SC/68B/INFO/28

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INTERNATIONAL WHALING COMMISSION

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Salvatore Cerchio[1,2,3], Andrew Willson[4,5,6], Emmanuelle C. Leroy[7], Charles Muirhead[2,8], Suaad Al Harthi[9], Robert Baldwin[4], Danielle Cholewiak[10], Tim Collins[11], Gianna Minton[12], Tahina Rasoloarijao[13], Tracey Rogers[7], Maïa Sarrouf Willson[9]

[1] African Aquatic Conservation Fund, Chilmark, MA, USA
[2]New England Aquarium, Anderson Cabot Center for Ocean Life, Boston, MA, USA
[3] Center for Coastal Studies, Provincetown, MA, USA
[4] Five Oceans Environmental Services, Shatti al Qurm, Sultanate of Oman
[5] University of Exeter, Environment and Sustainability Institute, Cornwall, UK
[6] University of Exeter, Centre for Ecology and Conservation, Exeter, UK
[7]Evolution and Ecology Research Centre, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, Australia
[8] University of Massachusetts Boston, School for the Environment, Boston, MA, USA
[9]Environment Society of Oman, Ruwi, Sultanate of Oman
[10]NOAA Fisheries, Northeast Fisheries Science Center, Protected Species Branch, Woods Hole, MA, USA
[11]Wildlife Conservation Society, Ocean Giants Program, Bronx, NY, USA
[12]Megaptera Marine Conservation, Den Hague, Netherlands
[13]Institut Halieutique et des Sciences Marines, Toliara, Madagascar

Abstract

Blue whales in the Indian Ocean (IO) are currently thought to represent two or three subspecies (*Balaenoptera musculus intermedia*, *B. m. brevicauda*, *B. m. indica*), and are structured into four populations with diagnostic song-types. Here we describe a previously unreported song-type that implies the existence of a population that has been undetected or conflated with another population. The song-type was recorded off Oman in the northern IO/Arabian Sea, off the western Chagos Archipelago in the equatorial central IO, and off Madagascar in the southwestern IO. As this is the only blue whale song that has been identified in the western Arabian Sea, we label it the "Oman" song-type to distinguish it from other regionally classified song-types. Spatiotemporal variation at the three sites suggested a distribution west of 70°E, with potential affinity for the northern IO/Arabian Sea, and only minor presence in the southwestern IO. Timing of presence off Oman suggests that intensive illegal Soviet whaling that took 1,294 blue whales in the 1960s likely targeted this population, as opposed to the more widely spread "Sri Lanka" acoustic population as previously assumed. Based upon geographic distribution and potential aseasonal reproduction found in the Soviet catch data, we suggest that if there is a northern Indian Ocean subspecies (*B. m.* c.f. *indica*), it is likely this population. Moreover, the potentially restricted range, intensive historic whaling, and the fact that the song-type has been previously undetected, suggests a small population that is in critical need of status assessment and conservation action.

1. Introduction

Resolving the taxonomy and population structure of baleen whales remains an essential process in defining population status and understanding conservation management requirements. Blue whales in the Southern Hemisphere are currently classified into two, three or four subspecies, depending on scientific opinion, with distinctions based on morphology, genetics, acoustics and known distribution. These include the Antarctic blue whale (*Balaenoptera musculus intermedia*

Burmeister, 1871), the “pygmy” blue whale (*B. m. brevicauda* Ichihara, 1966), the northern Indian Ocean blue whale (*B. m. indica* Blyth, 1849), and a currently unnamed Chilean blue whale (*B. musculus* ssp.) (Rice 1998; Pastene et al. 2019, Society for Marine Mammalogy Committee on the Taxonomy[1]). The absence of dedicated biological studies and genetic sampling of all blue whale populations across the Southern Hemisphere has meant that their taxonomy and population differentiation have not been resolved. However, the most widely accepted taxonomic division is between the Antarctic blue whale and the pygmy blue whale subspecies, supported by morphological and distributional differences (Branch et al. 2007a, 2007b, 2009). The pygmy subspecies is considered to be structured into several populations, generally defined by song-type and range (McDonald et al. 2006, see below). The classification of a northern Indian Ocean population as a separate subspecies, *B. m. indica*, as opposed to a population of pygmy blue whale, is debated and without scientific consensus (Rice 1998, Branch and Mikhalev 2008). Irrespective of taxonomic classification, a population reportedly resides year round in the northern Indian Ocean, ranging from the Arabian Peninsula in the west, to at least Sri Lanka in the east, and south at least to the Maldives (Rice 1998, Branch et al. 2007b, Branch and Mikhalev 2008, Anderson et al. 2012, Ilangakoon and Sathasivam 2012, de Vos et al. 2014).

The vocal behavior of blue whales globally has been characterized by stereotyped song-types that are diagnostic to populations, under the implicit assumption that individuals from different regional populations do not switch songs and thus adhere to distinctive song-types, i.e., “acoustic populations” (McDonald et al. 2006). Records from the Indian Ocean include one song-type from Antarctic blue whales, which are distributed around Antarctica during the summer, and migrate to lower latitude wintering regions that remain poorly defined and unstudied (Branch et al. 2007b). There are also records of at least three regional song-types that have been attributed to either pygmy or northern Indian Ocean populations (McDonald et al. 2006, Stafford et al. 2011, Samaran et al. 2013). Pygmy blue whales are distributed in tropical to temperate latitudes not much further south than 54ºS, and their year-round movement patterns are poorly understood (Branch et al. 2007a,b). In the southwest Indian Ocean, one pygmy blue whale acoustic population is defined by the “Madagascar” song-type, heard from the Madagascar Plateau to the central Indian Ocean (Ljungblad et al. 1998, McDonald et al. 2006, Samaran et al. 2013). A second pygmy acoustic population in the southeast Indian Ocean is defined by the “West Australia” song-type, heard from the central Indian Ocean to the west coast of Australia (McDonald et al. 2006, Samaran et al. 2013). In the central Indian Ocean, there appears to be a population defined by the “Sri Lanka” song-type, which was first documented off eastern Sri Lanka from boat-based recordings in the 1980’s (Alling and Payne 1987, Alling et al. 1991). Although there are no other published accounts of blue whale song in the Arabian Sea or elsewhere in the northern Indian Ocean aside from eastern Sri Lanka, this Sri Lanka acoustic population has been assumed to be synonymous with the northern Indian Ocean population, or subspecies (Branch et al. 2017b, Anderson et al. 2012). Since the early work of Alling et al. (1991), the Sri Lanka song-type has been documented in the equatorial Chagos Archipelago, as far south as the Amsterdam Island (43°S) and Crozet Island (46°S) basins, and even outside the Indian Ocean in the equatorial eastern South Atlantic off Angola, interpreted as a likely extralimital individual (Samaran et al. 2010, 2013, Cerchio et al. 2010, Stafford et al. 2011, Leroy et al. 2018). Therefore there is an apparent incongruence between the concept of a

[1] https://www.marinemammalscience.org/species-information/list-marine-mammal-species-subspecies/

regionally resident population/subspecies in the northern Indian Ocean and the documentation of its putative song-type well into the temperate latitudes of the Southern Hemisphere.

Most blue whale populations were hunted to near extirpation in the 20th Century (Branch et al. 2007b). Of particular consequence was a period of illegal whaling by the Soviet Union during 1963-1967 when 1,294 blue whales were caught in the northwestern Indian Ocean, south to 5ºS (Mikhalev 1996, 2000; data held by the International Whaling Commission, represented in Figure 1). The largest numbers of catches in the Arabian Sea was off northern Somalia (Gulf of Aden) and the Arabian Peninsula (ca. 10º-17ºN, 45º-55ºE), with additional smaller clusters in the central-eastern Arabian Sea off Lacshadweep/Maldives/western Sri Lanka (ca. 5º-10ºN, 65º-80ºE) and off the Indus Canyon in the northeastern Arabian Sea (ca. 22º-24ºN, 66º-68ºE). These catches are generally allocated to the northern Indian Ocean population (a.k.a., Sri Lanka acoustic population) (Branch et al. 2007a, Anderson et al. 2012). More recent visual observations confirm that blue whales continue to utilize the habitat in all of the regions, including off Oman (Willson et al. 2019), Pakistan (Moazam & Nawaz 2019), western India (Sutaria et al. 2016, 2017), the Maldives and Sri Lanka (Anderson et al. 2012). There were also large numbers of catches north of the Seychelles between ca. 2ºN-5ºS, and recently 30 visual sightings were made further west off Kenya between 2ºS-5ºS during geophysical surveys in the Austral spring; timing of these records suggest a potential breeding area, although it is not clear if these represent the Antarctic, Southwest Indian Ocean pygmy, or northern Indian Ocean subspecies/population (Branch et al. 2007a, Barber et al. 2016).

