Naval Information Warfare Center PACIFIC

TECHNICAL REPORT 3202
January 2020

FY18 Annual Report on Pacific Missile Range Facility Marine Mammal Monitoring

Cameron R. Martin
E. Elizabeth Henderson
Stephen W. Martin
Tyler A. Helble
Roanne A. Manzano-Roth
Brian M. Matsuyama
Gabriela A. Alongi

NIWC Pacific

Naval Information Warfare Center Pacific (NIWC Pacific)
San Diego, CA 92152-5001

This page is intentionally blank.

TECHNICAL REPORT 3202
January 2020

FY18 Annual Report on Pacific Missile Range Facility Marine Mammal Monitoring

Cameron R. Martin
E. Elizabeth Henderson
Stephen W. Martin
Tyler A. Helble
Roanne A. Manzano-Roth
Brian M. Matsuyama
Gabriela A. Alongi

NIWC Pacific

Administrative Notes:

This report was approved through the Release of Scientific and Technical Information (RSTI) process in December 2019 and formally published in the Defense Technical Information Center (DTIC) in January 2020

This reports content represents work performed under Space and Naval Warfare Systems Center Pacific (SSC Pacific). SSC Pacific formally changed its name to Naval Information Warfare Center Pacific (NIWC Pacific) in February 2019.

NIWC Pacific
San Diego, CA 92152-5001

NIWC Pacific
San Diego, California 92152-5001

M. K. Yokoyama, CAPT, USN
Commanding Officer

W. R. Bonwit
Executive Director

ADMINISTRATIVE INFORMATION

The work described in this report was performed by the Marine Mammal Scientific & Vet Support Branch (Code 71510) of Biosciences Division (Code 71500), Naval Information Warfare Center Pacific (NIWC Pacific), San Diego, CA. Funding for this effort was provided by COMPACFLT.

Released by
Eric D. Jensen, Branch Head
Marine Mammal Scientific & Vet Support Branch

Under authority of
Mark Xitco, Division Head
Biosciences Division

RJP

EXECUTIVE SUMMARY

This report documents Naval Information Warfare Center Pacific (NIWC Pacific) marine mammal monitoring efforts in fiscal year (FY) 2018 for Commander, Pacific Fleet (COMPACFLT) at the Pacific Missile Range Facility (PMRF), Kauai, Hawaii. The following list highlights tasks that were completed in FY18 in support of COMPACFLT monitoring goals:

1. Raw acoustic data from 62 bottom-mounted hydrophones at PMRF were recorded at the full bandwidth sample rate of 96 kHz and at a decimated sample rate of 6 kHz. Classified data were collected at the full bandwidth sample rate in February and August before, during, and after the Submarine Command Courses (SCCs) to evaluate the impact of mid-frequency active sonar (MFAS) on marine mammals.
2. Data from February 6, 2002 to August 20, 2018 have been processed to estimate long-term abundances for multiple species of marine mammals; this is the first time systematic results of all data from February 6, 2002 to September 12, 2006 are being presented. Localization and tracking results are provided for baleen whales (minke, humpback, and the low-frequency baleen whale group [fin/sei/Bryde's] whales), and localization results are provided for sperm whales. Localizing groups of odontocetes to the nearest hydrophone was done for Blainville's, Cuvier's, and Cross-Seamount type beaked whales, and killer whales. Results for Cuvier's beaked whales have not been reported previously, and detection and localization algorithms for sperm whales were refined in FY18. Cuvier's beaked whale and sperm whale results in this report are preliminary.
3. The long-term abundance results for baleen whales from February 2002 to August 2018 indicated that at any instant there was a maximum of nine minke whales tracked at the same time (in December 2007 and November 2015), compared to one or two humpback whales. From January 2011 to August 2018 there was a maximum of five tracks from the low-frequency baleen whale group that occurred at the same time (in December 2014 and February 2017). Singing humpback and other vocalizing low-frequency baleen whales had lower abundances compared to minke whales. In addition, one track from the low-frequency baleen whale group occurred in June 2018 and was manually validated to be a Bryde's whale.
4. The long-term abundance results for odontocetes (sperm, beaked, and killer whales) from January 2007 to August 2018 are presented. These include Blainville's beaked whales, which had an average of 1.5 dives per hour, and a maximum of 5.2 dives per hour (in June 2015). The number of fully validated Cross Seamount (CSM) beaked whale dives occurred far less frequently than Blainville's beaked whale dives, resulting in typically less than 0.2 dives per hour, and a maximum of 0.3 dives per hour (in October 2011). For the first time, Cuvier's beaked whale dives are presented and overall had a slightly higher number of group foraging dives per hour than CSM beaked whales, typically between 0.1 and 0.3 dives per hour, and a maximum of 0.5 dives per hour (in April 2013). In general, sperm whale clicks were localized between September and May; the number of localizations was highly variable over short time periods. The number of fully validated killer whale groups from January 2002 to August 2018 indicate sporadic presence, with the number of groups counted in a month varying from one to nine (in March 2010).
5. Data from February 2018 were processed and analyzed for hull mounted MFAS exposures on minke, humpback, and the low-frequency baleen group of whales. Only minke whale tracks occurred within the study area during the SCC. Four individual

minke whales were automatically tracked and validated and a cumulative sound exposure level (cSEL) was calculated over the duration of the animals' tracks for all hull mounted MFAS transmissions. The highest cumulative received level of 168.1 dB cSEL re: 1μPa^2s was observed for an animal track that started on February 14th at 23:58 and exhibited an abrupt heading change on February 15th at 05:00, which overlapped with MFAS transmissions during the onset of a new training event during the SCC. This animal continued to be tracked until February 15th at 13:23. For another minke whale track, a ship not transmitting MFAS closed in distance and had a closest point of approach (CPA) of 1 km to the animal. However, the animal continued to vocalize at the nominal call rate (~400-500 seconds) with no apparent change in heading for an additional 25 minutes until the onset of MFAS transmissions at a distance of 11.9 km, when the animal ceased vocalizing; this may indicate a behavioral response to MFAS by a cessation of calling.

6. Vessel-based tagging and photo-identification were conducted off Kauai, Hawaii February 4 – 12, 2018 with the intent to tag humpback whales with both LIMPET-configured SPLASH satellite tags from Wildlife Computers (Redmond, Washington, United States) and active high-frequency pinger tags developed in-house. The main goal of the project was to capture the habitat use and behavior of humpback whales both on and nearby the PMRF range. Additional goals were to 1) estimate how much time individuals spend on the range; 2) quantify their call/cue rates on the range to inform density estimation; and 3) opportunistically assess any behavioral responses that may occur to the SCC training that was conducted during and after the tagging effort. Six whales were successfully satellite tagged; unfortunately, no pinger tags were successfully deployed. Results are summarized in Henderson et al. (submitted).
7. Noise analyses were performed to determine the spectral density in the frequency band of baleen species' (i.e. minke, humpback, and the low-frequency baleen group of whales) vocalizations. A strong uptick in noise during a baseline data collection on January 21, 2017 coincided with a cessation of these baleen whales' calls for nearly a two-day period. Data from NOAA's Hanalei buoy reported decreased wave periodicity, increased wave height, and a shift in wave direction, and this weather event is evident in NOAA geostationary satellite imagery. This highlights that natural behavioral responses of whales are important to note when studying the impact of anthropogenic noise sources on the animals. Noise analyses will continue to be performed and will be expanded so that broadband integrated spectral density noise levels can be determined.

ACRONYMS

BARSTUR	Barking Sands Tactical Underwater Range
BSURE	Barking Sands Underwater Range Expansion
BREVE	ONR project Behavioral Response Evaluation Employing robust baselines and actual US Navy training. Award Number: N000141612859
COMPACFLT	Commander Pacific Fleet
CPA	Closest point of approach
CSM	Cross Seamount is the location southwest of Hawaii where clicks with rapid intervals and frequency modulation similar to beaked whale foraging clicks were discovered. It is believed these clicks are produced by a beaked whale species other than Cuvier's or Blainville's (McDonald, 2009).
DCLTDE	Detection, classification, localization, tracking and density estimation laboratory located at NIWC Pacific in San Diego, California.
FY	Fiscal year
HFM	High-frequency modulated vocalizations attributed to killer whales
LMR	Living Marine Resources program
M3R	Marine Mammal Monitoring on Navy Ranges, a Naval Undersea Warfare Center program which is a system installed at U.S. Navy ranges for detecting and localizing marine mammals.
MATLAB®	Mathworks copyrighted scientific software environment
MFAS	Mid-frequency active sonar (1-10 kHz) primarily from surface ship sonar
NUWC	Naval Undersea Warfare Center, Newport, RI
OASIS	Ocean Acoustical Services and Instrumentation Systems (OASIS), Inc., Lexington, MA, United States, developer of Peregrine, a parabolic equation propagation model
ONR	Office of Naval Research
PAM	Passive acoustic monitoring
Peregrine	Propagation model from Oasis Inc. currently being utilized to estimate receive levels on marine mammals from US Navy MFAS training.
PMRF	Pacific Missile Range Facility, Kauai, HI
SCC	Submarine Command Course training event
NIWC Pacific	Naval Information Warfare Center Pacific
SNR	Signal-to-noise ratio
SWTR	Shallow Water Training Range

This page is intentionally blank.

CONTENTS

Figures

Tables

This page is intentionally blank.

1. INTRODUCTION

In fiscal year (FY) 2018 the Naval Information Warfare Center (NIWC) Pacific Detection, Classification, Localization, Tracking, and Density Estimation (DCLTDE) Laboratory (San Diego, California) utilized passive acoustic data recordings from bottom mounted range hydrophones at the Pacific Missile Range Facility (PMRF) to monitor for vocalizing marine mammals both during baseline periods and during U.S. Navy training activities.

The overall goals of this ongoing effort are to:

(1) Collect raw acoustic data for detailed verification of automated processing results and to allow future processing with new marine mammal species detection, classification, and localization (DCL) algorithms;
(2) Understand short-term and long-term occurrence patterns and quantify abundance for multiple marine mammal species;
(3) Estimate sound levels that marine mammals were exposed to during U.S. Navy training with hull mounted mid-frequency active sonar (MFAS);
(4) Investigate behavioral responses to U.S. Navy training activities (e.g. changes/cessation in calling, changes to animal kinematics, and overall changes in abundance); and
(5) Collaborate with researchers conducting other monitoring efforts (e.g. tagging and visual surveys), along with other U.S. Navy laboratories, to fill data gaps and provide a more complete monitoring data product.

Overall, this report highlights multiple areas where progress was made in FY18. Advances continue to be made to the automated algorithms utilized for processing and analyzing the large inventory of raw acoustic data from multiple hydrophones spanning multiple years (Section 2.4.1). Advancements to algorithms included updates to the sperm whale detector and localizer. In addition, updates were made to an existing Cuvier’s beaked whale detector, and results for Cuvier’s beaked whales are presented for the first time in this report as the number of group dives per hour. Progress was also made to be able to run the current automated data processing algorithms on older data collections from PMRF that spanned from 2002 to 2006 for select species. Previously, these datasets were not fully processed alongside more recent datasets with automated detection and localization algorithms, since they were recorded at a different sample rate of 44.1 kHz compared to datasets collected later in 2006 to present, which are collected at a sample rate of 96 kHz. Therefore, for the first time, results for the entire archive of data recorded at PMRF from 2002 to 2018 are presented for select species in this report.

It is important to note that results are not available for all species currently processed across all years due to different physical array characteristics at PMRF and lower frequency sample rates collected prior to 2007. Results from 2002 to 2018 are available for minke, humpback, and killer whales. Results from 2007-2018 are provided for Blainville’s, CSM, and Cuvier’s beaked whales, with preliminary results for sperm whales. To date, only full bandwidth data have been processed for sperm whales, with plans to process data from 2002 to 2006 in the future. Results for the low-frequency baleen whale group (fin, sei, and Bryde’s whales) are only available since January 2011, when the first hydrophones capable of processing calls under 100Hz were installed (the Barking Sands Underwater Range Expansion [BSURE] replacement hydrophones).

The existing semi-automated tools to perform disturbance analyses for all animals tracked during the SCC (i.e. to determine ship-whale geometries relative to all surface ships, and cumulative sound exposure levels whales receive relative to all hull mounted MFAS transmissions) were utilized in this report for the February 2018 SCC (Section 3.6). This semi-automated analysis is similar to what was done in Martin et al. (2018a) for results during the February 2017 SCC, and what was done for results during the February 2014 SCC under a concurrent Office of Naval Research project (Martin et al., 2018b).

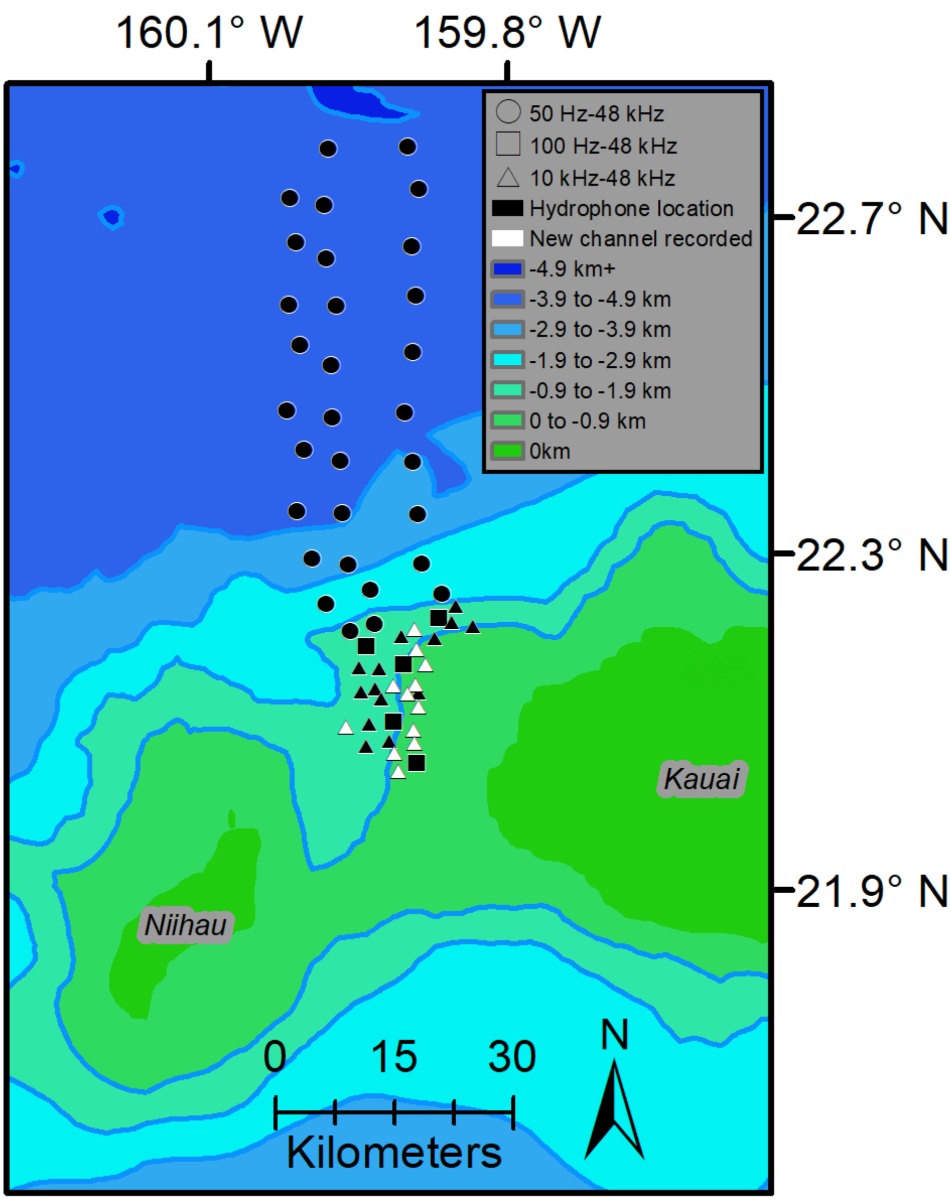
2. METHODS

2.1 PMRF RANGE DATA

Passive acoustic monitoring (PAM) data were recorded for 62 of the PMRF bottom mounted hydrophones (Figure 1) to support analyses of marine mammal vocalizations and MFAS transmission times and locations. An in-depth overview of historical and present hydrophone array configurations, data collection regimes, and hardware specifications (i.e. hydrophone frequency response and data recorder sampling rate) was provided in a prior report (Martin et al. 2017). However, it is important to review this information and note changes in the data collection regime, especially when viewing figures in Sections 3.3 to 3.5 since this helps to explain certain patterns in long-term abundances and gives a better understanding of the overall effort and results.

From February 2002 to April 2005, 24 hydrophones from the BSURE A-B and Barking Sands Tactical Underwater Range (BARSTUR) hydrophone arrays were recorded under a previous Office of Naval Research (ONR) effort at a sample rate of 44.1 kHz on a limited basis and during times when aerial surveys were conducted. From February 2006 to September 2006, these same 24 hydrophones were recorded, but the sample rate was increased to the current sample rate of 96 kHz. Starting in February 2006, recordings were performed under PACFLT funding on a regular basis during two separate periods a month. Between March 2007 and January 2011, the same 24 hydrophones were recorded, and an additional seven BARSTUR high-pass hydrophones were recorded to increase spatial coverage for beaked whales, for a total of 31 hydrophones. Starting in January 2011, recording of the 18 BSURE A-B array hydrophones ceased in favor of recording BSURE replacement hydrophones installed at different locations from the A-B hydrophones (but parallel to those locations). Starting in February 2011, classified recordings were collected during the SCC to enable analyses of Navy training and use of MFAS relative to marine mammals. Starting in August 2012, the data acquisition system was upgraded to allow recording an additional 31 BSURE replacement hydrophones, for a total of 62 hydrophones. In August 2014, decimated data collections (sample rate of 6 kHz) began to increase temporal coverage for detection of species such as Bryde’s whales which are present year round, but very intermittently. In June 2017, specifics of the hydrophones that were recorded changed, resulting in the recording of 36 broadband hydrophones and 14 high pass hydrophones. In February 2018, recording began for 12 additional high-pass hydrophones that previously were not recorded (for a total of 36 broadband hydrophones and 26 high pass hydrophones recorded). These high-pass hydrophones were selected to increase existing coverage of areas with sloped bathymetry (Figure 1) which has been shown to be preferred habitat for Blainville’s beaked whales (Henderson et al., 2016). In addition to the acoustic data, standard PMRF range data products (e.g., ship positions and expendable bathythermograph data) have been obtained for 16 biannually held SCC training events since February 2011.

In FY18, two types of acoustic recordings were obtained. Standard full-bandwidth recordings at the 96 kHz native sample rate (frequency response up to ~45 kHz) were recorded during two separate periods of time (for a minimum of 24 hours and up to a maximum of 45 hours) a month for all 62 hydrophones. During the February and August SCCs, additional full bandwidth recordings were collected to support U.S. Navy marine mammal monitoring efforts before, during, and after the SCCs (i.e. for baseline and exposure analyses). Decimated data recordings at the reduced sample rate of 6 kHz provide 3 kHz of bandwidth for longer term baseline sampling of both baleen whale vocalizations and lower frequency noise conditions. While the decimated data were recorded for longer durations, they were still constrained to not sample when training activities occurred on the range (Figure 1) The August 2018 SCC coincided with Hurricane Lane and the training event was ended early due to the approach of the hurricane. Only part of the training event was conducted, during which acoustic data were collected from the bottom mounted range hydrophones and standard PMRF range data products were obtained.



The white triangles indicate the approximate location of 12 high-pass hydrophones that were recorded starting in February 2018. Contours are color coded for depth, ranging from 0 km (bright green) to 4.9 km and deeper (dark blue).

Figure 1: Hydrophone array configuration.

2.2 OPPORTUNISTIC SURFACE HYDROPHONE DATA

During some of the SCC training events there has been a low-cost effort involving PMRF personnel on a weapon recovery vessel to collect recordings using a calibrated hydrophone deployed near the surface along with a time-depth data logger (as described in Martin et al., 2018a). This effort is intended to collect MFAS signals near the sea surface in order to validate received levels estimated by the Peregrine parabolic equation propagation model (Heaney and Campbell, 2016).

This effort has been performed by the weapons recovery craft personnel on an opportunistic and not-to-interfere basis, thus not all data collected may be usable for model validation if data do not contain MFAS signals, or if positional data for both the MFAS transmitting ship and recording platform are not available. Continuing to collect in situ measurements requires a low level of effort. Obtaining measurements for different geometries between a ship transmitting MFAS and the recording platform helps better characterize modeled MFAS received levels.

2.3 M3R PACKET RECORDER DATA FROM PMRF

Ongoing efforts have continued in order to transition from recording acoustic data on a Windows PC recorder (which has been utilized since collection began in February 2002 with some technical refreshments), to a Linux packet recorder node included within the Marine Mammal Monitoring on Navy Ranges (M3R) system installed at PMRF. Additional progress towards this effort was made during FY18, and personnel from the Naval Undersea Warfare Center (NUWC) Newport and NIWC Pacific continue to collaborate on testing and evaluating software, and implementing a Linux packet recorder at PMRF for NIWC Pacific to transition the data recording effort.

2.4 ALGORITHMS AND TOOLS

2.4.1 Automated Detection, Classification, and Localization Algorithms

Multiple algorithms are utilized to process PMRF recorded data to detect a variety of marine mammal vocalizations, and localize when possible. A custom C++ detection algorithm automatically processes detections of beaked whales (Blainville’s, CSM, and Cuvier’s), killer whales, sperm whales, baleen whales (minke whales, and the low-frequency baleen group of whales [Bryde’s, sei, fin, and blue whales] as a single group not identified to species), and MFAS sonar transmissions. When post-processing recorded data, different operating points can be utilized, and the data are available for future versions of the algorithms with capabilities to process additional species. For full bandwidth data recordings, the custom C++ algorithms process data at rates approximately 5 times faster than real-time. A custom MATLAB® algorithm separately processes humpback whale song detections and localizations. Most of these algorithms have been discussed in detail in peer-reviewed journal publications and reports (Martin et al., 2015; Martin et al., 2016; Martin et al., 2017; Manzano-Roth et al., 2016; Henderson et al., 2016; Henderson et al., 2018; Helble et al., 2012; Helble et al., 2015; Helble et al., 2016). The custom MATLAB® algorithm is also capable of localizing minke whales and the low-frequency baleen group of whales, allowing for cross validation between the two methods. Additionally, classification technology is currently being developed under funding from the Living Marine Resources (LMR) program to identify individual species from the low-frequency baleen whale group.

