Taylor & Francis
Taylor & Francis Group

Bioacoustics
The International Journal of Animal Sound and its Recording

ISSN: 0952-4622 (Print) 2165-0586 (Online) Journal homepage: http://www.tandfonline.com/loi/tbio20

Humpback whale singing activity off the Goan coast in the Eastern Arabian Sea

Shyam Kumar Madhusudhana, Bishwajit Chakraborty & G. Latha

To cite this article: Shyam Kumar Madhusudhana, Bishwajit Chakraborty & G. Latha (2018): Humpback whale singing activity off the Goan coast in the Eastern Arabian Sea, Bioacoustics, DOI: 10.1080/09524622.2018.1458248

To link to this article: https://doi.org/10.1080/09524622.2018.1458248

BIOACOUSTICS, 2018
https://doi.org/10.1080/09524622.2018.1458248

Taylor & Francis
Taylor & Francis Group

Check for updates

Humpback whale singing activity off the Goan coast in the Eastern Arabian Sea

Shyam Kumar Madhusudhana[a], Bishwajit Chakraborty[a] and G. Latha[b]

[a]CSIR - National Institute of Oceanography, Goa, India; [b]National Institute of Ocean Technology, Chennai, India

ABSTRACT
For over two decades, passive acoustic monitoring (PAM) methods have been successfully employed around the world for studying aquatic megafauna. PAM-driven studies in Indian waters have so far been relatively very scarce. Furthermore, cetacean populations inhabiting the north western Indian Ocean are far less studied than those in many other regions around the world. This work likely constitutes the first systematic study of the vocal repertoire of humpback whales (*Megaptera novaeangliae*) at a near-shore site along the western coast of India. Analysis of the observed vocalizations provides an insight into the behaviour of the species. This is significant as it assists in developing a better understanding of the habitat use of the non-migratory Arabian Sea humpback whale population. In contrast, other breeding populations such as those around the North Atlantic, South Pacific and Australia have been relatively well studied. Underwater passive acoustic data were collected during March 2017 using an autonomous logger at a shallow-water site off the eastern edge of Grande Island off the coast of Goa. Humpback whale vocalizations were found to occur over multiple days in the recordings. Time–frequency contours of individual units of vocalization were extracted with the aid of an automatic detection technique and the characteristics of the units were measured. Further, successive units were analysed for formation of phrases and themes. Reconstruction of putative songs from the identified units and themes was not possible due to the limitations imposed by the nature of data collection. Detailed analyses of units, phrases and themes are presented.

ARTICLE HISTORY
Received 10 November 2017
Accepted 7 March 2018

KEYWORDS
Arabian Sea humpback whales; passive acoustics; vocal repertoire; song

Introduction

Humpback whales (*Megaptera novaeangliae*) are a highly vocal species of marine mammals. At present, little is known about the extent of their distribution in the northern Indian Ocean. Our current knowledge of their presence in the northern Indian Ocean is predominantly based on beaching and stranding records and from limited visual surveys. Early reports of humpback whale presence in the Arabian Sea included those by Brown (1957) and Slijper et al. (1964). Generally, humpback whales have been known to migrate between high latitude summer feeding areas and low latitude winter breeding areas (Thompson et

CONTACT Bishwajit Chakraborty bishwajit@nio.org

al. 1977; Darling 1983; Darling and McSweeney 1985). In contrast, humpback whales in the Arabian Sea have been found to remain in tropical waters year-round (Mikhalev 1997). Their population identity had been a matter of dispute until Mikhalev (1997) offered argument for their status as a discrete population. A more recent study (Rosenbaum et al. 2017) assessed mitochondrial genetic population structure across global ranges of humpback whales offering conclusive evidence of the distinctiveness of the Arabian Sea humpback whale population. This study expands the current understanding of the vocal behaviour of humpback whales in the Eastern Arabian Sea and of their use of the region as a breeding ground.

Passive acoustic monitoring (PAM) is a non-invasive and cost-effective alternative to visual-based monitoring methods. PAM can provide insights into migratory and behavioural patterns of marine mammals. Systematic PAM-based studies of humpback whale vocalizations in Indian waters have been scarce. A previous study (Mahanty et al. 2015) reported observations of a very limited set of call units and themes from recordings near the coast off Alapuzha, Kerala. In this study, we analysed passive acoustic records of underwater sounds in the Arabian Sea off the Goan coast and discovered multi-day occurrence of humpback whale singing activity.

Humpback whales have a complex vocal repertoire that includes moans, high-frequency squeals, low-frequency rumbles, etc. Humpback whale sounds can be broadly classified as social calls and song calls. Humpback whale songs are likely the most studied underwater biological signals. While only male humpback whales have been known to produce songs (Darling 1983; Glockner and Venus 1983; Clapham 1996), the function of these elaborate vocal displays are generally attributed to mate attraction (Winn and Winn 1978; Tyack 1981; Smith et al. 2008) during breeding seasons and for mediation of interactions between singers (Darling and Bérubé 2001; Darling et al. 2006; Cholewiak 2008; Dunlop and Noad 2016). All males within a population/region generally sing very similar songs (Payne 1978; Winn and Winn 1978) and song patterns have been observed to evolve over seasons (Payne et al. 1983; Payne and Payne 1985; Cerchio et al. 2001; Garland et al. 2011). A collection of a few short time-bound call units that occur together in a specific order is termed a phrase, sequential repetitions of phrases are referred to as themes and combinations of themes form songs that generally last several minutes (Payne and McVay 1971). While the structure of humpback whale songs (characterized by their duration, ordering of constituent themes, etc.) has been found to be inconsistent (Helweg et al. 1990, 1992; Fristrup et al. 2003; Eriksen et al. 2005), phrase duration has been found to be one of the most stable features of a song (Frumhoff 1983; Payne et al. 1983; Cerchio 1993; Cerchio et al. 2001). In this study, vocalization analysis focuses strongly on developing a good understanding of the repertoire of units and phrases in songs of humpback whales in the region.

