



# Rice's whales in the northwestern Gulf of Mexico: call variation and occurrence beyond the known core habitat

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**ABSTRACT:** The endangered Rice's whale *Balaenoptera ricei*, with fewer than 100 individuals remaining, is the only year-round resident baleen whale found in the Gulf of Mexico (GOM) and occurs primarily along the northeastern shelf break near De Soto Canyon. Historical whaling records and predictive density modeling suggest that these whales potentially could occur more broadly throughout the GOM. High levels of anthropogenic activities in the GOM, including oil and gas exploration and extraction, fisheries, shipping, and the unprecedented *Deepwater Horizon* oil spill, highlight the need to better understand the distribution, ecology, and threats to this small population to improve protection of these endangered whales. We used long-term passive acoustic recordings from the northwestern GOM shelf break to explore the extent of Rice's whale distribution in the northern GOM and to evaluate whether they exhibit seasonal movements throughout this range. We describe 6 new stereotyped variants of Rice's whale long-moan calls, found predominantly in the western GOM, that share distinctive features with typical eastern long-moans, including a 150 Hz starting tone, an approximately 100 Hz tail with amplitude modulation, and a long call duration ranging from 10 to 35 s. Western long-moan variants were detected at 3 northwestern sites, occurring sporadically throughout the year on as many as 16% of days at the westernmost site, and infrequently at an eastern core-habitat site. These results indicate that some whales persistently occur over a broader range in the GOM than previously understood, which is important to consider when designating critical habitat and assessing threats to this Critically Endangered species.

**KEY WORDS:** Rice's whale · *Balaenoptera ricei* · Gulf of Mexico · Bryde's whale · *Balaenoptera edeni* · Passive acoustic monitoring · Distribution

## 1. INTRODUCTION

Rice's whale *Balaenoptera ricei*, the only year-round resident baleen whale found in the Gulf of Mexico (GOM), is one of the most endangered marine mammal species in the world, and basic ecological information needed to support the conservation of this species is lacking. Rice's whales historically

were thought to be a distinct population of Bryde's whales *B. edeni*, commonly called the Gulf of Mexico Bryde's whales or Gulf of Mexico whales, but recent studies indicated that they are a unique evolutionary lineage with sufficient divergence to be recognized as a separate species (Rosel & Wilcox 2014, Rosel et al. 2021). Their only known habitat (i.e. the core habitat; Rosel & Garrison 2022) is a

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small area along the northeastern GOM shelf break near the De Soto Canyon (Soldevilla et al. 2017), and their most recent mean abundance estimate from 2017–2018 line-transect surveys of US GOM oceanic waters is 51 individuals (CV 0.53; Garrison et al. 2020). Based on their localized distribution, low estimated abundance, and evidence that this population exhibits very low levels of genetic diversity (Rosel & Wilcox 2014), the US National Marine Fisheries Service (NMFS) has listed the Rice's whale as an endangered species under the US Endangered Species Act (ESA), and the ESA requires the development of conservation plans and designation of critical habitat. The high level of anthropogenic activities in the GOM, including oil and gas exploration and extraction, fisheries, shipping, and the 2010 *Deepwater Horizon* oil spill, highlight the need to better understand the distribution, ecology, and risks of this endangered species.

Historical records suggest that Rice's whales may once have occurred over a broader area of the GOM than their currently known core habitat, including west of the Mississippi River delta, although sightings in the northwestern GOM are now rare, despite substantial survey effort (Soldevilla et al. 2017, Rosel et al. 2021). Historical whaling records found balaenopterids in the north-central and southern GOM (Reeves et al. 2011), and these are presumed to be primarily Rice's whales as they are the only resident baleen whale found in the GOM and the only Bryde's-like whale to be genetically identified in the GOM (Rosel et al. 2021). Predictive density modeling highlights the importance of the 200 m isobath and indicates a potential area Rice's whales may occupy along the northwestern GOM shelf break (Roberts et al. 2015, 2016), which is supported by 1 genetically verified Rice's whale sighting off Texas in 2017, 2 medium-sized balaenopterid whale sightings off Louisiana, and 2 Bryde's-like whale strandings in the northwestern GOM (Rosel et al. 2016, 2021). Additionally, seismic survey mitigation protected species observers (PSOs) have reported numerous potential sightings between 2002 and 2014 that remain unconfirmed. Photos and notes from 13 unconfirmed Bryde's-like whale sightings from PSOs that occurred along the northwestern GOM shelf-break from 2010 to 2014 were reviewed by experts; 9 were ruled out, while 4 could neither be verified nor ruled out as Rice's whale sightings (Rosel et al. 2021). An additional 15 unconfirmed Bryde's-like whale sightings were reported in the western GOM between 2002 and 2008 (Barkaszi et al. 2012) but

have not been reviewed by experts. It remains unknown whether confirmed and potential Rice's whale sightings in the western GOM represent extralimital movements, if there has been a range contraction, possibly due to the extensive anthropogenic activities in the northwestern GOM (Rosel & Wilcox 2014), or if Rice's whales still occupy this northwestern region in low densities.

Autonomous passive acoustic monitoring (PAM) methods are the most successful tool for finding rare whale species in areas where they occur infrequently and areas where they were historically sighted by whalers (e.g. Munger et al. 2008, Mellinger et al. 2011). Rice's whale calls have been described (Rice et al. 2014a, Širović et al. 2014) and recently verified (Soldevilla et al. 2022). These calls were regularly detected in autonomous recordings in the known core habitat near De Soto Canyon (Rice et al. 2014a, Širović et al. 2014), indicating that passive acoustic methods are successful for documenting the temporal occurrence patterns of Rice's whales in their known distribution range in the northeastern GOM. Additionally, autonomous acoustic methods are increasingly being used to monitor ambient sound conditions for use in understanding risks of acute and chronic anthropogenic noise on acoustically sensitive whales (Hildebrand 2009, Hatch et al. 2012, Rolland et al. 2012). These methods provide important information on the sound conditions that Rice's whales are experiencing, and information to improve our understanding of call detectability in differing sound environments (e.g. Helble et al. 2013).

In this study, we used long-term passive acoustic recordings to investigate an area of potential importance to Rice's whales to better understand the extent of their distribution in the northern GOM and evaluate whether they exhibit seasonal movements throughout this range. We deployed autonomous passive acoustic recorders at 5 sites along the northwestern GOM shelf break in predicted Rice's whale habitat for 1 yr to (1) determine whether Rice's whales occur in waters beyond the northeastern GOM and, if so, (2) evaluate their seasonal occurrence and site fidelity at the 5 northwestern GOM sites. Additionally, we evaluated temporal occurrence of Rice's whale calls at a concurrently deployed long-term (since 2010) acoustic recording site in their known core northeastern shelf break habitat. Given the very small population size of these whales, it is imperative to determine the extent of their range and seasonality of their distribution to offer the best protection possible to this endangered species.

## 2. MATERIALS AND METHODS

### 2.1. Site selection and acoustic recording instrumentation

From June 2016 to August 2017, calibrated autonomous passive acoustic recorders were deployed at 5 sites along the shelf break in the northwestern GOM, and concurrent acoustic recordings were col-

lected at a long-term site in the northeastern GOM from August 2016 to July 2017 (Fig. 1, Table 1). The 5 new PAM sites were selected to maximize the likelihood of finding Rice's whales beyond their known habitat. Site selection was based on the median water depth of 221 m for Rice's whale sightings in the core northeastern habitat (Soldevilla et al. 2017), locations of historic sightings of unidentified baleen whales (Soldevilla et al. 2017), and an approximately

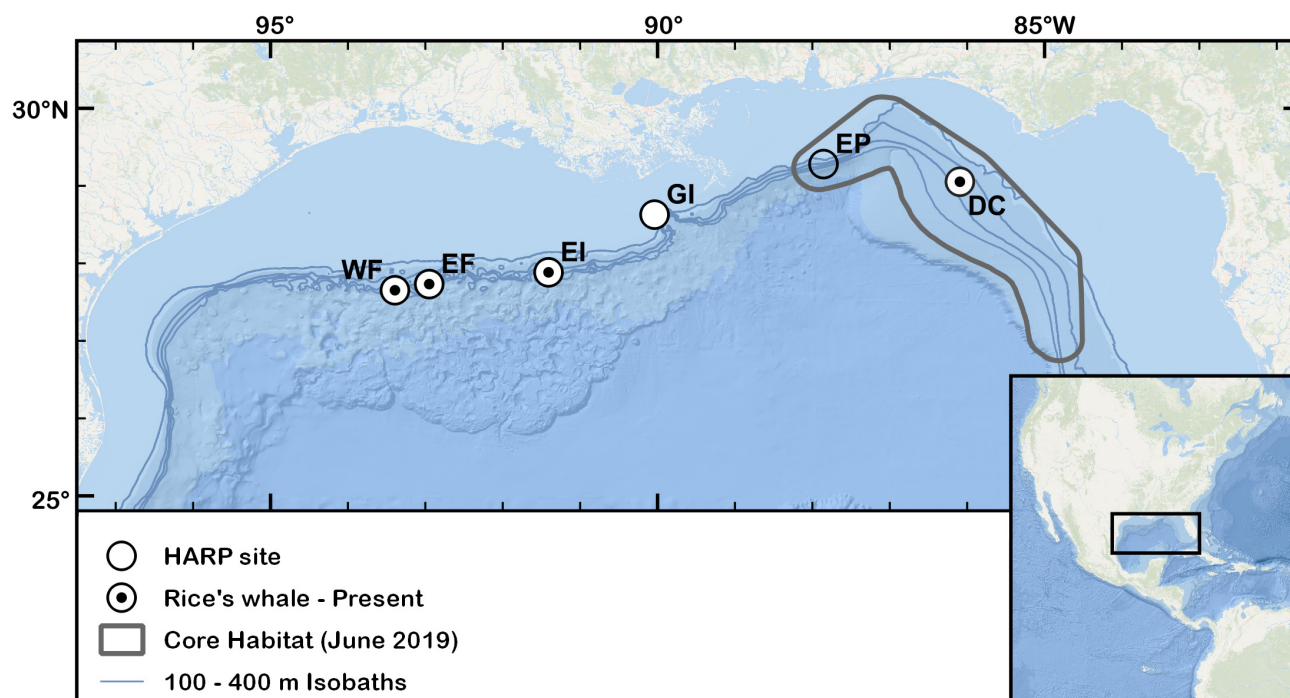


Fig. 1. Locations of 5 high-frequency acoustic recording packages (HARPs) deployed along the northern Gulf of Mexico (GOM) shelf break in areas of potential Rice's whale habitat from July 2016 to August 2017 and a long-term HARP (De Soto Canyon, DC) deployed in the Rice's whale core habitat in the northeastern GOM since 2010. White-filled circles indicate successful data collection; black dots indicate Rice's whale call presence. Known Rice's whale core habitat (gray outline, as of June 2019) and 100 m isobath contours from 100 to 400 m are also shown. WF: Flower Garden West; EF: Flower Garden East; EI: Eugene Isle South; GI: Grand Isle South; EP: East Main Pass