Notable changes to the C++ detection and localization algorithms included refinements to the Cuvier's beaked whale detector and the sperm whale detector and localizer, in addition to processing data from 2002-2006. The beaked whale click detection process has previously been discussed in detail in Martin et al. (2010) and Manzano-Roth et al. (2016). To review, the beaked whale detector has multiple stages that are consistent for detecting Blainville's, CSM, and Cuvier's beaked whales, and has progressed to baseline 4, with some initial work on baseline 5 as well (baseline numbers reflect that the software and algorithms are under software configuration control). The first stage detects clicks using signal-to-noise ratio (SNR) thresholds to compare in-band (i.e., within the frequency range of the clicks) signal level over background level, and mean in-band signal level over mean out-of-band level. The second stage sets another in-band over background SNR threshold with a smaller fast Fourier transform (FFT) and then utilizes click frequency modulation (FM) as a feature for species classification. During the second stage, additional processes are performed for Cuvier's beaked whale classification. This includes detecting a characteristic notch feature, as well as meeting duration and slope thresholds, in order to be categorized as Cuvier's beaked whales. Longman's beaked whales have also been detected, and the beaked whale click detector continues to be adapted to automatically separate those clicks as well.

In FY18 the sperm whale detection and localization processes were modified to improve performance and focused on reducing false positive detections and improving localizations. The sperm whale detector traditionally operated similarly to the beaked whale detectors, with a larger first-stage FFT determining periods when the signal exceeds a threshold, and a shorter second-stage FFT applied for those periods. The second-stage FFT was applied only in the 3 – 10 kHz bandwidth to ensure the maximum level exceeded an SNR threshold. In FY18, a minimum click duration and inter-click interval duration were set as well. Localizations were determined by using a queue of detections, calculating the ICI between each detection and the previous four detections, and then attempting localization using those sets of ICIs for combinations of four of the top 32 detections in the queue. If a good localization was found, the rest of the queue was checked for detections that could contribute to the localization initially formed by those four detections.

The data collected at a sample rate of 44.1 kHz were resampled to 96 kHz for compatibility with other data collections and processing. Data were resampled to a rational multiple of the original sample rate (i.e. the ratio to resample 44.1 kHz to 96 kHz is 320/147). Resampled data were examined and edge effect discontinuities were introduced in frequencies greater than and near the Nyquist frequency of 22 kHz. However, frequency content in the original 22 kHz of bandwidth was preserved and no discontinuities that would affect detectability of signals of interest were introduced into the resampled data.

2.4.2 Tracking and Annual and Long-Term Abundance Analyses

The existing semi-automated MATLAB® kinematic tracker was previously described in Martin et al. (2018a), and was utilized to track automated localizations for minke, humpback, and the low-frequency baleen group of whales. Tracks of individual baleen whales were analyzed via systematic snapshots taken every 10 minutes (Buckland et al., 2001). The logic is that at any instantaneous snapshot time, if a whale is being tracked (i.e. calls before and after the snapshot time) it is counted as present. This allows a census-type abundance estimate of whale counts in the study area.

The number of tracks represented by the snapshot results is a stable metric; baleen whale tracks that occur over the PMRF hydrophone array are assumed to have: a probability of detecting a calling whale equal, or very close to 1.0; a high probability of localizing all calls within a track; and improved localization accuracy as compared to tracks outside the array. As one extends the study area beyond the hydrophone array, both localization accuracy and the probability of detecting whale tracks decreases. In the previous annual report (Martin et al., 2018a) an expanded study area was utilized for tracking; however, for track results presented herein, all localizations were required to be within a smaller study area of ~1,100 km^2 that encompassed the hydrophone array in order to be tracked. Overall, this yielded fewer automated tracks, but with higher confidence in track kinematics and that tracks were true positives. When conducting detailed analyses (e.g. behavioral response in Section 3.6) or presenting results in a peer-reviewed journal, the automated results are manually verified so that performance metrics can be provided (e.g. false positive rate). Typical refinements correct for potential errors such as false positive tracks, multiple tracks established for a single animal, and the potential for two animal tracks to be combined. Peer-reviewed journal articles that members of the DCLTDE laboratory authored have manually verified and tracked automatic localizations for humpback (Henderson et al., 2018), Bryde's (Helble et al. 2016), and minke (Martin et al., 2015) whales. Overall, the number of semi-automatically tracked animals compares well with the number of animals that were manually verified and tracked, especially when a smaller study area that encompasses the hydrophone array was utilized for semi-automated tracking.

The species that are not able to be localized and individually tracked include Blainville's, CSM, and Cuvier's beaked whales, and killer whales. The calls detected from these species occur when multiple whales are within close proximity and emitting similar calls, such as the case when beaked whales emit echolocation clicks during a group foraging dive, which is the metric used to quantify abundance for that species. Calls concurrently detected on adjacent hydrophones are attributed to the same group, and the hydrophone with the most detections is considered the approximate location of the group. See Manzano-Roth et al., 2016 (for additional details).

The number of tracks and group dives can be used to estimate abundances on short-term (over the duration of a training event) to long-term (annual or decadal) scales. These abundance estimates are limited to the number of animals vocalizing, which is often related to behavioral state for baleen whales, and group activity for odontocetes. Overall, for baleen species these numbers represent a *minimum* number of calling whales and can be converted to a *minimum* density of calling animals on the range. Since most singing baleen whales in Hawaii are presumed to be sexually active adult males, that is what these numbers reflect. To estimate absolute densities for sexually active adult males would require knowing long-term average cue rates, which are currently unknown but could be obtained either through tagging or concurrent visual/acoustic surveys. To extend PAM analyses to include all members of a baleen whale species requires additional information relating the proportion of calling whales to all whales (i.e. females, calves, and juveniles), which is currently unknown. For some odontocete species (e.g. beaked whales) the group foraging dives can be converted to a minimum density of animals employing an average group size.

2.4.3 Propagation Modeling

Estimating sound levels (e.g. sound pressure level [SPL] and sound exposure level [SEL]) that marine mammals receive from acoustic events, such as MFAS training, requires either: (1) having acoustic tags on the whales to directly measure sound pressure levels or (2) utilizing propagation modeling, which requires locations of marine mammals and ships transmitting MFAS, along with the time of transmissions. To date, no acoustic tags have been attached to marine mammals during SCCs at PMRF to allow direct measurement of the sound levels that whales receive; therefore, propagation modeling is utilized to estimate whales' received levels from MFAS. Additional details about propagation modeling were provided in the previous annual report (Martin et al., 2018a). Use of the Peregrine parabolic equation propagation model has contributed to automating the process of estimating received levels on whales for all sonar transmissions from multiple ships.

2.4.4 Disturbance Analysis

Disturbance analysis is the process of investigating whether whale tracks overlap with anthropogenic activities such as MFAS transmissions and close proximity of ships (even when not transmitting MFAS), thereby conducting an opportunistic, passive acoustic behavioral response study (BRS). When overlap occurs, a variety of metrics are calculated/estimated such as whale orientations and distances relative to all ships. When ships are transmitting sonar (i.e. during SCC exercises and determined by PAM analysis of MFAS localizations), complex propagation modeling is utilized to calculate the cumulative SEL that an animal may have received from multiple ships over the duration it was acoustically tracked. A recently developed semi-automated disturbance analysis process can be performed for species in which calls are localized and confidently tracked (i.e. minke, humpback, and the low-frequency baleen group of whales). In addition to looking at the behavior of individual whales in response to ships and MFAS (see Section 3.6), we can also look at the overall impact of the training events on the occurrence and abundance of vocal animals before, during, and after the training event.

2.4.5 Noise Analysis

The primary goal of conducting noise analyses on PMRF acoustic data is to better understand PAM processing results that are effected by noise levels. The noise analyses characterize noise in relevant frequency bands of interest, to look for changes in noise over a wide variety of spatial and temporal scales, and to assess any impact these changes may have on detecting and localizing marine mammal vocalizations. Ocean noise is an important parameter that is often overlooked in marine mammal acoustic analyses. It can affect the probability of detecting a marine mammal signal, and therefore can influence PAM processed results for the number of detections and localizations (and possibly the number of tracks counted). Ocean noise can also influence marine mammal behavior, and characterizing ocean noise is important for both abundance estimation and behavioral response analyses. Current noise analyses processes are conducted for the following purposes:

- Identify data dropouts or suspicious “unnatural” noise readings that could affect recording effort.
- Look for long-term trends in changes in ambient noise over the last decade.
- Understand both the natural variability in background noise and those changes contributed from anthropogenic noise sources.
- Understand our limitations on our ability to detect and localize calls in different noise environments.
- Look for biological relationships between marine mammal activity and noise.

A recently developed noise analysis tool processes recorded data to provide spectrum level measurements for selected hydrophones. The spectrum level energy is also integrated over the frequency bands matching the processing bands for detection of species’ calls. These integrated noise band levels include all sources of sound in the ocean (e.g. species calls, environmental noise, and anthropogenic sounds) and when integrated over all frequencies provides a soundscape noise level. Noise analysis is a relatively recent and on-going effort and was implemented in FY18 on systematic samples (10%) of all data collected for four hydrophones for frequencies below 3 kHz (see Section 3.7 for example results).

This page is intentionally blank.

3. RESULTS AND DISCUSSION

Most of our FY18 goals in assessing baseline occurrence and abundance (short- and long-term) were accomplished and are presented. Systematic results from all recordings from 2002 to 2006 are presented for the first time for select species. New presentation methods are utilized to visualize results both over the current FY as well as the full long-term data set applicable to each species. Evolving noise analyses methods are now being conducted as a standard process; presented here is a major significant finding related to some whale species ceasing to call apparently due to non-anthropogenic noise sources. Improvements to the various DCL and tracking algorithms are an ongoing and evolving process. The FY18 improvements to the sperm whale and Cuvier's beaked whale detectors are reflected in the updated and new results presented here.

Results for disturbance analyses conducted for select February 2018 data are presented, including propagation modeled levels received by whales. An additional calibrated surface hydrophone recording was obtained in February 2018; this contribution was analyzed and added to the overall ongoing comparison of in situ recorded MFAS levels against propagation-modeled received levels.

3.1 PMRF RANGE DATA COLLECTION RESULTS

Details of PMRF data collection efforts since 2002 were described in Martin et al. (2018a). The FY18 data utilized for this report spanned from June 2017 to August 2018. The previous annual report (Martin et al., 2018a) utilized data through August 2017, however, at the time that report was written, only full bandwidth data for the period of June to August 2017 were available at the laboratory in San Diego for processing and were utilized for the report. Shortly after the previous annual report was written, decimated data from June to August 2017 were delivered to the laboratory in San Diego. Therefore, the FY18 results presented herein utilized all data collected between June 2017 and August 2018. The total hours of recording effort for full bandwidth and decimated data collections, and the percentage of time there was recording effort during these dates are shown in Table 1. Overall, full bandwidth and decimated data collections combined recorded 48.1% of the total number of hours between June 3, 2017 and August 21, 2018.

Table 1: Total hours of recording effort for full bandwidth and decimated data collections between June 2017 and August 2018.

Data type	Hours	Percentage of total number of hours recorded
Full bandwidth	1,772.2	16.6%
Decimated	3,361.5	31.5%

3.2 OPPORTUNISTIC SURFACE HYDROPHONE DATA RESULTS

A systematic in-depth analysis of the surface acoustic data collected during the February 2018 SCC has been performed. Due to the occurrence of Hurricane Lane in August 2018, the SCC ended early and no surface acoustic data were collected. The main purpose for collecting acoustic data at the surface was to validate the accuracy of the Peregrine modeling software. Overall, measurements in February 2018 agreed well with the modeled estimates. A total of 15 MFAS pulses were sampled from a 41 minute long data file and analyzed. Multiple pulses clustered in time were analyzed together to obtain an average received level for comparison with an average Peregrine modeled received level. Each Peregrine modeled received level had a low (0 to 0.63 dB re: 1µPa) standard deviation and agreed well with the in situ measurements. The results of an unpaired Welch two sample t-test showed that when alpha = 0.05, there was no significant difference between modeled and measured received levels ($p = 0.19$). The surface hydrophone data may also be helpful for comparing noise measurements at the surface with the long-term noise analysis conducted on the range hydrophones. It may be possible to predict the surface noise based on data recorded on the range hydrophones.

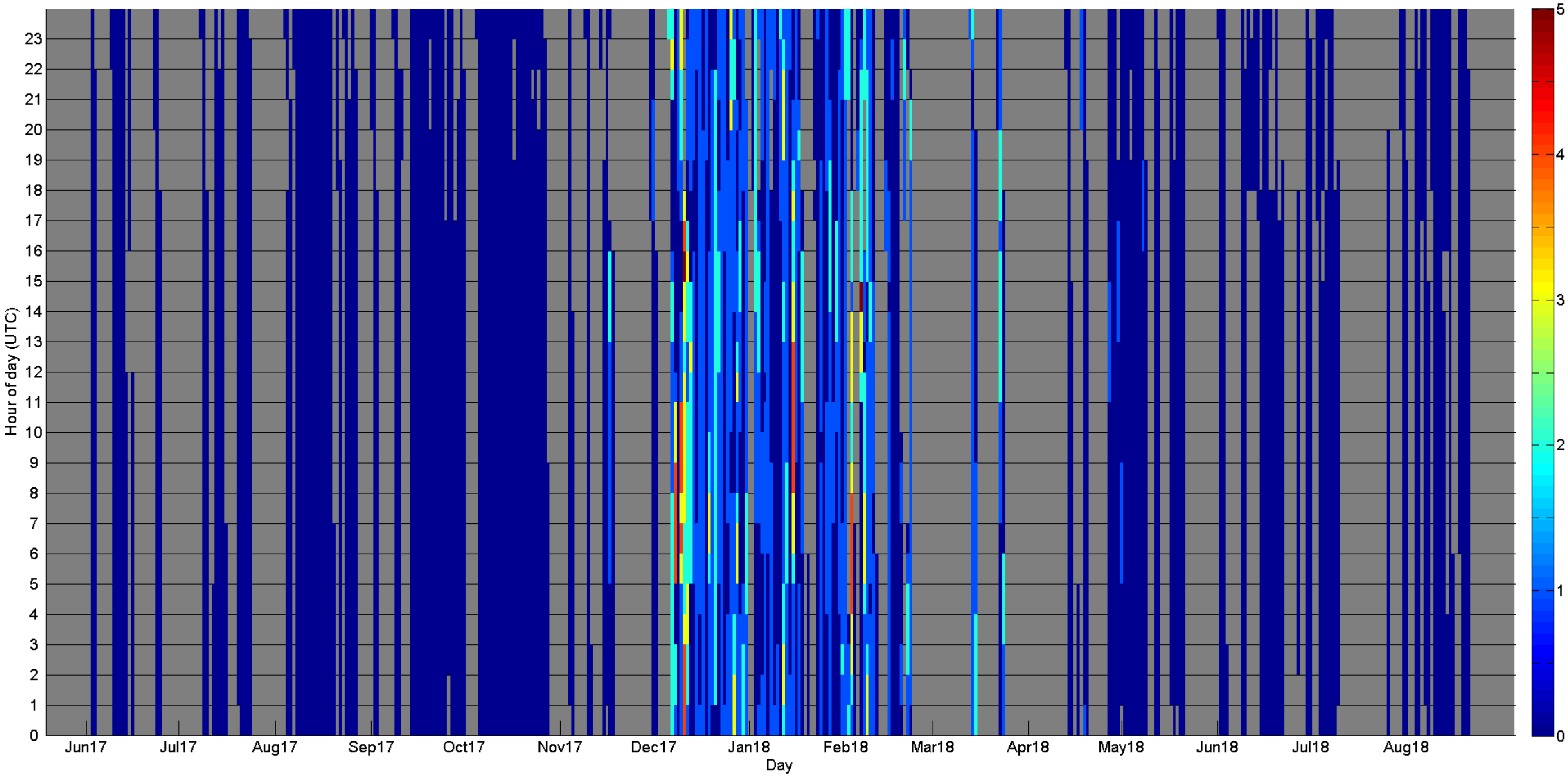
3.3 BALEEN WHALE FY18 ABUNDANCE

Baleen whale abundance is reported for the first time as a systematic analysis from the inception of recordings in 2002 through 2018 for select species. The results are provided utilizing a similar metric as presented in last year's report (i.e. the number of individual whales determined via systematic snapshot analysis of automated tracking results). Results are provided both for the FY18 data (Figure 2 to Figure 4) as well as the full 16 years of data collections (Figure 7 to Figure 9). The formats of these figures are different from those presented in the FY17 report to provide better insight into the results, and in the case of Figure 7 to Figure 9, to provide an indication of the amount of effort in terms of available hours of recorded data. Another important distinction of the baleen whale abundance compared to the last report is that the study area has been reduced to an area of ~1,100 km^2 (as discussed in Section 2.4.2). It is also important to keep in mind that the majority of the baleen whale calls being detected and localized are believed to be from sexually active males for breeding purposes. Therefore, the abundance plots indicate the number of baleen whales that are calling during periods of data collection effort, and do not reflect other members of the population (e.g. females, calves, juveniles, and sexually active males that are not vocalizing).

Results for the newest data, from June 2017 through August 2018, are provided for the number of calling minke, humpback, and low-frequency baleen group of whales via systematic snapshot analyses of tracks in Figure 2, Figure 3, and Figure 4 respectively. These figures provide the maximum number of animals tracked during each hour of the day in universal coordinated time (UTC) , indicating potential diurnal trends when adjusted for Hawaii Standard Time (HST [UTC-10:00]), and providing more details of the results over this period.

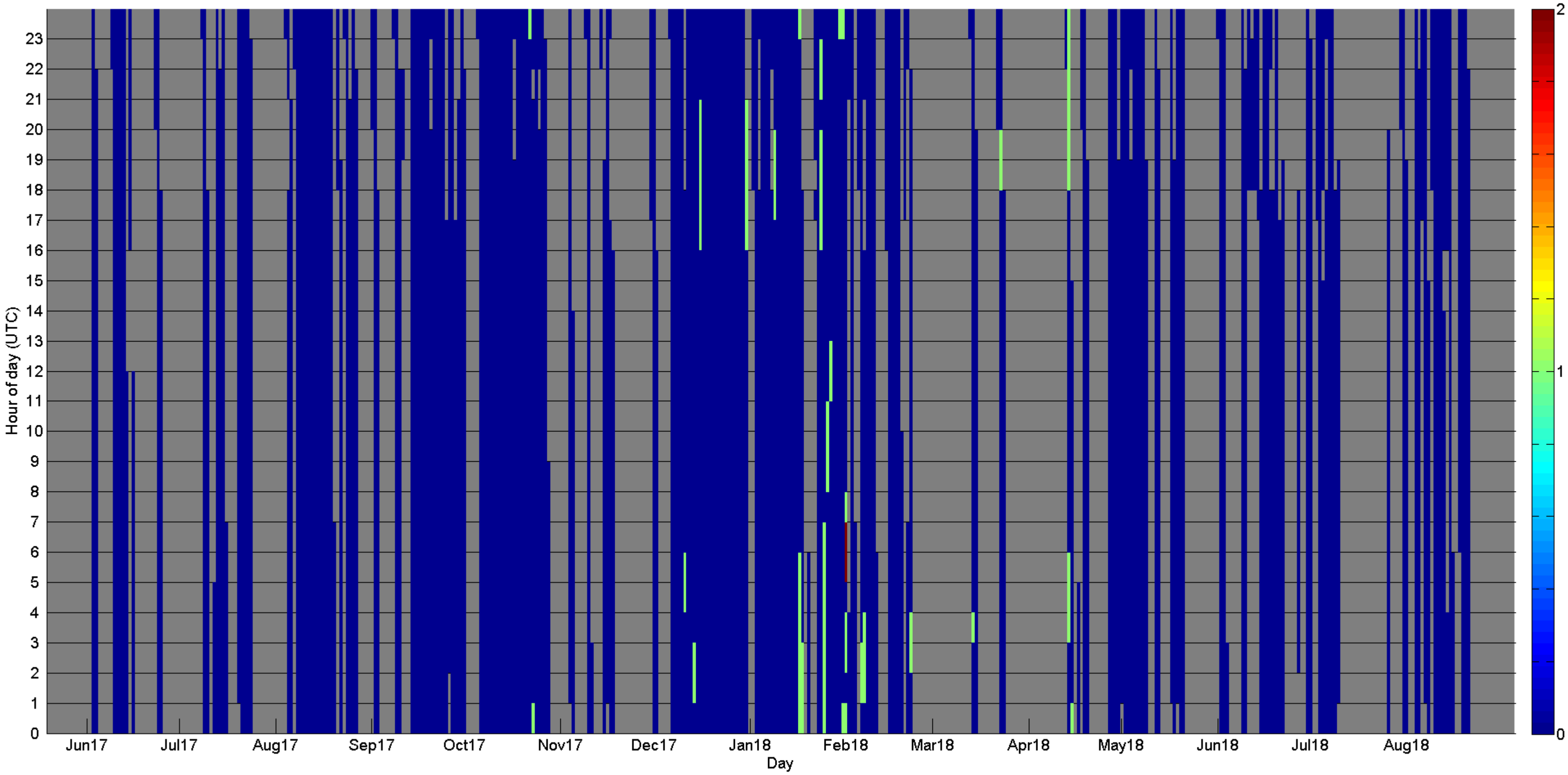
Of the baleen whales tracked at PMRF, vocalizing minke whales (Figure 2) have the highest abundance (maximum of five individuals tracked at one time) and frequency of occurrence. No diurnal pattern is observed in the FY18 minke whale tracks. Figure 3 and Figure 4 illustrate that singing humpback and vocalizing low-frequency baleen group of whales have lower abundances compared to the minke whales (a maximum of two humpback whales, and a maximum of four individuals from the low-frequency baleen whale group (not identified to species) were tracked at any one time) and occur less frequently. There does appear to be a diurnal pattern in humpback whale song (Figure 3), with only two singer tracks occurring between 8:00 and 16:00 UTC, corresponding to 18:00 and 2:00 HST. This goes against previously published findings of an increase in singing activity at night (e.g. Au et al., 2000). All years of recorded data should be examined for this trend to determine if a different diurnal pattern exists for offshore singing behavior. In contrast, there is no diel trend in the tracks of vocalizing low-frequency baleen group of whales (Figure 4). These results are very similar in terms of the maximum number of individuals of each species provided in the FY17 report, which reported a maximum of two humpback whales and four low-frequency baleen group of whales at any given time. The humpback whale results shown in Figure 3 reflect the known seasonality for the species, which have typically been observed between October/November and May, with peak presence from January to March, as observed in 2018. Results for minke whales were observed between November 2017 and May 2018 and show a pattern of seasonality very similar to that for humpback whales. The low-frequency baleen whale group includes Bryde’s whales, which are present year round and are apparent in June 2018 but could occur concurrently with fin and sei whales. Fin and sei whales appear to have a similar seasonal presence as minke and humpback whales and occurred between October 2017 and February 2018.