Methods

Acoustic recordings

Underwater audio was collected using a Wildlife Acoustics™ SongMeter 3 Marine autonomous recorder. The integrated recording equipment was calibrated at the standards compliant Acoustic Test Facility of the National Institute of Ocean Technology, Chennai, India. The autonomous unit was deployed in a shallow-water area near Grande Island, off the coast

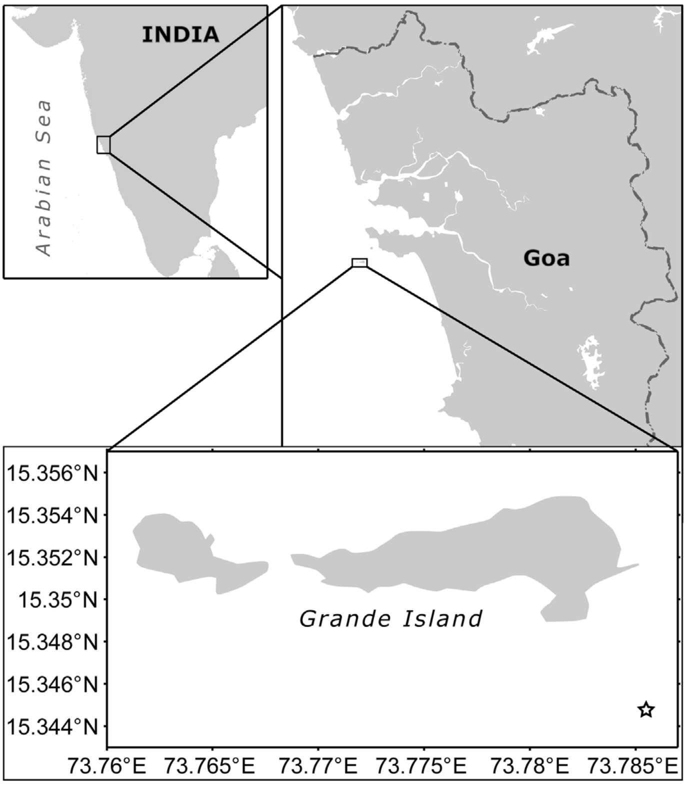

Figure 1. Data collection site.
Note: The location where recording equipment was deployed is indicated with a five-pointed star.

of Goa, India (see Figure 1). Seafloor depth at the recording site is 20 m and the recorder was moored with weights and flotation buoys such that the hydrophone was suspended at a depth of 9.25 m below the surface. Audio was recorded with a sampling rate of 24 kHz and no pre-amplifier gain, at a duty cycle of 1 min every 15 min from 14 to 23 March 2017. The digitized audio recordings were stored as 16-bit WAVE files. The goal of the acoustic data collection activity was multi-fold and also included sampling (acoustically) the region's marine biodiversity and characterization of the prevalent soundscape. Equipment configuration and recording period were chosen as described above in order to address the needs, while achieving maximum utilization of the limited funds and available resources (batteries, storage, availability of personnel and transport vessel, etc.).

Vocalization analysis

Recorded audio was analysed both aurally and visually (spectrograms) using Matlab programmes developed in-house. Visual analysis involved segmentation of the recording bandwidth into multiple segments – spectrograms were computed using parameters suited for effectively representing signals within the frequency ranges 5–150 Hz (250 ms Hamming window, 75% overlap), 100–1600 Hz (75 ms Hamming window, 65% overlap) and 1.5–12 kHz (10 ms Hamming window, 50% overlap) following appropriate bandpass filtering of audio signals using fourth-order Butterworth filters. Visualizations of the resulting spectrograms were restricted to the respective frequency ranges. In order to facilitate ready recognition of vocalizations by a human analyst, time–frequency contours of tonal signals (and of their overtones, if any) extracted using an automatic narrowband signal detector (Madhusudhana 2015) were overlaid with a contrasting colour on the displayed spectrograms. Since spectral intensities are represented in logarithmic (dB) scale in visual displays, signals with spectral levels only slightly higher than their immediate spectral vicinity often appear buried in the background in spectrograms that have large dynamic ranges. The automatic detector, which operates on linear scale spectrograms, was especially useful in highlighting vocalizations in such conditions. The automatic detector was configured to detect signals having spectral levels of 65 dB re $1\mu Pa^2/Hz$ or higher. In consideration of the observed background levels, the chosen threshold seemed appropriate as it allowed for detection of call units having very low signal-to-noise ratios (SNRs). The graphical user interface (GUI) of our programme also facilitated playback of selected segments of audio, with an optional pre-filtering step so that analysts could easily focus on the signals of interest. An analyst could quickly choose the type (low-pass, bandpass or high-pass) and spectral bounds for the filtering step. Call units identified from aural and visual analyses were annotated, via the GUI, by recording their temporal and spectral extents along with a label identifying the call type. The analysis process was carried out for all audio files in the recording set.

Ambient sound levels in the recordings varied considerably both temporally and spectrally, with dominant contributions during periods of higher levels being those from vessels (sporadic) and multiple types of fish choruses (diel rhythms). Consistency of the annotation activity was affected during periods when the SNR of humpback whale vocalizations were low. As a result, the first round of making annotations produced a set of around 40 different types of call units. By acknowledging the possibility of masking of overtones (harmonics) from varying background levels, thorough observations of similarities between labelled units and of their contexts (temporally neighbouring units) resulted in significant reduction of total number of call unit types. Following this, annotation-sequences corresponding to each audio file were analysed for identifying repeated groupings of call units. As call units were labelled with letters from the English alphabet, pattern-matching of character strings seemed a feasible option for identifying repetitive sequences. However, attempting matching using rigid patterns would fail (i) when call sequences cut across recording cycle boundaries or (ii) when the rates of occurrence of repetitive units or unit-groups within putative phrases are variable. This was tackled using regular expressions (Thompson 1968) instead of rigid pattern strings. We followed a trial-and-error approach using sets of different regular expression combinations (one regular expression per putative phrase type within each set) until the resulting groupings of matched unit sequences exhibited maximum consistency over the entire recording period. We ensured that the identification of humpback whale song phrases (both complete and incomplete) and phrase transitions remained consistent with the guidelines put forth by Cholewiak et al. (2013) for achieving analyser-independent delineation of phrase types. Mislabelled call units which were a result of analyser fatigue became evident during this stage as they prevented unit-groups from being matched with the regular expressions considered. The wrong labels were corrected by considering the context of each call unit, i.e. the phrase/theme that was active during the time-span of the mislabelled unit.

