Occurrence and Distribution of Gulf of Mexico Bryde's Whale Calls near De Soto Canyon

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Executive Summary

The Gulf of Mexico (GOM) Bryde's whale (*Balaenoptera edeni*), estimated to have a population size of 33 individuals in US (CV 1.07; Hayes et al. 2018), was listed as endangered under the US Endangered Species Act (ESA) in 2019. The majority of modern sightings occur in waters between the 100 – 400 m depths in an area near the De Soto Canyon off northwestern Florida. Occurrence patterns from one year of long-term passive acoustic monitoring in 2010-2011 and two recent summer and fall vessel-based surveys in 2018-2019 indicate the whales are found year-round within this core habitat, but also suggest there may be seasonal movements throughout the core habitat, and potentially beyond it into a broader range than has been fully documented. High densities of anthropogenic activities occur throughout the GOM, including oil and gas exploration and extraction, fisheries, shipping, and military activities, and several of these activities overlap with the whales' core habitat. Understanding inter-annual and seasonal distribution and density will improve understanding of potential impact of human activities in the core habitat and assist in developing effective mitigation measures as needed.

The SEFSC and Scripps Institution of Oceanography have been collaboratively deploying long-term passive acoustic monitoring stations at five GOM sites since 2010 to monitor the impacts of the Deepwater Horizon oil spill and subsequent restoration activities on cetaceans. High-frequency Acoustic Recording Packages (HARPs) deployed at the five sites, including the De Soto Canyon (DC) HARP in the core GOM Bryde's whale habitat, continuously recorded ambient noise and other acoustic events in the 10 Hz to 100 kHz frequency range from 2010 to 2018, and these 8-year near-continuous recordings are available for analysis to better understand long-term distribution and density trends of GOM Bryde's whales. The full analysis of the 8 years of historical data were conducted over the 2018-2020 project period, with the previously reported 2018-19 project period focus on developing automated GOM Bryde's whale call detectors and running and validating the automated detectors on data from the DC HARP in the core habitat collected between October 2010 and July 2014 (Soldevilla et al., 2020). The goals for the current work in 2020 were to complete the historical analyses for August 2014 – June 2018 to establish complete occurrence time-series for understanding seasonal and interannual trends and for future habitat modeling and density estimation, and to start an extended data collection project to improve our understanding of seasonal movement patterns within the GOM Bryde's whale core habitat.

During 2019, the development and characterization of automated detectors of GOM Bryde's whale calls was completed. The final spectrogram cross-correlation detectors for GOM Bryde's whale long-moan calls and downsweep pulse sequences were optimized to minimize miss rates without introducing an excessive number of false detections; false detections are removed in a subsequent validation step. Based on performance on a test dataset, the best long-moan detector had an expected miss rate of 6.5% and false detection rate of 26.4% on the test dataset while the best downsweep pulse sequence detector had an expected miss rate of 12.6% and false detection rate of 69%. Also in 2019, ambient noise analyses were completed on the entire 8-year dataset and evaluated to understand detectability of GOM Bryde's whale calls and potential masking effects. Further, the automated detectors were run on the complete 8-year dataset and the detections were validated for the first deployment. See Soldevilla et al., 2020 for additional details.

During 2020, work focused on validating the automated detections of long-moan calls and downsweep pulse sequences from the remaining nine deployments out to June 2018, and results are being prepared in a manuscript to submit for peer-review. Over the eight years of data collected at the De Soto Canyon site from 2010-2018, a total of 628,552 GOM Bryde's whale long-moan call detections were manually validated, yielding 466,982 true call detections, and a total of 115,729 GOM Bryde's whale downsweep pulse sequence detections were manually validated, yielding 17,449 true call detections. Manual validation results indicate average false detection rates per deployment of the two automated detectors were 29% (range: 13 - 57%) for long-moan detections and 85% (range: 68 - 98%) for downsweep pulse sequence detections; all false detections, repeat call detections, and detections labeled as potentially true calls were removed from further analyses during the manual validation process. True detections of both GOM Bryde's whale long-moan and downsweep pulse sequence call types were detected in all seasons and all years at the De Soto Canyon HARP site.

GOM Bryde's whale long-moan calls were detected on nearly all days of each deployment at the De Soto Canyon HARP site over the eight-year period, with calls present during an average of 95% of days with recordings per deployment (range: 80 - 100% of days), as well as for a substantial portion of the time throughout days with an average of 69% of recording hours containing long-moan calls (range: 34 - 88% of hours) per deployment. This region of the GOM is quieter than other areas in the GOM (Wiggins et al. 2016) and detection distances of these calls may be large; preliminary localization work indicates 20 km is common while instances with detection distances to at least 70 km have occurred. The core habitat is approximately 350 km long by 75 km wide and the HARP site is near the middle of the habitat so a substantial portion of the habitat may be sampled under some oceanographic and ambient noise conditions. In addition to the typical long-moan calls found in the northeastern Gulf, western long-moan variants were detected during some deployments, with western calls present on an average of 7.1% of recording days per deployment (range: 0 - 20% of days), and western calls present during an average of 0.9% of recording hours per deployment (range: 0 - 2.9% of hours). Preliminary analyses suggest interannual and seasonal variability in daily long-moan call detection rates with lower daily long-moan call detection rates in some years (2010, 2012, 2013) compared to other years with higher daily call detection rates (2011, 2018), and lower daily call detection rates in some months (late winter/early spring) with higher rates in other months (fall). Preliminary analyses also indicate increased hourly call detection rates in late afternoon to early evening. Final statistical evaluations of the significance of this variation will be included in the manuscript for peer-review.

GOM Bryde's whale downsweep pulse sequence calls were detected an order of magnitude less frequently than long-moan calls at the De Soto Canyon HARP site over the eight-year period, with calls present during an average of 31% of days with recordings per deployment (range: 14 - 52% of days), and an average of 7.3% of recording hours had downsweep pulse sequence detections present (range: 2.0 - 14.7% of hours) per deployment. Preliminary analyses suggest inter-annual and intra-annual variability in daily downsweep pulse sequence call detection rates with lower daily downsweep pulse sequence call detection rates in some years (2010, 2015) compared to other years with higher daily call detection rates (2011, 2018), and lower daily call detection rates in some months (August and late winter/early spring) with higher rates in other months (July and fall months). Preliminary analyses also indicate increased hourly downsweep pulse sequence call detection rates in late afternoon to early evening. Final statistical evaluations of the significance of this variation will be included in the manuscript for peer-review.

The high percentage of time GOM Bryde's whale calls are present throughout this 8-year period strongly supports the definition of this area as their core habitat, as based on sightings from visual surveys of the northern Gulf primarily conducted during summer and fall months. Seasonal and interannual variation in call detection rates described here may reflect 1) variation in ambient noise conditions or sound propagation conditions that impact detection ranges of the calls, and hence the HARP sampling area, 2) variation in call behavior, and 3) variation in spatio-temporal distribution and density of whales throughout the core habitat related to oceanographic variation. To improve management of human-based activities in the core habitat of these endangered whales, further research is needed to understand and predict seasonal and interannual movement patterns and the factors driving this variation.

A final goal for work during 2020 was to begin a new project to better understand the observed intra-annual variability in GOM Bryde's whale call occurrence with respect to the entire core habitat, by expanding passive acoustic monitoring to an additional 17 sites that should completely cover the core habitat. The study aims to provide further information to interpret the changes seen at the De Soto Canyon HARP site over 8 years and to understand how call density varies seasonally throughout the core habitat. The project will deploy 17 SoundTrap ST500 STD units concurrent with the long-term DC HARP in two lines of 9 PAM units each (inclusive of the HARP) to nearly completely cover the core habitat, for two six-month deployments. All equipment for the PAM moorings has been purchased and is ready to deploy. However, vessel schedule cancellations, high vessel demand, and travel restrictions and limitations due to the COVID-19 pandemic have delayed the deployment of these moorings over the last year with the project currently delayed by one year due to these challenges. Vessel time is scheduled on NOAA's *R/V Gordon Gunter* to deploy the SoundTrap moorings on May 1, 2021, for subsequent retrieval and redeployment in October 2021, and final recovery in May 2022. Data analyses of the recordings from the 17 SoundTraps as well as the concurrently deployed DC HARP data are planned upon retrieval of the first deployment, anticipated for November 2021.

Project Background

The SEFSC and Scripps Institution of Oceanography have been collaboratively deploying long-term passive acoustic monitoring stations at five Gulf of Mexico (GOM) sites since 2010 to monitor the impacts of the Deepwater Horizon oil spill and subsequent restoration activities on cetaceans (**Figure 1**). High-frequency Acoustic Recording Packages (HARPs), deployed at the five sites, including the De Soto Canyon (DC) HARP in the GOM Bryde's whale core habitat, have been continuously monitoring ambient noise and other acoustic events in the 10 Hz to 100 kHz frequency range, and 8 years of near-continuous recordings (2010-2018) are available for analysis to better understand distribution and density trends of cetaceans, potentially including GOM Bryde's whales. Data from the DC HARP site had previously only been evaluated for downsweep call sequences in the first year of data (Širović et al. 2014), and had not been evaluated for probable long-moan calls or constant tonal calls (Rice et al. 2014), which have also recently been recorded by SEFSC in the presence of GOM Bryde's whales. Over late 2018 through 2020, this project focused on developing automated GOM Bryde's whale call detectors and analyzing the full 8 years of data from the DC HARP in the core habitat (**Table 1**), to establish complete occurrence time-series for understanding seasonal and interannual trends and for future habitat modeling and density estimation. The 2018-19 goals were to develop the detectors and run and validate them on the first 38 months of data collected between October 2010 and July 2014. The 2020 goals were to complete the validation of the detector results on the remaining data and to begin a new data collection project that builds upon these results to better understand temporal variability in occurrence.

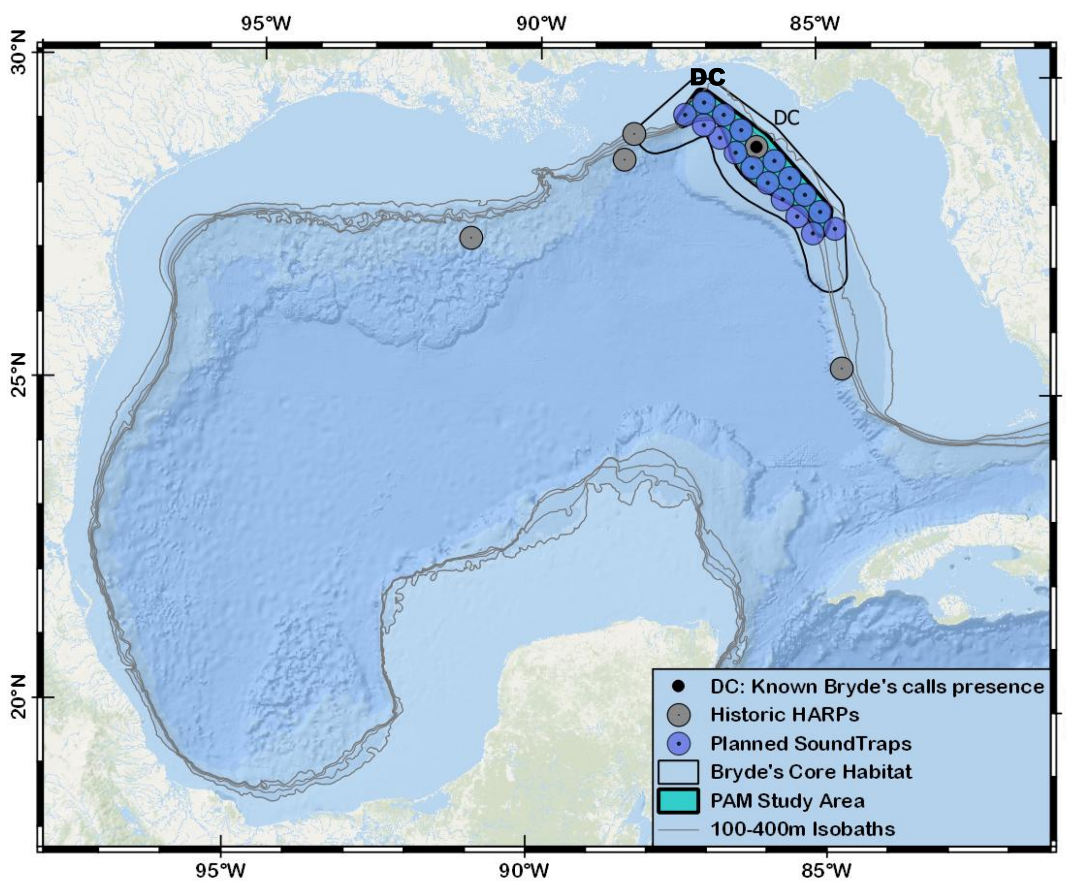


***Figure 1**. Historic long-term passive acoustic monitoring stations (HARPs) deployed in the Gulf of Mexico since 2010 and planned 2021 passive acoustic monitoring stations (SoundTraps). The NMFS core habitat of Gulf of Mexico Bryde's whales is indicated, including the De Soto Canyon (DC) site, where Gulf of Mexico Bryde's whale calls have previously been detected.*

Table 1. *Acoustic monitoring at site DC since October 2010. Asterisks indicate small gaps in the recording exist for these data sets. A four-day gap occurred in the DC04 dataset and two gaps, of 10 and 19.5 day durations, occurred in the DC06 dataset.*

Deployment	Start Date	End Date	Recording Duration (Days)	Recording Duration (Hours)
DC02	10/21/2010 0:00:00	2/6/2011 10:12:30	108.4	2602.2
DC03	3/21/2011 19:00:00	7/6/2011 2:01:14	106.3	2551.0
DC04	10/25/2011 23:59:59*	3/1/2012 17:19:59	123.6	2967.5
DC05	3/3/2012 12:00:00	12/9/2012 8:32:59	280.9	6740.5
DC06	12/9/2012 20:00:00*	9/25/2013 5:31:49	259.2	6219.9
DC07	12/18/2013 0:00:00	7/23/2014 5:31:59	217.2	5213.5
DC08	10/3/2014 0:00:00	5/25/2015 23:04:30	233.2	5597.4
DC09	8/3/2015 22:00:00	5/19/2016 4:18:44	289.3	6942.3
DC10	8/25/2016 18:00:00	7/16/2017 10:48:45	304.4	7306.1
DC11	7/17/2017 0:00:00	6/9/2018 0:43:00	303.5	7283.0

Gulf of Mexico Bryde's Whales

The GOM Bryde's whale (*Balaenoptera edeni*), estimated to have a population size of 33 individuals in US waters (CV 1.07; Hayes et al. 2018), was recently listed as endangered under the US Endangered Species Act (ESA). The majority of modern sightings occur in waters between the 100 – 400 m water depths in an area near the De Soto Canyon off northwestern Florida (Soldevilla et al. 2017). Occurrence patterns from one year of long-term passive acoustic monitoring in 2010-2011 and two recent summer and fall surveys in 2018-2019 indicate the whales are found year-round within this core habitat, but also suggest there may be seasonal movements throughout this core habitat, and potentially beyond it into a broader range than is currently documented. High densities of anthropogenic activities occur throughout the GOM, including oil and gas exploration and extraction, fisheries, shipping, and military activities and several of these activities overlap with the whales' core habitat. Understanding seasonal distribution and density will improve understanding of potential impact of human activities in the core habitat and assist in developing effective mitigation measures as needed.

In the GOM, one call type has been definitively identified to free-ranging GOM Bryde's whales (Širović et al. 2014), and four additional call types have been proposed as likely candidates (**Figure 2**; Rice et al. 2014, Širović et al. 2014).

Gulf of Mexico Bryde's Whale Downsweep Pulse Calls

The positively identified call type is a pair of short-duration downsweeps ranging from 110 ± 4 to 78 ± 7 Hz, with a mean duration of 0.4 ± 0.1 s, an inter-pulse interval of 1.3 ± 0.1 s, and source levels of 155 ± 14 dB re: 1 µPa at 1 m (Širović et al. 2014). Longer series of downsweeps (mean: 8 downsweeps, range: 2-25) with similar spectral and temporal features were detected in autonomous recordings and are presumed to be variants of the same call type (Rice et al. 2014, Širović et al. 2014). A third downsweep call type, higher in frequency (170 to 110 Hz), segmented, and typically occurring in repeated sequences of doublets, was also detected in autonomous recordings over a 5 day period and is proposed to be a possible Bryde's whale call (Širović et al. 2014).

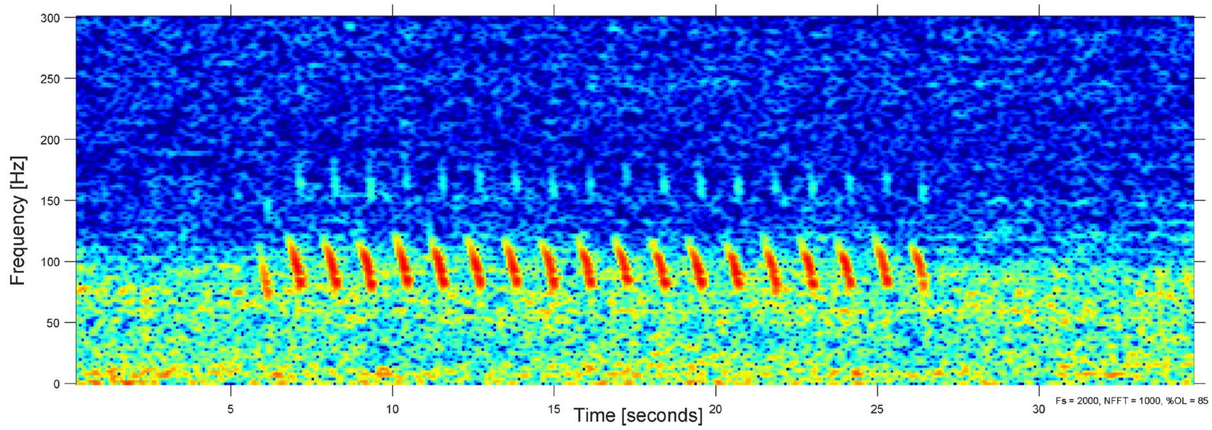


Figure 2. *Spectrogram of a Gulf of Mexico Bryde's whale downsweep pulse sequence at site DC.*

Gulf of Mexico Bryde's Whale Long Moan Calls

Two tonal call types detected on autonomous instruments are proposed as Bryde's whale calls based on baleanopterid-like features, movement patterns of tracked calls, and the known distribution of Bryde's whales. The long-moan call type is a long-duration, pulsed downsweep ranging from 208 to 43 Hz with a mean center frequency of 107 Hz, mean 22.2 s duration, and 3.4 pulse/s amplitude pulse rate (Rice et al. 2014). The tonal-sequence consists of 1-6 narrow-band constant-frequency tones in sequence following some long-moans, with individual tonals having a mean center frequency of 103 Hz and mean 3.6 s duration (Rice et al. 2014). GOM Bryde's whales have been preliminarily validated as the source of both the downsweep sequences and long-moans using paired directional sonobuoy call localizations that match whale sighting locations (Soldevilla, unpublished data). LTSA analyses and detector development will focus on downsweep sequences and long-moans but have the flexibility to discover additional calls in the Bryde's whale repertoire.