It is important to remember that the majority of the hydrophones with the necessary frequency response to detect these baleen whales (i.e. BSURE hydrophones) are located offshore in typically 4 km water depth. In the more nearshore areas (e.g. southern BSURE and BARSTUR) there are fewer broadband hydrophones and the shallower nearshore environment has considerably different noise levels. Localizing and tracking humpback whales is more difficult in this nearshore environment due to phone spacing, shallower and more variable bathymetry, a lower SNR due to noise, and higher density of humpback whale calls in the winter and spring. Higher densities of singing humpback whales are known to occur inshore (Frankel et al., 1995). It is unknown what the typical distributions are for vocalizing minke and low-frequency baleen group of whales, as these species have been observed both within 70 km of shore, and well offshore (Mobley et al., 1996; Smultea et al., 2010; Rankin and Barlow, 2005; Rankin et al., 2007) but are infrequently observed nearshore.



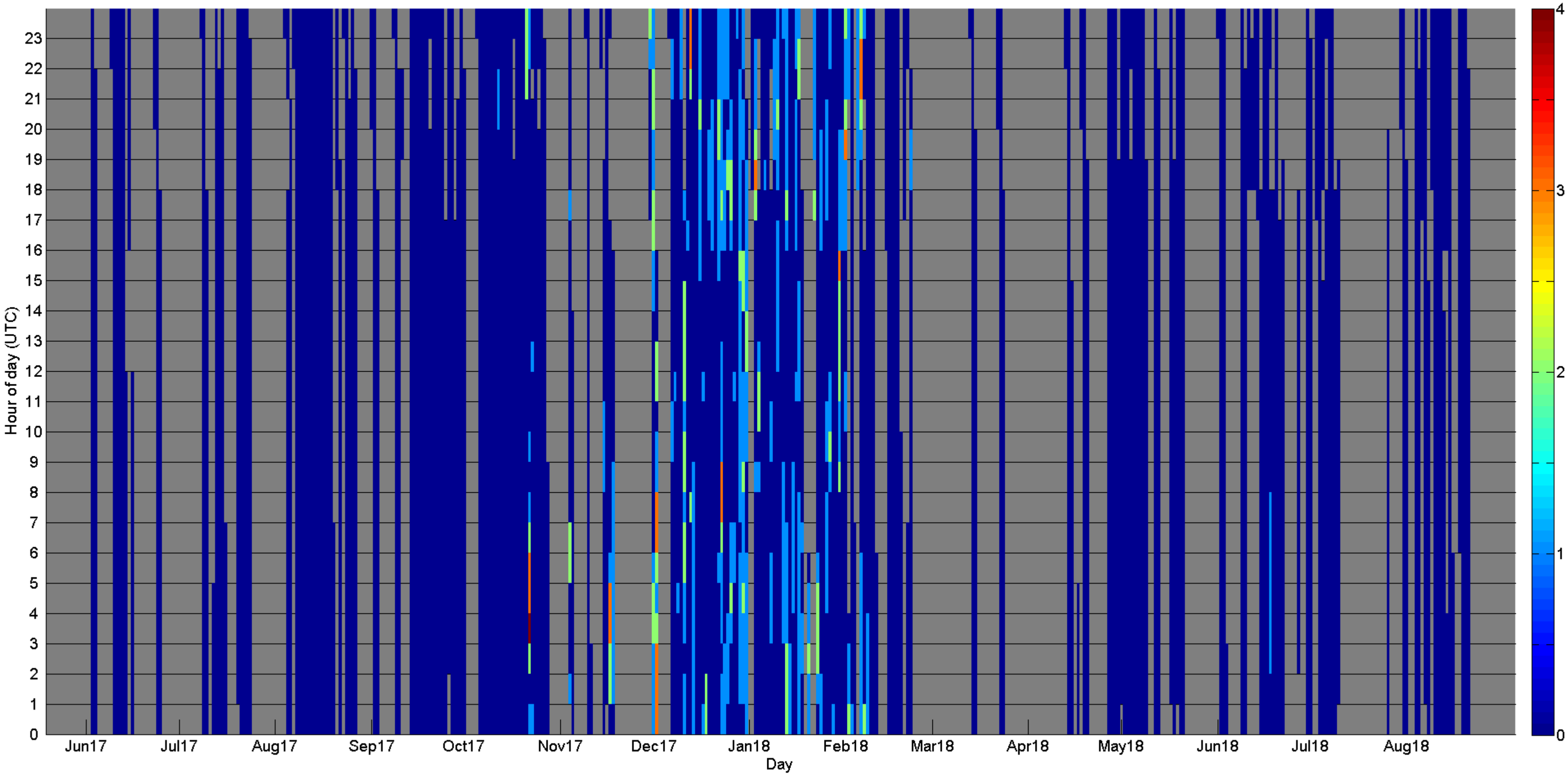
Wales tracked from June 3, 2017 to August 20, 2018. The number of tracks peaked at a maximum of five whales on December 11, 2017 at 15:00 UTC and February 6, 2018 at 14:00 UTC. Results are from both full bandwidth and decimated data collections. Gray areas indicate periods when recorded data were not available.

Figure 2: The maximum number of automatically tracked individual calling minke whales per hour.



Whales tracked from June 3, 2017 to August 20, 2018, which peaked at a maximum of two whales in an hour. Results are from both full bandwidth and decimated data collections. Gray areas indicate periods when recorded data were not available.

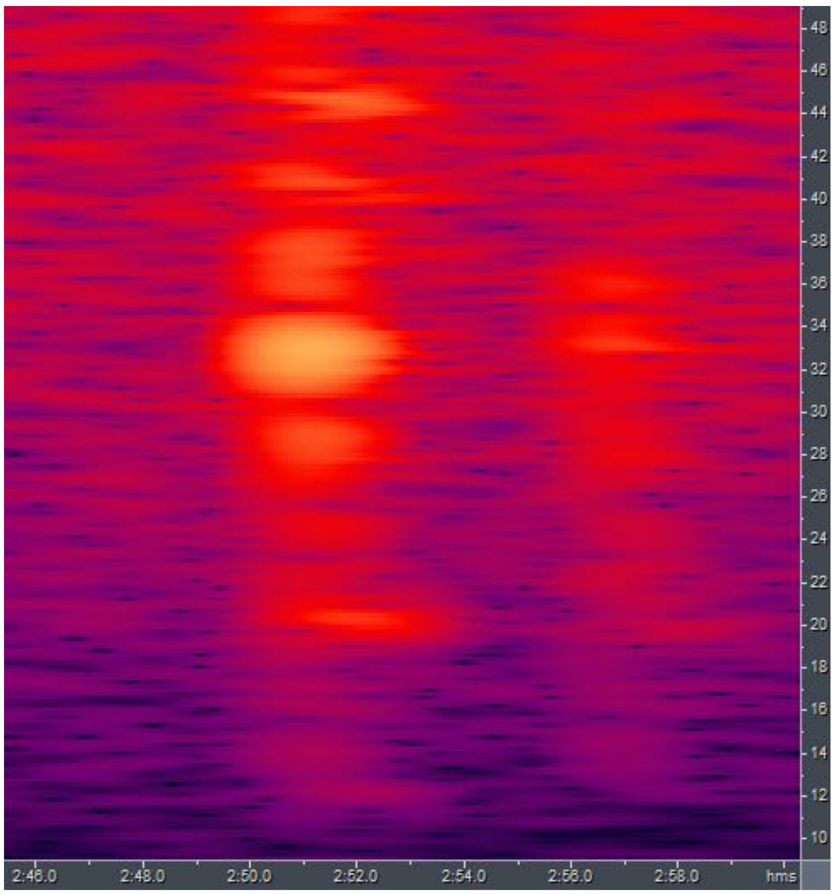
Figure 3: The maximum number of automatically tracked individual singing humpback whales for each hour of the day.



Whales tracked for each hour of the day from June 3, 2017 to August 20, 2018. These tracks peaked at a maximum of four whales in October 22, 2017 at 03:00 UTC. Results are from both full bandwidth and decimated data collections. Gray areas indicate periods when recorded data were not available.

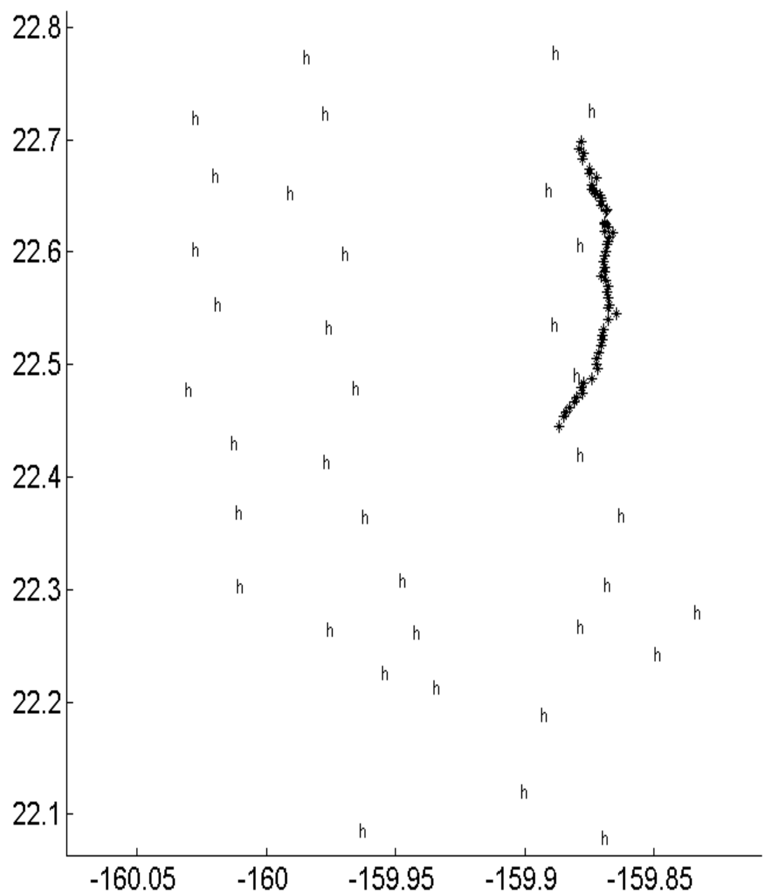
Figure 4: The maximum number of automatically tracked individual calling low-frequency baleen whales: (Bryde's, fin, or sei whales).

In Figure 4, one low-frequency baleen whale track occurred outside of the seasonal trend demonstrated by most species of migratory baleen whales on June 18, 2018 from 2:00 to 8:00 UTC. The raw acoustic data from nearby hydrophones at the time of the track were manually verified to contain calls that have been attributed to Bryde's whales (Martin and Matsuyama 2014, Helble et al. 2016). An example of a localized and tracked call is depicted in Figure 5, with peak spectral density at 33 Hz and a call duration of 4 seconds. This track started near the eastern center of the BSURE array and traveled heading north for 5 hours and 27 minutes over a total distance of approximately 30 km (Figure 6), indicating an average swim speed of over 5 m/s. Over the duration of this track, the animal emitted 57 calls, with a mean inter call interval of 5.8 minutes, which matches well with what has been previously observed and attributed to Bryde's whales.



The x-axis units are minutes and seconds and represent 15 sec of data. The y-axis represents frequencies from 10 to 48 Hz. Call duration is ~4 seconds long (2:50 to 2:54) with greatest spectral density at 33 Hz. A multipath arrival is evident approximately 6 seconds after the direct path arrival, indicating the whale is close to the location of the hydrophone. A 16,384-point FFT and a Blackman-Harris window were utilized to generate this spectrogram.

Figure 5: Example spectrogram of a detected, localized, and tracked call attributed to a Bryde's whale on June 18, 2018.



The track covered ~30 km and lasted 5 hrs and 27 mins.

Figure 6: Suspected Bryde’s whale track shown with the hydrophone array (h) from June 18, 2018. The track began to the south and traveled north.

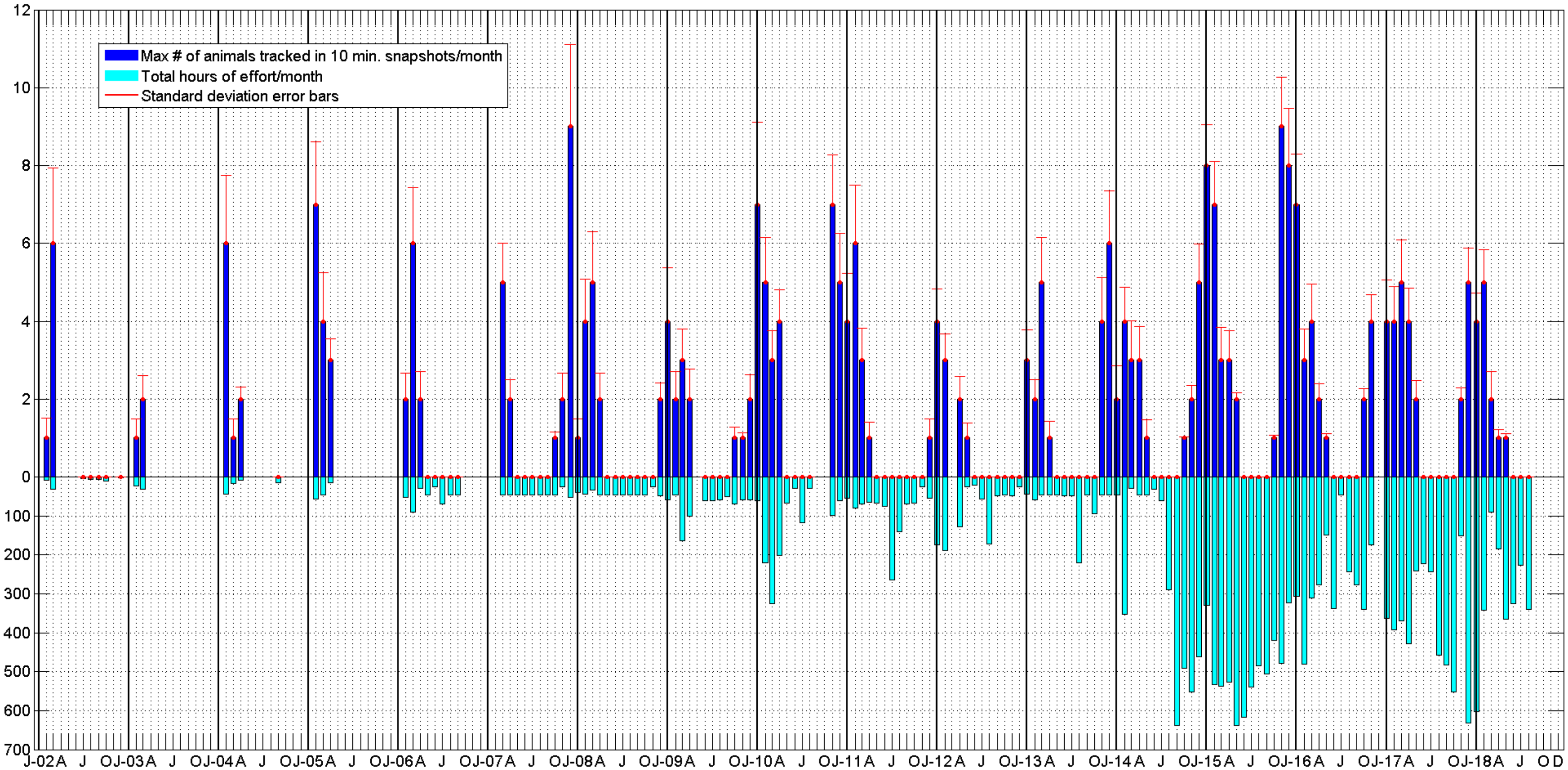
3.4 BALEEN WHALE LONG-TERM ABUNDANCE

To visualize long-term trends in baleen whale abundance, Figure 7 to Figure 9 are provided for the minke whales, humpback whales, and the low-frequency group of whales respectively. This format illustrates the abundance of species over the full period of data collection from 2002 to 2018, along with how much data were available for each month (as the number of hours recorded per month). The whale abundance is presented as the maximum number of individual whales tracked at any instant in a month. As discussed in Section 2.1, the number of hours recorded per month has increased substantially since the initial effort in 2002.

As mentioned in the methods section, the study area size was reduced compared to the study area utilized for tracking in the FY17 report, which gives higher confidence that the automatically generated tracks are actual tracks from vocalizing whales and not false positive tracks. Quantitatively characterizing the probabilities associated with tracking whales is a topic of continuing effort, along with reducing the false positive tracks. It is also important to remember there are significant differences in hydrophone capabilities, sample rates, and tracking parameters due to changes in numbers of hydrophones available over time, which are reflected in Figure 7 through Figure 9. Changes in terms of sample rates and the number of hydrophones recorded over the years had the most impact on detecting calls from the low-frequency baleen whale group, as hydrophone capabilities did not exist for those species until January 2011. Minke and humpback whale vocalizations can be observed in all data from 2002 to 2018; however, results cannot be directly compared across all years given the differences in the number (24 vice 47 or 36) and locations of hydrophones recorded, which can affect track results. The tracking parameters for the older data were slightly relaxed (e.g. by decreasing the number of hydrophones required in a localization solution, and increasing the least-square error threshold between modeled and actual time of arrivals) in an effort to make the results more comparable to the more recent data.

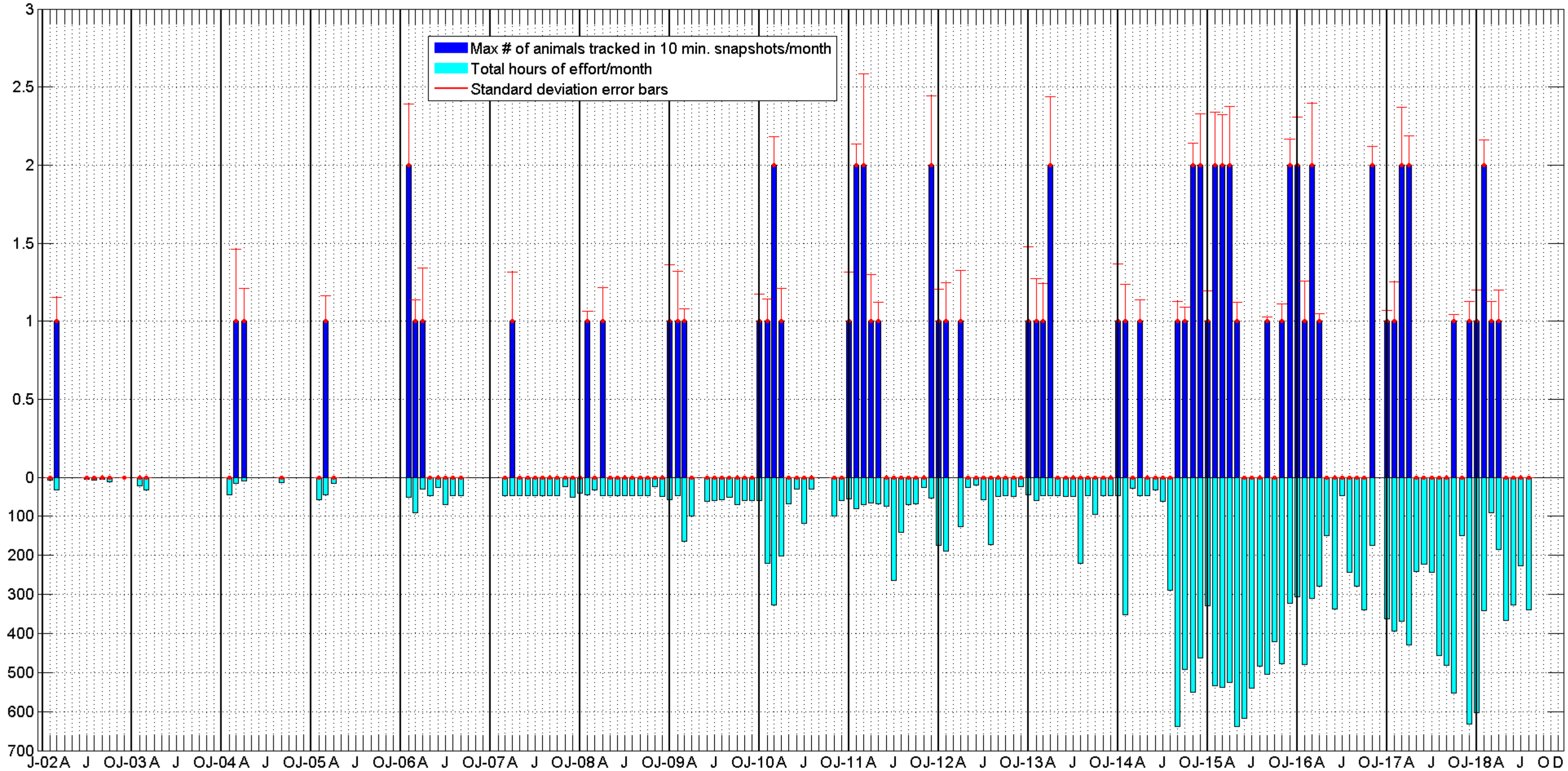
The period between August 2014 and August 2017 utilized identical PAM capabilities, which enables direct comparison of these three seasons to investigate year-to-year variability. Some variability is observed for minke whales (Figure 7), with the maximum numbers in a month varying from eight, nine, and five for each respective whale season. For humpback whales (Figure 8), the maximum number in a month was consistently two across these three whale seasons with similar frequency of occurrence. For the low-frequency baleen whale group, the maximum number in a month during the winter months was relatively stable, varying from five, four, and five for each respective whale season. Also evidenced are low-frequency baleen whale tracks attributed to Bryde's whales in the summer of 2014 (Martin and Matsuyama, 2014; Helble et al., 2016) and summer of 2015. The current metric of the maximum number of tracks that occurred at the same time could be influenced by a few instances of erroneously tracking single individuals as multiple whales resulting in this variability and requires additional validation effort. A current LMR effort is developing improved call classification that can help reduce validation effort. In addition, improving metrics by including the total number of tracked whales and track hours can help better reflect the frequency of species presence.