Results

Humpback whale vocalizations were detected in six out of the nine days of recordings. Calls were seen to occur at all times of a day and any effect of time of day or of the presence of different fish species on the calling behaviour were not apparent. A total of 5424 call units were detected. Spectro-temporal characteristics of identified call units are described in Table 1 and Figure 2. The lower extremities of observed durations of the units can be attributed to low SNRs and to units occurring at the edges of recording cycles. Data points at higher extremities of unit durations correspond to high SNR units and may be more accurate representations of true unit durations. Visual representations of the units are shown in Figures 3 through 6. In order to better represent the time–frequency structure of some of the call units, spectrograms in these figures are shown with logarithmic frequency axes wherever appropriate. A total of nine groupings of unit sequences were identified. The phrases and themes resulting from these groupings are listed in Table 2. Representative acoustic samples of the phrases are available as supplemental material (online only). Units C, R, S and T and unit pairs M-G and Y-Z predominantly occurred in bouts within phrases. Unit C was always seen to occur in trains of threes. Unit R was found to predominantly occur in trains of 4–5 and units S and T were found to occur in trains of up to seven and six, respectively. Unit pair M-G was found to predominantly occur in trains of 2–3 with rare occurrences in trains of four. Unit pair Y-Z was seen dominantly occurring in trains of twos with rare occurrences in trains of three.

Table 1. Details of observed unit types.

Unit type	Number of instances detected	Harmonics observed?	Fig. #
A	411	NA	5,6
B	409	Yes	3
C	1022	Yes	6
D	292	No	4
E	323	Yes	3
F	236	Yes	3
G	398	Yes	3
H	20	Yes	3
J	131	Yes	3
K	86	Yes	3
L	82	Yes	6
M	598	Yes	4
N	441	Yes	3
P	83	NA	5
Q	119	Yes	3
R	360	Yes	4
S	114	Yes	4
T	80	Yes	4
U	109	Yes	3
W	49	NA	5
Y	20	No	3
Z	29	Yes	3

Note: The last column indicates the number of the figure(s) which show spectrograms of the units.

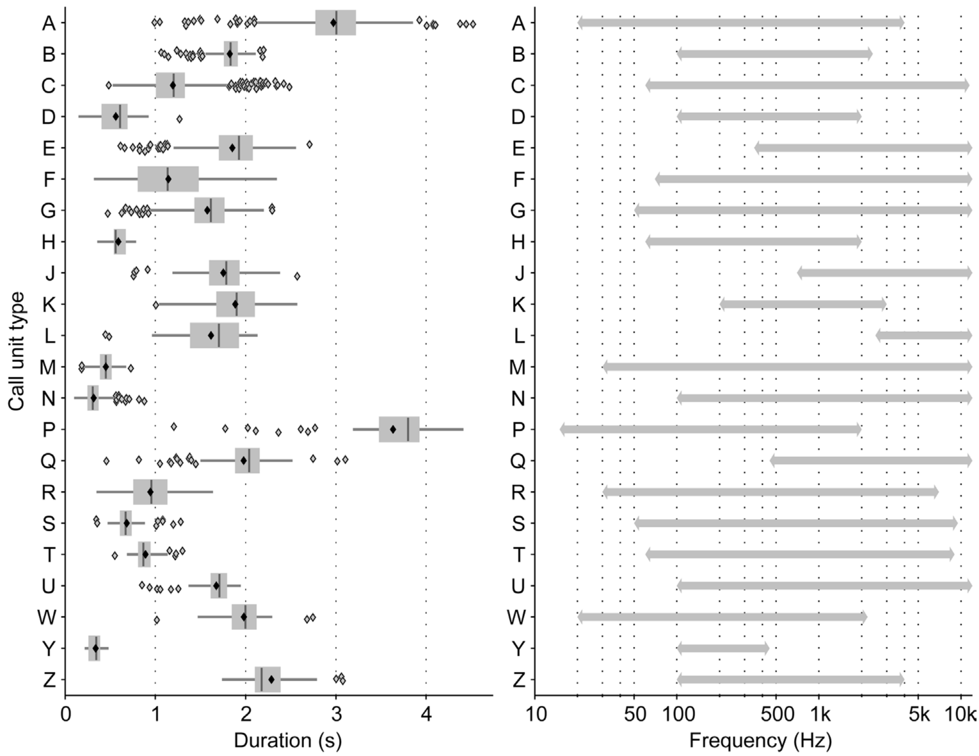

Figure 2. Box and whisker plots of durations (left panel) and frequency extents (right panel) of identified call unit types.

Notes: In the left panel, the left and right edges of the grey boxes represent the first and third quartiles (q_1 and q_3, respectively). The darker vertical lines and solid black diamond markers within the boxes represent the median and the mean durations, respectively. Data points outside of the range $[q_1 - (1.5 \times (q_3 - q_1), q_3 + 1.5 \times (q_3 - q_1)]$, called outliers, are indicated with hollow diamond markers. The whiskers (darker grey lines) emerging out of the boxes extend to the most extreme data points that are not considered as outliers. In the right panel, the upper frequencies (indicated by the right extents of the horizontal lines) encompass the highest harmonics observed for the respective unit type. The apparent capping (at 12,000 Hz) of upper frequency seen for many units is due to the limitation (Nyquist rate) of the recordings.

Composite and split units

Units composed of temporally separate constituent elements, or sub-units, are shown in Figure 4. Units R, S and M are composed of two types of sounds occurring in quick succession. They can be described, respectively, as grunt followed by a gently up-swept tonal, grunt followed by sharply down-swept tonal and grunt-whoop. In the case of units D and T, although there appears to be temporal discontinuities within each unit, the apparent sub-units were never observed independently or with other components or units. Hence, the respective parts were considered together as being constituents of single units. Both these units start with a whoop (sharp up-swept tonal) and terminate with down-swept tonal components. The two units differ in the range of frequencies covered and the presence of harmonics in the latter components – unit T has harmonics while unit D does not.

