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Acoustic monitoring for baleen whale vocalizations off southern Oman, 2020 to 2022

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INTERNATIONAL
WHALING COMMISSION

Acoustic monitoring for baleen whale vocalizations off southern Oman, 2020 to 2022

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Abstract

The waters off the coast of Oman have been documented as habitat for endangered populations of Arabian Sea humpback whales (ASHW), North Indian Ocean blue whales, and two poorly studied populations of Bryde's whales. In order to assess the population identity and presence of baleen whales off southern Oman, autonomous acoustic recorders were deployed in deep continental slope waters off Ras al Hasik, Dhofar, during the period March 2020 to April 2022, with an approximately one-year gap in recording effort between October 2020 and November 2021 due to malfunction of equipment. Humpback whales, blue whales and Bryde's whales have all been sighted during boat surveys in this region, and previous acoustic monitoring from the shelf has described the temporal distribution of humpback whale song and the putative Northwest Indian Ocean (NWIO) blue whale song. In these recent deployments humpback whale song was documented during the boreal winter breeding season in 2020 (late season only) and 2022, however at dramatically reduced frequency of occurrence compared to the previous acoustic monitoring in 2011/2012. These data imply a potential distribution shift of the Arabian Sea humpback whale population, as also suggested from the absence of ASHW sightings in the same area during boat surveys in March 2021. In addition to humpback song, four different songs/vocalizations were detected throughout the recording period, including two that have been previously attributed to blue whale populations, NWIO blue whale song, and CIO (Central Indian Ocean/Sri Lanka) blue whale song, and two that are of unknown species, one of which (dubbed Long-107Hz) is novel and previously unreported, and the other resembling the "Spot" or "P" call previously described in the Southern Hemisphere. NWIO song was more extensively documented than CIO song, and both were predominantly absent from January to April 2020, during the winter monsoon season. The Long-107Hz vocalization was recorded the most consistently with no extended periods of absence throughout the recording period, whereas the Spot-call was the least prevalent; it is possible that these represent the vocalizations of the two identified populations of Bryde's whales off Oman, inshore and offshore, respectively. If the current hypothesis that NWIO song and CIO song represent two different acoustic populations of blue whales, these data would imply that the two populations' ranges overlap in southern Oman, and the novel vocalization may be attributed to Bryde's whales. Alternatively, the presence of CIO song raises the possibility that all blue whales off Oman might belong to the CIO acoustic population, and that NWIO song may instead be attributed to Bryde's whales, contrary to the currently understood species attribution. Further research is recommended to distinguish between these scenarios.

Introduction

The coastal waters of Oman host diverse habitats where productivity is determined by the Arabian Sea monsoon cycle, with a north-easterly winter monsoon season from December to February and south-westerly summer monsoon from June to September (Bruce et al., 1994). At least three species of baleen whales have been documented off Oman, including humpback whales (*Megaptera novaeangliae*), blue whales (*Balaenoptera musculus*) and Bryde's whales (*B. edeni*) (Mikhalev 2000, Baldwin 2003, Minton et al. 2011, Anderson et al. 2012, Kershaw et al. 2013, Willson et al. 2019). All three species were extensively hunted during a period of illegal Soviet whaling in the Arabian Sea during the 1960s (Mikhalev 2000).

Existing genetic, demographic and behavioural evidence indicates that Arabian Sea humpback whales (from here on referred to as ASHW) represent an isolated and unique population (Minton et al. 2011, Pomilla, Amaral et al. 2014, Willson 2021). ASHWs exhibit a Northern Hemisphere breeding cycle and do not undergo the typical latitudinal migrations and seasonal separation of breeding and feeding ecology exhibited by other populations of humpback whales. Review of the population is a standing Scientific Committee (SC) agenda item and numerous recommendations for research and conservation actions have been made in the IWC's SC since 2010. These recommendations include the implementation of a Conservation Management Plan (CMP) for the population (e.g. IWC, 2016).

Bryde's whales have long been known to occur in the Arabian Sea (Mikhalev 2000, Baldwin 2003), but little is known about their population status or distribution. Mikhalev (2000) first suggested that there were two sympatric populations in the Arabian Sea with out-of-phase reproductive cycles based on foetus lengths in captured pregnant females (Mikhalev, 2000). More recently, genetic analyses of tissues collected from dead specimens indicated that two forms of Bryde's whales occur off Oman, *B. e. edeni* and *B. e. brydei* (Kershaw et al. 2013). The *B. e. edeni* samples came primarily from animals stranded along the coasts of Oman, and thus it is believed represent an inshore population. Conversely, the evidence for *B. e. brydei* was based on samples from two ship-strike carcasses, at least one of which was carried into a major port on the bow of large vessel, thus suggesting that they may occur offshore. These are regarded by some as separate species, the smaller, more coastal *B. edeni* (Eden's whale), and the larger and more oceanic *B. brydei* (Bryde's whale) (Wada et al. 2003).

Populations of Indian Ocean blue whales are thought to be defined by diagnostic song-types (McDonald et al. 2006). Antarctic blue whales are characterized by their own song-type, whereas pygmy/North Indian Ocean blue whales are thought to be structured into "acoustic populations" each with a diagnostic song-type: Southwest Indian Ocean pygmy (SWIO/Madagascar), Southeast Indian Ocean pygmy (SEIO/Australia-Indonesia) and Central Indian Ocean (CIO/Sri Lanka) are the three most widely documented. Within the North Indian Ocean, boat-based recordings in the 1980's off eastern Sri Lanka first documented the Sri Lanka song-type (Alling and Payne 1987) which has most recently been documented off the Lakshadweep Islands in the eastern Arabian Sea (Panicker & Stafford 2021). Through the use of long-term passive acoustic monitoring (PAM), the Sri Lanka song-type has been more extensively documented throughout the Central Indian Ocean from equatorial Chagos Archipelago, as far south as the Amsterdam Island (43°S) and Crozet Island (46°S) basins (Samaran et al. 2013, Stafford et al. 2011, Leroy et al. 2018). Despite the limited evidence in the North Indian Ocean, the Sri Lanka acoustic population had been assumed to be synonymous with the North Indian Ocean population, or subspecies (Branch et al. 2007, Anderson et al. 2012).

Recently, a previously unreported song-type was described, recorded off Oman in the Arabian Sea, off the western Chagos Archipelago, and off Madagascar, and attributed to blue whales (Cerchio et al. 2020a). Prior to Cerchio et al (2020a), there were no published accounts of song attributed to blue whales in the western Arabian Sea. At the time of the study, this was the only potential blue whale song detected off Oman, and in the absence of the CIO/Sri-Lanka song-type, it was attributed to a separate acoustic population, and referred to as the Northwest Indian Ocean (NWIO) song-type. Spatiotemporal variation suggested a distribution west of 70°E, with affinity for the North Indian Ocean/Arabian Sea, and only minor presence in the SWIO. Recordings from Oman were made from a shallow water recorder perched on the edge of the shelf-break, and consequently were limited in detection range and provided song occurrences that were degraded due to propagation loss from deep water sources onto the shallow shelf. Additional PAM effort in the deeper water of the shelf slope off Oman was recommended to provide higher quality data, greater detection range, better description of temporal distribution, and an assessment of the presence/absence of other song types.

