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Arabian Sea Humpback Whale (*Megaptera novaeangliae*) Singing Activity off Netrani Island, India

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Abstract

Arabian Sea humpback whales (*Megaptera novaeangliae*), listed as "Endangered" on the International Union for Conservation of Nature's *Red List*, remain resident throughout the year in the waters of the Arabian Sea and constitute a genetically isolated population. In the eastern Arabian Sea, information on humpback whales off the Indian coast has largely been limited to stranding records, local ecological knowledge, and opportunistic visual sighting data. These data, along with information from a long-term study off Oman, suggest that humpback whales migrate across the Arabian Sea into Indian territorial waters from October to March. To study the presence of Arabian Sea humpback whales in Indian waters more comprehensively, passive acoustic monitoring (PAM) was initiated along the west coast of India in 2019. Male humpback whales produce complex songs with a stereotyped structure; these songs are shared within a population, and song patterns are known to evolve progressively over time. In this article, a structural analysis of humpback whale song recorded over four days off the coast of Netrani Island, Karnataka, India, in December 2019 is presented. Time-frequency features of 2,641 individual call units were analysed. Call units had a fundamental frequency bandwidth ranging from 149.98 to 541.65 Hz, with a duration ranging from 1.19 to 5.5 s. The call units were used to identify phrases and themes required to construct the structure of the song, which can potentially help identify the population to which singing individuals belong. This study indicates the need for a long-term PAM program across the Arabian Sea to compare whale songs across the region. Simultaneous recordings over multiple seasons will best assess population connectivity, seasonal occurrence, and movement patterns within and between populations across the Arabian Sea and the Indian Ocean.

Key Words: Arabian Sea humpback whales, *Megaptera novaeangliae*, passive acoustic monitoring, song, vocal repertoire, India

Introduction

Humpback whales (*Megaptera novaeangliae*) are charismatic baleen whales with a near-cosmopolitan global distribution (Clapham & Mead, 1999). Within each ocean basin, humpback whale populations undergo long-range seasonal migrations between high-latitude summer feeding grounds and low-latitude winter breeding grounds (Thompson et al., 1977; Darling, 1983; Darling & McSweeney, 1985). In the Arabian Sea, movements of Arabian Sea humpback whales (ASHWs) have been documented between Oman (western Arabian Sea) and India (eastern Arabian Sea) (Minton et al., 2008; Sutaria, 2018, 2019; Willson et al., 2018). In addition, historical records of ASHWs (Brown, 1957; Slijper et al., 1964) indicate a distribution extending to the waters of India, Iran, Iraq, Kuwait, Oman, Pakistan, Sri Lanka, the United Arab Emirates, and Yemen (Minton et al., 2008).

Uniquely, ASHWs do not perform a seasonal migration as other populations do, instead remaining resident in tropical waters throughout the year (Mikhalev, 1997). Along with being geographically isolated and demonstrating behaviour atypical for humpback whales, ASHWs constitute a genetically isolated, discrete population (Pomilla et al., 2014). Mark-recapture studies using photo-identification data collected off the coast of Oman, though with a small sample size, have yielded a population estimate of 82 individuals (Minton et al., 2011). Although the ASHW is currently listed as "Endangered" on the International Union for Conservation of Nature's *Red List* (Minton et al., 2008), subsequent studies have recommended that the conservation status of this population be revised to "Critically Endangered" (Pomilla et al., 2014).

To study their presence in Indian waters, passive acoustic monitoring (PAM) for humpback whale songs was initiated along the west coast of India in 2019. PAM is a cost-effective and non-invasive method to study vocalising marine mammals and can augment distance sampling and mark-recapture-based visual surveys (Mellinger & Barlow, 2003). The analysis of vocalisations provides insights into the abundance, distribution, population structure, and behavioural patterns of marine mammal populations (Mellinger & Barlow, 2003). It represents a valuable opportunity to understand previously understudied populations such as the ASHW in Indian waters.

Humpback whales produce diverse and elaborate vocalisations, with a complex repertoire that has been broadly classified into stereotyped songs produced by males (Payne & McVay, 1971), non-song vocalisations (also called social sounds; Silber, 1986; Dunlop et al., 2007; Fournet et al., 2015), and feeding calls used during foraging for coordination or prey manipulation (Jurasz & Jurasz, 1979; Cerchio & Dahlheim, 2001; Sharpe, 2001). Humpback whale song, in particular, is one of the most studied animal vocalisations. The song has a highly stereotyped, hierarchical structure, with the basic time-bound call unit occurring together in a specific order, constituting a phrase. Phrases are then sequentially repeated a variable number of times to form themes. Each theme has its own phrase type, and themes in combination constitute songs that may be repeated consecutively and without breaks, sometimes for several hours (Payne & McVay, 1971).

Within a population or region, male humpback whales in acoustic contact tend to sing highly similar songs (Winn & Winn, 1978; Payne & Payne, 1985). All singing males in a population/region learn and incorporate changes into their song, leading to the evolution of song patterns over seasons (Payne et al., 1983; Payne & Payne, 1985; Cerchio & Dahlheim, 2001; Garland et al., 2011). Song structure has thus been found to be inconsistent, with variation seen both in intra- and inter-individual songs (Payne & McVay, 1971; Helweg et al., 1990, 1992; Eriksen et al., 2005). Phrase duration, however, is generally recognised as one of the most stable features of a song (Frumhoff, 1983; Payne et al., 1983; Cerchio & Dahlheim, 2001).

Although the exact functions of song have not been conclusively determined (reviewed in Herman, 2017), several hypotheses have been proposed to understand the role of male song in humpback whales. Song has been thought to function as a male breeding display (Payne & McVay, 1971; Au et al., 2006) by attracting females to the individual singer (Winn & Winn, 1978; Tyack, 1981) or an aggregation of singers as in a lek system (Herman, 2017). Here, a song might convey fitness information to females (Winn & Winn, 1978; Chu, 1988) and has even been suggested to stimulate female receptivity (Baker & Herman, 1984). However, female approach to lone male singers has not been substantiated either through playback tests (Tyack, 1983; Mobley et al., 1988) or observation (Darling & Bérubé, 2001; Nicklin et al., 2006; Smith et al., 2008). Singers have been observed to be approached by other males, however, indicating that song could function to mediate male–male interactions, particularly in affiliative contexts (Darling & Bérubé, 2001; Nicklin et al., 2006).

Humpback whales sing prolifically and predominantly on breeding grounds (Winn et al., 1975, 1981; Darling & Bérubé, 2001; Herman et al., 2013). A seasonal increase in testosterone, associated with spermatogenesis, has been proposed as a mechanism for song production on breeding grounds (Chittleborough, 1955; Symons & Weston, 1958; Clark & Clapham, 2004). Singing has also been recorded for other populations along migratory corridors (Norris et al., 1999; Charif et al., 2001; Clark & Clapham, 2004), although to a lesser extent; and in a few cases, song has even been observed in high-latitude foraging grounds (Clark & Clapham, 2004; Vu et al., 2012; Tyarks et al., 2021).

Characterisation of the vocal repertoire and subsequent construction of song structure is an essential step towards using PAM as a means of studying population and behavioural ecology, including local movement patterns and migrations (Rekdahl et al., 2018). As the ASHW population is nonmigratory, understanding temporal and seasonal patterns in song production here could potentially enable the testing of hypotheses on song function and mechanism by providing a comparison with migratory populations.

