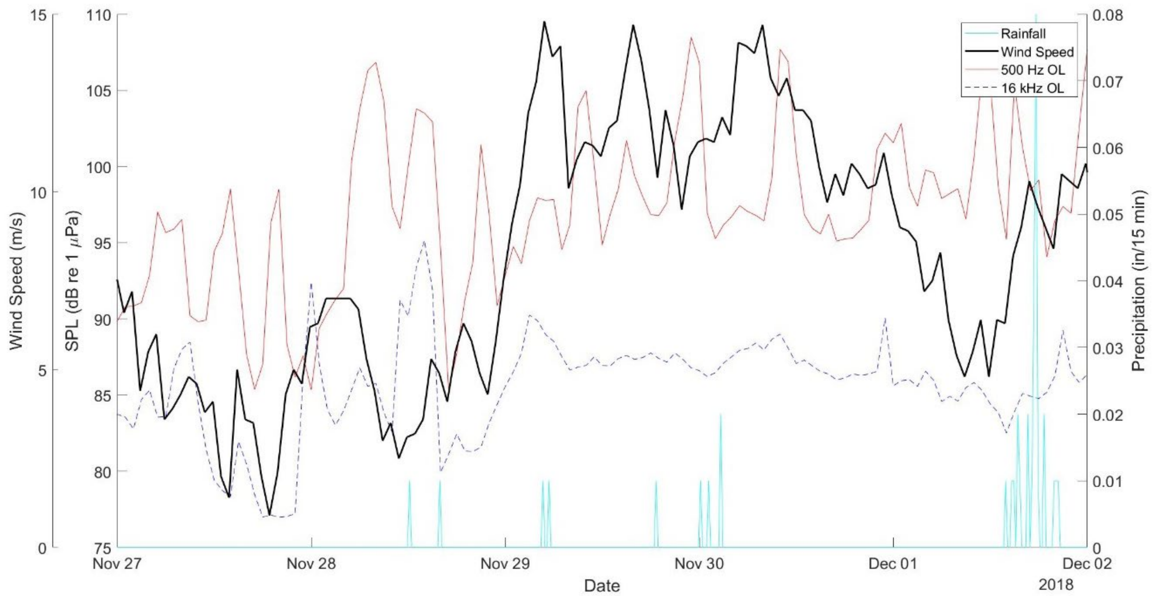
Storm 4 shows strong correlation between the rain instances and peaks in the two highest OLs at practically all of the rain peaks occurring during this storm (Figure 26).



500 Hz OL line is indicative of wind speed (black line). 16 kHz OL line is indicative of precipitation (cyan line).

Figure 26. MB02 Storm 4 OLs versus Wind Speed and Precipitation

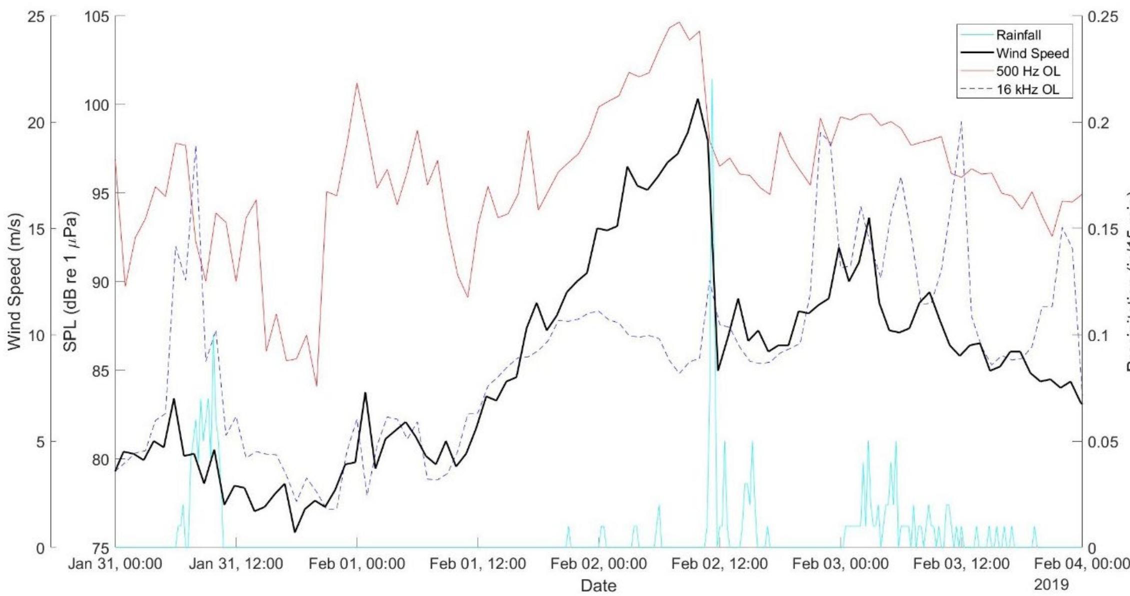
MB03 shows limited changes in the 8 and 16 kHz OLs during storm 1, but peaks in lower frequencies still indicate the passage of storm activity on November 29 (Figure 27).



500 Hz OL line is indicative of wind speed (black line). 16 kHz OL line is indicative of precipitation (cyan line).

Figure 27. MB03 Storm 1 OLs versus Wind Speed and Precipitation

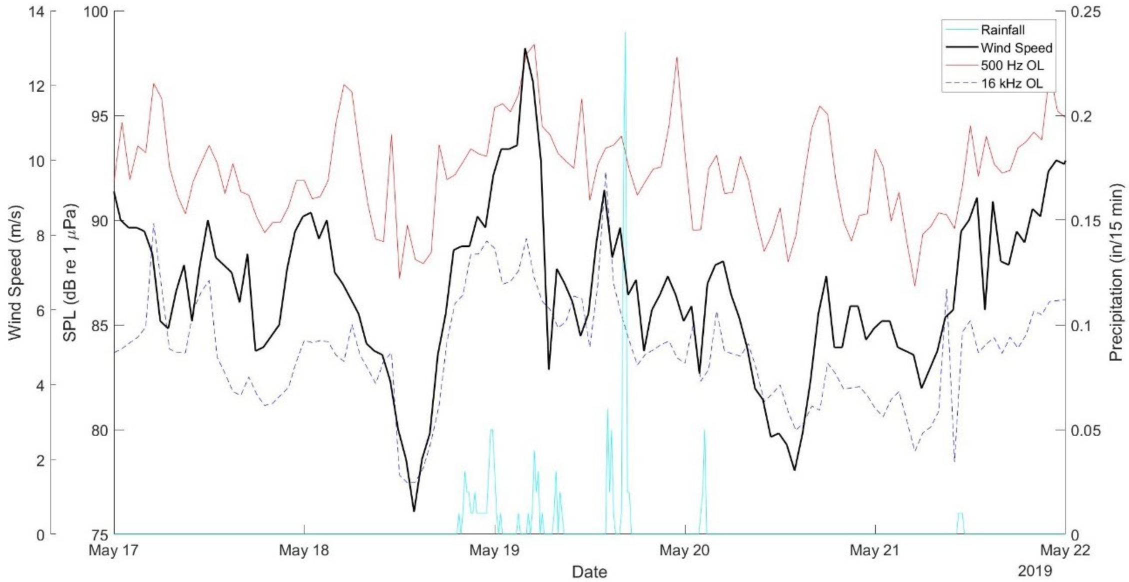
Although storm 2 did pass over MB03, it was a much lower reflectivity intensity that what was present at the other sites (Figure 28). There was still a small spike in the 16 kHz OL at the time of rainfall on January 31 and small peaks on February 2 and 3.



500 Hz OL line is indicative of wind speed (black line). 16 kHz OL line is indicative of precipitation (cyan line).

Figure 28. MB03 Storm 2 OLs versus Wind Speed and Precipitation

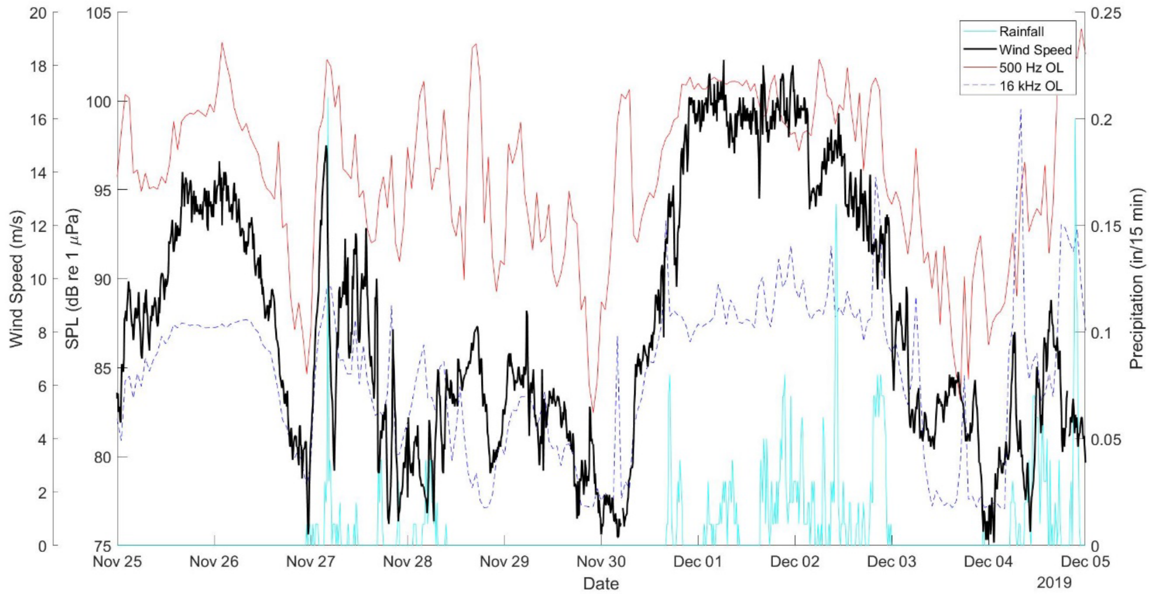
The first afternoon peak of May 19, and several of the peaks occurring earlier that morning match peaks in the 16 kHz OL (Figure 29). Radar reflectivity indicated that the afternoon storm had completely passed by 1500, so the absence of the largest rainfall peak in the OL band is to be expected.



500 Hz OL line is indicative of wind speed (black line). 16 kHz OL line is indicative of precipitation (cyan line).

Figure 29. MB03 Storm 3 OLs versus Wind Speed and Precipitation

During storm 4, many of the rainfall peaks match peaks in the 16 kHz OL, especially those occurring on November 27 and late on December 2 (Figure 30). Some of the rain peaks earlier on December 2 lag the OL peaks, while the peak on November 28 leads it.