Table 1. Gulf of Mexico high-frequency acoustic recording package (HARP) deployment details. Dates are given as mo/d/yr

Site	Site ID	Latitude (°N)	Longitude (°W)	Depth (m)	Start date (UTC, h)	End date (UTC, h)	Duration (d)	Data quantity (GB)
East Main Pass <sup>a</sup>	EP	29.2811	87.8583	233	7/19/2016 (18:00)	9/19/2016 (08:37)	62	19.8
Grand Isle South	GI	28.6292	90.0405	206	7/20/2016 (06:00)	8/13/2017 (12:10)	389.3	125.4
Eugene Isle South	EI	27.8845	91.4094	272	7/20/2016 (18:00)	5/15/2017 (22:27)	299.2	96.4
Flower Garden East	EF	27.7331	92.9513	261	7/21/2016 (06:00)	5/15/2017 (15:05)	298.4	96.1
Flower Garden West	WF	27.6541	93.3941	260	7/21/2016 (06:00)	5/15/2017 (12:24)	298.3	96.1
De Soto Canyon <sup>b</sup>	DC	29.0480	86.0975	270	8/25/2016 (00:00)	7/18/2017 (16:32)	304.4	97.9

<sup>a</sup>The East Main Pass instrument had a hardware failure after 2 mo

<sup>b</sup>The De Soto Canyon HARP data were decimated from a 200 kHz sample rate to a 2000 Hz sample rate since only low-frequency data were needed for this analysis. Data quantity represents the decimated data for closest comparison with the low-frequency configured HARPs which had a 2000 Hz sample rate. This dataset had a minor disk write error that missed approximately 5 s per 37.5 min file. The duration represents the total sum duration of the recordings, not the total number of unique days with recordings present

evenly spaced sampling along the northcentral to northwestern GOM shelf break.

The PAM devices used in this study were high-frequency acoustic recording packages (HARPs) which are moored to the seafloor and consist of a calibrated hydrophone tethered ~10 m above a packaged data logger, batteries, flotation, acoustic release, and ballast weight system (Wiggins & Hildebrand 2007). HARPs can be configured with different sample rates and number of hydrophones, depending on monitoring goals, which directly affect recording duration and deployment costs. In this study, we used 2 configurations: low-frequency and broadband. In both cases, recordings were continuous using a 16-bit analog to digital converter with data recorded to laptop-style hard disk drives. The HARPs at the 5 sites along the northwestern shelf break were configured as low-frequency recorders and set to sample at 2 kHz using a hydrophone with an effective frequency band of 10 Hz–1 kHz, which was sufficient for recording the fundamental frequency of all known and proposed Rice's whale calls. The long-term HARP on the shelf was part of another project and was configured as a broadband recorder set to sample a wider-band hydrophone at 200 kHz with an effective band of 10 Hz–100 kHz. However, since only low-frequency sounds were required for the Rice's whale analyses, the broadband recordings were decimated by a factor of 100 to provide an effective frequency bandwidth of 10 Hz–1 kHz.

The 2 types of hydrophones used in this study were custom designed and built for the 2 different configurations. Both hydrophone types consisted of lead-zirconium-titanate ceramic pressure transducers connected to low-power, low-noise signal conditioning electronics including a pre-amplifier, multi-stage low-pass filter, and differential signal line drivers. The low-frequency hydrophone used a combination of 6 Teledyne-Benthos AQ-1 cylindrical transducers to add more sensitivity prior to the pre-amplifier stage where the noise floor is set, whereas the broadband hydrophone used an International Transducer Corporation (now Gavial) ITC-1042 spherical sensor for a wider frequency range than the cylindrical transducers. Each type of transducer had a sensitivity of about  $-200$  dB re V/ $\mu$ Pa, and the overall effective hydrophone electronic noise floor at 1 kHz was measured to be approximately 40 and 34 dB re  $1 \mu\text{Pa}^2/\text{Hz}$  for the broadband and low-frequency hydrophones, respectively, well below the ambient sound levels in the GOM (Wiggins et al. 2016). Each signal conditioning electronics circuit board was calibrated at Scripps Institution of Oceanography, and

each hydrophone comes with a calibration frequency response. Representative hydrophone-circuit board-data logger systems were full-system calibrated at the US Navy Transducer Evaluation Center in San Diego, CA (e.g. Wiggins & Hildebrand 2007). These calibrations were used to convert all recordings to sound pressure levels.

## 2.2. Rice's whale call repertoire

The verified Rice's whale call repertoire includes several stereotyped pulsed and tonal call types (Rice et al. 2014a, Širović et al. 2014, Soldevilla et al. 2022). The pulsed downsweep sequence call type consists of sequences of 2 or more short duration downsweep pulses (mean: 8 downsweeps, range: 2–27) ranging in frequency from  $110 \pm 4$  to  $78 \pm 7$  Hz, (mean  $\pm$  SE) with a mean duration of  $0.4 \pm 0.1$  s, an inter-pulse interval of  $1.3 \pm 0.1$  s, and source levels of  $155 \pm 14$  dB re:  $1 \mu\text{Pa}$  at 1 m (Rice et al. 2014a, Širović et al. 2014). The downsweep sequences were also referred to as call Be9 by Širović et al. (2014). Given the recent species name change, we abandon this naming convention and use the call name established by Rice et al. (2014a). The frequency-modulated tonal long-moan call type is a long-duration downswept call with mean 95% frequency of 150 Hz, mean 5% frequency of 83 Hz, mean center frequency of 107 Hz, mean 90% duration of 22.2 s, and a mean 3.4 pulse/s amplitude modulation rate (Rice et al. 2014a). In some instances (3.2%), long-moans are followed by a tonal-sequence call type consisting of 1 to 6 narrow-band nearly constant-frequency tones in sequence, with individual tonals having a mean center frequency of 103 Hz and mean 90% duration of 3.6 s (Rice et al. 2014a). Beyond these 3 verified calls, 2 similar pulsed call types, high-frequency downsweeps (Širović et al. 2014) and low-frequency downsweeps (Soldevilla et al. 2022), have been proposed as potential Rice's whale calls. Other call types have been recorded from a juvenile Bryde's-like whale in rehabilitation after stranding along Florida's gulf coast (Edds et al. 1993), but these have not yet been recorded in the presence of free-ranging Rice's whales.

## 2.3. Acoustic analysis

To evaluate whether and when Rice's whale calls may occur, acoustic recordings at northwestern GOM sites were manually analyzed with a custom software program, Triton version 1.81.20120514, developed and

executed in MATLAB (The MathWorks). Raw acoustic HARP recordings were converted to XWAV format, a format similar to WAV that incorporates instrument meta-data in an expanded header along with precise recording time stamps. The raw acoustic data were compressed for efficient visual review by creating long-term spectral averages (LTSAs; Wiggins & Hildebrand 2007) from the XWAV files. LTSAs are essentially spectrograms created using the Welch algorithm (Welch 1967) to coherently average 5 one-second spectra created from 2000 samples with 0% overlapped and Hann-windowed data and display these averaged spectra sequentially over time. The resulting LTSAs had resolutions of 1 Hz and 5 s in frequency and time, respectively.

The use of LTSAs allows for rapid, efficient, and flexible analyst-review of these large acoustic datasets for a variety of acoustic signals. Using LTSAs, baleenopterid pulsed and tonal calls, wind events, ship passings, seismic surveys, and other acoustic phenomena can readily be distinguished from background sound levels (e.g. Wiggins & Hildebrand 2007). The Triton software package is designed to allow an analyst to investigate detections observed in the LTSA at higher temporal resolution by opening the LTSA-selected event in the originating XWAV as a time series waveform, spectrogram, or spectra for more detailed analyses. A logging tool, the Logger Remora feature, was available within Triton to select and output time and frequency characteristics of acoustic signals from identified events to comma-separated value files. The LTSAs were manually reviewed by a trained acoustic analyst (A.J.D.) for acoustic signals of interest, including known, potential, and novel call types. Due to the long durations of downsweep sequences, long-moan calls, and tonal-sequence calls, Rice's whale calls are easily detected in LTSAs. The acoustic analyst visually examined 30 min long LTSA segments for the presence of signals of interest for all available data from the 5 northwestern sites. When a signal of interest was detected by the analyst, it was more closely reviewed in a 40 s long XWAV spectrogram created from 850 sample discrete Fourier transforms (DFT) with no zero-padding and 95% overlap for 2.4 Hz and 0.05 s resolution. The start and end times of individual calls or other signals of interest were selected and logged using the Logger Remora feature. All detections were manually reviewed, confirmed, and categorized by a second experienced acoustician (M.S.S.). Start times of confirmed calls were used to calculate daily occurrence, hourly occurrence, and call detection rates for temporal analyses to evaluate occurrence, seasonality, and site fidelity in the northwestern GOM.

To evaluate when Rice's whale calls occur in the known core habitat for seasonal comparisons, acoustic recordings at the northeastern site were analyzed using semi-automated detection methods. The stereotyped long-moan calls are detected in such high numbers within the core habitat (e.g. Rice et al. 2014a) that a manual review and logging is not feasible. An automated long-moan call spectrogram correlation detector developed in Ishmael (e.g. Mellinger & Clark 2000) was run on concurrently collected data from the De Soto Canyon (DC) HARP site in the core habitat for efficient detection of these highly stereotyped calls. Spectrograms in Ishmael were calculated with 512 sample fast Fourier transforms (FFT), no zero-padding, and 50% overlap, with spectrogram equalization enabled with 3 s spectral averaging. The spectrogram correlation contour kernel included 2 consecutive parts, each with a contour width of 14 Hz: (1) a 1.1 s near-constant tone with start and end frequencies of 146 and 145 Hz, respectively, and (2) a 3.7 s downsweep from 145 to 112 Hz. Detector settings included a detection threshold of 4.5, detection function smoothing, minimum and maximum detection durations of 0.5 and 3.0 s, respectively, and a minimum duration of 0.5 s between subsequent detection events. The automated detector was developed on the first 5 days of recordings from an August 2015 to May 2016 deployment at the DC HARP site. A test dataset of 1% of the deployment, randomly sampled in 30 min sections, was manually annotated to characterize the detector, yielding a 6.4% miss rate and 26.4% false positive rate (A. Debich et al. unpubl.). The automated call detections in the 2016–2017 DC HARP deployment were manually validated by an experienced acoustic analyst (A.J.D.), and false detections were removed. The call start times of validated long-moan detections were used to calculate daily and hourly occurrence for comparison with results from the northwestern GOM recordings.