In this study, we investigated song occurrence and structure for ASHWs in nearshore waters off Netrani Island, India, in 2019. We describe units, phrases, and themes observed in the multi-day humpback whale singing activity recorded at the study site.

Methods

Acoustic data were collected off Netrani Island, Karnataka, India, using a bottom-mounted SoundTrap ST300 HF (Ocean Instruments Inc., Auckland, NZ; Figure 1). The recorder location and timeframe for deployment were based on secondary information gathered from semi-structured interviews with fishers and dive centre staff (Sutaria, 2018). Opportunistic sightings and vocalising individuals had been reported earlier from this location along the Karnataka coast of India (Sutaria, 2019). The device was deployed off Netrani Island's nearshore reef on a sandy substrate at a depth of ~15 m on 18 November 2019. A sampling rate of 288 kHz (16-bit resolution) and a 50% duty cycle of 30 min on and 30 min off were used to collect ambient sounds. Preamplifier gain was set to "High" on the SoundTrap software.

The recorder collected data from 18 November 2019 to 3 February 2020 (~77 d). Using a custom-written script, all files were downsampled to 24 kHz in *MATLAB*, Version 2021a (MathWorks Inc., Natick, MA, USA). Acoustic files were then converted into a Long-Term Spectral Average (LTSA) plot using the *MATLAB*-based program *Triton*, Version 1.93.20170330 (Scripps Institution of Oceanography, San Diego, CA, USA). The LTSA was calculated using a time average of 120 s and a frequency bin size of 100 Hz. Finally, the LTSA was visually scanned using a time window of 2 h to identify periods of humpback whale singing activity.

Files that contained whale song were then scanned visually and aurally in *Raven Pro*, Version 1.6 (K. Lisa Yang Center for Conservation Bioacoustics, Cornell Lab of Ornithology, Ithaca, NY, USA). The FFT parameters used to examine the dataset for humpback whale call units were as follows: 1,024 point Hamming window and 75% overlap. The recordings were systematically analysed using the standard hierarchical methodology for humpback whale song, as defined by Payne & McVay (1971), for the basic identification of call units, phrases, and themes. The guidelines in Cholewiak et al. (2013) were further employed for a more stringent delineation of phrase types to ensure that phrases identified in this article will be comparable with future studies. Units were identified with letters, while phrases and themes were identified using numbers. Time-frequency features of individual units were measured for every third call unit. Details of time-frequency features assessed from

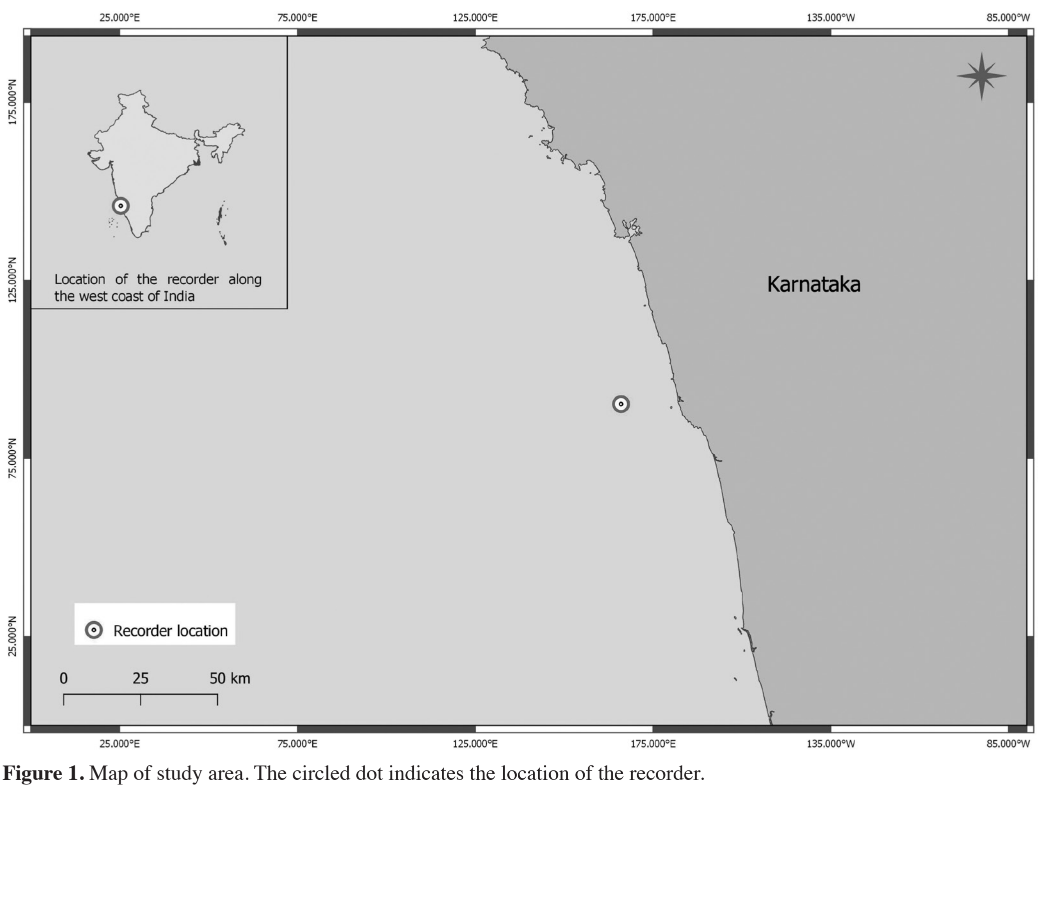


Figure 1. Map of study area. The circled dot indicates the location of the recorder.

the Netrani 2019-2020 song are given in Figure 2 and Table 1. Only signals with a signal-to-noise ratio (SNR) ≥ 6 dB were considered for these measurements (6 dB threshold verified using the SNR approximation of SNR NIST Quick measurement in *Raven Pro*). As humpback whale songs can have varying SNRs over the entire song length, SNR assessment was performed for whole songs and not quantified for individual call units (Cholewiak et al., 2013). The presence of harmonics was noted for each call unit type; however, no further measurements were obtained from the harmonics since the upper-frequency limit in the recordings was variable. Therefore, only fundamental frequencies of each call type were measured.

As the recorder was duty-cycled to operate for 30 min every 60 min, it was not possible to analyse continuous song sessions and their structure. However, we describe song characteristics, including phrases and themes, in the data recorded.