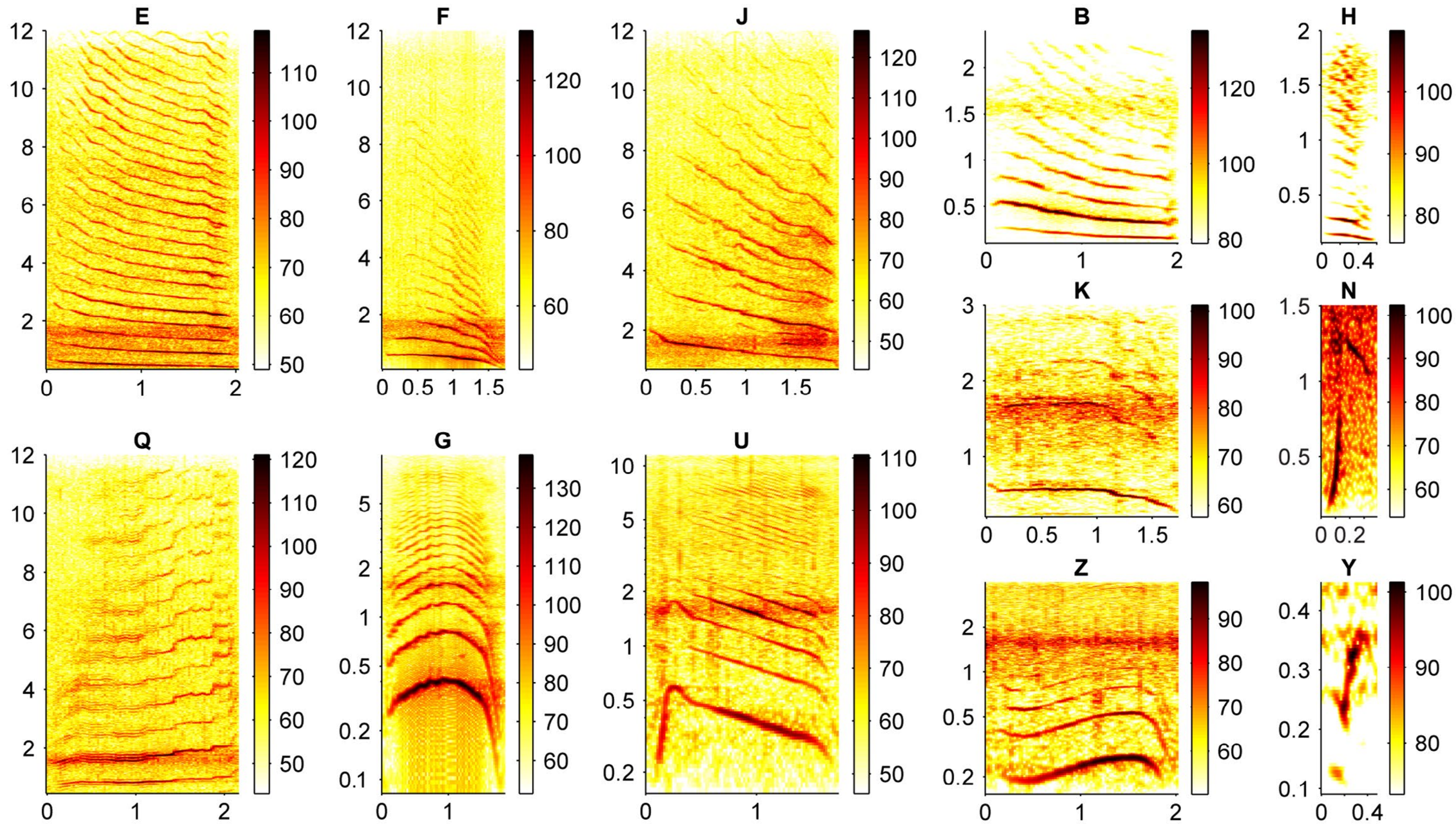

Figure 3. Spectrograms of some of the simple call units.

Note: In each panel in the figure (and in subsequent figures up to Figure 6), the horizontal and vertical axes are in units of time (s) and frequency (kHz), respectively, and spectral levels (colour mapping) are in units of dB re 1 $\mu Pa^2/Hz$.

Table 2. Phrases and themes of humpback whale vocalizations identified in the study.

Theme type	Unit sequence in the constituent phrase
I	B-C-C-C-D-E-A
II	(M-G-)*H-J-F
III	K-L-F
IV	P-Q
V	W-(R-)*U
VI	(S-)*U
VII	T*
VIII	(Y-Z-)*H-J-F
IX	M-N

Note: Asterisks (*) in the second column indicate that the preceding unit or unit-group (indicated with parentheses) occurs in bouts within the phrase.

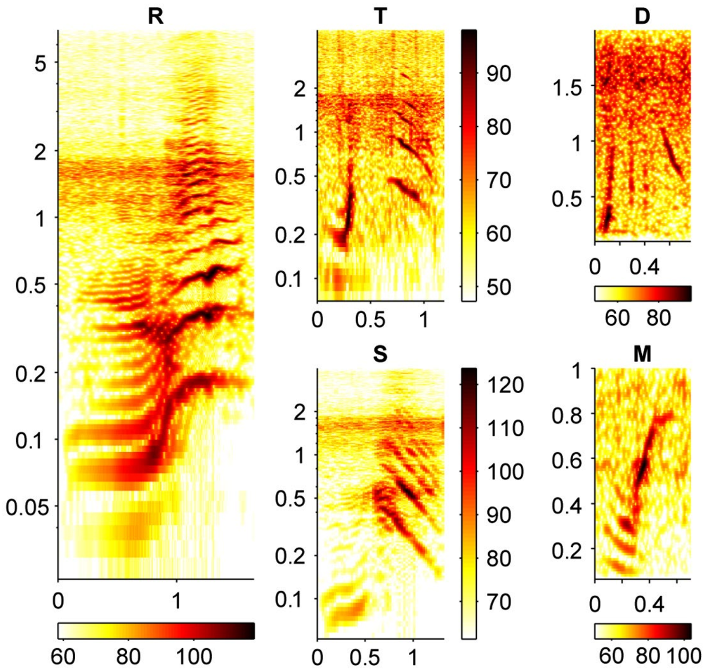

Figure 4. Spectrograms of composite units.

Complex units

Call units A, P and W were generally found to occur as broadband signals in spectrograms. However, presence of a low-frequency tonal component could be observed in these calls whenever there were drops in background noise levels at lower frequencies. The low-frequency tonal component in units A and P exhibit a gentle upsweep whereas in unit W its frequency profile was much flatter. Spectral peaks were found to occur in the range 25–45 Hz for type A, 21–31 Hz for type P and 32–42 Hz for type W. These are demonstrated in Figure 5. The bandpass filtered version of type P clearly shows the low-frequency component to be a pulsed (or AM) sound.