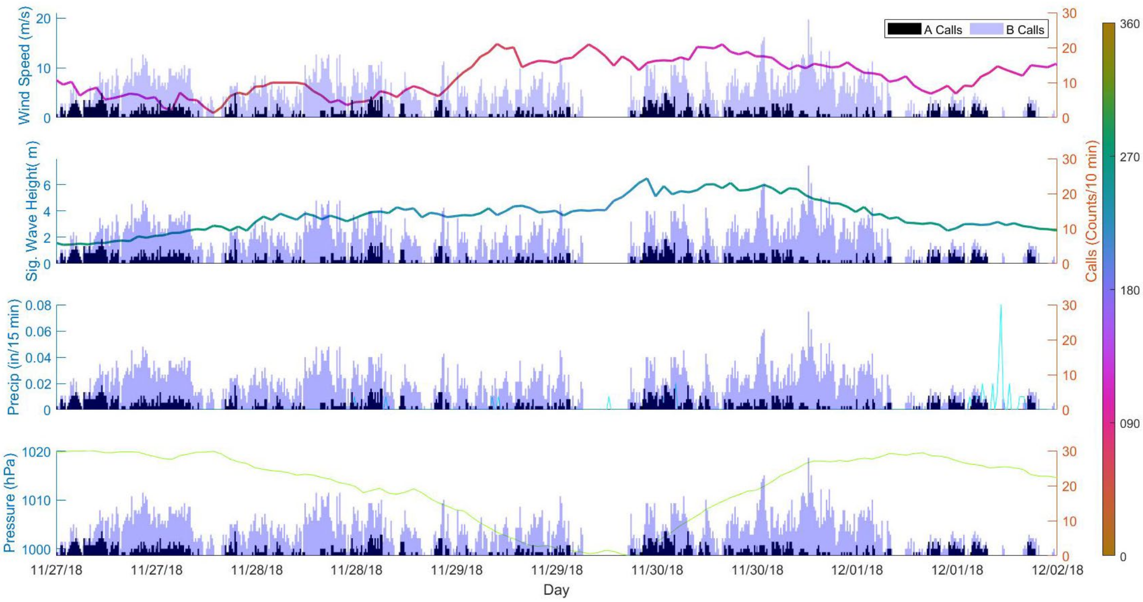


500 Hz OL line is indicative of wind speed (black line). 16 kHz OL line is indicative of precipitation (cyan line).

Figure 30. MB03 Storm 4 OLs versus Wind Speed and Precipitation

B. BLUE WHALES

Due to the complexities of overlapping calls, difficulties arose in analyzing blue whale vocalizations for traditional song patterns. Histograms were created for number of blue whale calls that started in 5-minute bins. During storm 4, blue whale histograms were plotted against wind speed and direction, significant wave height and direction, precipitation, and pressure changes in the atmosphere (Figure 31). These plots indicate that precipitation, in this case rain, has the greatest impact on the call density of blue whales. This relationship held true for both winter storms at all sites except for MB02, which recorded far fewer blue whale calls than any other site. To examine the effects of possible masking, the 50 and 80 Hz third octave levels (TOLs) were plotted against the blue whale histograms. These TOLs were chosen because they most closely match the frequency of B calls and A Calls, respectively.



Color of lines in wind speed (top plot) and wave height (second plot) indicate wind or wave direction as displayed on the colorbar. Data are from MARS Storm 4.

Figure 31. Example of Blue Whale Histograms versus Environmental Factors

Storm 1 is less conclusive, as the rain event occurs near the end of the established storm period (Figure 32). MARS and MB01 both show a marked decrease in blue calls once rain begins. MB02 did not receive many blue calls throughout storm 1. MB02 frequently recorded more background noise in the lower frequencies and did not have as many calls recorded (Figure 33). At MB03, rainfall peaks mostly occur during gaps in recorded vocalizations except for a small rain event on November 30.

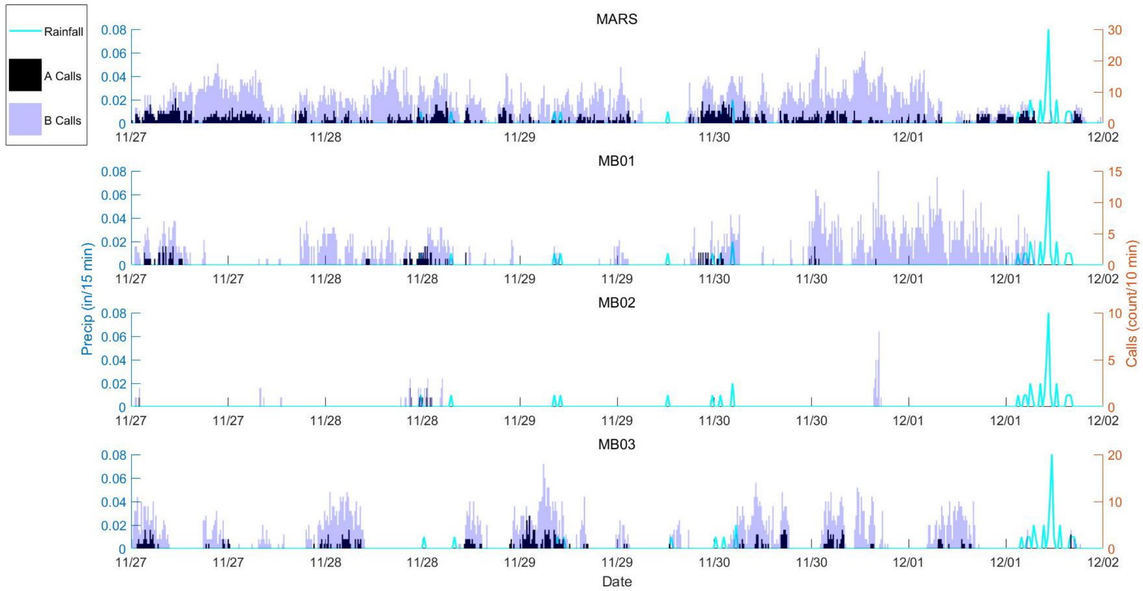
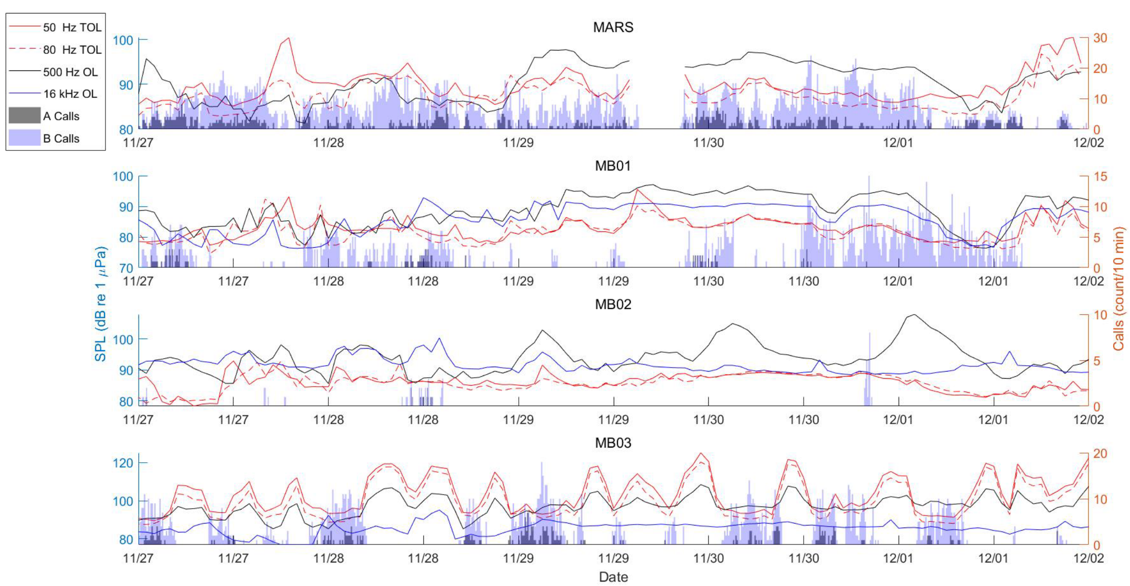


Figure 32. Storm 1 Blue Whale Calls versus Rainfall



Blue whale histograms compared to OLs. 50 Hz TOL identifies possible masking of B calls, 80 Hz TOL corresponds to A calls, and the 500 HZ and 16 kHz OLs correspond to wind and rain, respectively.

Figure 33. Storm 1 Blue Whale Calls Versus OLs

Although the influence of rain is less apparent during storm 4 at MARS, it still appears stronger than the other environmental factors (Figure 34). In most sites, the major peaks align with a reduction in call occurrence, but smaller peaks do not appear to have as much influence. A large decrease in calls also occurs after December 2, 2019, but lower OLS remain at similar levels (Figure 35). The early events of storm 4 show a matching pattern between calls and rainfall, but signals essentially cease after December 2.

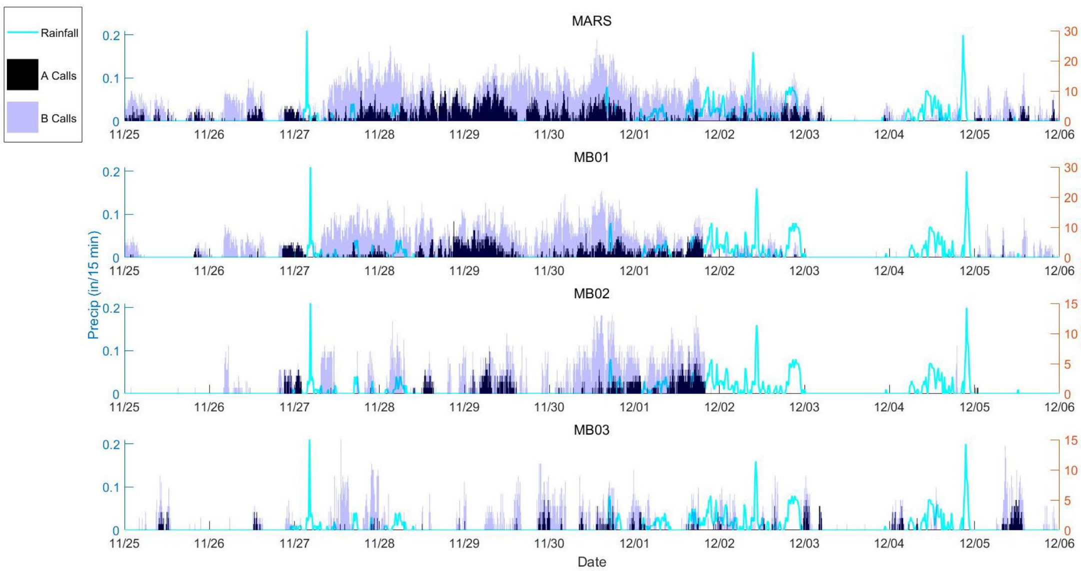
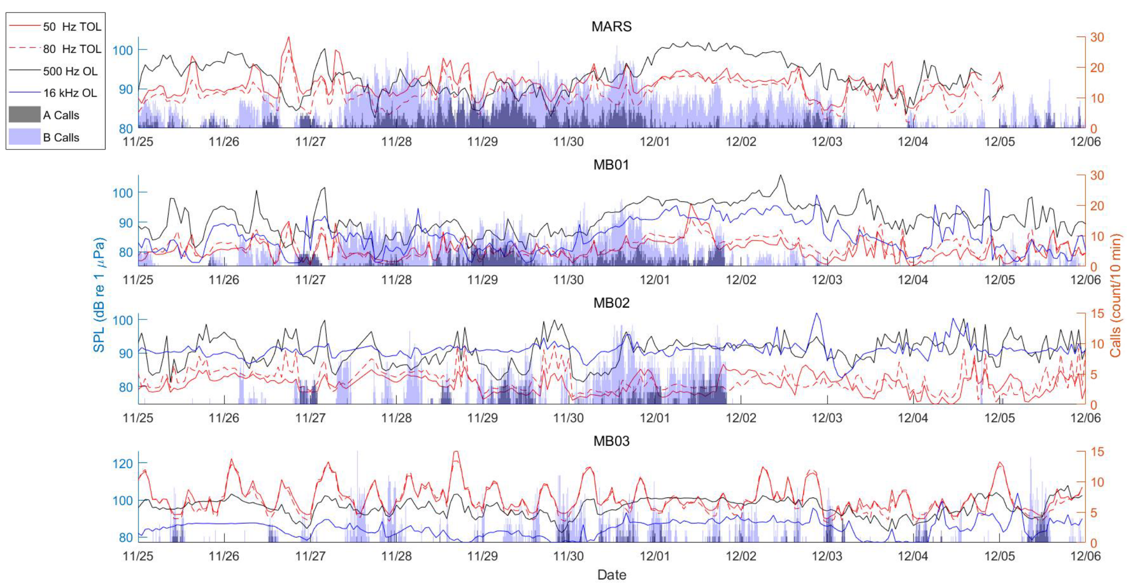