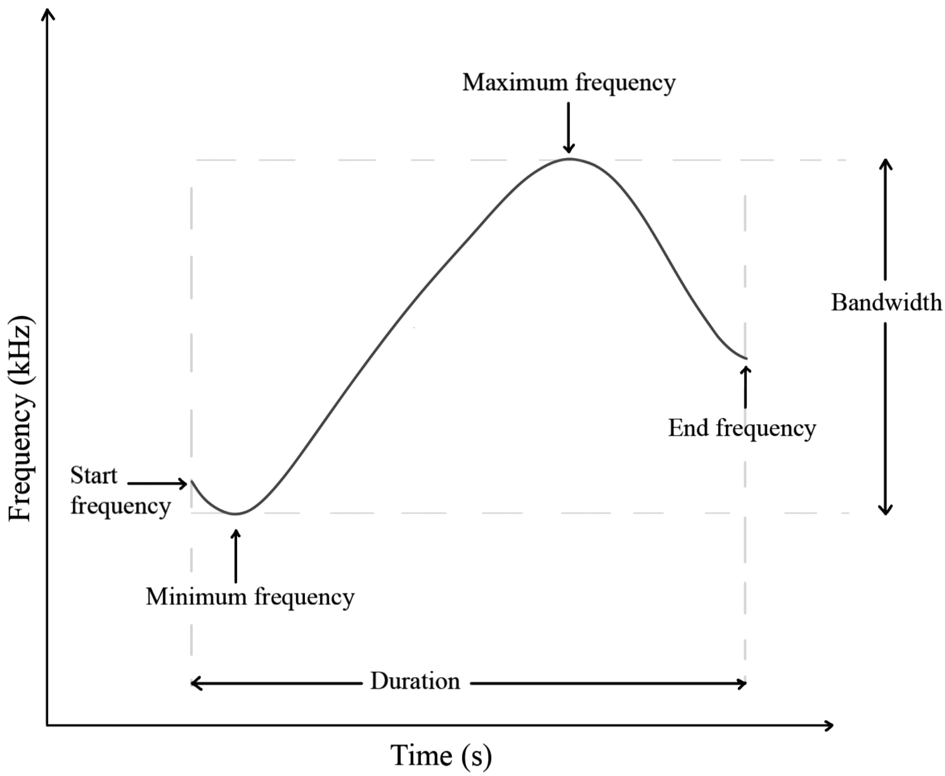


Figure 2. Spectrogram showing measured time-frequency acoustic features

Table 1. Summary of variables measured in the analysis and a brief description of measured acoustic features

Acoustic feature	Description
Start frequency (kHz)	Frequency at the beginning of the call unit
End frequency (kHz)	Frequency at the end of the call unit
Duration (s)	Time duration spanned by the entire call unit
Bandwidth (kHz)	Frequency spanned by the entire call unit
Maximum frequency (kHz)	Frequency at the highest point in the call unit
Minimum frequency (kHz)	Frequency at the lowest point in the call unit

Results

A total of 707.5 h (1,415 recordings of 30 min each) of data were available for analysis from the deployment period of 77 d and 5 h. Humpback whale vocalisations were detected in 83 recordings (each of 30 min duration), corresponding to nearly 4 d of singing activity. The first session of singing activity was recorded on 18 December 2019 at 2300 h IST, and the last session of singing activity was recorded on 22 December 2019 at 2000 h IST. However, singing activity was not consistently present over this period, and pauses in singing were observed (see Figure 3).

Over the 4 d when the singing was recorded, there was no apparent diurnal pattern in the time of singing. Further, the identified periods of singing activity in this study were observed to be without any temporal overlap with other humpback vocalisations, which likely indicates the presence of a single vocalising individual.

Call Units

A total of 39,767 humpback whale call units were identified. These call units were grouped into 11 call unit types, A to K, as shown in Table 2. Harmonics were observed for all call unit types. Spectrograms of the observed call units are shown in Figures 4 and 5.

Unit G was observed as having two variants: G1 and G2. Using the definition in Madhusudhana et al. (2019), these were classified as variants of the same unit as they occupy a similar position in their respective phrase types. However, Unit G2 was more common, with 3,379 occurrences (69.11% of total occurrences of Unit G). The observed variants of this unit type are shown in Figure 5.

The frequency of occurrence of individual call unit types is shown in Table 2 and Figure 6. Unit C was most frequent (20.46% of total call units identified), while Unit A occurred least frequently among all the call unit types (0.84% of total call units identified). As Unit K generally

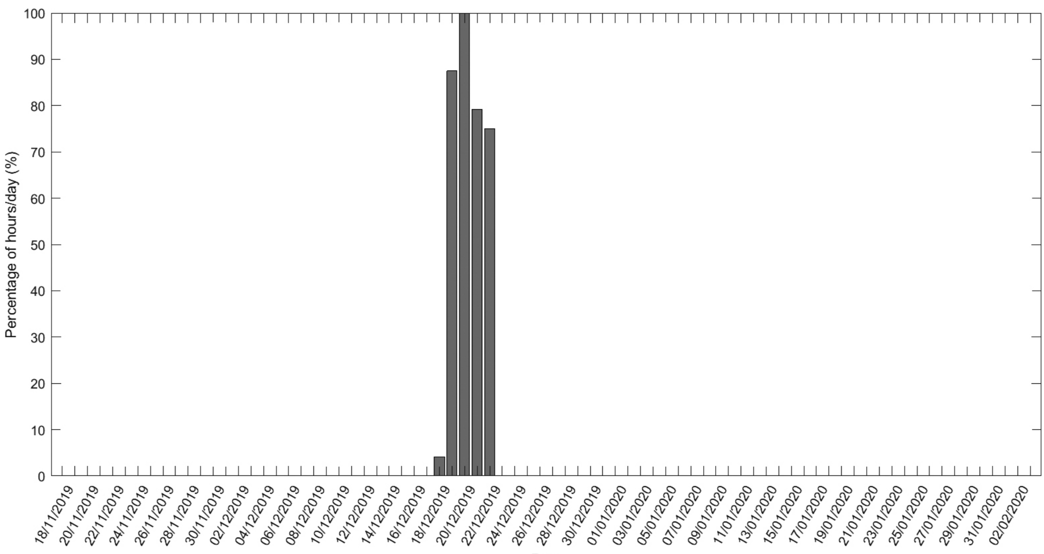


Figure 3. Percentage of hours of recording per day that include humpback whale (*Megaptera novaeangliae*) song over the deployment period

Table 2. Frequency of call unit type occurrence over 4 d of singing activity

Call unit	A	B	C*	D	E*	F	G1	G2	H	I	J	K*
Total number of occurrences	334	8,059	8,135	1,311	4,296	1,471	1,510	3,379	3,713	1,136	862	5,561
Number of units for which acoustic features were measured	66	628	None	287	None	330	139	395	332	264	200	None

*Acoustic features were not measured for composite call units (Units C, E, and K).