We report here a baleen whale song type that, to the best of our knowledge, has not been previously described. The song was recorded at three disparate locations in the western Indian Ocean separated by approximately 3,500km during three independent efforts of long-term passive acoustic monitoring. The locations include the waters off Oman in the western Arabian Sea, around the Chagos Archipelago in the central Indian Ocean, and off northwest Madagascar in the southwest Indian Ocean (Figure 1). Although it is difficult to definitively attribute a remotely recorded, previously undescribed song to a species, we believe it is a blue whale song-type, and discuss how this impacts our current understanding of blue whale population structure and behavior in the Indian Ocean.

2. Materials and Methods

2.1 Madagascar data collection and analysis

During 2016-2019, a passive acoustic monitoring effort was conducted off northwest Madagascar in the Nosy Be region, targeting southern hemisphere blue whales and other baleen whales (Cerchio et al. 2018). An Ocean Instruments SoundTrap 300-STD autonomous archival recorder was deployed during four 4-month deployments from December 2016 to April 2018, and two 6-month deployments from April 2018 to April 2019. The instrument was anchored just off the shelf break at position 13.28°S, 48.01°E, at depths ranging from 225-260m across deployments. The SoundTrap recorder had a flat response from 20Hz-60kHz (+/- 3dB) with a 34dB re 1V µPa^{-1} noise floor and a full scale response of 174.1 dB re 1V µPa^{-1} including system gain. During the 4-month deployments, recordings were made at 50% duty cycle (30min every 60min) and 24kHz SR; during the 6-month deployments, recordings were made at 33% duty cycle (20min every 60min) at 24kHz SR and 96kHz SR. The resulting wav files were down-sampled to 2kHz to reduce size and increase manageability of the data set for low-frequency analysis. Manual evaluation of spectrograms was conducted in Raven Pro 1.5 for review of baleen whale vocalizations and logging for hourly presence (0-65Hz bandwidth, 30min per spectrogram line, 4096pt FFT, 50% overlap, Hanning window). Review of data revealed extensive detections of both Southwest Indian Ocean (Madagascar) pygmy and Antarctic blue whale song-types, as well as fin whale and Antarctic minke whale song, in addition to the less frequent occurrence of the song-type described in this study (Cerchio et al. 2018). After identification of the target song-type, an additional browse was conducted (by SC) during the months when the song was detected to verify logged song sequences (particularly to distinguish between the more commonly occurring Antarctic blue whale song-type in an overlapping bandwidth) and evaluate missed detections at analysis parameters optimized for visualization of the specific song frequency bandwidth (14-35Hz bandwith, 30min per spectrogram line, 8192 point FFT, 50% overlap, Hanning window).

2.2 Oman data collection and analysis

During 2011/2012, passive acoustic monitoring was conducted off the coast of Oman in Hallaniyats Bay targeting Arabian Sea humpback whales (Cerchio et al. 2016). Three Wildlife Acoustics SM2M autonomous archival recorders were placed in shallow water at depths ranging from 16m to 33m; two of the recorders were placed in close proximity to the shelf break, and therefore had an acoustic "view" of nearby deep water. One site in particular was within <1km of the shelf break at 16m depth, and all data presented here were recorded at that site (17.40°N, 55.31°E). The SM2M recorder had a flat response from 2Hz-30kHz (+/- 2dB), a hydrophone sensitivity of -164dB re 1V μPa^{-1}, and was conditioned with a 3Hz high-pass filter and 12db gain. Three deployments were conducted with varying recording parameters: 23 November 2011 to 20 February 2012, continuous recording at 16kHz sample rate (SR); 24 February to 26 March 2012, continuous recording at 32kHz SR; and 29 March to 21 October 2012, 33% duty cycled recording (10min every 30min) at 22kHz SR. The original wav files were down-sampled to 2kHz to reduce size and increase manageability of the data set for low-frequency analysis. A manual evaluation of continuous spectrograms was conducted in Raven Pro 1.5 (by CM), at parameters optimized to detect signals of low frequency baleen whales such as blue and Bryde's whales (0-65Hz bandwidth, 30min per spectrogram line, 4096pt point FFT, 50% overlap, Hanning window). During the browse, all potential baleen whale vocalizations were logged for presence in half-hour bins, i.e. once during the first 30m and once during the second 30m for each hour. After identification of the target song type, an additional exhaustive browse was conducted (by SC) to verify logged song sequences and evaluate missed detections at analysis parameters optimized for visualization of the specific song frequency band (14-35Hz bandwith, 30min per spectrogram line, 8192 point FFT, 50% overlap, Hanning window).

2.3 Chagos Archipelago data collection and analysis

The Chagos Archipelago hydroacoustic dataset was obtained from the International Data Centre of the Comprehensive Nuclear Test-Ban Treaty Organisation (CTBTO) in Vienna. Data were recorded at the CTBTO hydrophone station HA08, located off Diego Garcia Island, an atoll of the Chagos Archipelago, in the central Indian Ocean. The HA08 station is comprised of two hydrophone triplets: the northern one, H08N, referred as Diego Garcia North (DGN, 06.3ºS, 071.0ºE) and consisting of the hydrophones H08N1, H08N2, H08N3, and the southern one, H08S, referred as Diego Garcia South (DGS, 07.6º S, 072.5ºE) and consisting of the hydrophones H08S1, H08S2, H08S3. Hydrophones within the triplets are separated by approximately 2.5km and DGN and DGS are about 220 km apart. DGN and DGS are believed to be independent acoustic sampling areas: the shallow depth and long north-south extension of the Chagos Bank act as an acoustic barrier between the western and eastern equatorial Indian Ocean. Sounds produced on either side of the Chagos Bank are unlikely to be heard on the other side (Pulli & Upton 2001). Thus, the northern site (i.e., DGN records) represents the soundscape west of the island, whilst the southern site (i.e., DGS records) represents the soundscape east of the island.

Hydrophones are moored in the sound fixing and ranging (SOFAR) channel (about 1000m deep) and cabled to Diego Garcia Island. They acquire data continuously, with a sampling rate of 250 Hz (see Hanson 2001 for details). Here, we used the data recorded by the hydrophones H08N1 and H08S1 from 2010 to 2013. To assist the manual browsing of this 4-year duration data set, an automated detection algorithm was first run on the acoustic data. This algorithm performs a dictionary-based detection by modelling mysticete vocalizations with sparse representations (Socheleau & Samaran 2017). The method uses a decision statistic that offers optimal properties with respect to false alarm and detection probabilities (Socheleau et al. 2015). As the signal of interest is modelled using a dictionary, the detector can be used for previously unknown or understudied recurrent signals. The dictionary was created using 310 vocalizations with good Signal-to-Noise Ratio (SNR), recorded at DGS in April 2010. The obtained detection time stamps were then imported into Raven Pro 1.5 as a selection table and displayed on the spectrogram for each year of data (spectrogram parameters 0-125Hz bandwidth, 20min per spectrogram line, 512pt point FFT, 50% overlap, Hanning window). Spectrograms were scanned (by ECL) to check all the detected events, identify and remove all false detections, assess the call quality, and estimate the number of singers (see below). Periods of data without automated detections were also carefully scrutinized to identify possible false negatives. Results were then converted into a metric of hourly presence.

All logged song sequences in each of the three sites were evaluated for the number of singers present, estimated at 1 singer, 2 singers or >2 singer (3+ singers). Each logged sequence was assigned a subjective rating of SNR and quality on a scale from A to D, such that A exhibited strong signals with all song units detectable and multiple harmonics present, and D represented song sequences in which only faint repetitive sequences of one song unit was detectable with no harmonics. To provide a preliminary description of spectral and temporal characteristics of the song-type, a small subset of the highest quality SNR sequences were qualitatively reviewed and measured in Raven Pro 1.5. Due to the generally low SNR of the majority of detections, and the resulting ambiguity in spectral features, a detailed quantitative analysis was not attempted.

3. Results

3.1 Description of the song-type

The new baleen whale song-type reported here was first detected during the low-frequency browse of the Madagascar data (by SC). In all cases it was detected at low SNR indicating distant animals recorded by the relatively deep water recorders on the Madagascar continental slope. During an assessment of humpback whale song on the Oman recorders (by CM and SC), the same signal was detected opportunistically, prompting the systematic low frequency browse of that dataset at the same standardized parameters used for the Madagascar assessment. Ultimately, the Oman data revealed more frequent rate of occurrence of the song type; however, the Oman detections were still relatively low SNR, as would be expected from a signal originating from a deep water source, and experiencing substantial propagation loss before being detected by a hydrophone located in shallow water. Finally, the same song-type was recognized on recordings from the deep water CTBTO recorders off the Chagos Archipelago (by ECL) upon viewing the song-type in Cerchio et al. (2018), prompting a review of four years of data from the Diego Garcia North (DGN) and Diego Garcia South (DGS) recording sites. As these recorders were placed at the depth of the SOFAR channel, the detection range was likely the largest and some of the cleanest examples of the song were recorded, however still at a predominantly low SNR.