To further characterize and compare calls across sites, the spectral and temporal features of detected baleen whale calls were logged in recordings from both northeastern and northwestern GOM sites. The long-moan call can be represented by 3 frequency-modulated features: (1) a short duration (2–3 s) nearly constant start tone at approximately 150 Hz, (2) a frequency-modulated transition zone that smoothly sweeps down in frequency, more steeply at the start and more gently toward the end, into (3) a lower frequency, longer duration (10–20 s) nearly constant tonal tail at approximately 100 Hz, which often contains amplitude modulation, and sweeps up slightly in frequency at the end of the tail (e.g. Rice et

al. 2014a). For call characterizations, the frequency and time of the start, inflection, and end of each of these 3 time-varying frequency-modulated components of the long-moan calls were logged in the Triton Logger Remora for all high-quality calls from the northwestern GOM sites and a subset of calls from the first 5 days of data recorded on the DC HARP in 2015.

#### 2.4. Ambient sound analyses

Ambient sound pressure levels may impact the detectability of Rice's whale calls (e.g. Helble et al. 2013). To evaluate temporal variability in sound pressure levels at each site, LTSAs were created from the HARP recordings, corrected for the hydrophone calibration, with a 1 Hz frequency and 5 s temporal resolution. System electronic noise pickup from data disk-writes was excluded from these averages by removing the appropriate period of data from the start of each raw data file. The broadband raw data files were 75 s long, while low-frequency raw data files were 2.1 h long. For the broadband recordings, hourly spectral averages and associated standard deviations were computed by combining sound pressure spectrum levels calculated from the last ten 5 s averages (total of 50 s each) of each 75 s raw data acoustic record within each hour. For the low-frequency recordings, hourly spectral averages and associated standard deviations were computed by combining all 5 s sound pressure spectrum levels within each hour, except the first 25 s of each file. Hours with partial recordings and hours with deployment/recovery ship sounds or with known instrument electronic noise were discarded. The spectra were further analyzed with custom MATLAB-based software to provide average and percentile sound pressure spectrum levels for each site over the study period, in addition to daily mean and standard deviation time series of sound pressure spectrum level at 150 Hz.

### 3. RESULTS

#### 3.1. Data quality

Four of the low-frequency-configured HARPs recorded a combined 1285 d and 414 GB of acoustic data over the deployment period (Table 1) from 19 July 2016 to 13 August 2017. The recordings were high quality throughout the entire deployment at all 4 sites. The 3 westernmost instruments collected data for nearly 10 mo, and the Grand Isle South (GI)

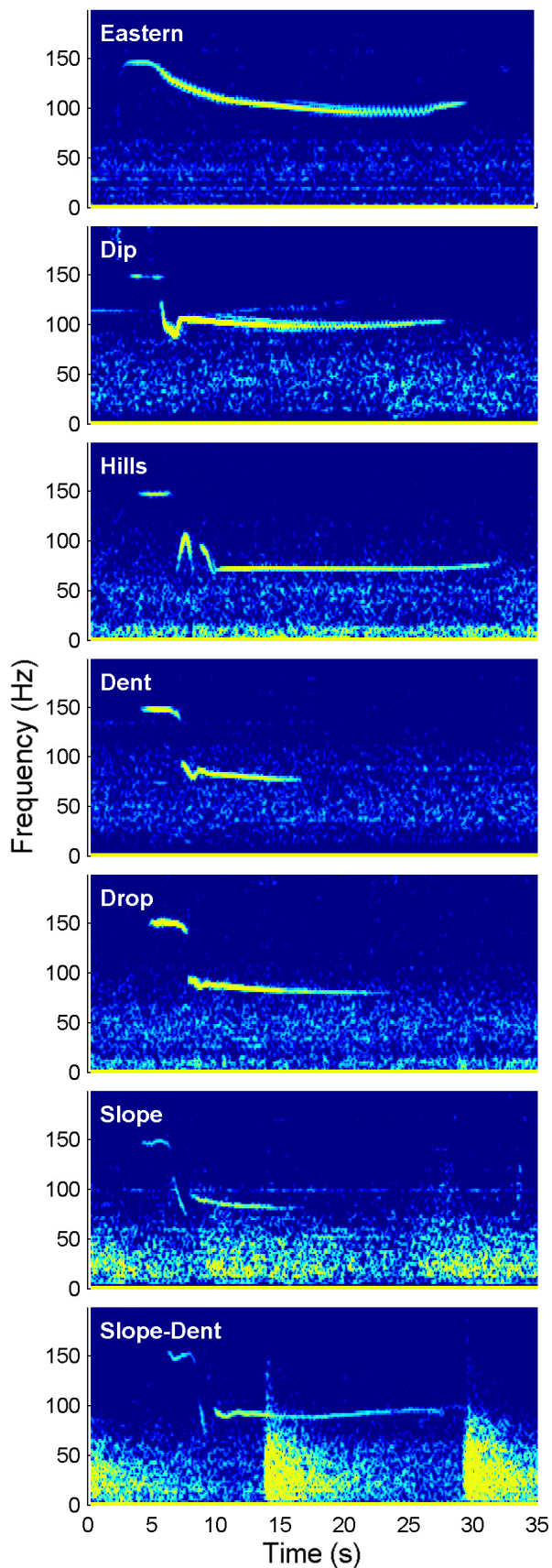
instrument collected data for nearly 13 mo (Table 1). A fifth low-frequency HARP, deployed at the East Main Pass (EP) site had a hydrophone malfunction early on in the 1 yr deployment, yielding only 62 d of high quality recordings. No Rice's whale calls were detected over the 2 mo period; this site is therefore not considered further in the data analyses. The concurrently deployed broadband HARP at the DC site recorded high-quality data over 11 mo, from 25 August 2016 to 18 July 2017 for a total of 304 d of recordings and 98 GB of decimated data.

#### 3.2. Rice's whale call characterization

##### 3.2.1. Call subtypes

Novel stereotyped tonal calls were detected during the manual LTSA analysis of recordings from 3 of the 4 HARP sites in the northwestern GOM. These calls are similar to the Rice's whale long-moan calls commonly detected in the core Rice's whale habitat in the northeastern GOM (Rice et al. 2014a, Soldevilla et al. in press), but with distinct differences from the northeastern calls and with at least 6 stereotyped variations (Fig. 2). Similar to the long-moan calls from the northeastern GOM, the 6 stereotyped calls detected on the western GOM HARPs can be represented by 3 features, with a short duration nearly constant start tone around 150 Hz, a variable frequency-modulated transition zone, and a lower frequency, longer duration nearly constant tonal tail, often around 100 Hz. The start tone appears most similar across calls and the tail is also similar though more variable across call types. However, across western calls, the transition zone is distinctly different from that found in the northeastern GOM, with a sharp frequency drop and stereotyped frequency modulation features that we use to define the different calls (Fig. 2). As opposed to the smooth frequency downsweep between the start tone and the tail in eastern calls, the western calls exhibit sharp disjointed transitions between the start tone and tail.

The time-frequency shapes of these transitions (Fig. 2; quantified in section 3.2.2) are used to provide characteristic names to categorize the subtypes: (1) Dip, which has a sharp frequency drop from the start tone that dips approximately 10–20 Hz below and then sweeps back up to the near tonal tail over a period of 1 s; (2) Hills, which has the most complex transition with a sharp frequency drop followed by 2 disjointed concave components followed by a lower frequency near-constant tonal tail; (3) Dent, which is



similar to Dip, but has a smaller difference in frequency between the minimum and the start frequency of the near-constant tonal tail; (4) Drop, which has a sharp drop off in frequency from the start tone to the lower-frequency near-constant tonal tail, and lacks a transition component; (5) Slope, which is similar to Dip, with a sharp frequency drop off into a disjointed downsweep after the start tone, and followed by a disjointed near-constant tonal tail starting at a higher frequency than the slope; and (6) Slope-Dent, which shares similarities with Slope and Dent with a sharp drop off into a disjointed downsweep followed by a dent that continues into the near-constant tonal tail.

### 3.2.2. Long-moan call component quantification

To quantitatively characterize the western long-moan subtypes and evaluate similarities and differences between the eastern long-moan call and the western GOM call subtypes, the frequency and time of the start, inflection, and end of each of the call components for 220 eastern long-moan calls and 560 western call subtypes are presented in Table 2. The measurements of the start tone component and of the tail component are compared between the eastern long-moan calls and the western subtype calls to evaluate whether the western GOM call subtypes are similar enough to be classified as variations of the Rice's whale long-moan call type identified in the northeastern GOM. Measurements are not compared for the transition component given the high variability and the clear differences among calls for this call component.

The spectral and temporal characteristics of the start tone of all call types were the most similar of the call components. There was little variability in the maximum frequency of the start tone, with the eastern long-moan ranging from 146 to 153 Hz, with a mean ( $\pm$  SD)  $150 \pm 1.1$  Hz while the western call types ranged between 147 and 158 Hz with means from 151 to 154 Hz and standard deviations from 1.3 to 2.3 Hz (Table 2, Fig. 3). The start frequencies of the start tone were slightly more variable, with means

Fig. 2. Example spectrograms of the Rice's whale verified long-moan call (top panel: eastern) from the northeastern Gulf of Mexico and long-moan call subtypes detected on autonomous northwestern high-frequency acoustic recording packages (6 lower panels). Seismic survey airgun signals and shipping noise are evident below 100 Hz. Spectrograms were computed using a 1000 point DFT, Hanning window, and 90% overlap

Table 2. Temporal and spectral characteristics of the 3 parts of each Rice's whale long-moan call type, given as mean  $\pm$  SD (with ranges in parentheses). In some calls, the transition was split into 2 parts which are shown here as Transition 1 and Transition 2. Transition parts that occur in multiple call types are reported as the same part across types. Dashes (–) indicate the transition part does not exist for that call type