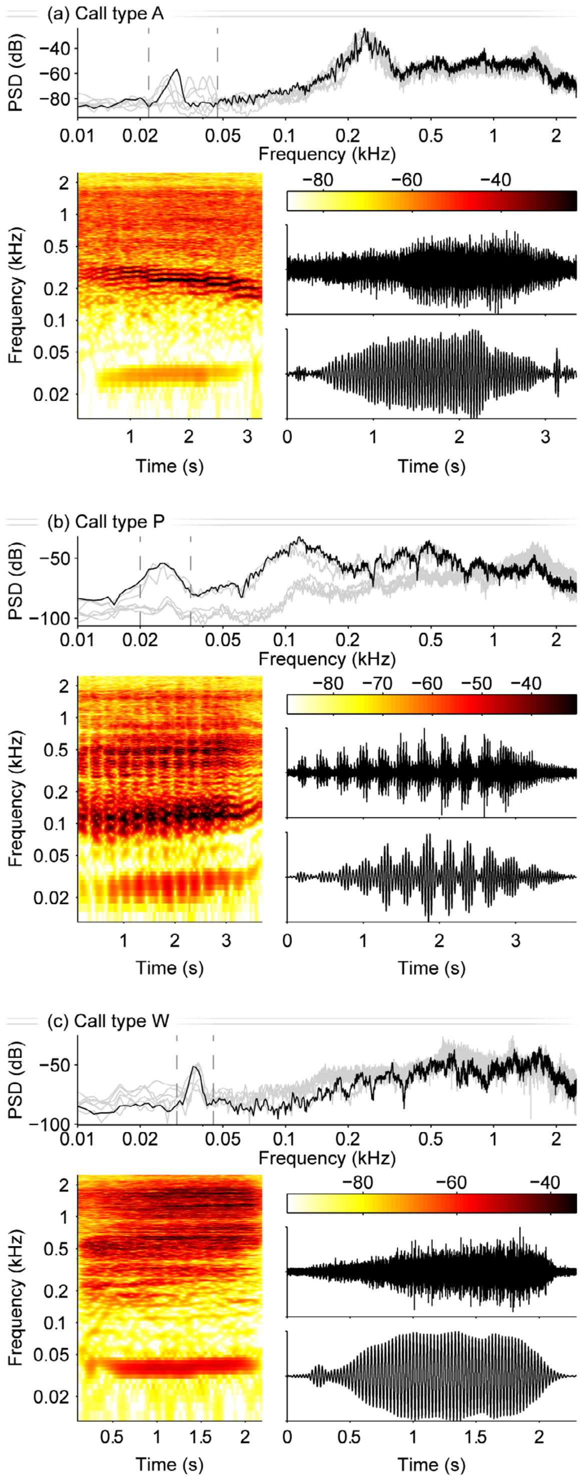

Figure 5. Analyses of call types (a) A, (b) P and (c) W.

Notes: Groupings of panels corresponding to each type include, counter-clockwise from top, normalized power spectral density estimates (PSD; computed using standard PWelch method) of a few clips of the respective unit, normalized spectrogram (200 ms Hamming window, 95% overlap), bandpass-filtered (12th order Butterworth filter) and normalized waveform, normalized waveform of the original clip and the range of spectral levels in the spectrogram. PSD of the audio clip considered for producing the spectrogram and the waveforms is shown with black line and the other clips are shown with grey lines. The respective filters' passband extents are indicated with grey dashed vertical lines in the PSD plots.

Units with variations

Units A and C were found to have 1 and 2 types of variants, respectively. Unit L, which is a high-frequency call, was found to be a highly variant type. With all three unit types, the variants were associated with the respective primary types based on their occurrences at same positions within the respective phrase types. Figure 6 shows the observed variants of units A and C and demonstrates a few variants of unit L. Note that the apparent absence of higher overtones in variant L3 could possibly be due to lower SNR at the respective frequencies. Its inclusion here is for demonstrating the differences in the fundamental frequency component. In the case of unit C, variant C1 occurred predominantly. In the case of unit

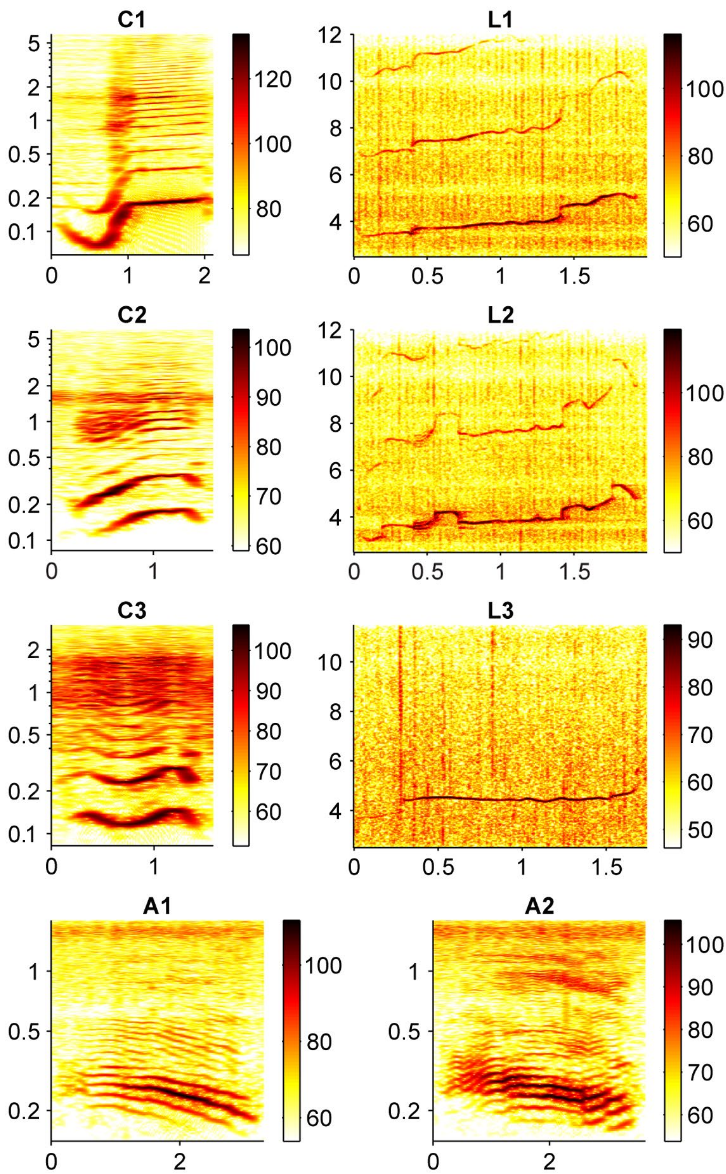

Figure 6. Observed variants of units A (A1–2) and C (C1–3), and samples of variants of unit L.

