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The life history, distribution, and acoustic ecology of the sei whale (*Balaenoptera borealis*) in the western North Atlantic Ocean remains poorly understood. In this study an array of bottom-mounted recorders captured previously undocumented low frequency 50 to 30-Hz triplet and singlet down sweep vocalizations in close association with signature 82 to 34-Hz sei whale down sweep vocalizations. Spatiotemporal correlations of acoustically tracked sei whales confirm the original vocalizations are produced by sei whales. The 50 to 34-Hz down sweep call types were characterized with a suite of five spectral and temporal measurements. The pattern and repetition of the full acoustic suite is suggestive of song structure and warrants further investigation. The discovery of vocalizations attributed specifically to sei whales enables historic acoustic records to be re-evaluated for the presence of this species throughout its range. https://doi.org/10.1121/1.5110713

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I. INTRODUCTION

The sei whale is a vastly understudied species of large whale whose life history and acoustic ecology are not well known (Waring *et al.*, 2015; Prieto *et al.*, 2014). In the western North Atlantic Ocean they show only sporadic incursions into coastal areas with great inter-annual variability (Mizroch *et al.*, 1984; Schilling *et al.*, 1992). Elusive species like the sei whale are difficult to study due to vast spatial habitat ranges and unpredictable seasonal movements. These factors, coupled with difficult field identification, have resulted in no reliable population estimates for sei whales in this region (Waring *et al.*, 2015). Stock assessment and behavior information on cetaceans typically entails extensive shipboard or aerial surveys that are highly weather dependent and resource intensive. Researchers are increasingly supplementing such efforts with passive acoustic monitoring (PAM), a remote monitoring method for the capture and analysis of animal sounds using underwater hydrophones and recorders (Van Parijs *et al.*, 2009; Mellinger *et al.*, 2007; Priede and Swift, 1992). Effective use of PAM requires broad knowledge of a species acoustic repertoire. While there have been major improvements in the ability to collect and process passive acoustic data in recent years (Sousa-Lima, 2013; Van Parijs *et al.*, 2009), the ability to correctly attribute captured vocalizations to the species that produce them is one that persists.

The sei whale, like all baleen whales, uses sound to communicate underwater, but the extent of their vocal repertoire is not well understood (Baumgartner and Fratantoni, 2008; Edds-Walton, 1997). Sei whale call types that have been documented globally include 100 to 44-Hz and 39 to 21-Hz down sweep calls in Hawaiian waters (Rankin and Barlow, 2007), a variety of tonal and down and up sweeps in Antarctica (McDonald *et al.*, 2005), and 93 to 42-Hz downsweeps in the south-eastern Pacific Ocean (Español-Jiménez *et al.*, 2019). In the western North Atlantic there have been two sei whale call types reported. The most consistently documented call type in this region, and a primary focus of this study, is a low frequency 82 to 34-Hz down sweep reported by Baumgartner *et al.* (2008) in the Great South Channel in Massachusetts Bay. Knowlton *et al.* (1991) also reported sei whales producing frequency modulated (FM) sweeps within the 1.5 to 3.5-kHz band off of the Nova Scotian shelf, which that article identifies as being similar to those reported by Thompson *et al.* (1979) from the same area. Identifying new call types normally requires the correlation of visual observations of species with the presence of acoustic vocalization data on a fine scale (Rankin and Barlow, 2005; Watkins, 1981). For this paper we used the passive acoustic tracking of the described 82 to 34-Hz down sweep sei whale calls, rather than visual presence, to compare with acoustic tracking of previously undocumented call types in order to attribute novel calls to species.

Using time delay of arrival (TDOA) differences between the same vocalization recorded on multiple acoustic sensors, the vocalizations of whales can be located (Watkins and Schevill, 1971; Cummings, 1968), and calls that arrive in series plotted over time can be used to track individual animals (Clark *et al.*, 1996). In this study this technique was applied to determine the movements of sei whales by tracking their signature down sweeps. Sei whale movement data

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derived from this tracking were then spatiotemporally compared with movement data from whales producing previously undocumented 50 to 30-Hz triplet and singlet call types. This comparative analysis was used to assess if sei whales producing the known calls were also producing the undocumented calls.

Several baleen whale species in the western north Atlantic produce a diverse, and at times ambiguous set of frequency modulated down sweep calls that cover similar frequency bands to sei whales (Ou *et al.*, 2015). These include blue whale 200 to 30-Hz calls (Berchok *et al.*, 2006), fin whale 75 to 40-Hz calls (Ou *et al.*, 2015; Watkins, 1981), and minke whale 118 to 80-Hz calls (Edds-Walton, 2000), however neither the fin and minke whale calls are extensively described. The novel 50 to 30-Hz call types described in this paper were measured and characterized based on several frequency, amplitude, and duration parameters.

