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Acoustic localization, validation, and characterization of Rice's whale calls

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ABSTRACT:

The recently named Rice's whale in the Gulf of Mexico is one of the most endangered whales in the world, and improved knowledge of spatiotemporal occurrence patterns is needed to support their recovery and conservation. Passive acoustic monitoring methods for determining spatiotemporal occurrence patterns require identifying the species' call repertoire. Rice's whale call repertoire remains unvalidated though several potential call types have been identified. This study uses sonobuoys and passive acoustic tagging to validate the source of potential call types and to characterize Rice's whale calls. During concurrent visual and acoustic surveys, acoustic-directed approaches were conducted to obtain visual verifications of sources of localized sounds. Of 28 acoustic-directed approaches, 79% led to sightings of balaenopterid whales, of which 10 could be positively identified to species as Rice's whales. Long-moan calls, downsweep sequences, and tonal-sequences are attributed to Rice's whales based on these matches, while anthropogenic sources are ruled out. A potential new call type, the low-frequency downsweep sequence, is characterized from tagged Rice's whale recordings. The validation and characterization of the Rice's whale call repertoire provides foundational information needed to use passive acoustic monitoring for better understanding and conservation of these critically endangered whales.

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I. INTRODUCTION

Rice's whale (*Balaenoptera ricei*) is one of the most endangered marine mammal species in the world and the only year-round resident baleen whale found in the Gulf of Mexico (GOM). Historically, Rice's whales were thought to be a distinct population of Bryde's whales (*Balaenoptera edeni*), commonly called the Gulf of Mexico Bryde's whales or Gulf of Mexico whales, but recent studies indicate they are geographically, demographically, and genetically isolated from all other balaenopterid whale lineages and they are now recognized as a separate species (Rosel and Wilcox, 2014; Rosel *et al.*, 2021). Currently, the Rice's whale's only known habitat is a small area along the northeastern GOM shelf break near the De Soto Canyon (Soldevilla *et al.*, 2017) and their abundance from 2017 to 2018 is estimated at 51 individuals [coefficient of variation (CV) 0.53; Garrison *et al.*, 2020]. A Rice's whale was also sighted along the GOM shelfbreak off Texas in 2017 (Rosel *et al.*, 2021). Developing a better understanding of their ecology, range, and seasonal distribution patterns is a priority for their conservation and recovery (Rosel *et al.*, 2016).

Autonomous passive acoustic monitoring (PAM) methods, which rely on the sounds produced by a species or population, are an efficacious tool for finding rare whale species in areas where they occur infrequently (Mellinger *et al.*, 2004; Mellinger *et al.*, 2007; Munger *et al.*, 2008; Mellinger *et al.*, 2011) and for understanding seasonal and interannual variability in their occurrence (e.g., Aulich *et al.*, 2019; Davis *et al.*, 2020). These methods could be an important tool for understanding the Rice's whale's distribution and seasonal movement patterns. For autonomous PAM to be effective, the call repertoire of the population must be known. Generally, balaenopterids produce a variety of low-frequency tonal and broadband calls, with durations ranging from 1 to 60 s, fundamental frequencies between 10–1000 Hz, and high source levels from around 145 to over 190 dB re: μPa at 1 m (Richardson *et al.*, 1995; Miller *et al.*, 2021). Within their varied call repertoires, most balaenopterids produce some call types that are distinctive, stereotyped, and unique at the species or population level, including blue whales, *B. musculus* (McDonald *et al.*, 2006), fin whales, *B. physalus* (Hatch and Clark, 2004; Delarue *et al.*, 2009; Castellote *et al.*, 2012), humpback whales, *Megaptera novaeangliae* (Cerchio *et al.*, 2001; Garland *et al.*, 2011), minke whales, *B. acutorostrata* (Mellinger *et al.*, 2000; Gedamke *et al.*, 2001; Rankin and Barlow, 2005; Risch *et al.*, 2014), sei whales, *B. borealis* (Rankin and Barlow, 2007; Baumgartner *et al.*, 2008; Calderan *et al.*,

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2014), and the Bryde's-like whales, *B. edeni, B. ricei*, and *B. omurai* (Oleson *et al.*, 2003; Širović *et al.*, 2014; Cerchio *et al.*, 2015), which are ideal for autonomous PAM surveys.

PAM data also provide valuable information for improving species identification during combined visual and passive acoustic surveys, particularly for distant sightings and for visually cryptic species. Species in the Bryde's whale complex can be challenging to identify to the species level during visual sightings, as observers must approach closely enough to see the characteristic three rostral ridges that distinguish them from other balaenopterids with a tall, falcate dorsal fin (e.g., fin and sei whales). Further, in areas where multiple Bryde's-like species have overlapping distributions, the Bryde's-like whale species cannot be visually distinguished from each other without supporting evidence, such as genetic sampling (Rosel *et al.*, 2021). Globally, Bryde's-like whales produce calls that are clearly distinguishable from those produced by fin and sei whales (e.g., Hatch and Clark, 2004; Rankin and Barlow, 2007; Baumgartner *et al.*, 2008; Delarue *et al.*, 2009; Castellote *et al.*, 2012), and are also distinguishable both among the Bryde's whale complex species and among populations within species of Bryde's-like whales (e.g., Cummings *et al.*, 1986; Oleson *et al.*, 2003; Heimlich *et al.*, 2005; McDonald, 2006; Kerosky *et al.*, 2012; Figueiredo and Simão, 2014; Cerchio *et al.*, 2015; Viloria-Gómora *et al.*, 2015). These calls can provide supporting evidence for species identification in cases of uncertain visual-based identification of Bryde's-like whales.

The call repertoire produced by Rice's whales[1] is not well understood. One call type has been determined to be produced by free-ranging Rice's whales (Širović *et al.*, 2014), four additional call types have been proposed as likely candidates (Rice *et al.*, 2014; Širović *et al.*, 2014), and two call types have been described during rehabilitation of a captive juvenile Bryde's-like whale that stranded along the Florida coast in the GOM (Edds *et al.*, 1993). The one validated call type, the downswept pulse pair [Fig. 1(a)], was localized to Rice's whales in a concurrent visual and PAM survey using directional sonobuoys, and consists of a pair of downswept pulses 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). The first proposed call type, the downsweep sequence [Fig. 1(b)], was detected only in autonomous recordings, and consists of longer series of downswept pulses[2] (mean: 8 downsweeps, range: 2–25) with similar features (mean frequency sweep: 143 ± 3 to 85 ± 6 Hz; mean duration: 0.7 ± 0.1 s; mean inter-pulse interval: 0.6 ± 0.2 s) that are presumed to be variants of the downswept pulse pair call type (Širović *et al.*, 2014). These same downsweep sequences were also reported on different autonomous instruments based on similar characteristics [median 19 downsweeps per sequence, range 2–27; frequency sweep: 113–51 Hz; mean duration: 0.3 s, 95% confidence interval (CI) 0.36–0.38 s; mean inter-pulse interval: 0.8 s, 95% CI 0.75–0.85 s; Rice *et al.*, 2014]. The second proposed call type, the high-frequency
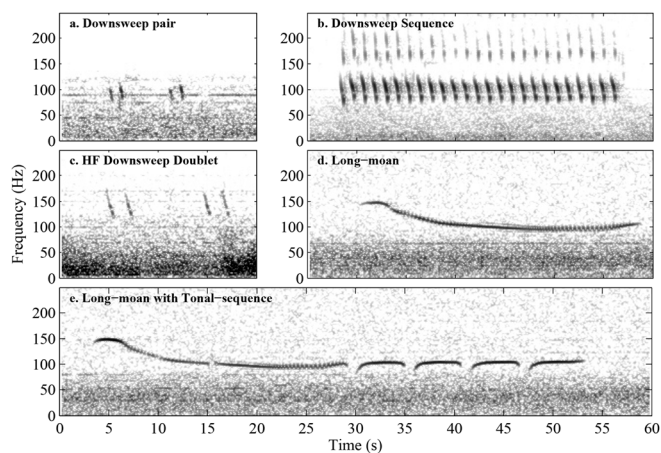

FIG. 1. Spectrograms of vocalizations previously proposed to be produced by Rice's whales from the Gulf of Mexico: (a) downswept pulse pairs verified by Širović *et al.* (2014), (b) downsweep sequences with similar features described from autonomous recordings (Širović *et al.*, 2014; Rice *et al.*, 2014), (c) high-frequency downsweeps described from autonomous recordings (Širović *et al.*, 2014), (d) long-moan, and (e) long-moan and tonal-sequences described from autonomous recordings (Rice *et al.*, 2014).