	Eastern	Dip	Hills	Dent	Drop	Slope	Slope-Dent
<b>Starttone</b>							
N	220	406	78	32	29	10	7
Startfreq (Hz)	146 $\pm$ 1.3 (142–149)	149 $\pm$ 1.8 (141–157)	148 $\pm$ 1.8 (144–153)	149 $\pm$ 1.8 (146–154)	149 $\pm$ 1.7 (144–151)	151 $\pm$ 3.0 (146–156)	151 $\pm$ 1.8 (149–154)
Maxfreq (Hz)	150 $\pm$ 1.1 (146–153)	151 $\pm$ 1.3 (149–158)	151 $\pm$ 1.7 (147–157)	152 $\pm$ 1.7 (149–156)	152 $\pm$ 1.5 (150–156)	153 $\pm$ 2.3 (150–157)	154 $\pm$ 2.1 (151–156)
Endfreq (Hz)	145 $\pm$ 1.4 (141–150)	146 $\pm$ 1.9 (138–151)	147 $\pm$ 2.2 (139–153)	143 $\pm$ 4.0 (134–149)	140 $\pm$ 5.5 (126–149)	145 $\pm$ 3.2 (141–149)	144 $\pm$ 3.0 (141–150)
Duration (s)	1.9 $\pm$ 0.3 (0.7–2.7)	3.0 $\pm$ 0.5 (0.5–4.4)	3.2 $\pm$ 0.5 (2.2–4.7)	3.0 $\pm$ 0.4 (1.8–4.2)	3.2 $\pm$ 0.6 (1.2–3.8)	2.3 $\pm$ 0.5 (1.8–3.2)	2.4 $\pm$ 0.4 (1.9–3.2)
<b>Transition1</b>							
N	224		78			10	7
Startfreq (Hz)	145 $\pm$ 1.4 (141–148)	–	82 $\pm$ 6.0 (69–103)	–	–	106 $\pm$ 9.3 (92–116)	102 $\pm$ 12.4 (91–126)
Midfreq (Hz)	–	–	108 $\pm$ 2.0 (102–112)	–	–	–	–
Endfreq (Hz)	126 $\pm$ 3.3 (114–135)	–	78 $\pm$ 7.2 (62–101)	–	–	76 $\pm$ 8.8 (59–91)	77 $\pm$ 12.5 (65–102)
Duration (s)	1.5 $\pm$ 0.4 (0.4–3.0)	–	1.0 $\pm$ 0.2 (0.5–1.4)	–	–	0.9 $\pm$ 0.3 (0.4–1.3)	0.6 $\pm$ 0.2 (0.4–1.0)
<b>Transition2</b>							
N	189	406	78	32			7
Startfreq (Hz)	125 $\pm$ 3.2 (114–133)	108 $\pm$ 5.2 (96–126)	–	95 $\pm$ 8.7 (82–112)	–	–	96 $\pm$ 2.3 (92–98)
Midfreq (Hz)	–	89 $\pm$ 2.4 (81–101)	96 $\pm$ 3.5 (89–102)	80 $\pm$ 3.7 (71–89)	–	–	87 $\pm$ 2.5 (83–91)
Endfreq (Hz)	113 $\pm$ 3.9 (104–127)	106 $\pm$ 2.4 (94–111)	75 $\pm$ 4.8 (63–86)	87 $\pm$ 5.1 (74–96)	–	–	93 $\pm$ 6.6 (89–107)
Duration (s)	2.1 $\pm$ 0.8 (0.8–4.6)	1.5 $\pm$ 0.2 (0.6–2.1)	0.8 $\pm$ 0.2 (0.3–1.1)	1.4 $\pm$ 0.2 (1.1–1.7)	–	–	1.2 $\pm$ 0.3 (0.7–1.8)
<b>Tail</b>							
N	109	406	78	32	29	10	7
Startfreq (Hz)	112 $\pm$ 3.2 (103–120)	106 $\pm$ 2.5 (94–111)	72 $\pm$ 3.9 (66–92)	87 $\pm$ 5.1 (74–96)	84 $\pm$ 3.8 (79–97)	92 $\pm$ 7 (86–109)	93 $\pm$ 6.5 (89–107)
Minfreq (Hz)	99 $\pm$ 2.9 (93–108)	97 $\pm$ 3.4 (69–103)	71 $\pm$ 3.2 (65–89)	78 $\pm$ 4.7 (71–89)	73 $\pm$ 3.1 (70–85)	81 $\pm$ 7.7 (72–97)	85 $\pm$ 7.6 (77–100)
Endfreq (Hz)	106 $\pm$ 4.0 (98–116)	99 $\pm$ 4.0 (70–107)	75 $\pm$ 3.7 (70–97)	80 $\pm$ 4.5 (71–90)	75 $\pm$ 2.6 (71–85)	82 $\pm$ 7.4 (73–97)	87 $\pm$ 8.3 (77–101)
Duration (s)	10.7 $\pm$ 3.6 (2.9–23.2)	14.9 $\pm$ 5.2 (0.4–25.4)	14.1 $\pm$ 5.0 (1.2–22.2)	9.9 $\pm$ 3.3 (3.5–15.5)	10 $\pm$ 2.9 (3.4–16.6)	5.9 $\pm$ 2.2 (4.0–11.1)	8.8 $\pm$ 5.9 (2.4–16.4)

ranging from 146 to 151 Hz and standard deviations ranging from 1.3 to 3.0 Hz across all call types. Eastern long-moan start tones were generally lower due to a slight upsweep before the tone while western GOM calls rarely included this initial upsweep, and occasionally occurred as a slightly downswept tonal rather than a near-constant tone (Table 2, Fig. 3). The end frequencies of the start tone were also more variable, with means ranging from 140 to 147 Hz and standard deviations from 1.4 to 5.5 Hz across all call types. The end frequencies were particularly vari-

able for the Dent and Drop calls, which often included a sharp decrease in frequency at the end of the start tone (Table 2, Fig. 3). The durations, while generally similar across calls, were the most variable feature of the start tone with eastern long-moan mean durations of 1.9  $\pm$  0.3 s (mean  $\pm$  SD) and western GOM call means ranging from 2.4 to 3.2 s with standard deviations of 0.4–0.6 s across the 6 call types (Table 2, Fig. 3).

There was greater variability in the spectral and temporal characteristics of the tails among the call



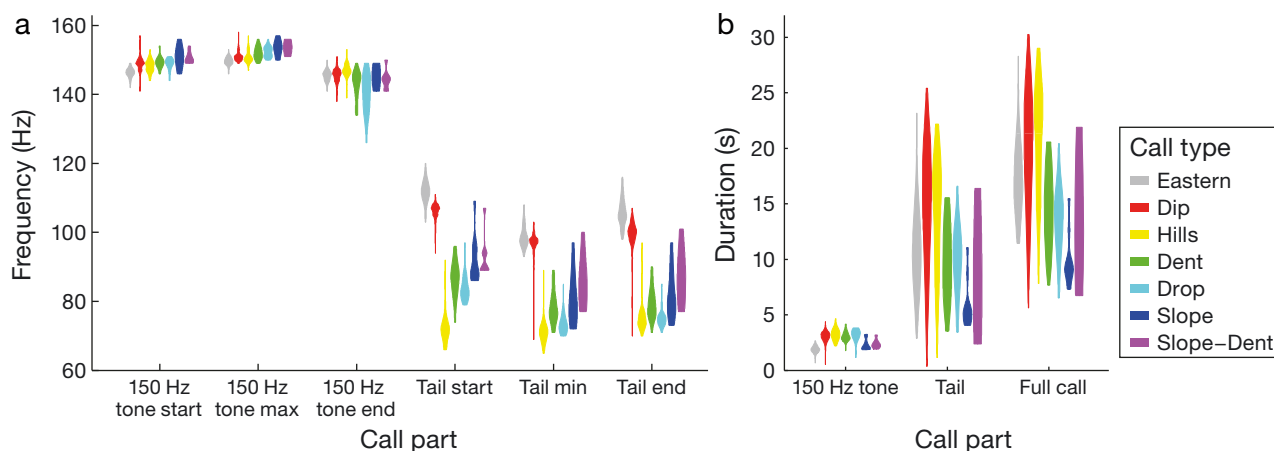


Fig. 3. Distributions of (a) frequencies and (b) durations of the 150 Hz tone and tail call parts for the 7 long-moan Rice's whale call types. Violin plots were created using 'gramm' software in Matlab (Morel 2018)

types, although similarities among them were evident (Table 2, Fig. 3). The frequency values of the 3 tail measurements were most similar between the eastern GOM long-moans and the western GOM Dip call, with mean frequencies of  $112 \pm 3.2$ ,  $99 \pm 2.9$ , and  $106 \pm 4$  Hz versus  $106 \pm 2.5$ ,  $97 \pm 3.4$ , and  $99 \pm 4.0$  Hz for the start, minimum, and end of the tails of the eastern and Dip calls, respectively (Table 2, Fig. 3). Further, both of these call types exhibit a gentle downsweep to the minimum frequency and a gentle upsweep to the end frequency, and often exhibit amplitude modulation throughout the tail (Figs. 2 & 3). On the other hand, the other western GOM call types have lower frequency values for the tail start, minimum, and end points, with the lowest values found for the Hills and Drop calls (minimum frequency means up to 28 Hz lower at  $71 \pm 3.2$  and  $73 \pm 3.1$  Hz, respectively; Table 2, Fig. 3). The durations of the tail component of all call types are variable and relatively long, with means ranging from  $5.9 \pm 2.2$  to  $14.9 \pm 5.2$  s (Table 2, Fig. 3). The tail component often has lower amplitude in the middle or toward the end, so duration measurements may be biased low due to inclusion of some calls with lower signal-to-noise ratio.

### 3.2.3. Other notable characteristics

Some of the calls detected in the western GOM HARP recordings had unusual features worth noting, including harmonic structure, precursor calls, and non-typical frequency modulations.

On occasion, particularly high-amplitude calls exhibited what appeared to be 1 or more harmonics of the 150 Hz start tone (Fig. 4a); however, the harmonic tone is at approximately 225 Hz, not 300 Hz,

indicating that the true fundamental frequency of this component is around 75 Hz, that the dominant frequency at 150 Hz is the 2<sup>nd</sup> harmonic, and the occasional tone at 225 Hz is the 3<sup>rd</sup> harmonic. In a few instances, the 75 Hz tone was observable (Fig. 4b–d). Further, the dominant frequency of the start tone does occasionally vary; in some instances, only a 225 Hz tone is present.

Another unusual feature was the occurrence of what appears to be a precursor to the call which was observed in 2 consecutive high signal-to-noise ratio calls (Fig. 4e,f). These are the only times this was observed; it is unknown if these occur commonly but are only detected when the source is close to the receiver or if this is an unusual occurrence. The precursors were of lower amplitude than the long-moan call, suggesting the former may be the case. Alternatively, the 'precursor calls' may be the coincidental occurrence of a call produced by a fish or other source.

Finally, there were several calls that wavered in frequency compared to the typical calls, which had nearly constant tones for the start tone and tail (Fig. 4g–j). Some had a caret-shaped start tone or other frequency wobbles instead of the constant tone at the start. Others wavered throughout the tail. The cause of this variation is unknown, but did not appear to be a sound-propagation effect.