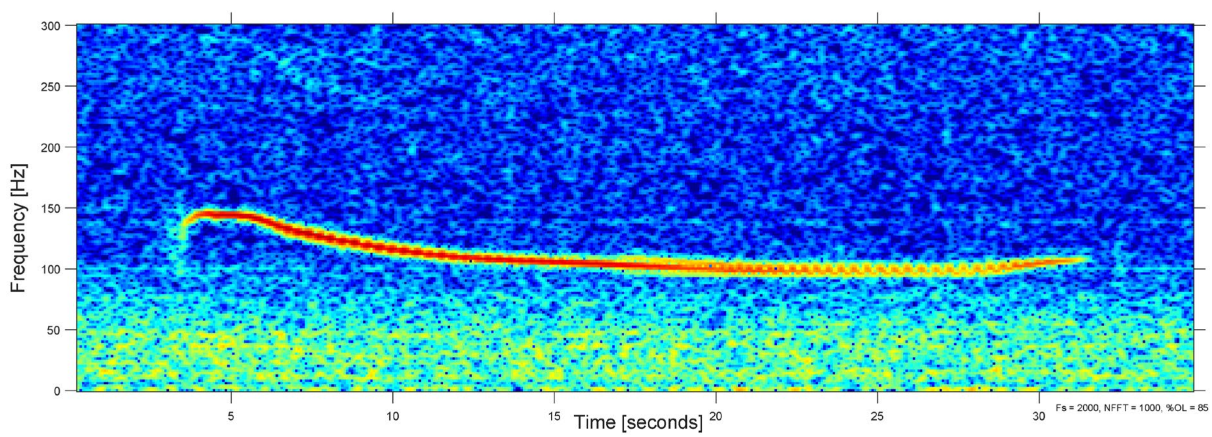


Figure 3. *Spectrogram of a Gulf of Mexico Bryde's whale long moan call detected on the De Soto Canyon HARP.*

Methods

High-frequency Acoustic Recording Package (HARP)

HARPs were used to record marine mammal sounds and characterize the low-frequency ambient soundscape in the GOM from 2010 through 2018. HARPs can autonomously record underwater sounds from 10 Hz up to 160 kHz and are capable of approximately 300 days of continuous data storage. The HARPs were deployed in either a seafloor mooring or a seafloor package configuration with the hydrophones suspended 10 m above the seafloor (**Figure 4**). Each HARP is calibrated in the laboratory to provide a quantitative analysis of the received sound field. Representative data loggers and hydrophones were also calibrated at the Navy's TRANSDEC facility to verify the laboratory calibrations (Wiggins & Hildebrand 2007).

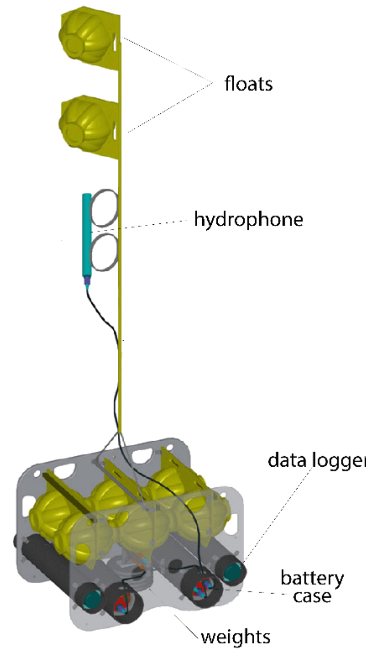


Figure 4. Schematic of a HARP seafloor package

Data Collected

No new data were collected as part of this historical data analysis project. Acoustic recordings have been collaboratively collected since 2010 by SEFSC and Scrips Institution of Oceanography at the De Soto Canyon site (29º 2.878' N 86 º 05.847' W, 270 m depth) using HARPs sampling at 200 Hz. The De Soto Canyon site is located approximately in the center of the GOM Bryde's whale core distribution area (**Figure 1**). This project includes the first half of ambient noise and whale call detection analyses for deployments DC02 to DC11 (**Table 1**) which include 2,226 days (53,424 hours) of data between 2010-2018.

Data Analysis

Recording over a broad frequency range of 10 Hz to 100 kHz allows detection of the low-frequency ambient soundscape, baleen whales (mysticetes), toothed whales (odontocetes), and anthropogenic sounds. Because analyses were focused on the GOM Bryde's whale and ambient noise, only the low-frequency data were required for these analyses. The HARP recordings were decimated by a factor of 100 to provide an effective bandwidth of 10 Hz to 1 kHz. LTSAs were created from the decimated data with a 1 Hz frequency and 5 s temporal resolution.

Low Frequency Ambient Soundscape

All recordings were converted to sound pressure levels calibration values obtained from full-system calibrations conducted at the U.S. Navy's Transducer Evaluation Center in San Diego, CA. Hourly spectral averages and associated standard deviations were computed by combining ten 5 s (50 s) sound pressure spectrum levels calculated from each 75 s acoustic record. System self-noise was excluded from these averages. Time series of the daily mean and standard deviation of the noise level at 125 Hz were developed from these data. They were also combined to obtain monthly spectral averages to evaluate longer term changes in the ambient soundscape and its potential impacts on baleen whale call detectability.

Gulf of Mexico Bryde's Whale Calls

Automated Call Detectors

During prior work conducted in 2018-2019, spectrogram cross-correlation detectors for long-moan calls and downsweep pulse sequences were developed in Ishmael (Mellinger & Clark 2000) using a 2-day training dataset and a separate testing dataset to characterize miss rates and false detection rates. Each detector was then run on spectrograms of recordings from all 10 DC HARP deployments, with spectrograms calculated using an FFT frame size of 512 samples, no zero-padding, and 50% overlap. Spectrogram equalization was enabled with 3 s spectral averaging.

Long Moan Detector Settings

Long moan call contours contain five sections which include the preliminary upsweep, the approximately 150 Hz tone, the first part of the downsweep (slope 1), the second part of the downsweep (slope 2), and the long nearly constant frequency tail (**Figure 5**). The cross-correlation contour kernel for the long-moan call focused on the 150 Hz tone and slope 1, the most consistent parts of the frequency-modulated tonal call. The kernel contour is defined by a 1.1 s tone from 146 Hz to 145 Hz followed by a 3.7 s downsweep from 145 Hz to 112 Hz, each with a 14 Hz contour bandwidth. Detection function smoothing was enabled. The detection threshold was set to 4.5, and minimum and maximum detection durations were 0.5 s and 3.0 s, respectively. The minimum time allowed between subsequent detection events was 0.5 s. The threshold of 4.5, yielding a 6.4% missed call rate and a 26.4% false detection rate on a test dataset, was selected to minimize miss rates without excessive false detection rates. Missed detections were typically associated with calls with low signal to noise ratios. The majority of false alarms were associated with disk write noise from the recording instrument as well as tonal sounds from passing ships.

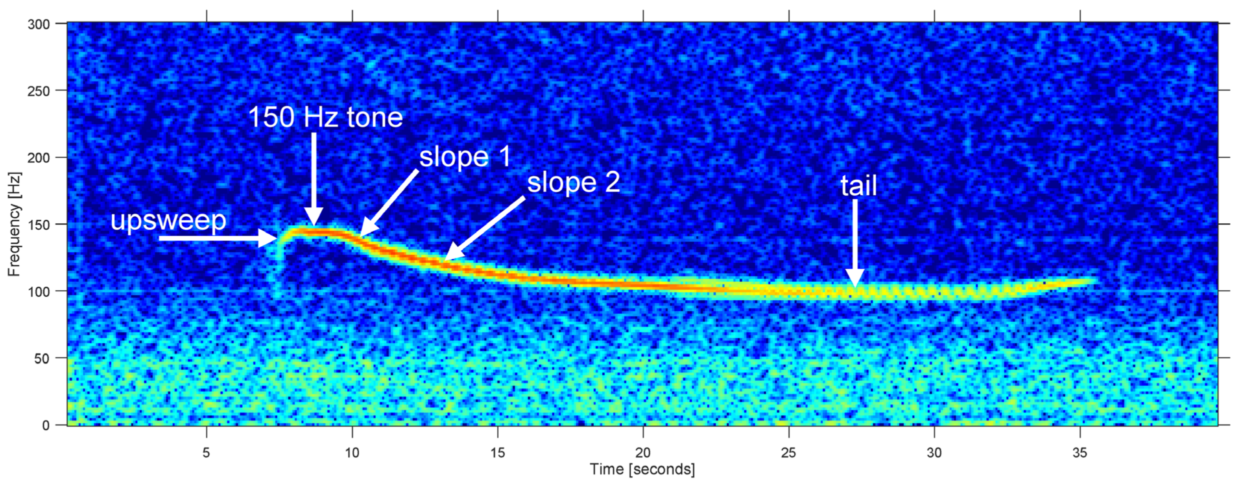


Figure 5*. Five sections of a long moan call. Two sections, the 150 Hz tone and slope 1 were used to create the contours in the long moan detector.*

Downsweep Pulse Sequence Detector Settings

The *Ishmael* downsweep pulse sequence detector used the regular sequence feature to detect sequences of individual downsweep pulses as a single call. The cross-correlation contour kernel was defined as a single 4 s downsweep from 120 Hz to 80 Hz, with a 20 Hz contour bandwidth. For regular sequences, the minimum and maximum repetition period between individual pulse detections were set to 0.9 s and 1.1 s, respectively, and an 11 s window with 75% overlap was used. The detection threshold was set to 11, and minimum and maximum detection durations were set to 0.1 s and 40 s, respectively. The minimum time allowed between detection events was 0.4 s. The threshold of 11, yielding a 12.6% missed sequences rate and a 69.1% false detection rate on a test dataset, was selected to minimize miss rates without excessive false detection rates. Missed detections were typically associated with calls with low signal to noise ratios. The majority of false alarms were associated with long-moan calls with strongly pulsed tails and seismic survey airgun pulses with unusually short inter-pulse intervals or strong multipath effects.

Automated call detections

Each detector was run on the entire DC HARP dataset for deployments DC02 – DC11. Rather than selecting a threshold with equal miss and false alarm rates, the threshold selections were skewed toward reducing missed detections as much as possible while balancing the need to keep false detections within a reasonable number. Therefore, these preliminary detections require a follow-up step to manually validate the detections and remove all false detections for a final dataset. This step of removing false detections is feasible, while reviewing the entire dataset for missed detections is not; final results will underestimate total call detections. In the validation step, each automated detection is manually reviewed and scored as a true or false detection, and false positive rates are calculated as the percentage of false positives to total detections. All detections were manually validated for all DC HARP deployments.

Results

The results of acoustic data analysis at the GOM DC HARP site from October 2010 to June 2018 are summarized below, including all results from 2018-2020 analyses. We describe the low-frequency ambient soundscape, the seasonal occurrence, and the relative abundance of GOM Bryde's whale signals. Final statistical analyses of these results are in progress and a manuscript reporting the results is being drafted for submission for peer-review in summer 2021.

Low Frequency Ambient Soundscape

• The underwater ambient soundscape at all sites had spectral shapes with higher levels at low frequencies compared to higher frequencies, owing to the dominance of ship noise and seismic airgun surveys at frequencies below 100 Hz and local wind and waves above 100 Hz (Hildebrand 2009); **Figure 6 & Figure 7**).

• The years 2016 and 2017 had the lowest spectrum levels below 100 Hz while Dec 2013-June 2014 and March, May and June 2018 also had lower levels (**Figure 6**).

• There appears to be a seasonal pattern in overall noise levels with lower noise levels in spring and summer compared to fall and winter, and this is typically apparent above 100 Hz (**Figure 6 & Figure 7**). This is likely due to the increased noise from wind and waves of winter storms.

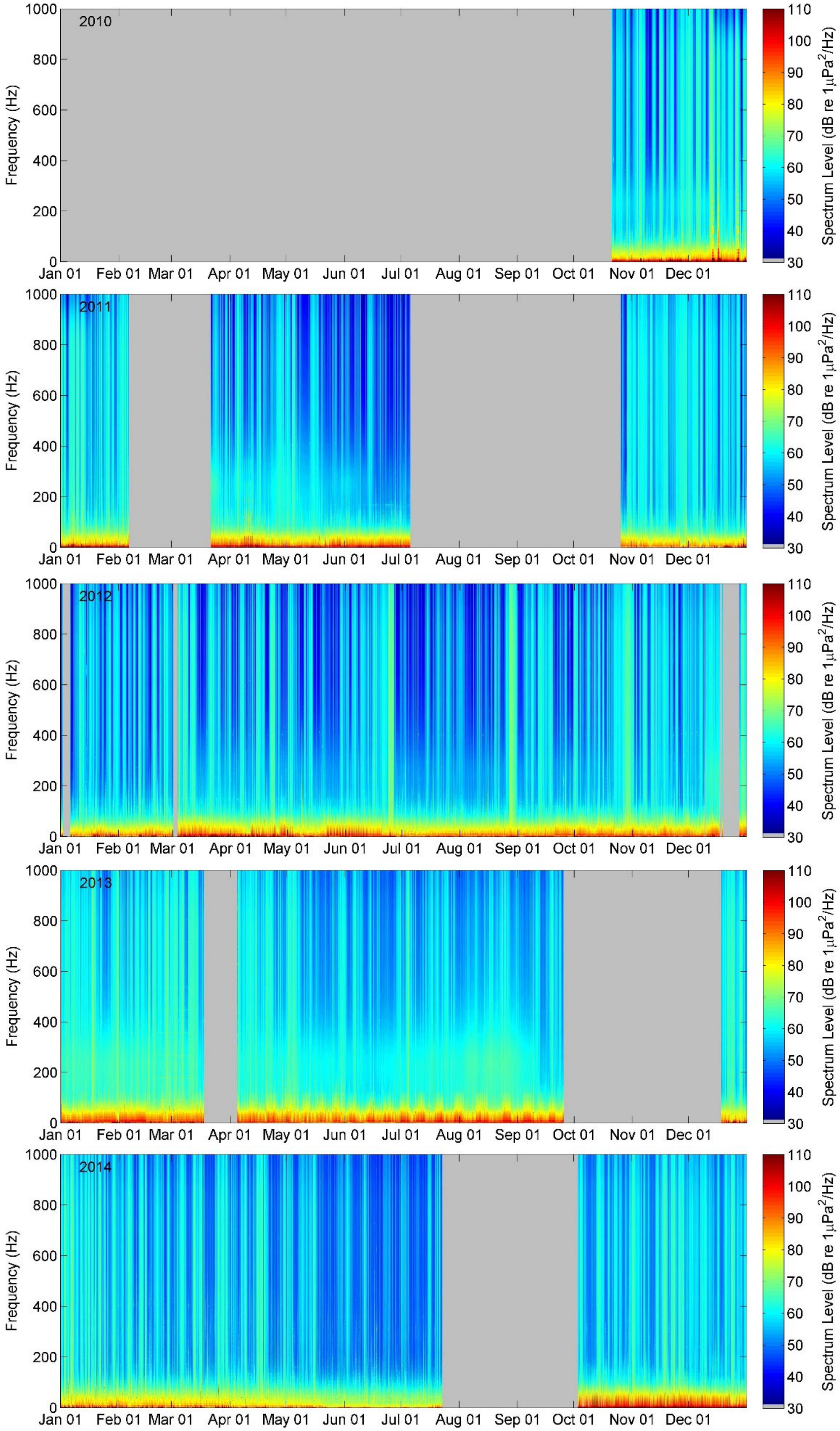
• Strong and brief peaks in broadband noise are evident at three times in summer and fall of 2012 (**Figure 6**) which coincide with the timing of Tropical Storm Debbie and Hurricane Isaac in the GOM, and unexpectedly with Hurricane Sandy which remained in the Atlantic. Similarly, Hurricanes Cindy and Irma are evident in June and September 2017, as is Hurricane Alberto in May 2018 (**Figure 6**).

• Noise levels across all frequencies were highest in Fall 2014 and 2015 (**Figure 6 & Figure 7**). Further investigation reveals that seismic surveys were prevalent in the recordings during these months.

• Noise levels across all frequencies were lowest in June 2017 (**Figure 6 & Figure 7**). No seismic surveys were operating in the GOM in June 2017. This may partially explain this reduction in noise levels, but it is surprising that the difference is greater at frequencies above 100 Hz than at the lower frequencies where seismic survey noise is typically dominant.

• Noise levels in the 100-200 Hz frequency band where GOM Bryde's whale calls occur were lowest in summers of 2014,2017, and 2018 and highest in fall 2010 and all of 2013 (**Figure 6 & Figure 7**).

• Spectral peaks around 100-300 Hz occur during spring 2011 and spring and summer 2013 (**Figure 6 & Figure 7**). We are evaluating if this has a biologic or self-noise source as it is present to varying degrees throughout the DC06 deployment.



2010
2011
2012
2013
2014
Frequency (Hz)
0
200
400
600
800
1000
Jan 01
Feb 01
Mar 01
Apr 01
May 01
Jun 01
Jul 01
Aug 01
Sep 01
Oct 01
Nov 01
Dec 01
Spectrum Level (dB re 1μPa²/Hz)
30
40
50
60
70
80
90
100
110

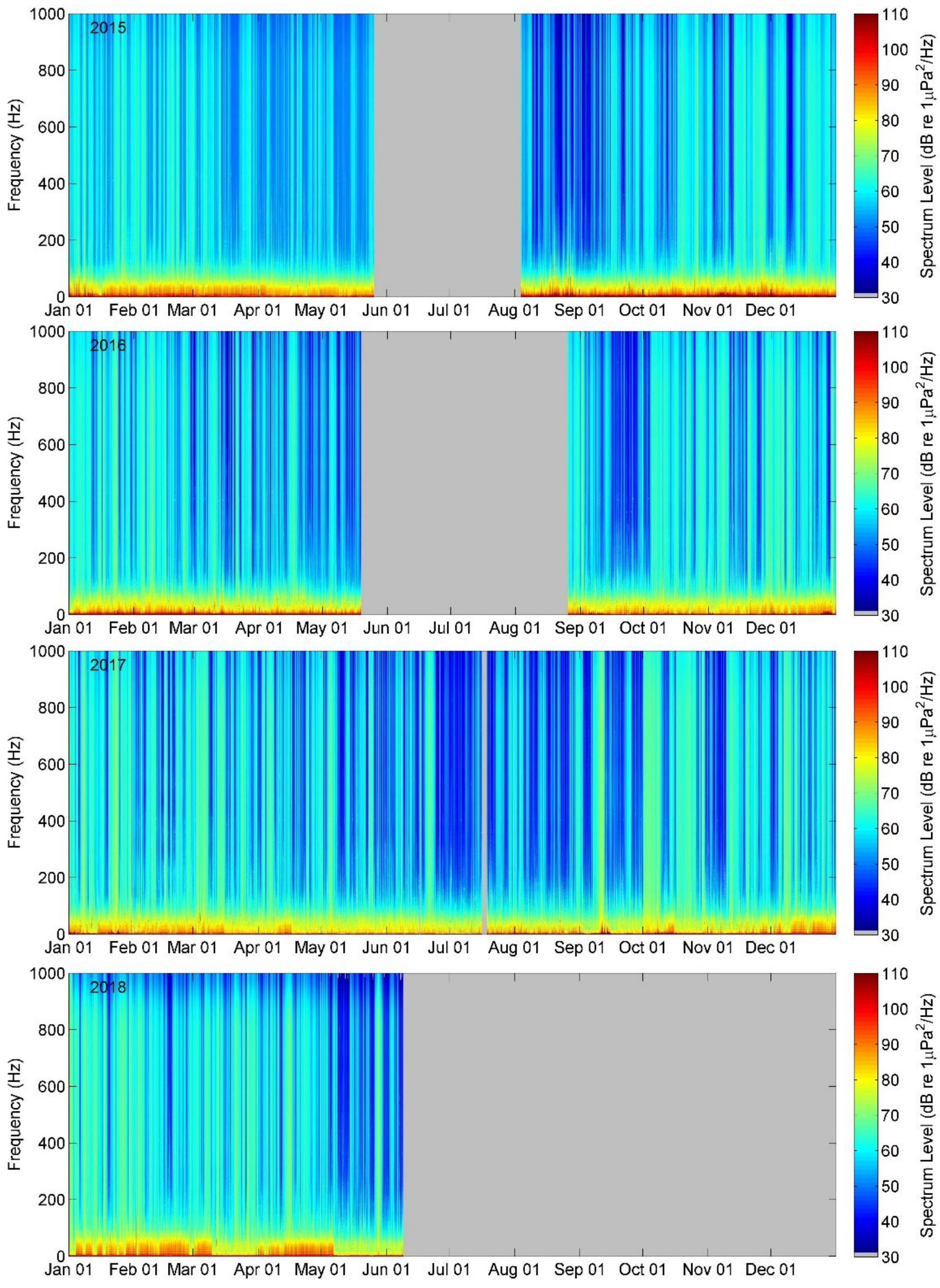


***Figure 6**. Hourly median long-term spectral average of 2010-2018 HARP deployments at the De Soto Canyon site showing recorded ambient noise levels from 10-1000 Hz. Gray indicates periods with no recording effort or corrupt data.*