downsweep [Fig. 1(c)], is another downsweep call type that was detected in autonomous recordings only, over a 5 day period. These short-duration downsweeps are higher in frequency (170–110 Hz), segmented, and typically occurred in repeated sequences of doublets (Širović *et al.*, 2014). The third and fourth proposed call types are tonal calls that were detected on autonomous instruments and were suggested as possible Rice's whale calls based on balaenopterid-like temporal, spectral, and amplitude features, movement patterns of tracked calls, and overlap between sites with call detections and the known distribution of Rice's whales (Rice *et al.*, 2014). The third call type, the long-moan call [Fig. 1(d)], is a long-duration, downsweeping frequency-modulated, amplitude-pulsed tonal that ranges 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 fourth call type, a constant tonal-sequence [Fig. 1(e)], 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). Beyond these five call types (one validated and four proposed) from free-ranging whales, call types recorded from the captive juvenile Bryde's-like whale include (1) discrete pulses (single or in series, 400–600 Hz, 10 ms durations and 50–130 ms inter-pulse intervals), and (2) pulsed short moans and growl-like moans (200–900 Hz, 0.5–51 s duration, 20–70 pulse/s modulation rate). While there were some similarities in call structure between the free-ranging and captive recordings, the frequency range was considerably higher in the captive juvenile. No genetic data exist to determine whether this ill, stranded whale was a local Rice's whale or a wandering Bryde's whale from the southern Caribbean or a more distant population; the species identity and the effects of animal age and health on vocalization are unknown and these

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calls may not be representative of calls produced by free-ranging Rice's whales.

The National Oceanic and Atmospheric Administration (NOAA) Southeast Fisheries Science Center conducted three marine mammal surveys with focused effort in the Rice's whale core habitat between 2015 and 2018, providing an opportunity to investigate the Rice's whale call repertoire and the source of potential Rice's whale calls previously detected in autonomous recordings. These surveys combined visual and acoustic methods to find Rice's whales for focused studies of their genetic lineage (e.g., Rosel *et al.*, 2021), dive behavior (e.g., Soldevilla *et al.*, 2017), and trophic ecology and provided an opportunity to investigate their call repertoire and the source of the downsweep sequence, high-frequency downsweep, long-moan, and constant tonal-sequence signals. This study used arrays of directional sonobuoys to record and localize potential Rice's whale calls concurrent with visual surveys, and validates Rice's whales as the source of the recorded signals. Additionally, two acoustic tags were deployed on Rice's whales and a new potential call type is characterized. Further, the distribution of call detections recorded on 178 sonobuoys during the two surveys in their core habitat is described. Last, we compare call types attributed to Rice's whales to those of other balaenopterids, including Bryde's-like whales, to understand their utility for autonomous PAM studies of distribution and seasonal movements and for use as supporting evidence of species identity during combined visual and acoustic surveys.

II. METHODS

A. Survey area and visual survey field methods

During September 2015 and July and November of 2018, the NOAA Southeast Fisheries Science Center conducted marine mammal visual surveys with concurrent sonobuoy deployments aboard NOAA's *R/V Gordon Gunter* in the Rice's whale northeastern GOM core habitat (Fig. 2). These surveys were part of dedicated Rice's whale studies focused on genetics, life history, trophic ecology, and tagging work, and included a total of 4226 km of visual survey effort in the core habitat over the three cruises. The surveys primarily followed four along-shelf track lines in the whales' preferred depth range from 180 to 260 m (e.g., Soldevilla *et al.*, 2017) to maximize the likelihood of finding Rice's whales. This study focuses on visual and passive acoustic survey data from the two 2018 surveys and tagging data from the September 2015 and July 2018 surveys.

Trained marine mammal observers collected standard line-transect data while transiting at 10 knots (18.5 km/h) along track lines during daylight hours in good weather (i.e., Beaufort state <6, no rain, fog, haze, or lightning) using 25×150 mm "Bigeye" binoculars mounted on the ship's flying bridge. While on effort, a single team of three observers searched for Rice's whales from the ship's flying bridge (13.9 m above the waterline). Visual observers also noted the presence of other mammals, fish, and anthropogenic activities throughout the
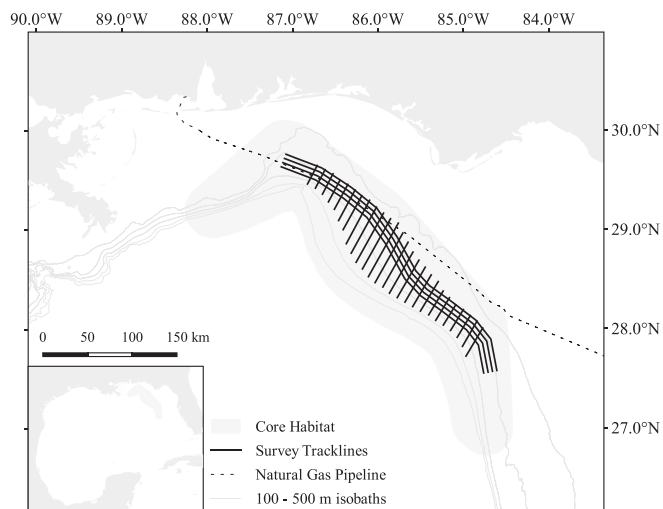

FIG. 2. Study area, including along-shelf survey lines and cross-shelf lines (primarily run at night for trophic ecology study). Shaded polygon represents Rice's whale core habitat (Rosel and Garrison, 2022), as identified in June 2019. Bathymetry represented includes 100, 200, 300, 400, and 500 m isobaths contours. Inset shows study area with respect to Gulf of Mexico.

surveys. Data collected during a sighting of one or more individuals included time, vessel position and heading, sighting cue type, species identification, bearing and radial distance to the sighting, number of individuals, behavior, identifying features, and environmental conditions. When baleen whales were encountered during favorable conditions, focal follows were conducted to collect additional data, including photo and video documentation, acoustic localization and acoustic-directed approaches, and to guide small boat operations for tagging and biopsy collection. During focal follow work, periodic whale resight locations were recorded to track animal movement. This study focuses on the acoustic localization and directed approaches, as well as behavioral tagging. Specifically, to identify sources of localized acoustic signals (see acoustic data collection methods in Sec. II B), directed surveys were conducted using information from PAM to guide the ship toward potential locations of whales. During these acoustic-directed surveys, the visual team was considered "off effort" while searching for potential sources of acoustic signals based on directions by the acoustic team.

For visual species identification, conducted prior to the species' renaming (i.e., Rosel *et al.*, 2021), baleen whale sightings were identified as: (1) Rice's (formerly Bryde's) whales when the three rostral ridges and other identifying characteristics were observed or a biopsy was obtained and confirmed the species; (2) Rice's or sei whales when the identifying features observed included a tall, falcate dorsal fin and medium-sized balaenopterid, but the presence or absence of rostral ridges could not be determined to reliably exclude either of the two species and biopsy samples could not be obtained to confirm species; (3) Rice's, sei, or fin whales, when the only identifying feature was a tall, falcate dorsal fin; or (4) unidentified balaenopterid when features observed were unreliable or insufficient to determine the species beyond this level.

B. Real-time acoustic data collection

Acoustic recordings to identify calls produced by Rice's whales in the northeastern GOM were collected using real-time drifting sonobuoys to ensure that low-frequency signals expected for baleen whales could be detected without masking effects of low-frequency flow noise or survey vessel noise. Specifically, directional frequency analysis and recording (DIFAR) AN-SSQ-53 sonobuoys (models E, F, or G) were deployed concurrent with visual surveys during daylight hours to detect, localize, and record low-frequency sounds potentially produced by Rice's whales and from anthropogenic sources. Sonobuoy survey strategies included (1) deploying single sonobuoys either at regularly spaced times or distances along tracklines or opportunistically near visually sighted baleen whales to detect presence of potential baleen whale calls or sounds from anthropogenic sources, and (2) as arrays of 2–3 sonobuoys spaced 1–10 km apart to localize calls when present. During the 2018 cruises, when successive calls were localized to a relatively consistent location within 20 km of the ship, an acoustic-directed visual survey effort might be initiated to determine whether Rice's whales or potential alternative sources were present nearby the call localization area.