II. METHODS

A. Data collection

Continuous passive acoustic recordings were made over a three-month period from September 7 to November 24, 2008 using Marine Autonomous Recording Units (MARUs, HTI 94-SSQ hydrophone, -168 dB re: 1 V/ 1 μPa sensitivity, 23.5 dB gain, 12-bit A/D converter; Calupca *et al.*, 2000) deployed in Massachusetts Bay, within the Stellwagen Bank National Marine Sanctuary (SBNMS, Fig. 1), located in the Southern Gulf of Maine region of the Northwest Atlantic Ocean. Ten MARU units were deployed at water depths of 30–100 m, with 9.3 km spacing to form an array configuration with the intent of localizing marine mammal sounds of interest. The GPS location of each MARU was recorded immediately upon deployment. All units sampled at 2000 Hz and 12 bit resolution, yielding an effective analysis bandwidth of 10–1000 Hz, with a flat frequency response ($\pm$1 dB) between 55 and 585 Hz for approximately 80 days. GPS synchronization was done twice, once prior to deployment and once after the array was recovered. This was done by placing all MARUs in a circle and producing an impulsive sound, using metal bars, at the center of the array, and at an observed GPS time. This common sound was recorded on each MARU. Finalized data recordings were sent to the Bioacoustics Research Program (BRP) for post processing, where the data were synchronized to $\pm$1 ms using the impulsive sound GPS time stamp. The ten-element array files were then merged together into a time-synchronized multi-channel sound file, allowing for the location of acoustic events within the ten-element array. Synchronization and file compilation tasks were completed by BRP using proprietary "Beast" software.

B. Acoustic analysis

The acoustic recordings were initially examined using the Low Frequency Detection and Classification Software (LFDCS, an acoustic detection and classification software applied to both real-time and post-processing applications for the low-frequency calls of baleen whales (Baumgartner and Mussoline, 2011). Data from one MARU were processed with LFDCS, focusing on detections of sei 82 to 34-Hz down sweeps. These signature down sweep calls are

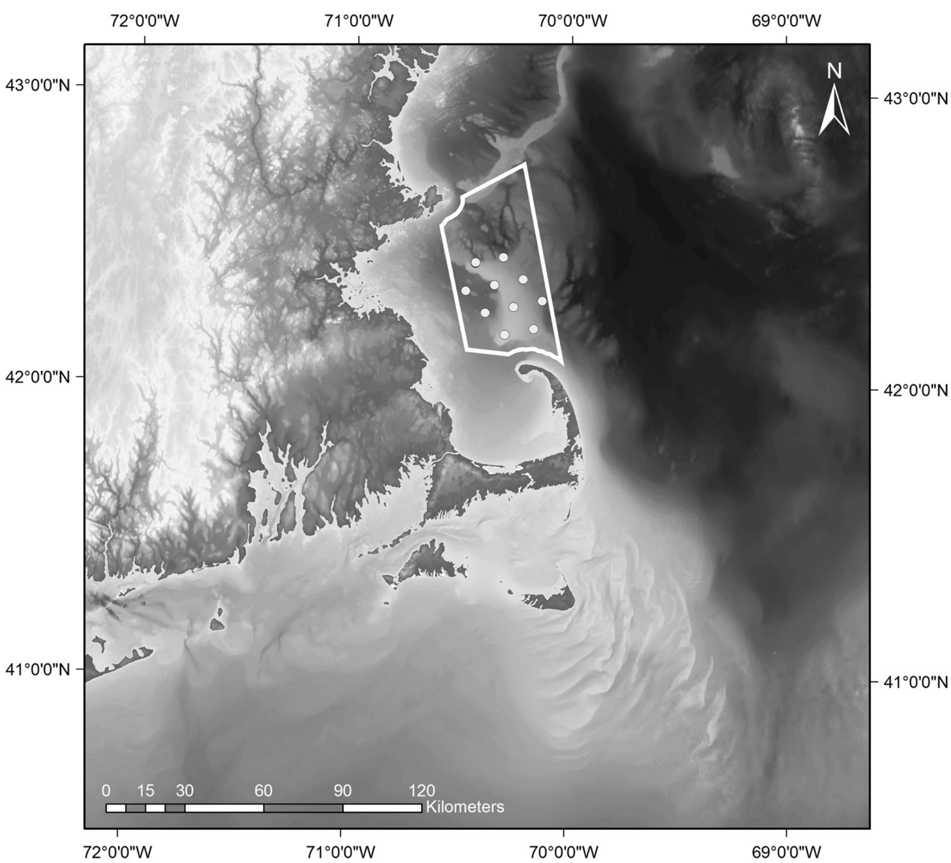

FIG. 1. Map of the study area in Massachusetts Bay, showing the locations of the 10 MARUs (white dots), and the outline of the Stellwagen Bank National Marine Sanctuary (white line).