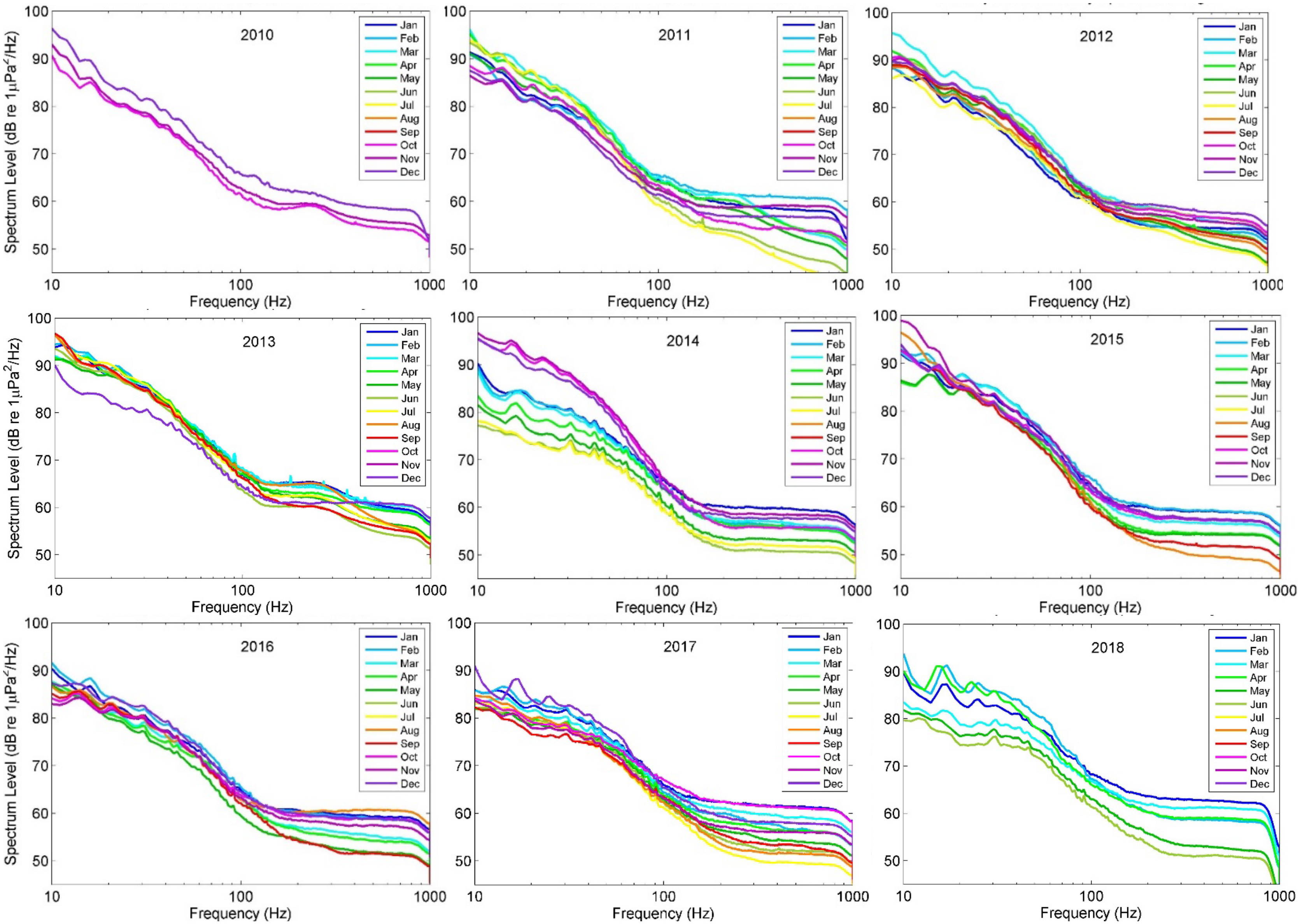


Figure 7*. Monthly means of hourly spectral averages for 2010-2018.*

Gulf of Mexico Bryde's Whale Long Moan Calls

There were a total of 628,552 automated call detections of GOM Bryde's whale long moan calls over the eight years of recordings at the De Soto Canyon HARP site, ranging between 24,041 and 127,756 detections per deployment, of which a total of 466,982 were validated as true long moan calls, with a range of 14,684 to 102,306 per deployment (**Table 4**). False detection rates per deployment averaged 28.5% and ranged between 13.2 and 56.5%. False detections of disk write noise were common in the DC03, DC05, and DC06 deployments which had the highest false detection rates. Results indicate true long moan calls were present during an average of 95% of days (range 80-100% of days) and during an average of 69% of hours (range 34-88% of hours) with recording effort per deployment (**Table 4**). GOM Bryde's whale long moan calls were detected in all seasons and all years at the De Soto Canyon HARP site, and there is potential evidence of seasonality in quantity of call detections with higher detections in fall and lower detections in late winter to early spring. (Note: Deployments DC06, DC10, and DC11 were impacted by periodic disk write errors which led to a slow drift in incorrect start-times (up to 7 hours) of automated call detections over each 4.5 day wavefile. Methods to correct the start-times are being developed, and once corrected, presence and call rates will be recalculated. The high percentage of time whale calls are present throughout this 8-year period strongly supports the definition of this area as their core habitat, as based on sightings from visual vessel-based surveys of the northern Gulf primarily conducted during summer and fall months. Detection ranges of the calls, and hence the HARP sampling area, remains unknown and likely vary over time depending on oceanographic sound propagation conditions and ambient noise levels. Limited preliminary data from directional sonobuoy deployments in the area suggests approximately 20 km ranges and possibly more than 70 km in some conditions. The core habitat is approximately 340 km long by 75 km wide. This suggests approximately 20-25% of the habitat may be acoustically sampled in some conditions, but it is unknown what is typical.

- Validation of auto-detections yielded false detection rates averaging 28.5% and ranging between 13.2% and 56.5% for the long-moan call detector for the DC02-DC11 deployments.
- A two week period in early November 2010 had very few long-moan detections (**Figure 8)**. A similar lack of downsweep sequence call detections was noted by (Širović et al. 2014), potentially indicating animals moved away from this site at this time. Noise conditions were typical during this period; variability in sound propagation conditions also could lead to reduced calls.
- True long-moan calls were generally present in high numbers throughout the year across all deployments; however, there were several notable extended periods in winter and early spring of some years with few call detections that appear to be seasonal: 1) March to early June 2012; 2) December 2012 through May 2013; and 3) March to June 2017 (**Figure 8** through **Figure 17)**. Periods in winter and spring 2014 and spring 2016 also had fewer periods with calls present than during the summer and fall throughout. Note: Noise levels increase in Dec 2012 through May 2013 with corresponding low numbers of long-moan detections; masking may be the cause of reduced detections in this period.
- Further, throughout the eight years there were numerous periods of approximately 1-2 weeks each with few detections (**Figure 8** through **Figure 16**). These include: a) early November 2010; b) end of June 2011; c) end of June (2012); d) end of October (2012); e) early Jan 2014; f) early April 2014; g) Late Nov 2014; h) mid-March 2015; i) early April 2015; j) late August 2015; k) mid-April 2016; and l) mid-October 2016. Several of these periods correspond to periods with high-noise from weather (**Figure 6**, **Figure 17**), including hurricanes, indicating masking may be a concern at these times.
- Additionally, there are several periods throughout the 8 years in which false detections are relatively high, including the following periods: a) first 2 weeks of Nov 2010; b) June – July 2011; c) March –

July 2012; d) late January to February 2012, e) January to June 2013; f) October to December 2014; g) December 2017; and h) February to March 2018 (**Figure 8** through **Figure 17**). The majority of these detections are diskwrite noise; the winter 2018 period detected seismic airgun signals.

- There appears to be a crepuscular late afternoon/pre-dusk peak in long-moan call presence across multiple years. In some years, there is a similar peak at dawn (e.g. first half of 2014; **Figure 8** through **Figure 16**).
- In addition to the typical long-moan calls found in the northeastern Gulf, western long-moan variants were detected during some deployments (**Table 4**), with western calls present on an average of 7.1% of recording days per deployment (range: 0 - 20% of days), and western calls present during an average of 0.9% of recording hours per deployment (range: 0 - 2.9% of hours).
- Potential interannual variation in daily call detection rates was evident. The median long-moan call detections per day were lowest in 2013, followed by 2010 and 2012, while they were highest in 2011 and 2018 (**Figure 18**). Noise levels in the GOM Bryde's whale call frequency band were high in 2013 and 2018 (**Figure 18**); noise levels may have affected the ability to detect calls in 2013 through masking effects, though there doesn't appear to be a similar impact in 2018. Analyses are underway to determine if the variation in detections and the variation in noise is significant.
- Potential seasonal variation in daily call detection rates was evident. Results indicate higher long-moan call detections per day in fall and early winter with moderate rates during summer and lower daily call detection rates in late winter and early spring (**Figure 18**). The increase in call detection rates during summer may be related to lower levels of ambient noise at call frequencies during summer, while the reverse may explain lower call rates in winter (**Figure 18**). Analyses are underway to determine if the variation in call rates among seasons is significant.
- Potential diel variation in hourly call detection rates was evident. Results indicate a slight diel pattern with an increase in hourly call detection rates from 22:00 to 3:00 GMT (17:00 to 22:00 CT) with a slight increase extending until 10:00 (5:00 CT) (**Figure 18**). Analyses are underway to determine if the variation in detections and the variation in noise is significant.

Table 2. *Number of long moan calls detected and true long moan calls validated per deployment at the DC site. A subset of true long moan call detections were the long moan variants found at sites in the western Gulf.*

Deployment	**Long Moan Call Detections**	**True Long Moan Calls**	**Western Long Moan Calls**	**Days Present (%)**	**Hours Present (%)**
	Automated	*Validated*			
DC02	28,002	22,239	35	104 (95)	1,881 (72.3)
DC03	36,215	19,149	0	105 (97)	1,888 (74.0)
DC04	58,063	44,046	53	125 (99)	2,613 (87.7)
DC05	47,542	20,667	0	264 (94)	3,099 (46.0)
DC06	24,041	14,684	0	216 (80)	2,151 (33.9)
DC07	48,109	39,088	220	208 (95)	3,490 (67.0)
DC08	101,071	68,477	347	228 (97)	4,507 (79.9)
DC09	72,709	63,137	80	286 (98)	5,510 (79.4)
DC10	85,044	73,189	150	325 (99)	5,533 (70.5)
DC11	127,756	102,306	187	327 (100)	6,493 (82.7)

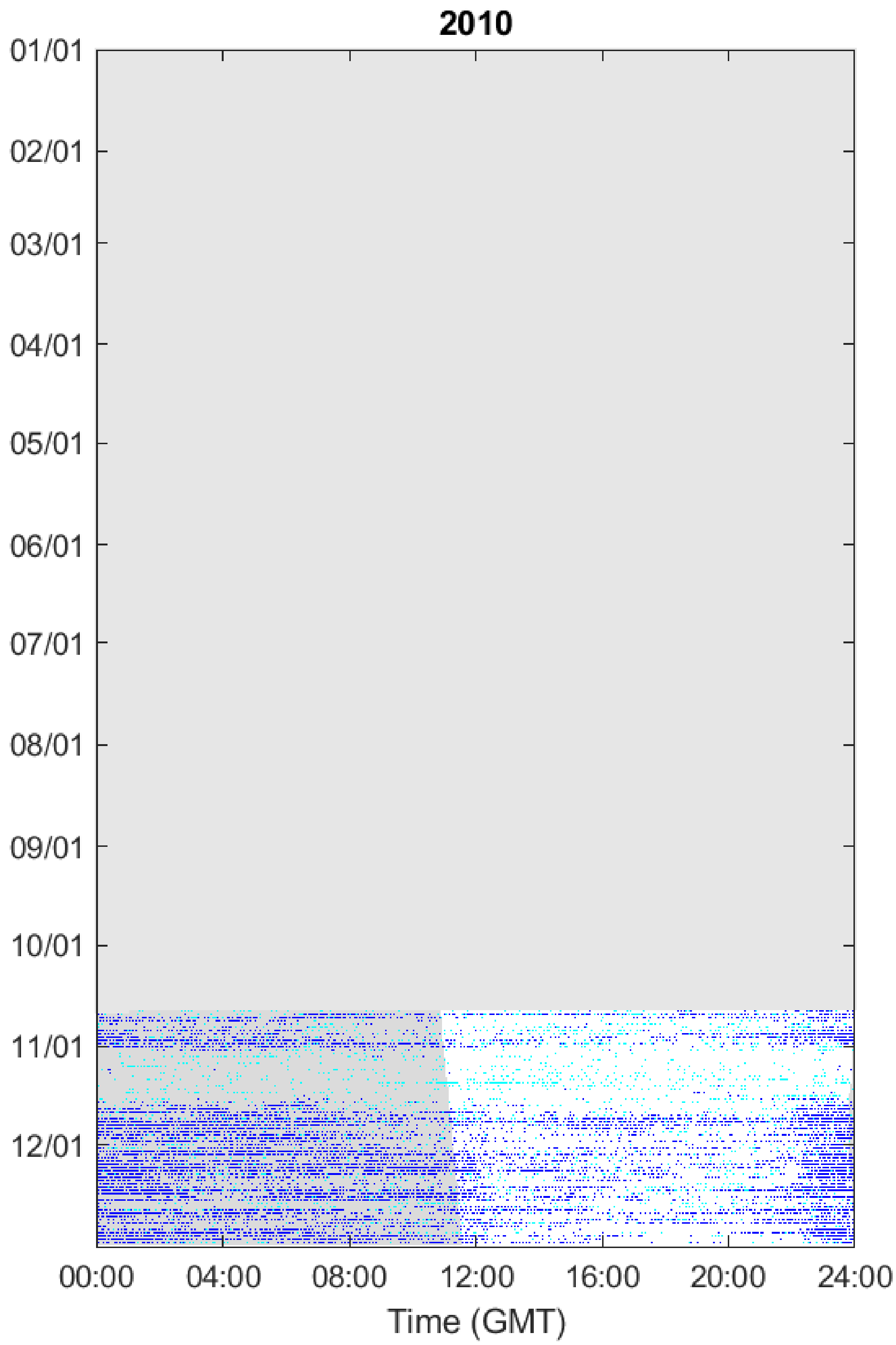


Figure 8. *Gulf of Mexico Bryde's whale long moan calls in 1-minute bins in 2010 at the DC site. Cyan marks represent verified false detections while blue marks represent true long moan detections. Night time is indicated by gray shading. The grayed blocked area represents time periods without recording effort.*

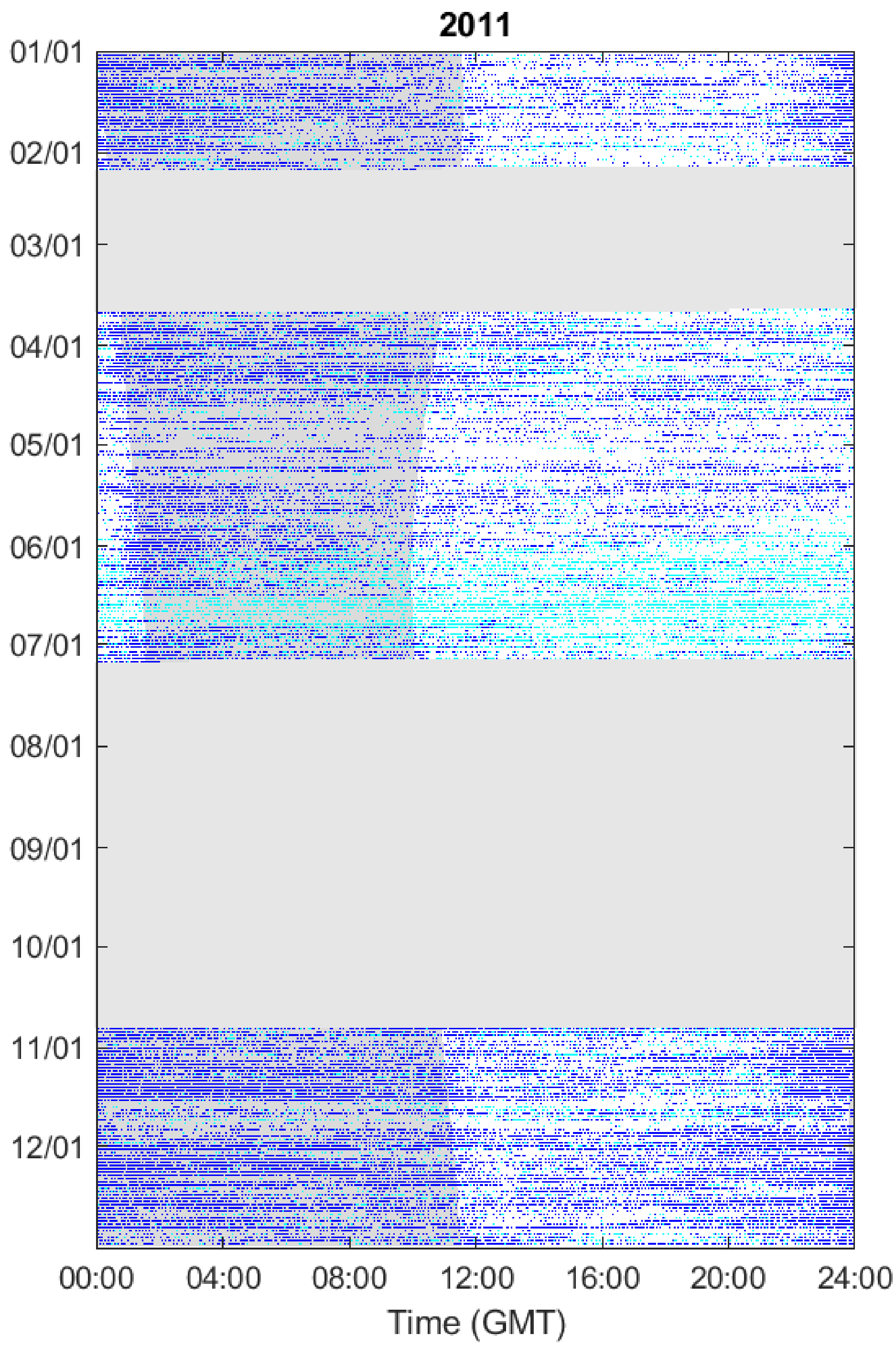


***Figure 9**. Gulf of Mexico Bryde's whale long moan calls in 1-minute bins in 2011 at the DC site. Cyan marks represent verified false detections while blue marks represent true long moan detections. Night time is indicated by gray shading. The grayed blocked area represents time periods without recording effort.*