Funding was approved by the IWC SC in 2020 to conduct a year of PAM in the deep continental slope waters off Oman and conduct an initial analysis of baleen whale vocalizations in the acoustic data set. This report represents the results of this effort, for which the temporal collection of data was extended though 2022 due to setbacks related to the COVID pandemic and unexpected malfunction of recording equipment, described herein. The objectives of the study were to collect PAM data off Ras al Hasik, Dhofar, in Southern Oman; document the temporal occurrence of NWIO blue whale song; assess the potential presence of other blue whale song types; and assess the occurrence of humpback whale song, as well as other baleen whale vocalizations that may be attributed to Bryde's whales.

Methods

Data collection

During 2020-2022, passive acoustic monitoring was conducted in southern Oman off Ras Hasik, Dhofar region, at the southwestern edge of Hallaniyats Bay (Figure 1). An Ocean Instruments SoundTrap ST500-STD autonomous archival recorder was deployed tethered to an InnovaSea Ascent AR acoustic release and suspended in the water column with a 11" deep sea trawl float. Three separate deployments were conducted commencing on 6 March 2020, 20 May 2021, and 22 November 2021 (Table 1). The recorder deployed in May 2021 malfunctioned and failed to record past day 5 of the deployment, returning no useful data to report on here. The instruments were anchored just off the shelf break at the same approximate position (17.38°N, 55.31°E), at depths ranging from 248-328m across deployments, and suspended approximately 10m above the sea bottom. The SoundTrap recorder specifications indicate that it has a flat response from 20Hz-60kHz (+/- 3dB) with a -9dB roll-off at 10Hz, and 34dB re 1V µPa-1 noise floor. Two manufacturer calibrated units were used, and hydrophone sensitivity plus system gain was -175.9dB re 1V µPa-1 for the March 2020 deployment, and -175.0dB re 1V µPa-1 for the November 2021 deployment. During the March 2020 deployment, recordings were made at 50% duty cycle (30min every 60min), 24kHz sample rate (SR) and 16-bit depth, yielding a 320 day manufacture-estimated expected endurance; during the November 2021 deployment, continuous recordings were made at 24kHz SR and a 16-bit depth, yielding a 176 day manufacture-estimated expected endurance.

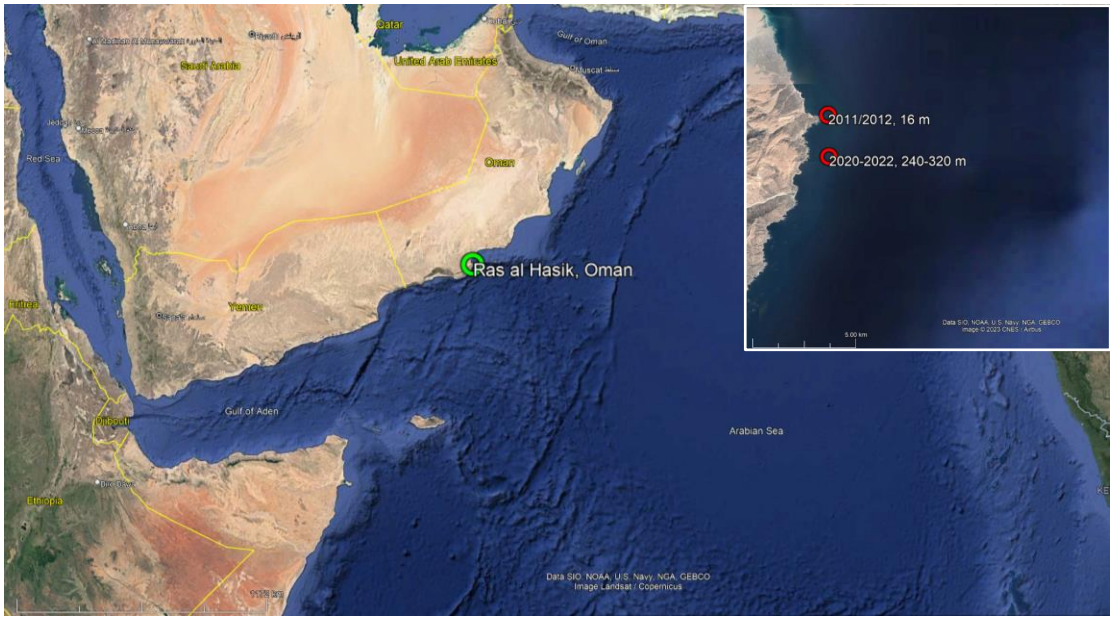

Figure 1. Map of study region showing location of Ras al Hasik, Oman (in green), and inset showing relative positions of shallow water and deep water recorders in 2011/2012 and 2020-2022, respectively.

Table 1. Details of three deployments (#01-03) of SoundTrap ST500-STD recorders and one deployment (#04) of an ST600-STD recorder off Ras al Hasik, southern Oman during 2020 to 2022. Depth of recorder was indicated by the InnovaSea acoustic release device; Duty Cycle was either recording 30min every 60min (50%), or recording continuously (100%); Expected Stop Date was estimated by the manufacturer provided endurance calculator, based upon sample rate, data compression ratio, and ambient temperature; Data Stop Date was the day on which the recording stopped, in all cases due to unexpected recorder malfunction (and in all cases the recorder continue to save files with no useable data).

Deploy#	Depth (m)	Duty Cycle	Deployment Date	Retrieval Date	Expected Stop Date	Data Stop Date	Days of Data
01	248	50%	6-Mar 2020	14-Mar 2021	20-Jan-2021	4-Oct 2020	212
02	328	50%	20-May 2021	21-Nov 2021	5-Apr-2022	25-May 2021	5
03	320	100%	22-Nov 2021	4-May 2022	17-May 2022	6-Apr 2022	135
04	286	50%	4-May 2022	pending	7-Apr 2023	pending	pending

Spectrograph review

The original 24 kHz SR wav files were down-sampled to 2 kHz to reduce size and increase manageability of the data set for low-frequency analysis. A first manual evaluation of continuous spectrograms was conducted in Raven Pro 1.5 (Bioacoustics Research Program 2014), at parameters optimized to detect signals of low frequency baleen whales. Since the analysis needed to distinguish two types of songs in different frequency bands, a double-panel spectrogram was viewed with different display parameters. The bottom panel was optimised for detection of NWIO song with units primarily in the 24-25 Hz band (15-40Hz displayed frequency band, 8192pt point FFT, 50% overlap, Hann window). The top panel was optimised for detection of CIO song with highest amplitude units in the 58-60 Hz band and 98-100 Hz band

(40-120 Hz displayed frequency band, 4096 point FFT, 50% overlap, Hann window). During the browse of spectrograms, a 60-min spectrogram was displayed on a line and all potential LF baleen whale vocalizations were logged for hourly presence in each one-hour bin. A second manual evaluation of spectrograms was conducted to review for humpback whale song; parameters optimized the detection of the long series of short units by using a high integration time to "smear" the patterned sequence in a broad frequency band (0-500 Hz displayed frequency band, 60min per spectrogram line, 8192 point FFT, 50% overlap, Hann window).