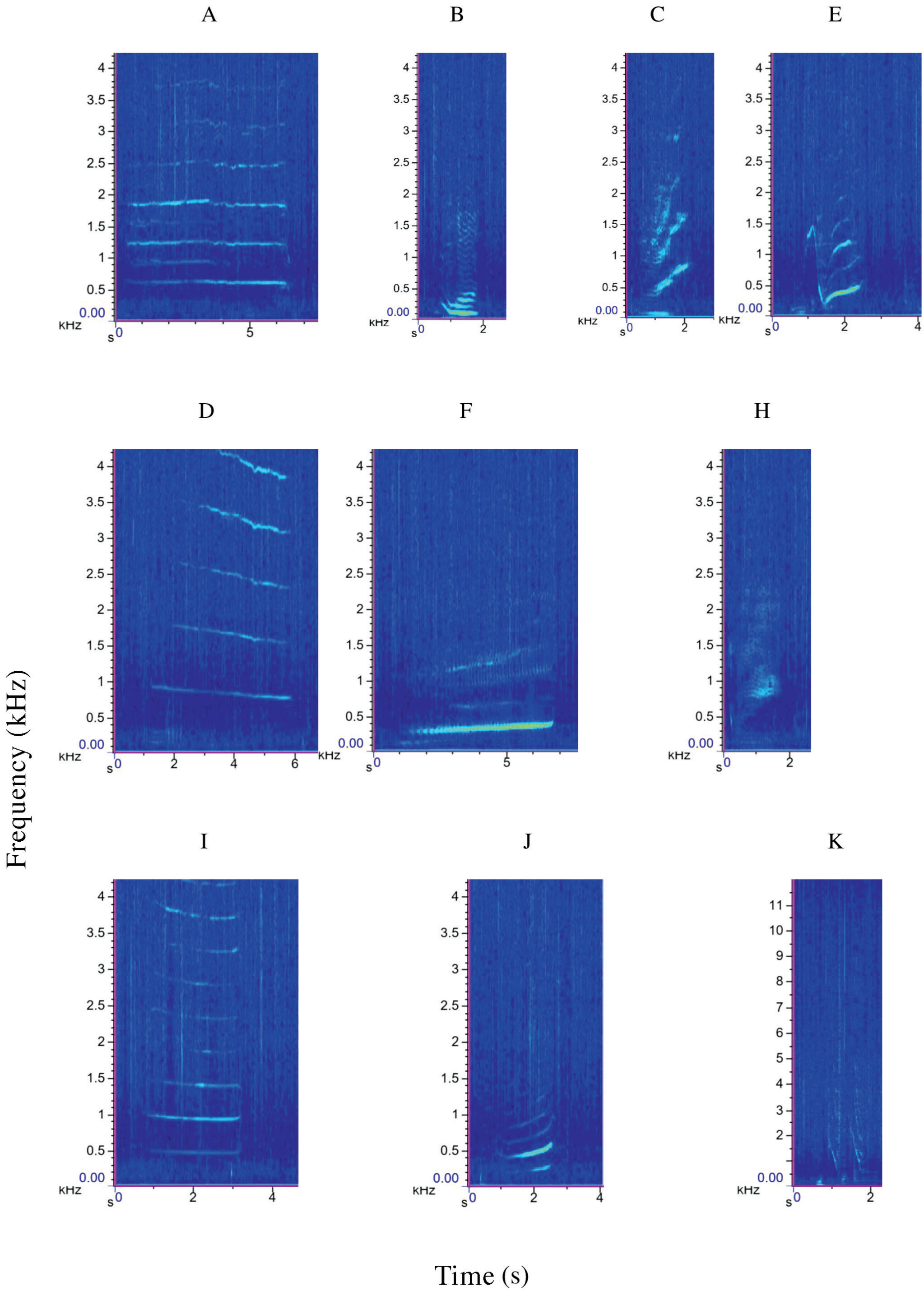


Figure 4. Spectrograms of observed call units (recorded on 22 December 2019 from 0500 h IST). FFT parameters: 1,024 point Hamming window and 75% overlap.

occurred at lower SNRs, the frequency of occurrence for Unit K is likely an underestimate.

Of the 83 recordings, 35 were assessed to have higher SNRs, corresponding to a 6-dB minimum cut-off. Time-frequency measurements were obtained for call units in these recordings, and the exact number of individual call units that were measured for each unit type is given in Table 2. Measured time-frequency features of call unit types are shown in Table 3.

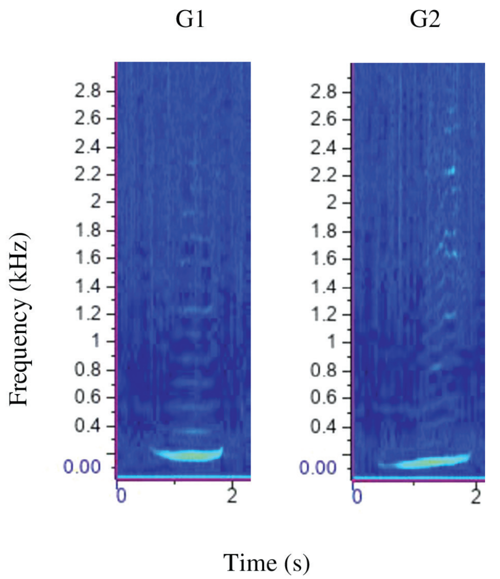


Figure 5. Spectrograms of G1 and G2, observed variants of Unit G (recorded on 22 December 2019 from 0500 h IST). FFT parameters: 1,024 point Hamming window and 75% overlap.

Units C, E, and K (Figure 4) comprise composite units of temporally separated constituent subunits. These units are considered composite because the respective separate subunits of these call unit types are consistently observed in these particular combinations, never individually or along with any other units or subunits, a characteristic of composite unit types (Madhusudhana et al., 2019). We did not measure time-frequency characteristics for these composite call units as individual subunits have different characteristics, requiring them to be measured independently.

Phrases and Themes

A total of 2,942 phrases were recorded. Specific single units or unit pairs were repeated a variable number of times in each phrase type and constituted within-phrase bouts. Bouts were found for every phrase type. In these bouts, the number of repeats, either of single units or unit pairs, varied between two to 26 times as shown in Table 4. Phrase 7 consists of variable numbers of Unit K repeats. However, due to the low SNR of this unit type, the repeats in a within-phrase bout are indistinguishable, and we refrain from estimating the exact number. Figures 7 and 8 show spectrograms of the main phrase types observed. In addition to