The song phrase consisted of two units arranged in a consistent simple pattern (Figure 2), repeated in a consistent rhythm (Figure 3), typical of song from other *Balaenoptera* species (Watkins et al. 1987, 2000, McDonald et al. 2006). In most detections the SNR was low, such that each unit consisted of a single band in the 22-26Hz bandwidth (see Figure 3b for example from Madagascar), however higher SNR detections indicated a 2-band pattern in the first unit at all sites (see Figure 2c for example from Madagascar, and Figure 3a for example from Oman). Some detections, found only off Oman and the Chagos Archipelago, indicated a fundamental frequency in the 11-12Hz bandwidth, and thus a 3-band pattern for the first unit, and 2-band pattern for the second unit (Figure 2a, Oman, and Figure 2b, Chagos). In high SNR examples, for which the fundamental frequency was present, there were often several bands at the same approximate 11.5Hz harmonic interval between 150 to 250Hz (Figures 2d), observed only off Oman (note that the Chagos data sampling rate was too low to record this bandwidth, and all examples from Madagascar were too low SNR to observe these higher harmonics).

The first unit commenced as a tonal signal with gradual onset (Figure 4c) and became amplitude modulated (Figure 4d) until termination of the unit (Figure 4e). Spectrograms showed that the initial tonal-component of unit 1 has more energy in the second harmonic (F_1) at 23 Hz, less in the third harmonic (F_2) at 34 to 35 Hz, and little (or no visible) energy in the fundamental (F_0) at 11 to 12 Hz. The second unit commenced as a tonal signal, with gradual onset (Figure 4f) and terminates as an amplitude modulated signal (Figure 4g). The initial tonal component had a fundamental frequency of 12 Hz, and in the second harmonic a 2 Hz FM upsweep from 24 to 26 Hz was evident. The second harmonic is obvious in most sequences and across all regions as this is where most energy is in unit 2 (Figure 4a). Unit duration ranged from at least 15-18 s for unit 1 and at least 9-14s for unit 2; total phrase duration ranged from at least 32-39 s. The phrases were always detected in rhythmic series with varying repetition rates (measured from the start of consecutive phrases), ranging at least from 60 s (Figure 3a) to 116 s (Figure 3b), or approximately 1.8x to 3.6x the phrase length. In most sequences, several repetitions occurred at a consistent rate interspersed with occasional longer gaps (Figure 3a, b).

3.2 Spatiotemporal Variation

The temporal distribution of the song-type detections over the monitored period varied substantially at the three sites (Figure 5). Off the coast of Oman, the song was detected predominantly during December and January, with a more sparse distribution of detections during six months from late November to late May, and it was not detected at all between June and October (Figure 5a). During a two-week period in December 2011, there were 12 days on which a chorus of two or more individual singers was evident in the spectrogram during one to five hours per day. Thus mid-December was the period of peak occurrence in 2011. Lack of data from other years precludes assessment of consistency in seasonality across years.

Off the Chagos Archipelago, the song was detected at DGN on the west side of the Chagos Bank broadly throughout the year, with substantial variation among the four sampled years and no consistent seasonal pattern (Figure 5b). The most singing activity was detected from mid-January to late April, particularly in 2010, but also to a lesser extent in 2013. A second broad peak in activity occurred from October to December in 2013 and to a lesser extent in 2010. Very few detections were made between May and September in both 2010 and 2013, such that these two years had largely similar bi-modal distributions in occurrence. Short periods of chorusing (2 or more singers) were detected during the peak occurrence periods in April 2010 and November 2013. During 2011 and 2012, the pattern of occurrence was more dispersed throughout the year without clear peaks, with generally fewer detections and a lower proportion of hours during days when detected. Off the eastern side of the Chagos, recordings from the DGS recorder had dramatically fewer detections during the four years (not represented in Figure 5). The song was only detected during a 20-day period in late April 2010, with a strong peak of singing activity from April 17 to 22 with choruses of 2 or more individuals on more than 50% of hours each day (detail shown in Figure 6). This was broadly concurrent with the peak of singing activity at DGN during April 2010, but overlapping with the lull in singing during the middle of that month (Figure 6), suggesting that a group of singers may have temporarily shifted distribution to the east side of the Chagos Bank. The song was not detected at all off DGS in 2011 and 2012, and in 2013 it was detected on only two hours of one day in mid-January.

Off Madagascar, the temporal distribution of detections was much more limited, occurring only during two months from early April to late May, and consistent in its seasonality between the two years examined (Figure 5c). In both 2017 and 2018, singing activity occurred in multiple distinct events of several days each separated by periods of no detections ranging from one to three weeks. Never was more than one singer evident at a time and all detections were comparatively low SNR.

It is important to consider here the differences in propagation characteristics at each site and the likely ranges at which songs were detected. The deeper recorders deployed off Chagos and Madagascar had an acoustically unobstructed "view" of the deep water soundscape and likely detected signals at much greater distance than the shallow water recorders perched on the top of the shelf break off Oman. Off Madagascar, there was much more extensive documentation and higher SNR detections of other baleen whale low-frequency songs in the same data set, including Antarctic and Madagascar pygmy blue whales, and fin whales (Cerchio et al. 2018). Therefore, we surmise that the detections of the new song-type off Madagascar were likely a few isolated events of relatively distant single animals. The recorders off Chagos likely had the furthest detection range of all three sites, since they were positioned in the SOFAR channel. This may in part explain the more widely distributed occurrence of the song compared to the other sites. Conversely, off Oman we expect extensive propagation loss of signals originating in deep water before they were detected on the shallow water shelf recorder. Given the generally pelagic distribution of blues whales, and that all observed sightings of blue whales off the Oman site were in deep water off the shelf break (Willson et al. 2019; see Discussion below), the low SNR detections likely represent relatively close individuals singing off the shelf in nearby deep water. Therefore, the observed distribution of detections may be a substantial underestimate of presence. Furthermore, given the presence of choruses of song on several days despite the poor propagation characteristics, it is possible that had monitoring been conducted off the shelf in deep water, much more extensive presence between December and June may have been documented.

4. Discussion

4.1 Species Attribution

It is often difficult to definitively attribute a new baleen whale song-type to a species when documented only from remote recorders with no associated visual sightings data. In this case we believe there are only two feasible candidates, blue whales and Bryde's whales, based upon the known species diversity at our research sites, and the current understanding of baleen whale song characteristics. Both species have been documented in the area where recording was conducted off Oman during boat surveys conducted between 2001-2019, including March 2012 when acoustic recording was conducted (Minton et al. 2010, Willson et al. 2019, Oman Cetacean Database, unpublished data; Figure 7). Comparing the positions of visual sightings with the temporal occurrence of recorded songs off Oman provides some circumstantial evidence for species attribution. When considering only days in 2012 when the song was recorded, there were Balaenopterid sightings on two occasions that were near-concurrent with occurrence of song. First, moderate to distant song was recorded during a two-hour period on the evening of 1 March and during six daytime hours on 3 March, although there were no Balaenopterid sightings during boat surveys on those two days. A single Bryde's whale was sighted 20km to the north on 2 March; however, this sighting did not correspond with concurrent detections of song, and is therefore not necessarily considered a strong candidate for species attribution. Conversely, there was a period of extensive singing from 23 to 26 March, including a chorus of more than two singers during a 3.5 hour period on the morning of 25 March, and high SNR song during 4.5 hours on the morning of 26 March, just prior to the recovery of the recorder. On the 26-27 March there were multiple blue whale sightings in the vicinity of the recorder position. The recorder was recovered on the morning of 26 March at 11:35, during a particularly high SNR sequence of song; later that afternoon, at 16:48 and again at 17:32, the survey boat identified an individual blue whale 4 km to the north-northeast, which traveled south to a point 6.2 km south of the recorder during a 44 min period (Figure 7 detail). This is the most direct evidence of blue whales being in the vicinity of the recorder during singing activity.

Off Madagascar, Bryde's whales have never been documented off the northwest coast study region despite extensive effort working with medium size Balaenopterids (Omura's whales), surveying inshore and offshore waters, and passive acoustic monitoring in shallow and deep water (Cerchio et al. 2015, 2018, 2019); however, they do occur regionally in the Southwest Indian Ocean far to the south of Madagascar on the Madagascar Ridge (Best 2001). Conversely, blue whales were detected extensively during passive acoustic monitoring off northwest Madagascar including the song-types of at least three separate populations (Antarctic, Madagascar and Sri Lanka song-types) in addition to the new Oman song-type (Cerchio et al. 2018); therefore it is clear that this region is habitat for overlapping blue whale populations.