Quantitative measurements

During spectrographic review, a novel vocalization was encountered that does not appear to have been previously reported in the literature (see Results). The vocalization took the form of a single tonal utterance that was typically repeated rhythmically in a series. In order to describe the vocalization, quantitative measurements of time-frequency acoustic features were made in Raven Pro 1.5. A subset of the highest signal-to-noise ratio (SNR) vocalizations were selected for quantitative measurement from the 2021/2022 data set (Deployment #03; Table 1), initially noted subjectively during spectrographic review. For each one-hour period that was annotated as having relatively high SNR vocalizations, the single clearest and highest amplitude example from a series was selected for measurement; this approach spread the selected samples across many hours and days, reducing non-independence and increasing likelihood of a representative sample among the population. Signal measurements were made by tightly boxing calls on Raven spectrograms using the down-sampled 2 kHz SR files, a window size and DFT size of 16,384 samples, 95% overlap, and a Hann window, with a resultant temporal resolution (time grid spacing) of 410 ms and frequency resolution (frequency grid spacing) of 0.122 Hz. The measurements included Duration (call end time - call begin time as measured by the temporal extent of the selection box, s), High Frequency (maximum of selection box, Hz), Low Frequency (minimum of selection box, Hz), and Central Frequency (The frequency that divides the selection into two frequency intervals of equal energy, Hz). For examples that occurred in series, the Repetition Interval (s) was measured as the start of the measured unit to the start of the next unit (except in cases where the unit was the last in a series, then the previous unit start time was used) The SNR (in dB) was measured using Raven's Inband Power function and the procedure recommended by the Center for Conservation Bioacoustics[1], comparing identical time/frequency-band selections of signal and background noise. Only samples that exceeded a SNR of 15 dB were used for reporting descriptive quantitative statistics in order to increase the likelihood of accurate time-frequency parameter measurement from the spectrogram.

Results

Deployments of recorders and available data

Three deployments of the ST500-STD recorders were conducted between March 2020 and May 2022, yielding a total of 347 days of usable acoustic data during that period (Table 1). In all cases the collection of data was impacted by malfunction of the recorder and premature cessation of recording. During Deploy #01, a recorder was deployed in March 2020 at 50% duty cycle and expected to record for 320 days until January 2021. The initial plan was to retrieve the recorder in November 2020 well ahead of expected endurance, and thus the use of a 50% duty cycle was a risk mitigation measure; however, due to the Covid pandemic, retrieval was not possible until

[1] https://ravensoundsoftware.com/knowledge-base/signal-to-noise-ratio-snr

March 2021. Upon retrieval it was found the unit had recorded for 212 days, and stopped recording useful data in October 2020 due to a malfunction. After a delay to allow for repair of the unit's hydrophone (suspected as the failing component), it was redeployed in May 2021 (Deploy #02); however, retrieval in November 2021 revealed that it stopped recording useful data five days after deployment, despite the recorder continuing to save files until October 2021. A different ST500 unit was deployed at the same site in November 2021 (Deploy #03), recording continuously; upon retrieval in May 2022, two weeks before the expected endurance, it was found to have recorded for 135 days, and stopped recording one month prematurely in April 2022. This second unit was thereafter tested, found to have a recording fault, and not redeployed. We have since switched entirely from ST500 recorders to the newer model ST600-STD recorder, one of which was deployed off Hasik in May 2022 (Deploy #04) and currently awaits retrieval. In response to the chronic failures of the ST500 model, available funds were re-prioritised to purchase two new ST600-STD models for deployment during 2023. The resulting data reported here come from two separate years with a 13.5 month gap in recording, but represent overlapping periods of the year in 2020 (early March through early October) and 2021/2022 (late November through early April), and considered together cover nearly the full range of seasons, albeit in different years.

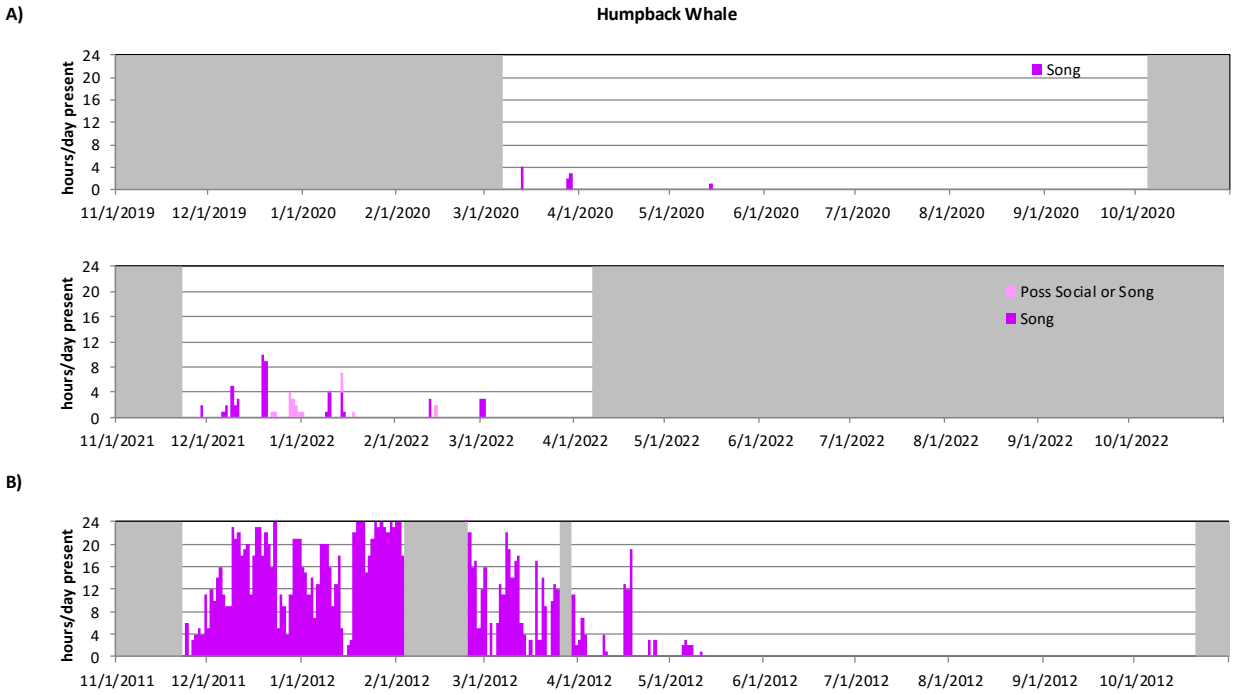

Figure 2. Occurrence of humpback whale song and possible social vocalizations off southern Oman. A) Occurrence during the 2020 and 2021 deployments in which infrequent periods of song were identified scattered throughout the recordings, along with some detections of low SNR vocalizations which appeared to be either distant units of song, or social vocalizations; B) occurrence during the 2011/2012 seasons for comparison, as recorded off Ras al Hasik on a shallow water recorder 2 km from the deep water recording site in 2020 through 2022.