The DIFAR sonobuoys contain hydrophones that allow directional bearing to be estimated for sounds within a bandwidth from 10 Hz to ~2 kHz. This frequency range is well suited for baleen whale vocalizations, which typically have their greatest sound energy concentrated below 1000 Hz. The acoustic data from the sonobuoys are transmitted back to the ship via a single vhf radio carrier frequency in an analog multiplexed format and are received by a ship-mounted antenna. Prior to deployment, all sonobuoys were programmed without Automatic Gain Control for a hydrophone depth of 69 or 122 m and a broadcast duration of 4 or 8 h. The radio signals were received by an omnidirectional antenna mounted on the aft mast at 26 m above the waterline. The effective radio reception range from the sonobuoys was approximately 10–15 km.

Amplified signals from the antennas were received on one of three G39WSBe WinRadios (Radixon Inc., Dallas, TX), providing the ability to receive and record data from up to three sonobuoys at one time. Received analog sonobuoy signals were digitized with an RME Fireface UC audio interface (Synthax, Inc., Fort Lauderdale, FL) sampling 24 bits at either 48 kHz or 96 kHz[3] sample rates and were recorded directly to SATA hard drives as multi-channel wav files using the software program Pamguard (Gillespie *et al.*, 2008). Incoming signals were monitored via headphones and visually via a scrolling spectrogram in Pamguard, which was used to record acoustic data, effort, and metadata logs to hard-disk, and to process DIFAR signals in real-time. Effort data, detection times and other metadata, and data on the bearing to sounds and the sound types were recorded using Pamguard Logger forms. A custom DIFAR demultiplexing module in Pamguard (Miller *et al.*, 2016) was used for real-time call detection, bearing estimation, and

localization when possible. The DIFAR module plots spectrograms and calculates difargrams of selected signals using the built-in Australian Marine Mammal Centre demodulation software, allowing estimation of magnetic bearing angles to calling animals, and maps the true bearings alongside the ship GPS trackline and sonobuoy deployment locations. When the same call was detected on two or more sonobuoys with a sufficient baseline separation, it was possible to estimate the source location, including some estimate of uncertainty, of the sounds by crossing two or more bearings. The PAM technicians calibrated each sonobuoy's compass following standard procedures (e.g., Miller *et al.*, 2015; Miller *et al.*, 2016), monitored the incoming signals continuously in real-time, and manually detected, classified, and localized potential whale sounds along with anthropogenic noises. At initial data collection, these sounds were broadly categorized as possible Rice's whale vocalizations (e.g., downswept pulse pairs, downsweep sequences, long-moan calls, tonal-sequences, and others). Successive calls with consistent bearings or localizations were classified as unique acoustic encounters to represent individuals or groups of closely spaced animals. Potential matches of acoustic localizations and visual sightings were noted.

In post-processing, acoustic encounters with consistent real-time localizations and potential visual matches were plotted alongside visual baleen whale sighting and resight locations, and locations of other potential sound sources such as other marine mammals, fish, or fishing vessels. The time difference and great-circle distance to the closest acoustic localization and visual match were calculated, and the acoustic encounter duration and spread of acoustic localizations were documented. Call types present, number of calls localized, and numbers of calls per type present were noted for each encounter. Acoustic localizations and visual matches within 2 km and 30 min are considered confirmed matches, while acoustic localizations within 4 km and 45 min are considered possible matches.

C. Archival acoustic recording tag data collection

Animal-borne suction-cup archival tags (Acousonde B003B – Greenridge Sciences, Inc., Santa Barbara, CA) were deployed on Rice's whales to improve our understanding of their call repertoire and behavior. During the 2015 and 2018 surveys, when Rice's whales were sighted in good weather conditions, whales were approached from an 18 m rigid hull inflatable boat (RHIB) to attach a suction-cup tag via a pole deployment method following best-practice guidelines (Andrews *et al.*, 2019). Data recorded during each sampling attempt included GPS location, time, date, sampler and recorder name, species, body location struck, behavioral reaction, and whether or not a sample was obtained. During 2015, tagged whales were tracked during daylight hours visually and via vhf receiver to ensure tag recovery, with prescribed transects following nightfall to allow for tag relocation. During 2018, in addition to the vhf

transmitter to aid in short-distance tag recovery, the Acousonde tag float contained a SPOT 258E satellite transmitter to aid in long-distance tag recovery operations when visual tracking was not possible. The vhf receiver allowed the tags to be detected when above the water surface within 20 km, and the vessel was maneuvered to track and recover the tags following detachment from the whales.

The multi-sensor suction-cup tag instrumentation included temperature and pressure sensors, triaxial magnetometers and accelerometers, and a hydrophone. The low-power hydrophone had a sensitivity of -187 dB re: 1 V/μPa with a flat frequency response from 22 Hz to 9.2 kHz. During the 2015 survey, all non-acoustic sensors were sampled at 5 Hz while acoustic data were continuously sampled at 9110 Hz with 16-bit resolution and no added gain. During the 2018 survey, temperature was sampled at 5 Hz, pressure sensors at 10 Hz, magnetometers at 40 Hz, and accelerometers at 800 Hz, while acoustic data were sampled at 9110 Hz with 16-bit resolution and no added gain. Acoustic and kinematic data from the tags were analyzed with customized routines using Matlab (Mathworks Inc., Natick, MA). To evaluate the relationship between call behavior and depth, known temperature effects on the Acousonde 3B pressure sensor were corrected using an empirically derived correction factor (Soldevilla et al., 2017).

D. Call characterization

Using the Matlab-based software, Triton (Scripps Whale Acoustics Laboratory, La Jolla, CA), the following characteristics of Rice's whale calls were measured: minimum and maximum call fundamental frequencies (measured from spectrograms with 2 Hz and 10 ms resolution), call start and end times (measured from time series plots that were bandpass filtered between 30 and 2000 Hz), and call received levels (measured as peak-to-peak from time series plots that were bandpass filtered between 30 and 2000 Hz). The pulse duration was measured between the 10 dB amplitudes at the beginning and end of the waveform. The number of pulses per call was noted and the inter-pulse interval (IPI) was calculated as the difference between the start of one pulse and the start of the subsequent pulse. The intercall interval (ICI) was calculated as the difference between the start of one call and the start of the subsequent call. Minimum, maximum, median, mean, and standard deviation of all measurements are reported.

III. RESULTS

A. Real-time acoustic call distribution and localizations

Over the 30 days of the two 2018 surveys, 178 sonobuoys were deployed that successfully transmitted signals, yielding 269 h of recordings, and the opportunity to conduct 28 acoustic-directed search efforts plus 6 opportunistic visual–acoustic match encounters (Table I). Of all sonobuoys, 131 were deployed as part of an array of 2 to 3 sonobuoys for call localization. Low-frequency tonal sounds were

TABLE I. Summary of survey effort and visual and acoustic detections during the summer and fall 2018 Rice's whale focused surveys.

	Summer 2018	Fall 2018
Survey start date	25 Jun 2018	11 Nov 2018
Survey end date	7 Jul 2018	3 Dec 2018
Survey days	13	17
Visual effort (km)	1466.6	1899.9
Baleen whale sightings	26	18
Acoustic effort (h)	122	147
Sonobuoys	88	90
Sonobuoys in arrays	71	50
Acoustic encounters	54	113
Sonobuoys with baleen whale–like calls present	75	59
Downswept pulse pairs	1	5
Downsweep sequences	28	14
Long-moan calls	75	59
Tonal-sequence calls	0	6
Other	1	0

detected on 85% of successful sonobuoys during the summer 2018 survey with 54 acoustic encounters[4] of individuals or groups of whales, while low-frequency tonal sounds were detected on 66% of successful sonobuoys during the fall 2018 survey with 113 acoustic encounters[4] of individuals or groups of whales (Table I). Long-moans, the most commonly detected sound, were detected throughout the core habitat during the summer 2018 and fall 2019 surveys, on all sonobuoys with calls present (Fig. 3, Table I). Downsweep sequences, including downswept pulse pairs, detected less commonly, were, respectively, present on 31% and 16% of the summer 2018 and fall 2018 sonobuoys with calls present, and exhibited spatial clustering within each survey (Fig. 3, Table I). Tonal-sequence calls were only detected on 6% of sonobuoys with calls present, and also exhibited spatial clustering (Fig. 3, Table I). Additionally, a pulsed sound similar to the sounds described below from the 2015 tag was detected once (see Sec. II C for call characterization).