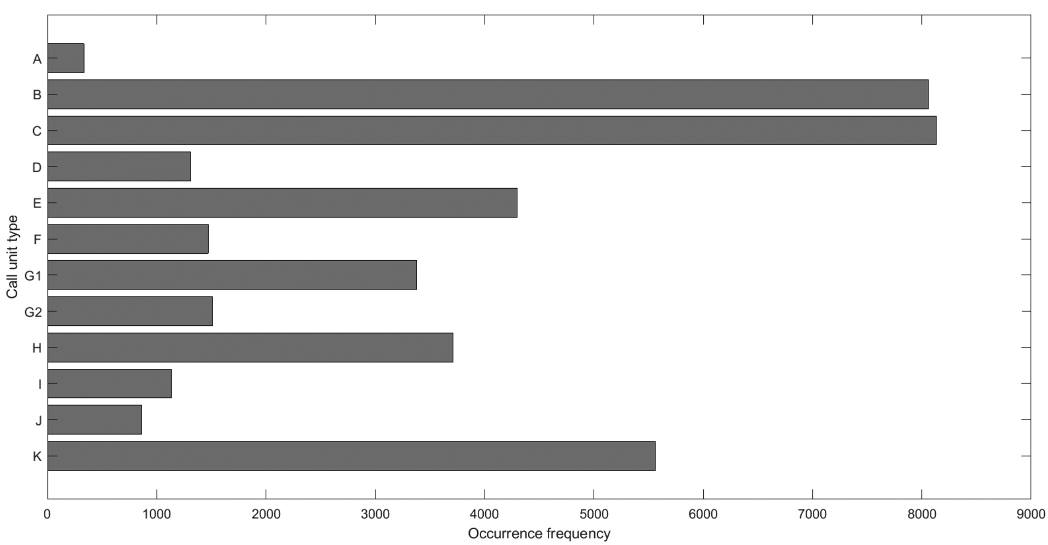
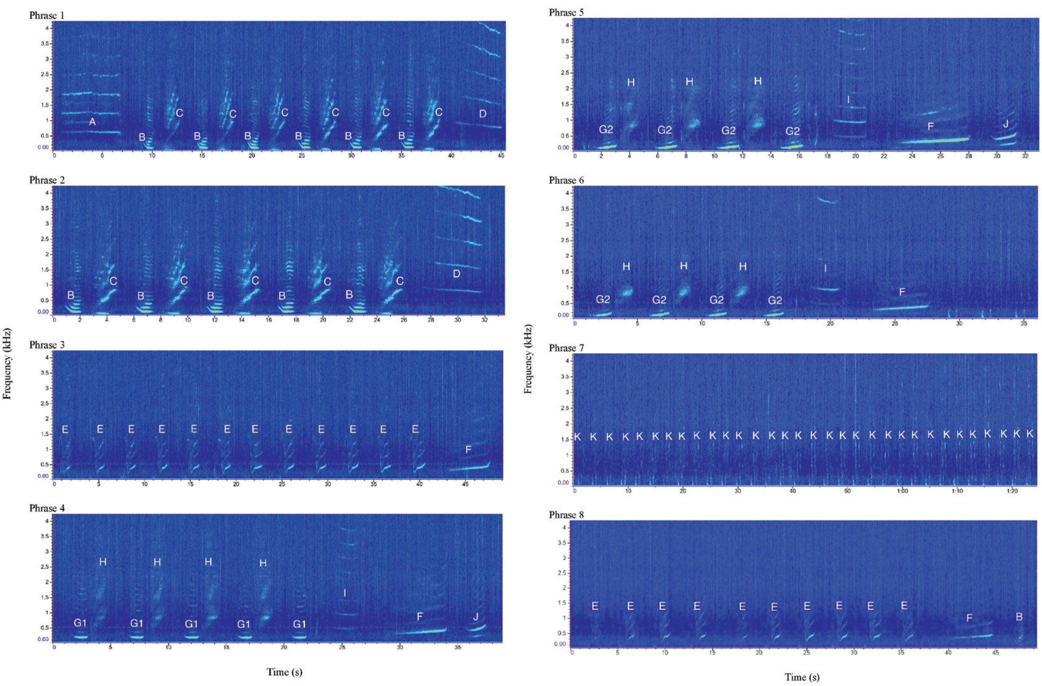


Figure 6. Occurrence frequency, measured as counts of each unit, for observed Units A through K. Individual occurrence frequencies of Unit G variants (G1 and G2) are shown separately.

Table 3. Summary of acoustic parameters of call unit types recorded; each value is reported as mean ± standard deviation.

	Start frequency (Hz)	End frequency (Hz)	Minimum frequency (Hz)	Maximum frequency (Hz)	Duration (s)	Bandwidth (Hz)
A (*n* = 66)	629.44 ± 18.97	580.79 ± 30.34	509.67 ± 39.12	692.87 ± 31.14	5.5 ± 0.43	183.2 ± 57.82
B (*n* = 628)	280.85 ± 33.9	110.9 ± 43.83	68.03 ± 11.85	298.08 ± 27.73	1.19 ± 0.13	230.05 ± 30.7
D (*n* = 287)	941.64 ± 48.64	752 ± 30.1	706.75 ± 88.65	979.99 ± 103.99	4.46 ± 0.41	273.24 ± 56.51
F (*n* = 330)	280.72 ± 42.46	467.6 ± 50.85	248.27 ± 19.08	492.63 ± 55.67	4.91 ± 0.48	244.36 ± 57.87
G1 (*n* = 139)	241.98 ± 24.5	235.58 ± 18.85	113.12 ± 16.1	263.09 ± 22.48	1.32 ± 0.16	149.98 ± 29.22
G2 (*n* = 395)	100.76 ± 17.37	214.65 ± 21.02	66.11 ± 12.61	226.43 ± 18.23	1.5 ± 0.16	160.32 ± 23.49
H (*n* = 332)	495.38 ± 62.77	1,028.19 ± 77.12	487.52 ± 61.32	1,029.17 ± 83.45	1.2 ± 0.15	541.65 ± 81.76
I* (*n* = 264)	994.73 ± 40.68	976.03 ± 23.84	869.24 ± 37.47	1,028.26 ± 42.58	2.25 ± 0.2	159.02 ± 46.52
J* (*n* = 200)	420.56 ± 26.96	607.15 ± 29.22	362.32 ± 17.28	625.01 ± 25.72	1.7 ± 0.17	262.69 ± 33.94

*Characteristics for Units I and J are listed for the first harmonic as fundamentals are very low in intensity.



Figures 7 & 8. Spectrograms of representative phrases (recorded on 22 December 2019 from 0500 h IST for Phrases 1 through 7 and 1600 h IST for Phrase 8). FFT parameters: 1,024 point Hamming window and 75% overlap.

Table 4. Composition of phrases recorded

Phrase type	Unit sequence in the constituent phrase	Number of repetitions in a within-phrase bout
1	A-(B-C)*-D	Varies from 4 to 15
2	(B-C)*-D	Varies from 3 to 12
3	(E)*-F	Varies from 5 to 26
4	(G1-H)*-G1-I-F-J	Varies from 3 to 6
5	(G2-H)*-G2-I-F-J	Varies from 2 to 4
6	(G2-H)*-G2-I-F	Varies from 2 to 4
7	(K)*	Indistinguishable
8	(E)*-F-B	Varies from 10 to 19

*Indicates that the units within parentheses occur multiple times in a bout within the phrase.

Table 5. Constituent unit sequences of observed rare phrases

Unit sequence	Number of repetitions in a bout
G2-(G1-H)*-G1-I-F-J	3, 4
A-(E)*-F	13
E-(B-C)*-D	6
(E)*-B-F	7, 8
(G1-H)*-G2	4
G2-H- G2-H-G2-B-B-B-B-B	No repetition
(E)*-B-E	10

these phrases, seven were observed either only once or a maximum of twice in the recordings. These "rare" phrases are presented in Table 5.

The themes are subsequently numbered I through VIII, with Theme I being composed of Phrase 1, Theme II composed of Phrase 2, and so on.

Regularity in Theme Transitions

Thirty-five recordings having a sufficient (≥ 6 dB) SNR were used to study the regularity in theme transitions and sequences. Song sessions that were not present entirely in the recording and cut off in the duty cycle were not considered. For 110 song sessions present, seven theme transition combinations were found. The most frequent sequences of themes were I-II-III-VI-V-VI-VII (76.36% of song sessions) and I-II-III-VI-VI-VII (15.45% of song sessions). The themes I-II-III-VII (2.73%) and I-III-VI (0.91%) were less frequent. The remaining theme transitions (4.55%) featured rare phrases not found in more than two song sessions (see Table 5).