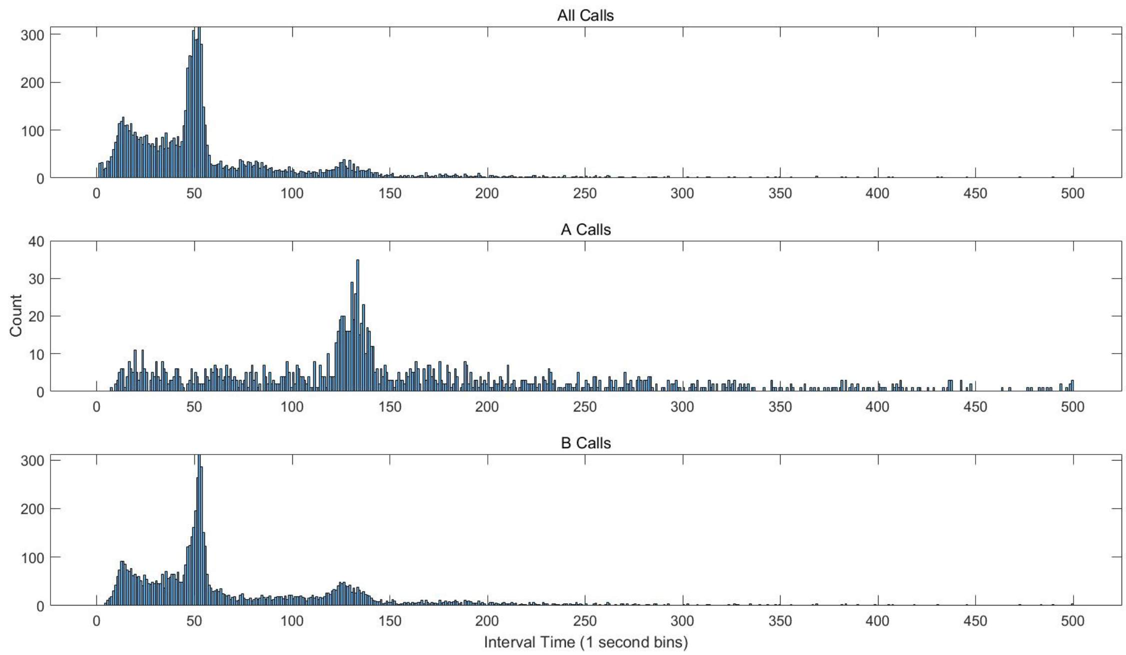
Figure 34. Storm 4 Blue Whale Calls versus OLs



Blue whale histograms compared to OLs and TOLs. 50 Hz TOL identifies possible masking of B calls, 80 Hz TOL corresponds to A calls, and the 500 HZ and 16 kHz OLs correspond to wind and rain, respectively.

Figure 35. Storm 4 Blue Whale Calls versus OLs and TOLs

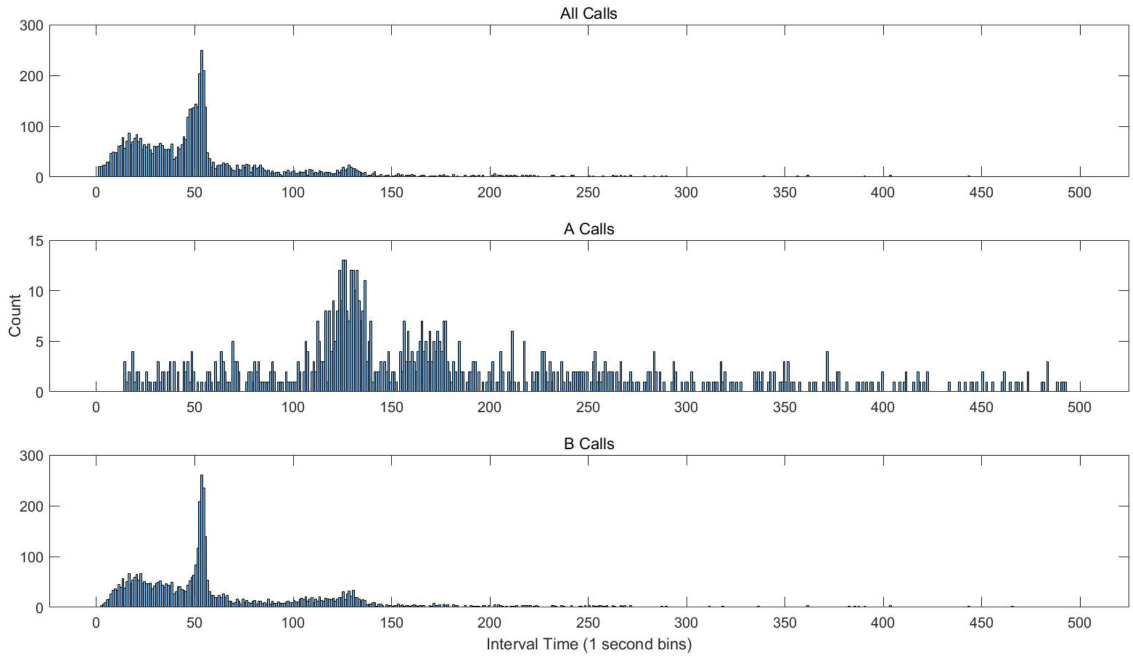
To solve the mystery of overlapping calls, the interval between any one call and the next call was calculated. Figure 36 shows these values grouped into 1 second bins. All data sets demonstrated an overall peak at 50 seconds, with another smaller peak around 130 seconds.



This is an example of the time elapsed between the start of any one call and the start of the next call (top), any one A call and the next A call (middle), and any one B call and the next B call (bottom). Data are from MB01 Storm 4

Figure 36. Blue Whale Inter-Call Intervals

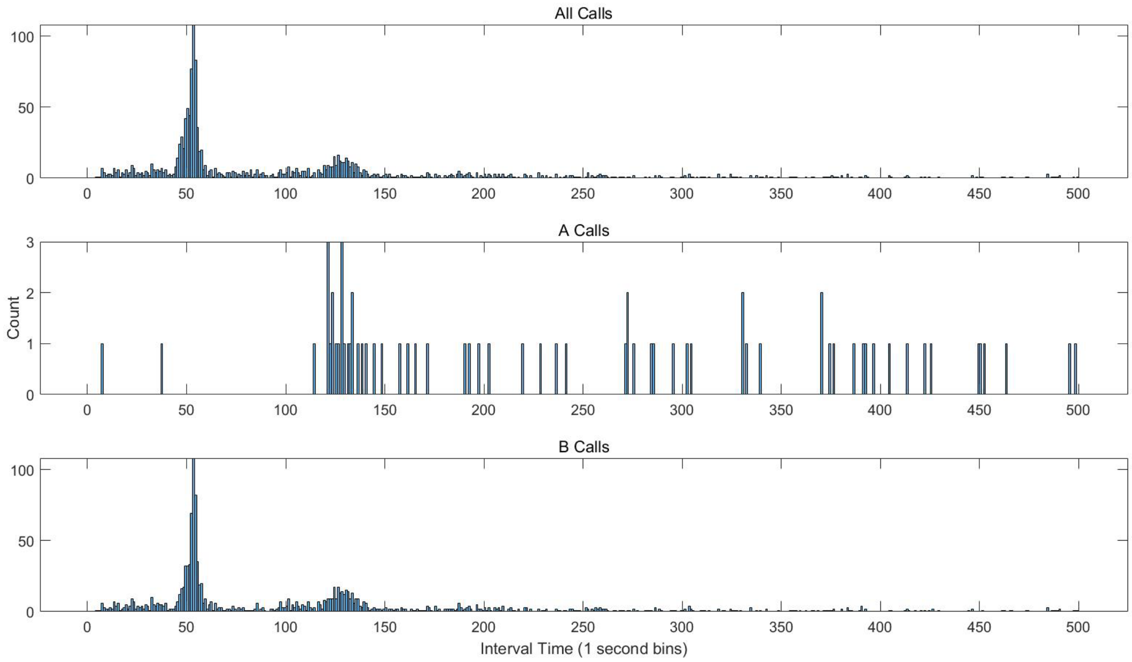
Deeper water sensors sometimes displayed higher levels of shorter intervals (Figure 37). Separating the A and B calls further defined these peaks. B calls displayed a strong peak at 50 seconds, with a smaller peak usually presenting at 130 seconds. A calls showed 130 seconds as their primary, and normally only peak.



This is an example of the time elapsed between the start of any one call and the start of the next call (top), any one A call and the next A call (middle), and any one B call and the next B call (bottom). Data are from MARS Storm 1

Figure 37. Blue Whale Inter-Call Intervals, Deep Water Site

Even the MB01 data set from storm 1 showed this peak, despite a scarcity of A-calls in general (Figure 38). The only exception was MB02 during storm 1, in which there were only 15 A calls recorded for the entire storm period.



This is an example of the time elapsed between the start of any one call and the start of the next call (top), any one A call and the next A call (middle), and any one B call and the next B call (bottom). Data are from MB01 Storm 1

Figure 38. Blue Whale Inter-Call Intervals for scarce calls

Once the primary intervals of 50 seconds (B calls) and 130 seconds (A and B calls) were determined, each recorded call was assigned a category based on the interval between that call and the next recorded call and plotted (Table 6).