In addition to visual sighting evidence indicating the potential source of an acoustic signal, the structure of a vocalization can be a good indicator of species attribution when considered in context of the known vocal repertoires of the candidate species. In this case, the features of the described song-type are much more congruent with identified song-types of blue whales (McDonald et al. 2006) as compared to Bryde's whales (Oleson et al. 2003, Heimlich et al. 2004). The key acoustic attributes of all known blue whale song-types that match this song-type include: a phrase made up of generally 2 to 4 low-frequency (<50 Hz) stereotyped units displaying a combination of amplitude-modulated and tonal structure; the relatively long duration of the units (in excess of 10 s), and the phrase (in excess of 30 s); and a repetition rate of phrases in the song sequence that is relatively short in comparison to the phrase, on the order of only 2-3 times the phrase length (McDonald et al. 2006). Existing knowledge of Bryde's whale vocalizations indicates that most described units tend to be much shorter, primarily <3 s without long tonal components, and sequences of units have comparatively longer repetition rates, ranging from 2 to 6 min, so on the order of 40-100 times the length of the phrase (Oleson et al. 2003, Heimlich et al. 2004). Therefore, this song type would be much more unusual for a Bryde's whale song, representing an extreme outlier within the species group, as compared to a blue whale song-type, for which it matches documented unit and phrase structure for populations worldwide. Given the acoustic attributes of the song type, and the documented close proximity of a blue whale to the recorder in Oman when it was recorded, we conclude that this is almost certainly a blue whale song.

4.2 Implications for blue whale population structure in the Indian Ocean

Assuming this is a correct species attribution, these observations raise several implications and questions in regard to our understanding of population structure and definition of stocks of blue whales in the Indian Ocean. Different song-types have been used to distinguish between populations of blue whales in the Indian Ocean as well as globally. Given that this song-type has not been reported before, the presence of this song across a large geographic region indicates the existence of a previously undefined population of blue whales in the western Indian Ocean. This is of particular consequence to the interpretation of existing whaling data, sightings data and acoustic data. The northern Indian Ocean population of blue whales is currently considered to be acoustically defined by the "Sri Lanka" song-type; however, our results indicate that there are at least two blue whale acoustic populations that range into the northern Indian Ocean. Furthermore, analyses of the Oman acoustic data did not reveal any occurrence of the Sri Lanka song-type. Therefore, given that this song-type has not been previously reported in studies that documented the Sri Lanka song-type, and that no Sri Lanka song-types were detected in our analysis of the data off Oman, there may be a longitudinal division of these populations between (a) the Arabian Sea / general western Indian Ocean, and (b) Sri Lanka / Bay of Bengal / general central Indian Ocean. We propose that this song be given the label "Oman song-type", in keeping with previous naming conventions (McDonald et al. 2006), since it is the only song-type currently documented off Oman or in the western Arabian Sea.

It is worth emphasizing here that the only published evidence of the Sri Lanka song-type in the Northern Hemisphere comes from limited boat-based recordings off the eastern coast of Sri Lanka during February to April 1984, and May 1985 (Alling and Payne 1987, Alling et al. 1991).

The Sri Lanka song-type has been most extensively documented off the equatorial Chagos Archipelago and other sites throughout the Southern Hemisphere (Stafford et al. 2011, Samaran et al. 2013, Leroy et al. 2018). To the best of our knowledge, prior to this study there was a complete absence of acoustic data from the Arabian Sea, and thus no confirmation of any song-type. Therefore, the attribution of Arabian Sea sightings and whaling catches to the Sri Lankan acoustic population by various authors and the International Whaling Commission Scientific Committee (Branch et al. 2007b, 2019, Anderson et al. 2012, Ilangakoon & Sathasivam 2012) has been based entirely upon the assumption that there was/is a single population in the northern Indian Ocean. There is relatively extensive documentation of blue whales on the eastern, southern and western sides of Sri Lanka (Anderson et al. 2012, Ilangakoon and Sathasivam 2012, Randage et al. 2014, de Vos et al. 2014), but currently no published long-term acoustic monitoring from Sri Lanka, or any other location in the eastern Arabian Sea. Therefore it is an open question as to whether the blue whales in the eastern Arabian Sea, including off the west coast of Sri Lanka, belong to the "Sri Lankan" acoustic population, or the new Oman acoustic population described here. We note that Anderson et al. (2012, Fig. 5) indicated inverse peak occurrence of blue whale sightings off west Sri Lanka (June-August) and northeast/south Sri Lanka (ca. January-May for northeast, November-April for south), which may represent the co-occurrence of two populations with varying temporal distributions. It is noteworthy that the peak occurrence off west Sri Lanka is concurrent with the apparent absence of the Oman song-type off Oman, whereas the peaks off northeast and south Sri Lanka (during which time the Sri Lanka song-type was recorded, Alling et al. 1991) are concurrent with the presence of the Oman song-type off Oman.

The patterns of documented presence in this study suggest that the Oman song-type was detected more extensively and during a more extended period of the year off Oman than off Madagascar, but most extensively throughout the year off western Chagos. It is again important to emphasize here the difference in detection ranges associated with different propagation characteristics among the sites, with the acoustic occurrence off Oman likely being highly underrepresented due to the relatively shallow recorder placement compared to the other sites, and the Chagos site likely having the longest detection range. Irrespective of this caveat, the data indicate that the Oman acoustic population is not limited to the northern Indian Ocean, and like other blue whale populations, is capable of extensive movements. However, the limited presence in the Madagascar data suggests this population may be more associated with the northern Indian Ocean, and only an occasional visitor, possibly at the southern extreme of its range, in the southwest Indian Ocean and the Mozambique Channel. The variable presence off the Chagos throughout the year may represent movements south and north at different periods; the data from 2010 and 2013 have a minor indication of some bimodal seasonality that would be indicative of migratory movement, but it is not well-defined and not consistent across all monitored years.

Anderson et al. (2012) proposed a hypothesis for the migratory movements of blue whales in the northern Indian Ocean, striving to interpret all existing spatiotemporal data of sightings, catches, strandings and acoustic records. Predictions of this migration hypothesis were based on an assumption that the data represented a single population, which was reasonable given the understanding at the time. However, our results indicate that there are likely at least two populations with potentially distinct or partially overlapping distributions. Anderson et al. (2012) predicted occurrence off the Arabian Peninsula during the southwest monsoons, May to October; however, the Oman song is almost entirely absent in the Oman data during that time, with the exception of scattered infrequent detections in May. Without a clear understanding of singing seasonality, absence of song does not necessarily indicate absence of animals, but within our data from all sites some singing activity occurred throughout the year and was recorded off Chagos when none was recorded off Oman (Figure 5 & 8). Therefore we have reason to believe that in this case song may be considered a reasonable indicator of presence/absence. Moreover, Anderson et al. (2012) suggested that the population disperses widely during the northeast monsoons, December to March, migrating eastwards north of the Maldives and south of Sri Lanka during December-January; however, this is when the occurrence of blue whale song off Oman is at its peak. These contradictions may result from the interpretation of the existing data by Anderson et al. (2012) under the assumption of a single northern Indian Ocean population.

Inasmuch as song represents movements of a population, the strongly seasonal occurrence of the Oman song-type off Madagascar during April-May (at least in 2017 and 2018) could suggest a possible southerly movement out of the Arabian Sea, and the occurrence off western Chagos Archipelago further supports this possible scenario, but with less clear seasonality and strong variation among years. Focusing exclusively on the data collected concurrently during November 2011 to November 2012 off Oman and Chagos, the observed temporal distribution of song detections is consistent with presence in the Arabian Sea during the early period of the northeast monsoon, when it is absent off the Chagos, followed by movement south into the region west of the Chagos starting in February, and being absent from Oman by June (Figure 8). The variability of occurrence off the Chagos across the four years examined suggests that movement patterns likely do not follow a regimented seasonal migratory cycle (i.e., long distance latitudinal migration associated with temporal separation of feeding and breeding ecology). Rather, the movements of this and other blue whale populations may reflect the complex dynamic processes in the Indian Ocean, with population distribution shifts following yearly variable changes in productivity. Interannual variability has been documented in the northern Indian Ocean and hypothesized to drive variation in blue whale distribution off the Maldives and Sri Lanka (Balance et al. 2001, de Vos et al. 2014). Redfern et al. (2017) predicted that suitable blue whale habitat should exist off the Arabian Peninsula and the Gulf of Aden in both monsoon seasons, applying GAM models developed with extensive datasets from the Eastern Pacific Ocean, and remote sensing data of environmental variables in the northern Indian Ocean, but averaged across two decades without accounting for interannual variability. Therefore it is possible that the single year of monitoring off Oman does not capture the full seasonal variability in blue whale distribution, and that the multi-year patterns off Chagos is related to interannual variability in environmental conditions.

The near absence of the Oman blue whale song in data from the eastern side of the Chagos (Diego Garcia South recorder) is striking in comparison to its geographically widespread presence in the western Indian Ocean from Oman to Madagascar. Since the Chagos Bank acts as an acoustic barrier between the DGN and DGS recorders (Pulli & Upton 2001), it appears that the Chagos (roughly 70°E) may represent an eastern boundary for the population, suggesting a truly western Indian Ocean distribution. This is in contrast to the Sri Lanka acoustic population which is heard more broadly on both the west (DGN) and east (DGS) side of the Chagos (Stafford et al. 2011, Samaran et al. 2013) although throughout a broader range of months on the east side (see Samaran et al. 2013, Figure 5b). Moreover, the Sri Lanka acoustic population appears to have a more central Indian Ocean distribution, documented more extensively on recorders east of 70°E but far less frequently to the west of 70°E (eastern sites DGN, DGS, NEAMS, SWAMS as compared to western sites MAD, CROZET, SSEIR, NCRO, WKER, as defined in Samaran et al. 2013, and Leroy et al. 2018).