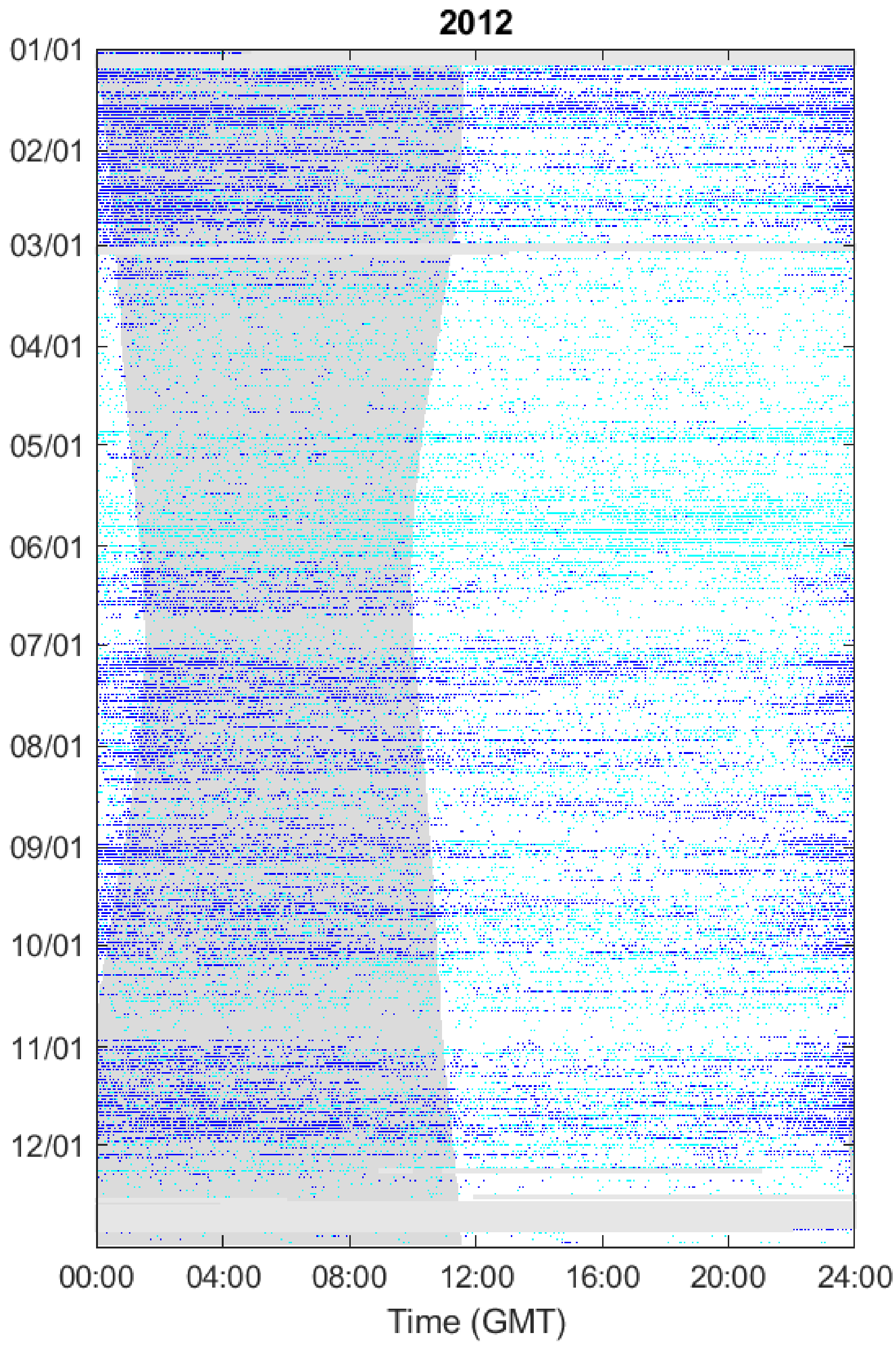


Figure 10. *Gulf of Mexico Bryde's whale long moan calls in 1-minute bins in 2012 at the DC site. Cyan marks represent verified false detections while blue marks represent true long moan detections. Night time is indicated by gray shading. The grayed blocked area represents time periods without recording effort.*

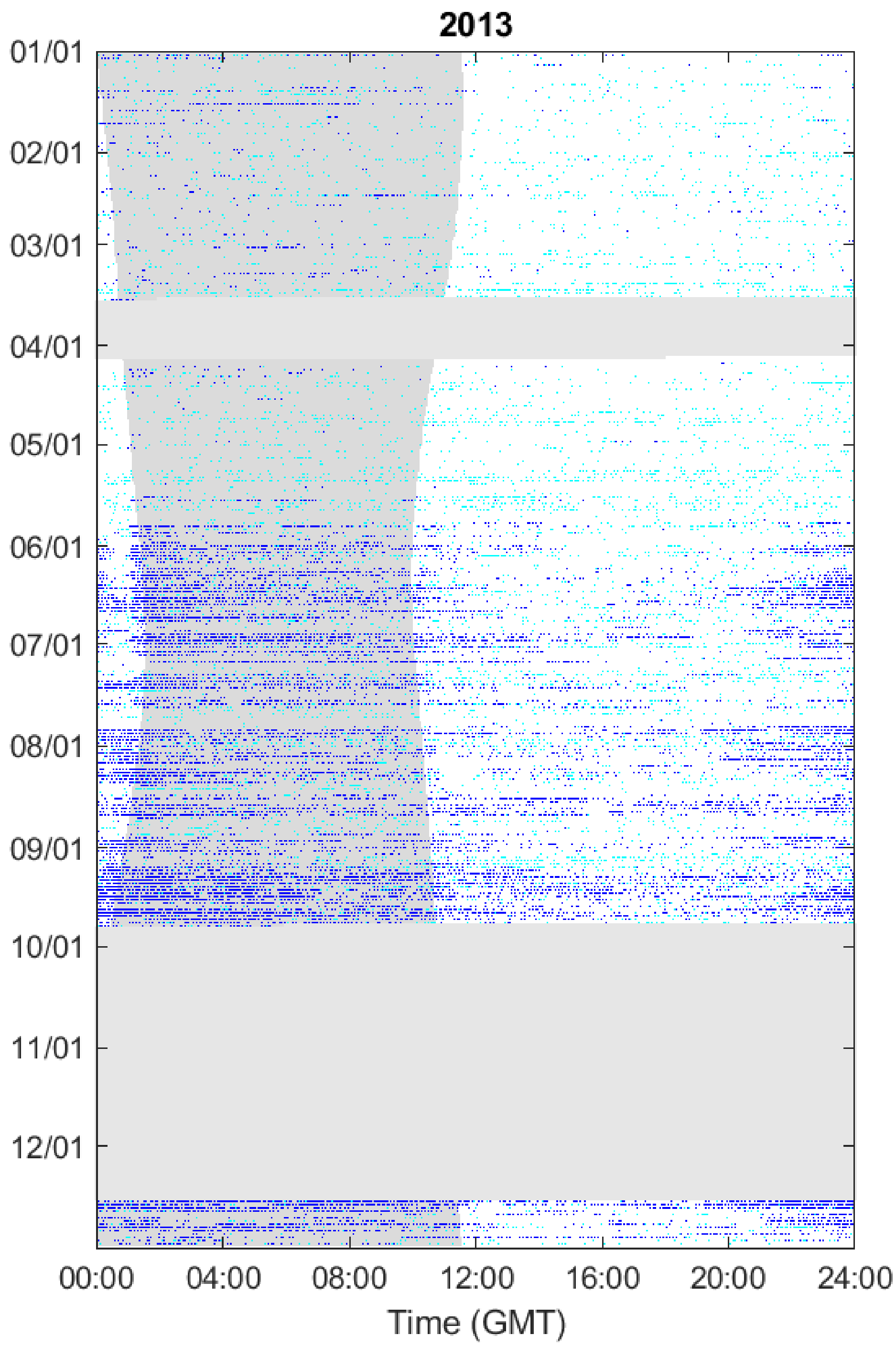


Figure 11. *Gulf of Mexico Bryde's whale long moan calls in 1-minute bins in 2013 at the DC site. Cyan marks represent verified false detections while blue marks represent true long moan detections. Night time is indicated by gray shading. The grayed blocked area represents time periods without recording effort.*

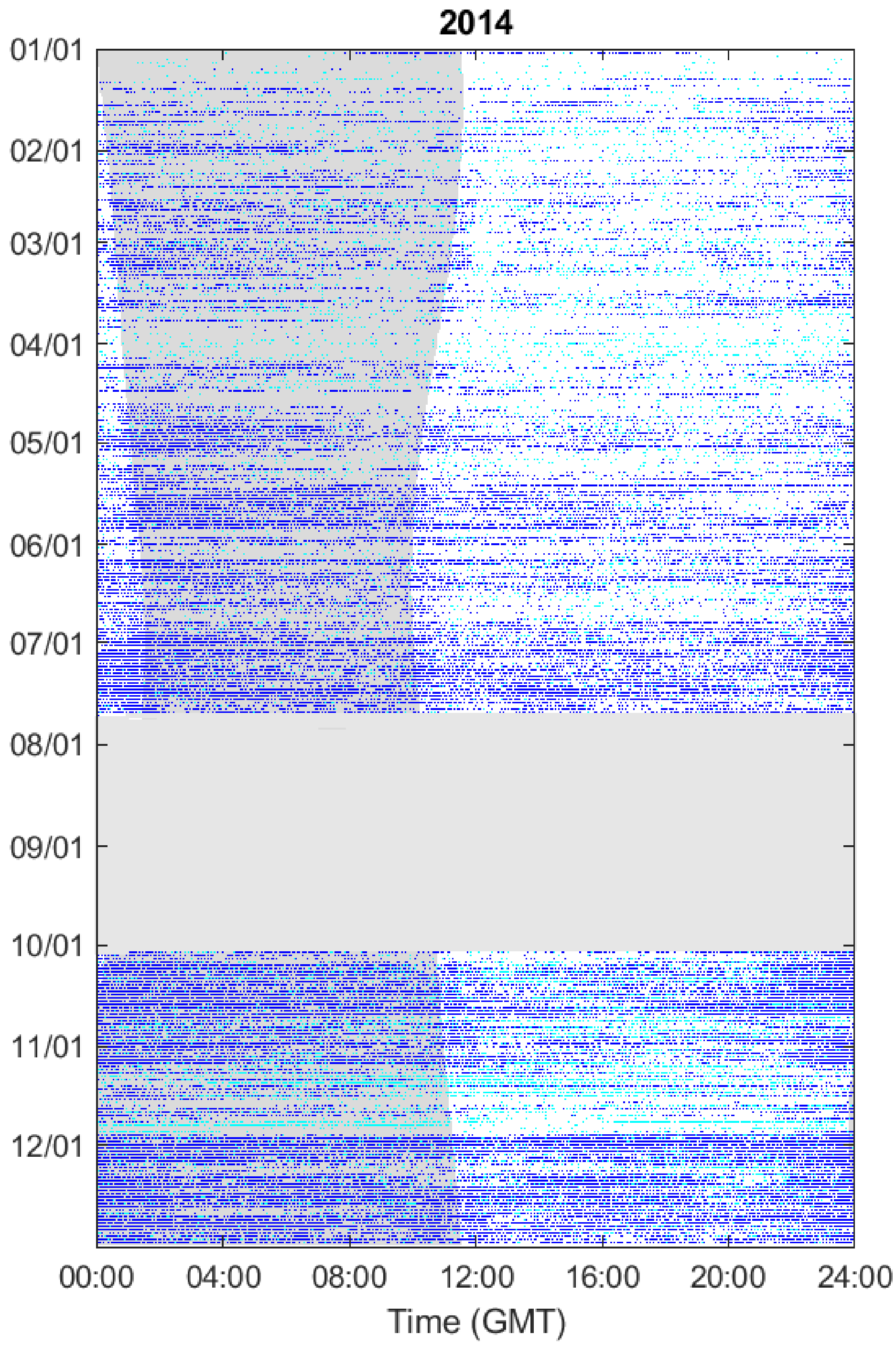


Figure 12*. Gulf of Mexico Bryde's whale long moan calls in 1-minute bins in 2014 at the DC site. Cyan marks represent verified false detections while blue marks represent true long moan detections. Night time is indicated by gray shading. The grayed blocked area represents time periods without recording effort.*

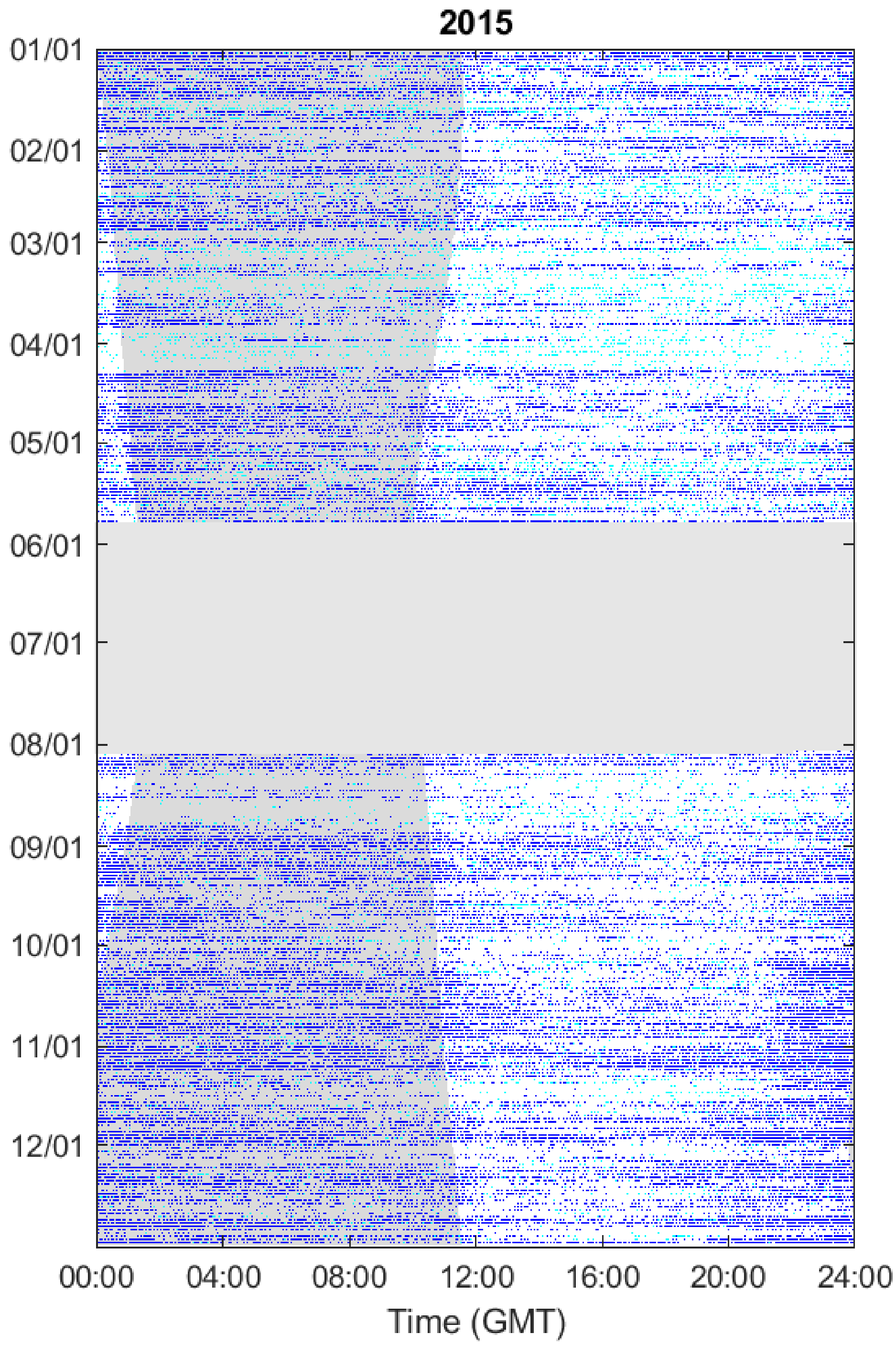


Figure 13. *Gulf of Mexico Bryde's whale long moan calls in 1-minute bins in 2015 at the DC site. Cyan marks represent verified false detections while blue marks represent true long moan detections. Night time is indicated by gray shading. The grayed blocked area represents time periods without recording effort.*

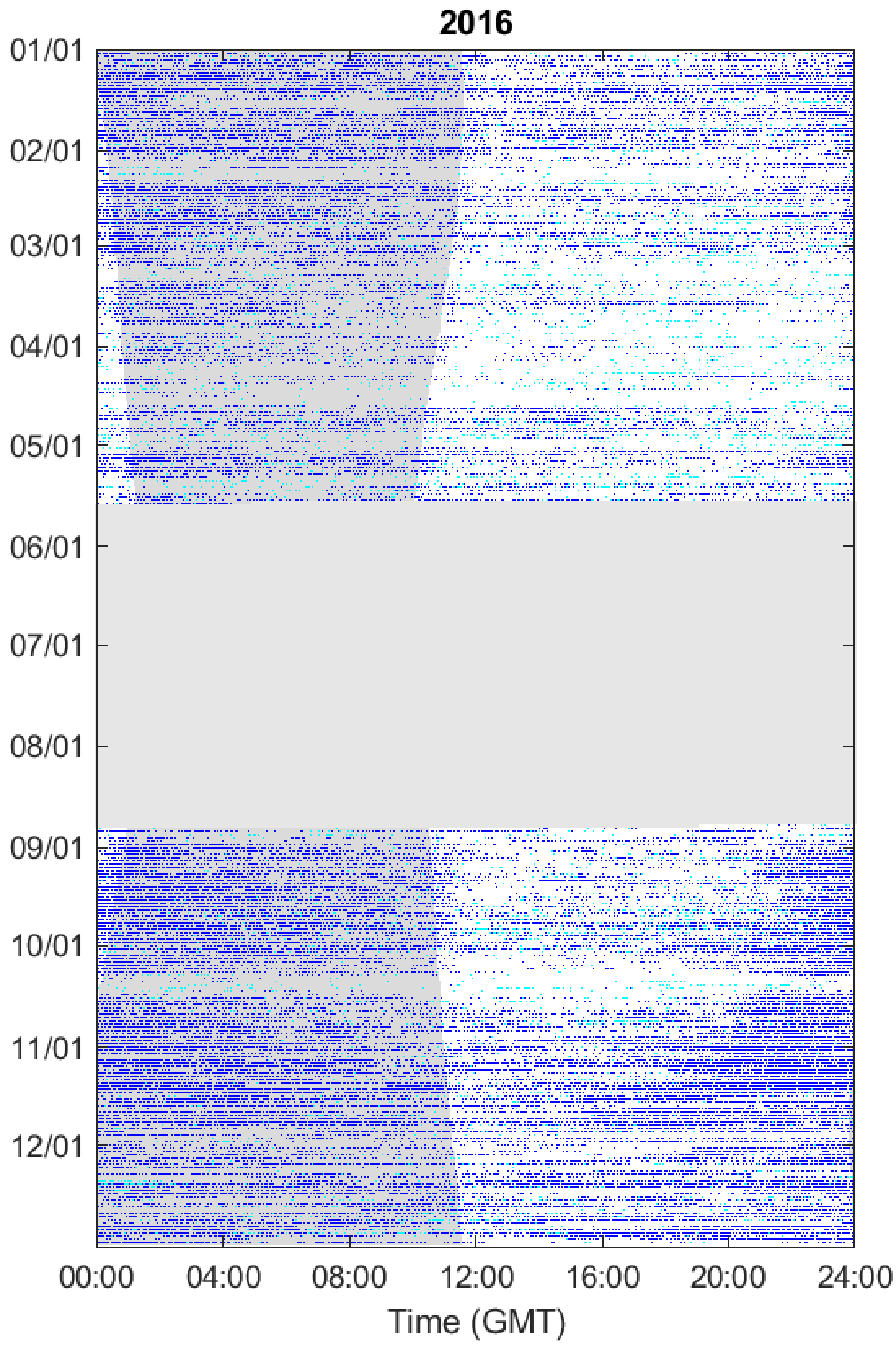


Figure 14. *Gulf of Mexico Bryde's whale long moan calls in 1-minute bins in 2016 at the DC site. Cyan marks represent verified false detections while blue marks represent true long moan detections. Night time is indicated by gray shading. The grayed blocked area represents time periods without recording effort.*