During the summer 2018 survey, acoustic-directed approaches were conducted during 16 acoustic encounters to validate the source of localizable calls (Table II). Of these, 11 approaches led to visual sightings of baleen whales within 2 km and 30 min of the nearest call localization for the associated acoustic encounter–these are considered confirmed acoustic–visual matches (Table II, Fig. 4). An additional two encounters led to visual sightings within 4 km and 45 min of the nearest call localization, and are considered possible acoustic–visual matches (Table II). The remaining three acoustic-directed approaches did not lead to visual sightings. One of these was ended due to diminishing daylight before reaching the localization, while another was ended after calls stopped for an extended period. In addition, two opportunistic acoustic encounters had call localizations occur within 4 km and 45 min of a visual sighting that may be possible acoustic–visual matches (Table II).

Of the 11 confirmed directed-approach acoustic–visual matches from the summer 2018 survey, 8 could be
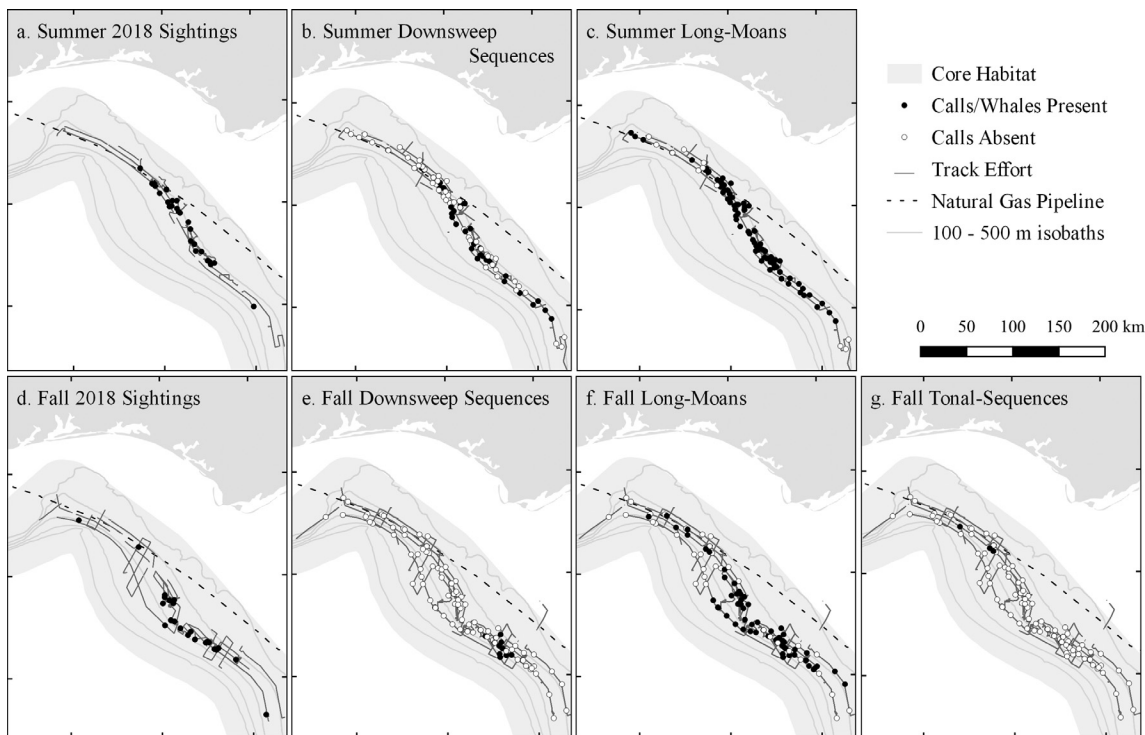
FIG. 3. Maps of sonobuoy deployment distribution and call presence by call type for the summer and fall 2018 surveys.

positively identified to species as a Rice's whale (based on observation of the diagnostic three rostral ridges), while the remaining three balaenopterid whales could not be positively identified at the species level (Table II). The two possible acoustic–visual matches could only be identified as balaenopterids. Of the two opportunistic encounters, one associated sighting was positively identified as a Rice's whale and the other balaeopterid whale could not be identified to the species level. All visually matched acoustic encounters from the summer 2018 survey included

TABLE II. Acoustic and visual matches from the summer 2018 survey. LM = long-moan; DS = downsweep sequence. ID = identity. Bold encounters are mapped in Fig. 4.

	Date	Time	Call types	Total LM calls	Total DS Calls	Localized calls	Encounter duration (h)	Localization range (km)	Nearest match (min)	Nearest match (km)	Visual Species ID	Visual Group Size
Acoustic-Directed Approaches												
Confirmed	28-Jun-2018	14:15	LM	18	—	4	0.3	2.4	27.1	1.2	Rice's/Sei	2
	28-Jun-2018	20:12	LM	35	—	26	4.2	13.0	11.1	1.3	Rice's	3
	28-Jun-2018	23:01	LM	27	—	19	1.4	6.3	27.9	0.7	Balaenopterid	1
	30-Jun-2018	**12:54**	**LM; DS**	**29**	**18**	**40**	**6.6**	**20.8**	**12.0**	**0.5**	**Rice's**	**2**
	30-Jun-2018	**13:13**	**LM; DS**	**52**	**8**	**42**	**7.8**	**22.8**	**0.6**	**0.6**	**Rice's**	**11**
	2-Jul-2018	16:14	LM	86	—	67	6.0	24.1	14.2	1.7	Rice's	2
	2-Jul-2018	23:22	LM	29	—	13	0.7	11.4	19.0	1.4	Rice's	4
	3-Jul-2018	12:20	LM; DS	39	9	48	9.3	40.7	14.5	1.3	Rice's	2
	3-Jul-2018	12:25	LM	74	—	57	9.1	33.4	13.9	0.8	Rice's	4
	6-Jul-2018	14:43	LM	33	—	15	5.2	14.3	29.8	1.0	Rice's	1
	6-Jul-2018	18:00	LM	12	—	10	1.9	6.7	2.8	1.2	Rice's/Sei/Fin	1
Possible	28-Jun-2018	20:27	LM	13	—	14	1.5	27.9	42.7	0.4	Balaenopterid	1
	29-Jun-2018	20:03	LM	14	—	7	3.8	7.8	16.2	3.4	Balaenopterid	2
Unconfirmed	1-Jul-2018	23:41	LM	5	—	3	0.3	2.5	—	—	—	—
	6-Jul-2018	15:06	LM; DS	13	5	2	0.3	17.8	—	—	—	—
	7-Jul-2018	16:12	DS	0	4	2	0.1	4.2	—	—	—	—
Opportunistic localizations												
Possible	26-Jun-2018	14:32	LM	10	—	3	1.4	17.1	31.6	3.8	Rice's	3
	28-Jun-2018	13:18	LM	18	—	12	4.4	0.8	36.4	0.7	Rice's/Sei/Fin	3