Humpback whales

Humpback whale song was detected at relatively low frequency of occurrence in both the 2020 and 2021 deployments compared to data collected in 2011/2012 (Figure 2). The general timing

was congruent with the established Northern Hemisphere breeding season for this population, with song heard in months from November to May. During the 2020 deployment song was detected on 3 days in March, none in April, and 1 day in May; during the 2021 deployment, the first detection of song occurred on 29 November 2021, 7 days after deployment, and thereafter in only 53 hours on 15 days until 1 March 2022 (Figure 2A). Possible humpback whale social sounds, or very distant song that could not be unambiguously diagnosed, were detected on an additional 9 days. No humpback whales were detected after 1 March until the recorder stopped on 6 April 2022.

Blue whales and vocalizations of unknown origin

In addition to humpback whale song, four different baleen whale songs or vocalization types were detected with regularity throughout both deployments: two that have been previously attributed to blue whale populations, and two that are of unknown species attribution. Those currently attributed to blue whales include the NWIO song (Figure 3), and the CIO song (Figure 4). Those of unknown origin include a novel vocalization that we here refer to as "Long-107Hz" (Figure 5 and 6), and a vocalization at 26 Hz (Figure 7) that most closely resembles the "P" or "Spot" call previously reported in the South Indian and Southern Ocean (Leroy et al. 2017, Ward et al. 2017). Multiple song or vocalization types were often recorded simultaneously in the same one-hour period (Figure 8). There was also one very low SNR detection of what appeared to be a distant SWIO (Madagascar) blue whale song type, with two units at the characteristic frequency bands of 33 Hz and 22 Hz, detected during two hour-sample periods on 12 March 2020. The signal was too faint to adequately depict in a spectrogram figure.

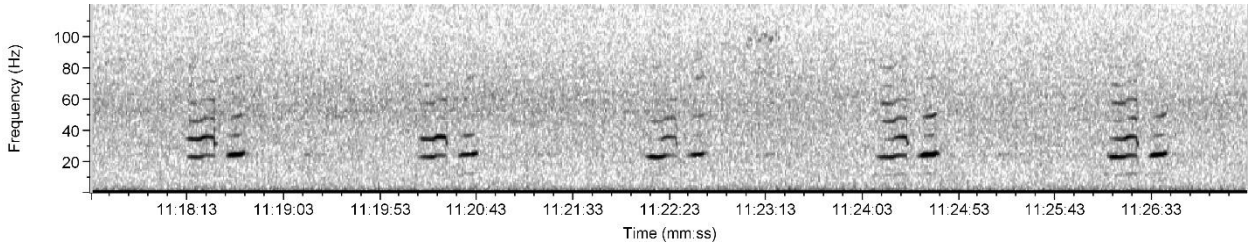

Figure 3. Example of Northwest Indian Ocean (NWIO) blue whale song recorded off Southern Oman on 18 June 2020; a 10 min sequence of five songs is presented. (Spectrogram: 2kHz sample rate, 2048 pt FFT, 50% overlap, Hann window).

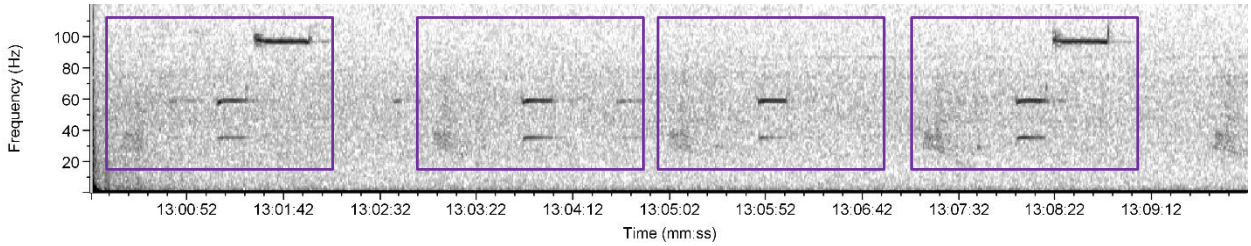

Figure 4. Example of Central Indian Ocean (CIO) blue whale song recorded off Southern Oman on 13 June 2020; a 10 min sequence of four songs is presented, each boxed, illustrating the tendency of singers to exclude the 3rd Unit at 98 Hz in many songs. A second singer is evident in the background, from the presence of the 2nd Unit 60 Hz band. (Spectrogram: 2kHz sample rate, 2048 pt FFT, 50% overlap, Hann window).