4.3 Implications for conservation of blue whales in the Arabian Sea

The presence of this acoustic population off the coast of Oman during the Boreal winter/spring, from November through May, is congruent with the timing of Soviet catches in the region (Mikhalev 1996, 2000) and visual observations off Oman (Willson et al. 2019). Soviet catches of 1,294 blue whales in the Arabian Sea occurred during October-December 1963-1965 (Mikhalev 1996, 2000), with the predominant catches being off the Arabian Peninsula during November (see Figure 1). Although we do not have acoustic data from Oman during November, the peak occurrence of the song during December suggests that the population hunted by Soviet whalers in the Gulf of Aden and the western Arabian Sea was very likely the Oman acoustic population, not the Sri Lanka acoustic population. The general assumption up until now has been that all whales taken in the northern Indian Ocean came from the Sri Lanka acoustic population (Branch et al. 2007b, 2019). Since blue whale acoustic populations are generally considered to be synonymous with biological populations (McDonald et al. 2006, Branch et al. 2007b), it is now clear that at least some if not most of these catches in the northern Indian Ocean came from a distinct population that has not been previously accounted for. This discovery has major consequences for the conservation status of northern Indian Ocean blue whales. Given the size of the Soviet catch within such a relatively restricted region, it is conceivable that the population was severely depleted. A very small population size, in combination with the lack of recording effort in the Arabian Sea, may explain why this song-type has gone undetected for so long. Arabian Sea humpback whales were also severely impacted by Soviet whaling operations, and currently are estimated to have a very low population abundance, with likely fewer than 100 animals and a point estimate of 82 individuals (95% CI 60-111), leading to their classification as Endangered according to the IUCN Red List of Threatened Species (Minton et al. 2008, 2011). The Soviet whalers took 242 humpback whales off the coasts of Oman, Pakistan and India, of a population they estimated to be on the order of 400 individuals (Mikhalev 1997). Given the size of the blue whale catch, the source population was clearly much larger than the humpback whale population; however, it seems feasible if not likely that the blue whale population was reduced to an equally small fraction of the original population size, with total numbers of catches decreasing from 1,060 during the 1963/64 and 1964/1965 cruises, to 234 during the 1965/66 and 1966/67 cruises (Mikhalev 1996, 2000). It is worth noting that blue whale sightings off Oman are very rare (Baldwin 2003, Minton et al. 2010), which may be related to distribution, but may also be a reflection of very low numbers of individuals in the current population.

Currently there is some debate and difference of opinion regarding the taxonomic status of blue whales in the northern Indian Ocean. Rice (1998) recognized the classification of the subspecies *B. m. indica* (Blyth, 1859), assigning it to a population ranging in the northern Indian Ocean, but also suggesting that this nomenclature may have precedence over *B. m. brevicauda*. Branch and Mikhalev (2008) found little support for subspecies classification of northern Indian Ocean blue whales based on length at maturity data from the Soviet catches, noting that different subspecies should be distinct based upon geographic distribution as well as attributes of "morphology, genetics or behavior" (Branch et al. 2007a). Mikhalev (1996, 2000) reported differences in the size of fetuses among the separate regions of Soviet catches, separating the fetus data into three categories of (a.) early development, (b.) small size and (c.) big size. He reported the Seychelles-

Equator catches were entirely early development (5) and small size (39), congruent with a Southern Hemisphere breeding cycle. Conversely, the northern Indian Ocean catches were more evenly split between early development (20), small (23) and big (42) sizes, particularly for the Gulf of Aden/Oman and Lacshadweep/Maldives catch regions. Mikhalev (1996, 2000) interpreted these data as evidence of two peaks of reproduction coinciding with both Southern and Northern Hemisphere cycles; however, examination of Mikhalev (1996) Figure 8 (and the identical Mikhalev 2000, Figure 4), suggests not a bimodal distribution of fetal length, but rather a more continuous distribution of fetal lengths. This would imply aseasonal reproduction or a protracted period of conception throughout a long period of the year, also noted by Branch et al. (2019). If this population does not conform to either a Northern or Southern Hemisphere breeding cycle, but rather conceives throughout the year, this could represent a distinct life history pattern that would reinforce the subspecies classification. Moreover, the *B. m. indica* designation may be more applicable to the Oman acoustic population depending on the provenance of the holotype specimen. Irrespective of decisions on nomenclature, if there is a separate subspecies in the northern Indian Ocean, then based upon geographic and life history parameter distinctiveness, it may more likely be the Oman acoustic population than the Sri Lanka acoustic population.

The observation and initial assessment of this new song-type should lead to dedicated research to better understand this potentially distinct population, particularly in light of the conservation implications. Efforts to conduct deep water acoustic monitoring off the coast of Oman are critical to validate the existing observations, and combined with boat-based surveys and recording in the vicinity of blue whales will allow definitive attribution to species. Additional acoustic monitoring should be conducted throughout the Arabian Sea, particularly off the coasts of Pakistan and Northern India in the region of the Soviet whaling in the northeastern Arabian Sea to assess if these clusters of catches belonged to the same acoustic population; recent observations of blue whales confirms that a population continues to utilize this habitat in this region of the Soviet catches (Sutaria et al. 2016, 2017, Moazam & Nawaz 2019). Acoustic monitoring should also be conducted off Southern India and Sri Lanka to distinguish between the ranges of the Sri Lanka song-type and the Oman song-type acoustic populations. Existing acoustic datasets throughout the Indian Ocean should be evaluated for the presence of this song-type, particularly for datasets for which only automated detection of previously described song-types has been targeted (i.e., for which lack of manual browsing would have hindered discovery of an unexpected or previously undescribed vocalization). Current data and discussions on the population structure and conservation status of Indian Ocean blue whales (e.g., Branch et al. 2019) should be reconsidered in light of the possibility that at least two distinct populations may range in the northern Indian Ocean. Most importantly, efforts should be made to assess the genetic identity and conservation status of blue whales in the Arabian Sea (including the Arabian Gulf, Gulf of Oman, Arabian Sea and Gulf of Aden) and the wider western Indian Ocean, particularly given the following key conclusions: (1) that there now appears to exist a distinct population (the Oman acoustic population) that has gone unrecognized due to being conflated with another more widespread population (the Sri Lanka acoustic population); (2) that the Oman acoustic population was likely the main target of the extensive Soviet illegal catches; (3) that this population may be a candidate as a separate subspecies given current data on distribution and reproductive timing; and (4) that it is potentially severely depleted as a result of the intensive illegal whaling within its restricted range in the 1960s, and therefore in need of critical conservation actions similar to those being proposed for the Arabian Sea population of humpback whales.

5. Acknowledgements

In Oman, we are grateful to the Ministry of Environment and Climate Affairs & Ministry of Agriculture and Fisheries Wealth, Oman, for participation of staff in field activities and issuing of permits to conduct field research. We thank all staff at the Environment Society of Oman (www.eso.org.om) and Five Oceans Environmental Services through whom the field project is run, and the network of volunteers for continued support of whale and dolphin research and conservation in Oman. Sincere thanks are given for financial support for Oman fieldwork provided by Renaissance Services S.A.O.G since 2011, and funding for analysis provided by Shell-Oman in 2015 and by Five Oceans Environmental Services in 2019. In Madagascar, equipment was made available by funding initially provided by the U.S. Marine Mammal Commission, with additional equipment support from Sofie van Parijs, and a grant from the International Whaling Commission Scientific Committee. Research authorization in Madagascar was obtained from partners Centre National de Recherches Océanographiques, Nosy Be, and L'Institut Halieutique et des Sciences Marines de l'Université de Toliara. Access to the hydroacoustic data from the CTBTO hydrophone station HA08 operated by USA at Chagos Archipelago was made available to T.L.R. through a virtual Data Exploitation Centre - vDEC Contract (https://www.ctbto.org/specials/vdec/) with the University of New South Wales, School of BEES, and the CTBTO Preparatory Commission for the project entitled ‘Blue Whales in the Southern Hemisphere’. The views expressed herein are those of the authors and do not necessarily reflect the views of the CTBT Preparatory Commission.