Table 6. Intervals

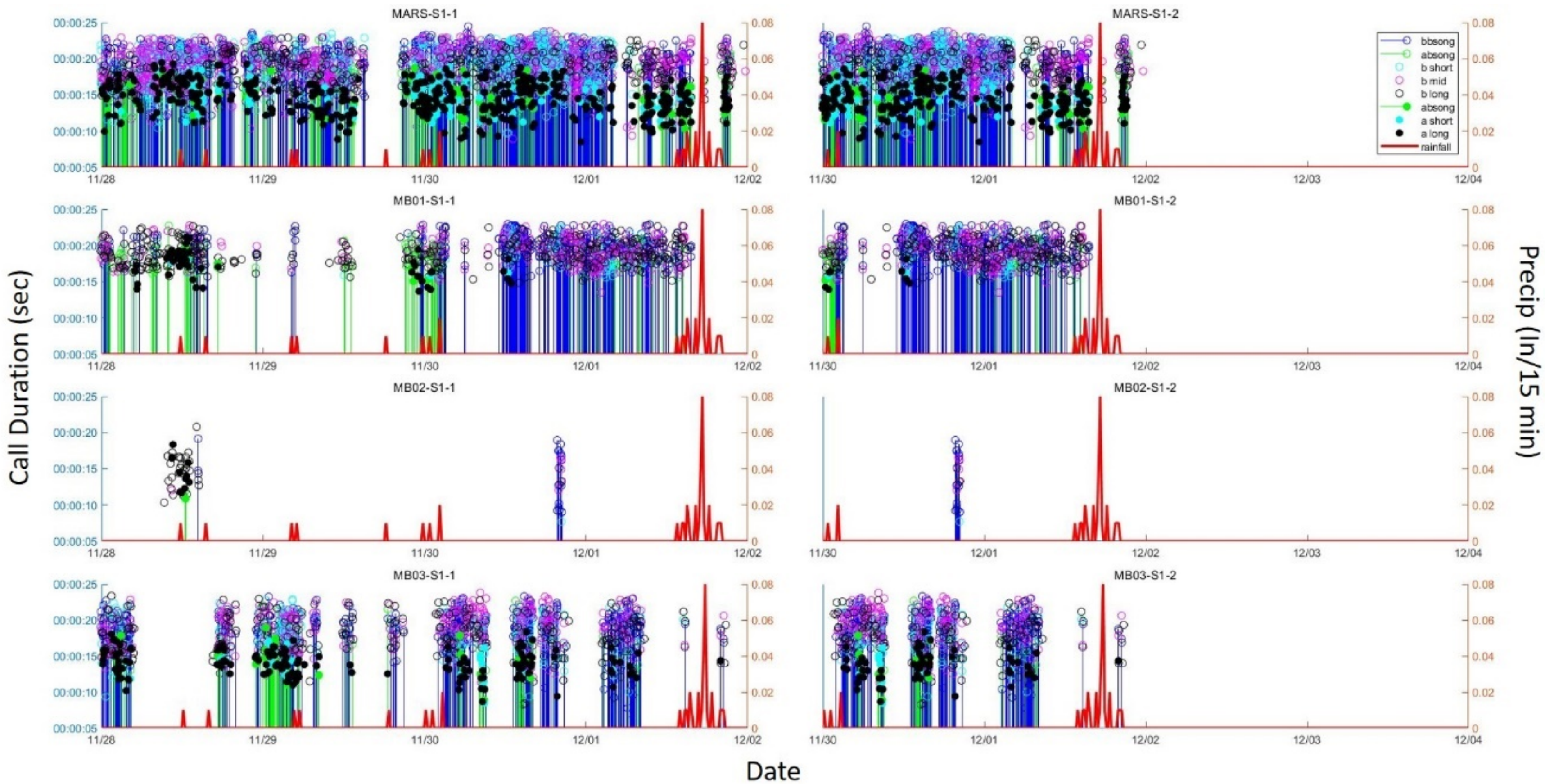
Interval (secs)	Description
<45	A short
45-55	B Pattern
55-125	B mid
125-135	AB Song
>135	Long

Inter-call time bins used to group calls for analysis.

During storm 1, there were two primary rain events that were considered for analysis of call patterns utilizing these intervals, one on November 30, 2018, around 0300 and one on December 1 around 1900. There was a reduction or cessation of blue whale calls during the December 1 event (Figure 39). The deep-water sites outside of the bay, MARS and MB03, saw a short period of activity once the rain had stopped before stopping completely. In relation to the primary storm events considered, MB02 recorded minimal activity during this time. At MB03, calls appear to resume as the rain event is ending on 30 November.

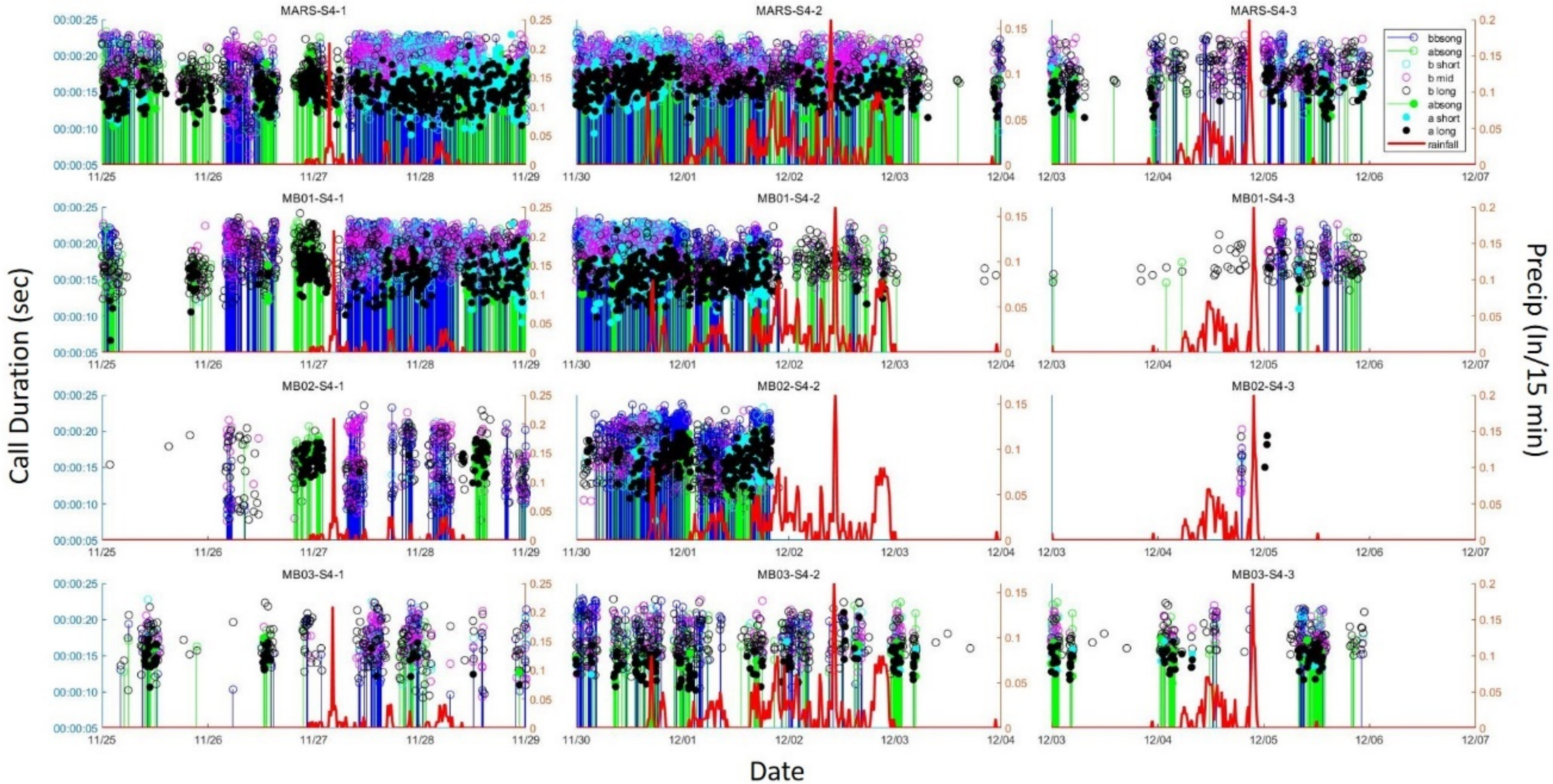
Like storm 1, storm 4 was also divided into rain events, one on November 27, 2019, around 0430, one on December 2 around 1000, and a third on December 4 around 2200. The first rain event of storm 4 saw the most striking changes observed in vocalization type (Figure 40). During the peak event on November 27, the primary call pattern changed from an AB song to a pattern consisting primarily of repeated B calls at MARS, MB01, and MB02. MB03 recorded a reduction in calls during this time, but the pattern is harder to discern. MB02 recorded minimal calls after December 2. During the December 5 event, all four sites saw a pause in vocalization.

To further investigate possible patterns, all calls with intervals less than those identified for songs, and B calls with intervals longer than 130 seconds were removed, and the data replotted. This reduction makes it easier to identify patterns that can be considered an AB song, or B call patterns, while still including possible ABBB patterns. MARS data from storm 1 indicate a slight shift from AB patterns to a pattern of B calls before switching back to an AB pattern (Figure 41).



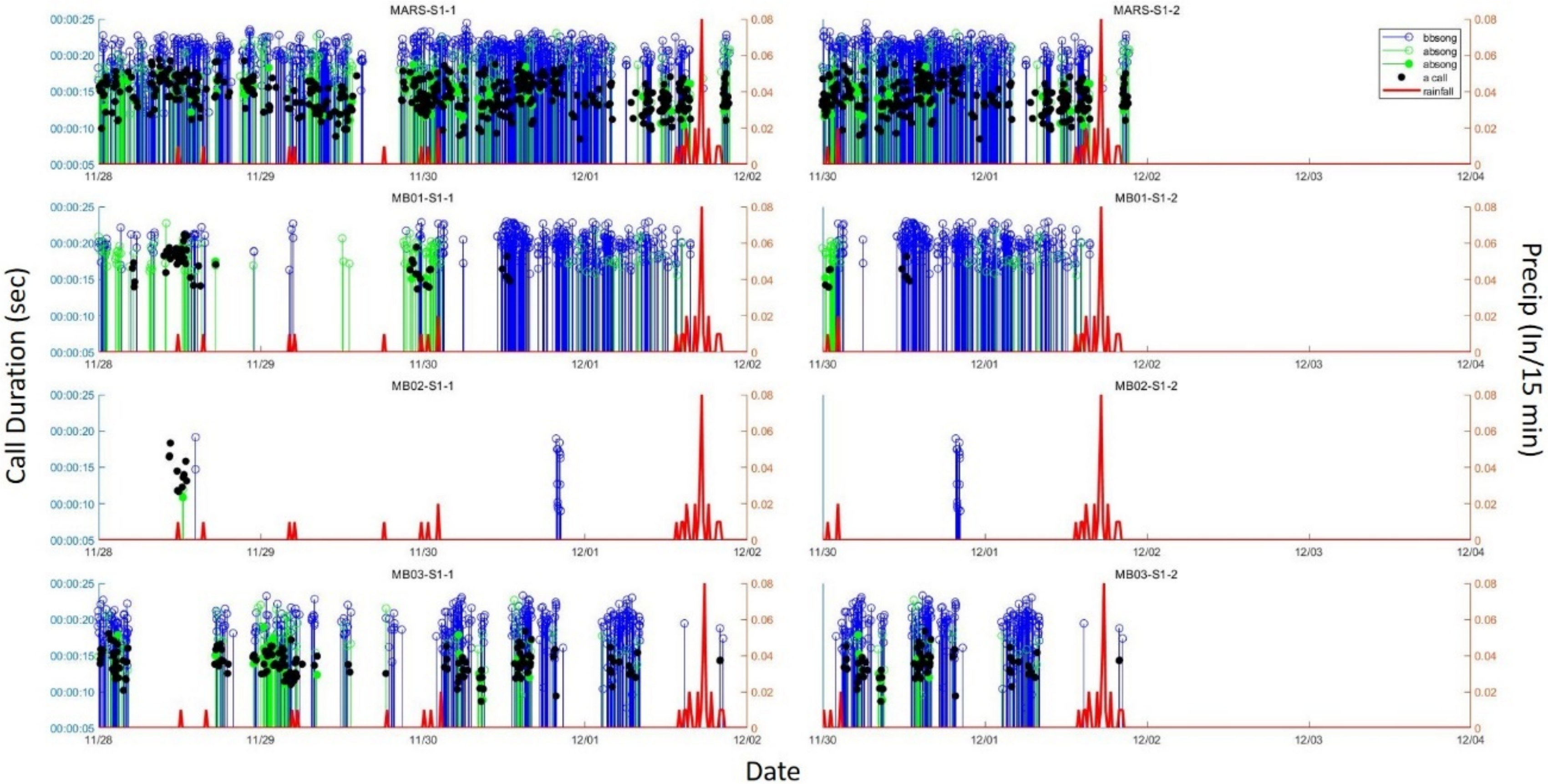
Call patterns for storm 1 with all call intervals accounted for. Color coding for calls is based on the intervals described in Table 6.