Discussion

This study describes ASHW singing activity detected over multiple days off Netrani Island, Karnataka, in December 2019. Calls were seen to occur at all times of the day for 4 d, exhibiting no apparent diurnal pattern in singing activity, which is similar to observations in a previous study on the west coast of India (Madhusudhana et al., 2019). Over the entire period of singing, calls were found to occur without temporal overlap of other calls, indicating the presence of a single vocalising individual. While the exact duration of song sessions could not be determined due to limitations of the duty cycle, song sessions were found to last multiple hours, assuming singing was continuous during off-effort duty cycle periods. This is consistent with earlier descriptions of humpback whale song (Payne & McVay, 1971). Interestingly, no other vocalisations were recorded for the rest of the deployment period, suggesting that only one singing individual had been present off Netrani Island during that time, but this individual, too, had only passed through the area.

The overall frequency range of the fundamental frequency component (not including harmonics) of the humpback whale vocalisations recorded varied from around 66 Hz, the minimum frequency for Unit G2, to around 1,029 Hz, the maximum frequency for Unit H. Two call unit types (Units G1 and G2) were grouped as variants of the same call unit. They had similar spatiotemporal characteristics, specifically occupying similar positions in their respective phrase types, and these phrases showed consistency over multiple days. Unit C was the most frequently identified call unit, followed by B, K, G, and E. Due to the extremely low received levels of Unit K in many recordings, its true incidence may be higher. Variation in duration and frequency measurements obtained for individual call unit types is also likely a result of the variability of the SNRs of the recordings.

Eight main themes were identified, similar to previous studies like Payne & Payne (1985), which found five to nine themes in a given year, and Hawkey et al. (2020), which found 10 themes in a year. Recorded phrases were found to have a variable number of repeats of particular units in within-phrase bouts. These were classified as belonging to the same phrase type due to the presence of the same sequence of call units, irrespective of the different number of particular units repeated in bouts within the phrase. This corresponded to the definition of phrases belonging to the same phrase type as "inexact replicas" (Payne & McVay, 1971, p. 593). Finally, given that song recordings from a single individual should not be used to describe song structure (Cholewiak et al., 2013), a long-term program along the west coast of India would be required to construct song structure.

This study helps characterise humpback whale song along the west coast of India and signifies the potential for the use of acoustics in long-term monitoring studies for ASHWs in the area. The presence of humpback whales has been suggested all along the west coast of India, with particular areas of interest off Gujarat, Goa, Karnataka, Kerala, and around Kanyakumari in the Gulf of Mannar, based on interview surveys, stranding records, and sighting records (Sutaria, 2018, 2019; Anderson et al., 2022); however, their spatiotemporal distribution patterns are largely unknown. In 2015, a limited set of call units and themes were recorded in shallow waters off the coast of Kerala, India, and first indicated the possible use of the area as a winter breeding ground (Mahanty et al., 2015). Units, phrases, and themes of humpback whale song recorded opportunistically in Goa, India, were reported in a more recent study (Madhusudhana et al., 2019); however, limitations in the recording duty cycle (1 min every 15 min for 10 d) restricted the construction of a detailed song structure. Using a longer duty cycle than the previous studies allowed a more detailed elucidation of phrase and theme composition.

While there is little comparative information on the acoustic behaviour of humpback whales across the Arabian Sea, a study from 1985 suggested close similarities between humpback whale songs from Oman and Sri Lanka (Whitehead, 1985). A better understanding of the transmission of song patterns between populations can help to infer population connectivity, ultimately helping prioritise conservation management measures (Minton et al., 2015). The cultural transmission of songs between different regional populations in the South Pacific, for example, has resulted in several phrases becoming common to all populations in the area (Helweg et al., 1998; Garland et al., 2015). Investigating shared themes and elucidating song-level comparisons even within the Arabian Sea requires long-term PAM studies in the region. Increasing the recording period to cover multiple seasons and years, recording continuously instead of duty-cycling, and simultaneous recording multiple populations will help facilitate these necessary comparisons.

A comparison between the singing activity analysed in this study with songs recorded in other regions across the Arabian Sea was not presently possible for a variety of reasons. First, as already stated, the presence of a single vocalising individual recorded in this study precludes any delineation of the overall song structure. Second, studies from simultaneous time periods in potentially interacting populations like those in Oman in the northwest Arabian Sea are unavailable. Moreover, humpback whale song has been shown to have a short temporal turnover mediated by cultural transmission, with songs changing over a few months as well as undergoing song revolutions (Noad et al., 2000; Rekdahl, 2012). This generally means that comparisons between songs recorded across different years are not applicable. Further, our data were not continuously recorded due to a 50% duty cycle and the short time period of 4 d.

A long-term PAM program is required to expand our knowledge of whether the eastern Arabian Sea has breeding, calving, and foraging grounds for ASHWs and whether individuals from other populations, such as the Southwest Indian Ocean humpback whale population, also use these waters. Long-term acoustic monitoring has been initiated at two locations on the west coast of India, and future analyses will include regional comparison if songs are present on both sides of the Arabian Sea.

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Literature Cited

Anderson, R. C., Isha, Sutaria, D. N., & de Vos, A. (2022). A note on humpback whales (*Megaptera novaeangliae*) in the central Indian Ocean. *The Journal of Cetacean Research and Management*, *23*(1), 49-57. https://doi.org/10.47536/jcrm.v23i1.341

Au, W. W. L., Pack, A. A., Lammers, M. O., Herman, L. M., Deakos, M. H., & Andrews, K. (2006). Acoustic properties of humpback whale songs. *The Journal of the Acoustical Society of America*, *120*(2), 1103-1110. https://doi.org/10.1121/1.2211547

Baker, C. S., & Herman, L. M. (1984). Aggressive behavior between humpback whales (*Megaptera novaeangliae*) wintering in Hawaiian waters. *Canadian Journal of Zoology*, *62*(10), 1922-1937. https://doi.org/10.1139/z84-282

Brown, S. G. (1957). Whales observed in the Indian Ocean: Notes on their distribution. *The Marine Observer*, *27*, 157-165.

Cerchio, S., & Dahlheim, M. (2001). Variation in feeding vocalizations of humpback whales *Megaptera novaeangliae* from southeast Alaska. *Bioacoustics*, *11*(4), 277-295. https://doi.org/10.1080/09524622.2001.9753468

Charif, R. A., Clapham, P. J., & Clark, C. W. (2001). Acoustic detections of singing humpback whales in deep waters off the British Isles. *Marine Mammal Science*, *17*(4), 751-768. https://doi.org/10.1111/j.1748-7692.2001.tb01297.x

Chittleborough, R. (1955). Aspects of reproduction in the male humpback whale, *Megaptera nodosa* (Bonnaterre). *Marine and Freshwater Research*, *6*(1), 1-29. https://doi.org/10.1071/MF9550001

Cholewiak, D. M., Sousa-Lima, R. S., & Cerchio, S. (2013). Humpback whale song hierarchical structure: Historical context and discussion of current classification issues. *Marine Mammal Science*, *29*(3), E312-E332. https://doi.org/10.1111/mms.12005

Chu, K. C. (1988). Dive times and ventilation patterns of singing humpback whales (*Megaptera novaeangliae*). *Canadian Journal of Zoology*, *66*(6), 1322-1327. https://doi.org/10.1139/z88-194

Clapham, P. J., & Mead, J. G. (1999). *Megaptera novaeangliae*. *Mammalian Species*, *604*, 1-9. https://doi.org/10.2307/3504352

Clark, C. W., & Clapham, P. J. (2004). Acoustic monitoring on a humpback whale (*Megaptera novaeangliae*) feeding ground shows continual singing into late spring. *Proceedings of the Royal Society of London B: Biological Sciences*, *271*(1543), 1051-1057. https://doi.org/10.1098/rspb.2004.2699

Darling, J. D. (1983). *Migrations, abundance and behavior of Hawaiian humpback whales,* Megaptera novaeangliae (Unpub. doctoral dissertation). University of California, Santa Cruz.