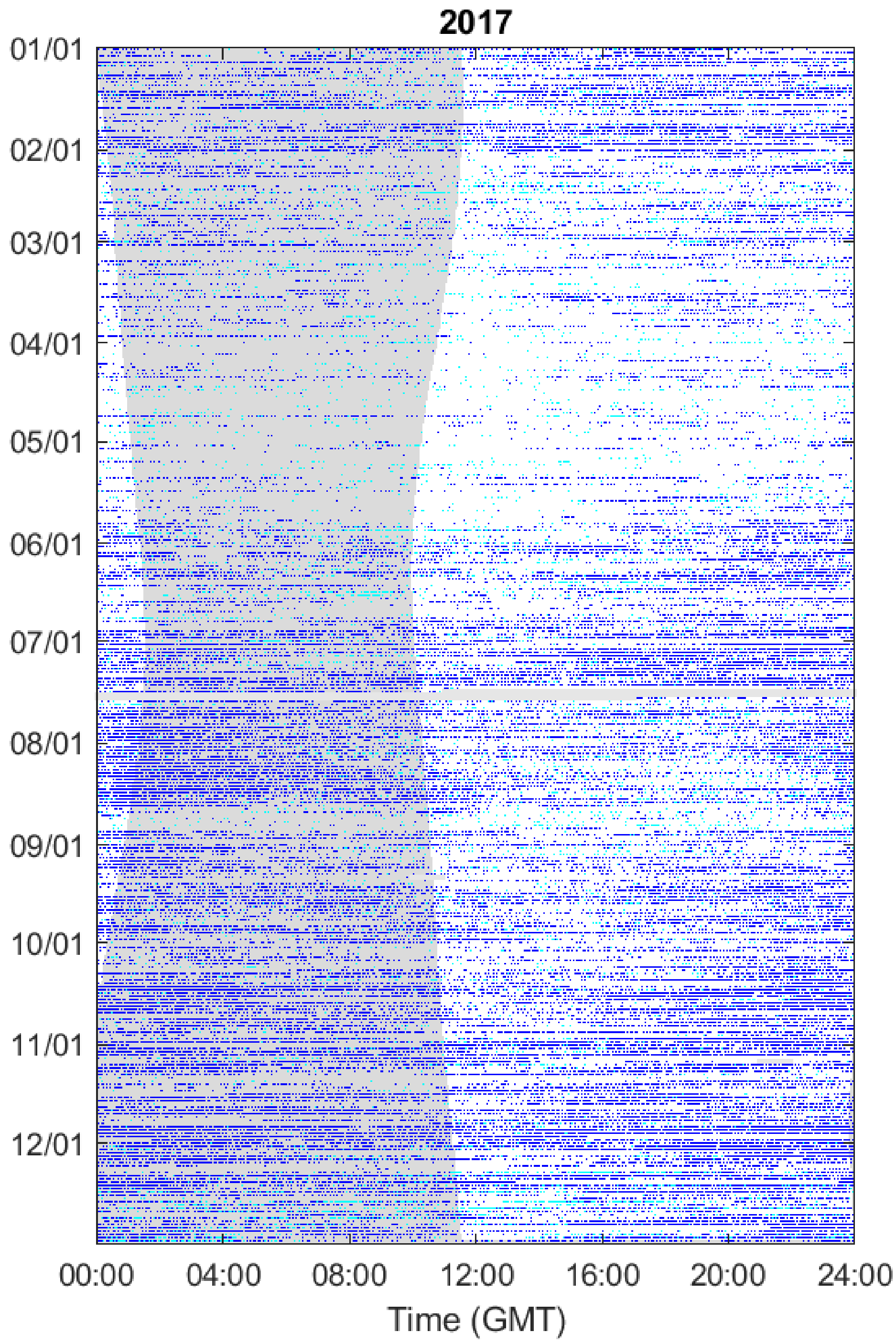


Figure 15*. Gulf of Mexico Bryde's whale long moan calls in 1-minute bins in 2017 at the DC site. Cyan marks represent verified false detections while blue marks represent true long moan detections. Night time is indicated by gray shading. The grayed blocked area represents time periods without recording effort.*

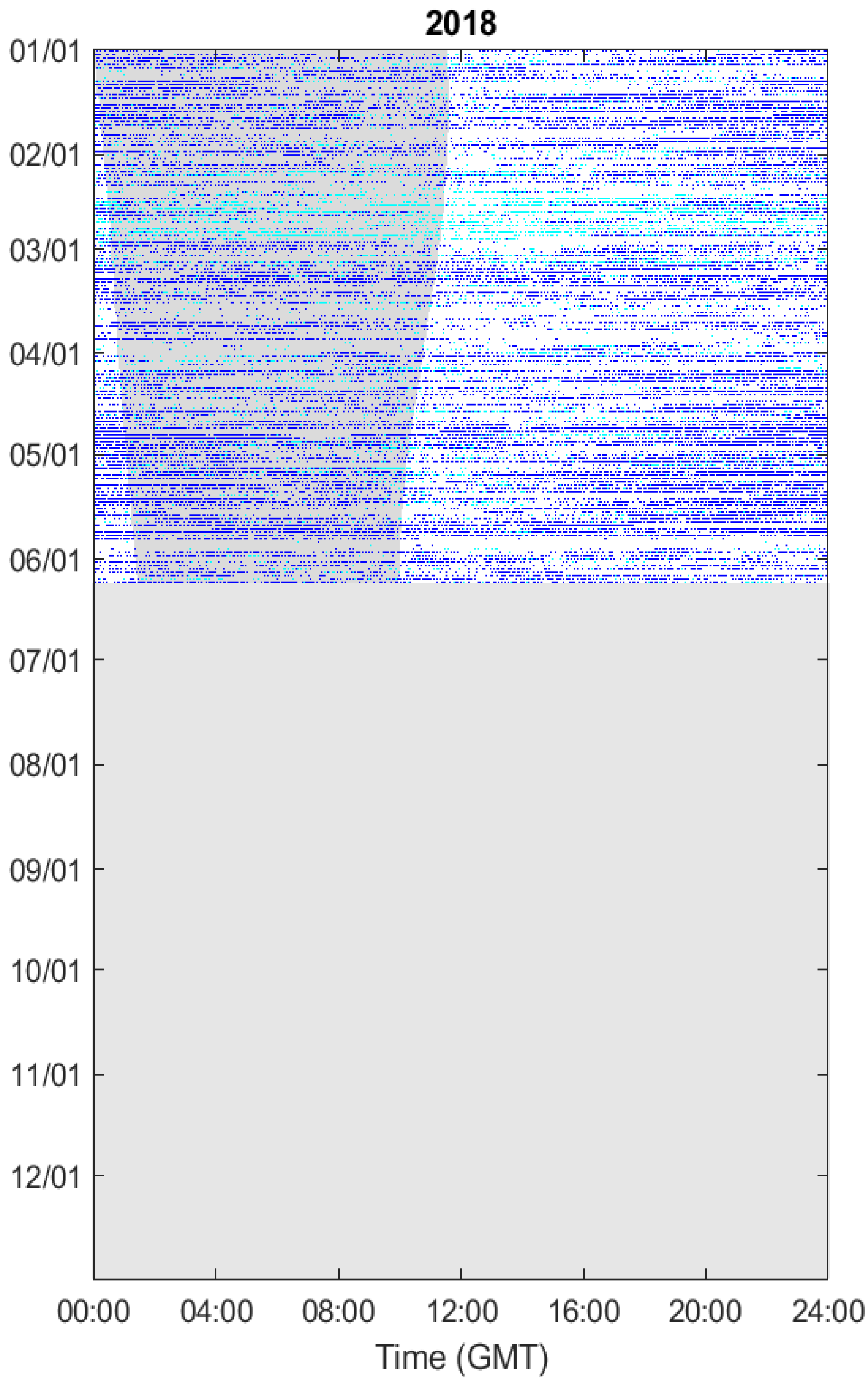
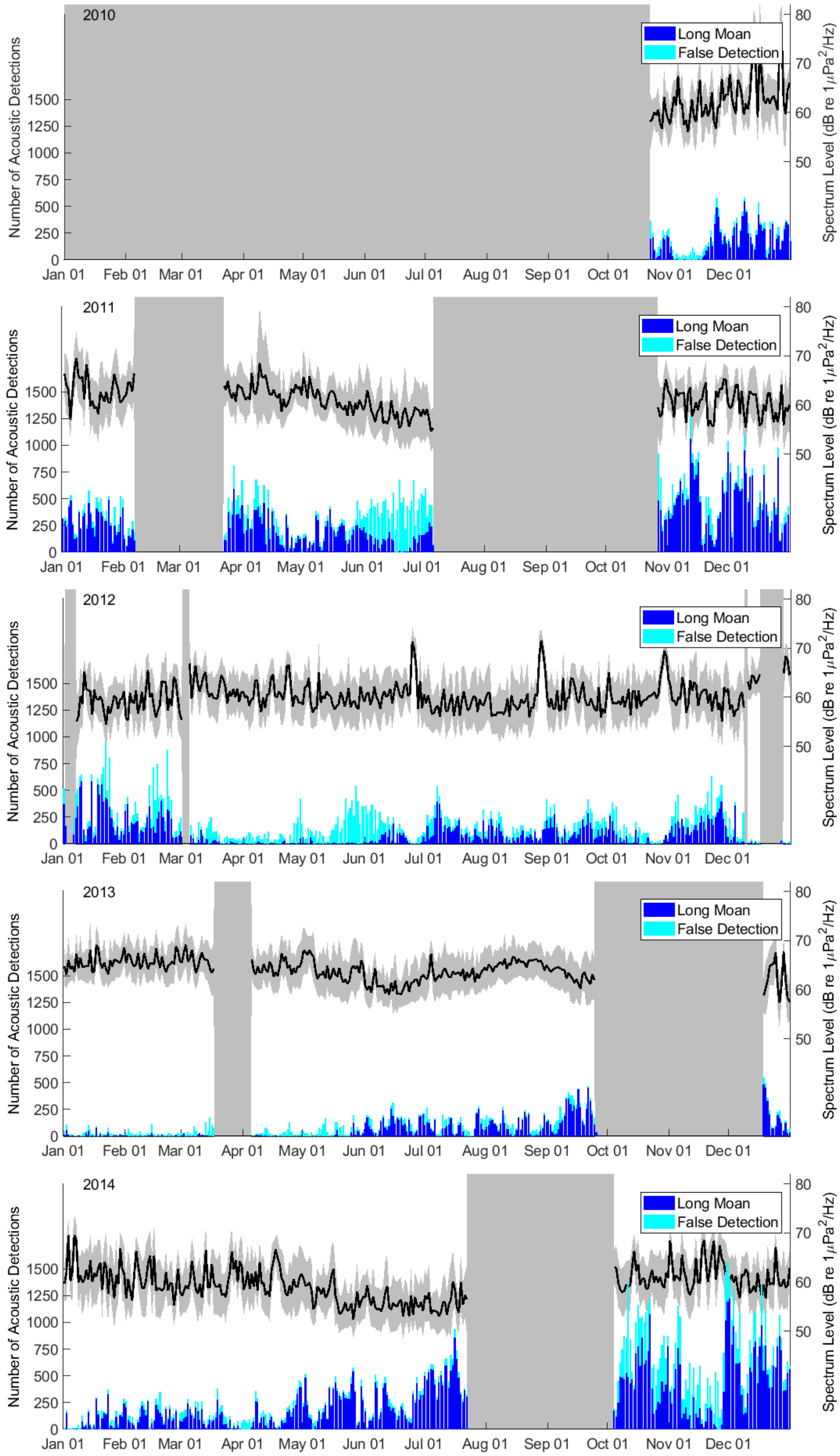


Figure 16*. Gulf of Mexico Bryde's whale long moan calls in 1-minute bins in 2018 at the DC site. Cyan marks represent verified false detections while blue marks represent true long moan detections. Night time is indicated by gray shading. The grayed blocked area represents time periods without recording effort.*


2010
2011
2012
2013
2014
Long Moan
False Detection
Number of Acoustic Detections
Spectrum Level (dB re 1μPa^2/Hz)
0
250
500
750
1000
1250
1500
50
60
70
80
Jan 01
Feb 01
Mar 01
Apr 01
May 01
Jun 01
Jul 01
Aug 01
Sep 01
Oct 01
Nov 01
Dec 01

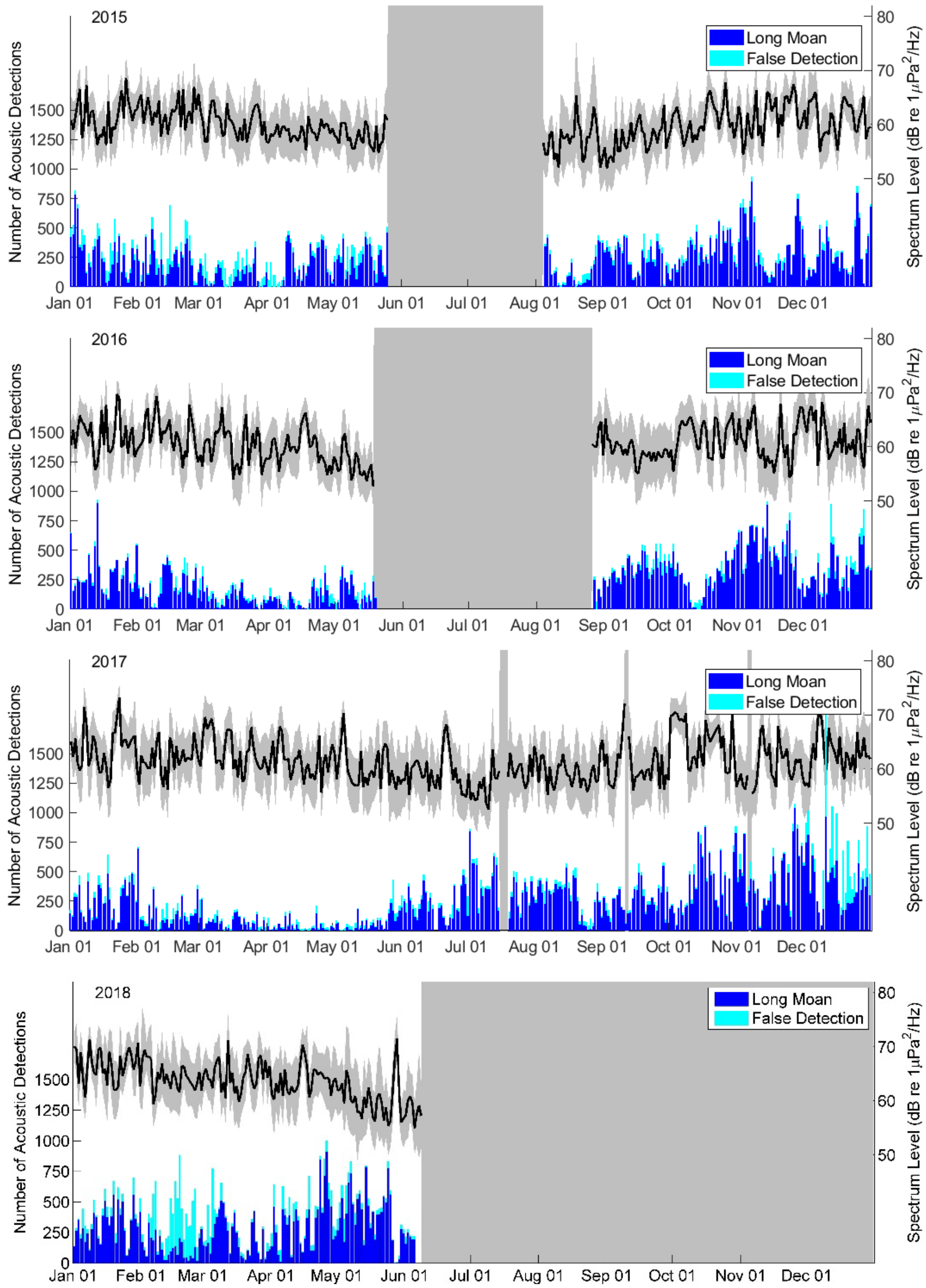


Figure 17. *Daily total of long moan detections (blue=true; cyan = false) and daily average (black) and variance (gray) in noise levels in the 125 Hz frequency band at the De Soto Canyon HARP site from 2010-2018. Gray blocks indicate periods with no data.*

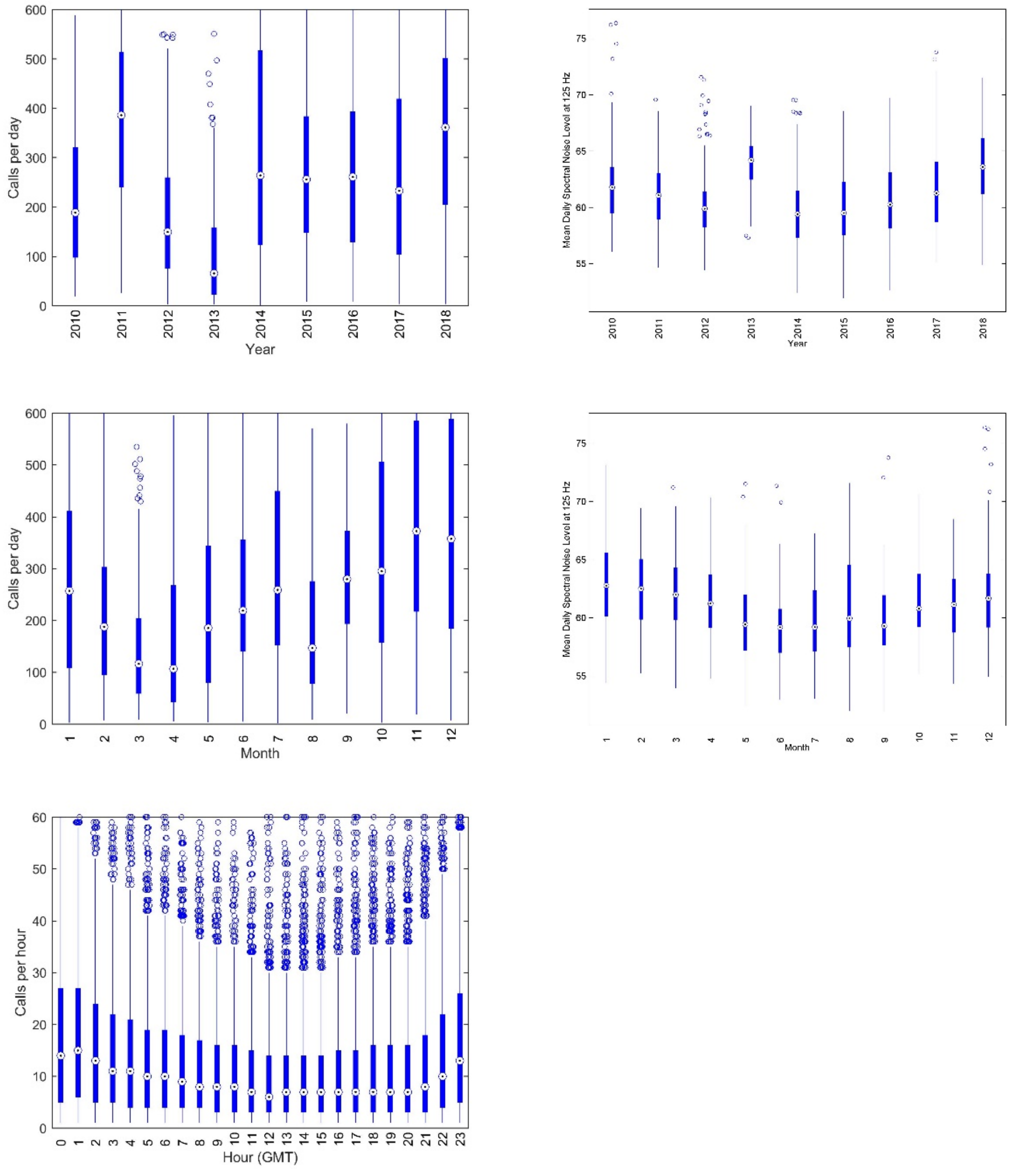


Figure 18. *Comparisons of hourly diel, and daily seasonal and interannual patterns in long-moan detections and noise. Note y-axes are set to enhance view of medians and 25-75 percentiles; outliers extend beyond the y-axis limits.*

Gulf of Mexico Bryde's Whale Downsweep Pulse Calls

GOM Bryde's whale Downsweep Pulse Sequences also were detected in all seasons and all years, although they were far less common than long moan calls and there was no apparent evidence of seasonality in occurrence. Automated call detections yielded a total of 115,729 Downsweep Pulse Sequence detections with 6,803 to 23,067 detections per deployment for deployments DC02-DC11 (**Table 5**). A total of 17,449 verified downsweep pulse sequence detections were present during an average of 31% of days (range 14-52% of days) and during an average of 7.3% of hours (range 2.0-14.7% of hours) with recording effort per deployment (**Table 5, Figures 19-27**). Note DC06, DC10, and DC11 were impacted by disk write errors and Ishmael auto-detections have start-time errors (up to 7 hours) that need to be corrected; diel, hourly, and daily rates will be recalculated for these datasets after these corrections are completed. Verified detections were sparse and occurred sporadically over time, with no evidence of seasonality. Calls were clustered over several hours, and often over several days, and were occasionally absent for extended periods of time (e.g. 2012, 2013, 2015; **Figures 19-28**). False detection rates per deployment (mean: 85%, range: 68-98%) were higher than expected for this detector (69%). Extreme peaks in false detections in some time series (2010, 2011, and 2013) represent periods with anthropogenic noise sources present, including seismic surveys and ships (**Figure 29**). Further development to improve this detector may yield better results. There were very few downsweep calls in the original detector training dataset so redevelopment with more data may be sufficient to tune the detector and improve accuracy; however, given the pulsing nature of the calls and the high prevalence of seismic survey activity in the area, a machine learning approach may be more reliable. While detection ranges of these calls remains unknown, as described above for long moan calls, limited data suggests presented by Rice et al 2014 indicates some calls were detected on 3 PAM units with a maximum spacing of 150 km between them indicating a minimum detection distance of 75 km at those times.