In the summer of 2017, 11 of the 47 BSURE hydrophones were not available to record; however, results for the 2017 - 2018 whale season look similar for minke whales (both 2016-2017 and 2017-2018 whale seasons had a maximum of 5 tracks), suggesting the loss of the 11 phones did not impact the results significantly. The 2015-2016 whale season utilized the same hydrophones as the 2016–2017 whale season and had a maximum of 9 tracks; this difference could be attributed to the natural variability of minke whale presence at PMRF. For humpback whales there is only one month in the 2017–2018 whale season with two calling humpback whales present at the same time whereas there were three months in the 2016–2017 whale season in which two calling humpback whales occurred at the same time. The results for the 2017–2018 whale season may reflect a decrease in tracked whales compared to the 2016– 2017 whale season, which may be due to the loss of the 11 phones. Alternatively, this could be due to a lower presence of calling humpback whales in the area; continuing effort will investigate this possibility. For the low-frequency baleen whale group, the results for the 2017–2018 whale season are similar to the results for the 2016–2017 whale season in which there was a maximum of four and five whales per month, respectively.



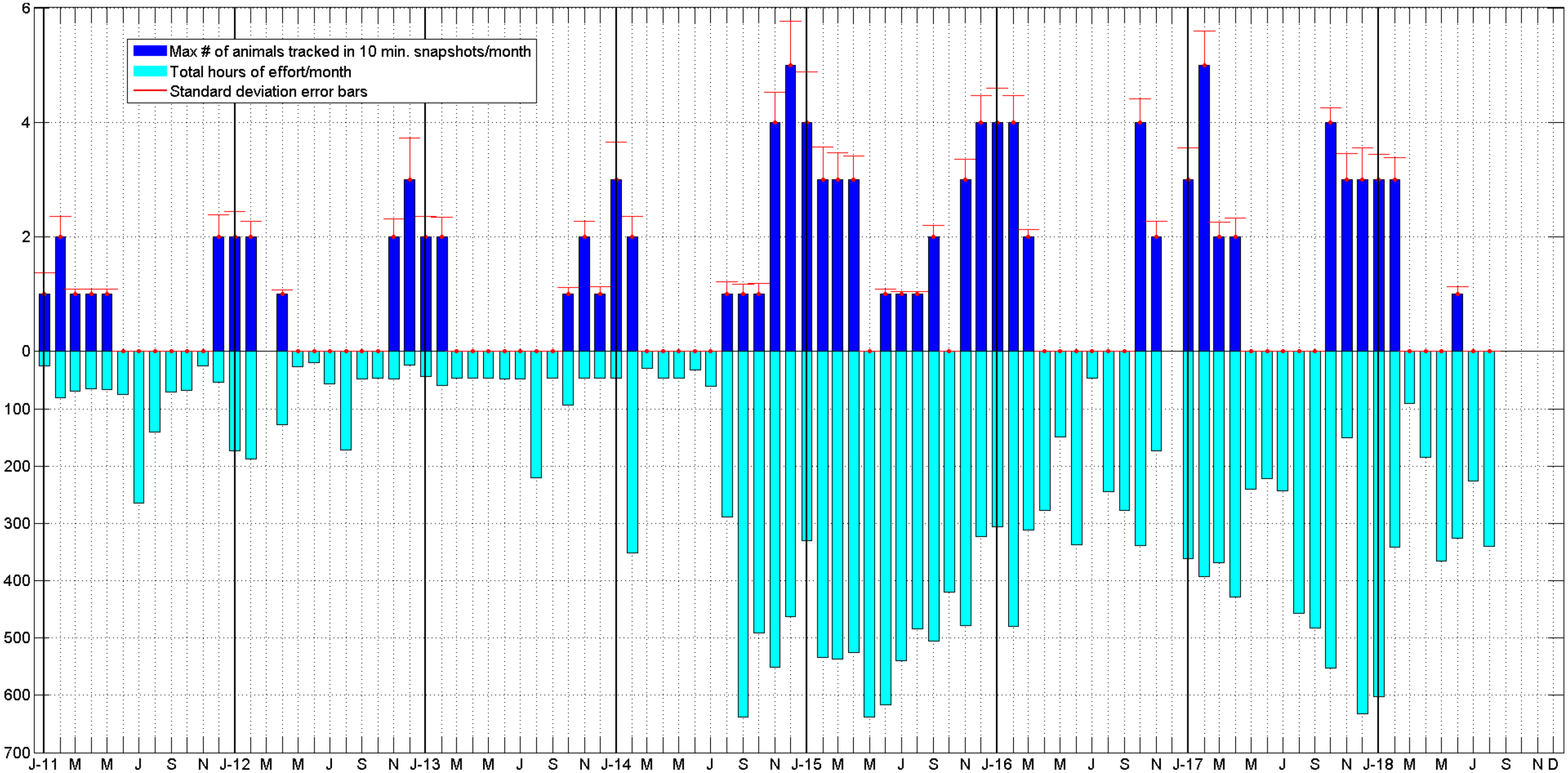
Snapshots were taken every 10 minutes for each month from 2002-2018 (dark blue vertical bars) shown with the standard deviation of all snapshots in the month (red error bars). Hours of recording effort per month from 2002-2018 include full bandwidth and decimated data collections (light blue vertical bars). The horizontal axis is gridded by month, with Januarys shown as solid black lines and calendar years indicated (e.g. J-02 indicates January 2002) and months of April, July, October and December indicated with A, J, O and D for 2018 only. Note that if light blue bars exist but dark blue bars do not exist, then data were recorded for that month but no whales for the given species were present. If nothing is plotted for a month then no data were recorded.

Figure 7: The maximum number of automatically tracked individual calling minke whales in snapshots.



Snapshots were taken every 10 minutes for each month from 2002-2018 (dark blue vertical bars) shown with the standard deviation of all snapshots in the month (red error bars). Hours of recording effort per month from 2002-2018 include full bandwidth and decimated data collections (light blue vertical bars). The horizontal axis is gridded by month, with Januarys shown as solid black lines and calendar years indicated (e.g. J-02 indicates January 2002) and months of April, July, October and December indicated with A, J, O and D for 2018 only. Note that if light blue bars exist but dark blue bars do not exist, then data were recorded for that month but no whales for the given species were present. If nothing is plotted for a month then no data were recorded.

Figure 8: The maximum number of automatically tracked individual singing humpback whales in snapshots.



Snapshots were taken every 10 minutes for each month from 2011-2018 (dark blue vertical bars) shown with the standard deviation of all snapshots in the month (red error bars). Hours of recording effort per month from 2011-2018 include full bandwidth and decimated data collections (light blue vertical bars). The horizontal axis is gridded by month, with Januarys shown as solid black lines and calendar years indicated (e.g. J-11 indicates January 2011) and months of March, May, July, September, November, and December indicated with M, M, J, S, N, and D for 2018 only. Note that if light blue bars exist but dark blue bars do not exist, then data were recorded for that month but no whales for the given species were present. If nothing is plotted for a month then no data were recorded.

Figure 9: The maximum number of automatically tracked individual calling whales from the low-frequency baleen whale group in snapshots.

3.5 ODONTOCETE ABUNDANCE

Odontocete abundance is reported for the first time for the 16 years of data collection since the inception of recording in 2002 to 2018 for killer whales, and for 11 years of data collected from 2007 to 2018 for all other odontocete species. In FY18, improvements were made to the sperm whale detection and localization processes, and an existing Cuvier's beaked whale detector underwent further development and results are presented for the first time.

Cuvier's beaked whale and sperm whale processing are evolving and are still in the process of being characterized for their performance. Results presented herein this report for Cuvier's beaked whales and sperm whales are considered preliminary and are subject to continuing development. In this report, data for Cuvier's beaked whales, killer whales, and sperm whales were only processed for baseline periods (e.g. no SCC data was analyzed for these species).

3.5.1 Beaked Whales

The number of automatically grouped beaked whale dives are provided for Blainville's (Figure 10), CSM (Figure 11), and Cuvier's (Figure 12) beaked whales from 2007 to 2018. This is the first time results from over a decade of beaked whale detections have been presented together, and the first time results for Cuvier's beaked whales have been presented. Results from the total number of automatically grouped beaked whale dives in a month were normalized by the total number of hours of full bandwidth data collection in a month. This yields the metric of dives per hour of total recording effort each month, which is used in Figure 10 to Figure 12. Note that only full bandwidth 96 kHz data has sufficient bandwidth to detect beaked whale clicks and therefore the total number of hours of data collected per month since 2014 may differ from the hours given for baleen whales, which also include decimated data.

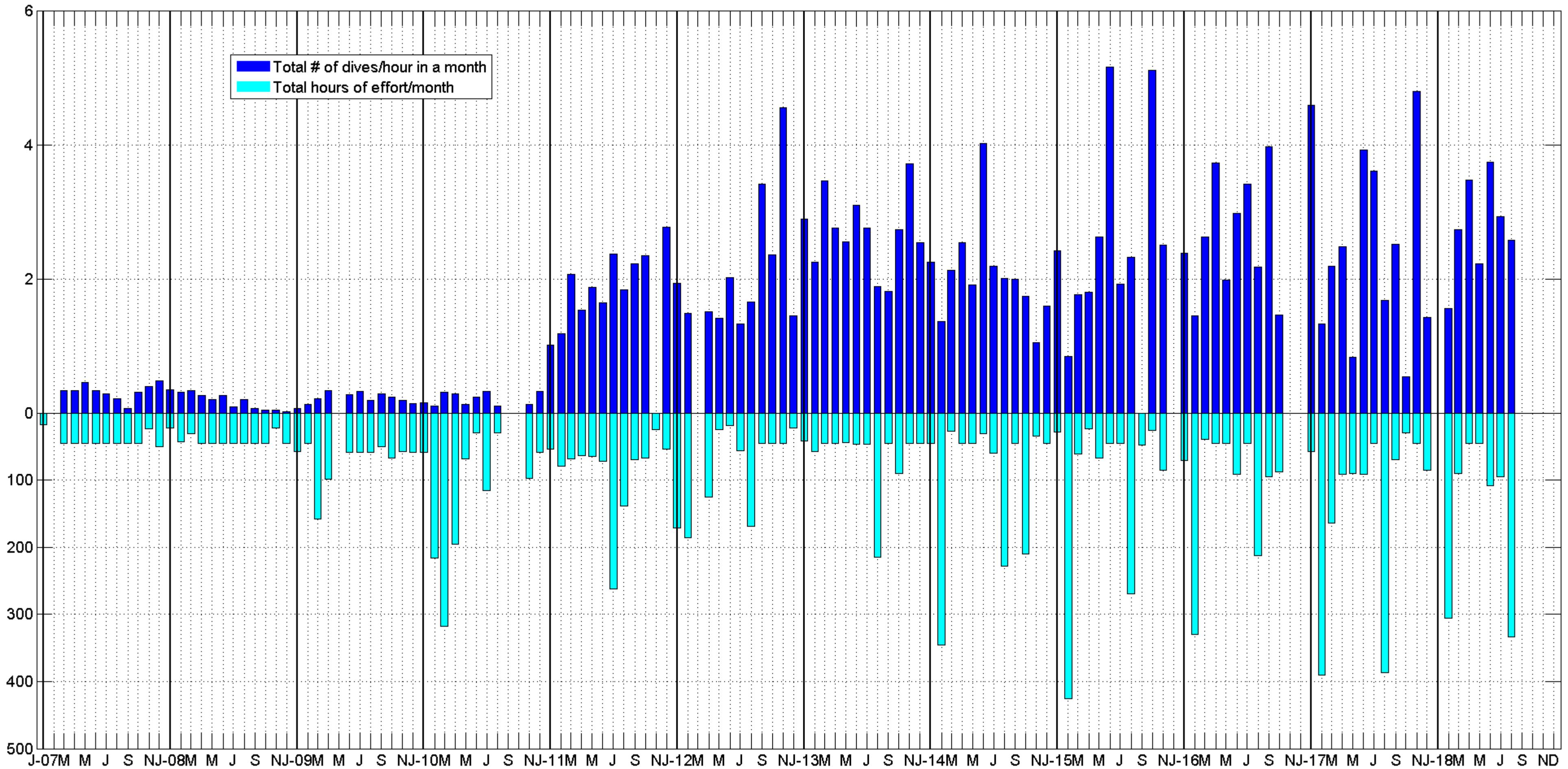
For Blainville's beaked whales, four to six datasets that contained group foraging dives were randomly selected for each year to be manually validated. For validated data from FY18, the total number of validated dives was the sum of dives composed of Blainville's beaked whale clicks and dives composed of mixed detections of Blainville's beaked whale clicks along with clicks from other species, for a true positive rate of 92.8%. The total number of automatically grouped dives that did not contain Blainville's beaked whale clicks resulted in a false positive rate of 7.2%. These six validated datasets represented 235.5 hours of acoustic data and contained 360 validated true positive dives and 28 validated false positive dives, which equates to 1.53 validated true positive dives per hour. Overall, the number of automatically detected group dives compares well with the number of manually validated group dives. Including automatic results for all FY18 datasets, there were overall 2.3 dives per hour, which compares well with published manually validated results from PMRF (Manzano-Roth et al., 2016 and Henderson et al., 2016) and previously reported automated results from PMRF (Martin et al., 2018a).

The number of hydrophones recorded impacted the resulting number of group dives detected. For example, data from 2007 through 2010 were based on recordings from 13 hydrophones, resulting in relatively fewer detected dives compared to datasets from 2011 to 2012, and 2012 to 2018 with 31 and 62 hydrophones recorded, respectively. The 2011 and early 2012 data approached the same number of dives per hour as the data from August 2012 to August 2018. The data from February 2018 onward reflects the change in the hydrophone array configuration due to hydrophone data availability from PMRF; the new set of 62 hydrophones includes 12 hydrophones over the slope area, which is the preferred habitat for Blainville's beaked whales

(Henderson et al., 2016). In the latter half of 2018 there appeared to be a slightly more consistent level of group foraging dives per hour; this pattern will need to be investigated to determine the impact this hydrophone array configuration has on capturing Blainville's beaked whale year-round presence. Overall, the data continues to demonstrate no clear seasonal or interannual trends in Blainville's beaked whale abundance, with a relatively stable mean dive count since 2011 of about 1.5–3 dives per hour on average, and a maximum of 5.2 dives per hour. It should be noted that the five highest peaks of Blainville's beaked whale presence correspond to months when there was only approximately 50 hours of recording effort per month, indicating that the metric of group dives per hour of effort for a month is influenced by the amount of data collection in a month. The periodic increase and decrease of group foraging dives per hour do not seem to occur at specific times in the year. Although in some years the decreases appear to correlate in time with SCCs (i.e. in February and August), they do not always align, and the peak periods appear to occur anytime throughout the year.

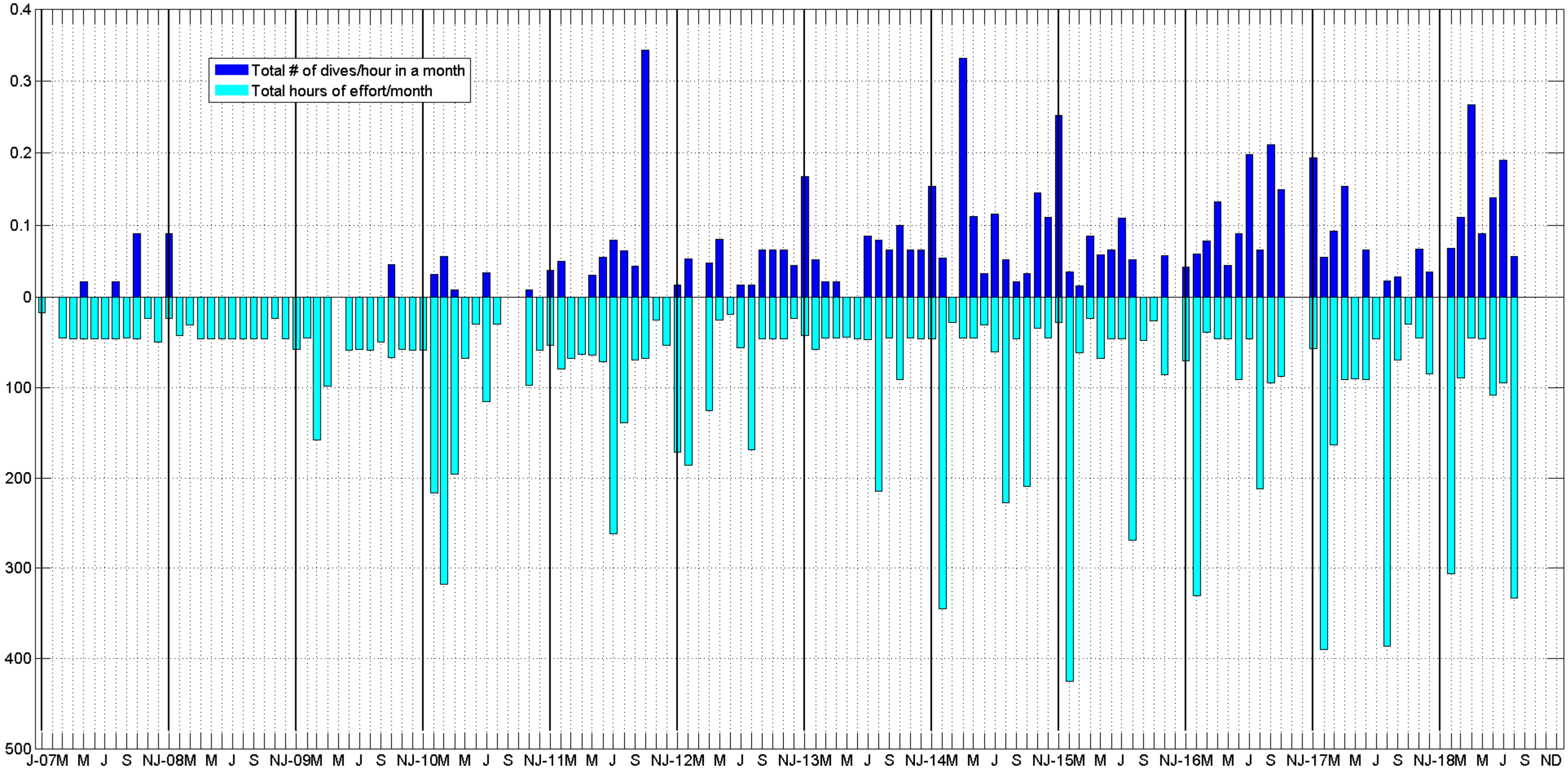
CSM beaked whale dives occurred far less frequently than Blainville's beaked whale dives, typically less than 0.2 dives per hour, and a maximum of 0.3 dives per hour (Figure 11); due to these lower numbers, and higher false positive rates than for Blainville's beaked whales, all CSM dives were fully manually validated. Although they appear to occur more frequently after 2010, this is likely an artifact of the increase in recorded hydrophones in 2011. This can be examined more closely in the future by only utilizing the 13 hydrophones that were available from 2007 to 2010 to re-process data from 2011 and later to determine if the dive counts and distribution are similar to what was observed from 2007 to 2010. CSM dives occur throughout the year with no seasonal pattern, similar to the Blainville's beaked whales. However, unlike Blainville's beaked whales, CSM dives do not occur in every recording. There are occasionally mixed group foraging dives that include both CSM and Blainville's beaked whale clicks; these should be examined further to determine if these species simply are co-located in space or if there are actually mixed groups.

Cuvier's beaked whale dives are presented here for the first time from 2007 to 2018 (Figure 12), and overall have a slightly higher number of group foraging dives per hour than CSM beaked whales at 0.1 to 0.3 dives per hour, and a maximum of 0.5 dives per hour. Again, there is an increase in the number of dives detected when the number of recorded hydrophones increased starting in 2011. This species also occurs on the range throughout the year, although there may be a slight increase in group foraging dives per hour during winter months. However, none of the Cuvier's beaked whale dives have been manually validated, so these represent preliminary data that may change slightly once validated, as there may be some false positives detections that could be attributed to dolphin clicks included in these current results. An analysis of the detector performance and false positive and miss rates still needs to be conducted for the Cuvier's beaked whale detector in order to better characterize their occurrence and abundance patterns. In addition, once the detectors for all three species have been assessed and the dive data have been validated, an analysis of the spatial and temporal distribution of the three species can be conducted to determine how much overlap occurs between them or if any niche partitioning is occurring.