Darling, J. D., & Bérubé, M. (2001). Interactions of singing humpback whales with other males. *Marine Mammal Science*, *17*(3), 570-584. https://doi.org/10.1111/j.1748-7692.2001.tb01005.x

Darling, J. D., & McSweeney, D. J. (1985). Observations on the migrations of North Pacific humpback whales (*Megaptera novaeangliae*). *Canadian Journal of Zoology*, *63*(2), 308-314. https://doi.org/10.1139/z85-047

Dunlop, R. A., Noad, M. J., Cato, D. H., & Stokes, D. (2007). The social vocalization repertoire of east Australian migrating humpback whales (*Megaptera novaeangliae*). *The Journal of the Acoustical Society of America*, *122*(5), 2893. https://doi.org/10.1121/1.2783115

Eriksen, N., Miller, L. A., Tougaard, J., & Helweg, D. A. (2005). Cultural change in the songs of humpback whales (*Megaptera novaeangliae*) from Tonga. *Behaviour*, *142*(3), 305-328. https://doi.org/10.1163/1568539053778283

Fournet, M. E., Szabo, A., & Mellinger, D. K. (2015). Repertoire and classification of non-song calls in southeast Alaskan humpback whales (*Megaptera novaeangliae*). *The Journal of the Acoustical Society of America*, *137*(1), 1-10. https://doi.org/10.1121/1.4904504

Frumhoff, P. (1983). Aberrant songs of humpback whales (*Megaptera novaeangliae*): Clues to the structure of humpback songs. In R. Payne (Ed.), *Communication and behavior of whales* (AAAS Selected Symposia Series, pp. 81-127). Westview Press.

Garland, E. C., Goldizen, A. W., Rekdahl, M. L., Constantine, R., Garrigue, C., Hauser, N. D., Poole, M. M., Robbins, J., & Noad, M. J. (2011). Dynamic horizontal cultural transmission of humpback whale song at the ocean basin scale. *Current Biology*, *21*(8), 687-691. https://doi.org/10.1016/j.cub.2011.03.019

Garland, E. C., Goldizen, A. W., Lilley, M. S., Rekdahl, M. L., Garrigue, C., Constantine, R., Hauser, N. D., Poole, M. M., Robbins, J., & Noad, M. J. (2015). Population structure of humpback whales in the western and central South Pacific Ocean as determined by vocal exchange among populations. *Conservation Biology*, *29*(4), 1198-1207. https://doi.org/10.1111/cobi.12492

Hawkey, J. S., Elwen, S. H., James, B. S., Prinsloo, A. S., & Gridley, T. (2020). First look at humpback whale (*Megaptera novaeangliae*) song structure from western South Africa. *African Zoology*, *55*(3), 224-232. https://doi.org/10.1080/15627020.2020.1796524

Helweg, D. A., Herman, L. M., & Forestell, P. H. (1990). Comparison of songs of humpback whales (*Megaptera novaeangliae*) recorded in Japan, Hawaii, and Mexico during the winter of 1989. *Scientific Reports of Cetacean Research*, *1*, 1-20.

Helweg, D. A., Frankel, A. S., Mobley, J. R., & Herman, L. M. (1992). Humpback whale song: Our current understanding. In J. A. Thomas, R. A. Kastelein, & A. Ya. Supin (Eds.), *Marine mammal sensory systems* (pp. 459-483). Springer US. https://doi.org/10.1007/978-1-4615-3406-8_32

Helweg, D., Jenkins, P., Cat, D., McCauley, R., & Garrigue, C. (1998). Geographic variation in South Pacific humpback whale songs. *Behaviour*, *135*(1), 1-27. https://doi.org/10.1163/156853998793066438

Herman, L. M. (2017). The multiple functions of male song within the humpback whale (*Megaptera novaeangliae*) mating system: Review, evaluation, and synthesis. *Biological Reviews*, *92*(3), 1795-1818. https://doi.org/10.1111/brv.12309

Herman, L. M., Pack, A. A., Spitz, S. S., Herman, E. Y. K., Rose, K., Hakala, S., & Deakos, M. H. (2013). Humpback whale song: Who sings? *Behavioral Ecology and Sociobiology*, *67*(10), 1653-1663. https://doi.org/10.1007/s00265-013-1576-8

Jurasz, C. M., & Jurasz, V. P. (1979). Feeding modes of the humpback whales, *Megaptera novaeangliae*, in southeast Alaska. *Scientific Reports of the Whales Research Institute*, *31*, 69-83.

Madhusudhana, S. K., Chakraborty, B., & Latha, G. (2019). Humpback whale singing activity off the Goan coast in the eastern Arabian Sea. *Bioacoustics*, *28*(4), 329-344. https://doi.org/10.1080/09524622.2018.1458248

Mahanty, M. M., Latha, G., & Thirunavukkarasu, A. (2015). Analysis of humpback whale sounds in shallow waters of the southeastern Arabian Sea: An indication of breeding habitat. *Journal of Biosciences*, *40*(2), 407-417. https://doi.org/10.1007/s12038-015-9525-5

Mellinger, D., & Barlow, J. (2003). *Future directions for acoustic marine mammal surveys: Stock assessment and habitat use* (NOAA OAR Special Report, NOAA/PMEL Contribution No. 2557). Report of a Workshop held in La Jolla, CA. 37 pp.

Mikhalev, Y. (1997). Humpback whales *Megaptera novaeangliae* in the Arabian Sea. *Marine Ecology Progress Series*, *149*, 13-21. https://doi.org/10.3354/meps149013

Minton, G., Reeves, R., Collins, T., & Willson, A. (Eds.). (2015). *Report on the Arabian Sea Humpback Whale Workshop: Developing a collaborative research and conservation strategy*, Dubai. https://www.mmc.gov/wp-content/uploads/Arabian_SeaHumpback_whale_0115.pdf

Minton, G., Collins, T. J. Q., Pomilla, C., Findlay, K. P., Rosenbaum, H. C., Baldwin, R., & Brownell, R. L., Jr. (2008). *Megaptera novaeangliae* (Arabian Sea subpopulation). In International Union for Conservation of Nature (Ed.), *2008 IUCN red list of threatened species*. IUCN. www.iucnredlist.org/details/132835

Minton, G., Collins, T., Findlay, K., Ersts, P., Rosenbaum, H., Berggren, P., & Baldwin, R. (2011). Seasonal distribution, abundance, habitat use and population identity of humpback whales in Oman. *The Journal of Cetacean Research and Management* (*Humpback whales: Status in the Southern Hemisphere*, Special Issue 3), 185-198.