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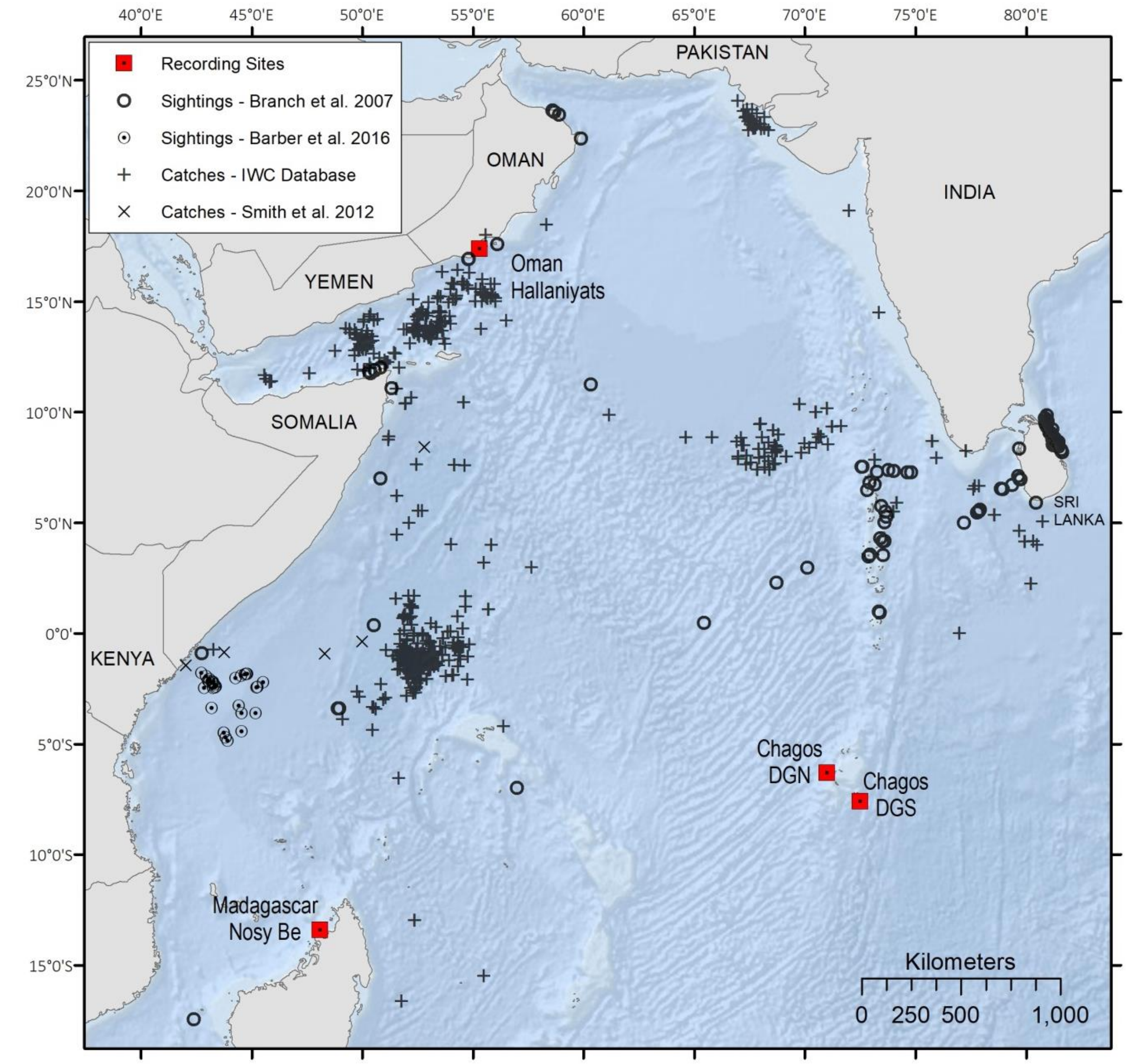


Figure 1. Map of Western Indian Ocean with recording sites in Oman (Hallaniyats Bay), Chagos Archipelago (Diego Garcia North and Diego Garcia South), and Madagascar (Nosy Be). Also depicted are catches of pygmy blue whales from the International Whaling Commission data base, including illegal Soviet catches from Mikhalev (1996, 2000), 19th Century (1853) catches from Smith et al. (2012), and blue whale sightings reported by Branch et al. (2007b) and Barber et al. (2016).

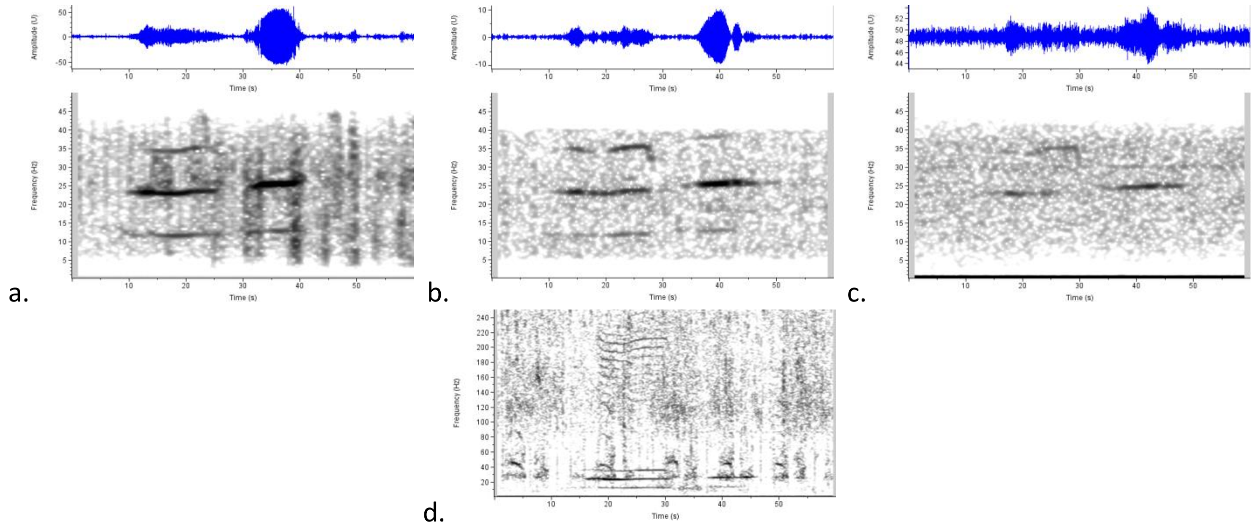


Figure 2. Example phrases for new song phrase recorded off (a) Oman, showing the 3-band structure in the first unit (2000Hz SR, 4096pt FFT, 75% overlap, bandpass filtered 5-40Hz); (b) Diego Garcia, 3-band first unit (250Hz SR, 512pt FFT, 75% overlap, bandpass filtered 5-40Hz); and (c) Madagascar, 2-band first unit (2000Hz SR, 4096pt FFT, 75% overlap, bandpass filtered 5-40Hz). (d) Example from Oman illustrating mid frequency harmonics between 150-250Hz present only on high SNR detections that also contain first harmonic band (2000Hz SR, 2048pt FFT, 75% overlap); note, the short repetitive vocalizations with fundamental frequency near 40Hz is a humpback whale in the background..

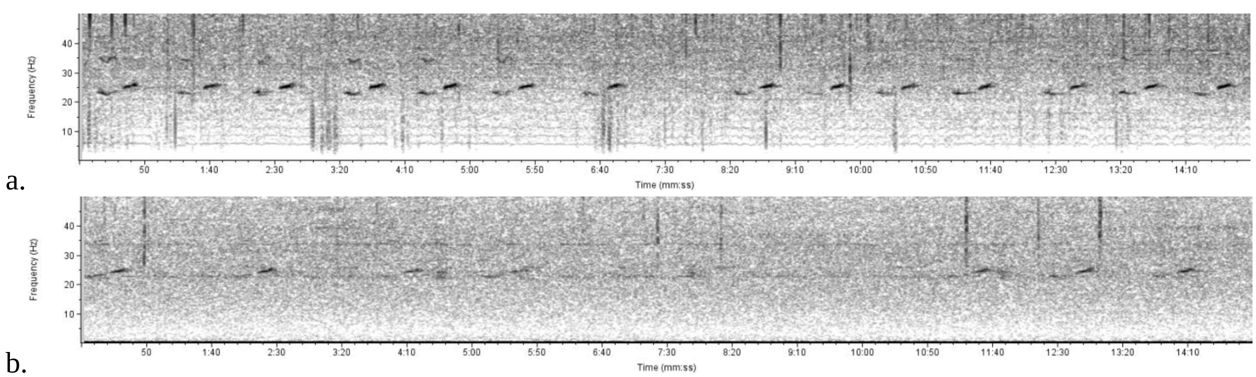


Figure 3. Example sequences of phrases for new song type recorded off Oman and Madagascar, illustrating typical repetition rates and varying Signal-to-Noise ratios (2000Hz SR, 8192pt FFT, 75% overlap). Represented are sequences of (a) a moderate SNR example recorded off Oman illustrating 2-band and 1-band units; and (b) a low SNR example recorded off Madagascar illustrating 1-band phrase sequences.