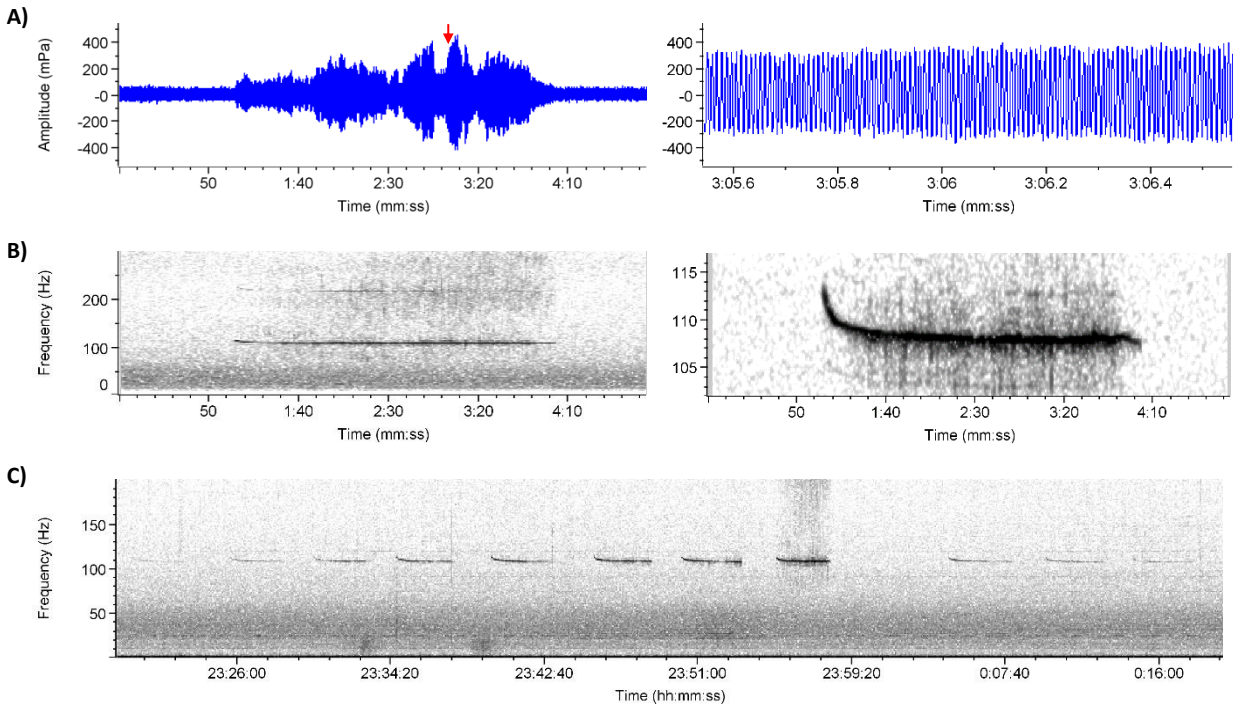

Figure 5. Examples of the "Long 107Hz" vocalization detected off Oman, recorded on 12 November 2021, displaying: a) waveform of complete unit, and a detail section indicated by red arrow; b) spectrograms of a high SNR example, displayed in the 0-300 Hz band showing 2nd harmonic, and a detail in 102-117 Hz band showing unit shape; c) one-hour segment showing a series of 11 units as a whale apparently moved within and then outside of detection range of recorder. (Spectrograms: 2kHz sample rate, Hann window, 4096 pt FFT, 50% overlap; except frequency band detail: 8192 pt FFT, 90% overlap).

The NWIO blue whale song was the predominant song detected throughout the recording period (Figure 9A) detected in 3602 hrs on 203 days in 2020, and 916 hrs on 50 days in 2021/2022. It was heard consistently on a daily basis during March to October 2020, with apparent decreases in singing activity during late-June to mid-July, and mid-August to late-September, but never disappeared. It was also consistently present in 2021 from late November through December. The only period when it was not recorded was during the winter/spring months of 2022, when it was absent from 1 January to mid-March, and only sporadically heard thereafter until early April. The decreases in singing activity roughly correlate to the monsoons, whereas the inter-monsoon period of 2020 is the longest stretch of consistent presence.

The CIO blue whale song was also heard throughout the recording period, but at a lower daily occurrence rate (present fewer hours per day) than the NWIO song (Figure 9B), being detected in 1424 hrs on 160 days in 2020, and 210 hrs on 28 days in 2021/2022. It is noteworthy that the rises and falls of CIO song appeared to roughly parallel the occurrence of NWIO song, with the exception of May 2020 when CIO song activity was substantially reduced while NWIO was at a peak occurrence. However, CIO song disappeared in late December 2021, and like NWIO was absent for much of the period from January to April 2022. During the logging of CIO song presence, it was noted that in many cases, the third unit of the typical CIO song, at approximately 98 Hz, was omitted from the song, as also described by Paniker & Stafford (2021). Occurrences of songs with and without the third unit were regularly mixed in series of consecutive songs without any obvious pattern (Figures 4 and 8).

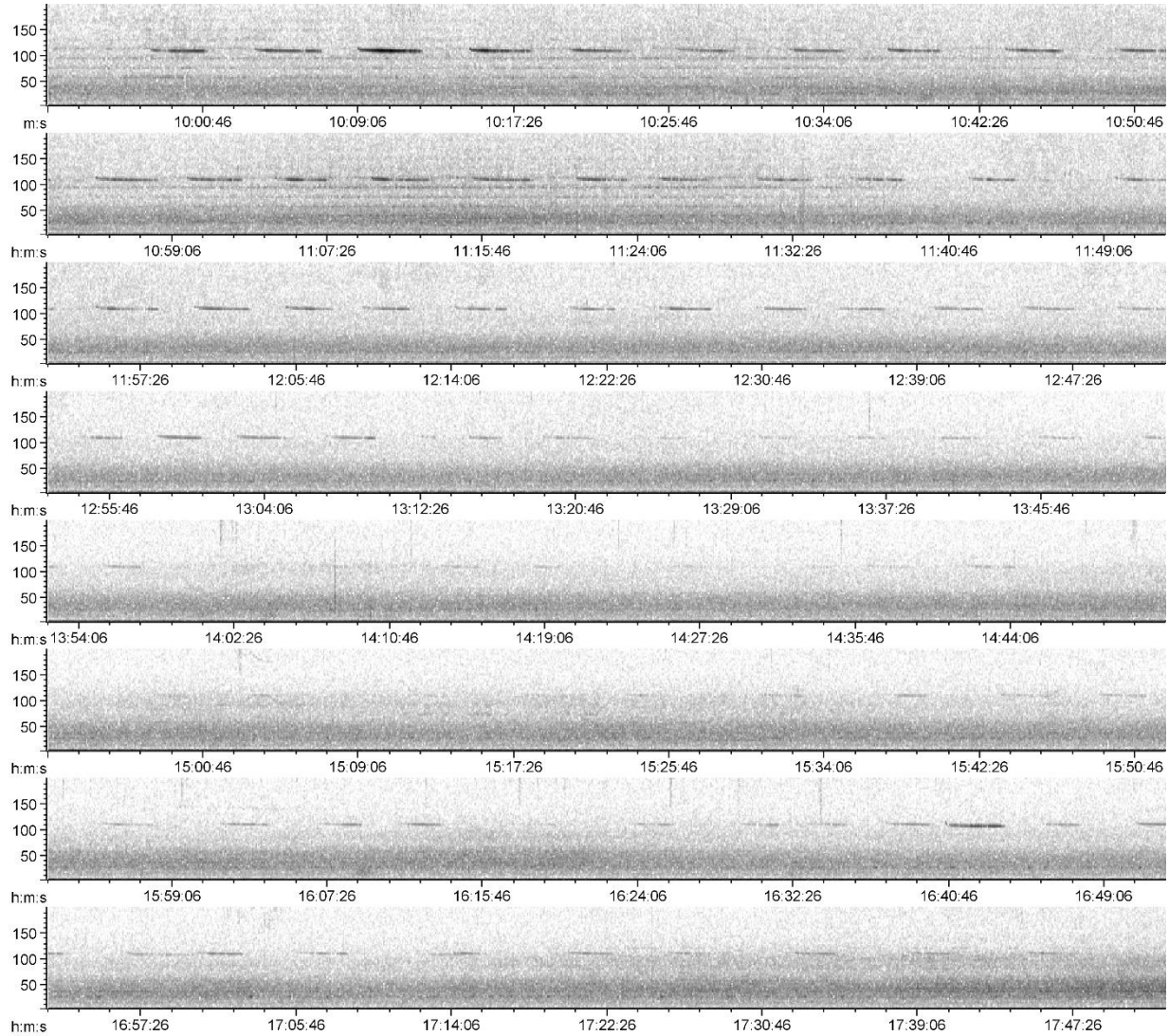

Figure 6. An 8-hour continuous recording showing an extended series of the Long-107Hz vocalizations starting on 5 December 2021 at 09:52. It is likely that this represented the vocal behavior of either 1 or 2 individuals, with much of it being a consistent series in a regular rhythm without a break or fade out (09:52 to at least 14:00). (Spectrogram at 2kHz SR, 2048 pt FFT, 50% OL, Hann window).