Figure 39. Storm 1 Full Call Pattern



Call patterns for storm 4 with all call intervals accounted for. Color coding for calls is based on the intervals described in Table 6.

Figure 40. Storm 4 Full Call Pattern



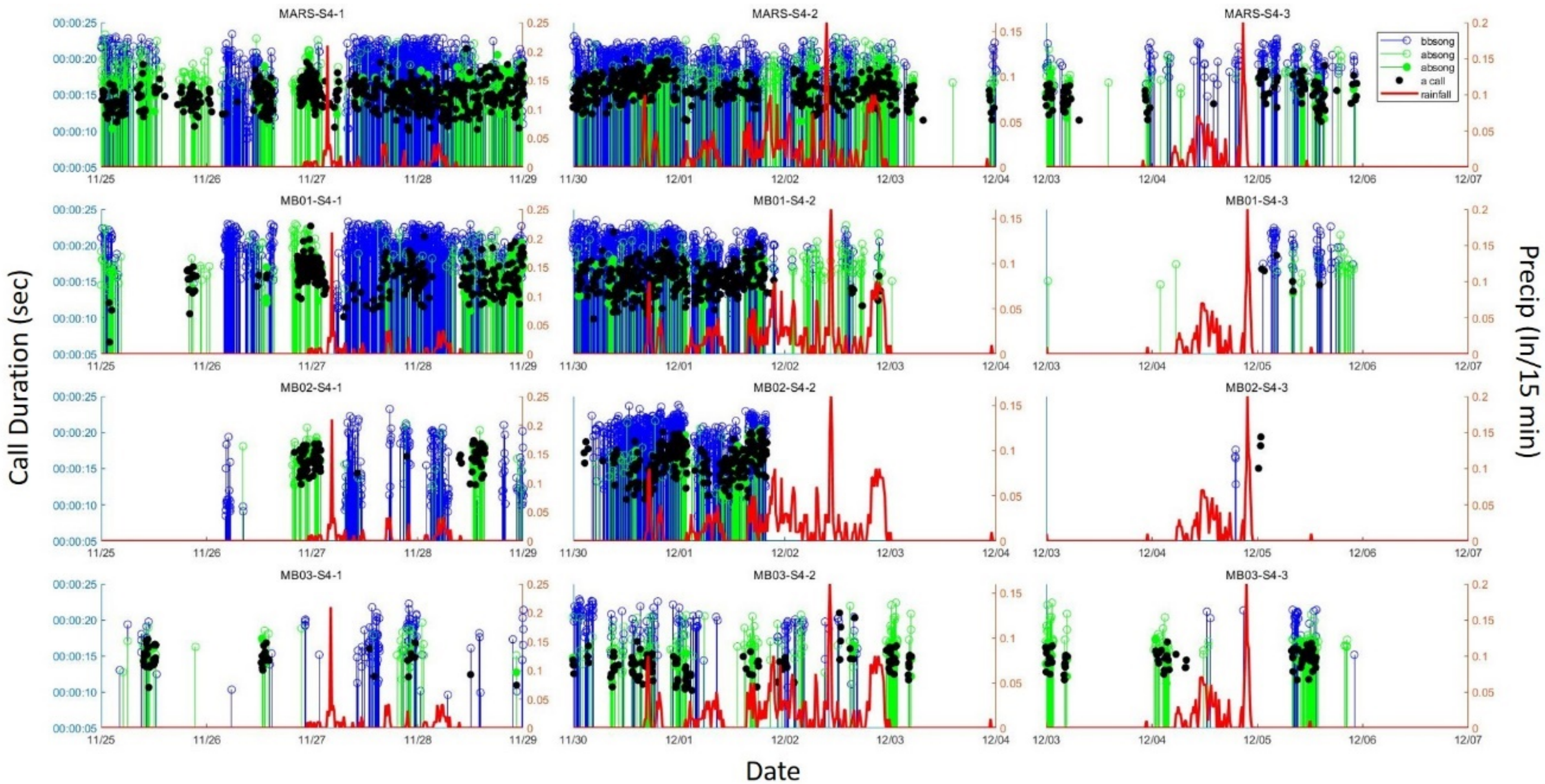
Call patterns for storm 1 only considering intervals indicating AB songs and primarily B call patterns.

Figure 41. Storm 1 Possible Songs

MARS and MB01 demonstrated AB patterns followed by a reduction in call amounts followed by a change to a pattern favoring B calls during the first event of storm 4 on November 27, 2019 (Figure 42). MB02 switched from primarily AB calls to primarily B calls during this event. MB03 was less striking as an initial AB pattern became predominantly B before switching back to AB with breaks coinciding with peaks in rainfall. On 2 December, MB01 switched from a possible ABBB to an AB pattern during the rain event before stopping until after the 5 December rainfall. MB03 Also saw a pattern shift during the second rainfall of storm 4. B calls tended to dominate before returning to AB song patterns. With the removal of other calls, MB03 appears to have been primarily AB song just before the rain, with a short switch to either B or ABBB patterns after the rain before resuming AB patterns.

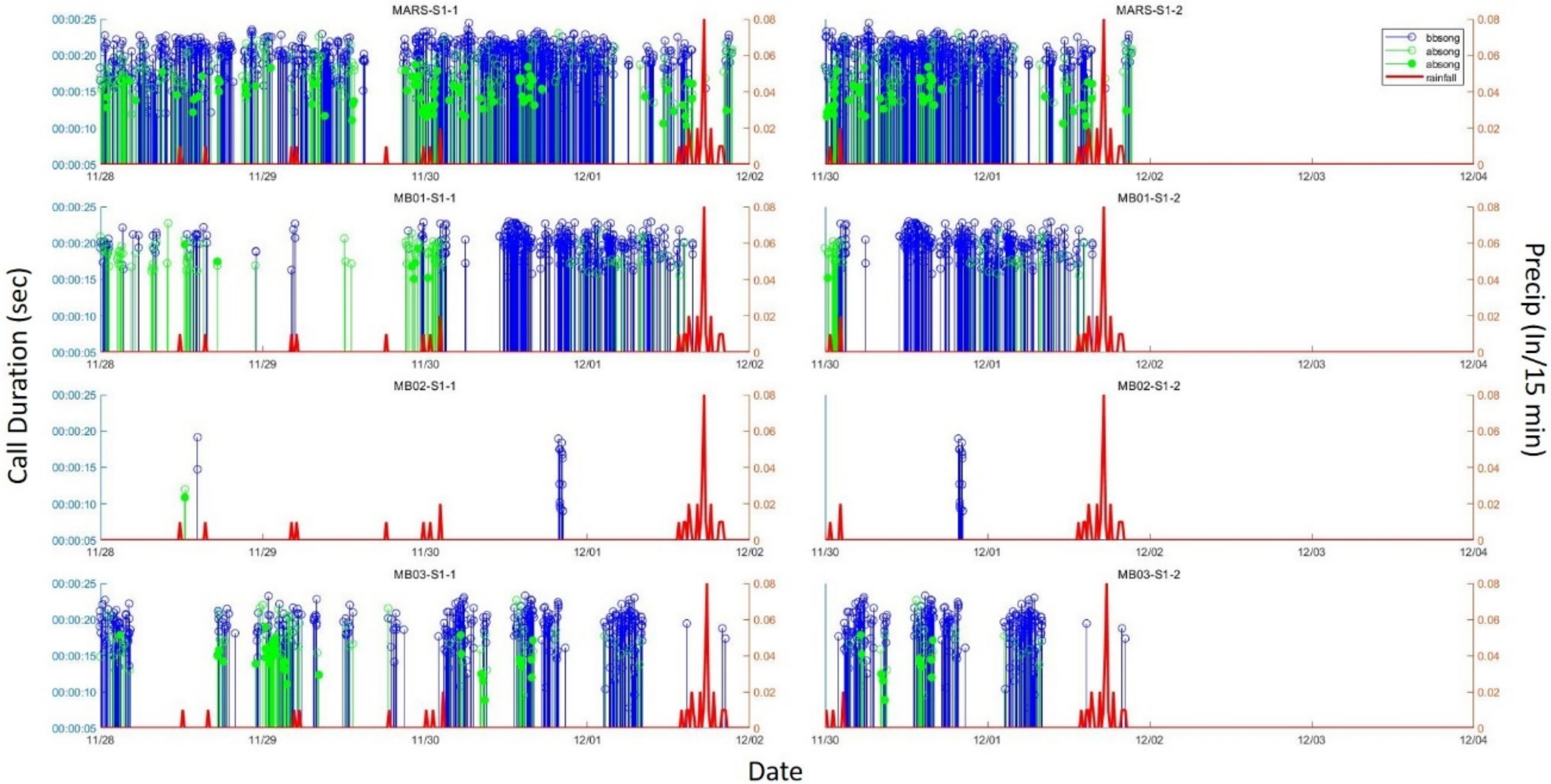
For further analysis of MARS data, anything not part of an AB or B pattern was removed. On November 30, 2018, all sites, except MB02, indicate a higher percentage of B patterns following the rain event (Figure 43).

The previously discussed AB to primarily B to AB shift also appears during the December 2 rain event at the MARS site, and most of the other sites where calls continued as well (Figure 44).



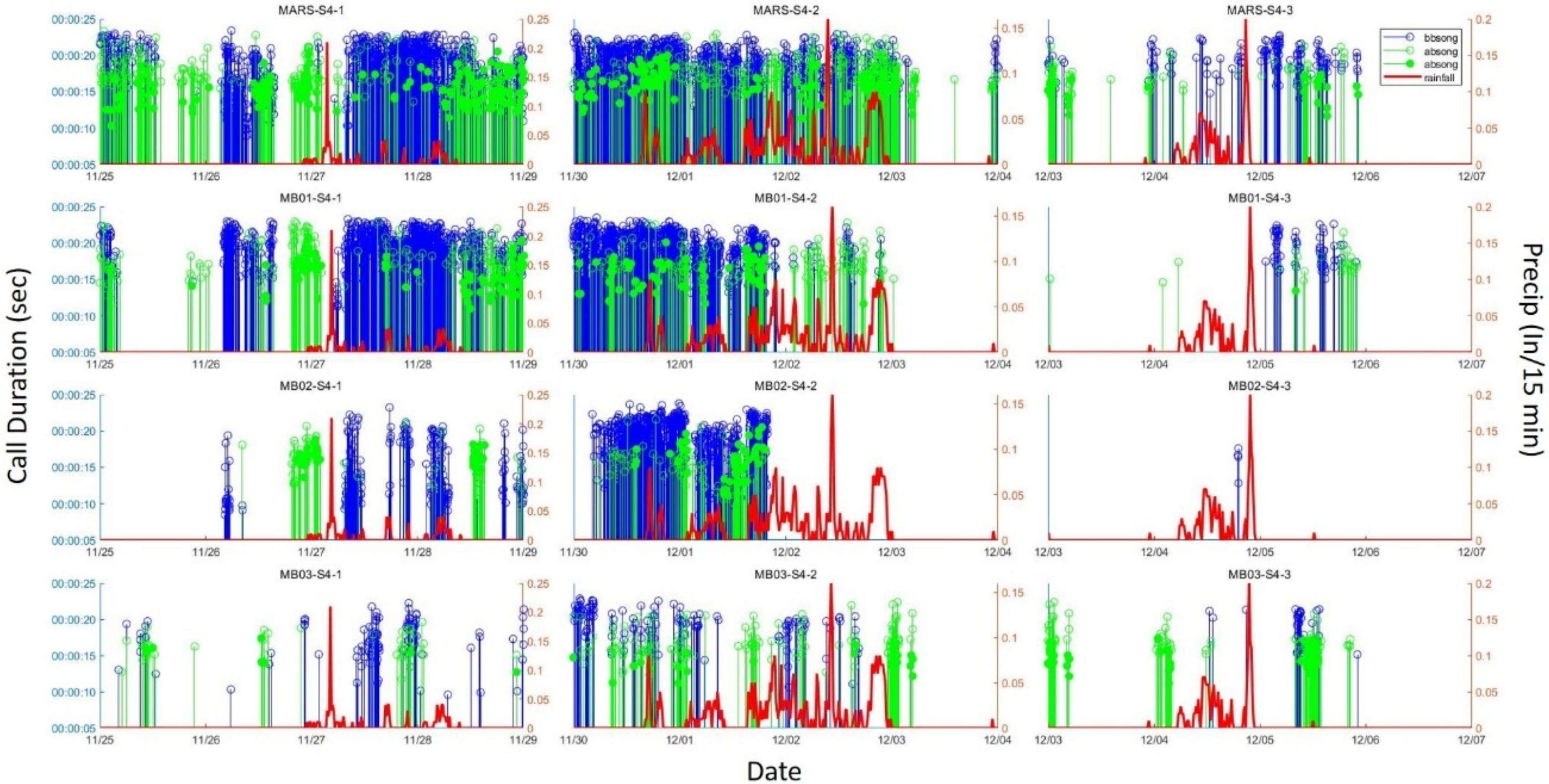
Call patterns for storm 4 only considering intervals indicating AB songs and primarily B call patterns.