referred to as type A (Fig. 2) calls in this paper. The eXtensible BioAcoustics Tool (XBAT), a Matlab-based sound analysis software, was used to manually browse LFDCS detection results and to confirm and log occurrences of sei whale down sweep calls across all other nine data channels. Other uncategorized call types found associated with the sei 82 to 34-Hz down sweep call type were also logged and marked as novel 50 to 30-Hz down sweep calls. These novel call types are referred to as types B, C, and D in this paper (Fig. 2). Type A, B, C, and D calls that had high signal-to-noise ratio were selected for localization analysis. Locations of calls were obtained using a correlation sum estimation algorithm (CSE) applied in the XBAT environment (Cortopassi and Fristrup, 2005). The CSE localization method calculates accumulated cross-correlation sums for all channel pairs across a grid of spatial points and selects the point that maximizes the correlations sum as the likely location.

C. Descriptive call measurements

Descriptive measurements of the novel type B, C, and D calls were collected using the mean statistics of one hundred examples of each novel call type from ten separate days. These calls were extracted and analyzed using toolboxes in Raven Pro 1.4 for conducting basic metric analysis. Each call example was manually selected and measured for Frequency 5%, Frequency 95%, Duration 90%, Center Frequency, and Peak Frequency (Window: Hann, FFT size: 512). For call types B and C, where multiple elements made up a given call type, each sweep was measured separately and then all elements of the call were measured as a whole. Measurements were taken of the call features that displayed consistent amplitude and frequency characteristics throughout the sample set (Table I).

D. Movement track building

All XBAT locations of type A, B, C, and D down sweep calls were plotted in ArcGIS 9.2 at one-day resolution. Type A calls were compiled to generate sei whale movement tracks, and types B, C, and D were compiled to generate the novel call movement tracks. A subset of quality locations was selected for each day and a separate movement track was created for each call type. The time-stamp data for each movement track were reviewed for time continuity.