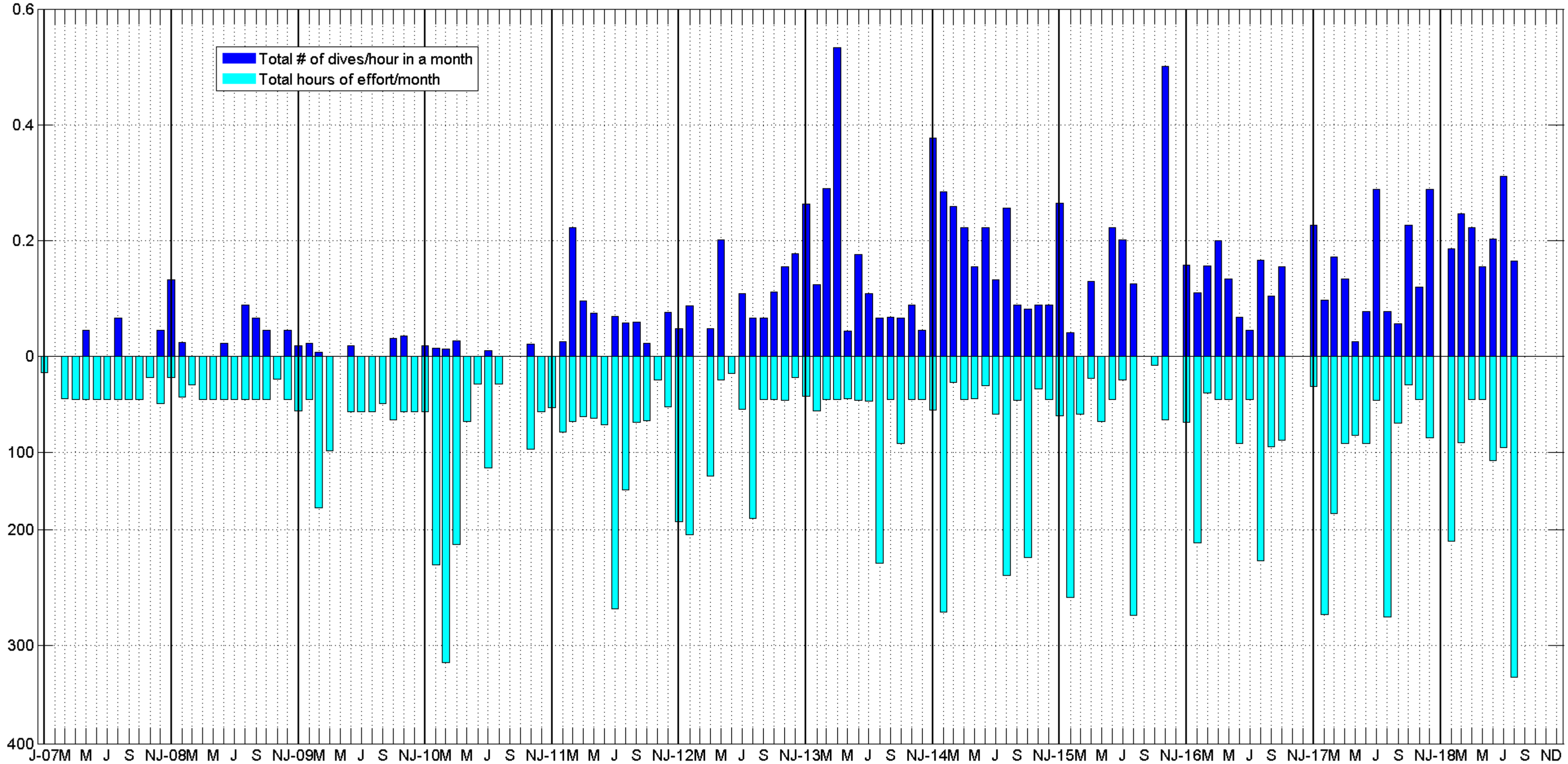
Recording effort occurred from 2007-2018 (dark blue vertical bars). Hours of recording effort per month from 2007-2018 include full bandwidth data collections only (light blue vertical bars). The horizontal axis is gridded by month, with Januarys shown as solid black lines and calendar years indicated (e.g. J-07 indicates January 2007) and months of March, May, July, September, November, and December indicated with M, M, J, A, S, N, and D for 2018 only. Note that if light blue bars exist but dark blue bars do not exist, then data were recorded for that month but no whales for the given species were present. If nothing is plotted for a month then no data were recorded.

Figure 10: The total number of Blainville's beaked whale group foraging dives per hour of total recording effort each month.



Foraging dives occurred from 2007-2018 (dark blue vertical bars). Hours of recording effort per month from 2007-2018 include full bandwidth data collections only (light blue vertical bars). The horizontal axis is gridded by month, with Januarys shown as solid black lines and calendar years indicated (e.g. J-07 indicates January 2007) and months of March, May, July, August, September, November, and December indicated with M, M, J, A, S, N, and D for 2018 only. Note that if light blue bars exist but dark blue bars do not exist, then data were recorded for that month but no whales for the given species were present. If nothing is plotted for a month then no data were recorded.

Figure 11: The total number of CSM beaked whale group foraging dives per hour for each month.



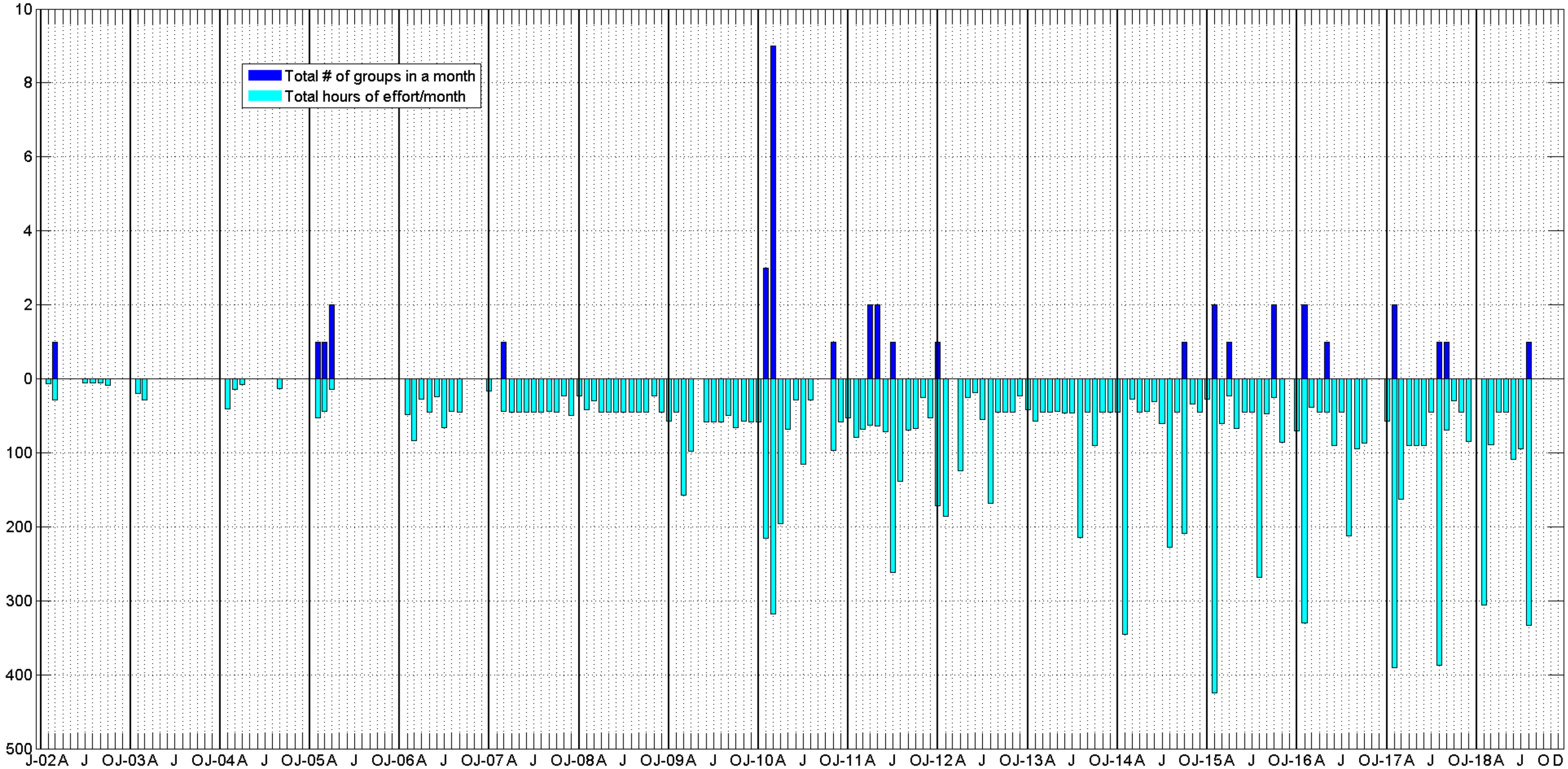
Foraging dives occured from 2007-2018 (dark blue vertical bars). Hours of recording effort per month from 2007-2018 include baseline full bandwidth data collections only (light blue vertical bars). The horizontal axis is gridded by month, with Januarys shown as solid black lines and calendar years indicated (e.g. J-07 indicates January 2007) and months of March, May, July, August, September, November, and December indicated with M, M, J, A, S, N, and D for 2018 only. Note that if light blue bars exist but dark blue bars do not exist, then data were recorded for that month but no whales for the given species were present. If nothing is plotted for a month then no data were recorded.

Figure 12: Preliminary results for the total number of Cuvier's beaked whale group foraging dives per hour for each month.

3.5.2 Killer Whales

Figure 13 provides the total number of manually verified killer whale HFM calling groups for each month between February 2002 and August 2018. The results presented here do not include decimated data since those data do not have sufficient bandwidth (only up to 3 kHz) for the detectable portion of killer whale HFM calls (10-35 kHz). The data from 2002 to 2005 were from the earliest recordings that were only sampled at 44.1 kHz (bandwidth up to 22 kHz) and therefore only detected the bottom of the HFM calls. Due to relatively low levels of abundance and occurrence, all automatically grouped killer whale calls were manually verified to contain killer whale HFM calls. Typically, 1-2 HFM calling groups were detected in only one full bandwidth data set per month, with a maximum of 9 groups in 3 data sets from March 2010. Between February 2002 and August 2018, full bandwidth data collection occurred in 155 months, of which HFM calling groups were manually validated to occur in 22 months. As discussed in Martin et al. (2018a), the slight increase in abundance in the fall, winter, and early spring may be related to the seasonal presence of baleen whales, but killer whales occur year round as well, likely due to the presence of other marine mammal species (Baird et al., 2006).

Only a few sightings of killer whales on the PMRF instrumented range have been documented and no killer whales have been tagged in the area. In August 2017, killer whale calls were detected and an immediate acoustic behavioral response was observed in rough-toothed dolphins that had been present on the range for several hours (Jarvis et al., 2019).



Calling groups detected from 2002-2018 (dark blue vertical bars). Hours of recording effort per month from 2002-2018 include full bandwidth data collections only (light blue vertical bars). The horizontal axis is gridded by month, with Januarys shown as solid black lines and calendar years indicated (e.g. J-02 indicates January 2002) and months of April, July, October and December indicated with A, J, O and D for 2018 only. Note that if light blue bars exist but dark blue bars do not exist, then data were recorded for that month but no whales for the given species were present. If nothing is plotted for a month then no data were recorded.

Figure 13: The total number of manually verified killer whale HFM calling groups detected for each month.

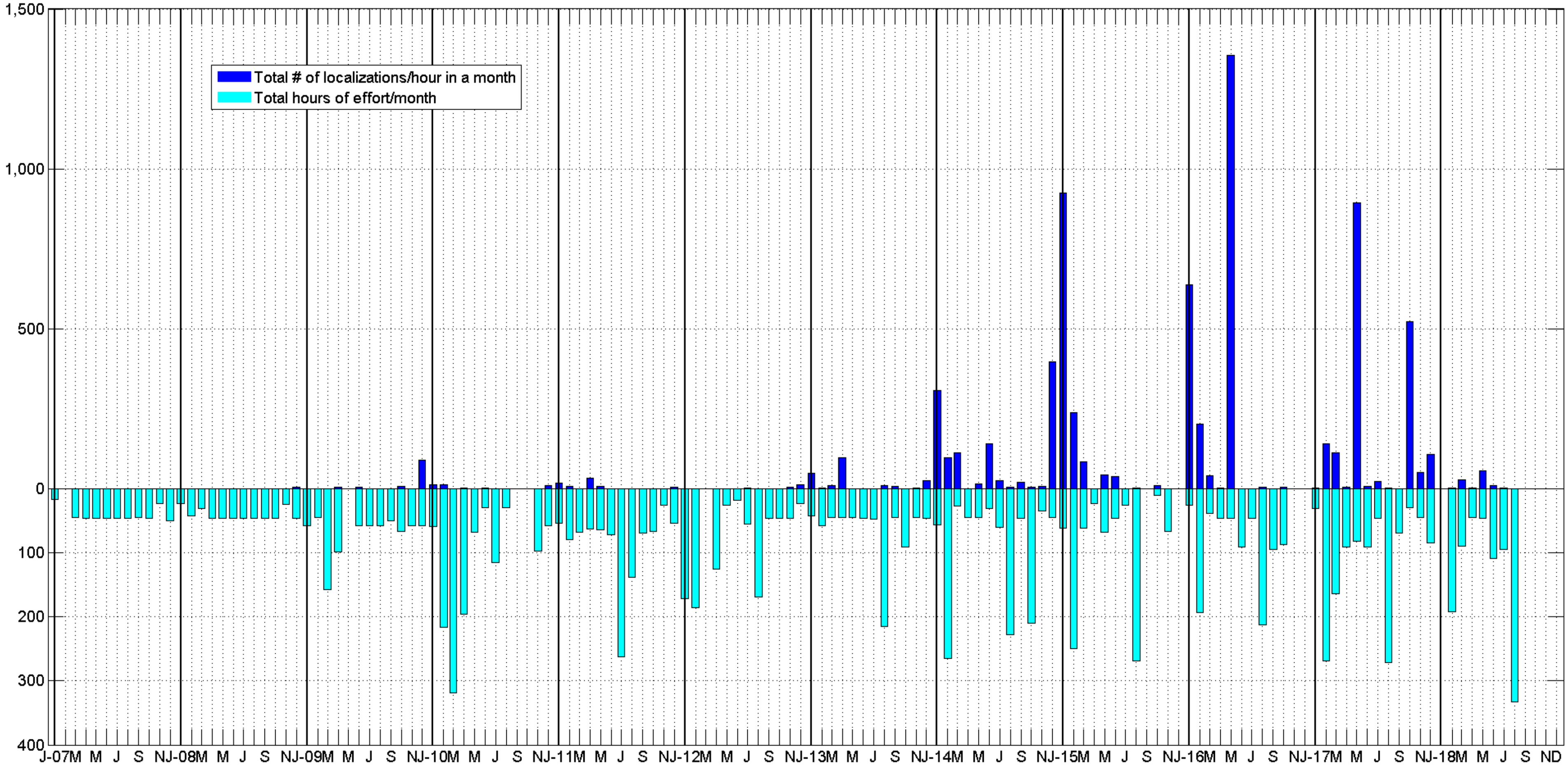
3.5.3 Sperm Whales

Sperm 2007 to 2018. Efforts in FY18 refined the sperm whale detection and localization processes, as mentioned in Section 2.4.1, compared to the detection and localization process utilized to generate results that were presented in Martin et al. (2018a).

Although sperm whales are believed to be present year-round, the localization results in Figure 14 seem to indicate some seasonality in the occurrence and abundance of sperm whales at PMRF, with localizations occurring from approximately September to May, although that varies from year to year. Localizations peak in the winter months (December through February), although again that peak seems to vary across years. It is important to keep in mind that these results are preliminary and have not been characterized in terms of false positive detections and localizations, therefore what appear to be seasonal peaks could be a result of false positives or reflect intermittent presence at PMRF.

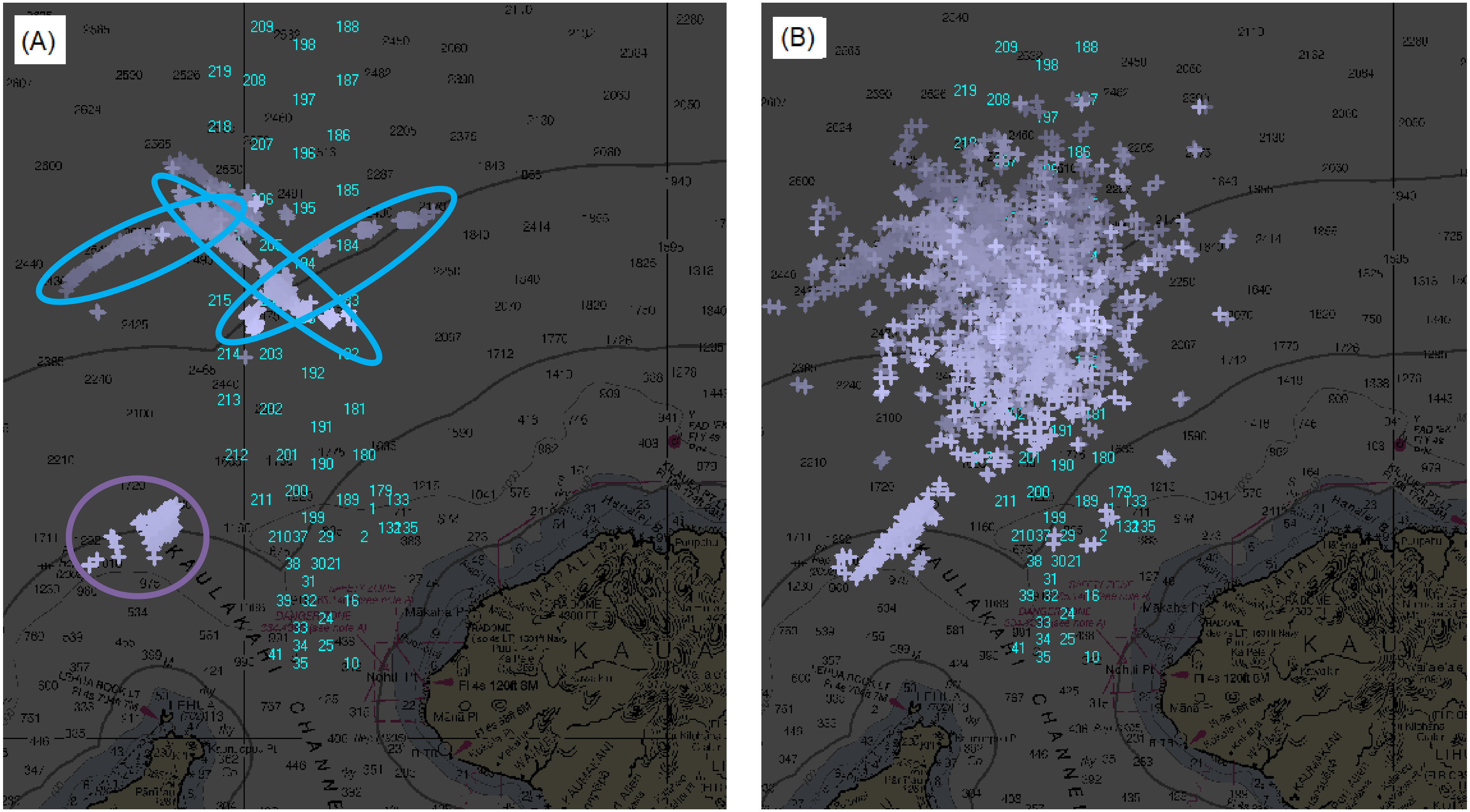
There is a high degree of variability in the number of sperm whale localizations seen over short periods of time using current processing capabilities. This variability could be indicative of groups of multiple sperm whales moving into the instrumented range and emitting regular foraging echolocation clicks with an ICI that can vary between 0.5 and 2 sec (Miller et al., 2004), resulting in a large increase in localized clicks. Conversely, a rapid spike in localizations could be due to localization of false positive detections that should instead be attributed to anthropogenic sources, natural variations in noise, or a combination thereof. An example of the high variability of results over short periods of time can be seen in September 2017 when there was a total of 69.2 hours of data collection and 76 total localizations resulting in 1.1 localizations per hour (not discernable in Figure 14). However, in October 2017 there was a dataset in which the number of localizations dramatically increased (15,486 total localizations over a total of 178 hours of data collected in the month, resulting in 522 localizations per hour). This highlights that the metric of localizations per hour is impacted by the hours of effort in a month, and also a high degree of variability from tens of localizations to tens of thousands of localizations can occur.

Figure 15 depicts localized sperm whale clicks that were detected on five or more hydrophones over an 8 hour and 20 minute period between January 30, 2016 at 17:25 UTC and January 31, 2016 at 01:45 UTC using FY18 updated (A) and previously used processing methods (B). These results show a subset of time for a 25.5 hour long dataset in which peak sperm whale activity occurred. For this dataset, previous processing methods generated 89,248 detections; of those, 23,549 met additional criteria (e.g. a minimum ICI threshold) and were suitable to attempt to localize, and generated 4,126 localizations. Updated processing methods produced substantially more detections (413,650 total detections and 89,256 detections suitable to attempt to localize), and localizations (10,117). Systematic characterization of the updated sperm whale detection and localization process still needs to be performed. As evidenced in Figure 15 (A), updates to the localization queue sorting process (Section 2.4.1) appeared to have the greatest impact on improving localization accuracy. It is important to remember that sperm whale clicks detected on PMRF vary based on type and ICI depending on the behavior of the individual or group. A review of some datasets with a low number of sperm whales producing slow clicks has shown that their localized clicks could be visually tracked when viewed in an interactive situational display (similar to the localizations circled in light blue in Figure 15 (A). In contrast, when multiple sperm whales are aggregated in a foraging group and producing regular echolocation clicks, it may be necessary to report the number of groups relative to the nearest hydrophone (similar to beaked whales) rather than localizations. In this instance, localizations would appear densely clustered due to difficulties attributing clicks to individuals (similar to the localizations circled in gold in Figure 15 (A). Different metrics (i.e. groups vs localizations and tracks) need to be further investigated to properly report sperm whale presence and abundance during different behavioral states. The ability to track localizations attributed to an individual sperm whale could yield a density of individual acoustically active sperm whales..



Whale clicks were measured from 2007-2018 (dark blue vertical bars). Hours of recording effort per month from 2007-2018 include full bandwidth data collections only (light blue vertical bars). The horizontal axis is gridded by month, with Januarys shown as solid black lines and calendar years indicated (e.g. J-07 indicates January 2007) and months of March, May, July, August, September, November, and December indicated with M, M, J, A, S, N, and D for 2018 only. Note that if light blue bars exist but dark blue bars do not exist, then data were recorded for that month but no whales for the given species were present. If nothing is plotted for a month then no data were recorded.

Figure 14: The total number of automatically localized sperm whale clicks per hour for each month.



Results span January 30, 2016 at 17:25 to January 31, 2016 at 01:45 UTC. Localizations were detected on five or more hydrophones. Potentially different behavioral states are highlighted with bouts of clicks, potentially by an individual whale (light blue ellipse), and regular echolocation foraging clicks produced by a foraging group (gold circle).