A, variant A1 occurred predominantly while variant A2 only occurred in the first of the phrase train in theme type I.

Phrase and theme analysis

Determination of true durations of phrases was difficult because (i) sometimes one or more units in phrases had low SNR and were themselves not identified, and (ii) often parts of phrases were outside the edges of the 1-min recording intervals. For assessing durations of the various phrase types, only phrases that had their first and last units intact were considered. For convenience, we shall refer to such phrases as complete phrases. The silence periods between successive pairs of phrases within themes were also determined by considering complete phrases. The results are listed in Table 3. Note that the notion of a complete phrase cannot be applied for theme type VII. Hence, the resulting measurements of phrase durations showed large variations. The larger variations in durations of phrases in theme types II, VI and VIII are attributed to the variations in the bout lengths of constituent units as mentioned earlier. As can be seen from column 6 of Table 3, while the silence durations between successive phrases of theme type III could not be ascertained due to lack of observations, the phrase constituting theme type VI was found to occur without repetitions.

Discussion

Overall, the frequencies of humpback vocalizations were seen to cover a wide range – from as low as 21 Hz with type P call units to as high as 12 kHz (the Nyquist rate of the recordings) with the harmonics of call units types E, J, G, etc. When the relative levels of noise in the recordings were moderate-to-low and call units could be easily detected and identified, the units were always seen to occur only as parts the corresponding phrases (listed in Table 2). Certain pairs (or small groups) of unit types shown in Figures 3 through 6 appear to have similar spectro-temporal characteristics. We initially considered the possibility that the propagation channel characteristics and changes in the vocalizing whale's orientation (relative to the recorder) may have caused alterations in the spectro-temporal

Table 3. Durations (in seconds) of the identified phrases and of the silence periods between successive phrases within each theme.

	Phrase				Intra-theme phrase transitions				
Theme type	Mean ± Std. dev.	Median	Min.	Max.	Count	Mean ± Std. dev.	Median	Min.	Max.
I	19.804 ± 0.700	19.994	17.247	21.040	127 (301)	1.155 ± 0.159	1.134	0.844	1.885
II	14.669 ± 3.110	15.054	6.894	23.550	62 (112)	1.877 ± 0.865	1.541	1.074	6.811
III	7.410 ± 0.268	7.421	6.519	7.923	0(11)	–	–	–	–
IV	5.943 ± 0.481	6.046	4.062	6.690	59(93)	1.849 ± 0.237	1.861	1.009	2.475
V	13.968 ± 1.090	13.666	12.062	15.834	19(47)	2.830 ± 0.493	2.668	2.386	4.477
VI	12.783 ± 4.164	14.604	2.238	15.548	0(0)	–	–	–	–
VII	6.980 ± 2.839	7.280	0.799	11.354	–	–	–	–	–
VIII	14.670 ± 1.596	13.698	13.222	17.106	6(8)	1.358 ± 0.166	1.290	1.197	1.592
IX	1.079 ± 0.105	1.078	0.797	1.420	300 (372)	1.128 ± 0.186	1.115	0.742	3.440

Notes: The temporal variabilities of silence periods between successive pairs of phrases were determined by considering only those pairs where both were complete phrases. The number of such instances encountered is shown in column 6, with the number within parenthesis indicating the total number of pairs observed.

characteristics of vocalizations such that a single type of unit at source could possibly be perceived as different units at the receiver. However, each of the identified units was seen to occur consistently at the same positions within the corresponding phrases and the phrases also exhibited consistency across multiple days. Hence, we can conclude that the final list (Table 1) of identified types is free from duplicates.

In view of developing an automatic song-unit classification system, composite units (R, S and M) and split units (T and D) deserve additional attention as it may be possible to identify their constituent sub-units independently. In a previous study, Pace et al. (2010) had shown that consideration of sub-units as the basic constituents of songs offered improved classification accuracy. In consideration of the repertoire studied here, recognition of song phrases and themes using automated methods may also see improved performance as five of the nine identified themes contain divisible units. Also, given the relatively short temporal separation between constituent sub-units of types T and D, they may serve as good test candidates in studies on understanding the processing of acoustic landmarks by non-human animals (Roch 2016).

Among the units identified, unit type B was observed to be the loudest type with its first harmonic being the most dominant. Instances of unit type B with received levels as high as 144 dB were observed. In determining range estimates, we assumed the mean source levels of humpback whale vocalizations to be 174 dB (Frankel 1994). By accounting for transmission losses resulting from theoretical spherical spreading alone, it can be seen that vocalizing humpback whales were within 1 km of the recorder. In view of the shallow depths at the recording site, consideration of cylindrical spreading losses may be a more appropriate choice. Accounting for transmission losses resulting from theoretical cylindrical spreading reduces the range estimate to around 30 m from the recorder, although it is highly unlikely that perfect cylindrical spreading occurs in a real marine environment. Note that attenuation due to absorption losses has been assumed to be negligible in these calculations and accounting for these additional losses would further lower the range estimates. With these considerations, it can be argued that at their closest approach to shore, vocalizing whales were well within 1 km from the recorder.

The sequence of units in each phrase type was seen to be consistent across all occurrences of the different phrase types, with the only variations observed being those intra-phrase ones resulting from the variations in units A, C and L. Also, over the entire recording period, the identified phrases were observed to occur independently and free from temporal overlap with other humpback vocalizations. While these observations may suggest the possibility that the recorded vocalizations may have been produced by a single singing individual, we shall refrain from making such speculations here due to lack of visual sampling.