Figure 42. Storm 4 Possible Songs



Call patterns for storm 1 only considering intervals indicating AB songs and B call patterns.

Figure 43. Storm 1 AB Songs



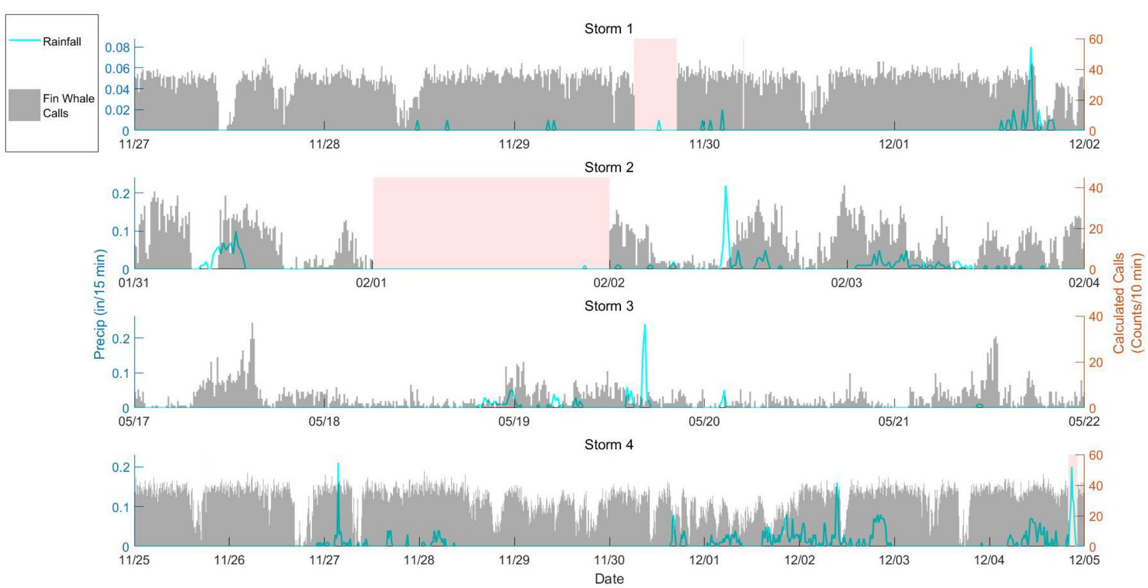
Call patterns for storm 1 only considering intervals indicating AB songs and B call patterns.

Figure 44. Storm 4 AB Songs

C. FIN WHALES

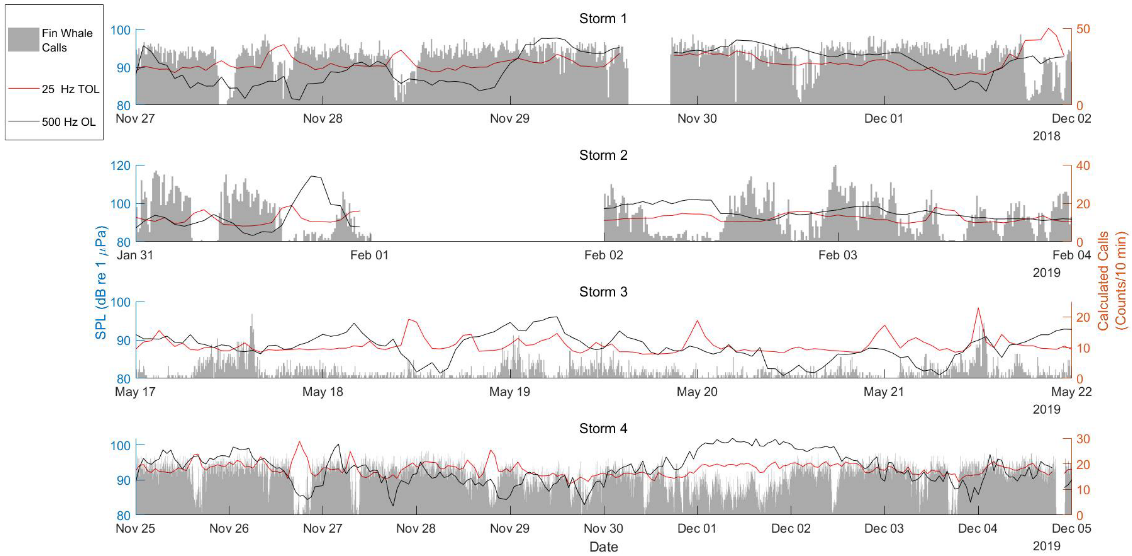
The same methodology for comparing fin whales to the three primary environmental factors used for blue whales were also applied to fin whale calls. The primary difference is that the 25 Hz and 40 Hz TOLs were selected to examine masking effects, instead of the 50 or 80 Hz TOLs used for the blue whales, due to differences in the primary frequencies of calls.

Fin whales appear to show less dependence upon most of the natural factors covered in this study. At MARS, there appears to be little influence of smaller events, but a possible reaction of the larger rain peaks during storm1 (Figure 45). During November 30, the decrease in calculated fin whale calls occurs as the 25 Hz TOL remains mostly constant (Figure 46). During storm 2, the decrease in calculated calls corresponds to increases in the 31.5 Hz OL. Storm 3 shows much lower occurrence of fin whale calls and tend to be inversely related to the OL peaks. During storm 4, there was no reaction to the November 27 peak. There is a possible correlation between the rain peak on December 2 and the subsequent drop in fin calls that cannot be explained by the OLs as they do not change very much.



Red boxes indicate missing PAM data.

Figure 45. MARS Fin Whale Calls versus Rainfall



Fin whale histograms compared to OLs and TOLs. 25 Hz TOL identifies possible masking of calls at 20 Hz, and the 500 HZ and 16 kHz OLs correspond to wind and rain, respectively.

Figure 46. MARS Fin Whale Calls versus OLs and TOLs

At MB01, the rain peak on December 1, 2018, correlates to a drop in fin calls, despite a spike in calls near the end of the event (Figure 47). This initial drop is not explained by significant changes in the 25 Hz TOL as it is decreasing during the gap in calls (Figure 48). During storm 2, the periods of silence may be explained by peaks in the 25 Hz TOL masking any calls, but these main peaks in TOL come after the rain event on February 2. There were negligible numbers of fin whale calls calculated by the storm 3 data at MB01. Storm 4 is much more complex as the OLs fluctuate significantly, but the rain only appears to affect the fin whale calls during the November 27 rain event.

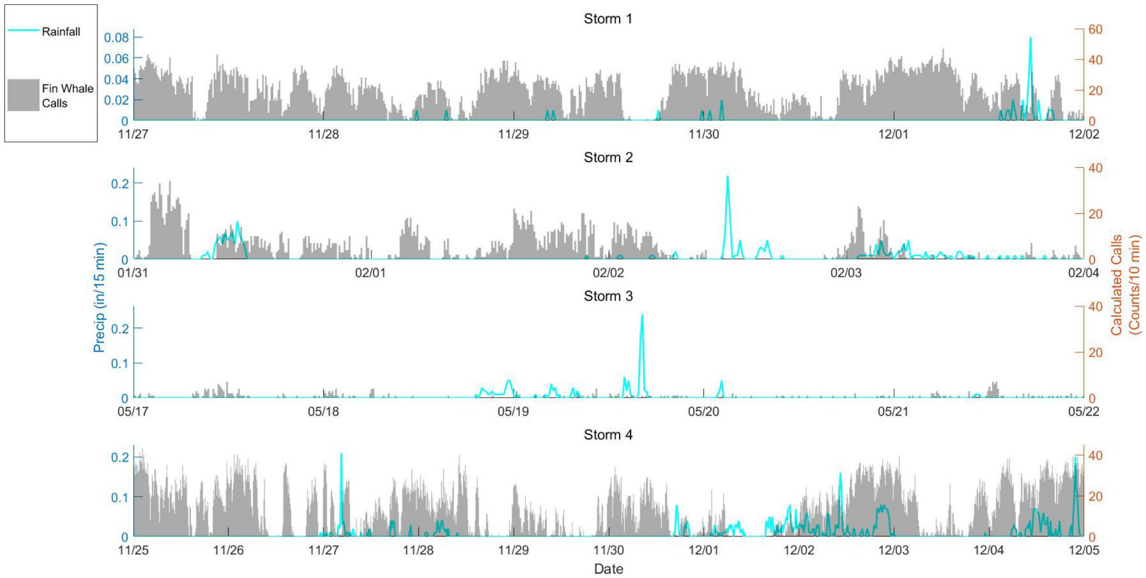
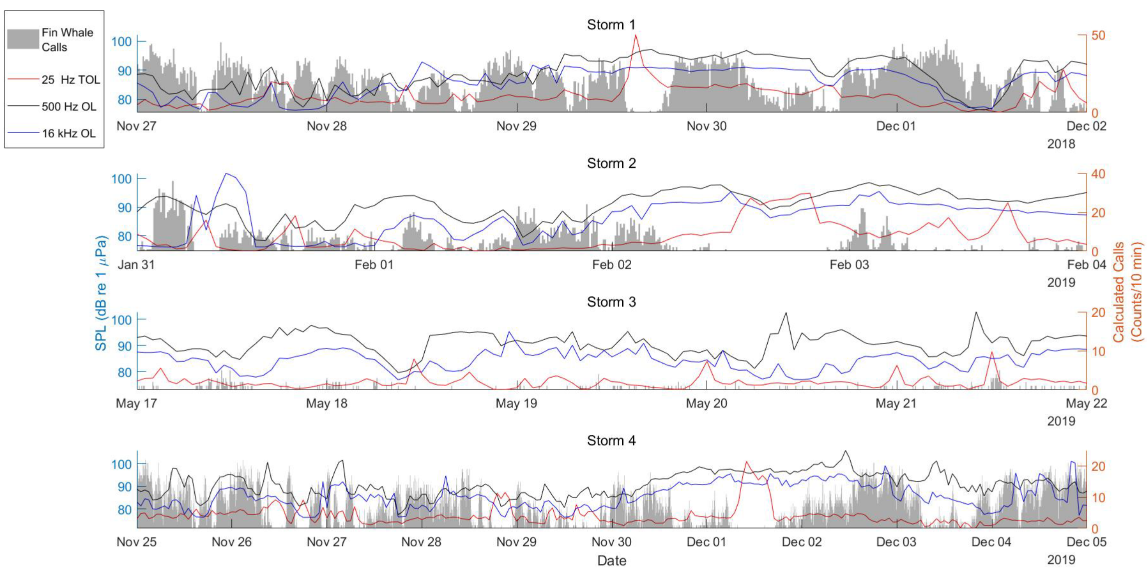