Figure 15: Sperm whale localizations produced with FY18 updated (A), and previously used (B) processing methods.

3.6 DISTURBANCE ANALYSIS RESULTS

Disturbance analyses described in Section 2.4.4 were performed for minke whale tracks during the portion of the February 2018 SCC that overlapped with ship presence and hull-mounted MFAS transmissions. Results are shown for fully validated minke whale tracks within the study area that encompasses the extent of the hydrophone array. Validation of the automatically generated tracks consisted of inspecting the call intervals and estimated velocities for consistency with known minke whale characteristics, as well as reviewing the frequency of the dominant signal component of tracked calls, and manually reviewing vocalization waveforms, spectrograms, spectra, and call intervals from samples of tracked calls. The disturbance analysis process was also performed for the other species currently tracked (low-frequency baleen and humpback whales) during the February 2018 SCC; however, no tracks from these species were within the hydrophone array during the time of the training event (a few tracks from these species were present but outside the study area). Four minke whale tracks were within the hydrophone array during the February 2018 SCC and were in the proximity of ships and hull mounted MFAS transmissions (Figure 16). The cumulative sound exposure level (cSELs) for the four minke whale tracks are depicted in 5-minute bins in Figure 17. Note that the color of the tracks in Figure 16 correspond to the color of the cSEL lines in Figure 17. An overview of ship-whale geometries and cumulative sound exposure levels in 5-minute bins over the duration of an animal's track is provided for track 2 in Figure 18. These plots summarize pertinent metrics of the disturbance analysis process and are only provided in this report for track 2 since this was the longest track, had the most overlap with ship only activity and MFAS transmissions, and had the highest cumulative received level of the four minke whale tracks analyzed.

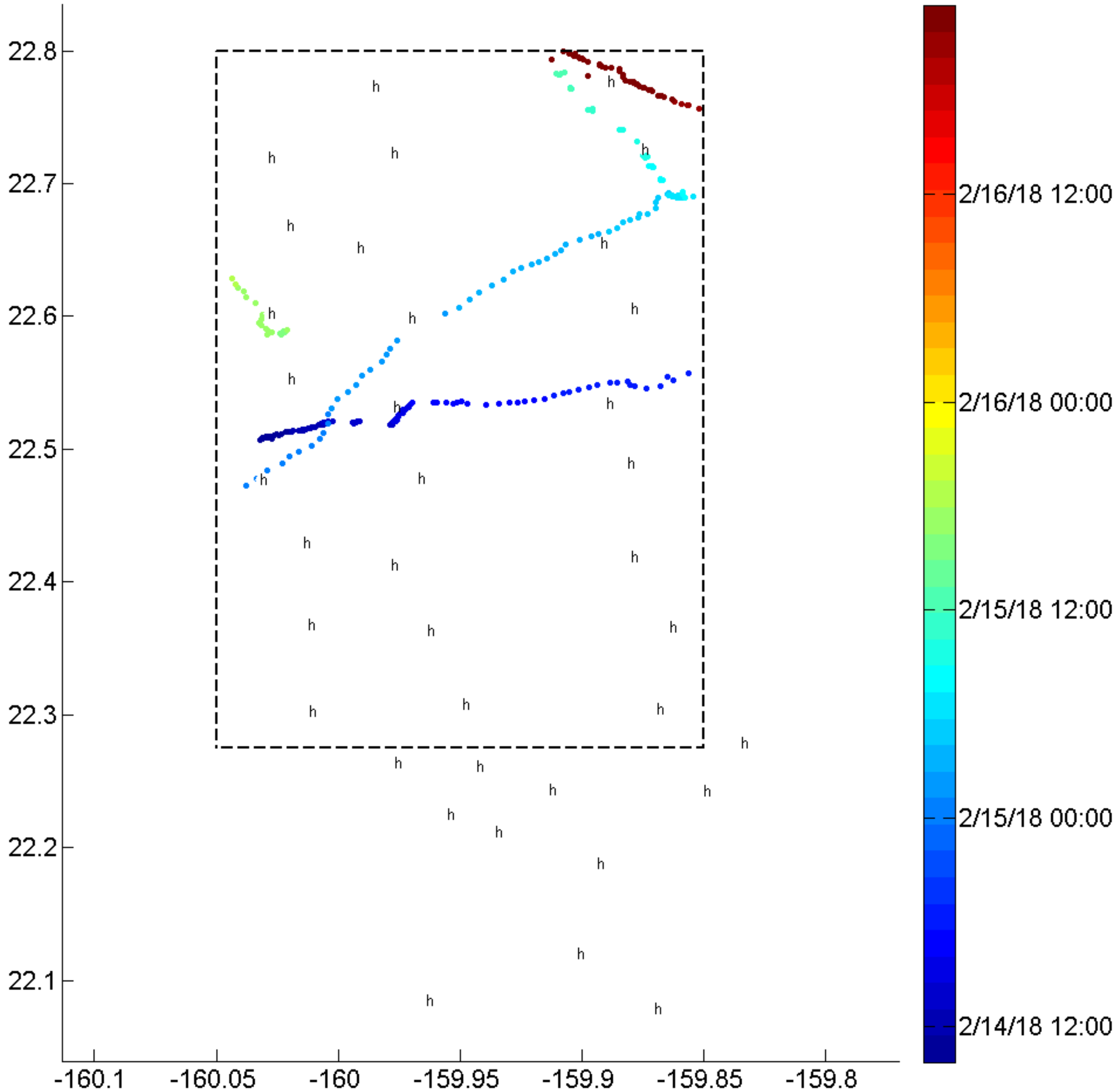
Examining these tracks individually and in chronological order, first, track one is depicted in dark blue and started on February 14th at 09:44 UTC and 22.51° latitude and -160.03° longitude and was tracked for 9 hours and 20 minutes, ending on February 14th at 19:04 UTC and 22.56° latitude and -159.86° longitude. The first 8 hours and 40 minutes of this animal track did not overlap with ship or sonar activity, while the remaining 40 minutes (eight total bins that are 5 minutes each) overlapped with ship presence and MFAS transmissions. In the 35 minutes (bins 1-7) leading up to the end of the track, there was overlap with the onset of ship presence only. The ship closest to the animal started out 5 km away and approached the animal resulting in a minimum closest point of approach (CPA) of 1 km on February 14th at 18:39 UTC while the animal was off the starboard beam sector of the ship. After the minimum CPA to ship only, the closest ship passed the animal and opened in range to ~9 km, with the animal off the stern sector. Throughout the encounter, the animal continued to emit calls at the nominal call rate of ~ 400 – 500 seconds and made heading adjustments similar to those made prior to the encounter, showing no discernable behavioral response to the close proximity of a ship. The last 5 minutes (bin 8) was the only portion of the track that overlapped with MFAS activity, at which point the animal was 11.9 km away and off the stern sector of the closest ship that transmitted MFAS. The cumulative received level in the last 5-minute bin, and therefore the cumulative received level for the entire track, was 150.6 dB cSEL re: 1μPa^{2}s. The fact that the animal stopped calling when the MFAS began could indicate a response to the MFAS activity. As depicted in Figure 16, this track started near the study area boundary. Upon further investigation this track started outside of the study area boundary when a larger study area was utilized for tracking the animal's localizations. However, this track ended within the study area boundary depicted in Figure 16.

Second, track 2 is depicted in light blue and started on February 14th at 23:58 UTC and 22.47° latitude and -160.038° longitude and was tracked for 13 hours and 25 minutes, ending on February 15th at 13:23 UTC and 22.78° latitude and -159.91° longitude. Of the four minke tracks within the hydrophone array that overlapped with the February 2018 SCC, track 2 had the highest cSEL of 168.1 dB re: 1µPa^{2}s. The entirety of this animal's 13 hour and 25 minute long track overlapped with multiple instances of both ship movement and MFAS transmissions. This is due to periods when ships repositioned between MFAS training events and transited across the range, as can be seen in (C) of Figure 18 where there are ~2-hour gaps between sonar bouts. For the first 5 hours, this animal transited on a NE heading and overlapped with both ship movements and MFAS transmissions that varied in range between 16 and 40 km distant. After the NE transit, the animal made maneuvers with an abrupt heading change to NW. Leading up to this the animal was in the presence of ships only for the preceding 2 hours and had a minimum CPA 15.2 km away and off the starboard beam sector of the closest ship; this was the minimum CPA to a ship for the entire duration the animal was tracked (A) and (B) of Figure 18. The abrupt heading change the animal made on February 15th at 05:00 UTC occurred at a time when the animal was exposed to MFAS while 19.5 km away (the minimum CPA to MFAS) and off the bow of the closest ship that transmitted MFAS (A) and (B) of Figure 18. The abrupt heading change could be a response to the closest ship transmitting MFAS. This appeared to be the onset of a new training event that had relatively less MFAS activity. At this time, the whale was off the bow of the closest ship transmitting MFAS, which was relatively closer to the whale than previous ships had been. Shortly after this exposure, there were 3 cycles where the animal overlapped with ship only movement for ~1.5 to 2-hours followed by overlap with MFAS. During this time the animal was on a consistent NW heading while the closest distance to a ship ranged from 18 to 55 km, and the closest distance to MFAS ranged from 20 to 54 km. During the last overlapping bout of MFAS transmissions, the closest MFAS transmission was primarily 20 to 24 km away while the animal was off the stern sector and port beam. Although this did not result in an abrupt heading change, it did correspond to the end of the animal track and a cessation of vocalization. As depicted in Figure 16, this track started and ended near the study area boundary. Upon further investigation by utilizing a larger study area to track this animal's localizations, the resulting track remained within the study area boundary depicted in Figure 16.

Third, track 3 is depicted in green and started on February 15th at 15:39 UTC and 22.59° latitude and -160.02° longitude. This animal was tracked for 2 hours and 40 minutes, ending on February 15th at 18:19 UTC at 22.63° latitude and -160.04° longitude. The cSEL at the end of the animal track was of 162.1 dB re: 1µPa^{2}s. The onset of this track overlapped with ship and MFAS transmissions followed by a 2-hour gap of overlap with ships only, during which time ships repositioned between training events. The animal had its minimum CPA to the closest ship at 5.8 km away and off the starboard beam sector. Leading up to this there was a heading change by the animal from NE to W/NW. This occurred when the animal was off the bow sector of the closest ship not transmitting sonar and the distance decreased from 8 km to the minimum CPA of 5.8 km. After the minimum CPA to a ship not transmitting sonar, the animal was primarily off the stern sector of the closest ship not transmitting sonar and the distance increased as the ship moved away. The remainder of the animal track was on a NW heading and overlapped with ship and MFAS activity (minimum CPA of 22 km off the stern sector of the closest ship transmitting MFAS) until the end of the animal track. As depicted in Figure 16, this track ended near the study area boundary. Upon further investigation this track ended outside of the study area boundary when a larger study area was utilized for tracking the animal's localizations, indicating the animal continued to vocalize beyond the end of this track.

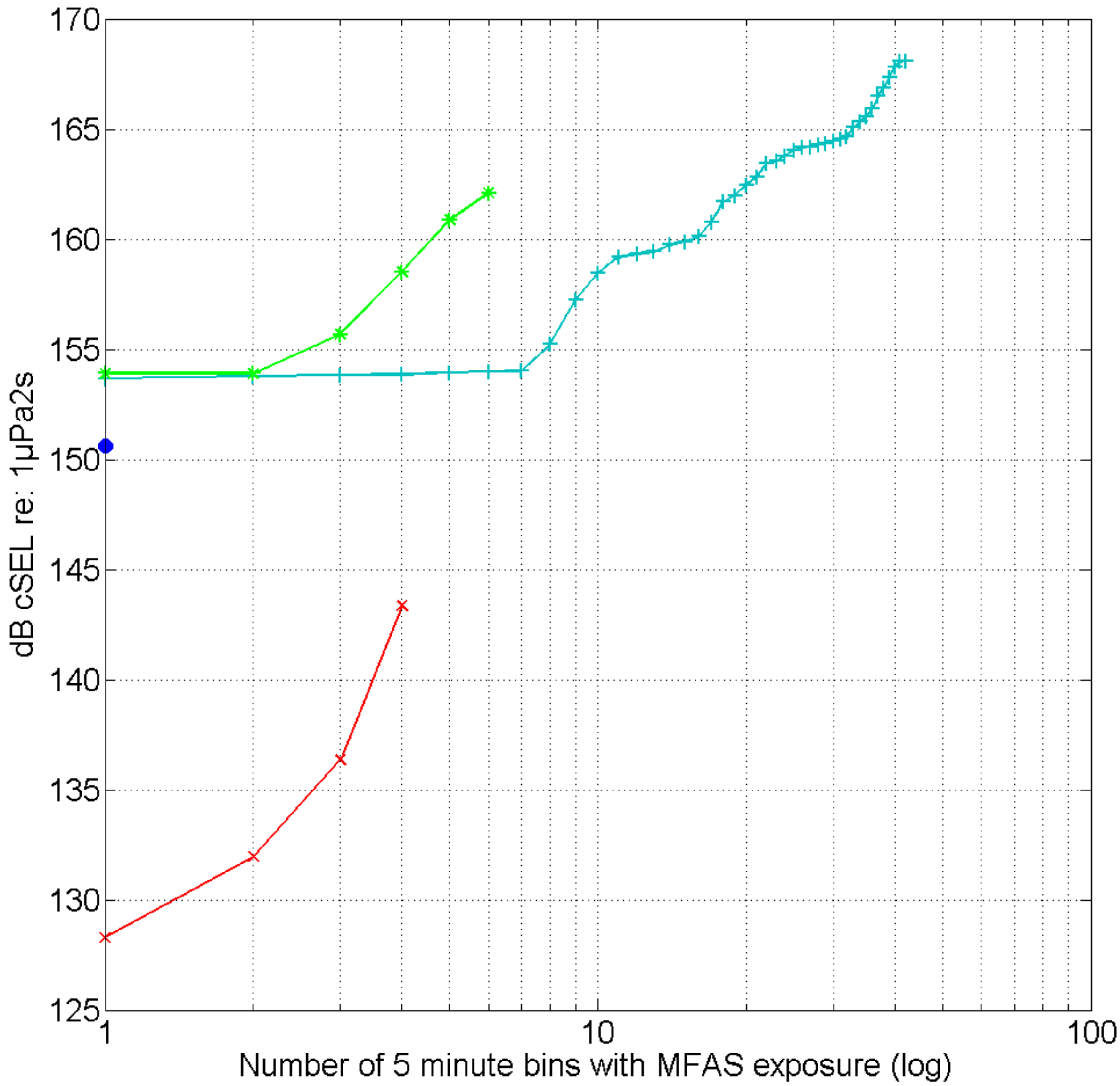
Last, track 4 is depicted in red and started on February 16th at 21:05 UTC and 22.76° latitude and -159.85° longitude headed in a NW direction. This animal was tracked for 2 hours and had a cSEL of 143.3 dB re: 1µPa^{2}s. Similar to track 3, track 4 overlapped with ship and MFAS activity at the onset of the track, followed by overlap with ships only during repositioning, and finally overlap with ship and MFAS activity again. Track 4 ended on February 16th at 23:05 UTC and 22.78° latitude and -159.88° longitude and overall was fairly distant from ship and MFAS activity with a minimum CPA to the closest non-active ship of 53.4 km while the animal was off the bow sector, and a minimum CPA to the closest ship transmitting MFAS of 42.9 km while the animal was off the bow sector. As depicted in Figure 16, this track started and ended at the study area boundary. Upon further investigation this track started and ended outside of the study area boundary when a larger study area was utilized for tracking the animal's localization.

Overall, these data indicate that minke whales continued calling when exposed to cSELs up to 168.1 dB cSEL re: 1µPa^{2}s, although an apparent change in whale heading was exhibited by one whale (track 2). In comparison to the February 2017 disturbance analyses done in the previous annual report (Martin et al., 2018a), the highest cSEL in that report was 169.8 dB cSEL re: 1µPa^{2}s. This may suggest that animals may cease vocalizing when exposed to cSELs at approximately this level; however, it is more likely a culmination of other factors such as distance to ships and angle off the bow. There appeared to be no apparent change in call rate or whale heading when a ship not transmitting MFAS closed in distance to a whale with a CPA of 1 km (track 1). However, this same animal may have ceased calling as a behavioral response to the onset of MFAS activity when the cSEL was 150.6 dB cSEL re: 1µPa^{2}s. Conversely, another minke whale appeared to make an apparent change in heading while a ship not transmitting sonar closed in distance to it and had a minimum CPA of 5.8 km with the whale off the bow. This whale then appeared to resume its intended heading as a ship not transmitting sonar opened in distance to the whale, which at that time was primarily off the stern sector of the ship. As noted for each track, the start, end time, and location of a track may be influenced by utilizing a reduced study area that only encompasses the hydrophone array, as was done for this report. This is a known limitation of using a reduced study area for localizing and tracking whale calls, and alternative ways to report tracks and disturbance analysis results are being investigated.



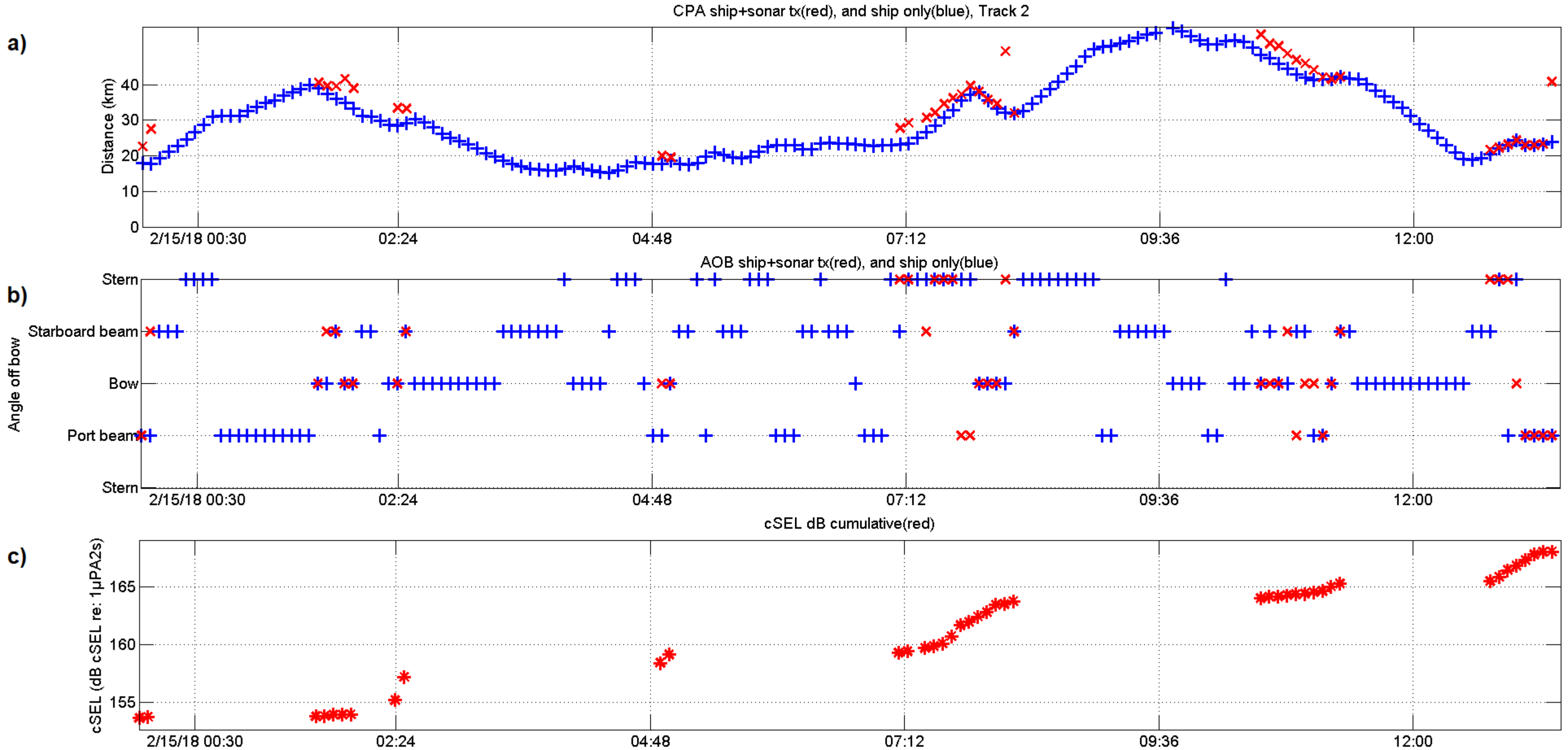
The study area it outlined with black dashed lines. Four calling minke whales were tracked during this time. Track 1 is depicted in blue, track 2 in light blue, track 3 in green, and track 4 in red.

Figure 16: Minke whale tracks within the study area, before, during, and after the portion of the February 2018 SCC that utilized hull mounted MFAS.



This shows the number of 5-minute bins an animal track was exposed to MFAS and does not represent the entire duration of an animal track (track start and end times in above text). Track 1 is depicted in blue, track 2 in light blue, track 3 in green, and track 4 in red.

Figure 17: Plot showing the estimated cumulative sound exposure level in 5-minute bins during the time minke whale tracks overlapped with hull mounted MFAS transmissions during the February 2018 SCC.



Measurements were taken during the February 2018 SCC. The time axis on all three plots is scaled for the start and end time of the track with a 10 minute buffer before the start and after the end. (A) shows the distance from the closest ship transmitting sonar (red markers) and the closest ship not transmitting sonar (blue markers). (B) shows the orientation of the animal relative to the closest ship transmitting sonar (red markers) and the closest ship not transmitting sonar (blue markers). (C) depicts the cumulative sound exposure level the animal received over the duration it was tracked, energy was only accumulated during times of MFAS training when transmissions were localized.

Figure 18: Timeline overview (in 5-minute bins) of ship-whale geometries and cumulative received levels for minke whale track 2.

