Analysis of humpback whale sounds in shallow waters of the Southeastern Arabian Sea: An indication of breeding habitat

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The primary objective of this work was to present the acoustical identification of humpback whales, detected by using an autonomous ambient noise measurement system, deployed in the shallow waters of the Southeastern Arabian Sea (SEAS) during the period January to May 2011. Seven types of sounds were detected. These were characteristically upsweeps and downsweeps along with harmonics. Sounds produced repeatedly in a specific pattern were referred to as phrases (PQRS and ABC). Repeated phrases in a particular pattern were referred to as themes, and from the spectrographic analysis, two themes (I and II) were identified. The variation in the acoustic characteristics such as fundamental frequency, range, duration of the sound unit, and the structure of the phrases and themes are discussed. Sound units were recorded from mid-January to mid-March, with a peak in February, when the mean SST is ~28°C, and no presence was recorded after mid-March. The temporal and thematic structures strongly determine the functions of the humpback whale song form. Given the use of song in the SEAS, this area is possibly used as an active breeding habitat by humpback whales during the winter season.

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1. Introduction

Details of the ecology of humpback whale (*Megaptera novaeangliae*) populations in the Southeastern Arabian Sea (SEAS) have been sparse, due to the lack of continuous acoustic observations and the scattered nature of historical sighting reports (Mikhalev 1997). Extensive sighting surveys of cetaceans have been conducted onboard the FORV (Fisheries and Oceanographic Research Vessel) ship *Sagar Sampada* in the Indian Exclusive Economic Zone (EEZ) and contiguous seas. The survey areas included the coastal and oceanic waters of the Indian EEZ and the Sri Lankan Sea, extending between 5°and 23°N latitude, and 66°and 95°E longitude with a depth range of 20–5000 m, during the period October 2003 to November 2011 (Vivekanandan and Jeyabaskaran 2012). When compared with a number of sighting surveys, the SEAS showed the highest species diversity followed by the southern Sri Lankan Sea (Afsal *et al*. 2008). Stranding and sighting records showed that 25 species of cetacean habitat exist in the Indian seas (Kumaran 2002). Many sighting surveys (Mathew 1948; Muthiah *et al*. 1988; Papastavrou 1991; Baby 2009) provided valuable information on the humpback whales, particularly in the Arabian Sea, Bay of Bengal and Sri Lankan waters.

Humpback whales (*Megaptera novaeangliae*) migrate from high latitude areas used for summer feeding (‘feeding areas’) (Payne and McVay 1971; Winn and Winn 1978; Tyack 1981; Darling 1983; Silber 1986) to low latitude areas used for breeding (‘wintering areas’), where mating and calving take place (Thompson *et al*. 1977; Jurasz and Jurasz 1979). Brown (1957) reported that the Arabian Sea humpback whales migrate from Antarctic feeding grounds, while Slijper *et al*. (1964) suggest that they come from the

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North Pacific to the Gulf of Aden near Oman, in the Persian Gulf and off Ceylon. A total of 24 winter breeding areas were determined by Rasmussen (2006), all within 30 degrees of the equator, worldwide. Among these areas, one known humpback whale habitat is the Arabian Sea in the Northern Indian Ocean (Reeves *et al*. 1991; Mikhalev 1997). The SEAS is characterized by certain oceanographic features that appear typical of other humpback whale breeding areas such as shallow waters, preferably with banks less than 60 m (Whitehead and Moore 1982) near island groups or inshore waters near the mainland (Dawbin 1966; Clapham and Mead 1999). They exhibit behaviours associated with reproduction, such as males attracting sexually mature females (Tyack and Whitehead 1983; Darling and Berube 2001; Darling *et al.* 2006; Cholewiak 2008) by using typical underwater stereotyped sounds (Scheidat *et al*. 2000).