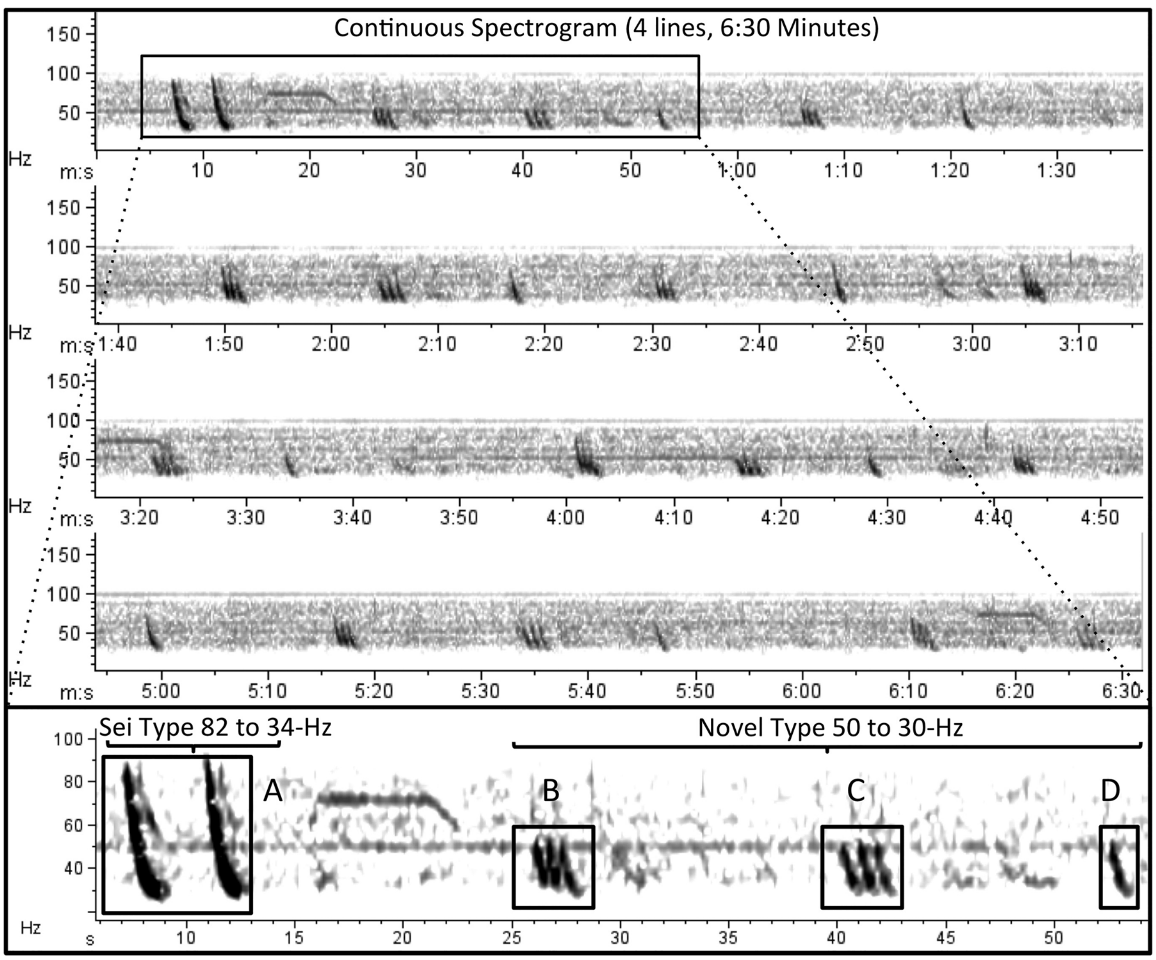

FIG. 2. A spectrogram example of a sequence of sei whale calls with the "type A" sei 82 to 34-Hz call and the novel type B, C, and D 50 to 30-Hz sei whale calls utilized in the call location, movement track building, and movement track correlation analysis. The top panel shows a continuous spectrogram example over four lines, with the type A call arriving first and multiple type B, C, and D calls repeated throughout, indicative of song. The lower panel shows a zoomed in view of the four call types. The type B and C calls are each comprised of a set of three down sweeps that occur in quick succession, whereas the type D call is a single down sweep, roughly half the frequency sweep of a sei 82 to 34-Hz type A sei whale call. The spectrogram includes a 23-Hz high pass and 89-Hz low-pass filter.

TABLE I. This table contains descriptive measurements for the sei whale call types B, C, and D found to be spatially correlated with 82 to 34-Hz down sweep Type A sei whale calls. These call types have not yet been described in the literature, and here are described in detail, based on a sample size of 100 for each call type (Window: Hann, FFT Size: 512). Types B and C are distinct calls, with each call comprised of three down sweeps occurring in rapid succession.

	Center frequency (Hz)	Duration 90% (s)	Frequency 5% (Hz)	Frequency 95% (Hz)	Peak frequency (Hz)
Type B $n = 100$					
Sweep 1	39.15	0.31	33.78	44.9	37.12
Sweep 2	36.81	0.34	32.18	42.14	35.86
Sweep 3	34.71	0.32	30.06	39.34	21.75
Sweep Suite	38.34	1.68	31.59	52.75	35.97
Type C $n = 100$					
Sweep 1	34.57	0.35	29.58	38.92	34.20
Sweep 2	34.21	0.33	30.18	38.62	34.03
Sweep 3	33.10	0.34	29.22	37.78	32.86
Sweep Suite	35.62	1.94	29.94	49.36	35.00
Type D $n = 100$					
Sweep 1	37.34	0.6	29.6	49.05	36.69

Movement tracks that contained time gaps >10 min between locations were rejected (following Risch *et al.,* 2014). Each confirmed movement track was processed using the Adehabitat package (Calenge, 2006) executed within the R software package (v3.1.2) to measure movement track characteristics (total distance, displacement, speed, straightness index (SI), and direction of travel between points). Each processed movement track was then smoothed using a five-point moving average (MA) function in R. Final movement tracks were plotted and instances where a sei type A down sweep movement track overlapped with a novel type B, C, and D sweep movement track in time and space were noted. Spatiotemporal comparisons between sei whale 82 to 34-Hz calls (type A) and novel call types (Types BCD) were all conducted within the same base framework (the MARU array), meaning each movement track was subject to identical temporal and spatial parameters.

III. RESULTS

A. Spatiotemporal comparisons of whale movement tracks

Seventy-six days of acoustic data (9/8/2008–10/18/2008) were analyzed for the presence of sei whale calls. Sei type A down sweep calls were found on 67 of the 76 days (88%). Thirty-four of these days contained calls that were clearly present across multiple channels, allowing for accurate location analysis. Six days of acoustic data contained both type A down sweeps and novel type B, C, and D down sweep calls clearly present across multiple channels and of sufficient spectrogram resolution to warrant acoustic characterization and spatiotemporal track correlation analysis. Fourteen movement tracks were analyzed for spatial correlation between the known and novel call types. In each of these cases the spatiotemporal patterns closely align (Figs. 3 and 4).