3.7 NOISE ANALYSIS RESULTS

Natural variations in noise occur on PMRF on a multitude of time scales, with discernable differences observed between years, seasons, lunar cycles, and diurnally. Noise analyses methods were first developed in FY17 to observe the noise levels in recorded data at multiple hydrophones, and also to integrate the noise levels over some species' processing bands (primarily baleen whales initially). This type of analysis is useful in identifying issues with the recorded data (e.g. when noise levels can be either extremely high, or low, compared to normal noise levels) as well as understanding the probabilities of detecting signals. Figure 19 shows the yearly noise average using samples from all available unclassified data over frequencies up to 3 kHz from a single hydrophone (J-9) recorded from January 2012 to June 2017 (as this is the period of time hydrophone J-9 was recorded). The data suggest a possible upward trend in background noise levels. The increase in noise in the 1,700 Hz range is likely due to system self-noise, and is observed in the data from all hydrophones.

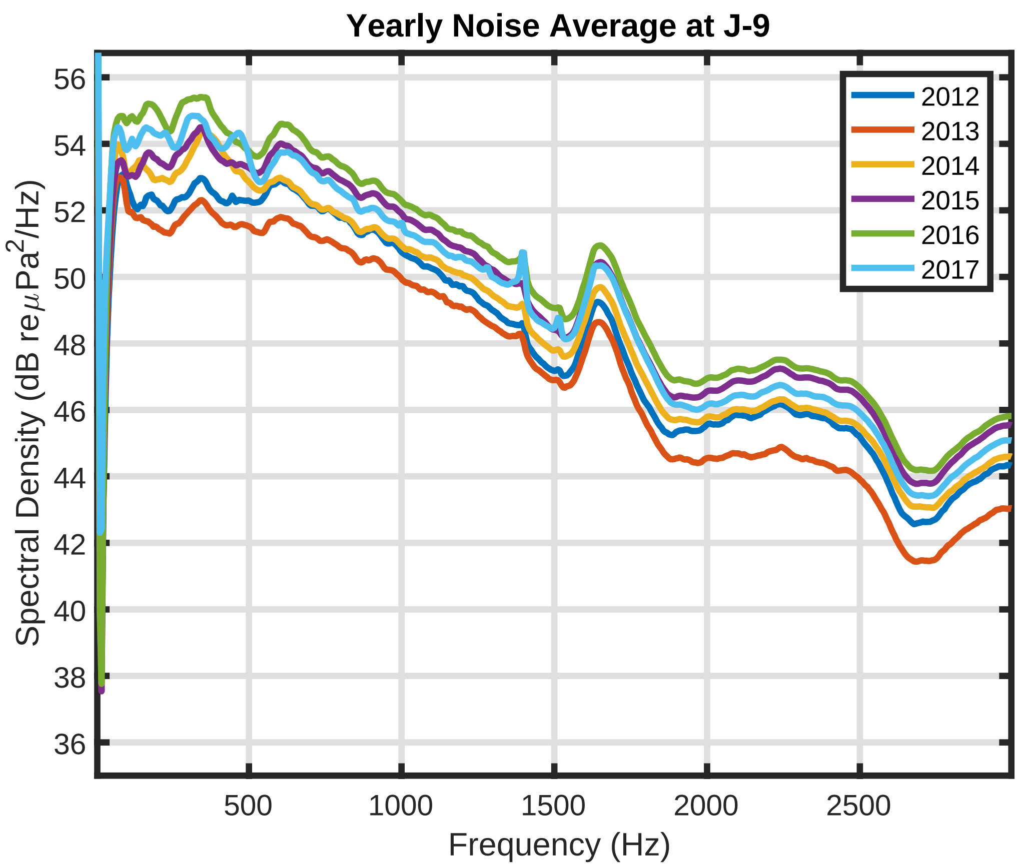
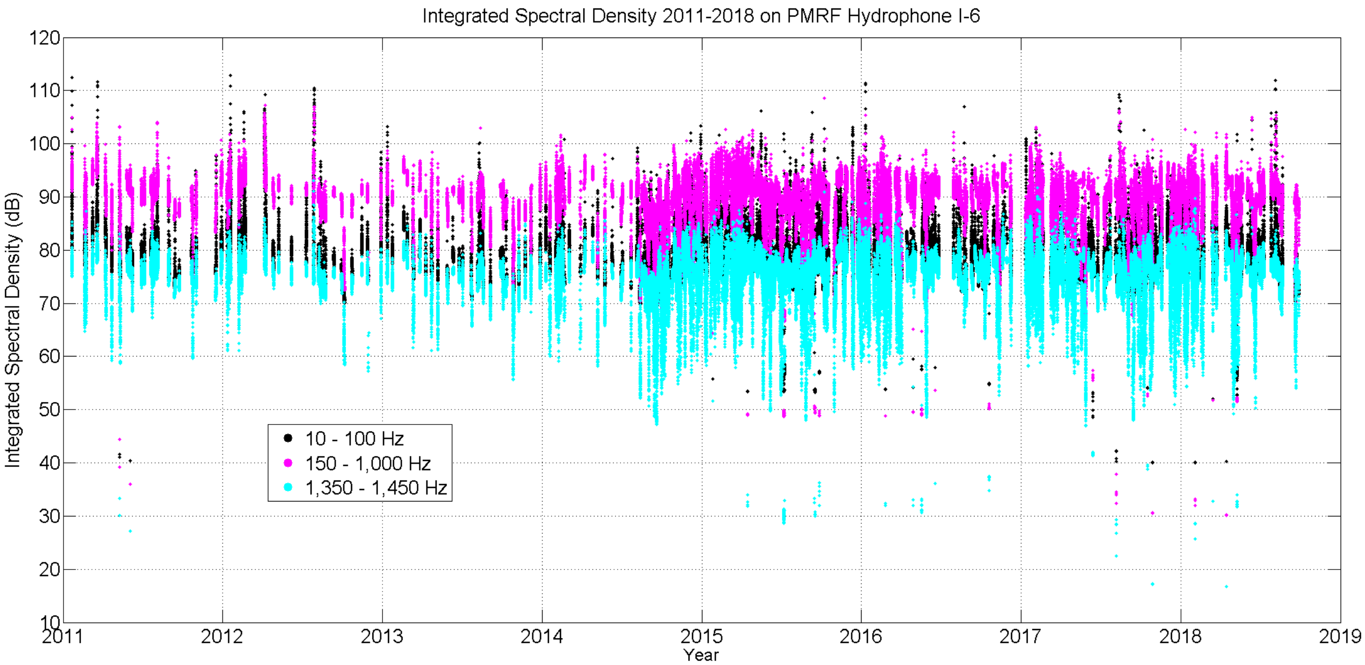


Figure 19: Yearly sampled noise average reported as spectral density (dB re uPa^2/Hz) recorded at hydrophone J-9 from 2012-2017.

Figure 20 shows the integrated spectral density in three bands of interest from 10 to 100 Hz (occupied by the low-frequency baleen whale group), 150 Hz-1,000 Hz (occupied by mid-frequency baleen whales such as humpback whales), and 1,350 to 1,450 Hz (occupied by minke whales). A variation of 15 to 20 dB in background noise levels are not uncommon, and can happen over the course of hours or days, as shown in Figure 20. Corrupt data segments can also be seen in Figure 20, when noise recorded is abnormally low. These time periods mark data dropouts, and represent the instrument noise floor.

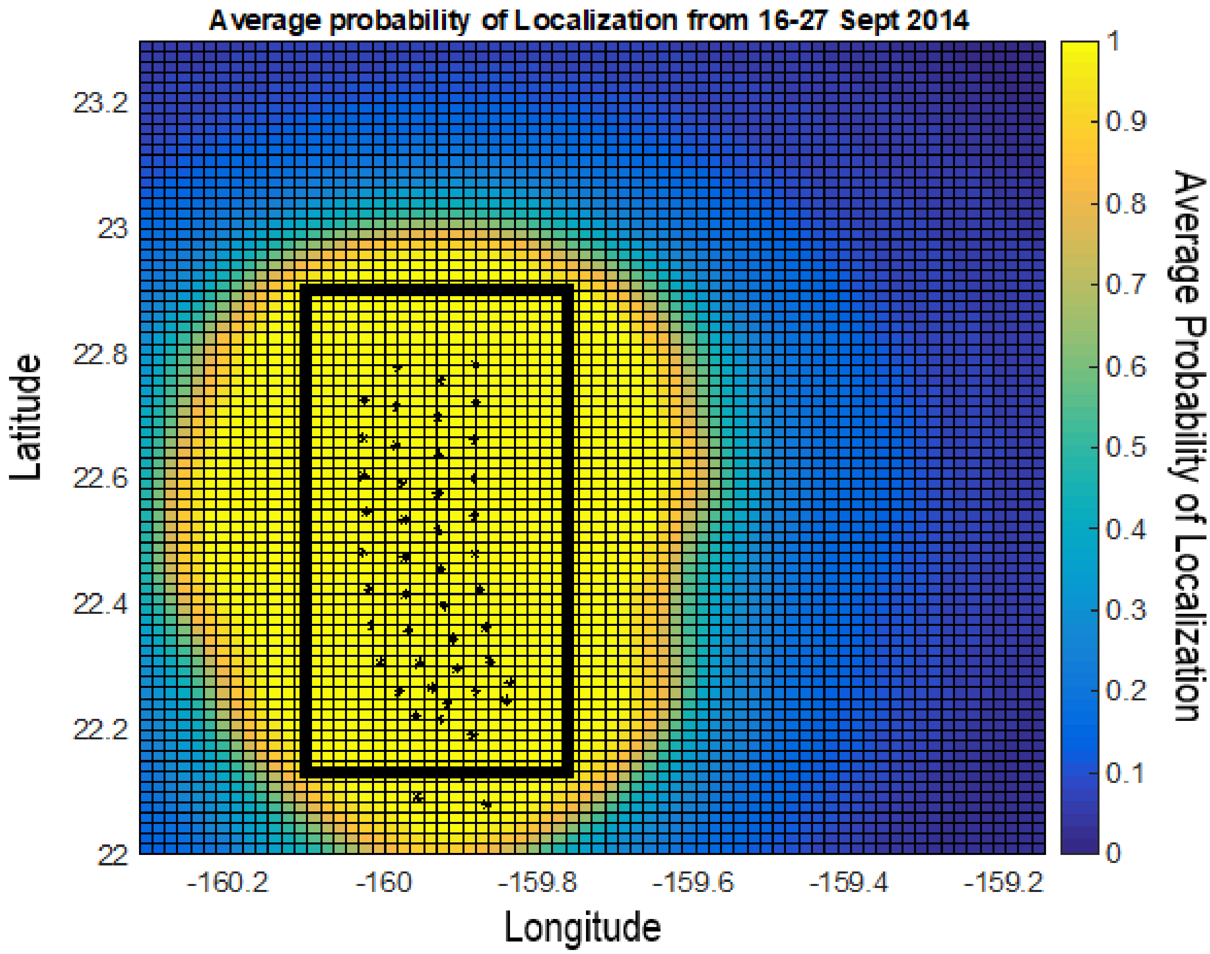


Abnormally low noise levels in 2011, 2015, 2016, 2017, and 2018 appear as outliers and indicate corrupt data segments.

Figure 20: Integrated spectral density in various frequency bands recorded at hydrophone I-6 from 2011-2018.

Noise measured from all hydrophones on the range can be used as an input to determine the probability of detecting and localizing calls for various species of marine mammals on the PMRF range. By estimating the animal source level, the SNR required for successfully detecting a call, and transmission loss between the marine mammal and each hydrophone on the range, a probability of localization map can be created using actual PMRF data. For example, Measurements were taken from September 16-27, 2014. The bright yellow area indicates that the probability of localizing a minke whale boing is equal to one over all noise conditions experienced during the 11-day period.

Figure 21 shows a probability of localization map for minke whale vocalizations over the period of September 16-27, 2014. The probability of localization constantly changes with the varying background noise, with this map representing this one period of time. The bright yellow area indicates that the probability of localizing the animal is equal, or very close, to one for all noise conditions experienced during the 11 day monitoring effort. Therefore, if the boxed area is used for studying minke whales, we can safely assume that our probability of localization is one, or very close to one. These findings support the use of the smaller study area for FY18 analyses of baleen whale tracks. The simulation software is an important new tool for validating that the study area used for reporting marine mammal tracks is stable over all likely noise environments.



Measurements were taken from September 16-27, 2014. The bright yellow area indicates that the probability of localizing a minke whale boing is equal to one over all noise conditions experienced during the 11-day period.

Figure 21: Average probability of localizing a minke whale on the PMRF range.

Using both the noise analysis tool and probability of localization tool, it is now possible to look for changes in animal behavior in relation to changes in background noise. Chart plots demonstrate the presence of minke whale tracks along (A) latitude and (C) longitude for the period of 18 – 26 January 2017. Plot (B) provides the acoustic integrated spectral density in the minke whale vocalization bandwidth in dB re 1 µPa2 for the same time period.

Figure 22 (A) and (C) show the latitude and longitude for several minke whale tracks from January 18 to 26, 2017. Chart plots demonstrate the presence of minke whale tracks along (A) latitude and (C) longitude for the period of 18 – 26 January 2017. Plot (B) provides the acoustic integrated spectral density in the minke whale vocalization bandwidth in dB re 1 µPa2 for the same time period.

Figure 22 (B) shows the acoustic integrated spectral density in the minke whale vocalization band. A strong uptick in noise on January 21st coincides with a cessation of minke whale calls for nearly a two day period. Cessation of minke whale boing calling has previously been attributed to MFAS activity (e.g. Martin et al., 2015); however, no MFAS activities were detected in the acoustic data. The U.S. Navy’s Sonar Positioning and Reporting System database was checked to verify if any MFAS activities were reported in the region, with nothing found. In addition, no killer whale HFM calling groups were detected in January 2017, which eliminates attributing cessation of calling to a predator response. Using the probability of localization tool, it was verified that the probability of localization was still equal to one, even with these noise conditions. Further investigation of this unusual cessation of minke whale calling event revealed unusual sea conditions based upon NOAA's Hanalei buoy data over this period of January 21 to 23, 2017. Figure 24 shows decreased wave periodicity (both the dominant and average wave periods shown), increased wave heights, and a shift in wave direction. NOAA geostationary satellite imagery data also revealed an interesting situation, with the arrival of a weather front near the time the whale tracks ceased. Wind conditions from Lihue airport also indicated strong wind speeds of 40+ MPH on January 21st. Therefore, it appears that the whales stopped calling, rather than the calls being masked by the strong background noise or moving off the range. The humpback and low-frequency baleen group whale tracks were also preliminarily investigated to see how they related to the minke whale cessation of calling. Chart plots show latitude (A) and longitude (B) on the y-axes and Julian day on the x-axis. The 1.44 day long period between January 21st at 06:43 and January 22nd at 17:16 (i.e. between Julian day 21.28 and 22.72) corresponds to the period of time in Figure 22 (B) when the background noise level increased. The green track ceased around the same time the minke whales ceased calling in Figure 22.

Figure 23 illustrates that one humpback whale track ended around the time minke whale calling ceased, which reinforces the concept of natural conditions being responsible for a cessation of baleen whale calling. Continuing analysis of the humpback band integrated noise levels and probability of localizing humpback calls is investigating this further. The only low-frequency baleen whale tracks in this dataset did not begin until January 23rd, around the time when the minke whales resumed calling in the area. The time when baleen whales resumed calling corresponded to a decrease in wave height and stabilized wave periodicity and wave direction, although wave periodicity was still relatively low and wave direction was still shifted relative to wave direction prior to cessation of calling. These types of natural behavioral responses of whales are important to note when studying the impact of anthropogenic noise sources on the animals.

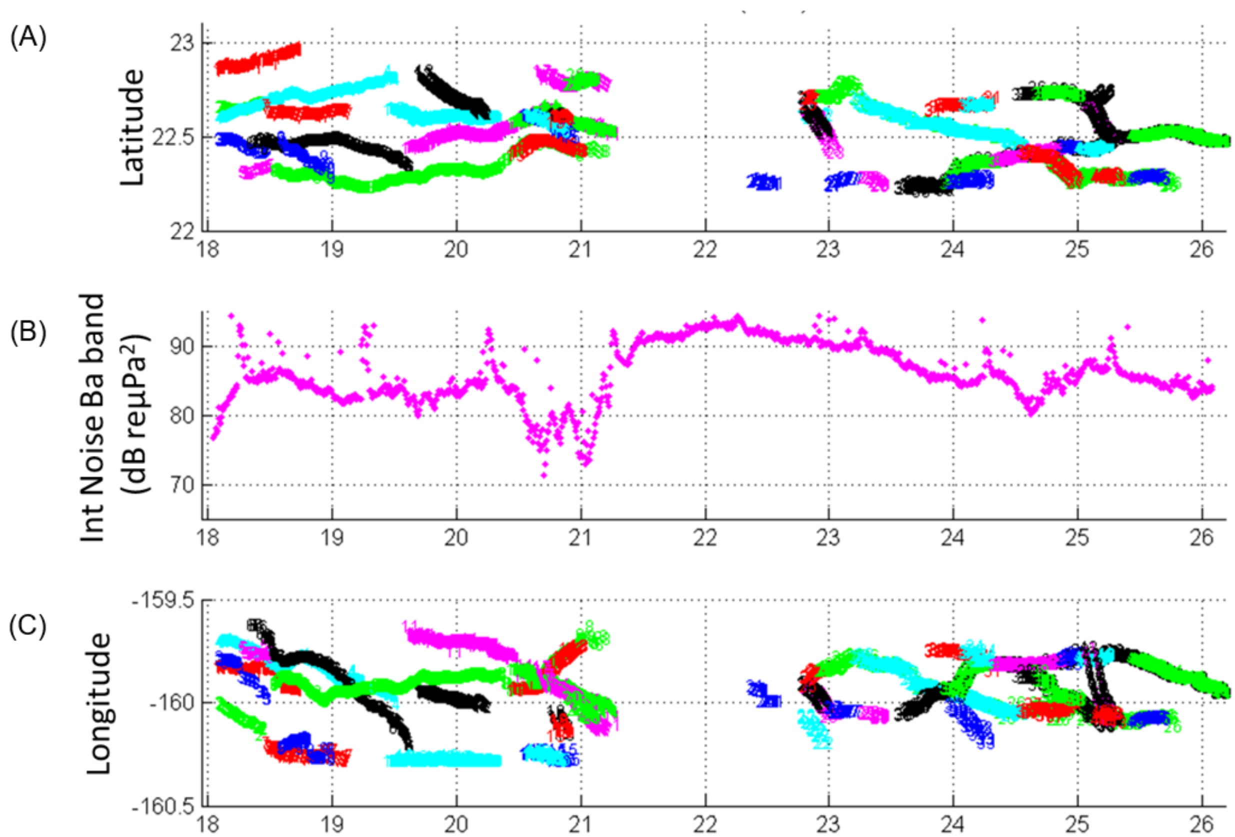


Chart plots demonstrate the presence of minke whale tracks along (A) latitude and (C) longitude for the period of 18 – 26 January 2017. Plot (B) provides the acoustic integrated spectral density in the minke whale vocalization bandwidth in dB re 1 µPa^2 for the same time period.

Figure 22: Minke whales respond to a storm event (marked by increase in background noise level) by ceasing to call.

(A)

(B)

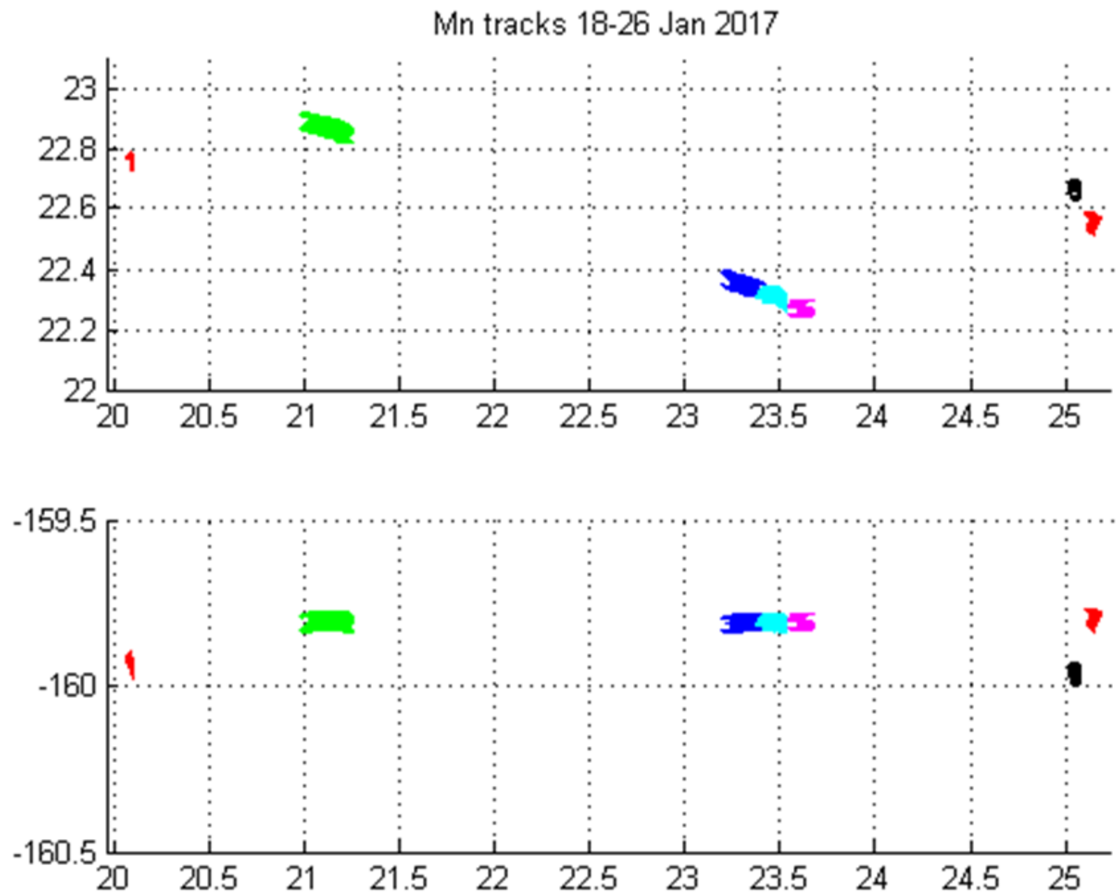
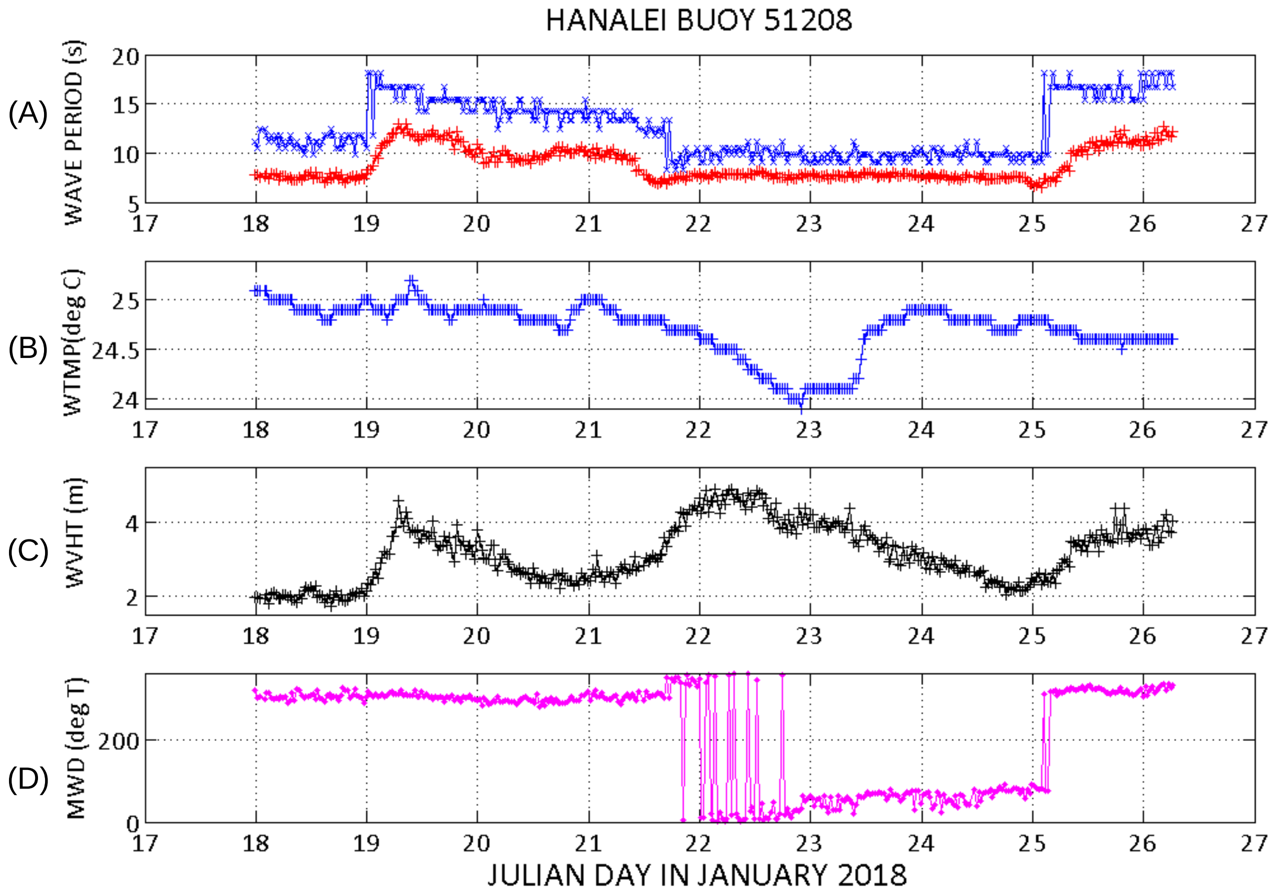