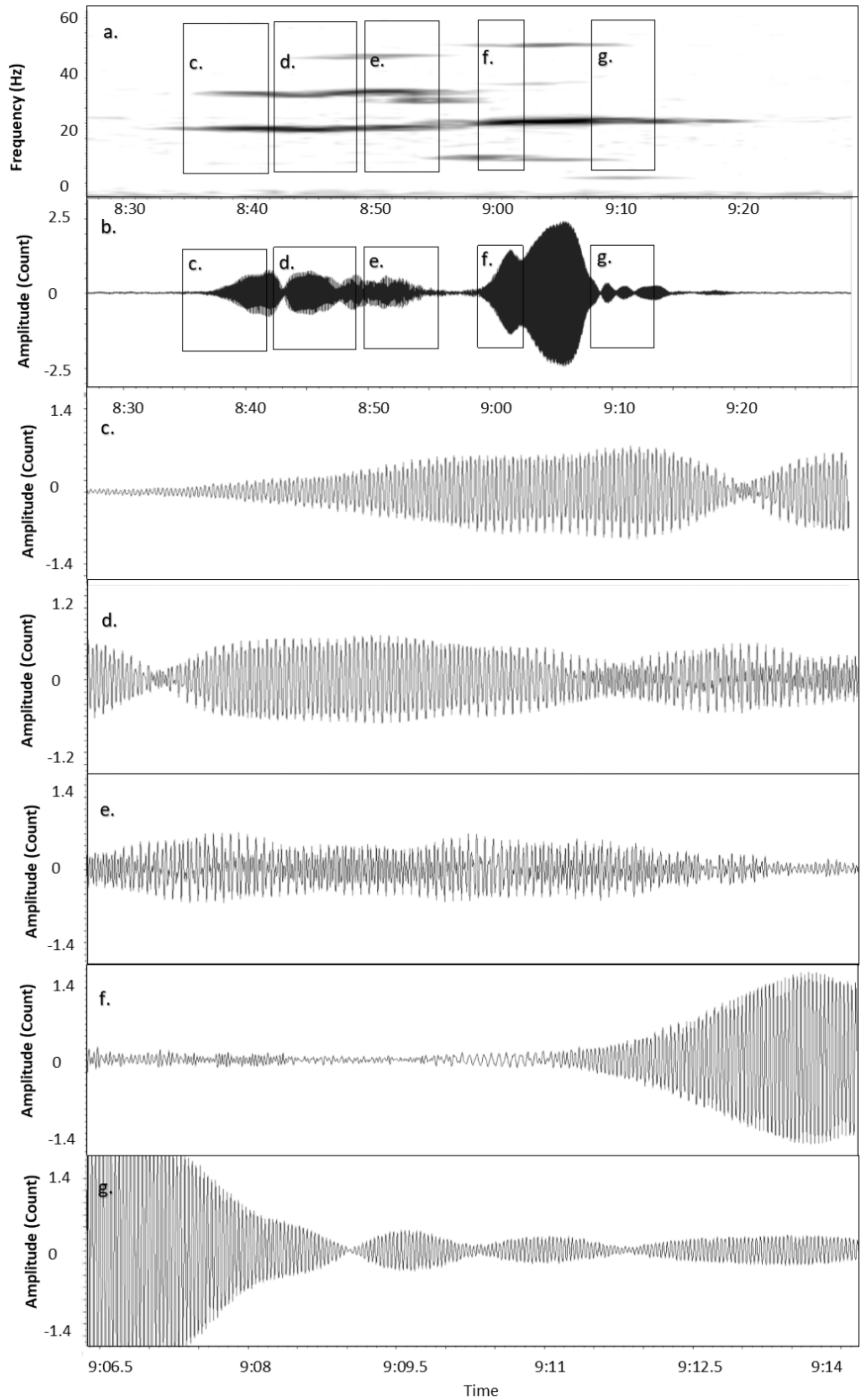
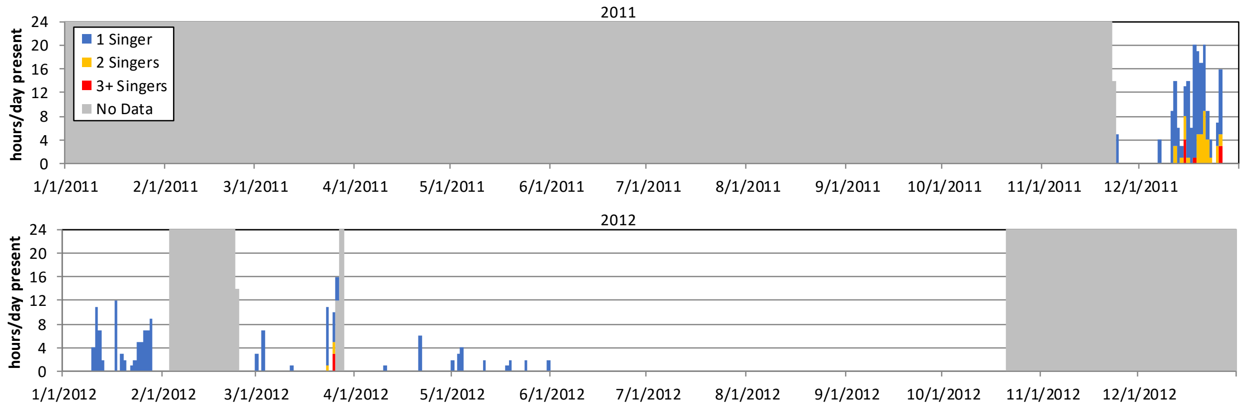


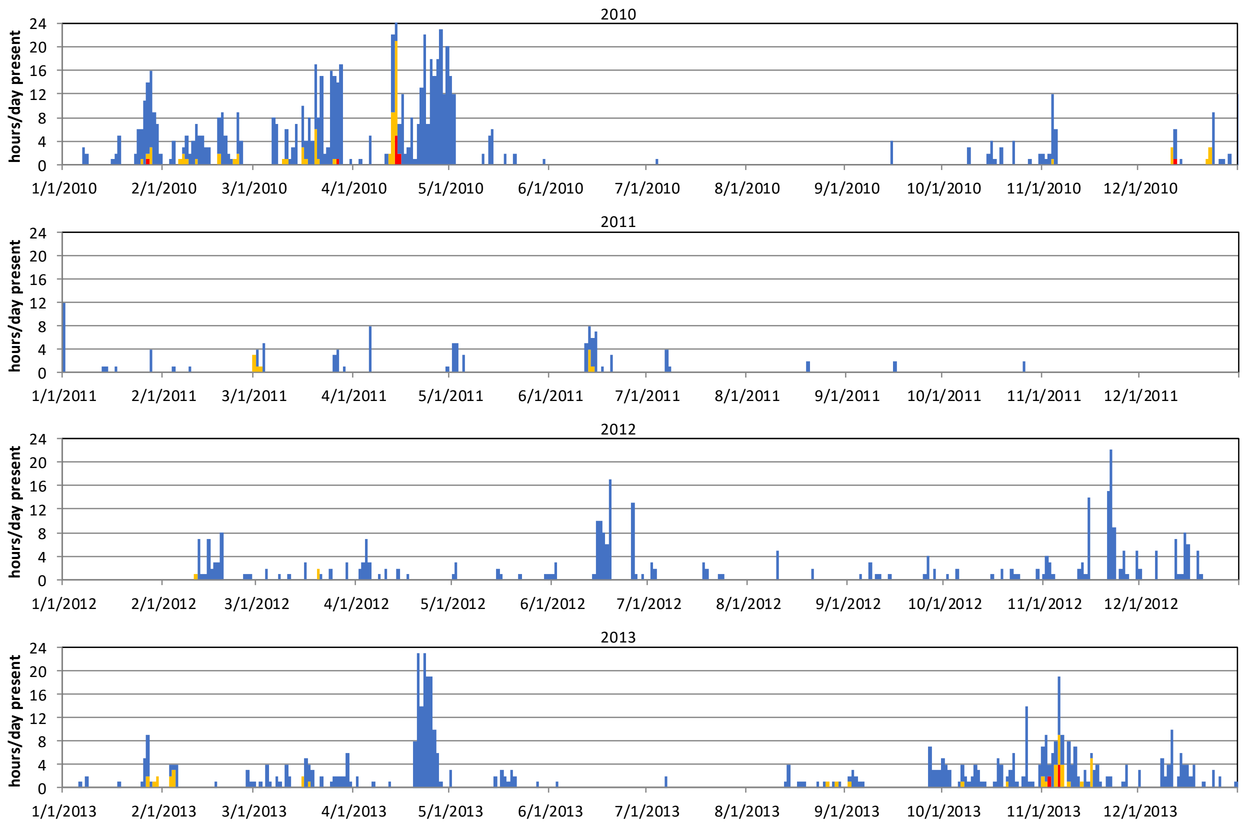
Figure 4. Spectrogram (a) and waveform (b) of an Oman phrase recorded on the western side of the Chagos Archipelagos with boxes identifying waveform details of: c) tonal signal at the start of unit 1, (d) commencement of amplitude modulating of unit 1, (e) amplitude modulation terminating unit 1, (f) tonal signal at commencement of unit 2, (g) amplitude modulated termination of unit 2. (250Hz SR, 512pt FFT, 75% overlap, Hamming window).

Figure 5. (next page) Hourly occurrence of detections of Oman blue whale song at three sites examined: A. Hallaniyats Bay, Oman; B. western Chagos Archipelago; C. Nosy Be, Madagascar. Data represent deployments of autonomous recorders from 24 November 2011 to 20 October 2012 off Oman, from 10 December 2016 to 6 November 2017 off Madagascar, and four years of CTBTO data during 2010, 2011, 2012 and 2013 from the Chagos Archipelago (from the Diego Garcia North recorder); grey bars represent hours and days of no data before, between and after deployments in Oman and Madagascar. All 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 song was detected based upon a manual browse of spectrographic data from 0-60 Hz, and hourly detections are stratified based on whether 1, 2 or more than 2 individuals were assessed to be visible on the spectrogram.