### 3.2.4. Call timing

Across all sites, timing between subsequent western long-moan call detections, or intercall intervals (ICIs), was variable with no obvious pattern, and had a highly right-skewed distribution (Fig. 5). After removing all ICIs greater than 1 d, western long-moan

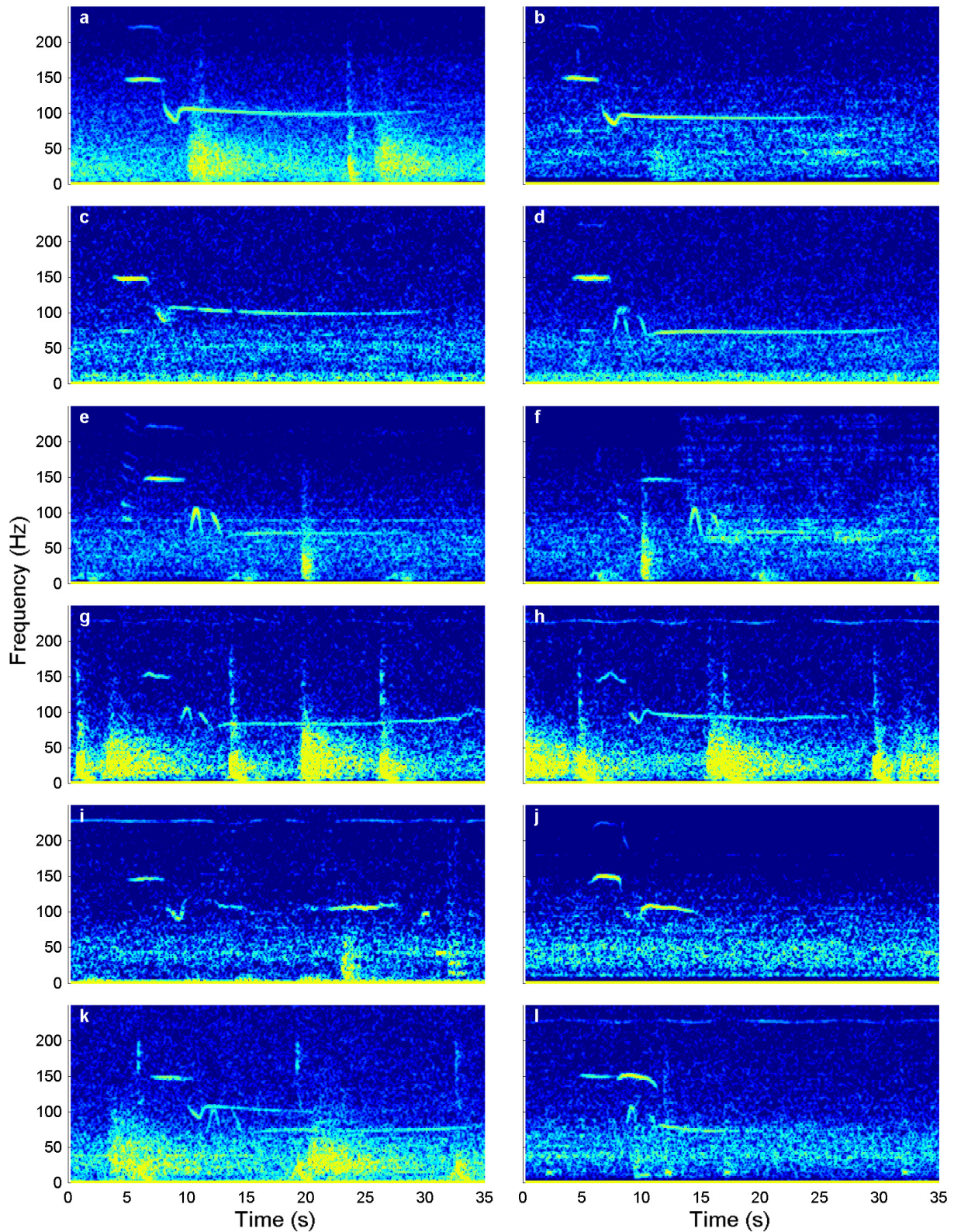


Fig. 4. Spectrogram examples of unusual call features present in some calls including: (a–d) harmonic structure and evidence of 75 Hz fundamental frequency for start tone; (e, f) a pre-cursor call; and (g–j) calls that wavered in frequency modulation. Two examples of overlapping calls indicating the presence of more than 1 whale: (k) Dip and Hills and (l) Hills and Drop. Seismic survey airgun signals and shipping noise are evident, primarily below 100 Hz. Spectrograms were computed using a 1000 point DFT, Hanning window, and 90% overlap

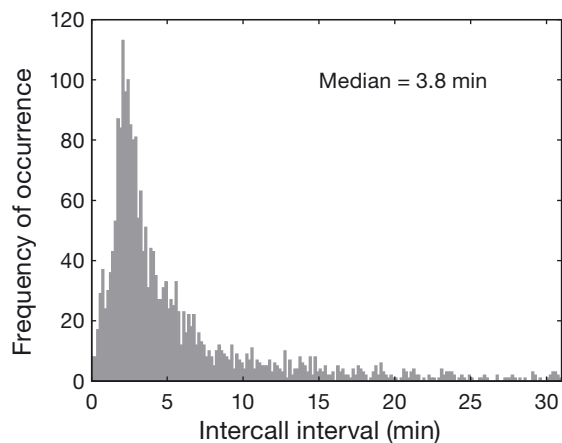


Fig. 5. Western long-moan intercall intervals, with 10 s resolution, at the WF, EF, EI, and DC sites (see Fig. 1 for full site names). Intercall intervals represent the timing between subsequent call detections, which are not necessarily the same as call production rates

call ICIs across the 4 sites ranged between 1 s and 22.7 h, with 90 % of ICIs less than 31 min, a modal ICI of 2.1 min, and a median ICI of 3.8 min. Note that these ICIs are not necessarily individual call production rates, since they may represent times between calls from multiple animals and they do not account for calls that were not detected.

Overlapping calls were noted on several occasions, which may represent echoes or multiple individuals present and producing calls (Fig. 4k,l). In some instances, the overlapping calls were of different call subtypes, indicating at least 2 individuals calling during that encounter. At the Flower Gardens West (WF) site, there were at least 6 instances of overlapping calls, including overlapping Dip and Hills call subtypes and Hills and Drop call subtypes, over the 6 d period from 28 August to 2 September 2016. At the Flower Gardens East (EF) site, there were at least 2 instances of overlapping calls during the same period, on 1 September 2016. At the DC site, there were at least 14 instances, on 12 and 23 November 2016, when western long-moan calls overlapped with 1 or more eastern long-moan and downsweep sequence calls, but there were no instances with 2 overlapping western long-moan calls at this site.

### 3.3. Call occurrence by site

The variants of the long-moan calls made up the majority of balaenopterid-like calls detected on the western GOM HARPs. The western GOM long-moan variants were de-

tected most frequently at the westernmost WF site, with 1939 calls detected over 47 d (16 % of days with effort; Table 3). Call detections decreased heading east across the western sites with 429 calls detected on 18 d (6 % of days with effort) at the EF site, 22 calls detected on 3 d (1 % of days with effort) at the Eugene Isles South (EI) site, and no calls detected at the GI site (Table 3). Farther east in the core northeastern habitat, the western GOM calls were detected infrequently on the DC HARP and represent <0.25 % of calls detected at this eastern site, with only 150 long-moan variant calls detected on 21 d (6.4 % of days with effort, Table 3), out of a total of 66 583 manually validated long-moan automated detections during this deployment at this site. In contrast, at the western sites, only a single possible eastern GOM long-moan was detected on the WF HARP on 30 August 2016 and 3 probable high-frequency downsweep sequences were detected on the WF HARP on 2 November 2016. The single possible eastern GOM long-moan detection had a low signal-to-noise ratio and could not be positively identified to any call type; it cannot be ruled out as a western GOM call, but it is the only detected call that could have potentially been an eastern GOM long-moan call. Besides these 4 instances of possible eastern GOM call types at WF, no confirmed eastern GOM call types were recorded on any of the other HARPs over the 10–12 mo deployment periods.

Of the 6 long-moan call subtypes, 4 (Dip, Hills, Dent, Drop) were detected on all 3 western HARPs, while Slope and Slope-Dent were not detected at the EI site. The Dip subtype was the most commonly recorded, with 723 detections across the 3 western HARPs, and Hills was the second most commonly recorded subtype, with 445 detections across the 3 western HARPs. Drop and Dent subtypes were

Table 3. Recording availability and number of Rice's whale calls manually detected on 5 high-frequency acoustic recording packages located in the northern Gulf of Mexico (GOM). Only the western GOM long-moan variant calls are reported for De Soto Canyon (DC); more than 66 000 eastern GOM long-moan calls were detected at the DC site. Site abbreviations as in Table 1

July 2016 – August 2017	WF	EF	EI	GI	DC
Recordings available					
Days	299	299	300	378	326
Hours	7160	7162	7181	9072	7799
Long-moan calls					
No. of calls	1939	429	22	0	150
Days present (%)	47 (15.7)	18 (6.0)	3 (1.0)	0 (0)	21(6.4)
Hours present (%)	330 (4.6)	80 (1.1)	11 (0.2)	0 (0)	59 (0.8)

Table 4. Rice's whale call detections per high-frequency acoustic recording package site by long-moan subtype. Site abbreviations as in Table 1

Long-moan subtype	Site			
	WF	EF	EI	DC
Dip	678	41	4	30
Hills	393	47	5	9
Drop	79	2	1	0
Dent	47	6	2	0
Slope	21	1	0	0
Slope-Dent	6	1	0	0
150 Hz tone only	393	253	4	0
Unidentifiable	322	78	6	111

detected 82 and 55 times, respectively, across the 3 western HARPs. Slope and Slope-Dent were detected 22 and 7 times, respectively, across the WF and EI HARPs. Only Dip and Hills call subtypes were positively identified in the eastern DC HARP recordings (Table 4). An additional 406 long-moan calls were too faint to be confidently identified to subtype, and a total of 650 possible long-moan calls only had the 150 Hz tone detectable (Table 4). The 150 Hz tone was typically the highest amplitude part of the long-moan subtypes and the possible calls represented by only the 150 Hz tone occur in cases when signal to noise ratios are low, such as occurs with more distant callers or when vessel traffic and seismic survey noise common at these sites is present. Nearly all (95%) of 150-Hz-tone-only calls occurred within 30 m of other tones or long-moan subtypes, and typically had similar ICIs and tone durations to those of confirmed calls with sharp onset and offset and near-constant frequency, suggesting that the majority of these possible calls are true western long-moan subtype calls.

Long-moan variant call detections occurred in sporadic clusters throughout the year at the WF site, and although the EF and EI sites had fewer call detections, they followed a similar pattern (Fig. 6), without any obvious seasonality on any of the HARPs (Table 5). At least 1 call was detected in every month of the year (Table 5) on the western GOM HARPs. The peak call detections and days present per month occurred in August at WF and EF, with high numbers in September, December, and March as well. The peak number of western long-moans at DC occurred in November. The number of calls detected per day peaked at 241 at the WF site in August (Fig. 7), with calls clustered over a period of 10 consecutive days. The 4 most common subtypes were usually all detected on days when long-moan variants were

present, though the frequency of occurrence of a given subtype varied (Fig. 7). Finally, western long-moan call detections rarely occurred on multiple HARPs on the same day. There were 8 days with call detections present on both of the closely spaced WF and EF HARPs (~40 km spacing), including 2 periods in which the same calls were detected at both sites. There was only 1 day when call detections were present on both of the distantly spaced DC and EF HARPs (~700 km spacing), while calls were detected on consecutive days on DC and either WF or EF HARPs on 2 occasions in December 2016. At these distances, it is unlikely the calls on eastern and western sites came from the same whales.