Chart plots show latitude (A) and longitude (B) on the y-axes and Julian day on the x-axis. The 1.44 day long period between January 21st at 06:43 and January 22nd at 17:16 (i.e. between Julian day 21.28 and 22.72) corresponds to the period of time in Figure 22 (B) when the background noise level increased. The green track ceased around the same time the minke whales ceased calling in Figure 22.

Figure 23: Humpback whale acoustic tracks between January 20 and 25, 2017.



The wave period (A), decreased under 10 seconds after noon (UTC) on January 21st. The wave heights (C), also began an increase to over 5 m with the sea temperature near the surface (B), began a decline of 1° C on the January 21st. The wave direction (D), also shows a shift from the NW to the NE.

Figure 24: NOAA buoy 51208 off Hanalei, Kauai, Hawaii data for January 17-27, 2017, including the period of time with anomalously high noise recordings

This page is intentionally blank.

4. CONCURRENT AND RELATED EFFORTS

The ONR BREVE project (PI: S. Martin) is an ongoing joint effort involving the National Marine Mammal Foundation, the Centre for Research into Ecological Environmental Modelling (CREEM) at St. Andrew's University, and NIWC Pacific. The primary goal is to develop and apply methods to determine if baleen whale species' behavioral responses to actual Navy training can be determined statistically using existing large data sets of PAM data from PMRF. The monitoring effort for Pacific Fleet has worked collaboratively with this effort in developing tools for streamlined analyses, primarily in the disturbance analyses. Results from this collaborative effort include finding some significant changes in spatial utilization of the area, swim speeds, and turning patterns in before, during and after training datasets. Some of these results were presented at the ESOMM meeting in The Hague, The Netherlands in September 2018 and have been submitted for publication in a special issue of Aquatic Mammals.

A project funded by the LMR program (PI: T. Helble) involves developing tools to help automatically classify tracks from the low-frequency baleen whale group to the species level, to help semi-automate processes involved in determining marine mammal kinematics and exposures, and examine the source level of baleen whale calls for a potential Lombard effect due to varying background noise levels. This project is directly applicable to the BREVE project and exposure analyses conducted in NIWC Pacific's DCLTDE laboratory, and can be leveraged in the future to use on PACFLT monitoring data.

An ongoing internal NIWC Pacific Science and Technology effort (PI: E. Henderson) has the goal of attaching acoustic pingers to humpback whales, supplemented by satellite tags, to demonstrate that they can be tracked by pinger emissions using the bottom mounted range hydrophones at PMRF. However, no pinger tags were successfully deployed in 2018. As no pinger tags were deployed, and no animals crossed the range while satellite-tagged (precluding recording any vocalizations), call rates cannot be assessed at this time. Additional pinger tag efforts were not funded by internal NIWC Pacific Science and Technology funding for FY19, so at this time that effort is on hold. In FY18, six satellite tags were deployed on whales before and during the February SCC, and five of the six whales were exposed to MFAS. The movement behavior of the whales was somewhat different from those tagged in 2017, with one whale traveling to Oahu and others spending more time near Kauai before moving west to Niihau. Although there were some bouts of extreme movement behavior (e.g. rapid bursts of movement and high turning angles), only one statistically significant change in behavior was observed relative to MFAS. That was the dive behavior of a whale that was traveling north onto the range at the onset of a period of MFAS. The animal changed direction and began traveling south, while executing a series of steep dives of increasing depths. Received levels estimated at the bottom of each dive indicated that levels were lower during these deeper dives; the whale may have been trying to dive below the surface duct to reduce their received levels while traveling away from the range. Their dive behavior returned to normal at the end of the period of MFAS, and they turned around and began traveling north again at that point as well. These results, combined with those from 2017, seem to indicate that humpback whales generally spend little time on or near the range, which would reduce their likelihood of exposure to ship movement or MFAS. When they are exposed to MFAS, these animals generally did not appear to respond, and the one apparent response ended as soon as the sonar ended and therefore did not lead to a long duration response. This effort was largely supported through NIWC Pacific funding, but a portion of the work was funded by PACFLT as well. These results were also presented at the ESOMM meeting in The Hague, The Netherlands in September 2018 (Henderson et al., 2018) and have been submitted for publication in a special issue of Aquatic Mammals (Henderson et al., submitted). Additional satellite tagging effort is planned for FY19; after that the three years of satellite tag data will be combined to conduct a habitat use analysis for humpback whales.

5. FY18 REPORTS AND PUBLICATIONS

5.1 REPORTS AND PUBLICATIONS

Henderson, E. E., Helble, T. A., Ierley, G., and Martin, S. 2018. Identifying behavioral states and habitat use of acoustically tracked humpback whales in Hawaii. Marine Mammal Science 34(3):701–717 | https://doi.org/10.1111/mms.12475

Henderson, E. E., Aschettino, J., Deakos, M., Alongi, G., Leota, T. 2018. Satellite Tracking of Migrating Humpback Whales in Hawaii. SPAWAR Systems Center Pacific Technical Report TR-3106. 38 p.

Jarvis, S. M., E. E. Henderson, T. Brookens, and D. Webster. 2019. Acoustic Observation of the Reaction of Rough Toothed Dolphin (Stenella bredanensis) to the Presence of Killer Whales (Orcinus orca) off Kaua'i. Marine Mammal Science.

Martin, C.R., S.W. Martin, E.E. Henderson, T.A. Helble, R.A. Manzano-Roth, B.M. Matsuyama, and G.C. Alongi. 2018. SSC Pacific FY17 annual report on PMRF Marine Mammal Monitoring.

5.2 PRESENTATIONS

Harris, C.M., Martin, S. W., Martin, C. R., Helble, T. A., Henderson, E. E., Paxton, C., and Thomas, L. 2018. Quantifying behavioural responses of minke whales to sonar activity during Navy training exercises. 6th International Meeting on the Effects of Sound in the Ocean on Marine Mammals. 9-14 September 2018, The Hague, Netherlands.

Helble, T.A., Martin, S.W., Matsuyama, B., Martin, C.R., Henderson, E.E. and Alongi, G.C. 2018. Improving marine mammal classification using context from multiple hydrophones, DCDLE Paris, June 5, 2018.

Helble, T.A., Martin, S.W., Matsuyama, B., Martin, C.R., Henderson, E.E. and Alongi, G.C. 2018. PMRF Preliminary Noise Analysis, U.S. Navy Marine Species Monitoring Technical Review Meeting, San Diego, CA, March 19-21, 2018.

Helble, T.A., Martin, S.W., Matsuyama, B., Martin, C.R., Henderson, E.E. and Alongi, G.C. 2018. Localization using multiple hydrophones and time difference of arrival, Density Estimation Workshop, October 28, 2017. 22nd Biennial on the Biology of Marine Mammals. Halifax, Nova Scotia.

Henderson, E.E. 2018. Marine Mammal Behavioral Response Functions for Navy EIS Analysis. Double-MOCHA Workshop, 15 September 2018. The Hague, The Netherlands.

Henderson, E. E., Aschettino, J., Deakos, M., Alongi, G., Leota, T., and Engelhaupt, D. 2018. Tracking the offshore and migratory movements of humpback whales in Hawaii. 22nd Biennial on the Biology of Marine Mammals. October 22-27, 2017. Halifax, Nova Scotia.

Henderson, E. E., Helble, T., Alongi, G., Martin, C., Matsuyama, B., and Martin, S. 2018. Long-term cetacean occurrence and abundance at PMRF. US Navy Marine Species Monitoring Program Annual Meeting. 19-21 March 2018, San Diego.

Henderson, E. E., Aschettino, J., Deakos, M., Helble, T., Alongi, G., Martin, C., and Martin, S. 2018. Behavioral response of humpback whales to US Navy mid-frequency active sonar. 6th

International Meeting on the Effects of Sound in the Ocean on Marine Mammals. 9-14 September 2018, The Hague, Netherlands.

Martin, S.W., Henderson, E.E., Matsuyama, B., Helble, T.A., Martin, C.R., Alongi, G.C., Manzano-Roth, R. 2017. Automated passive acoustic detection, classification, localization and tracking methods applied to recorded data from the Pacific Missile Range Facility, Kauai, Hawaii. 174th Meeting of the Acoustical Society of America. 4-8 December 2017, New Orleans, Louisiana.

Martin, S.W. and Martin, C.R. 2018. PAM based exposure and response estimation for marine mammals at PMRF. U.S. Navy Marine Species Monitoring Technical Review Meeting, San Diego, CA, March 19-21, 2018.

Martin, S.W., Martin, C.R., Matsuyama, B., Henderson, E.E., Helble, T.A., Thomas, L., Harris, C., Ierley, G. 2018. Baleen whales acoustically derived behaviors with potential responses to U.S. Navy sonar training. 6th International Meeting on the Effects of Sound in the Ocean on Marine Mammals. 9-14 September 2018, The Hague, Netherlands.

REFERENCES

Au, W.W., J. Mobley, W.C. Burgess, M.O. Lammers, and P.E. Nachtigall. 2000. Seasonal and diurnal trends of chorusing humpback whales wintering in waters off western Maui. Marine Mammal Science, 16(3), 530-544.

Miller, P.J., M.P. Johnson, and P.L. Tyack. 2004. Sperm whale behavior indicates the use of click buzzes "creaks" in prey capture. Proceedings of the Royal Society of Biological Sciences 271(1554), 2239-2347.

Baird, R.W., D.J. McSweeney, C. Bane, J. Barlow, D.R. Salden, L.K. Antoine, R.G. LeDuc, D.L. Webster. .2006. Killer whales in Hawaiian Waters: Information on Population Identity and Feeding Habits. Pacific Science 60(4), 523-530. Last accessed 25 Apr 2018. http://www.cascadiaresearch.org/files/Projects/Hawaii/Baird%20et%20al%20Hawaii%20killer%20whales.pdf

Buckland, S. T., Anderson, D. R., Burnham, K. P., Laake, J. L., Borchers, D. L., & Thomas, L. 2001. Introduction to distance sampling estimating abundance of biological populations.

Frankel, A. S., Clark, C. W., Herman, L., & Gabriele, C. M. 1995. Spatial distribution, habitat utilization, and social interactions of humpback whales, *Megaptera novaeangliae*, off Hawai'i, determined using acoustic and visual techniques. Canadian Journal of Zoology, 73(6), 1134-1146.

Heaney, K. D. and R.L. Campbell. Three-dimensional parabolic equation modeling of mesoscale eddy deflection. .2016. J. Acoust. Soc. Am. 139(2), 918-926.

Helble, T. A., G. R. Ierley, G. L. D'Spain, M. A. Roch, and J. A. Hildebrand. 2012. A generalized power-law detection algorithm for humpback whale vocalizations. J. Acoust. Soc. Am. 131(4), 2682-2699.

Helble, T. A., G. R. Ierley, G. L. D'Spain, S.W. Martin. 2015. Automated acoustic localization and call association for vocalizing humpback whales on the Navy's Pacific Missile Range Facility, J. Acoust. Soc. Am. 137(11), 11-21.

Helble, T. A., S.W. Martin, G. R. Ierley and E.E. Henderson. 2016. Swim track kinematics and calling behavior attributed to Bryde's whales on the Navy's Pacific Missile Range Facility. J. Acoust. Soc. Am. 140(6), 4170-4177.

Henderson, E.E., S.W. Martin, R.A. Manzano-Roth, B.M. Matsuyama. 2016. Occurrence and habitat use of foraging Blainville's beaked whales *Mesoplodon densirostris*) on a U.S. Navy range in Hawaii. Aquatic Mammals 42(4), 549-562.

Henderson, E.E., Helble, T. A., G.R. Ierley, S.W. Martin. 2018. Identifying behavioral states and habitat use of acoustically tracked humpback whales in Hawaii. Mar. Mamm. Sci. 34(1).

Jarvis, S., E.E. Henderson, T. Brookens, and D. Webster. (submitted). Acoustic Observation of the Reaction of Rough Toothed Dolphin (*Stenella bredanensis*) to the Presence of Killer Whales (*Orcinus orca*) off Kaua'i. Mar. Mamm. Sci.

Manzano-Roth, R.A., E.E. Henderson, S.W. Martin, C.R. Martin, B.M. Matsuyama. 2016. Impacts of U.S. Navy training events on beaked whale (*Mesoplodon densirostris*) foraging dives in Hawaiian waters. Aquatic Mammals 42(4), 507-518.

Martin, C.R., S.W. Martin, E.E. Henderson, T.A. Helble, R.A. Manzano-Roth, B.M. Matsuyama, G.A. Alongi. 2018a. SSC Pacific FY17 annual report on PMRF Marine Mammal Monitoring. Last accessed 24 Jan 2019. https://www.navymarinespeciesmonitoring.us/index.php/download_file/view/1909/

Martin, S.W., L. Thomas, C. Harris, T. Helble, E.E. Henderson 2018b. Behavioral Response Evaluations Employing Robust Baselines and Actual Navy Training. Office of Naval Research FY18 report.

Martin, C.R., S.W. Martin, E.E. Henderson, T.A. Helble, R.A. Manzano-Roth, B.M. Matsuyama. 2017. SSC Pacific FY16 annual report on PMRF Marine Mammal Monitoring. Last accessed 12 Jan 2018. https://www.navymarinespeciesmonitoring.us/files/7114/9762/6108/Martin_et_al._2017_SPAWAR_FY16_PMRF_Marine_Mammal_Monitoring_Feb2017.pdf.

Martin, C.R., S.W. Martin, E.E. Henderson, T.A. Helble, R.A. Manzano-Roth, B.M. Matsuyama. 2016. SSC Pacific FY15 annual report on PMRF Marine Mammal Monitoring. Last accessed 16 Jan 2018. http://www.navymarinespeciesmonitoring.us/files/3014/6601/1362/Martin_et_al_2016_SPAWAR_FY15_PMRF_Marine_Mammal_Monitoring_Mar2016.pdf.

Martin, S.W., C.R. Martin, B.M. Matsuyama, E.E. Henderson. 2015. Minke whales (*Balaenoptera acutrorostrata*) respond to navy training. J. Acoust. Soc. Am. 137(5), 2533-2541.

Mobley, Joseph R., M. Smultea, T. Norris, and D. Weller. 1996. Fin whale sighting north of Kaua'i, Hawai'i. Pacific Science 50(2), 230-233.

Office of Naval Research Marine Mammal & Biology Program Review, 20-24 March 2017 Abstract book pages 92-93. Last accessed 16 Jan 2018. https://www.onr.navy.mil/en/Science-Technology/Departments/Code-32/All-Programs/Atmosphere-Research-322/Marine-Mammals-Biology

Rankin, S., & Barlow, J. 2007. Vocalizations of the sei whale Balaenoptera borealis off the Hawaiian Islands. Bioacoustics, 16(2), 137-145.

Rankin, S., Norris, T. F., Smultea, M. A., Oedekoven, C., Zoidis, A. M., Silva, E., & Rivers, J. 2007. A visual sighting and acoustic detections of minke whales, Balaenoptera acutorostrata (Cetacea: Balaenopteridae), in nearshore Hawaiian waters. Pacific Science, 61(3), 395-398.

Smultea, M. A., Jefferson, T. A., & Zoidis, A. M. 2010. Rare sightings of a Bryde's whale (Balaenoptera edeni) and sei whales (B. borealis)(Cetacea: Balaenopteridae) northeast of O'ahu, Hawai'i. Pacific Science, 64(3), 449-457.

Tiemann, C.O., S.W. Martin and J.R. Mobley 2006. Aerial and Acoustic Marine Mammal Detection and Localization on Navy Ranges. IEEE Jouirn of Ocean Engineering 31(1):107-119.

INITIAL DISTRIBUTION

84310	Library	(1)
85300	Archive/Stock	(1)
71510	E. E. Henderson	(1)
71510	S. W. Martin	(1)
71510	T. A. Helble	(1)
71510	R. A. Manzano-Roth	(1)

Defense Technical Information Center
Fort Belvoir, VA 22060–6218 (1)

This page is intentionally blank.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-01-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden to Department of Defense, Washington Headquarters Services Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
January 2020	Final	

4. TITLE AND SUBTITLE

FY18 Annual Report on
Pacific Missile Range Facility
Marine Mammal Monitoring

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS

Cameron R. Martin
E. Elizabeth Henderson
Stephen W. Martin
Tyler A. Helble
Roanne A. Manzano-Roth
Brian M. Matsuyama
Gabriela A. Alongi
NIWC Pacific

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

NIWC Pacific
53560 Hull Street
San Diego, CA 92152–5001

8. PERFORMING ORGANIZATION REPORT NUMBER

TR 3202

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Commander, U.S. Pacific Fleet
250 Makalapa Drive
Pearl Harbor, HI 96860 -3131

10. SPONSOR/MONITOR'S ACRONYM(S)

COMPACFLT

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A: Approved for public release.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report documents Naval Information Warfare Center Pacific (NIWC Pacific) marine mammal monitoring efforts in fiscal year (FY) 2018 for Commander, Pacific Fleet (COMPACFLT) at the Pacific Missile Range Facility (PMRF), Kauai, Hawaii.
1. Raw acoustic data from 62 bottom-mounted hydrophones at PMRF were recorded at the full bandwidth sample rate of 96 kHz and at a decimated sample rate of 6 kHz.
2. Data from February 6, 2002 to August 20, 2018 have been processed to estimate long-term abundances for multiple species of marine mammals; this is the first time systematic results of all data from February 6, 2002 to September 12, 2006 are being presented.
3. The long-term abundance results for baleen whales from February 2002 to August 2018 indicated that at any instant there was a maximum of nine minke whales tracked at the same time (in December 2007 and November 2015), compared to one or two humpback whales.
4. The long-term abundance results for odontocetes (sperm, beaked, and killer whales) from January 2007 to August 2018 are presented. These include Blainville's beaked whales, which had an average of 1.5 dives per hour, and a maximum of 5.2 dives per hour (in June 2015).
5. Data from February 2018 were processed and analyzed for hull mounted MFAS exposures on minke, humpback, and the low-frequency baleen group of whales.
6. Vessel-based tagging and photo-identification were conducted off Kauai, Hawaii February 4 – 12, 2018 with the intent to tag humpback whales with both LIMPET-configured SPLASH satellite tags from Wildlife Computers (Redmond, Washington, United States) and active high-frequency pinger tags developed in-house.
7. Noise analyses were performed to determine the spectral density in the frequency band of baleen species' (i.e. minke, humpback, and the low-frequency baleen group of whales) vocalizations.

15. SUBJECT TERMS

PMRF range data; passive acoustic monitoring; opportunistic surface hydrophone data; M3R packet recorder data; propagation modeling; disturbance analysis; noise analysis

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19B. TELEPHONE NUMBER *(Include area code)*
U	U	U	U	72	E. Elizabeth Henderson (619) 553-5067

This page is intentionally blank.

This page is intentionally blank.

DISTRIBUTION STATEMENT A: Approved for public release.

Naval Information Warfare Center Pacific (NIWC Pacific)
San Diego, CA 92152-5001