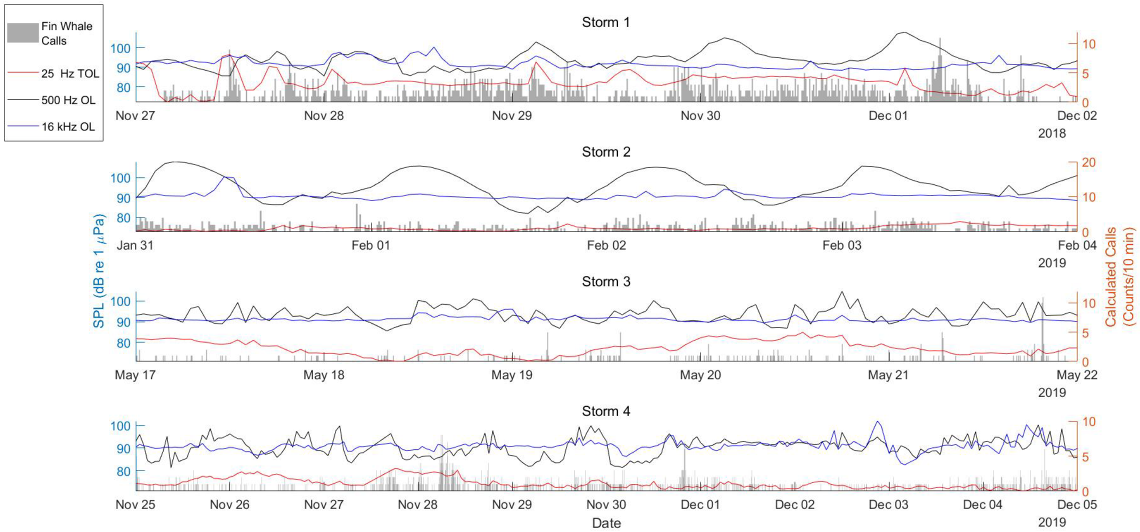
Figure 47. MB01 Fin Whale Calls versus Rainfall



Fin whale histograms compared to OLs. 25 Hz TOL identifies possible masking of calls at 20 Hz, and the 500 HZ and 16 kHz OLs correspond to wind and rain, respectively.

Figure 48. MB01 Fin Whale Calls versus OLs

MB02 also shows a correlation only between the highest rain amount during storm 1 (Figure 49). This station did not yield very many calculated calls, but calls appear to case when rain increases. Like MB01, MB02 did not see much fin whale activity throughout most of storm 3.



Fin whale histograms compared to OLs. 25 Hz TOL identifies possible masking of calls at 20 Hz, and the 500 HZ and 16 kHz OLs correspond to wind and rain, respectively.

Figure 49. MB02 Fin Whale Calls versus OLs

MB03 appears to show further influence of rain as the gaps present during rainfall correlate to decreasing OLs (Figures 50 and 51). During storm 2, the January 31 even shows a lack of fin whale calls, but there is an increase in calls during the February 2 event. This storm deviates from the others in that higher numbers of calculated calls occur during peaks in the 25 Hz TOL. Storm 3 also shows a more favorable correlation between high calculated calls and high OLs rather than any relation to rainfall amounts. Storm 4 show some correlation between rainfall and decreases in calls on November 27 and December 4, but less so with the rainfall peak on December 2. When considering the OLs, the shifted peak of the 16 kHz OL appears to match the decrease in calls.

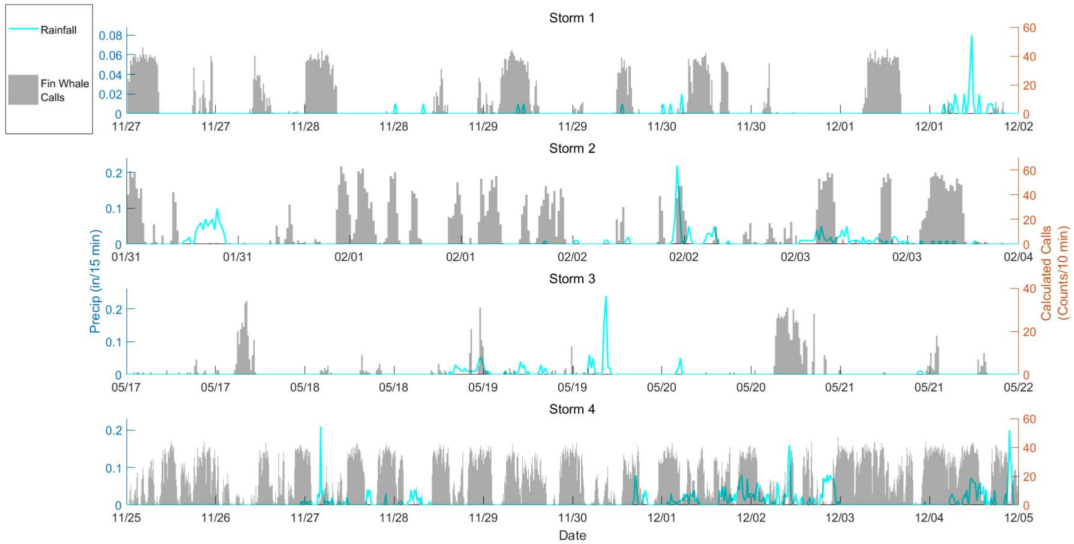
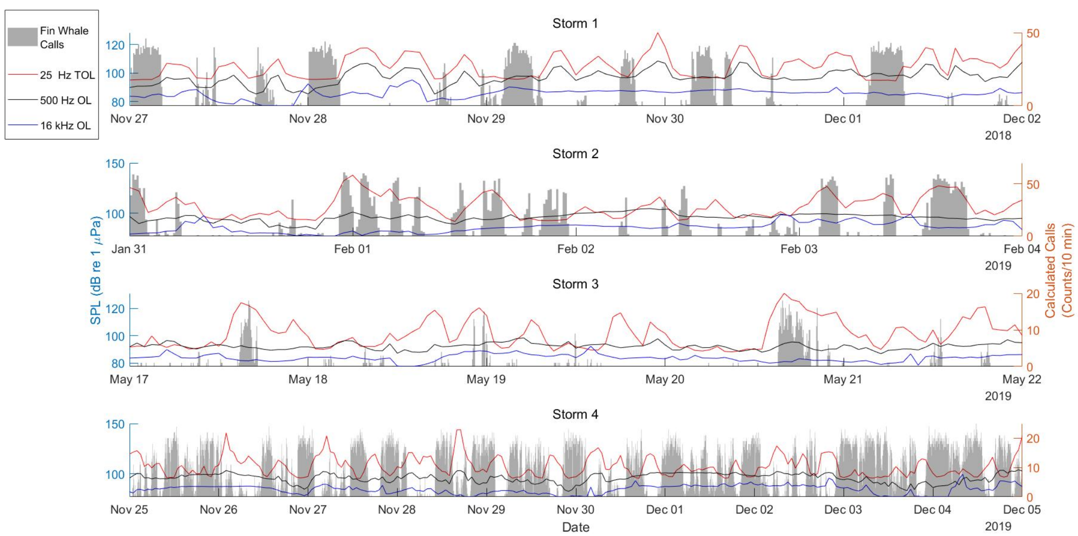


Figure 50. MB03 Fin Whale Calls versus Rainfall

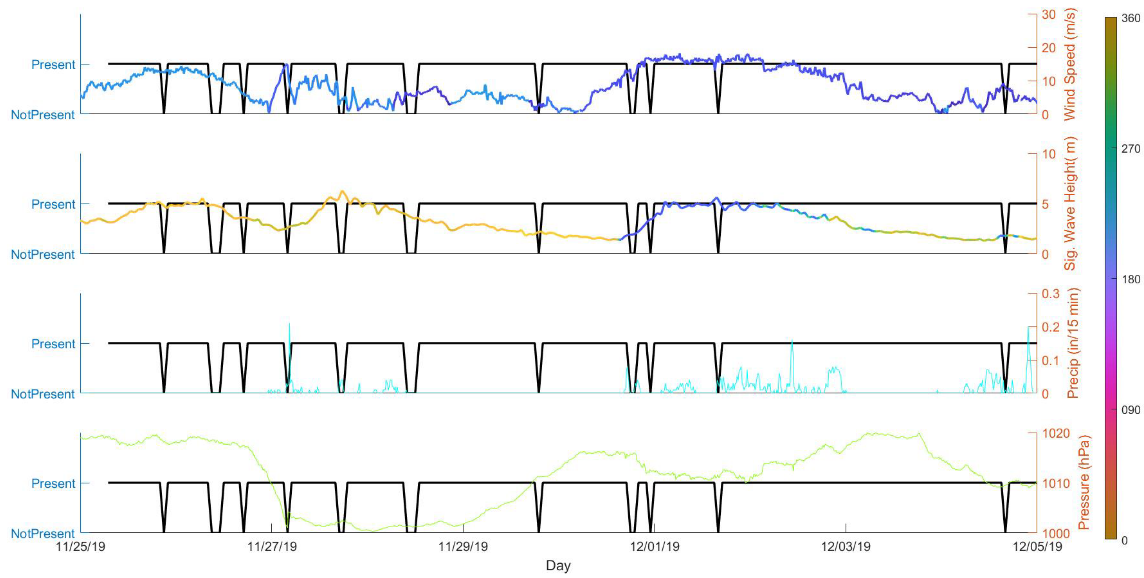


Fin whale histograms compared to OLs and TOLs. 25 Hz TOL identifies possible masking of calls at 20 Hz, and the 500 HZ and 16 kHz OLs correspond to wind and rain, respectively.