### 3.4. Sound levels

Ambient sound pressure spectrum levels varied substantially among the sites (Fig. 8), although nearly all sites had high sound pressure spectrum levels at low frequencies that decreased by 20–25 dB re 1  $\mu\text{Pa}^2/\text{Hz}$  as frequency increased until flattening around 200 Hz. The DC site had the lowest sound pressure spectrum levels overall, with median sound pressure spectrum levels in the 60–160 Hz band (Rice's whale call frequency) ranging between 58 and 72 dB re 1  $\mu\text{Pa}^2/\text{Hz}$ . Sound pressure spectrum levels at the WF site, with the next lowest median sound pressure spectrum levels in the 60–160 Hz band, were around 7 dB re 1  $\mu\text{Pa}^2/\text{Hz}$  higher than at the DC site, ranging between 65 and 79 dB re 1  $\mu\text{Pa}^2/\text{Hz}$ . Median sound pressure spectrum levels in the 60–160 Hz band were still higher at the EF site, ranging between 67 and 82 dB re 1  $\mu\text{Pa}^2/\text{Hz}$ , and were highest at EI, ranging between 73 and 83 dB re 1  $\mu\text{Pa}^2/\text{Hz}$ . Further, the variance in noise levels was higher at EI, with 95% percentile sound pressure spectrum levels ranging between 86 and 100 dB re 1  $\mu\text{Pa}^2/\text{Hz}$ . The GI site, near the head of the Mississippi Canyon, was the only site at which sound pressure spectrum levels were approximately flat across the 60–160 Hz band, though tonal signals were present at harmonics of approximately 30 Hz (Fig. 8). The median sound pressure spectrum levels in the 60–160 Hz band ranged between 73 and 77 dB re 1  $\mu\text{Pa}^2/\text{Hz}$ . Median sound pressure spectrum levels at the lower frequencies at GI were generally lower than at the other sites (e.g. 3 dB re 1  $\mu\text{Pa}^2/\text{Hz}$  lower than WF at 75 Hz), while median sound pressure spectrum levels at the higher frequencies were substantially higher than at the other sites (e.g. 11 dB re 1  $\mu\text{Pa}^2/\text{Hz}$  than WF at 150 Hz; Fig. 8).

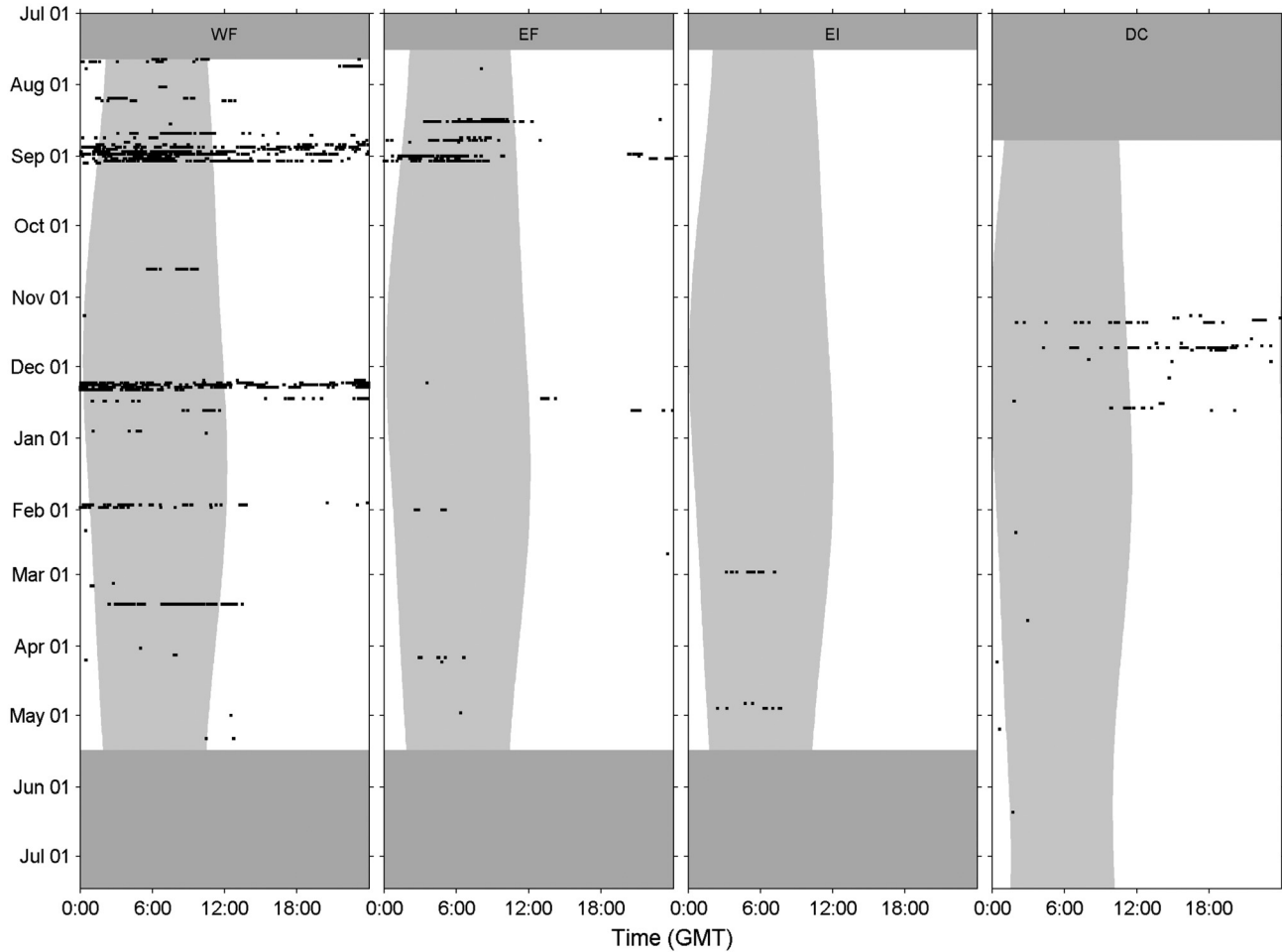


Fig. 6. Temporal occurrence of Rice's whale calls from long-term spectral average analyses at the WF, EF, EI, and DC sites (see Fig. 1 for full site names) from 2016 to 2017. Gray hourglass shading represents nighttime, while darker gray shading indicates periods of no effort. The black markers represent western long-moan variant calls; eastern long-moans detected at site DC are not plotted

Table 5. Rice's whale long-moan variant call detections per month per high-frequency acoustic recording package site. Site abbreviations as in Table 1; na: data not available

	Detected calls				Days with detections (%)			
	WF	EF	EI	DC	WF	EF	EI	DC
July <sup>a</sup>	14	1	0	na	2 (18)	1 (9)	0	na
August	792	214	0	na	14 (45)	6 (19)	0	na
September	332	184	0	0	4 (13)	3 (10)	0	0
October	31	0	0	0	1 (3)	0	0	0
November	1	0	0	128	1 (3)	0	0	11 (37)
December	574	17	0	17	10 (32)	3 (10)	0	5 (16)
January	68	0	0	0	3 (10)	0	0	0
February	1	7	13	1	1 (4)	2 (7)	1 (4)	1 (4)
March	102	0	0	1	3 (10)	0	0	1 (3)
April	5	8	9	1	3 (10)	3 (10)	2 (7)	1 (3)
May <sup>a</sup>	3	0	0	1	2 (13)	0	0	1 (3)
June	na	na	na	1	na	na	na	1 (3)

<sup>a</sup>July 2016 and May 2017 were partial months at the 3 western sites, with 11 and 15 d with recordings present, respectively

#### 4. DISCUSSION

The long-moan call variants described here from autonomous recorders in the northwestern GOM are new calls that have not previously been described; we assess that they are a Rice's whale call type based on the strong similarities to the long-moan calls recorded in the presence of Rice's whales in the eastern GOM. Typical Rice's whale long-moan calls are distinctive among marine animal vocalizations as they have a highly stereotyped, complex frequency-modulated call structure which includes tonal and amplitude-modulated components and extensive durations of 20–40 s that are distinctly different from calls produced by other baleen whales (Rice et al. 2014a, Soldevilla et al. 2022).

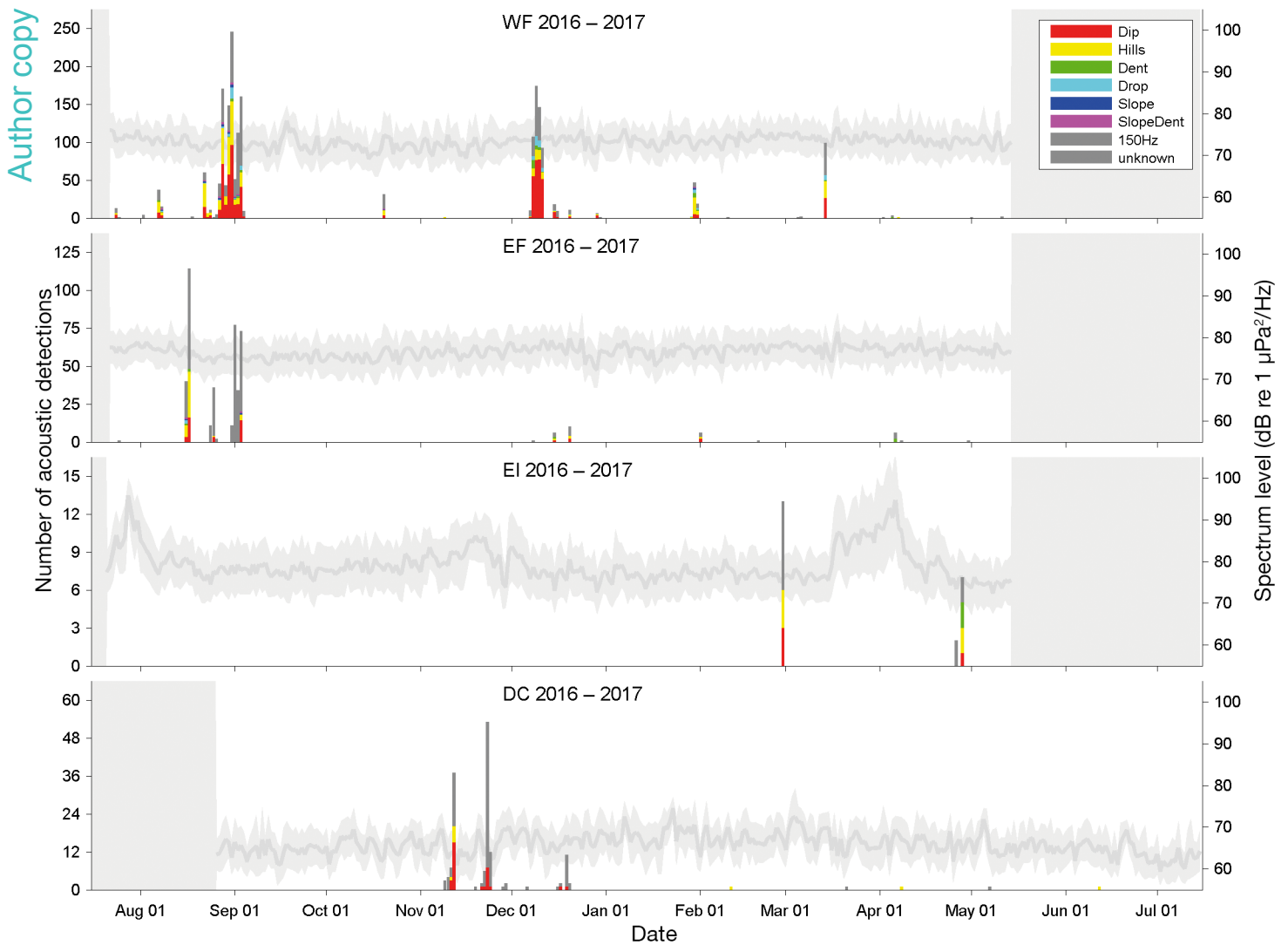


Fig. 7. Daily detections of Rice's whale western long-moan subtypes (bars) and sound pressure spectrum levels at 150 Hz (average: thick line, standard deviation: shading). Gray shaded periods at start or end indicate no recording effort. Note that acoustic detections on the y-axes are on different scales for each site (see Fig. 1 for full site names)