Two sets of animal movement data are reported (Table II). The first are the overall movements of each sei type A and novel type B, C, and D call paths regardless of how each overlapped with one another. The second set was for each track only during the time when they overlapped with one another that reveals information about how the two track types compared in time and space. The mean duration of overlapped track events was 40 min. For the sei type A down sweep call types the mean total distance traveled was 2.29 km, total displacement was 2.2 km, average swim speed was 6.75 km/h, and showed a straightness index of 0.96. For the novel type B, C, and D down sweep call types the mean total distance traveled was 3.49 km, total displacement was 3.32 km, average speed was 10.05 km/h, and straightness index was 0.96. Results indicate slight value elevations in each category of the novel type B, C, and D down sweep calls vs the sei type A calls.

B. Call characteristics of type B, C, and D calls

Call types B and C are each a similar set of three low-frequency down sweeps that occur in rapid succession (Fig. 2). The type B call is overall slightly shorter in duration (1.68 s), steeper (52.75 to 31.59-Hz), and higher in overall frequency (35.97 Hz) compared to the type C call, which is longer duration (1.94 s), less steep (49.36 to 29.94-Hz) and lower in peak frequency (35.0 Hz). The type D call is a single, low-frequency down sweep (49.05 to 29.6-Hz) with a duration of 0.6 s and a peak frequency of 36.69 s (Table I). Type A, B, C, and D calls often occurred in a repeated pattern of "AABCDBD" (see Fig. 2 example), though this was not always the case.

IV. DISCUSSION

Based on the closely aligned spatiotemporal mapping of the sei type A down sweep and novel type B, C, and D down sweeps reported here, we are confident sei whales are responsible for producing all calls profiled in Fig. 2. The movement statistics indicate that the sei whales tracked during this study moved at a moderate pace (∼7–10 km/h) and in relatively straight lines (SI = 0.97−0.96) when calling. There were differences in overall movement statistics between movement tracks created with sei type A down sweep calls and those created with types B, C, and D calls