Figure 51. MB03 Fin Whale Calls versus OLs and TOLs

D. HUMPBACK WHALES

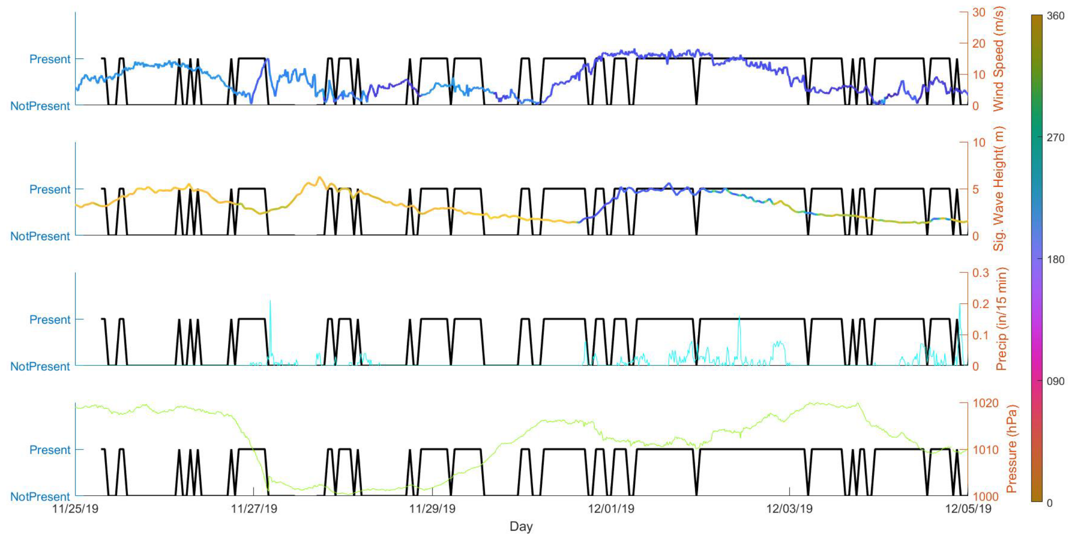
There were no Humpback calls recorded at either MB01 or MB02 during the first or third storm periods. During storms 2 and 4, humpback vocalizations were much more prevalent. MB01 recorded more hours containing humpback vocalizations during both events. During storm 2, there was no humpback presence near the time of the peak rainfall/storm. Storm 4 showed a brief absence of humpback calls during the November 27 event, but presence continued through the other rain events during this storm at MB01 (Figure 52).



Color of lines in wind speed (top plot) and wave height (second plot) indicate wind or wave direction as displayed on the colorbar.

Figure 52. Storm 4 Humpback Whale Presence at MB01 versus Environmental Factors

During the short pause in humpback vocalizations, the wind speeds decreased, and wave height increased slightly, but the rainfall peaked during that time. MB02 registered an additional absence during the December 4event, but also showed no impact from the December 2 event (Figure 53).



Color of lines in wind speed (top plot) and wave height (second plot) indicate wind or wave direction as displayed on the colorbar.

Figure 53. Storm 4 Humpback Whale Presence at MB02 versus Environmental Factors

V. DISCUSSION

Differences in local environmental factors, and instrumentation, at each instrument site led to a variety of differences in the results. Across all data sets, MB02 saw the fewest number of calls from all whale types. This was expected due to several factors. MB02 located in much shallower water, sitting in almost half the depth of MB01 and less than 10% of the depth of MARS and MB03. In addition to extremely shallow waters, it also sits beneath the transit areas for vessels entering/departing Monterey harbor. These factors combine to greatly reduce the chances of most whale species venturing close to the sensor, and most of the calls recorded likely come from individuals located in deeper waters.

A. STORM VERIFICATION

The method of estimating rainfall occurrence at each site appears to have been largely successful despite several difficulties. The primary difficulty stems from the fact that high radar reflectivity does not necessarily mean that there was higher rainfall. This is countered by the fact that there were peaks in the 16 kHz OL around the times that rainfall was to be expected (Ma and Nystuen 2005). There were also peaks in this OL that did not align with the offset rain data, and it is difficult to know if these were unaccounted for rain events, or some other phenomenon entirely. Higher fidelity could be accomplished by applying a more complex offset scheme rather than the simple one value per site used in this study. At the time scales examined, there did not appear to be enough of a difference to require that level of effort for most of the data sets.

MB03 is also very removed from the weather sites located in the bay, so there are some questions regarding the accuracy of atmospheric data collected 25 Nautical Miles to the north of the hydrophone. However, the general patterns of the winds recorded at the NOAA buoy match the large-scale patterns of the OLs recorded at MB03. Differences in peaks of lower OLs are likely due to the passage of shipping traffic along the routes straddling the hydrophone.

B. BLUE WHALES

Although more analysis of blue whale patterns is required to further identify song occurrence, the use of interval bins provided significant initial insight into the call patterns recorded during this study. This method allowed the interpretation of AB song based only on B call data, so a song could be identified even if the higher frequency A calls were attenuated before reaching the hydrophone. In 70% of rain events, a change in blue whale vocalization patterns was easily recognized, usually in the form of a switch from AB patterns to predominantly B patterns. Of the remaining 6 cases, one was inconclusive due to a lack of data at the time in question and two others exhibited a possible change. The lack of response during these times could be due to a lack of data such as occurred at MB02, or due to mitigations of a storms impact due to deeper waters. Deeper waters not only move the surface noises further away, but the deep-water sites also saw increased occurrence of overlapping calls. During normal circumstances, it is uncommon for more than one whale in a group to vocalize (Lewis and Širović 2018). The occurrence of overlaps such as those shown in Figure 10 are likely caused by one whale vocalizing relatively close to the hydrophone (the A call), and another vocalizing from much farther away (the B call). Although the data was not recorded for each call, there were often differences in brightness in a spectrogram, indicating a difference in power levels, between overlapping calls.

These patterns' changes could be due to a variety of reasons. The two most likely reasons are either feeding, or storm avoidance. Blue whales generally do not emit A or B calls while feeding (Oleson et al. 2007). There were many signatures that could have possibly been feeding 'D calls', but they were not considered or logged due to their variability. Due to the reception of distant calls, it is expected that a departure would still provide some calls, albeit at lower power levels than those present before departure.

An interesting, and mostly unexplained phenomenon occurs around 3 December 2019. Starting on 2 December, the number of vocalizations recorded from MB01 and MB02 plummet, and do not begin to return until after December 5. MARS sees a similar drop on December 3. None of the natural phenomenon explain this decrease, and there were significant periods of minimal ambient noise during this time. It is believed that one possible explanation for this silence is the reporting of a pod of killer whales (*Orcinus orca*) by the Monterey Bay Whale Watch team during the afternoon of December 4 (Black

2020). Although instances of predation on blue whales have not been recorded in Monterey bay, there have been several instances of killer whales caught on video while harassing blue whales near Monterey Bay (Gibbens 2017). It is possible that the blue whales may have left the relatively confined waters of the bay to avoid trapping by the killer whales.

C. FIN WHALES

Fin whales were much harder to diagnose any influence of storm activity. Approximately half of the rain events saw a change in fin whale call amounts. MARS and MB01 were the most likely to see a change in behavior. During this study, there were instances of the number of calls both increasing and decreasing around the time of rain events. Based on previous studies of a fin whale calf skull, it is likely that rainfall noise of 16 kHz is just on the edge of the fin whale's peak upper hearing frequency of 12 kHz (Cranford and Krysl 2015). This supports the observation that larger rain peaks were more likely to see some form of a response by fin whales in these data sets. Another possibility is that the fin whales were resting on the surface and dove back underwater, and began vocalizing, after being disturbed by the rainfall (Watkins et al. 1987). The calculation of call occurrence removes any chance of detailed analysis of call or inter call patterns but provides a much faster estimate of presence. A further detailed analysis could provide insight into nuances of behavior during the times of interest.

D. HUMPBACK WHALES

The humpback whales also only appeared to cease vocalizations for the strongest of rain events on November 27, 2019. It is unknown if this pause is due to rainfall in particular, or if there were other factors present due to the sharp peak of the storm that affected the whales. Although it is not recorded, it is possible that any communication conducted during this time was via methods other than song vocalizations (Dunlop et al. 2010). The smaller rainfall events could have seen stoppages or changes in vocalizations, but at much lower temporal scales than the hourly records used for this study. When comparing MB01 and MB02 data, it is apparent that MB01 recorded humpback songs during times when MB02 did not, but MB02 never recorded songs that MB01 did not. These differences indicate that the whales recorded during this time were likely offshore of MB01. Once again, a more detailed analysis could provide much more insight to nuances of behavior that may have changed during these times.

E. FUTURE WORK

There are four main areas that open avenues for future work. First and foremost, more storm events need to be analyzed to determine if the patterns observed are present more often. More and more storm events will become available as the SanctSound hydrophones, or any other similar projects, continue to collect data. The second area for continued work is to utilize more intensive analysis techniques to fully understand patterns present. Although machine learning is rapidly advancing, human intervention is still generally required to reduce false alarm rates (Baumgartner et al. 2020). Human analysis has the potential to be more complete but requires time to both train an analyst and for the analyst to conduct the analysis of the available data. As machine learning capabilities continue to grow, they will eventually be able to dramatically reduce the time required to analyze the large datasets yielded by passive acoustic sensors. The third method for continuation involves obtaining 'ground truth' data regarding both animal presence and atmospheric conditions. For the animal presence, inclusion of data from any manner of tracking would help definitively identify presence and range from sensors to aid in determining behavior. Deployment of atmospheric measurement sensors, especially for precipitation, in close proximity to the hydrophones would reduce the ambiguity of if rain actually occurred at a site and eliminate the need for calculation of offsets. The fourth and final opportunity for expansion is to analyze data from a site other than Monterey Bay. Analysis of different sites will help determine if patterns are influenced by local effects or are truly due to the weather phenomenon analyzed.

There is promise for utilizing violin plots to visualize the probability density functions of SPLs within various OLs or TOLs. By analyzing the shape and positioning of the violin plots, it may be possible to identify the primary source of noise present, such as wind, rain, or shipping. Further investigation is required to fully interpret parameter choices and possible noise sources that may be presented on these plots. This method would allow analysts to quickly identify common noise sources, or to compare between different times or locations.

VI. CONCLUSION

The undersea soundscape is a vast and nuanced web of interconnected sounds produced by geologic, biologic, and anthropogenic sources. Deciphering the interactions at play are crucial to understanding the relationships between the creatures inhabiting the ocean and the ocean itself. Passive acoustic monitoring provides exceptional opportunity to observe the environment without disrupting natural processes by noise from boat machinery or active emissions. Additionally, these sensors allow observation for a much lower cost across a much wider range of environmental factors. This 'always on' collection method does yield its own challenges regarding data storage, transmission, and interpretation. The wide variety of available sensors mean there is great choice in designing an apparatus to best approach searching for the answers to the ocean's mysteries.

During this study, several interesting patterns were observed among the cetaceans of Monterey Bay National Marine Sanctuary. Most striking were the reactions of the blue whales. Not only did those individuals habitually stop vocalizations when storms occurred, but they frequently shifted their call patterns away from patterns containing A calls as well. Fin whales were less consistent, but they too displayed a reaction to higher amounts of rainfall during storm events. Unlike blue whales, the change in vocalization patterns seems to depend on the behavior in progress when rain stops. Vocalizing whales appeared to go quiet, while quiet whales began vocalizing almost immediately following a rain event. Unsurprisingly, the humpback whales within the bay were less affected by storm activity around them. During the periods of observation, humpback whales only appeared to cease vocalizing during the strongest storm event.

In the course of analyzing environmental factors, the ability to determine occurrence of rainfall at locations remote from actual rain gauges was tested as well. By combining a known rainfall quantity, available radar reflectivity products, and octave level analysis, a reasonable estimation was made regarding the timing of rainfall at hydrophones located almost 40 Nautical Miles away from the rain gauge.

This study highlighted the difficulties inherent in analyzing the soundscape for specific animal behaviors. Similar to how a person's voice and speech patterns may vary, so to do the patterns exhibited by many whales. These variations, combined with the influence of environmental factors and long ranges inherent to sound propagation underwater, prevent the easy application of automatic identification and require a human analyst to examine the data in a very time-intensive process. As more and more data are collected and analyzed, the understanding of oceanic processes will increase as well. When we better understand the inner workings of the ocean environment, better decisions can be made regarding the best way to protect our natural resources while maximizing the ability to utilize the underwater world.

This study adds to a continuously growing effort to establish baselines used to interpret marine mammal vocalizations. These baselines can aid in understanding changes to the overall environment and soundscape. This increased understanding can allow other research to consider impacts of other noise sources, such as anthropogenic sources, on the environment.

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