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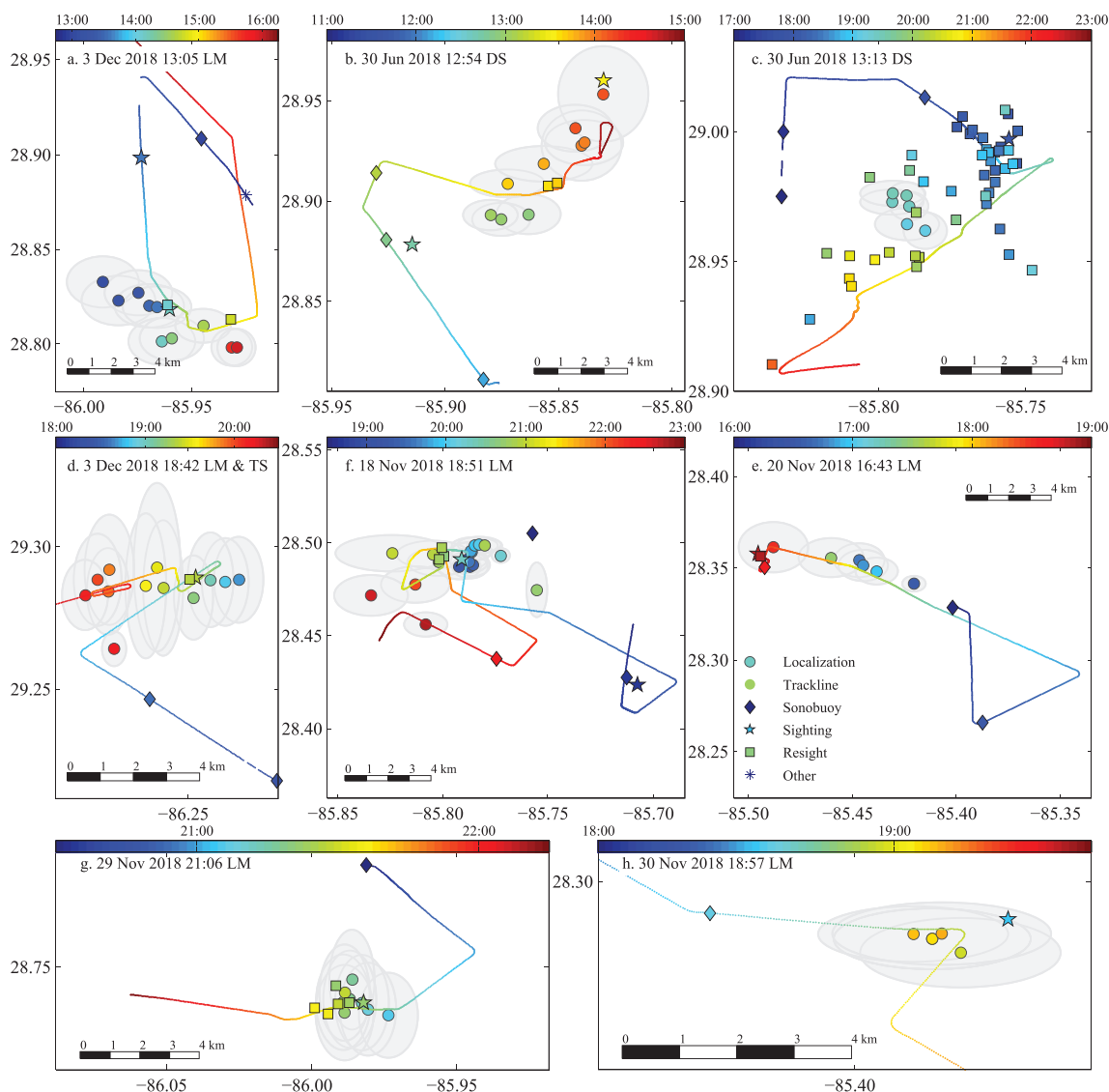
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FIG. 4. Examples of visual sighting and acoustic localization matches from the summer and fall 2018 surveys. Diamonds are sonobuoy locations. Stars are the initial sighting location; squares are visual sighting updates. Circles are acoustic localizations, including standard error (gray ovals). Color indicates time into event. Ship trackline indicated by colored line.

localizations of the long-moan call. Two of the confirmed directed-approach acoustic–visual matched encounters also included the downsweep sequence calls [Fig. 4(b) and 4(c)].

During the fall 2018 survey, acoustic-directed approaches were conducted during 12 acoustic encounters to validate the source of localizable calls (Table III). Of these, seven approaches led to visual sightings of baleen whales within 2 km and 30 min of the nearest call localization for the associated acoustic encounter (Table III, Fig. 4). An additional two encounters led to visual sightings within 4 km and 45 min of the nearest call localization, and are considered possible acoustic–visual matches (Table III). The remaining three acoustic-directed approaches did not lead to visual sightings as they were diverted early to conduct acoustic-directed approaches of closer or more precisely localized acoustic events. Additionally, one opportunistic acoustic

encounter began within 2 km and 30 min following a baleen whale visual encounter, and three acoustic encounters occurred during intensive gridded line-transect operations (part of an alternative component of this project) with call localizations occurring within 2 km and 30 min (Table III).

Of the seven confirmed directed-approach acoustic–visual matches from the fall 2018 survey, two could be positively identified as Rice's whales, while the remaining five balaenopterids could not be identified to the species level (Table III). Of the additional four confirmed opportunistic acoustic–visual matches, three could be positively identified as Rice's whales, while one balaenopterid could not be identified to the species level. The balaenopterid sightings from the two possible acoustic-directed acoustic–visual matches also could not be identified to the species level. All acoustic encounters from the fall 2018 survey were localizations of the long-moan call. Additionally, one of the seven directed-approach

TABLE III. Acoustic and visual matches from the fall 2018 survey. LM = long-moan; TS = tonal- sequence. Bold encounters are mapped in Fig. 4.

	Date	Time	Call types	Total LM calls	Total TS calls	Localized calls	Encounter duration (h)	Localization range (km)	Nearest match (min)	Nearest match (km)	Visual Species ID	Visual Group Size
Acoustic-directed approaches												
Confirmed	**18-Nov-2018**	**18:51**	**LM**	**22**	**—**	**18**	**3.9**	**6.5**	**1.4**	**0.2**	**Rice's/Sei**	**1**
	19-Nov-2018	17:37	LM	50	—	9	4.4	10.6	1.0	0.6	Rice's	2
	19-Nov-2018	16:25	LM	38	—	4	1.1	3.9	21.7	1.4	Rice's	1
	20-Nov-2018	**16:43**	**LM**	**9**	**—**	**5**	**1.8**	**5.1**	**14.5**	**0.8**	**Balaenopterid**	**1**
	29-Nov-2018	**21:06**	**LM**	**32**	**—**	**8**	**0.4**	**1.8**	**1.0**	**0.8**	**Rice's/Sei**	**1**
	3-Dec-2018	**13:05**	**LM**	**15**	**—**	**10**	**2.9**	**7.3**	**0.4**	**1.9**	**Balaenopterid**	**1**
	3-Dec-2018	**18:42**	**LM; TS**	**19**	**3**	**12**	**1.5**	**4.7**	**2.5**	**0.9**	**Balaenopterid**	**1**
Possible	29-Nov-2018	14:46	LM	13	—	9	4.5	9.2	8.6	3.1	Rice's/Sei	1
	29-Nov-2018	19:12	LM	2	—	1	—	—	34.5	4.1	Rice's/Sei	1
Unconfirmed	18-Nov-2018	18:53	LM	19	—	18	3.0	5.9	—	—	—	—
	20-Nov-2018	15:00	LM	12	—	3	0.3	4.3	—	—	—	—
	29-Nov-2018	14:03	LM	21	—	18	3.3	13.4	—	—	—	—
Opportunistic localizations							—					
Confirmed	18-Nov-2018	15:49	LM	87	—	3	0.2	12.1	29.1	0.5	Rice's	2
	30-Nov-2018	16:49	LM	13	—	3	0.6	2.1	1.7	0.6	Rice's	3
	30-Nov-2018	15:52	LM	15	—	7	3.3	3.9	1.4	0.5	Rice's	3
	30-Nov-2018	**18:57**	**LM**	**15**	**—**	**5**	**0.2**	**1.0**	**24.8**	**1.1**	**Rice's/Sei/Fin**	**1**

acoustic–visual matched encounters included the tonal-sequence [Fig. 4(d)].

B. Archival acoustic tag results

Tagging occurred twice during the 2015–2018 surveys, once on 20 September 2015 and once on 3 July 2018. The dive behavior over the 64 h of the 2015 data has been described (Soldevilla *et al.*, 2017), and associated acoustic recordings are presented here with respect to dive behavior. During the summer 2018 survey, the 25 h of dive behavior are the subject of a separate study, but no calls were detected in these data.

Seven calls were detected in the data from September 2015, which all occurred during the first 2 surface intervals over the first 1.5 h of the 64 h tag deployment period (Fig. 5). The calls occurred in 2 bouts, with 5 calls detected during the first surface interval between 9:42 and 9:48 and two calls detected during the second surface interval between 10:36 and 10:38, on September 20, 2015. Call detections occurred during periods when the whale was between 1 and 14 m depth (mean: 6 ± 5) and occurred near the bottom of a shallow dive in five of the seven cases [Fig. 5(b)–(d)].

The seven calls were all of a similar structure consisting of a series of three to five downswept pulses with one to two harmonics. The fundamental frequencies of the individual pulses downswept from 58 ± 6 Hz to 35 ± 4 Hz, and lasted 0.3 ± 0.06 s in duration (Table IV). Within calls, mean IPIs were 0.7 ± 0.06 s, and the mean ICI was 1.5 ± 0.1 min ($n = 5$; the 48.3 min ICI between bouts was removed; Table IV). Received levels of individual pulses ranged between 167 and 185 dB$_{p-p}$ re: 1 μPa (Table IV), and were similar among the 7 calls (Fig. 6). Within calls, they typically had a lower amplitude pulse at the start of the call and the highest amplitude for the last or second to last pulse (Figs. 5 and 6).

The second call, recorded while the whale was at the surface, followed this received level pattern across pulses, but with lower received levels across all pulses compared to the other six calls (Figs. 5 and 6). Signal-to-noise ratios also varied across the calls; generally, those detected in the upper 5 m, near the surface, had lower noise levels than those detected at 10–15 m depths. A potential call with similar frequency and time characteristics was recorded on one occasion on a sonobuoy during the summer 2018 survey (Table IV, Fig. 7).