The calls detected on the western GOM HARPs share numerous features in common with eastern GOM long-moans, including a 20–40 s total call duration, the frequency range and 2–3 s duration of the 150 Hz start tone, and the approximately 10–20 s duration tail with the similar frequency range, amplitude modulation and slight final frequency upsweep in some western subtypes. In particular, the Dip subtype is most similar to the typical long-moan across durations and frequencies of these features, with the transition zone being the main component of the call that is different. Such complex and long-duration calls are exclusively produced by marine mammals. Some fish produce very long-duration calls (McIver et al. 2014), and one complex frequency-modulated

call has been recorded from an unknown fish species, possibly Atlantic midshipman *Porichthys plectrodon* (Wall et al. 2012), but calls that are both long-duration and exhibit complex tonal and amplitude modulation have not previously been reported from fish. Anthropogenic noise source production of the eastern long-moan call has been ruled out by extensive field investigations (Soldevilla et al. 2022). On the other hand, baleen whales commonly produce complex, stereotyped, frequency-modulated calls (Richardson et al. 1995, Au & Hastings 2008), some with high source levels (Širović et al. 2007) and some with comparably long durations (Thompson et al. 1996, Mellinger et al. 2000, McDonald et al. 2006). Further, the stereotyped eastern long-moan calls

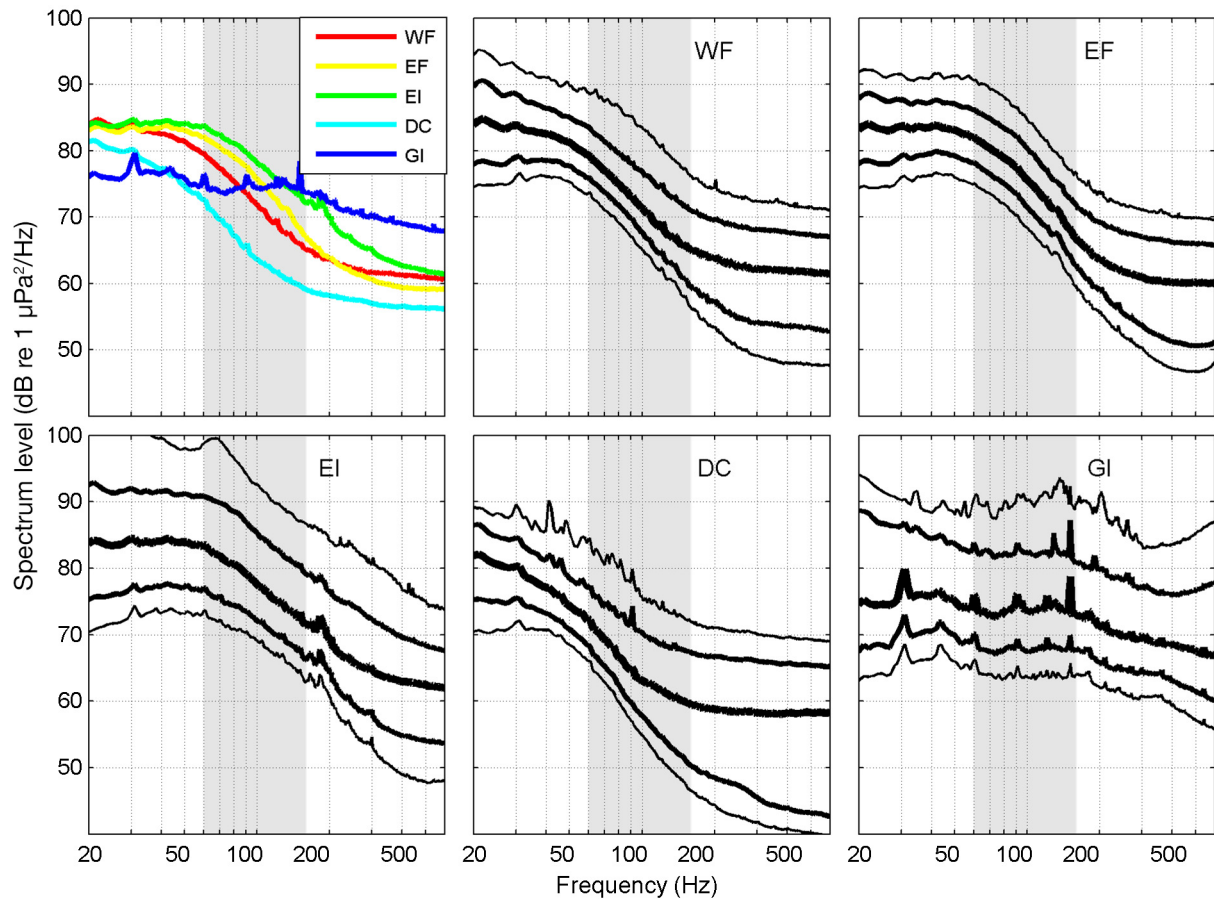


Fig. 8. Average sound pressure spectrum levels by site over the entire deployment period (upper left panel) and site-specific distribution of daily average sound pressure spectrum levels as percentiles: 1 (lowest), 10, 50 (thick middle line), 90, and 99% (highest). Gray shading indicates the Rice's whale call frequency band. See Fig. 1 for full site names

produced by Rice's whales are distinctly different from calls of any other baleen whale species (Rice et al. 2014a, Soldevilla et al. 2022), including those that occasionally occur in the GOM (Würsig et al. 2000). Based on the described call features, the high source levels as evidenced by the same calls being detected on the WF and EF HARPs spaced over 40 km apart, and the relatively frequent occurrence of calls throughout the year, the source of the western long-moan call variants is a baleen whale, and Rice's whales are the only resident baleen whale found in the GOM. Moreover, the western variants were occasionally heard on the HARP in the core Rice's whale habitat, including during times eastern long-moans and downsweep sequences were detected. Finally, the strong similarity in the features of the start tone and tail between the calls recorded in the eastern and western GOM, and the dissimilarity of these calls to those of any other baleen whale species, suggest these are variants of the typical long-moan call produced by Rice's whales in the eastern GOM.

Understanding the distribution of the Rice's whale is essential for developing a recovery plan to protect critical habitat and reduce impacts of harmful human activities on this endangered species (Rosel et al. 2016), and this study's autonomous acoustic mooring results provide crucial information to improve that understanding. Baleen whale calls in the 100–150 Hz frequency range can generally be detected on scales of tens of kilometers in pelagic environments (e.g. McDonald 2004). Therefore, the intermittent occurrence of the long-moan call at 3 sites in the northwestern GOM throughout the year-long deployments indicates that some Rice's whales regularly occur in waters beyond their known core habitat in the northeastern GOM. Several historic unidentified balaeopterid sightings and recent unverified public sightings near the WF site (e.g. Soldevilla et al. 2017, Rosel et al. 2021), and a genetically verified sighting of a Rice's whale further west along the Texas shelf break in August 2017 (Rosel et al. 2021) support these findings. Considering the decreasing acoustic occur-

rence from 16% of days at the westernmost WF site to 1% of days at the central EI site, and the recent sighting off Texas, it is important to continue this investigative work to determine if the whales' distribution continues further west and how frequently calls are detected there. Based on known water depth preferences of 100–400 m, the current acoustic findings at the 3 sites with up to 16% days present at WF, and the recent sighting offshore of Corpus Christi, Texas, the habitat features of the northwestern GOM shelf-break region from the Texas sighting to the EI mooring site should be considered when designating critical habitat for this species. Further, our results highlight the need to continue searching beyond the known habitat to determine if their distribution extends into deeper waters or southern waters of the GOM or into the northern Caribbean Sea.

An additional goal of this study was to evaluate whether the whales exhibit seasonal migrations or other movement patterns within the northern GOM. While Rice's whales have been sighted in all seasons in the core northeastern habitat (Rosel et al. 2016), a year of acoustic data within the habitat indicated a slight decrease in long-moan call occurrence and few downsweep sequence call types during fall, and potentially continuing into winter when a data gap occurred (Rice et al. 2014b, Širović et al. 2014). More data are needed to understand if seasonal patterns occur in the core habitat and if so, whether they represent movement patterns or changes in detectability with changing ambient noise levels. While long-moan variant call occurrence exhibited temporal clustering throughout the year at the 5 sites throughout the northern GOM, calls were present in all seasons at the WF and EF mooring sites with no obvious seasonality among sites (Figs. 6 & 7, Table 5). Considering the lack of detections at site GI and in the 2 mo of data from EP, it remains unknown whether animals are moving between the northwestern and northeastern sites or whether these represent different groups of animals. If future studies find Rice's whales in the southern GOM or beyond, it will be important to re-evaluate intra-annual movement patterns at that time.

An intriguing question is why the calls detected on the western GOM HARPs are more variable than, and differ slightly from, the calls typically detected in the eastern GOM. No confirmed eastern GOM long-moan calls were heard on the western GOM HARPs, while the western GOM calls were heard on 21 days (6.4%) on the eastern GOM HARP. One explanation is that the call-type production may be context-specific (e.g. Oleson et al. 2007), with some behaviors

and associated calls occurring in one location while others occur at a different location. For example, humpback whales *Megaptera novaeangliae* primarily produce social and foraging calls on their northern foraging grounds, while males produce songs on their migration route and southern breeding grounds (Cerchio et al. 2001, Stimpert et al. 2011). However, Rice's whales do not appear to exhibit seasonal migrations (Fig. 7; Rosel et al. 2016), similar to coastal Bryde's whale populations (Best 2001) and other baleenopterid populations found in the tropics, subtropics, and enclosed seas (Corkeron & Connor 1999, Pomilla et al. 2014, Cerchio et al. 2015). Oceanographic or prey-based contexts might drive the call variation, as could the differing noise levels among areas (e.g. Parks et al. 2007). Another explanation could be individual or group variation in call production, such that certain individuals, sexes, age classes, clans, or populations produce a given call type (e.g. Payne & McVay 1971, Ford 1991, Rendell & Whitehead 2003, Parks et al. 2005, McDonald et al. 2006, Gero et al. 2016, McCordic et al. 2016). Potential impacts of low genetic variability (Rosel & Wilcox 2014) of this small population cannot be ruled as a potential source of the variation.