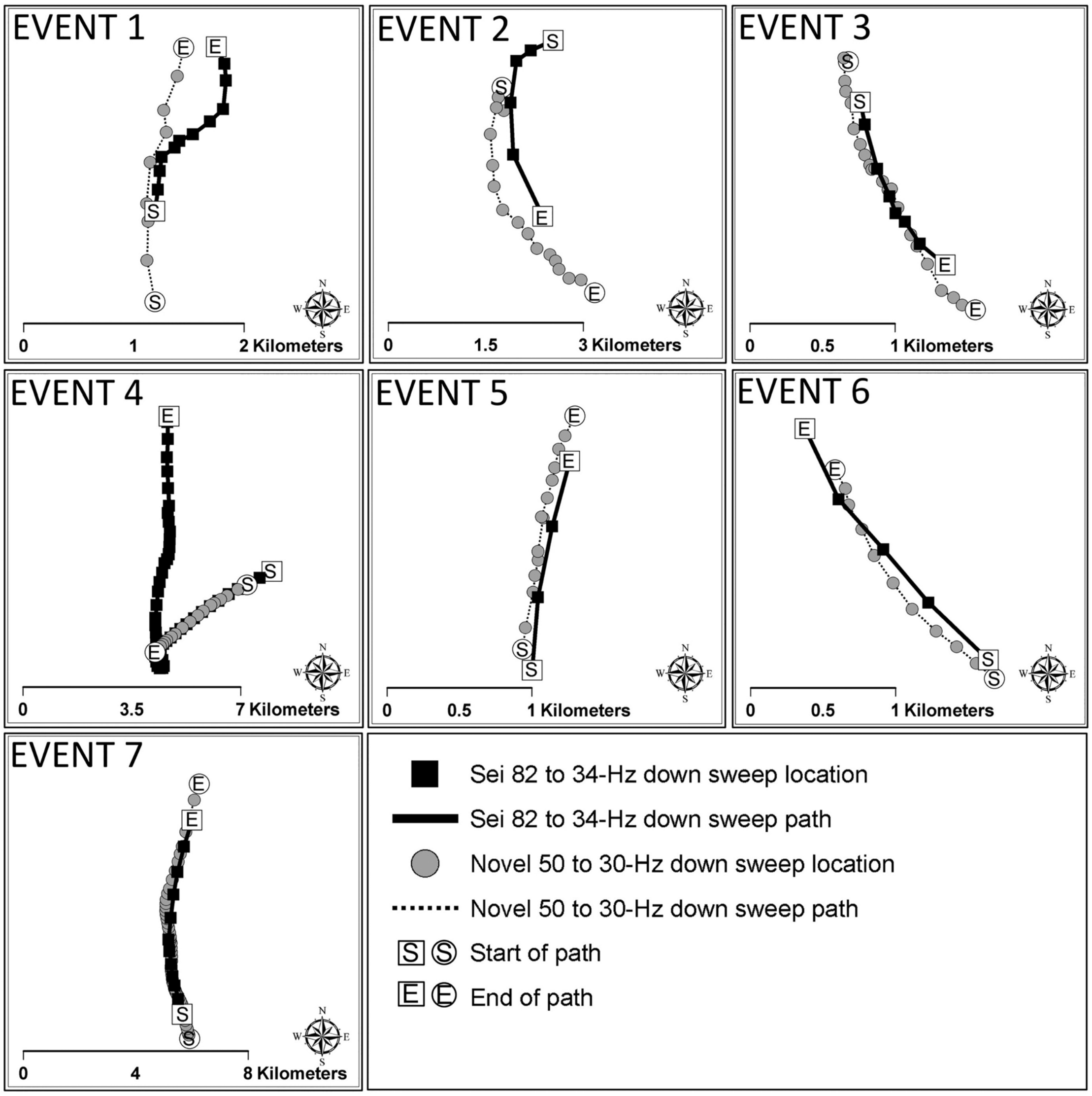

FIG. 3. Spatiotemporal comparisons of seven events where movement track of sei 82- to 34-Hz down sweep calls (type A) overlapped with the movement track of novel 50- to 30-Hz triplet and singlet calls (types B, C, and D). A square with an "S" and "E" marks the start and end of a type A movement track, with black squares representing a located call. A circle with an "S" and "E" marks the start and end of a novel type B, C, and D movement track, with a gray circle representing a located call. A black line marks a sei type A movement track, and a dashed line marks a novel type B, C, and D movement track. In each case, the movement track of each call type was closely aligned in time and space.

during the time where they overlapped. One potential cause for this could be the number of locations derived for B, C, and D calls versus the type A calls. During patterned calling bouts, sei whales are producing the type B, C, and D calls more frequently than the type A calls, as shown in Fig. 2. This did result in a higher number of located events for the B, C, and D calls and ultimately higher resolution movement tracks, resulting in a greater degree of calculated movement.

As these results draw upon mapping of movements over time and space, any error associated with the acoustic array parameters must be considered. There could be some error in drop locations of recorders due to drift in the water column while the unit falls through the water column. This study also did not document variations in sounds speed due to changing oceanographic conditions over the course of the study period, which would have an effect on the acoustic propagation of biological sounds. However, a distinction must be drawn between this study, which compares acoustically tracked animals with *acoustic* co-occurring variables (other vocalizations recorded by the same acoustic array), and a study that compares the movements of acoustically tracked animals with *non-acoustic* co-occurring variables (e.g., prey mapping, other oceanographic conditions). This study documented spatiotemporal comparisons between the movement track data sets observed within the same base framework (the MARU array), and therefore each data set is subjected to identical temporal and spatial parameters. This factor improves the determination that the overlap between call types is accurate.

Two of the three novel 50 to 30-Hz signals examined in this paper, type B and C, were comprised of three down sweeps occurring in quick succession. Acoustic signals produced by baleen whales propagate through the water column in multiple directions. If the signal is of sufficient amplitude and is within range of an acoustically reflective surface, such as the sea floor or ocean surface, it may be picked up