- There were many fewer downsweep pulse sequence call detections than long moan detections per deployment (2-10x more long moans), with an average of 11,573 downsweep sequence detections per deployment, and a range from 6,803 to 23,067 detections (**Tables 4, 5**).
- There were also many fewer verified detections of true downsweep pulse sequences (20-140x more long moans), with an average of 1,745 calls (range 228 - 5,504 calls) per deployment (**Tables 4, 5**). The highest number of calls were detected during the DC11, DC 10 and DC07 deployments and the lowest number of calls were detected during the DC02, DC06, and DC05 deployments.
- False detection rates for the Ishmael spectrogram correlation detector were very high, averaging 85% of total detections across deployments, and with a range from 68% to 98% (**Table 5**). These false detection rates were even higher than expected based on the testing data characterization (69%). In DC02, which had a strong spike in false detections in November **(Figure 19**), nearly 65% of the false detections occurred over the course of a few days when ship noise was prevalent. Other periods with high false detections were also related to anthropogenic noise, including seismic airgun surveys.
- Verified detections of downsweep pulse sequences were present on an average of 31% of days with effort (range: 14 – 52% of days) and during 7.3% of hours with effort (2.0 – 14.7% of hours) per deployment (**Table 5**).
- True downsweep detections were generally sparse and sporadic throughout the year and tended to cluster over several hours and often over several days. Occasionally, there were extended periods (1-2 months) with few if any downsweep sequence detections; this occurred more commonly during the 2012-2015 period. (**Figure 19** to **Figure 28**).

- Median daily call detection rates for downsweep sequences were highest in 2011 and 2018, and lowest in 2010 and 2015 (**Figure 29**). Analyses are in progress to evaluate if this variation is significant. Noise levels were highest in 2013 and 2018 (**Figure 18**), which does not appear to explain these differences in call detection rates at this scale.
- Median daily call detection rates for downsweep sequences were highest in July, followed by November, December and October, and were lowest in March, April, February and August. Analyses are in progress to evaluation if this variation is significant. Median noise levels at 125 Hz were lower in June and July which may relate to higher call detection rates in July (**Figure 29**). Conversely, median noise levels were higher in January, February, and March, and levels were higher in August compared to nearby months which may lead to reduced detection ranges at these times and the lower call detection rates (**Figure 18**).
- Median hourly call detection rates for downsweep sequences were higher between 23:00 – 02:00 GMT which may represent a crepuscular increase in calling around sunset (**Figure 29**).

Table 3. *Number of downsweep pulse sequences detected per deployment.*

Deployment	**Downsweep Pulse Sequence Detections**	**True Downsweep Pulse Sequences**	**Days Present (%)**	**Hours Present (%)**
	Automated	*Validated*		
DC02	9,266	228	15 (14)	52 (2.0)
DC03	6,803	964	50 (46)	269 (10.5)
DC04	9,859	1,522	56 (44)	336 (11.3)
DC05	13,666	649	50 (18)	181 (2.7)
DC06	14,221	603	38 (14)	151 (2.4)
DC07	6,941	2,241	78 (35)	531 (10.2)
DC08	10,107	1,283	60 (26)	354 (6.3)
DC09	8,066	1,732	76 (26)	401 (5.8)
DC10	13,733	2,723	122 (37)	588 (7.5)
DC11	23,067	5,504	169 (52)	1,156 (14.7)

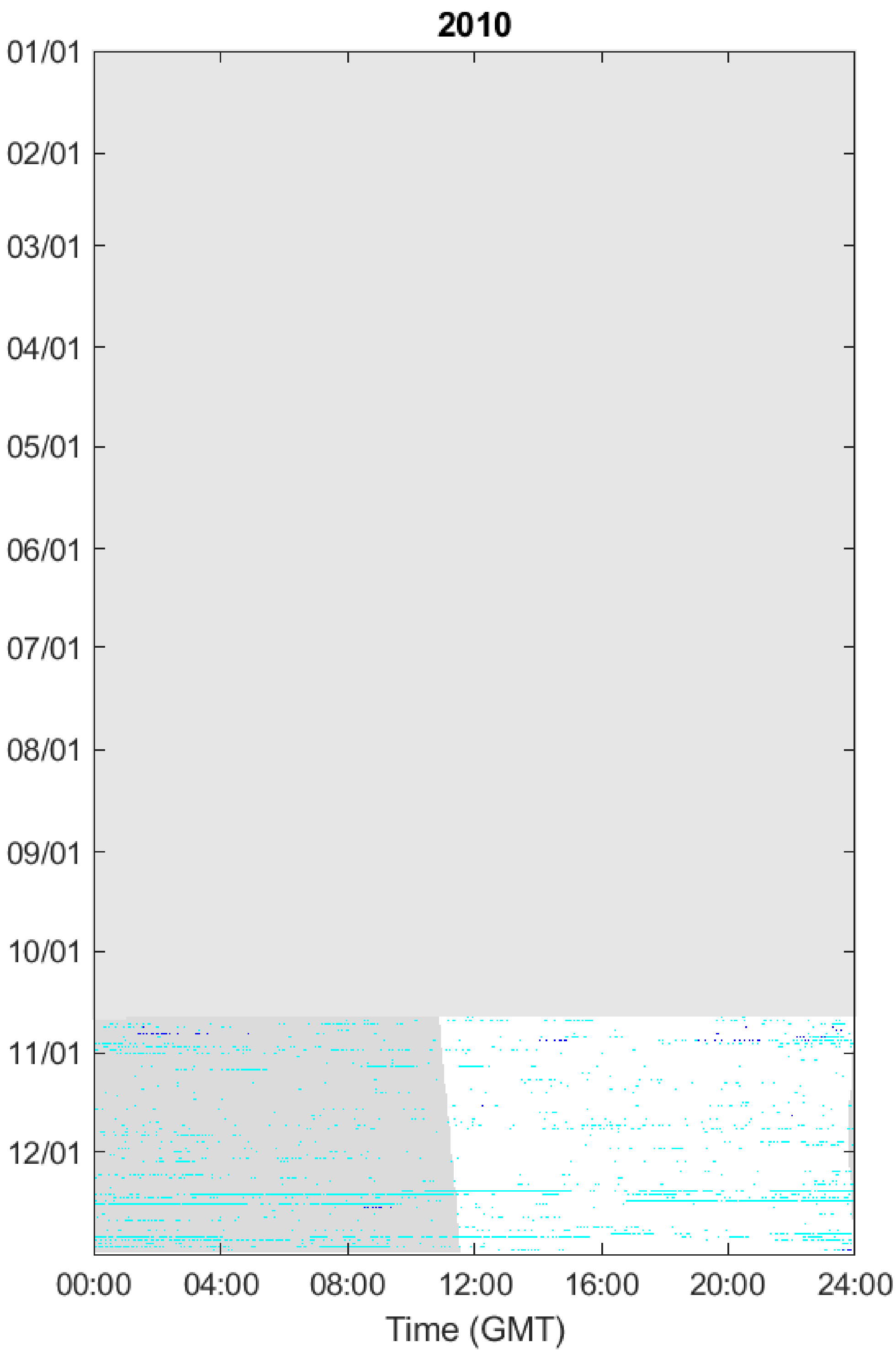


Figure 19. *Gulf of Mexico Bryde's whale downsweep pulse sequences in 1-minute bins in 2010 at the DC site. Cyan marks represent verified false detections while blue marks represent true long moan detections. Night time is indicated by gray shading. The grayed blocked area represents time periods without recording effort.*

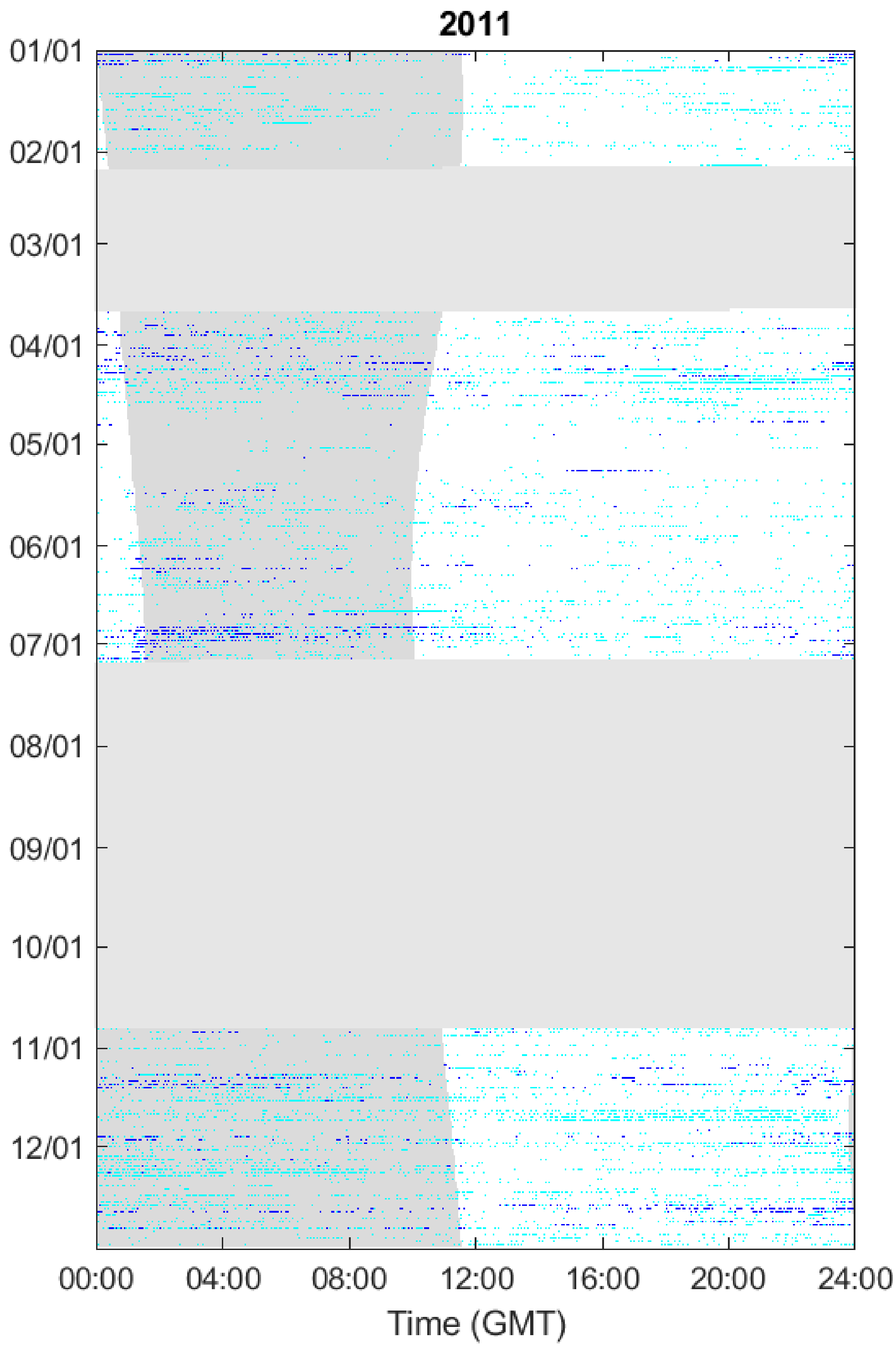


Figure 20. *Gulf of Mexico Bryde's whale downsweep pulse sequences in 1-minute bins in 2011 at the DC site. Cyan marks represent verified false detections while blue marks represent true long moan detections. Night time is indicated by gray shading. The grayed blocked area represents time periods without recording effort.*

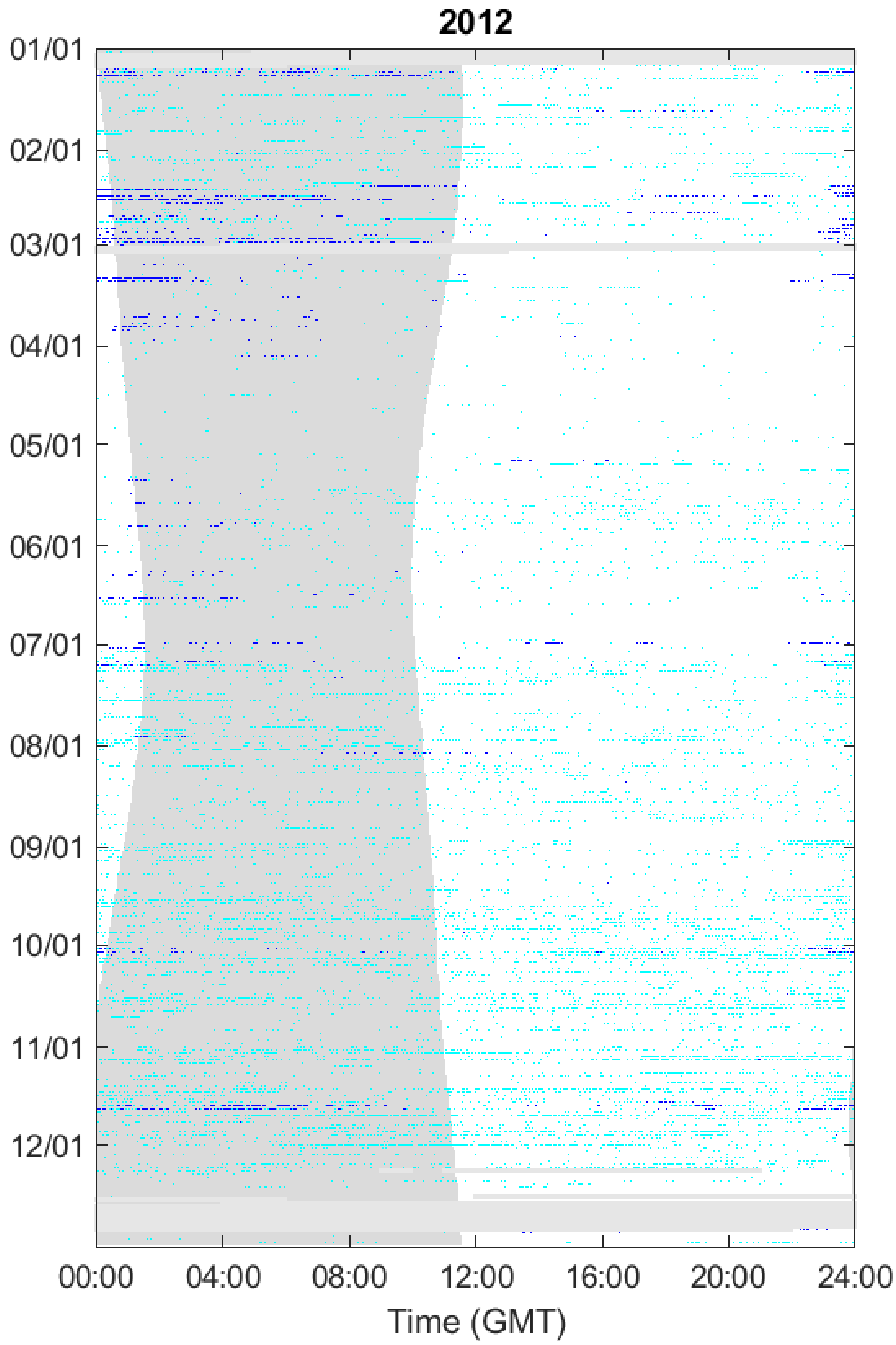


Figure 21. *Gulf of Mexico Bryde's whale downsweep pulse sequences in 1-minute bins in 2012 at the DC site. Cyan marks represent verified false detections while blue marks represent true long moan detections. Night time is indicated by gray shading. The grayed blocked area represents time periods without recording effort.*

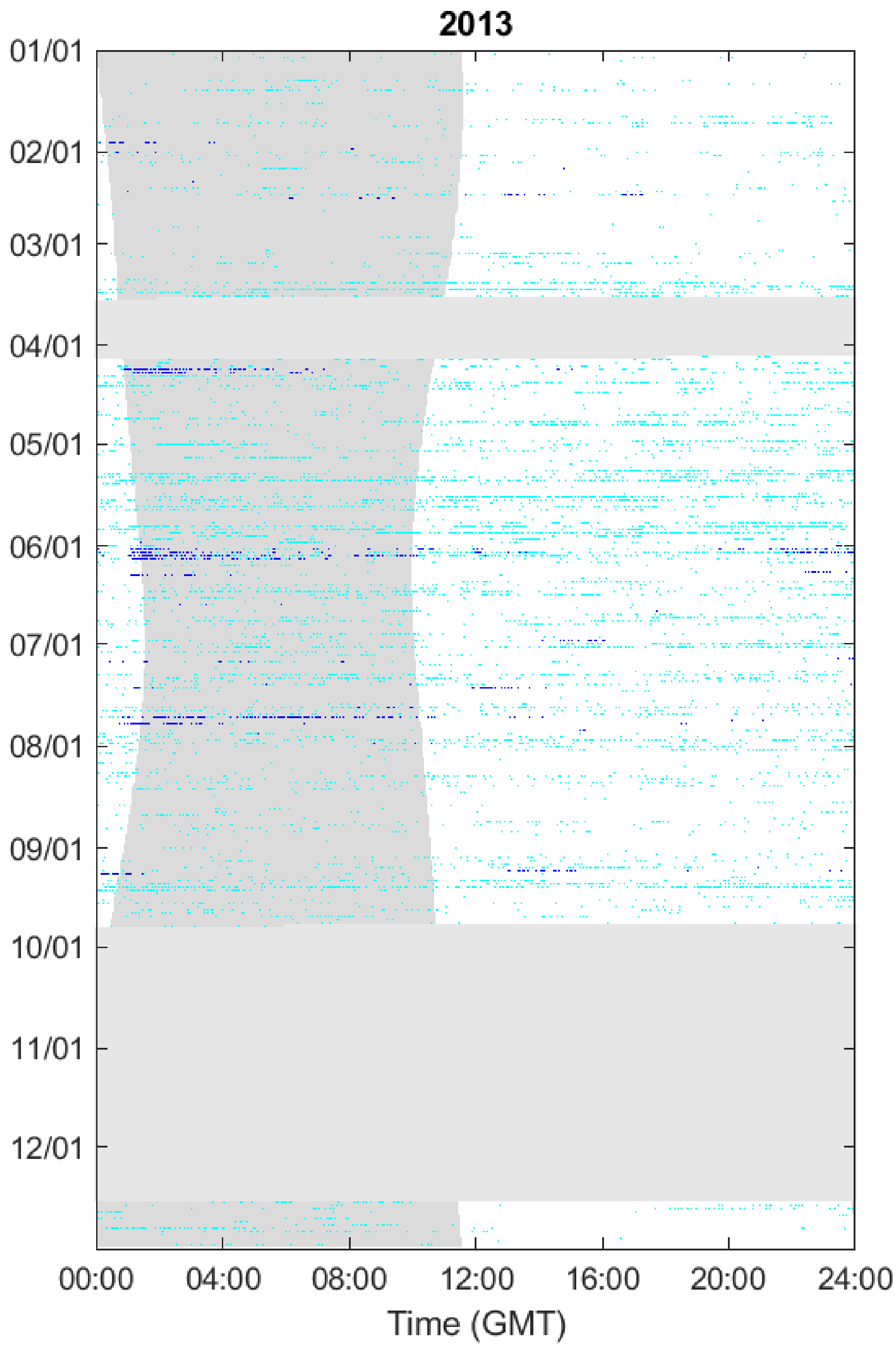


Figure 22. *Gulf of Mexico Bryde's whale downsweep pulse sequences in 1-minute bins in 2013 at the DC site. Cyan marks represent verified false detections while blue marks represent true long moan detections. Night time is indicated by gray shading. The grayed blocked area represents time periods without recording effort.*