An important question is how many whales are found in the western GOM, but this is a difficult question to answer from sparse single-sensor autonomous moored passive acoustic units. Overall, there seem to be fewer whales or more sparsely spaced whales in the western GOM compared to the eastern GOM, with calls present on fewer days, lower call detection rates, and far fewer call detections in the western GOM. Rice's whale long-moan variant calls were present on a maximum of 16% of days at western GOM sites compared to 90–100% of days present per month typical at eastern GOM sites (Rice et al. 2014b). The rate of call detections throughout the year also is considerably higher in the eastern GOM than at the western GOM WF site where long-moan variants were most commonly detected, with at least 8.3 calls h<sup>-1</sup> among 4 eastern GOM sites over 110 deployment days (Rice et al. 2014a) compared to 0.27 calls h<sup>-1</sup> over the 299 d deployment at WF. During this study period, just under 2000 calls were detected at the WF site over 10 mo compared to more than 66 000 total long-moan detections (eastern and western) at the DC site over 11 mo for a factor of approximately 30 times more calls detected at the DC site. Sound propagation conditions and site-specific ambient sound levels influence our ability to detect Rice's whale calls and the area over which whales can be detected, making it difficult to directly



compare acoustic call detections among these sites; higher numbers of detections at a site may reflect higher call production rates or larger detection areas rather than higher numbers of animals present. With ambient noise levels at Rice's whale call frequencies approximately 6 dB re  $1\mu\text{Pa}^2/\text{Hz}$  higher at WF than DC (Fig. 8), detection ranges are expected to decrease at WF to approximately 25–50% of those at DC under spreading conditions ranging from spherical to cylindrical, which would yield a decrease in detection area at WF to 12.5–25% of that at DC (e.g. Terhune & Killorn 2021). Therefore, one would expect approximately 4–8 times as many calls at DC compared to WF under geometric spreading loss conditions if ambient noise were the only factor, and whale densities and call rates were similar across sites, rather than 30 times as many.

Some evidence of detection ranges exists in acoustic recordings from the western and eastern GOM. On 2 occasions in the western GOM, several calls were detected on both the WF and EF sites at the same time, while calls prior to and following the overlap were only detected at 1 site. This suggests maximum detection distances of around 20 km at this time if the whale(s) were centered between the 2 sites that are 40 km apart. In the eastern GOM, at least 1 call was heard on 3 hydrophones with a maximum spacing of 150 km (Fig. 7b in Rice et al. 2014a), which indicates that the calls can be detected to at least 75 km in some circumstances. The difference between these maximum detection ranges falls within the 25–50% reductions expected for the 6 dB difference in ambient noise levels between the WF and DC sites, thereby supporting the hypothesis that differences in call rates or animal densities are also a contributing factor to differences in call detections between these sites. Future passive acoustic studies focused on estimating absolute call densities, and potentially whale densities, that account for detection area (e.g. using distance sampling, spatially-explicit capture–recapture, or simulation approaches; Buckland et al. 2001, Küsel et al. 2011, Martin et al. 2013) are needed to fully address these uncertainties.

Additional information on the minimum number of whales producing western variant calls can be found by reviewing overlap in calls in recordings from a single site, concurrent occurrence of different whales at multiple sites, and comparisons of call detection rates to call production rates. The presence of occasional calls that overlap in time (Fig. 4) indicates that at least 2 whales were producing calls in the western GOM. Similarly, the presence of long-moan variant calls on consecutive days at the WF and DC sites,

separated by 740 km (a distance too far for 1 whale to travel in 1 d), supports that at least 2 whales produced these calls. Additionally, a comparison of eastern GOM call production rates from tracked individuals with western GOM ICIs suggests that western GOM acoustic encounters may typically include more than 1 individual. In the eastern GOM, 3 tracked calling whales had average call production rates of 6.3, 8.3, and 10.0 calls  $\text{h}^{-1}$  (Rice et al. 2014a). The median ICIs between western GOM call detections is 3.8 min (Fig. 5), or 15.7 calls  $\text{h}^{-1}$ , suggesting multiple individuals are typically calling or that individual whales are producing calls at higher rates in the western GOM. Notably, with the exception of a few days when the same calls could be heard on both the WF and EF HARPs in which calls moved from west to east and back west again over time, calls were only once detected on multiple HARPs on the same days. This suggests the possibility that a small group of a few whales are moving back and forth along the shelf-break. A focused fine-scale visual survey including photo-identification, a larger-scale densely-spaced moored passive acoustic array survey, or a multi-platform glider survey along the shelf-break could help to answer questions about spatial density and total numbers of animals.

Anthropogenic sources, including seismic survey airgun pulses and shipping traffic noise, appear to be the main contributors to the increased noise levels that lead to reduced detection ranges in the western GOM. The 3 westernmost HARP sites are not far from a major shipping fairway, with WF farthest from it (distances to center of fairway: WF = 15.7 km; EF = 10.0 km, EI = 5.2 km), and vessel traffic noise was common in these recordings. Received levels of vessel noise from a vessel at the center of the fairway would be reduced from source levels by 62.9, 60, and 55.7 dB at the WF, EF, and EI sites, respectively, assuming geometric spreading transmission loss of  $15 \times \log_{10}(\text{Range}[\text{m}])$ , a typical empirical loss rate in these water depths (e.g. Širović et al. 2014). Therefore, maximum received levels of shipping noise from a given ship in the center of the fairway would be 7.2 dB lower at WF than EI, 4.3 dB lower at EF than at EI, and 2.9 dB lower at WF than EF. These noise level differences are supported by ambient noise analyses from the 3 HARPs (Fig. 8). Under these typical transmission loss rates for these water depths, a 4.5 dB re  $1\mu\text{Pa}^2/\text{Hz}$  increase in ambient noise levels may reduce the acoustic detection distance of calls by 50% and the acoustic area sampled by 75% (e.g. Terhune & Killorn 2021). Additionally, the duration of time that received levels are in-

creased for a given vessel transit will be longer for sites closer to the shipping fairway. The effects of low-frequency noise from shipping traffic and airguns on call detections were evident in the detectable features of Rice's whale calls in the western GOM. Many of the manually detected calls at these PAM sites were comprised of only the 150 Hz tone due to increased noise levels below 125 Hz, and these were often of low signal-to-noise ratio likely due to a combination of sound propagation losses with distance and higher levels of shipping or seismic survey noise at the lower frequencies.

The presence of whales in the western GOM suggests they may have an increased risk of interaction with potentially harmful human activities. While their northeastern GOM core habitat is an area that is less impacted by human activities, the western GOM has high levels of shipping traffic, fishery activity, oil and gas exploration (including seismic airgun surveys), and oil and gas production activity (Rosel et al. 2016, Soldevilla et al. 2017). Collisions with vessels represent a major risk to most baleen whale species, including Rice's whales, and vessel traffic is higher in the northwestern GOM where the shipping fairway is close to the shelf break (Soldevilla et al. 2017). Further, it remains unknown whether animals occur in the northcentral GOM or are traveling between the northwest and northeast across areas of high shipping traffic near the Mississippi River delta. No Rice's whale calls were detected at the GI site or in 2 brief months of recordings at the EP site, in the north-central GOM. This could indicate the true absence of whales, the absence of calling whales, or the inability to detect whales in these areas of the northcentral GOM due to higher ambient noise conditions (Fig. 8) and sound propagation conditions associated with the recorder being within the Mississippi Canyon. Rice's whale western long-moan variants were detected both at the westernmost sites and a site in the eastern GOM habitat, which could suggest movements between areas. On a few occasions, western variants were detected on the same or consecutive days at the WF and DC sites, separated by 740 km. Since this is too far for 1 whale to travel in a single day, it is clear that different whales were producing calls at these distant sites. Satellite tagging of whales in the western GOM or intensive dedicated surveys including photo-identification may be needed to determine movement patterns, and a risk assessment will be important to understand the potential impacts of ship strikes throughout their entire habitat. The high number of oil and gas rigs in the northwestern GOM present a

risk of oil spill impacts for whales in this area. Rice's whales were one of the most impacted species by the 2010 *Deepwater Horizon* oil spill (*Deepwater Horizon* Natural Resource Damage Assessment Trustees 2016), and another similar spill in their habitat could be catastrophic to this very small population (Rosel et al. 2016). Finally, noise produced by human activities, including shipping and airgun surveys, has the potential to degrade their habitat, reduce their listening space, mask biologically important sounds, and potentially cause injury (Rosel et al. 2016). Median sound pressure spectrum levels in the communication frequency range of Rice's whales are 6–13 dB higher at northwestern sites compared to the site in the core northeastern GOM habitat, and seismic survey noise was nearly constantly present in all western GOM recordings. The potential for higher-level impacts from each of these industries for whales found in the western GOM should be considered when planning for the recovery of these endangered whales.

## 5. CONCLUSIONS

The persistent occurrence of Rice's whales has been documented for the northwestern GOM. New variants of Rice's whale long-moan calls were discovered along the northwestern GOM shelfbreak that were determined to share distinctive and similar features with typical eastern GOM long-moans (including a 150 Hz starting tone, an approximately 100 Hz tail with amplitude modulation, and an overall long duration ranging from 10 to 35 s), indicating that Rice's whales as the source is the most plausible explanation. These western long-moan variants were detected at 3 of the 4 sampled northwestern sites, as well as infrequently at a site in the eastern habitat; however, eastern long-moans were never detected at any of the western sites. Rice's whale calls were detected most frequently at the westernmost site, present on 1 of every 6 days sampled, with sporadic encounters clustered over several days, and no obvious evidence of seasonality. In combination with a 2017 sighting of a genetically identified Rice's whale at the shelf break off Corpus Christi, Texas, these data provide evidence for the persistent occurrence of some Rice's whales over a broader distribution in the GOM than previously understood and will be important to consider when designating critical habitat for this endangered species. It will be important to determine the number and overall spatial density of whales in this area, as well as the potential distribu-

tion in deeper waters and southern waters of the GOM. Additionally, given the differences in call type production described here, it will be important to understand the relationship between the whales found in the western and eastern GOM, including movement patterns of individuals throughout the GOM. The northwestern GOM has high levels of anthropogenic activity that may present a risk to these whales, and it will also be important to assess risk of these activities to these whales, particularly if whales are moving between the heavily trafficked waters of the central GOM.

**Data availability.** The data used in this study are archived at NOAA National Centers for Environmental Information (NCEI) (NOAA SEFSC 2022, <https://doi.org/10.25921/4SGC-2N83>).

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