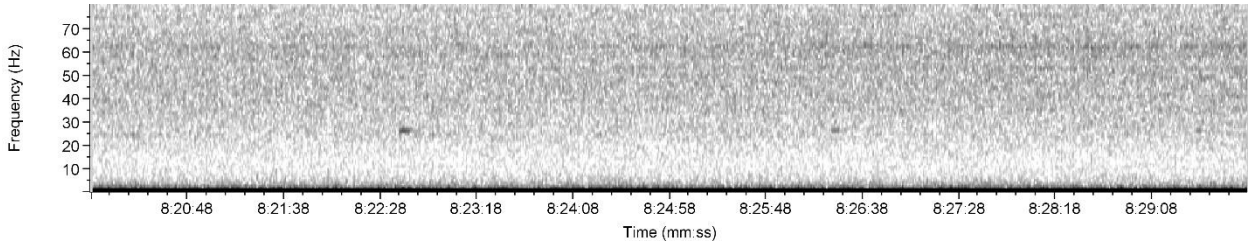

Figure 7. Example of 26 Hz signal resembling “Spot” or “P” calls recorded off Southern Oman on 13 March 2020; a 10 min sequence of four is presented. (Spectrogram at 2kHz sample rate, 2048 pt FFT, 50% overlap, Hann window).

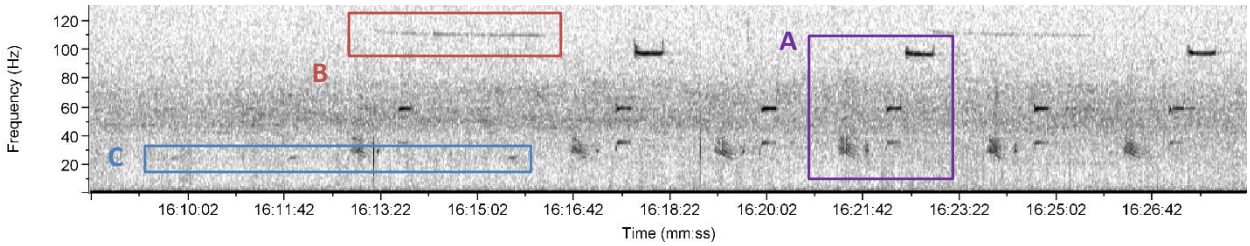

Figure 8. A 20-minute segment of recording from 13 June 2020, showing the simultaneous presence of three prominent song types found off Oman: A) a high SNR example of CIO song, composed of a series of 6 separate songs, only three of which contain the third 98 Hz unit; B) moderate SNR example of two Long-107Hz vocalizations; and C) low SNR series of NWIO songs at 24 Hz. (Spectrogram at 2kHz SR, 4096 pt FFT, 50% OL, Hann window).

The novel vocalization Long-107Hz requires some description, here done qualitatively (Figure 5), and with an initial quantitative assessment using a set of 67 examples that were extracted for measurement from 67 different hours on 46 different days between 27 Nov 2021 and 28 Mar 2022 (Table 2). The mean SNR of the measured sample was 24.2 dB ±5.8 dB (range, 15.3-43.2 dB; Table 2). The vocalization consists of a single, long narrow-band signal, ranging in duration from approximately 90 sec to 4 min, with a mean of 177 s ±28.2 s among the measured sample (Figure 5, Table 2). It presented as primarily tonal, with moderate amplitude modulation (Figure 5A). Qualitatively (as shown in Figure 5B), the fundamental frequency of the unit sweeps down relatively rapidly from a high frequency of approximately 114 Hz to 110 Hz over a period of approximately 7-10 sec; the slope then becomes more gradual sweeping to 108 Hz over approximately 30 sec, and then stabilizes at a relatively constant 107-108 Hz tone for the remainder of its duration. Among the measured sample, the fundamental frequency swept from a mean High Frequency of 113.1 Hz ±1.2 Hz (range, 110.7-115.7 Hz) to a mean Center Frequency of 107.9 Hz ±0.6 Hz (range, 105.6-109.0 Hz) with a nearly indistinguishable Low Frequency (Table 2). The highest SNR examples show a lower amplitude 2nd harmonic band (Figure 4B). The majority of occurrences adhered to this general description, with the exception of several examples in which the units were similar in duration and shape but at a notably lower frequency in the 90-100Hz range (each time accompanied by the more common 107-108 Hz unit during the same one-hour period); this minority of “atypical” examples were not included in the measured sample. The units were typically uttered in a series with a spacing that was at times consistent and rhythmic, with a mean repetition interval of 539 s ±224 s (8.98 m ±3.73 m) and range of 257 s to 1128 s (4.28 m to 18.80 m) (Figure 5C), and at times could be somewhat variable and inconsistent between adjacent units in the same series. Lower frequency atypical examples never occurred in a series, always being uttered singly. Series of units were occasionally very long, lasting hours without a break in rhythm (Figure 6), but most often a series would fade in and then fade out of the recording, apparently as the vocalizing individual moved within and then out of detection range of the recorder (Figure 5C). There were also frequent examples of just a single unit uttered (9 of the 67 measured examples were singular units). Therefore, whereas the vocalization frequently took on the characteristics of a typical balaenopterid song (stereotyped and rhythmically repetitive), it was also sometimes uttered in a non-rhythmic and variable manner more characteristic of non-song calls. For this reason we do not to refer to it broadly as “song”, since it appeared to be used in a singing behavioural context only during a portion of the time.