IV. DISCUSSION

A. Rice's whale call repertoire

The use of directional sonobuoys and tagging has allowed the validation of the Rice's whale call repertoire, including three of the four previously proposed call types. The acoustic localization from sonobuoys followed by acoustic-directed approaches that led to sightings of Rice's whales on multiple occasions supports the finding that the source of downsweep sequences, long-moan calls, and tonal-sequence calls previously suggested as potential Rice's whale calls (e.g., Rice *et al.*, 2014; Širović *et al.*, 2014) should be attributed to the Rice's whale. Of 28 acoustic encounters that were targeted for acoustic-directed approaches, 64% led to confirmed acoustic–visual matches, 15% led to possible matches, 14% were ended prematurely, and 7% were misses where calling ended or no whale was observed. Most call localizations (79%) led to sightings of balaenopterid whales. Rice's whales are the only balaenopterid whale to be identified in the GOM during these surveys and the only whale previously identified within the northeastern GOM core Rice's whale habitat, Bryde's-like whales in this area of the Gulf of Mexico have only ever been
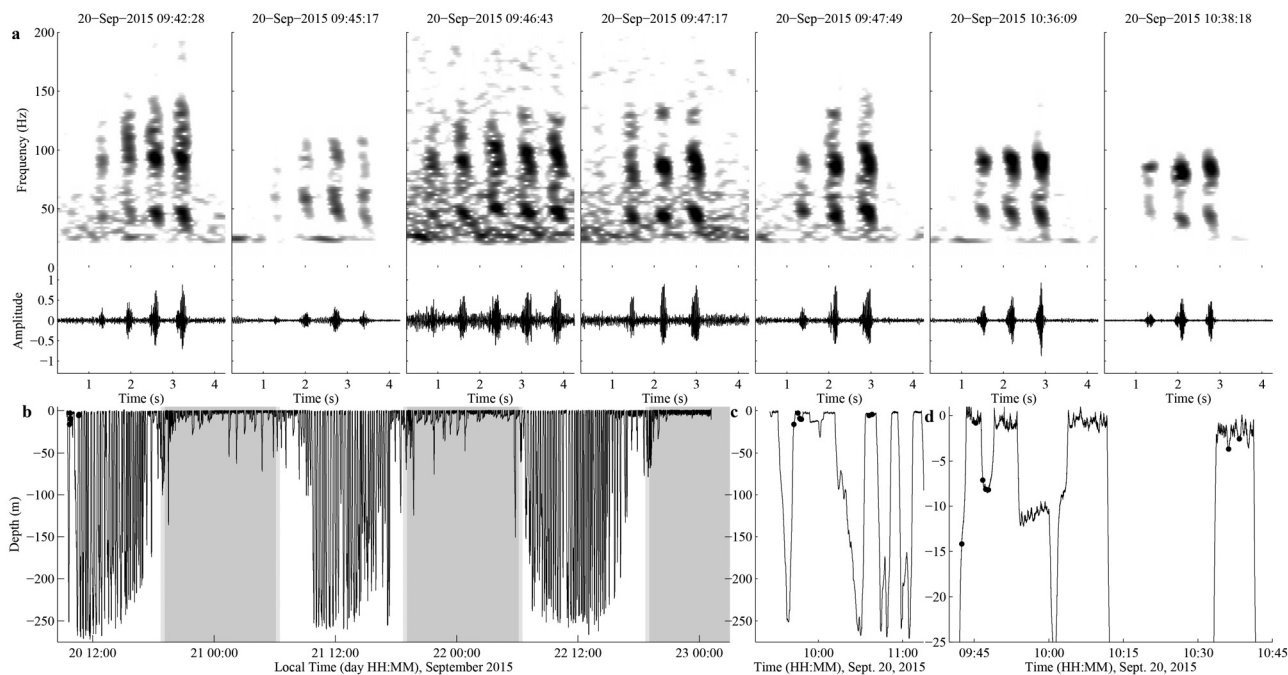
FIG. 5. Spectrograms with waveforms (a), and call occurrence timing during dive cycle (b–d) for 50 Hz downsweep pulse series recorded on a multi-sensor Acousonde tag attached to a Rice's whale in the Gulf of Mexico for 3 days in September 2015. Spectrogram resolution is 3 Hz x 3 ms based on DFT of 3037 samples and 99% overlap. Black dots on dive cycles indicate whale locations during each call detection. The seven plots in (a) represent the only calls detected during the 2.7 days tag deployment. Plot (b) indicates when in the 2.7 days period calls were detected (shading indicates nighttime). Plots c and d provide more detail in time and depth of where calls were detected with respect to the dive cycle.

genetically identified as Rice's whales (Rosel *et al.*, 2021), and fin and sei whales have only been reported in the northern GOM during stranding events. Further, no fin or sei whale calls were recorded during this study. Combined, these facts offer strong support that these calls are produced by Rice's whales. More conclusively, of the 18 confirmed matches during directed approaches, 10 long-moan encounters and 2 downsweep sequence encounters were associated with positively identified Rice's whales, plus 3 additional long-moan encounters were opportunistically confirmed matches with positively identified Rice's whales. While tonal-sequence calls were localized with a visual match on one occasion, the sighting was only identified to the level of

balaenopterid. Tonal-sequence calls are always preceded by a long-moan call, and during this encounter, the long-moan calls localized to the same area as the tonal-sequence call. This indicates that these sounds are produced by the same source and hence, should also be attributed to Rice's whales. Finally, this study provides supporting evidence to the Širović *et al.* (2014) assertion that the downsweep sequence call is a variant of the downswept pulse pair and the source can be attributed to Rice's whales. Two downsweep sequence encounters were confirmed to match with Rice's whale sightings and additionally downsweep sequences appeared to be produced by the same source as the previously validated downswept pulse pairs during four

TABLE IV. Call characteristics of the low-frequency downsweep pulsed calls recorded on the tag, and a similar sound recorded on a sonobuoy.

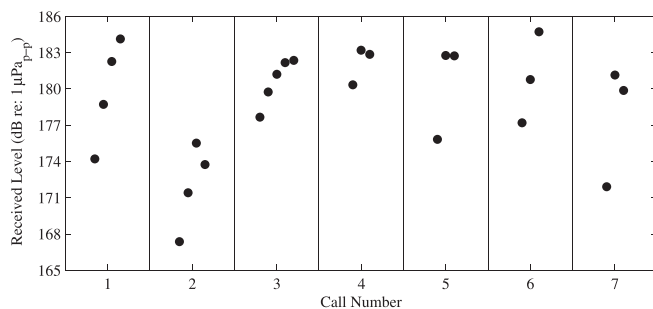|	Pulses per call	Start frequency (Hz)	End frequency (Hz)	Pulse duration (s)	Inter-pulse interval (s)	Intercall interval (min)	Received level (dB$_{p-p}$)
Tag	N = 7 calls						
Min	3	47	26	0.1	0.6	0.5	167.4
Max	5	71	43	0.4	0.8	48.3	184.8
Median	3	56	36	0.3	0.7	1.8	180.3
Mean	4	58	35	0.3	0.7	1.5	179.0
StDev	1	6	4	0.1	0.1	0.1	4.5
Sonobuoy	N = 1 call						
Min		40	19	—	0.8	—	—
Max		51	22	—	1.2	—	—
Median	8	50	19	—	1.0	—	—
Mean		48	20	—	1.0	—	—
StDev		4	1	—	0.1	—	—

FIG. 6. Received levels of individual downsweep pulses from each of the seven calls detected in the Acousonde tag recordings.

encounters in which both call types co-occurred. The fourth proposed call type, the high-frequency downsweep (Širović *et al*., 2014), was not recorded during this study, and the source remains unvalidated. The validated call repertoire of the Rice's whale therefore includes downsweep sequences (including downswept pulse pairs), long-moan calls, and tonal-sequence calls.