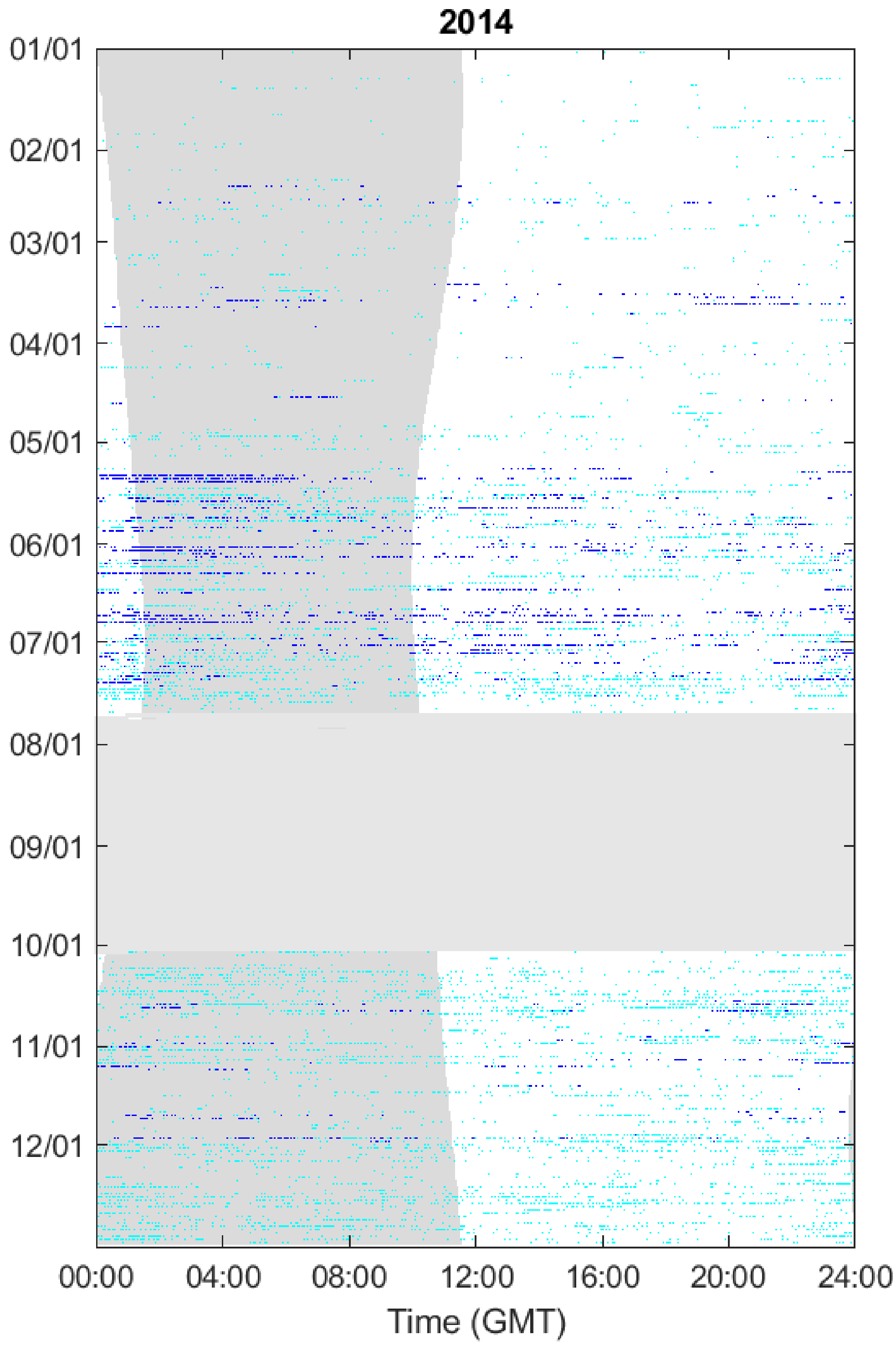


Figure 23. *Gulf of Mexico Bryde's whale downsweep pulse sequences in 1-minute bins in 2014 at the DC site. Cyan marks represent verified false detections while blue marks represent true long moan detections. Night time is indicated by gray shading. The grayed blocked area represents time periods without recording effort.*

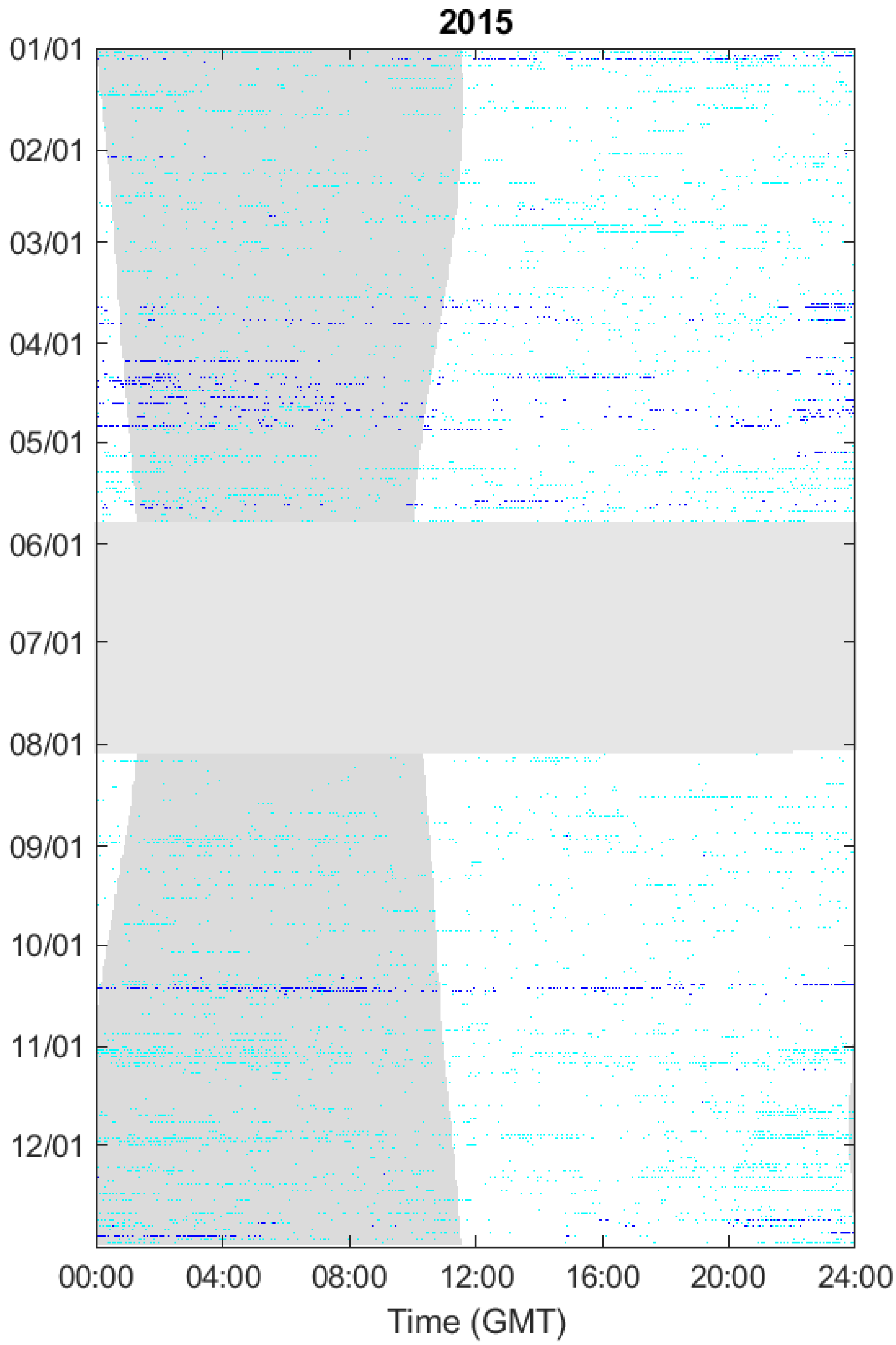


Figure 24. *Gulf of Mexico Bryde's whale downsweep pulse sequences in 1-minute bins in 2015 at the DC site. Cyan marks represent verified false detections while blue marks represent true long moan detections. Night time is indicated by gray shading. The grayed blocked area represents time periods without recording effort.*

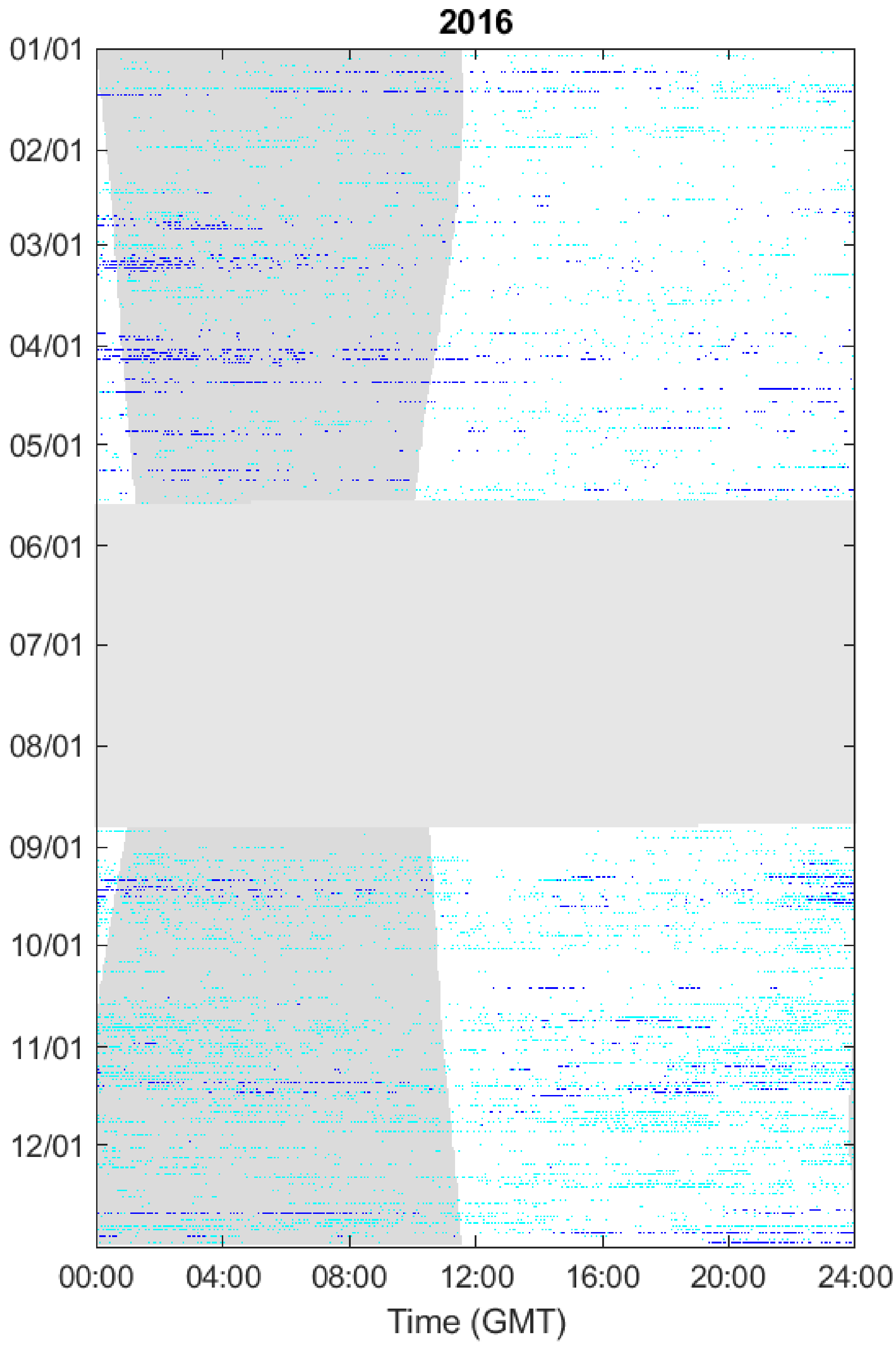


Figure 25. *Gulf of Mexico Bryde's whale downsweep pulse sequences in 1-minute bins in 2016 at the DC site. Cyan marks represent verified false detections while blue marks represent true long moan detections. Night time is indicated by gray shading. The grayed blocked area represents time periods without recording effort.*

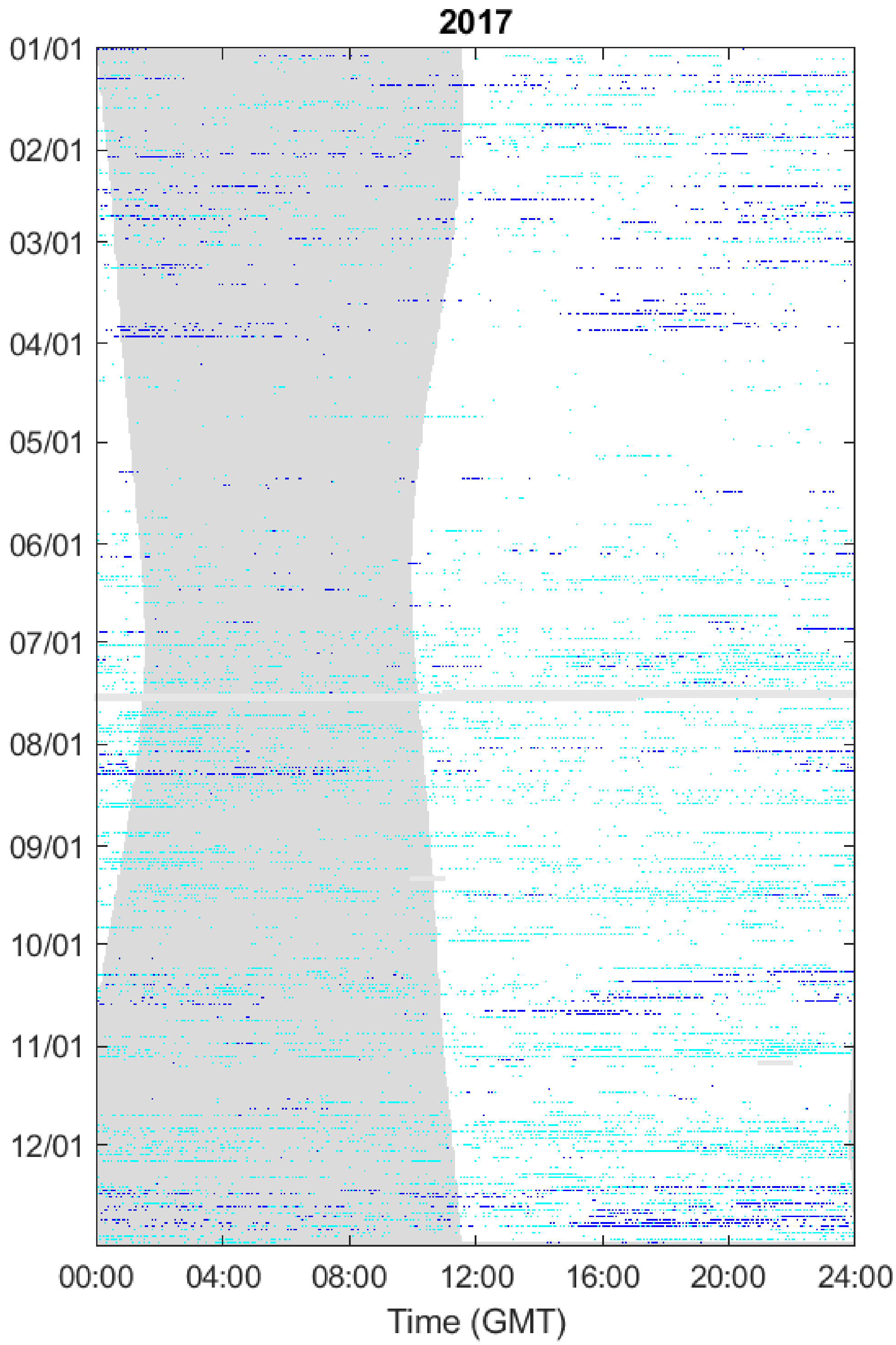


Figure 26. *Gulf of Mexico Bryde's whale downsweep pulse sequences in 1-minute bins in 2017 at the DC site. Cyan marks represent verified false detections while blue marks represent true long moan detections. Night time is indicated by gray shading. The grayed blocked area represents time periods without recording effort.*