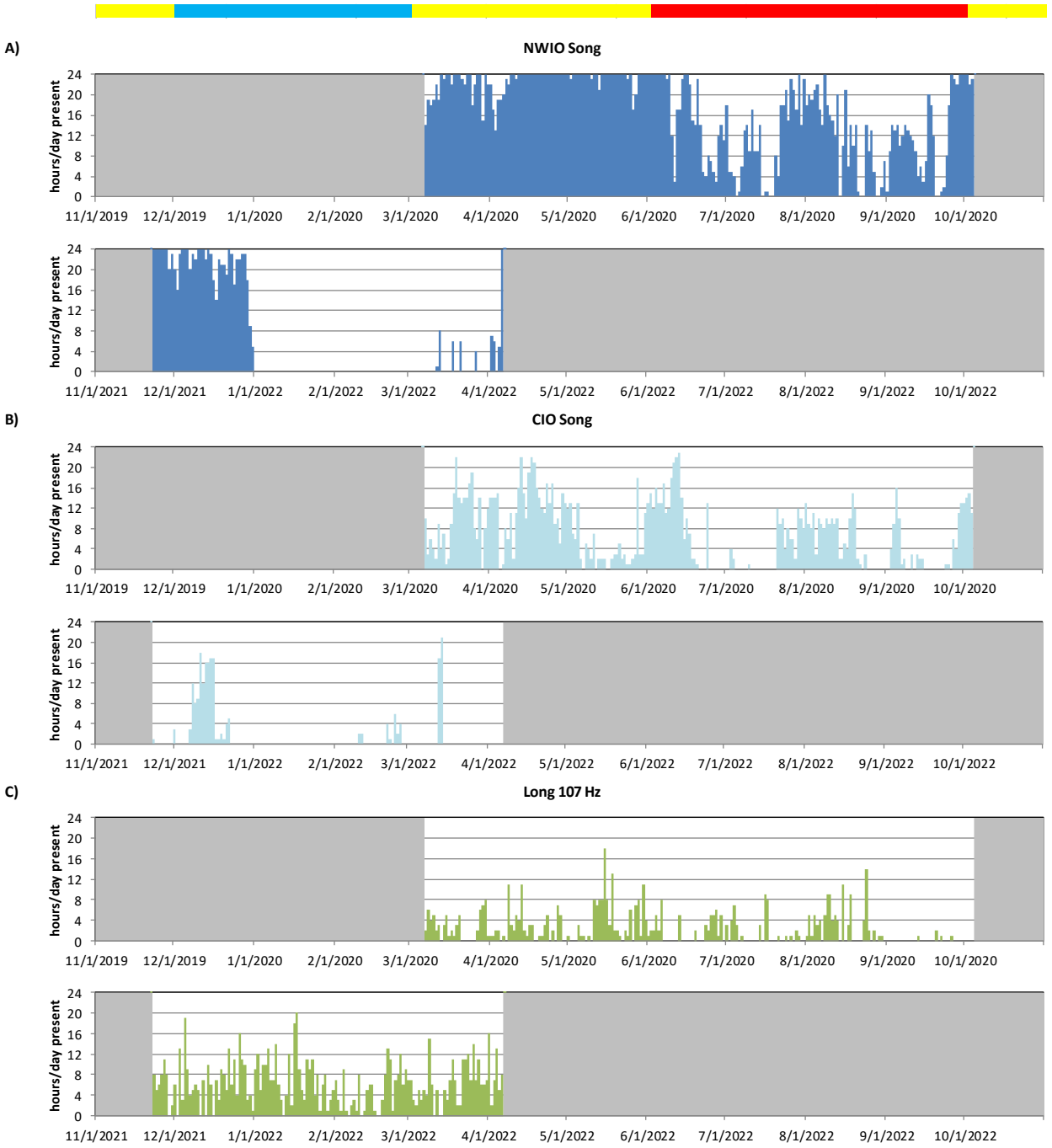

Figure 9. Hourly occurrence of baleen whale vocalizations off southern Oman, during 6 March to 4 October 2020, and 22 November 2021 to 6 April 2022; data has been aligned so that each histogram represents a complete year, despite different timing of effort. For each day, bars represent the number of hours in which whale vocalizations were detected; grey represent periods of no data before and after deployments. Paired panels present occurrence of: A) NWIO song, recently proposed as a blue whale population (Cerchio et al. 2020a); B) CIO song, recognized as blue whale song initially recorded off Sri Lanka; C) the novel vocalization we term "Long-107Hz" described herein; D) other baleen whale songs, including a single occurrence of SWIO blue whale song, and a 26 Hz vocalization that most closely resembles the "P" or "Spot" call previously described in the South Indian Ocean. The top bar marks the timing of the winter monsoon (blue), summer monsoon (red), and inter-monsoon periods (yellow).

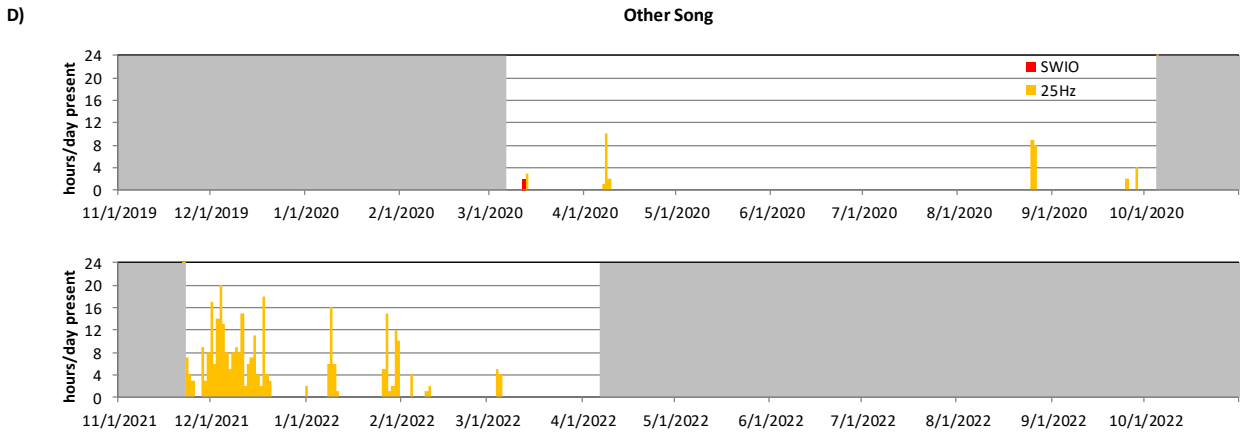

Figure 9. (Continued).

Table 2. Quantitative measurements on a sample of 67 Long-107Hz units. Samples were selected by choosing the highest amplitude example in a given series, drawn from 67 different hours on 46 different days between 27 Nov 2021 and 28 Mar 2022.

	Duration (s)	High Freq (Hz)	Cent Freq (Hz)	Low Freq (Hz)	Repetition Interval (s)	SNR (dB)
Mean	177.0	113.1	107.9	107.2	538.6	24.2
Std Dev	28.2	1.2	0.6	0.6	223.9	5.8
Min	100.3	110.7	105.6	105.1	256.7	15.3
Max	232.2	115.7	109.0	108.6	1127.8	43.2

Occurrence of the Long-107Hz vocalization was the most temporally consistent across the entire recording period (Figure 9C), detected in 868 hrs on 124 days in 2020, and 472 hrs on 117 days in 2021/2022. Within days, it was never detected at the hourly rate of NWIO song during its peak occurrence, however this is potentially due to different propagation characteristics and likely greater detection range of the lower frequency NWIO song. Although there was a marked decrease is activity during September 2020, the species producing the Long-107Hz appeared to be the only whale that did not either leave the area, or cease vocalizing for some period, particularly during the winter/spring months of 2022 (Figure 9C).

The last vocalization that was regularly detected was a simple 26 Hz tonal signal, that most closely resembled the “P-call” (Leroy et al. 2017) or “Spot-call” (Ward et al. 2017), previously described in the South Indian and Southern Oceans (Figure 7). The 26 Hz signal was recorded less often than the other types, and predominantly during the winter months of 2020 from late November to late February (Figure 9D). In all detections of the 26 Hz vocalization, the signal was low to very low SNR, and of an apparently distant offshore source.