The long-moan call is commonly produced in the northeastern GOM (e.g., 460 call localizations reported over 3 days by Rice *et al*., 2014), and it could be argued that, with so many of these calls being produced, and with Rice's whales primarily found in this area, it is merely a coincidence that baleen whales are sighted where calls are localized. We assess that alternative sources for the long-moan, including other marine mammals, fish, or anthropogenic sources, such as fishing vessel winches or noise from the natural gas pipeline that runs along the northern part of the habitat, as previously described by Rice *et al*. (2014), are unlikely. During the two surveys in 2018, other marine mammals sighted in the core habitat include bottlenose dolphins (*Tursiops truncatus*), Atlantic spotted dolphins (*Stenella frontalis*), pantropical spotted dolphins (*Stenella attenuata*), and spinner dolphins (*Stenella longirostris*). During 10 of the 28 acoustic–visual match attempts, bottlenose dolphin or unidentified dolphin sightings occurred in the general area with Rice's whale sightings. However, it was far more common to find a Rice's whale in the localization area than dolphins, and dolphins are not known to produce stereotyped long-duration, low-frequency sounds like these while baleen whales are known to produce them (e.g.,
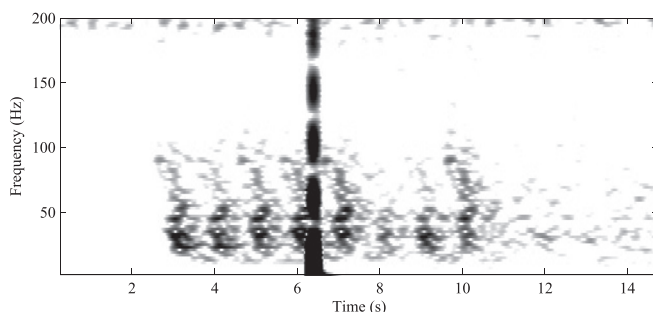

FIG. 7. Potential low-frequency downsweep call detected on sonobuoy during the summer 2018 survey. Note the broadband impulse is an artifact of the ship's radar system picked up by the sonobuoy receiving antenna.

Richardson *et al*., 1995). Similarly, schools of tuna were frequently sighted in association with Rice's whales during these surveys and were present during eight of the 28 acoustic–visual match attempts. Further, some deep-water species, such as tilefish (Malacanthidae species) and yellowedge grouper (*Hyporthodus flavolimbatus*), share a similar distribution with Rice's whales (Farmer *et al*., 2016) and could have been present yet unseen. While long-moans occurred frequently, they did not occur as frequently as one would expect from chorusing schools of fish. Further, documented tuna and yellowedge grouper sounds are much shorter in duration with no complex frequency modulation (Allen and Demer, 2003; Schärer *et al*., 2012) while the tilefish family is not known to produce sound (Fine and Parmentier, 2015). These other non-whale biological sources are unlikely. We were able to rule out anthropogenic sources as the origin of these calls during these 2018 surveys and pilot sonobuoy studies from the 2015 survey. Fishing vessels were uncommon during all three surveys, with sports fishing vessels, long-line vessels, and trawlers seen on 12 occasions, of which 5 occurred during the acoustic–visual matched encounters described in this study. Call localizations did not point to the vessels as the sound sources on any of these occasions. Finally, the natural gas pipeline in the northern part of the core habitat can also be ruled out as a sound source. While calls were frequently localized near the pipeline during the start of the 2015 pilot study, Rice's whales were also present above the pipeline during those encounters. Throughout the 2018 surveys and later parts of the 2015 pilot study, calls were detected and localized throughout the core habitat, including areas far from the pipeline (Fig. 3), indicating the pipeline could not be the source of these sounds.

The common detection of long-moan calls is likely due to long propagation ranges, with calls detectable on scales of 20–75 km, suggesting a Rice's whale call could be detected over as much as $1/4$ of their core habitat in some conditions. In the western GOM, which has higher mean ambient noise levels that would lead to smaller detection distances, the same long-moan calls were detected on 2 sensors 40 km apart, suggesting the calls can be detected to distances of at least 20 km (Soldevilla *et al*., 2022). In the core habitat, Rice *et al*. (2014) document an occurrence of the same call on three sensors with a maximum of 150 km spacing, suggesting they can be detected out to distances of at least 75 km at times. In addition to explaining why these calls might be detected so frequently, these long detection ranges of 20–75 km add additional support for whales as the source, as no fish or dolphin species are known to produce sounds with high enough source level to be detected at such great distances.

Beyond verifying Rice's whales as the source of the three previously described call types, this study characterizes a potential new low-frequency pulse-sequence call type from recordings of the tagged whale. This sound shares many similar features to the previously described downswept pulse pairs and downsweep sequences (Rice *et al*.,

2014; Širović *et al.*, 2014), including a frequency downsweep, mean pulse durations of 0.3–0.7 s, and mean IPIs of 0.6–1.3 s. However, the pulses in the tag recordings occur at around half the frequency (sweeping from 58 to 35 Hz) of the previously described downsweep sequences (sweeping from 110 to 75 Hz). Acoustic recording tags are attached directly to the whales and, at such close proximity, may pick up parts of calls that are not detectable on sonobuoys or moored recorders at greater distances. It is possible these newly characterized sounds may be the previously described downsweep sequence calls, and the tag picked up the fundamental frequency that was previously undetectable at greater range. However, typical downsweep sequences recorded on sonobuoys and seafloor recorders exhibit the 110–75 Hz frequency pulse with harmonics at 220–150 kHz, a multiple of 2, rather than 1.5, which supports the 110–75 Hz frequency range as the fundamental frequency of typical downsweep sequences and supports the 58–35 Hz low-frequency downsweeps as a new call type. Interestingly, the tagged whale was reported to be associated with a smaller whale throughout the day (although the size difference and behavior did not indicate that the smaller animal was a dependent calf), and may have been part of a mother–juvenile pair (Soldevilla *et al.*, 2017). North Atlantic right whale (*Eubalaena glacialis*) mom–calf pairs produce low amplitude calls that are distinct from the usual right whale call repertoire (Parks *et al.*, 2019), and it is possible this call could represent a mom–calf contact call. Alternatively, these calls may represent stress-related calls given that the seven calls occurred during the first two dive intervals following tag placement, when it is expected that the whale is still reacting to the tagging event. During this tag deployment, a reaction is evident in the unusually long-duration dive that occurred between the two calling bouts. Last, there is the possibility that these sounds were not produced by the tagged whale at all, and come from the associated whale or other biological or anthropogenic sources in the area. There were no other vessels documented in the area on this day, and at least 2 h elapsed between dolphin sightings and the time these sounds were detected on the tag. The tagging boat was nearby to the whale during this period, and was also in the water the day the similar call was detected on the sonobuoys, but this sound has never been detected on any other occasions that the tagging vessel was in the water and near sonobuoys. Further, the association of the sound detection timing with specific depths (less than 15 m) and specific points in the dive profile (at the bottom of shallow dives in five of seven instances), along with the consistency in received levels, support the tagged whale as the source of these sounds.

B. Acoustic species identification

The stereotyped long-moan, tonal-sequence, and downsweep sequence calls recorded from Rice's whales share similar features to those of other baleen whales, yet each call type is distinctive from any other baleen whale call and

therefore can be used to identify the species during real-time or autonomous PAM studies. Visually, Rice's whales cannot be distinguished from other Bryde's-like whales during vessel-based surveys unless a corresponding biopsy sample is obtained, and frequently they cannot be distinguished from other balaenopterids unless a vessel is able to closely approach and document the three rostral ridges. The three Rice's whale call types are clearly distinguishable from all known calls of balaenopterids in the North Atlantic (Mellinger *et al.*, 2000; Mellinger and Clark, 2003; Oleson *et al.*, 2003; Hatch and Clark, 2004; Baumgartner *et al.*, 2008; Delarue *et al.*, 2009; Stimpert *et al.*, 2011; Cerchio *et al.*, 2019), and also are clearly distinguishable from all known calls of other Bryde's-like whales around the globe (Cummings *et al.*, 1986; Oleson *et al.*, 2003; Heimlich *et al.*, 2005; McDonald, 2006; Kerosky *et al.*, 2012; Figueiredo and Simão, 2014; Cerchio *et al.*, 2015; Viloria-Gómora *et al.*, 2015). In particular, the commonly detected long-moan call is quite distinctive among all baleen whale calls for its extended duration, which is similar only to blue whale song calls (around 20 s durations, e.g., McDonald *et al.*, 2006) and North Atlantic minke whale pulse trains (up to 60 s duration, Mellinger *et al.*, 2000). The one baleen whale call type that shares similar features to the Rice's whale downsweep sequences is the Be6 call recorded from Bryde's whales in the Eastern Tropical Pacific (ETP), with pulses that downsweep from 208 to 76 Hz with inter-pulse intervals of 0.5 s (Oleson *et al.*, 2003; Širović *et al.*, 2014). However, the pulse sequencing is different, with Rice's whale downsweep sequences composed of single pulses to trains of 2–25 (mean 8) pulses compared to Be6 calls typically composed of repeated series of 1–4 downsweeps (Oleson *et al.*, 2003), and it is highly unlikely that ETP Bryde's whales would occur in the GOM to be confused with Rice's whales. Conversely, the long-moan and tonal-sequence call types described for Rice's whales are clearly distinct from the stereotyped Be7 call that was recorded and localized to multiple individual Bryde's whales in the nearby southern Caribbean (Oleson *et al.*, 2003). While the Be7 call is also nearly constant in frequency, with a slight downsweep, its fundamental frequency of 44 Hz is lower, and it has harmonic overtones and a mean duration of 1.6 s. Both the long-moans and tonal-sequences are higher in frequency and longer in duration, and, additionally, the long-moan has strong frequency modulation at the call start and an amplitude-pulsed nature. These distinctive calls from Rice's whales therefore can be used to confirm species identity of concurrent ambiguous visual sightings of balaenopterids and to distinguish them from southern Caribbean Bryde's whales and Omura's whales that occur in the tropical North Atlantic. Further, they can be used to identify the species' presence in autonomous PAM recordings.