Mobley, J. R., Herman, L. M., & Frankel, A. S. (1988). Responses of wintering humpback whales (*Megaptera novaeangliae*) to playback of recordings of winter and summer vocalizations and of synthetic sound. *Behavioral Ecology and Sociobiology*, *23*(4), 211-223. https://doi.org/10.1007/BF00302944

Nicklin, C. P., Darling, J. D., & Jones, M. E. (2006). Humpback whale songs: Do they organize males during the breeding season? *Behaviour*, *143*(9), 1051-1101. https://doi.org/10.1163/156853906778607381

Noad, M. J., Cato, D. H., Bryden, M. M., Jenner, M-N., & Jenner, K. C. S. (2000). Cultural revolution in whale songs. *Nature*, *408*(6812), 537. https://doi.org/10.1038/35046199

Norris, T. F., McDonald, M., & Barlow, J. (1999). Acoustic detections of singing humpback whales (*Megaptera novaeangliae*) in the eastern North Pacific during their northbound migration. *The Journal of the Acoustical Society of America*, *106*(1), 506-514. https://doi.org/10.1121/1.427071

Payne, K., Tyack, P., & Payne, R. (1983). Progressive changes in the songs of humpback whales (*Megaptera novaeangliae*): A detailed analysis of two seasons in Hawaii. In R. Payne (Ed.), *Communication and behavior of whales* (AAAS Selected Symposia Series, pp. 9-57). Westview Press.

Payne, R. S., & McVay, S. (1971). Songs of humpback whales. *Science*, *173*(3997), 585-597. https://doi.org/10.1126/science.173.3997.585

Payne, K., & Payne, R. (1985). Large scale changes over 19 years in songs of humpback whales in Bermuda. *Zeitschrift für Tierpsychologie*, *68*(2), 89-114. https://doi.org/10.1111/j.1439-0310.1985.tb00118.x

Pomilla, C., Amaral, A. R., Collins, T., Minton, G., Findlay, K., Leslie, M. S., Ponnampalam, L., Baldwin, R., & Rosenbaum, H. (2014). The world’s most isolated and distinct whale population? Humpback whales of the Arabian Sea. *PLOS ONE*, *9*(12), e114162. https://doi.org/10.1371/journal.pone.0114162

Rekdahl, M. (2012). *Humpback whale vocal communication: Use and stability of social calls and revolutions in the songs of east Australian whales* (Unpub. doctoral dissertation). University of Queensland, Brisbane.

Rekdahl, M. L., Garland, E. C., Carvajal, G. A., King, C. D., Collins, T., Razafindrakoto, Y., & Rosenbaum, H. (2018). Culturally transmitted song exchange between humpback whales (*Megaptera novaeangliae*) in the southeast Atlantic and southwest Indian Ocean basins. *Royal Society Open Science*, *5*(11). https://doi.org/10.1098/rsos.172305

Sharpe, F. A. (2001). *Social foraging of the southeast Alaskan humpback whale,* Megaptera novaeangliae (Doctoral dissertation). Simon Fraser University, Burnaby, British Columbia. https://www.researchgate.net/publication/35725428_Social_foraging_of_the_southeast_Alaskan_humpback_whale_Megaptera_novaengliae

Silber, G. K. (1986). The relationship of social vocalizations to surface behavior and aggression in the Hawaiian humpback whale (*Megaptera novaeangliae*). *Canadian Journal of Zoology*, *64*(10), 2075-2080. https://doi.org/10.1139/z86-316

Slijper, E. J., van Utrecht, W. L., & Naaktgeboren, C. (1964). Remarks on the distribution and migration of whales, based on observations from Netherlands ships. *Bijdragen Tot de Dierkunde*, *34*(1), 3-93. https://doi.org/10.1163/26660644-03401001

Smith, J. N., Goldizen, A. W., Dunlop, R. A., & Noad, M. J. (2008). Songs of male humpback whales, *Megaptera novaeangliae*, are involved in intersexual interactions. *Animal Behaviour*, *76*(2), 467-477. https://doi.org/10.1016/j.anbehav.2008.02.013

Sutaria, D. (2018). *Baleen whale reports from the eastern Arabian Sea based on interview surveys and stranding reports – update from India* (SC/67b/CMP15). Paper presented to the IWC Scientific Committee, Bled, Slovenia (Unpub.). 5 pp.

Sutaria, D. (2019). *A report on baleen whale records and recent developments in marine mammal research and conservation policy – update from India* (Paper SC/68A/CMP/10). Presented to the IWC Scientific Committee, Nairobi, Kenya (Unpub.). 6 pp.

Symons, H. W., & Weston, R. D. (1958). Studies on the humpback whale (*Megaptera nodosa*) in the Bellingshausen Sea. *Norsk Hvalfangst-Tidende*, *47*, 53-80.

Thompson, P. O., Cummings, W. C., & Kennison, S. J. (1977). Sound production of humpback whales, *Megaptera novaeangliae*, in Alaskan waters. *The Journal of the Acoustical Society of America*, *62*(S1), S89. https://doi.org/10.1121/1.2016437

Tyack, P. (1981). Interactions between singing Hawaiian humpback whales and conspecifics nearby. *Behavioral Ecology and Sociobiology*, *8*(2), 105-116. https://doi.org/10.1007/BF00300822

Tyack, P. (1983). Differential response of humpback whales, *Megaptera novaeangliae*, to playback of song or social sounds. *Behavioral Ecology and Sociobiology*, *13*(1), 49-55. https://doi.org/10.1007/BF00295075

Tyarks, S. C., Aniceto, A. S., Ahonen, H., Pedersen, G., & Lindstrøm, U. (2021). Humpback whale (*Megaptera novaeangliae*) song on a subarctic feeding ground. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.669748

Vu, E., Risch, D., Clark, C., Gaylord, S., Hatch, L., Thompson, M., Wiley, D., & van Parijs, S. (2012). Humpback whale song occurs extensively on feeding grounds in the western North Atlantic Ocean. *Aquatic Biology*, *14*(2), 175-183. https://doi.org/10.3354/ab00390

Whitehead, H. (1985). Humpback whale songs from the north Indian Ocean. *Investigations on Cetacea*, *17*, 157-162.

Willson, A., Leslie, M., Baldwin, R., Cerchio, S., Childerhouse, S., Collins, T., Findlay, K., Genov, T., Godley, B. J., Al Harthi, S., Macdonald, D. W., Minton, G., Zerbini, A., & Witt, M. J. (2018). *Update on satellite telemetry studies and first unoccupied aerial vehicle assisted health assessment studies of Arabian Sea humpback whales off the coast of Oman* (IWC/SC67B/CMP13Rev1). Paper presented to the IWC Scientific Committee, Bled, Slovenia (Unpub.).

Winn, H. E., & Winn, L. K. (1978). The song of the humpback whale *Megaptera novaeangliae* in the West Indies. *Marine Biology*, *47*(2), 97-114. https://doi.org/10.1007/BF00395631

Winn, H. E., Edel, R. K., & Taruski, A. G. (1975). Population estimate of the humpback whale (*Megaptera novaeangliae*) in the West Indies by visual and acoustic techniques. *Journal of the Fisheries Research Board of Canada*, *32*(4), 499-506. https://doi.org/10.1139/f75-061

Winn, H. E., Thompson, T. J., Cummings, W. C., Hain, J., Hudnall, J., Hays, H., & Steiner, W. W. (1981). Song of the humpback whale: Population comparisons. *Behavioral Ecology and Sociobiology*, *8*(1), 41-46. https://doi.org/10.1007/BF00302842