Comparisons of songs recorded in different oceans could help uncover patterns of cultural transmission of songs between interacting populations. However, comparing vocalizations from our study with those from prior studies is difficult due to several reasons. First, the nature of spectrograms in the literature are not always conducive for making visual comparisons, given their quality and/or differences in the choice of spectrogram parameters (FFT length, overlap amount, bandwidth limits, etc.) employed. Often, two spectrograms may appear similar, but the underlying sounds could seem quite different when analysed aurally. Second, for several prior studies, representative acoustic samples are not available in the public domain and hence it is not possible to compare song units and phrases aurally. Given the short duty cycle of our recordings, it is also not possible to make theme- and song-level comparisons. Further, given the possibility of song 'revolution' (Noad et al. 2000; Rekdahl 2012), there is little scientific value in comparing song units and phrases of different populations from recordings made several years apart; and at the time of this writing, literature describing humpback whale vocalizations from more recent years were not available. Owing to these limitations, making exhaustive comparisons is not feasible and we present here a limited analysis highlighting similar vocalizations found in a few prior studies. Garland et al. (2013) found several similarities in humpback whale songs recorded over 2009–2010 at multiple locations along the eastern Australian migratory corridor and in the Antarctic feeding grounds. Units that occurred in bouts in theme K of the Antarctic area song (see Figure 2 in Garland et al. 2013) are very similar to unit N in our data-set. Among the different phrases/themes that they had found to occur commonly across their data-sets, a three-unit phrase that constituted theme M1 (see Figures 2 through 4 in Garland et al. 2013) bears a high degree of similarity with the unit sequence B-C-C (part of theme I) in our data-set. Detailed aural and visual comparative analyses showed that units B and C were of marginally longer duration and of slightly lower frequencies than their counterparts. In a different study, Stimpert et al. (2011) have described possible causes for the apparent differences (spectro-temporal) in the perception of same/similar sounds from different data-sets. If we assumed similar causes at play in our comparisons, phrase I from our study may be seen as an evolved version of phrase M1 from Garland et al. 2013. Salgado Kent et al. (2012) show representative vocalizations of the migratory west Australian humpback whale population. Units having some visual resemblance to M and/or N units from our study can be seen in spectrograms from both 2010 and 2011 (see Figure 4 in Salgado Kent et al. 2012). Spectrograms of recordings from 2010 (Figure 4(a) in Salgado Kent et al. 2012) contain units that appear very similar, both spectrally and temporally, to units G, H, S and U from our study. Interestingly, units from groups G-H and S-U (and their respective counterparts) occur together within respective phrases in both data-sets. Given the geographical proximity of the northern extents of the migration routes of the west Australian population to the southern extents of the Arabian Sea population's habitat, comparing songs recorded over same or similar periods could help learn about possible interactions between the two populations.

Formal collaborative studies in the Arabian Sea region are in their early stages. Cursory comparison of vocalizations from this study with those collected off Oman from the same year provides some indication of shared themes (2017 email exchanges between S Madhusudhana and researchers S Cerchio, AJ Willson and MS Willson studying humpback whales along the coast of Oman; unreferenced, personal communication); however, this requires further dedicated analysis. These preliminary findings concur with comparison of historical song samples between Hallaniyat Bay in Oman and Sri Lankan side of the Gulf of Mannar that were found to have 'virtually the same content' (Whitehead 1985). Understanding regional transmission of song patterns is considered as a gateway to evaluating the connectivity between humpback whales in the Arabian Sea, and considered a priority for conservation management measures (Minton et al. 2015). Further collaboration on evaluation of song structure between these data-sets is warranted.

Short duty cycles and limited duration of data collection imposed a variety of restrictions on the subsequent analysis phase of the study. Some of these restrictions have been made evident in this section. In future studies, increasing the duty cycle to cover entire songs (typically > 10 min) would not only enable assessment of theme transitions and song varieties but also enables making theme- and song-level comparisons with any interacting populations. Also, increasing the recording period to cover multiple years would not only allow for song evolutions to be studied but also facilitates learning of possible seasonal variabilities in calling behaviour.

Conclusion

In this study, vocal repertoire of singing humpback whales in the Eastern Arabian Sea has been catalogued in terms of song units, phrases and themes. Reconstruction of complete songs from the identified units and themes was not possible due to the short duty cycle of recordings. Though we have not directly established any association between the non-migratory Arabian Sea humpback whale population and the calls studied in this work, the detailed analyses of song units, phrases and themes presented here are expected to facilitate making comparisons readily with other studies that may establish such associations. We have presented as much information as possible from our analyses of the recordings and hope that it may support any ongoing and future studies of humpback whales in the region.

Acknowledgements

The authors are grateful to Kerri Seger for validating the analysis approach employed in the study, Anita Murray for offering guidance on making comparisons with prior studies, Dipani Sutaria for facilitating interactions with researchers studying whales along the coast of Oman and the anonymous reviewers for their valuable comments that helped improve the quality of the manuscript. We thank Dr T Ramprasad (Project Lead, Geoscape Project) and William Fernandez (Sr. Technical Officer) at the National Institute of Oceanography for assistance with the study.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Council of Scientific and Industrial Research (CSIR) [project number PSC 0107]; and ESSO – National Institute of Ocean Technology (Ministry of Earth Sciences, Government of India) [project number GAP 2938]. This is CSIR-NIOs publication number 6188.

ORCID

Shyam Kumar Madhusudhana http://orcid.org/0000-0002-4142-3881

References

Brown SG. 1957. Whales observed in the Indian Ocean. Notes on their distribution. Mar Obs. 27:157–165.

Cerchio S. 1993. Geographic variation and cultural evolution in songs of humpback whales (*Megaptera novaeangliae*) in the eastern North Pacific [dissertation]. San Jose (CA): San Jose State University.

Cerchio S, Jacobsen JK, Norris TF. 2001. Temporal and geographical variation in songs of humpback whales, *Megaptera novaeangliae*: synchronous change in Hawaiian and Mexican breeding assemblages. Anim Behav. 62(2):313–329.

Cholewiak D. 2008. Evaluating the role of song in the humpback whale (*Megaptera novaeangliae*) breeding system with respect to intra-sexual interactions [dissertation]. Ithaca (NY): Cornell University.

Cholewiak DM, Sousa-Lima RS, Cerchio S. 2013. Humpback whale song hierarchical structure: historical context and discussion of current classification issues. Mar Mammal Sci. 29(3):E312–E332.

Clapham PJ. 1996. The social and reproductive biology of humpback whales: an ecological perspective. Mamm Rev. 26(1):27–49.

Darling JD. 1983. Migrations, abundance and behavior of Hawaiian humpback whales, *Megaptera novaeangliae* [dissertation]. Santa Cruz: University of California.

Darling JD, Bérubé M. 2001. Interactions of singing humpback whales with other males. Mar Mammal Sci. 17(3):570–584.

Darling JD, Jones ME, Nicklin CP. 2006. Humpback whale songs: do they organize males during the breeding season? Behaviour. 143(9):1051–1101.

Darling JD, McSweeney DJ. 1985. Observations on the migrations of North Pacific humpback whales (*Megaptera novaeangliae*). Can J Zool. 63(2):308–314.