For PAM surveys, it is also important to understand the behavioral context in which different call types are produced to be able to interpret what the presence or absence of calls may represent. In some baleen whale species, song is produced by males in reproductive contexts primarily during

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mating seasons and in breeding habitats (Payne and McVay, 1971; Watkins *et al.*, 2000; Croll *et al.*, 2002; Oleson *et al.*, 2014), while other call types are associated with maintaining contact (Clark, 1983), foraging (Oleson *et al.*, 2007; Stimpert *et al.*, 2007), migration (Crane and Lashkari, 1996), social activity (Parks and Tyack, 2005), and mom–calf interactions (Parks *et al.*, 2019), which in some cases also have age, sex, season, or location constraints to their production. While this study included concurrent visual and acoustic survey effort of Rice's whales, there is limited information to identify the behavioral role of the call types described. Rice's whale behavior was primarily described as unknown (11 sightings) or slow travel (9 sightings), but also included fast travel, diving, milling, resting, and complex social behaviors. In one case, long-moan calls were associated with a group in a slow-travel state from which one whale was subsequently tagged. The tagged whale conducted deep foraging dives throughout daylight hours of the 25 h tag deployment, similar to the behavior described by Soldevilla *et al.* (2017), though this whale did not produce any calls during the tag deployment period. It is possible then that the group was foraging and long-moans are associated with foraging behavior or are used as contact calls during these deep dives. Alternatively, many of the highly stereotyped and distinctive species- or population-specific calls produced by balaenopterids represent song used in reproductive contexts (Payne and McVay, 1971; Winn *et al.*, 1981; Croll *et al.*, 2002; McDonald *et al.*, 2006). While these Rice's whale calls are highly stereotyped and distinctive to this species, they do not appear to exhibit the consistent timing between consecutive calls that is associated with song in other species (e.g., Payne and McVay, 1971; Sirovic *et al.*, 2017). However, since Rice's whale call localizations were not sufficiently accurate to determine the number of whales that were present at a given location and timing inconsistencies may reflect the presence of multiple whales, this possible behavioral context cannot be ruled out at this time. Additional tagging and focal follow studies, as well as concurrent visual surveys with moored acoustic tracking surveys, may yield further insights into Rice's whale vocal behavior.

C. Limitations and biases

This study, based on directional sonobuoy localizations, defines confirmed visual and acoustic matches as those occurring within 2 km and 30 min, though in most cases, the timing and distance were closer than this, with the best case match between a sighting and acoustic localization at 200 m at 1.4 min. Several factors make it challenging to link visual and acoustic detections more precisely than this. First, the nominal angular precision of directional sonobuoys is 10° (Miller *et al.*, 2015). In general, this means calls from sources closer to the sonobuoy are more precisely localizable than more distant sources, but there is still room for substantial error in the location, as seen in Fig. 4. Second, the accuracy of localizations from two sonobuoys is highly

dependent on the source location with respect to the spatial configuration of the sonobuoy array, with sources close to the perpendicular bisector of a line between the sonobuoys having the lowest localization error and those close to parallel to the line between the sonobuoys having the highest localization error. Third, the sonobuoys are drifting instruments, which adds error to localizations that assume they are stationary, and they additionally may drift at different rates if there is a long period of time between individual deployments of the units in the array. In one case during the summer 2018 survey, opportunistic visual observations of an array of three sonobuoys with 3.3–7.0 km spacing deployed over a 50-min period indicated they had drift rates of 0.7 to 1.4 km/h. Future studies should attempt to account for sonobuoy drift (Miller *et al.*, 2018), when possible, for localizations that are more accurate. Fourth, animal movement combined with differences in when animals can be seen (while breathing at the surface) and when animals produce calls (while underwater during dives) means that whale sightings and acoustic localizations of calls will rarely if ever occur in the exact same location. This divergence may be exacerbated by long dive durations; Rice's whales dives were generally 10–12 min in duration, though longer duration dives are possible, as evidenced by the 22 min dive exhibited by the 2015 tagged whale following tag placement. During focal follows of the 2015 tagged whale, consecutive surfacings within a surface interval were recorded ranging from 50 to 200 m distance between them, and subsequent surfacings following a dive were recorded with 300–1300 m between them over 6–13 min dive intervals. These travel distances support our chosen scales for temporal and spatial match associations. Fifth, there were often multiple whales present in the area during this study and it is challenging to know which sighted whales match the acoustic localizations. Not all visually sighted whales will be producing sounds, and not all acoustically active whales will be sighted every time they surface, especially when visual observers are tracking multiple whales. Finally, on numerous occasions, these whales appeared to exhibit a cryptic vocalization behavior in which they stopped producing calls when the survey vessel started approaching them and did not start calling again until the vessel turned away or passed their last known location. In these cases, silent periods were 30–60 min or more in duration. For example, in the case shown in Fig. 4(f), the whale stopped producing calls for 55 min as the vessel approached. The visual and acoustics teams finally gave up searching for this whale and turned the vessel 90° from the prior trackline. Within minutes after this turn, the whale produced another call, which localized to exactly where the vessel had changed course, and we were able to turn the vessel around, deploy another sonobuoy, and direct the visual observers to finally observe the whale. Even in light of these challenges and limitations, based on the number of acoustic–visual matches, similarities in animal movement between visual and acoustic locations, and a lack of reasonable alternative sources, we attribute the previously described long-moan and tonal-

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sequence call types (e.g., Rice *et al.*, 2014) and downsweep sequences (e.g., Rice *et al.*, 2014; Širović *et al.*, 2014) to the Rice's whale.

V. CONCLUSIONS

Using arrays of sonobuoys to localize low-frequency sound sources, three previously proposed call types (long-moan calls, tonal-sequence calls, and downsweep sequences) have been verified as being produced by Rice's whales. Further, the low-frequency downsweep sequences recorded on the single acoustic tag may be a new call type or a variation on the previously described downsweep sequences, and further efforts should be made to obtain more recordings on acoustically tagged whales or through sonobuoy studies to test these hypotheses. A solid understanding of the Rice's whale call repertoire is crucial for using autonomous PAM to study spatiotemporal patterns in Rice's whale occurrence, which is a critical research need identified during the endangered species listing status review (Rosel *et al.*, 2016). Further, knowledge of the call repertoire is useful during real-time surveys, both as additional evidence of species identity for balaenopterid or Bryde's-like whales sighted in or near the GOM, and to assist in finding whales for targeted research as needed to better understand the ecology of these endangered whales. The attribution of these calls to Rice's whales is particularly important for using autonomous PAM to understand seasonal and long-term trends in call occurrence within the core habitat, and for investigating whether these whales are found more broadly throughout the GOM or beyond.

ACKNOWLEDGMENTS

[1]All prior acoustic studies were conducted before the species was renamed and referred to the whales as Bryde's whales. We will refer to them as Rice's whales from here forth when referencing work prior to the name change.

[2]These were referred to as call Be9 by Širović *et al.* (2014). Given the recent species name change, we abandon this naming convention and use call names established by Rice *et al.* (2014).

[3]DIFAR 53G sonobuoys are capable of broadcasting GPS location information on a 36 kHz carrier frequency and were sampled at 96 kHz to allow recording. However, the GPS signal was not recorded during this work as it required specialized communication hardware to activate this feature following deployment.

[4]Acoustic encounters do not represent unique individuals or groups of animals. Over the course of the two surveys, it is likely that the same animals were sampled repeatedly. Further, multiple acoustic encounters might represent the same individuals over the course of a single day. For example, multiple bearings from the same direction on a single buoy identified as one encounter might be resolved into multiple encounters with the additional location information provided when a second buoy was deployed.

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