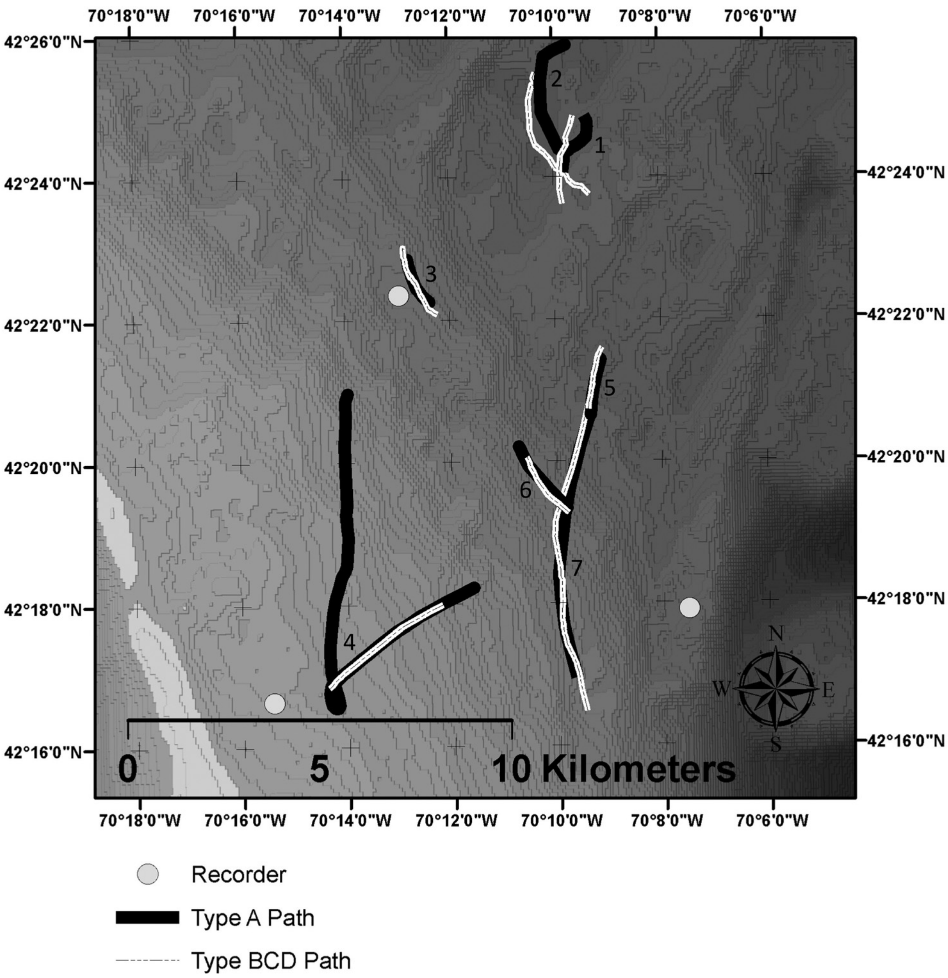

FIG. 4. Map depicting all spatiotemporal comparisons of seven events where movement track of sei 82 to 34-Hz down sweep calls (type A) overlapped with the movement track of novel 50 to 30-Hz triplet and singlet calls (types B, C, and D). A black line marks a sei type A movement track, and a dashed line marks a novel type B, C, and D movement track. A light gray dot represents a recorder that captured the calls used in this analysis. Movement tracks 1 and 2 are outside of the array space, which may account for slightly more location error in the movement track overlap.

multiple times by an acoustic recorder. The resulting multipath signals arrive as multiple representations of the same signal repeated in rapid succession one after another (Weirathmueller *et al.*, 2017). Under certain circumstances the multiple sweeps observed in the type B and C call might resemble multipath signals. However in the case of this study the range to depth ratios are much too high (>100:1) to produce a multipath event that would result in the signal observed in the type B and C calls, which could only occur in an environment with similar (horizontal) ranges and depths (1:1) (McDonald *et al.*, 1995; Nosal and Neil Frazer, 2006). It should also be noted that within the call patterns described in this paper (see Fig. 2 pattern example, "AABCDBD"), the triplet calls B and C are of similar amplitude to the singlet call D. If multipath effect was at play, call D would be expected to also arrive as a triplet, yet does not. These factors indicate that each sweep that makes up calls B and C are in fact individual direct path signals, not multipath.

As multiple baleen whale species produce down swept vocalizations in the western North Atlantic (Ou *et al.*, 2015), it is critical that the characterization of these calls is accurate for future analysis consideration. The call pattern featured in Fig. 2, which is indicative of the call pattern found throughout this data set, shows type B and C triplet calls and the type D singlet calls co-occurring within similar time and space. These calling data reported in this paper reveal that sei whale vocalization behavior is more complex than previously reported. The triplet B and C calls are unique from other baleen whale downsweeps that typically occur as singlets. These calls are also easily distinguished from the type A 82 to 34-Hz sei whale calls they are associated with due to the much shorter duration and lower frequency range. The type D singlet call may be not unique enough to be easily distinguished from other baleen whale down sweep calls, however it was typically found alongside occurring alongside the other type A, B, and C calls. The type D singlet call is also similar to the 39 to 21-Hz sei whale down sweep described from Hawaiian waters (Rankin and Barlow, 2007). The three new call types (B, C, and D) profiled in this study will be a valuable resource for future acoustic studies into distribution and behavior of this species in the western North Atlantic Ocean. There is a significant lack of information regarding the life history and ecology of sei whales in the North Atlantic Ocean, and including these calls in both past and future passive acoustic monitoring analysis may give a better understanding of their distribution (Prieto *et al.*, 2014). There exists no reliable population estimate or *in situ* measurements of foraging ecology for this species, and minimal data on their movement behavior (Prieto *et al.*, 2014). A cursory examination has also found examples of these call types present off the coast of Nova Scotia, Canada, North Carolina, USA, and Ireland (personal communications), indicating that this vocal behavior may be prevalent throughout a great swath of the Atlantic Ocean.