Discussion

Humpback whales

This PAM study off Oman between 2020 and 2022 was the first concerted effort since autonomous recorders were deployed during 2011/2012 in Hallaniyats Bay (Hasik), and 2012/2013 in the Gulf of Masirah (Cerchio et al. 2016). The low occurrence rate that we documented in this study off Ras al Hasik was in stark contrast to the occurrence of humpback whale song documented 10 years earlier during the 2011/2012 season at the same site (Cerchio et al. 2016), when song was detected in 1,500 hours on 113 days between 24 November 2011 and 11 May 2012 (Figure 2B). There was a methodological difference between the studies, with monitoring in 2011/2012 occurring at 16 m depth within <1 km of the shelf edge, directly off the point of Ras al Hasik with the coast <1 behind the recorder, and thus listening to the deeper water offshore (Figure 1, inset). The current monitoring occurred on the slope at 248 m and 320 m, and therefore had different propagation characteristics; however, the deep water site was only 2026 m south-southeast offshore of the shallow site (Figure 1), and thus would likely have been detecting singers in the same general area. Moreover, it would be expected that the deeper site would have a greater detection range than the shallow site, and thus any a priori expectation would be the reverse trend, with more singers detected at the deep water site. Therefore, it seems the observed trend is an indication of dramatically reduced singing activity off Hasik during these 2020 and 2022 seasons. This is congruent with recent visual boat-based surveys in Hallaniyats Bay during March 2021, during which there were no sightings of humpback whales in 105 hrs of effort (Willson et al. 2021, Minton et al. 2023). The acoustic monitoring results imply that the same conditions or phenomenon at play in March 2021 may have been driving a low occurrence of humpback whales in Hallaniyats Bay during the spring of 2020 and the winter/spring of 2022 as well. Together these data imply either a shift in seasonal distributions of humpback whales off Oman, a response to inter-annual fluctuations in ecological conditions or prey availability (Minton et al. 2023), or could potentially represent an indicator of population decline. With so few individuals in the population, the loss of a relatively small number of males could dramatically impact the occurrence of song.

Blue whales and Bryde's whales

We document the occurrence of three different song types that have been attributed to blue whales, and two vocalizations that have not been attributed to a species (one of which is completely novel having not been previously reported). First, the brief single occurrence of a SWIO blue whale song was unexpected. The SNR was very poor, and if our identification is correct, then this may be a vagrant individual from the Southern Hemisphere; however, the timing on 12 March is quite unusual as it corresponds to the Austral autumn when that population typically is just commencing migration to its breeding grounds. In the Mozambique Channel, SWIO blue whales were primarily south of 13 ºS during March, and passed through the northern Channel past a northwest Madagascar PAM site between late April and early August on their northward migration (Cerchio et al. 2020b). So an animal in the Arabian Sea in mid-March is completely out of its migratory cycle.

The regular co-occurrence of four additional different song and vocalization types has several implications for previous interpretations and understanding of blue whale and baleen whale ecology of the Arabian Sea. Blue whales and Bryde's whales are the only baleen whale species

other than humpback whales recognised to occur in the waters off Oman (Minton et al. 2010. Baldwin et al. 2021). Cerchio et al. (2020a) first described the NWIO song and attributed it to a previously undescribed acoustic population of blue whales based on three primary factors: (1) the song was recorded at high SNR on an autonomous recorder within 5 hours of visually sighting blue whales in the vicinity of the recorder, on a day when no Bryde's whales were sighted; (2) during the 11-month recording effort off Hasik, Oman, in 2011/2012, no CIO blue whale songs were ever detected, whereas the NWIO song was detected frequently in December 2021 and then sporadically from January to June 2022; and (3) the structure of the song was more congruent with known blue whale songs than with calls attributed to Bryde's whales. Despite these arguments, the attribution remains unconfirmed by the simultaneous recording of the song in the immediate presence of a blue whale. A consequential finding of the present study is the regular occurrence of CIO blue whale song off southern Oman, which essentially removes argument (2) used above for justifying attribution of NWIO song to blue whales; this raises the possibility that all the blue whales sighted off Oman are of the CIO song acoustic population, and that the NWIO song might in fact be attributed to Bryde's whales.

There are two forms of Bryde's whales that occur broadly in the waters of Oman, *B. e. edeni* and *B. e. brydei*, as indicated by genetic analyses of tissues from stranded and ship-strike carcasses (Kershaw et al. 2013). No specimens used in Kershaw et al. (2013) were collected in the Hasik area, however the whale that is frequently encountered there is generally thought to be the coastal form, *B. e. edeni* (Baldwin et al. 2021), given that sexually mature females in the Soviet catches were as small at 11.9 m (Mikhalev 2000), and aerial photogrammetry of a Bryde's whale mother estimated its length at 11.4 m (Wilson et al 2021). No vocalizations have yet been attributed to this whale, but they are sighted with generally high frequency of occurrence in the Hasik area, and consequently in the vicinity of our recorder site (Minton et al. 2023). Thus it stands to reason that one of the vocalizations that we describe in this study represents that of a local Bryde's whale population. Furthermore, Bryde's whales appear to be resident in the region (Minton et al. 2010, Corkeron et al. 2011, Baldwin et al. 2021, Minton et al. 2023), and therefore we may expect to record their vocalizations throughout the year. With this reasoning, it is conceivable that the Long-107Hz vocalization may be a Bryde's whale. The structure is unusual for any baleen whale, with an extremely long extended unit, particularly considering that all Bryde's whale vocalizations that have been described to date are very short (<10sec) and low frequency (<50Hz). However, the description of Rice's whale (*B. ricei*) song demonstrates that the medium-sized balaenopterids in this clade are capable of long vocalizations in this frequency range, and indeed, among all described baleen whale vocalizations the Long-107Hz most resembles the Long-moan call of the Rice's whale (Rice et al. 2014). Lastly, it is worth noting that the detection of the 26 Hz vocalization could represent the second Bryde's whale form; it's infrequent and low SNR character would be congruent with an offshore population of *B. e. brydei*. The different temporal distribution of the these two vocalizations, along with the marked difference in typical SNR (with many Long-107Hz being high SNR coming from apparently nearby whales, and all 26 Hz being poor SNR and apparently distant animals) suggests that they are likely from different populations.

Thus we can describe multiple scenarios regarding the attribution of the vocalizations recorded off southern Oman, each with different implications and interpretations. It is possible that both the NWIO song and CIO song represent two different acoustic populations of blue whales, as proposed in Cerchio et al. (2020a), and that the other vocalizations described here can be attributed to the two forms of Bryde's whales described for Oman. This scenario maintains the

interpretations of blue whale ecology and distribution described in Cerchio et al. (2020a), with the addition that the coast of Oman represents an overlap area for the two different blue whale acoustic populations. The observation that the NWIO and CIO song follow similar temporal distribution patterns reinforces this scenario, as the movement of the two populations may be influenced by the same ecological parameters. Alternatively, the presence of CIO song off Oman may be an indication that the blue whales throughout the Arabian Sea could belong to the same acoustic population, and that the NWIO song is possibly attributed to a local Bryde's whale population. In this scenario, the Long-107Hz vocalization would have to be a second vocalization type attributed to either the blue whales or local Bryde's whales; this is somewhat problematic, since the temporal occurrence of these vocalizations does not closely follow the occurrence of the songs, and it is present throughout the year. Given the uncertainties, we advise that further directed research be conducted to more confidently attribute vocal behaviour to both the blue whales and the Bryde's whales that occur off southern Oman, specifically by a concerted effort to collect appropriate acoustic recordings from a boat in the presence of the whales.

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