Dunlop RA, Noad MJ. 2016. The “risky” business of singing: tactical use of song during joining by male humpback whales. Behav Ecol Sociobiol. 70(12):2149–2160.

Eriksen N, Miller LA, Tougaard J, Helweg DA. 2005. Cultural change in the songs of humpback whales (*Megaptera novaeangliae*) from Tonga. Behaviour. 142(3):305–328.

Frankel AS. 1994. Acoustic and visual tracking reveals distribution, song variability and social roles of humpback whales in Hawaiian waters [dissertation]. Manoa: University of Hawaii.

Fristrup KM, Hatch LT, Clark CW. 2003. Variation in humpback whale (*Megaptera novaeangliae*) song length in relation to low-frequency sound broadcasts. J Acoust Soc Am. 113(6):3411–3424.

Frumhoff P. 1983. Aberrant songs of humpback whales (*Megaptera novaeangliae*): clues to the structure of humpback songs. In: Payne R, editor. Communication and Behavior of Whales. AAAS Selected Symposia Series 76. 1st ed. Boulder (CO): Westview Press. p. 3481–3411.

Garland EC, Gedamke J, Rekdahl ML, Noad MJ, Garrigue C, Gales N. 2013. Humpback whale song on the Southern Ocean feeding grounds: implications for cultural transmission. PLoS One. 8(11):e79422.

Garland EC, Goldizen AW, Rekdahl ML, Constantine R, Garrigue C, Hauser ND, Poole MM, Robbins J, Noad MJ. 2011. Dynamic horizontal cultural transmission of humpback whale song at the ocean basin scale. Curr Biol. 21(8):687–691.

Glockner DA, Venus S. 1983. Determining the sex of humpback whales (*Megaptera novaeangliae*) in their natural environment. In: Payne R, editor. Communication and Behavior of Whales. AAAS Selected Symposia Series 76. 1st ed. Boulder (CO): Westview Press. p. 447–464.

Helweg DA, Frankel AS, Mobley JR, Herman LM. 1992. Humpback whale song: our current understanding. In: Thomas JA, Kastelein RA, Supin AY, editors. Marine mammal sensory systems. Boston (MA): Springer. p. 459–483.

Helweg DA, Herman LM, Yamamoto S, Forestell PH. 1990. Comparison of songs of humpback whales (*Megaptera novaeangliae*) recorded in Japan, Hawaii, and Mexico during the winter of 1989. Sci Rep Cetacean Res. 1:1–20.

Salgado Kent CP, Gavrilov AN, Recalde-Salas A, Burton C, McCauley RD, Marley S. 2012. Passive acoustic monitoring of baleen whales in Geographe Bay, Western Australia. In: Proceedings of Acoustics 2012; Nov 21–23; Fremantle (WA): Australian Acoustical Society. p. 1–8.

Madhusudhana SK. 2015. Automatic detectors for underwater soundscape measurements [dissertation]. Perth (WA): Curtin University. Chapter 3, p. 43–79.

Mahanty MM, Latha G, Thirunavukkarasu A. 2015. Analysis of humpback whale sounds in shallow waters of the Southeastern Arabian Sea: An indication of breeding habitat. J Biosci. 40(2):407–417.

Mikhalev YA. 1997. Humpback whales *Megaptera novaeangliae* in the Arabian Sea. Mar Ecol Prog Ser. 149:13–21.

Minton G, Reeves R, Collins T, Willson A. 2015. Arabian sea humpback whale workshop: developing a collaborative research and conservation strategy. Dubai.

Noad MJ, Cato DH, Bryden MM, Jenner MN, Jenner KC. 2000. Cultural revolution in whale songs. Nature. 408(6812):537.

Pace F, Benard F, Glotin H, Adam O, White P. 2010. Subunit definition and analysis for humpback whale call classification. Appl Acoust. 71(11):1107–1112.

Payne RS. 1978. Behavior and vocalizations of humpback whales (*Megaptera sp.*). Report on a workshop on problems related to humpback whales, Washington (DC): U. S. Department of Commerce. p. 56–78.

Payne RS, McVay S. 1971. Songs of humpback whales. Science. 173(3997):585–597.

Payne K, Payne R. 1985. Large scale changes over 19 years in songs of humpback whales in Bermuda. Ethology. 68(2):89–114.

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: Payne R, editor. Communication and Behavior of Whales. AAAS Selected Symposia Series 76, 1st ed. Boulder (CO): Westview Press. p. 9–58.

Rekdahl M. 2012. Humpback whale vocal communication: use and stability of social calls and revolutions in the songs of east Australian whales [dissertation]. Brisbane: The University of Queensland.

Roch M. 2016. Neural-inspired segmentation of audio streams into phone-like units. J Acoust Soc Am. 140(4):3240–3240.

Rosenbaum HC, Kershaw F, Mendez M, Pomilla C, Leslie MS, Findlay KP, Best PB, Collins T, Vely M, Engel MH, et al. 2017. First circumglobal assessment of Southern Hemisphere humpback whale mitochondrial genetic variation and implications for management. Endanger Species Res. 32:551–567.

Slijper EJ, Van Utrecht WL, 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.

Smith JN, Goldizen AW, Dunlop RA, Noad MJ. 2008. Songs of male humpback whales, *Megaptera novaeangliae*, are involved in intersexual interactions. Animal Behav. 76(2):467–477.

Stimpert AK, Au WW, Parks SE, Hurst T, Wiley DN. Common humpback whale (*Megaptera novaeangliae*) sound types for passive acoustic monitoring. 2011. J Acoust Soc Am. 129(1): 476–482.

Thompson K. 1968. Programming techniques: Regular expression search algorithm. Commun ACM. 11(6):419–422.

Thompson PO, Cummings WC, Kennison SJ. 1977. Sound production of humpback whales, *Megaptera novaeangliae*, in Alaskan waters. J Acoust Soc Am. 62(S1):S89–S89.

Tyack P. 1981. Interactions between singing Hawaiian humpback whales and conspecifics nearby. Behav Ecol Sociobiol. 8(2):105–116.

Whitehead H. 1985. Humpback whale songs from the North Indian Ocean. Invest Cetacea. 17:157–162.

Winn HE, Winn LK. 1978. The song of the humpback whale *Megaptera novaeangliae* in the West Indies. Mar Biol. 47(2):97–114.