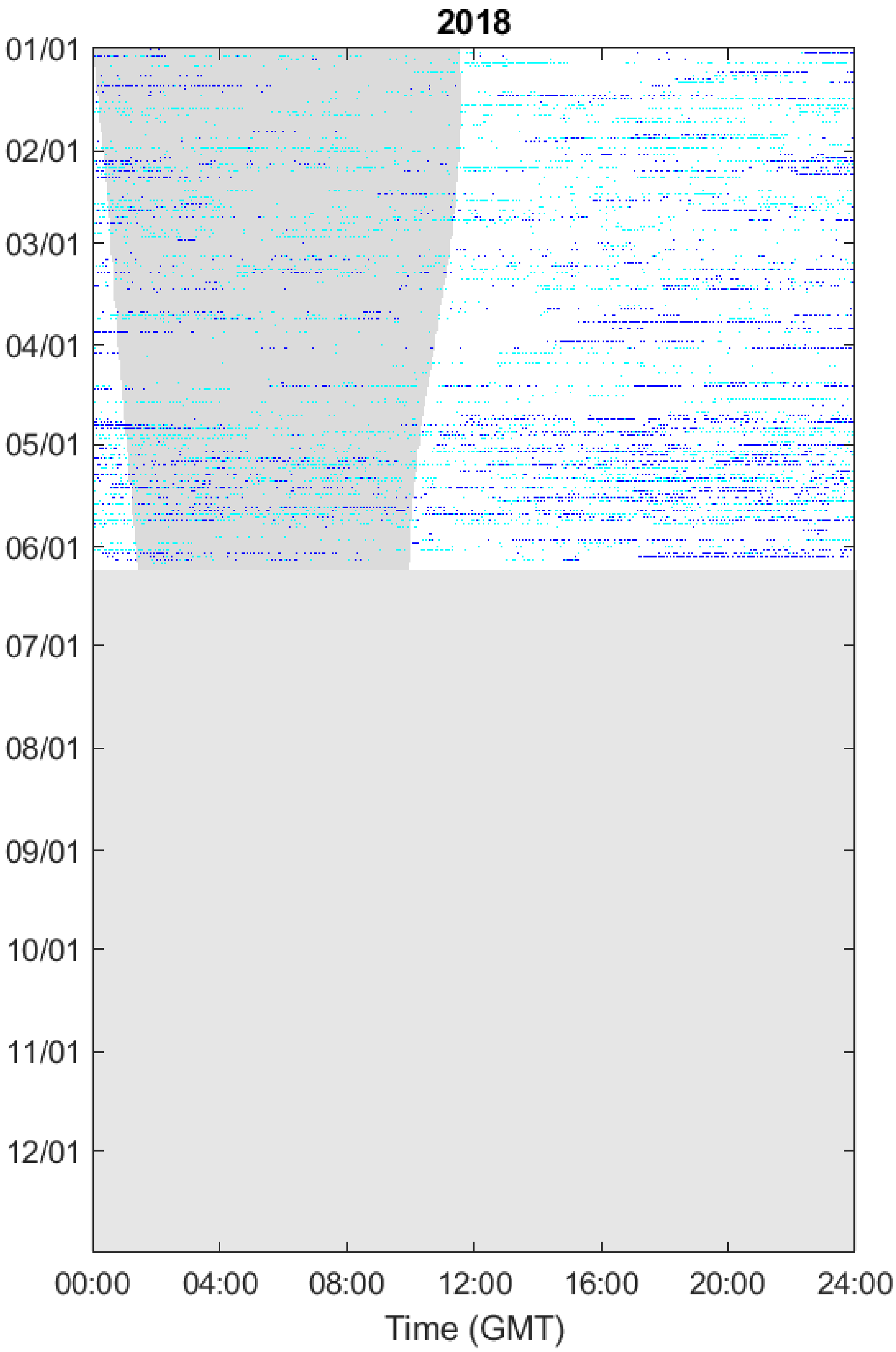
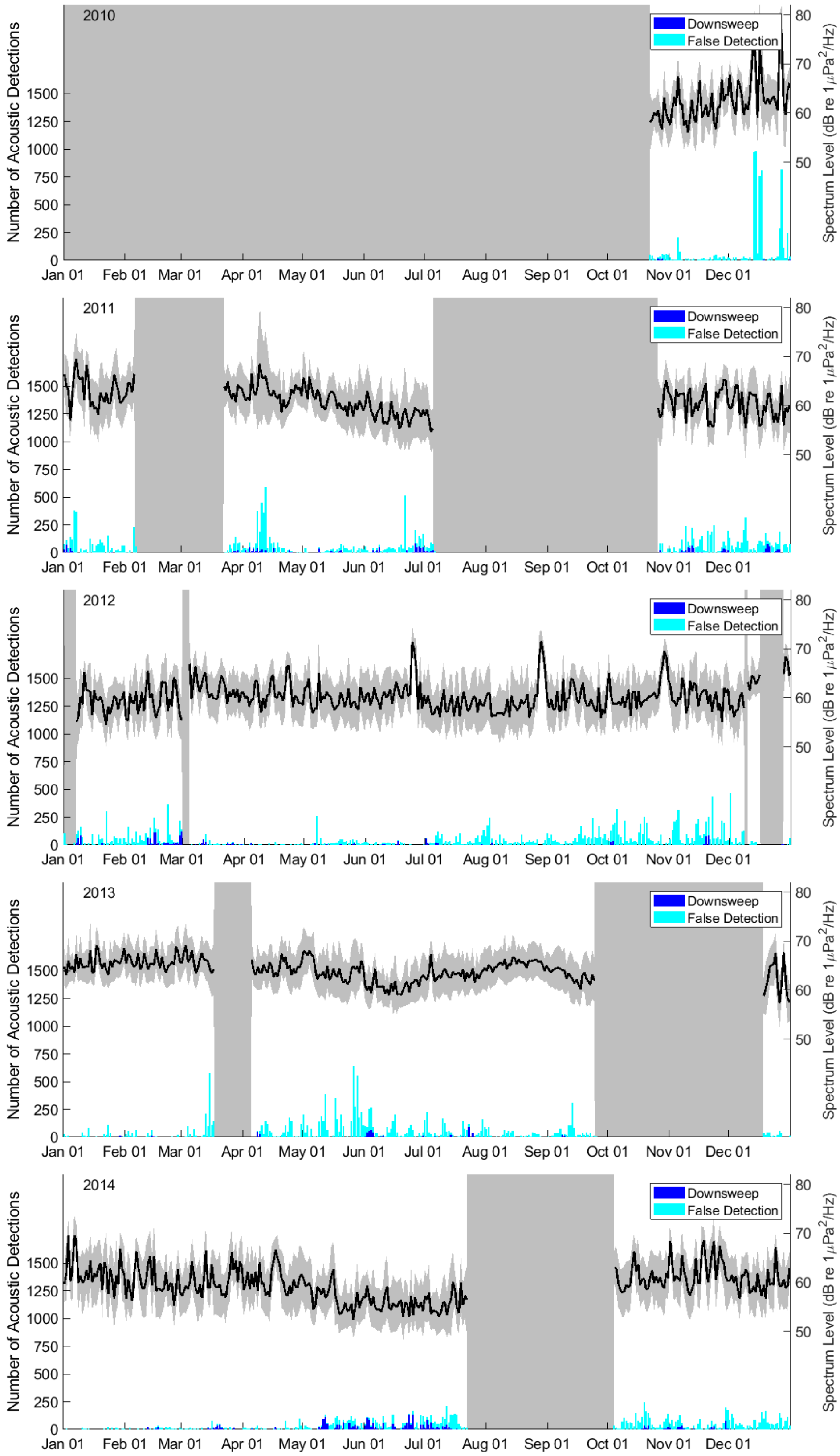


Figure 27. *Gulf of Mexico Bryde's whale downsweep pulse sequences in 1-minute bins in 2018 at the DC site. Cyan marks represent verified false detections while blue marks represent true long moan detections. Night time is indicated by gray shading. The grayed blocked area represents time periods without recording effort.*



2010
2011
2012
2013
2014
Downsweep
False Detection
Number of Acoustic Detections
Spectrum Level (dB re 1μPa^2/Hz)
0
250
500
750
1000
1250
1500
50
60
70
80
Jan 01
Feb 01
Mar 01
Apr 01
May 01
Jun 01
Jul 01
Aug 01
Sep 01
Oct 01
Nov 01
Dec 01

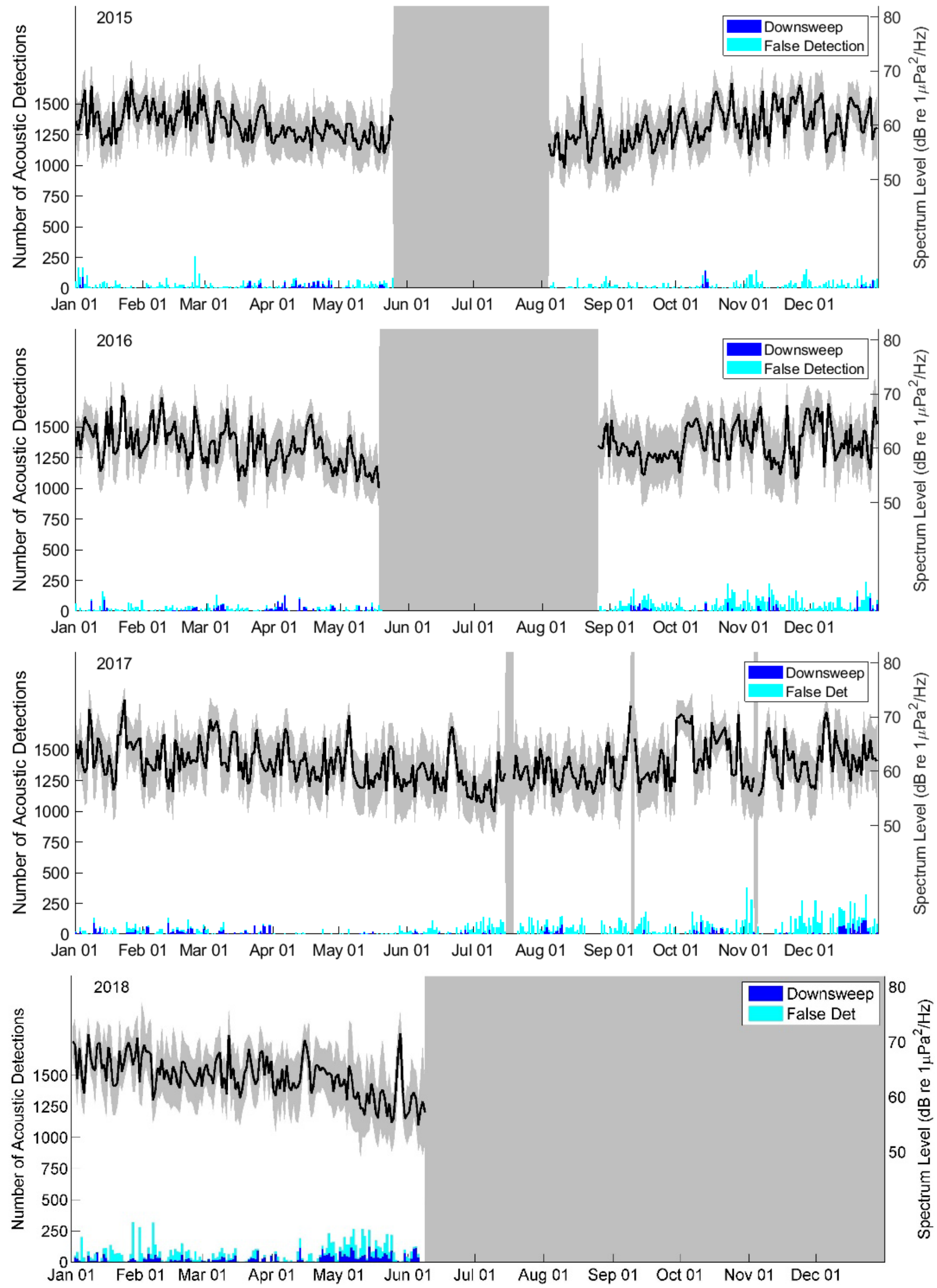


Figure 28*. Daily total of Gulf of Mexico Bryde's whale downsweep pulse sequence detections (blue=true; cyan = false)) and daily average (black) and variance (gray) in noise levels in the 125 Hz frequency band.at the De Soto Canyon HARP site from 2010-2018. Gray blocks indicate periods with no data.*

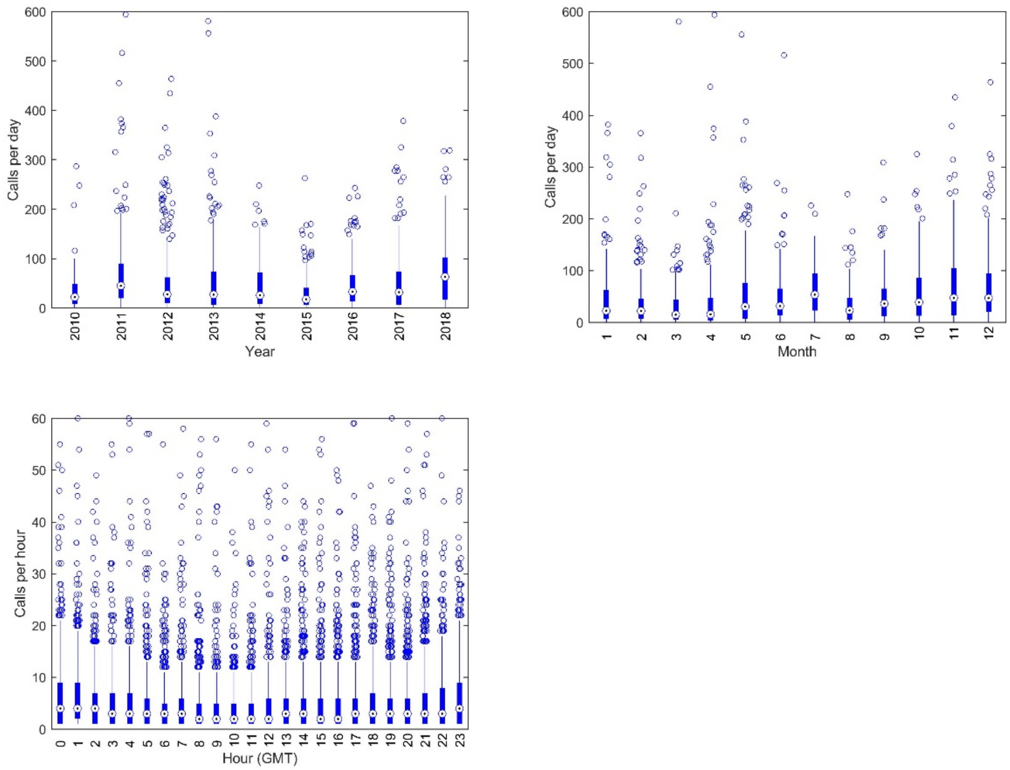


__Figure 29__. Comparisons of hourly diel, and daily seasonal and interannual patterns in long-moan detections and noise.

Future Research Needs:

The results from analyses of the 8-year time-series at the De Soto Canyon HARP site, deployed from 2010-2018, provide insights into the frequency of occurrence of calling Gulf of Mexico Bryde's whales and their usage of this core habitat area that can be used to inform management needs, such as defining critical habitat and developing mitigation measures that permit anthropogenic activities while recovering this endangered species. While the results indicate the consistent year-round presence of calling whales near this area throughout most years of the study, a full interpretation of these results requires additional information. During periods with decreased call detections, it is important to distinguish whether animals move out of the area, remain in the area but with diminished detection distances, or remain in the area but changed their calling behavior due to needs for communication with conspecifics or to reduce detectability in the presence of predators. Noise from anthropogenic activity, including seismic airguns and shipping, was evident during this period and may have led to reduced detection ranges during periods with increased noise levels in the 80-160 Hz frequency band. Variation in the position of the Loop Current and its eddies, or Mississippi River outflow may impact animal distribution as well as sound propagation conditions and associated call detection distances.

The ability to detect a baleen whale using passive acoustic monitoring is dependent on the animal producing a call while within detection range of the sensor. Both the likelihood of a whale calling and the detection range of a given call may vary over time. Knowledge of call behavior that affects how often and when a whale will produce specific call types and whether this varies by age or sex is needed, as is knowledge of call source levels (by call type) and their variability. Environmental conditions affecting sound propagation distances may lead to smaller or larger detection ranges over time for calls of a given source level and caller at a given depth, and changes in the ambient soundscape can reduce call detection distances due to masking. The persistence of individual noise sources in an area will also impact whether any calls are detected from an individual whale producing multiple calls over a period of time. With this in mind, several key data needs remain to understand the variability in numbers of calls detected each day over the 8-year period.

1. Source levels by call type, age class, and sex
2. Call production rates by call type, age class, and sex
3. Caller depth at call production
4. Oceanographic conditions and expected sound propagation distances
5. Call detection distances (empirical or modeled)
6. Integration of ambient noise conditions, source levels, and sound propagation conditions over time to normalize call detection rates by time-specific detection probability.

Further, to permit and mitigate anthropogenic activities in this core habitat area where these endangered whales consistently occur year-round, predictive habitat models will be important to assess when and where the whales might be found to determine if we can better predict finer-scale spatial occurrence. While the anticipated study deploying an array of PAM units throughout the core habitat will provide important information to understand how spatial density of calls changes throughout the area over the course of the year, additional understanding can be obtained from temporal habitat models developed from this 8-year time series. For example, habitat models being developed using historic sightings data and recent Bryde's whale focused vessel-based surveys suggest the importance of the Mississippi River outflow and its interaction with upwelling near the De Soto Canyon. Developing predictive habitat models incorporating environmental proxies of prey occurrence, ambient noise levels, and modeled detection distances with passive acoustic detections as the response variable will help determine which dynamic factors drive the occurrence of calling Bryde's whales at this site. Additionally, the high degree of interannual variability found over the 8-year period suggests that it may be important to conduct the broader spatial coverage PAM study over multiple years to ensure results sample the expected variability under different multi-year periods (e.g. El Niño and La Niña years, and the seasonal interaction of the Loop Current extension with Mississippi River outflow).

Core Habitat Seasonal Movements Study Background and Update:

Better understanding seasonal and internannual distribution and density of GOM Bryde's whales throughout the core habitat is needed to improve understanding of potential impact of human activities on these whales and to assist in developing effective mitigation measures as needed. Long-term, broad-coverage passive acoustic monitoring is a highly effective tool for investigating seasonal and interannual occurrence patterns. This study aims to deploy an array of 17 PAM units concurrent with a single long-term High-frequency Acoustic Recording Package to completely cover the GOM Bryde's whale core habitat (**Figure 1**) for at least one year to provide the necessary data to understand seasonal distribution and density. During 2020, our focus was on conducting preliminary analyses for GOM Bryde's whale calls from existing HARP data (described above) and preparing for deployment of the 17-unit array which will be active over two 6-month periods. After the end of each of the two deployment periods, we plan to retrieve the instruments and concentrate on completing analyses of all data for GOM Bryde's whale calls.

As part of our 2020 work, we planned to deploy 17 SoundTrap ST500 STD units concurrent with a long-term DC HARP in two lines of 9 PAM units each to nearly completely cover the core habitat, for two six-month deployments, starting in spring 2020 (Figure 1). The SoundTrap ST500 STD are calibrated long-term recorders capable of continuously recording underwater sound in the 20 Hz – 48 kHz frequency range, including GOM Bryde's whale calls and ambient noise, for up to 6 months. All equipment for the PAM moorings has been purchased and is ready to deploy. However, vessel schedule cancellations, high vessel demand, and travel restrictions and limitations due to the COVID pandemic have delayed the deployment of these moorings over the last year. The project is currently delayed by one year due to these challenges. We have vessel time scheduled on NOAA's *R/V Gordon Gunter* and plan to deploy the SoundTrap moorings on May 1, 2021, for subsequent retrieval, data recovery, and redeployment in October 2021, and final recovery in May 2022. SEFSC acousticians will begin data analyses on the recordings from the 17 SoundTraps as well as the concurrently deployed DC HARP data once they have been retrieved in November 2021.

References

Hayes SA, Josephson E, Maze-Foley K, Rosel PE (2018) US Atlantic and Gulf of Mexico Marine Mammal Stock Assessments - 2017. NOAA Technical Memorandum NMFS-NE-245, US Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northeast Fisheries Science Center, Woods Hole, Massachusetts

Hildebrand JA (2009) Anthropogenic and natural sources of ambient noise in the ocean. Marine Ecology Progress Series 395:5-20

Mellinger DK, Clark CW (2000) Recognizing transient low-frequency whale sounds by spectrogram correlation. Journal of the Acoustical Society of America 107:12

Rice AN, Palmer KJ, Tielens JT, Muirhead CA, Clark CW (2014) Potential Bryde's whale (*Balaenoptera edeni*) calls recorded in the northern Gulf of Mexico. The Journal of the Acoustical Society of America 135:3066-3076

Širović A, Bassett HR, Johnson SC, Wiggins SM, Hildebrand JA (2014) Bryde's whale calls recorded in the Gulf of Mexico. Marine Mammal Science 30:399-409

Soldevilla MS, Hildebrand JA, Frasier KE, Aichinger Dias L and others (2017) Spatial Distribution and Dive Behavior of Gulf of Mexico Bryde’s Whales: Potential Risk for Vessel Strikes and Fisheries Interactions. Endangered Species Research 32:533-550

Wiggins SM, Hall J, Thayre BJ, Hildebrand JA (2016) Gulf of Mexico low-frequency ocean soundscape dominated by airguns. Journal of the Acoustical Society of America 140:176-183

Wiggins SM, Hildebrand JA (2007) High-frequency Acoustic Recording Package (HARP) for broadband, long-term marine mammal monitoring. International Symposium on Underwater Technology 2007 and International Workshop on Scientific Use of Submarine Cables and Related Technologies 2007:551-557