TABLE II. Movement statistics for sei 82 to 34-Hz (type A) and novel 50 to 30-Hz (Type B, C, and D) down sweep movement tracks derived from the adehabitat package analysis in R. For each full track for each call type (upper table), and the movement during overlap by call type (lower table) statistics were calculated.

Date	Time (EST)	Track event	Track type	Duration (min)	Total distance traveled (km)	Total displacement (km)	Average speed (km/h)	Straightness index (0–1)
Movement statistics for each full track representing both call types								
9/24/08	1819–1921	1	A	61	1.80	1.60	3.93	0.89
	1802–1918		BCD	76	2.38	2.32	7.50	0.97
9/24/08	2019–2132	2	A	74	3.16	2.72	5.07	0.86
	2022–2132		BCD	71	4.10	3.47	10.90	0.85
10/6/08	1922–1953	3	A	31	1.30	1.26	6.96	0.97
	1923–1952		BCD	29	2.11	1.92	9.46	0.91
10/10/08	0614–0819	4	A	125	13.55	6.02	13.80	0.44
	0620–0654		BCD	34	3.70	3.68	17.03	0.99
10/15/08	0630–0703	5	A	33	0.97	0.97	7.30	0.99
	0637–0703		BCD	26	1.67	1.66	9.60	0.99
10/16/08	0656–0735	6	A	39	2.05	2.03	8.99	0.99
	0703–0730		BCD	27	1.85	1.81	8.63	0.98
10/18/08	2218–2357	7	A	99	7.06	6.92	9.56	0.98
	2218–2355		BCD	97	3.90	3.85	12.65	0.99
	Mean of all tracks		A	66	4.27	3.07	7.94	0.87
			BCD	51	2.82	2.67	10.82	0.95
Movement statistics for each track during overlap by call types								
9/24/08	1819–1918	1	A	59	1.63	1.48	4.23	0.91
			BCD		1.65	1.61	5.03	0.98
9/24/08	2022–2132	2	A	70	2.78	2.56	5.92	0.92
			BCD		4.10	3.47	8.28	0.85
10/6/08	1923–1952	3	A	29	0.92	0.90	7.28	0.98
			BCD		2.11	1.90	9.46	0.91
10/10/08	0620–0654	4	A	34	3.67	3.53	9.84	0.96
			BCD		3.70	3.68	17.03	0.99
10/15/08	0637–0703	5	A	26	0.47	0.47	5.85	1.00
			BCD		1.67	1.66	9.63	0.99
10/16/08	0703–0730	6	A	27	0.48	0.48	3.98	1.00
			BCD		1.85	1.81	8.63	0.98
10/18/08	2218–2355	7	A	37	6.07	5.97	8.87	0.98
			BCD		9.36	9.08	12.32	0.97
	Mean of all tracks		A	40	2.29	2.20	6.57	0.96
			BCD		3.49	3.32	10.05	0.95

Of great future interest is the pattern in which these calls are produced (Fig. 2). Males of multiple baleen whale species are known to sing, for example, fin, blue, and humpback whales (McDonald *et al.*, 2006; Watkins *et al.*, 1987; Payne and McVay, 1971). What constitutes song for each of these species varies, ranging from a series of repeated 20 Hz signals for fin whales to long, complex vocalizations of humpback whales that span across many frequencies (Cholewiak *et al.*, 2013; McDonald *et al.*, 2006). The sequences of vocalizations reported in this paper are indicative that sei whales also produce song, as there are characteristic patterns made up of the sei 82 to 34-Hz down sweep and novel 50 to 30-Hz call types that are repeated throughout the data set. Further analysis will focus on describing these song patterns in detail.

As passive acoustic monitoring (PAM) for cetaceans is now a fundamental applied science for commercial, academic, and government entities as both an environmental mitigation measure and method of advanced research, the quality of the results from such investigations is affected by the breadth and reliability of call repertoire referenced for each study species. Often, large-scale acoustic monitoring projects are designed such that sensors are deployed for months or years at a time with no concomitant visual data collection, and the analysis practices rely on a small set of well-studied call types that are sub-sampled temporally. The findings from such studies can have significant influence on long-term marine mammal mitigation efforts, and there may be ecological ramifications for species that are underrepresented because their call repertoires are not thoroughly investigated. For this study, pertinent new information emerged from both a contextual and associative analysis with known calls. The vocalizations reported in this paper were recorded in a geographic area that has been well sampled, both biologically and acoustically, and on broad and fine scales, for decades. To minimize potential misrepresentation of lesser-understood species, a greater focus on visual validation of species traveling over acoustic arrays or in-depth acoustic associative analysis may be warranted.

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