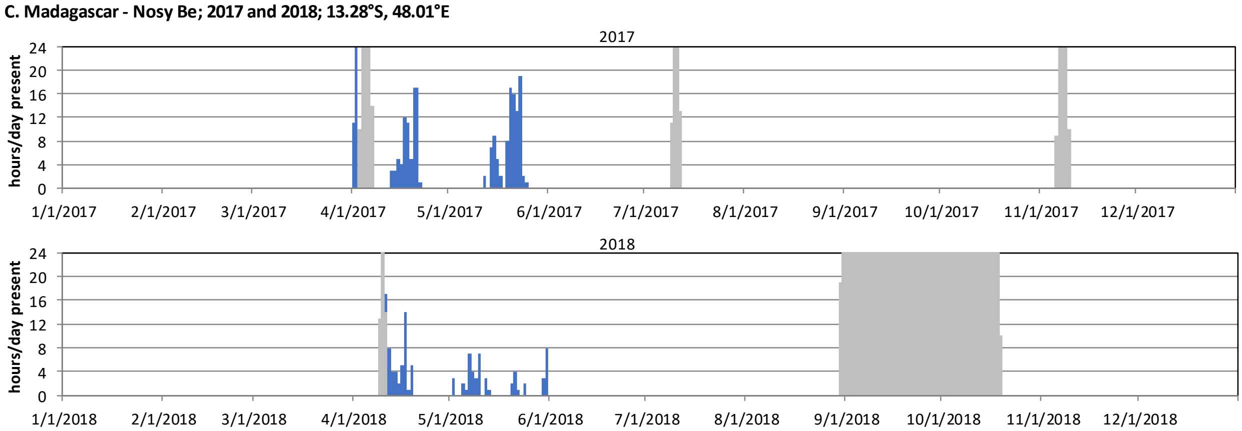
A. Oman - Hallaniyats Bay; November 2011 to October 2012; 17.40°N, 55.31°E



B. West Chagos Archipelago - Diego Garcia North; 2010, 2011, 2012 and 2013; 6.30°S, 71.00°E



C. Madagascar - Nosy Be; 2017 and 2018; 13.28°S, 48.01°E



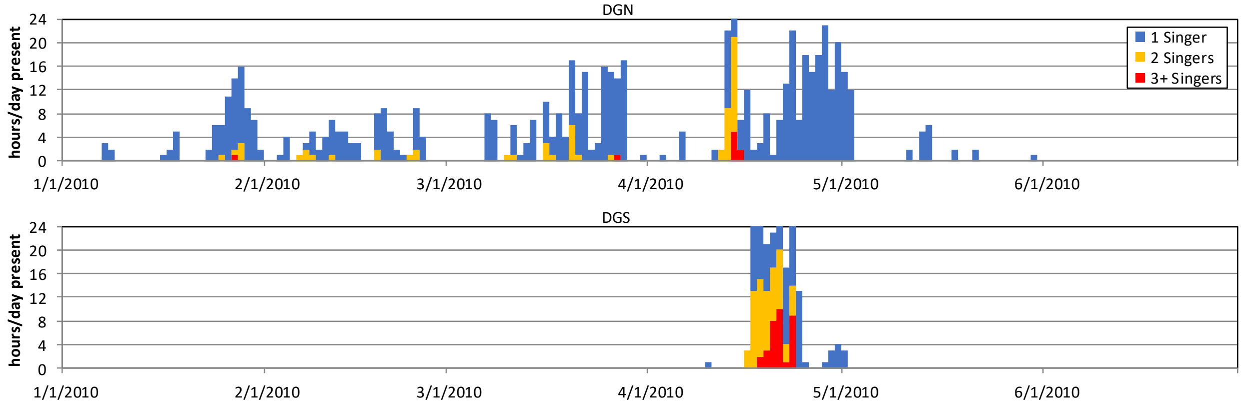


Figure 6. Detail of hourly occurrence at Chagos Archipelago, showing the first six months of 2010 from Diego Garcia North (DGN, western Chagos) and Diego Garcia South (DGS, eastern Chagos), during the only period when the song was detected at DGS.

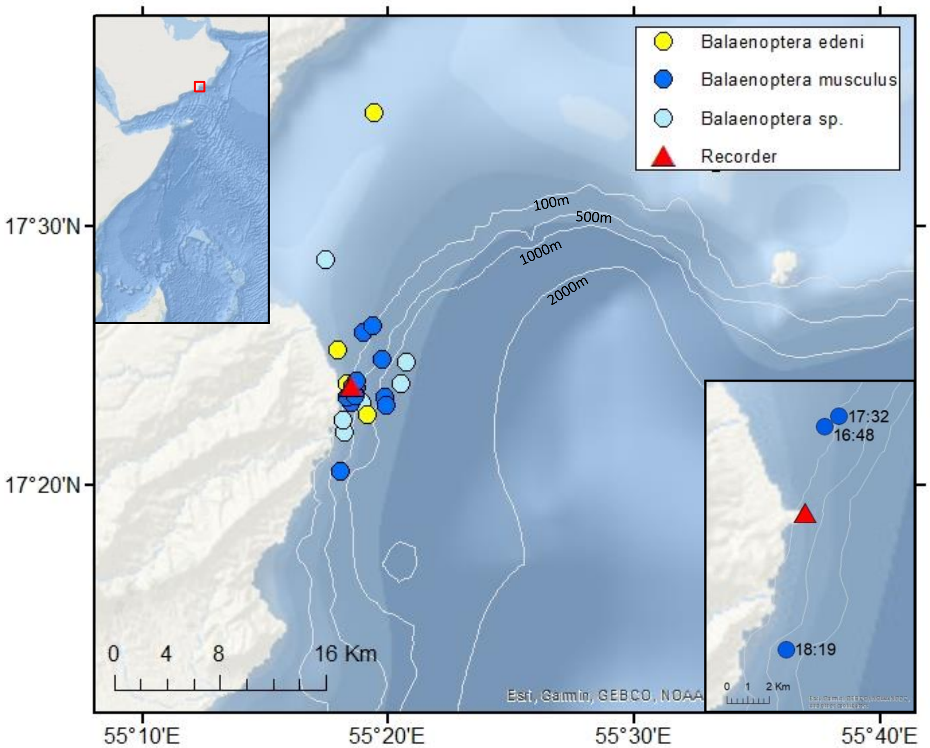


Figure 7. Positions of blue whale and Bryde's whale sightings relative to position of the Oman recorder site (Hallaniyats Bay) during surveys from 2004 to 2019, with top inset indicating location of site in the west Indian Ocean. Bottom inset detail: positions of a blue whale sighting on 26 March 2012, when there was high signal-to-noise ratio blue whale song recorded prior to the recorder being recovered at 11:35; that afternoon at 16:48 a blue whale was sighted 4km north of the recorder, and followed 10km south until 18:19.

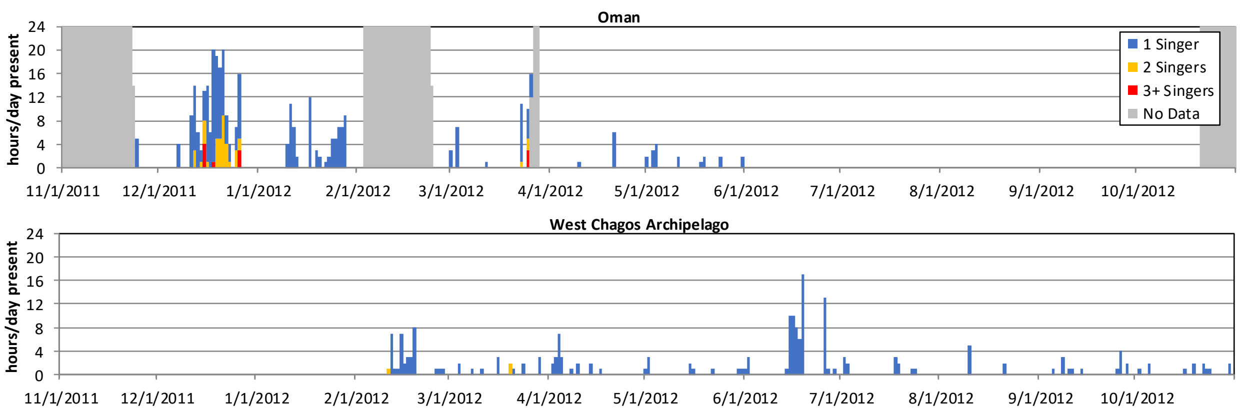


Figure 8. Detail of hourly occurrence of detections of Oman blue whale song during the period of concurrent data collection at Hallaniyats Bay, Oman, and western Chagos Archipelago, November 2011 to October 2012.