Payne and McVay (1971) described the humpback whale song as a hierarchical pattern of units, phrases, themes and songs. The shortest sound is called a unit. A set of units is combined to form a phrase. Repeated phrases constitute a theme. Themes are grouped into song. Song units include both harmonic and broadband elements with a frequency range 30–10000 Hz (Payne *et al*. 1983; Silber 1986; Cerchio *et al*. 2001), and occasional high frequency harmonics extend beyond 24000 Hz (Au *et al.* 2006). Sounds produced by humpback whales are usually 60 to 8000 Hz (Levenson 1969, 1972; Norris 1995) with peak frequencies around 315 to 630 Hz (Au *et al*. 2000). Units are 0.1 to 4.45 s long, and are separated by silent intervals of 0.1 to 6 s (Payne *et al.* 1983; Cato 1991; Mednis 1991; Cerchio *et al.* 2001; Au *et al*. 2004, 2006). Typical durations of phrases range between 5 and 30 s (Payne and McVay 1971; Thompson 1981; Frumhoff 1983; Payne *et al*. 1983). The high intensity, with repetitive low frequency signals of humpback whale songs, are detectable at distances of 9–32 km or more using a hydrophone (Winn *et al.* 1975; Levenson and Leapley 1978; Winn and Winn 1978).

Frankel (1994) collected data from an array of hydrophones and estimated the source level of the singing humpback whales to be about 140 to 170 dB re 1 μPa, where most of the whales were 2 to 8 km away. In different functions of the sound type, the source levels varied ranging from 155–189 dB re 1 μPa (Winn *et al.* 1970; Friedl and Thompson 1981; Cato 1991; Abileah *et al.* 1996; Au *et al*. 2001a). At any given time all males within a region sang very similar songs (Payne 1978; Winn and Winn 1978); however, units, phrases and the thematic structure of the songs changed progressively through different breeding seasons (Payne 1978; Winn and Winn 1978; Winn *et al*. 1981; Guinee *et al*. 1983; Payne *et al*. 1983; Payne and Payne 1985). Whitehead (1985) recorded male humpback whale songs off Oman in January, which exhibited a well-defined breeding display, and differed from those recorded in the North Pacific and North Atlantic (Clapham 1996). During the mating season, humpback whale sounds lasted from early January to late May with a peak in early March, preceded by calving in December with a peak in February (Chittleborough 1958; Au *et al.* 2000). Watkins *et al.* (2000) reported seasonal callings coinciding with the possible reproductive season, with more calls between December and February.

The purpose of this study was to analyse the humpback whale sounds recorded by using passive acoustic measurement in the shallow waters of the SEAS, which provides an indication of their breeding habitat.

2. Methods

2.1 *Vertical hydrophone mooring*

An autonomous subsurface noise measurement system was developed for time series measurements in shallow waters, and deployed in the SEAS from January 2011 to May 2011 (figure 1). The subsurface system comprised of a vertical linear array (VLA) of 12 omnidirectional hydrophones (Keltron Electro Ceramic) with associated data acquisition modules (PCI based data acquisition card) and battery back in an enclosure, along with subsea floats and a surface marker buoy in the mooring line. The sensors were calibrated against a standard sensor at the underwater Acoustic Test Facility of NIOT, which is the only NABL accredited laboratory in India. The system is deployed at an ocean depth of around 30 m and VLA positioned at the mid water column, so that the noise due to the surface and bottom reflections could be measured effectively. The first element of the VLA has been taken for analysis. The omnidirectional hydrophones are capable of measuring in the frequency range 50–10000 Hz, with the sampling rate of 50000 Hz per channel simultaneously, for a sampling duration of 30s, once in every 3 h. The voltage reading from the hydrophone was converted to units of micropascal (μPa) by applying the preamplifier gain and receiving sensitivity (−170dB) of the hydrophone.

2.2 *Acoustic parameter and spectrographic analysis*

A Dutterworth high-pass filter with 20 Hz cut-off was applied to every time series data set in order to eliminate low frequency background noise falling below the minimum reported frequency for humpback whale sound units (Payne and Payne 1985; Mednis 1991; Au *et al.* 2006). Spectrograms, oscillograms and Welch's averaged periodiogram power spectral density (dB re 1 $\mu Pa^2 Hz^{-1}$ spectrum level) function are calculated using MATLAB (version 7.11), with 2048 point fast Fourier transforms (FFTs), Hamming window, 24.4 Hz frequency resolution and 50% overlap. Visual inspection of the spectrogram confirmed the fundamental frequency (f_0) of the signal. Basic acoustic parameters were calculated

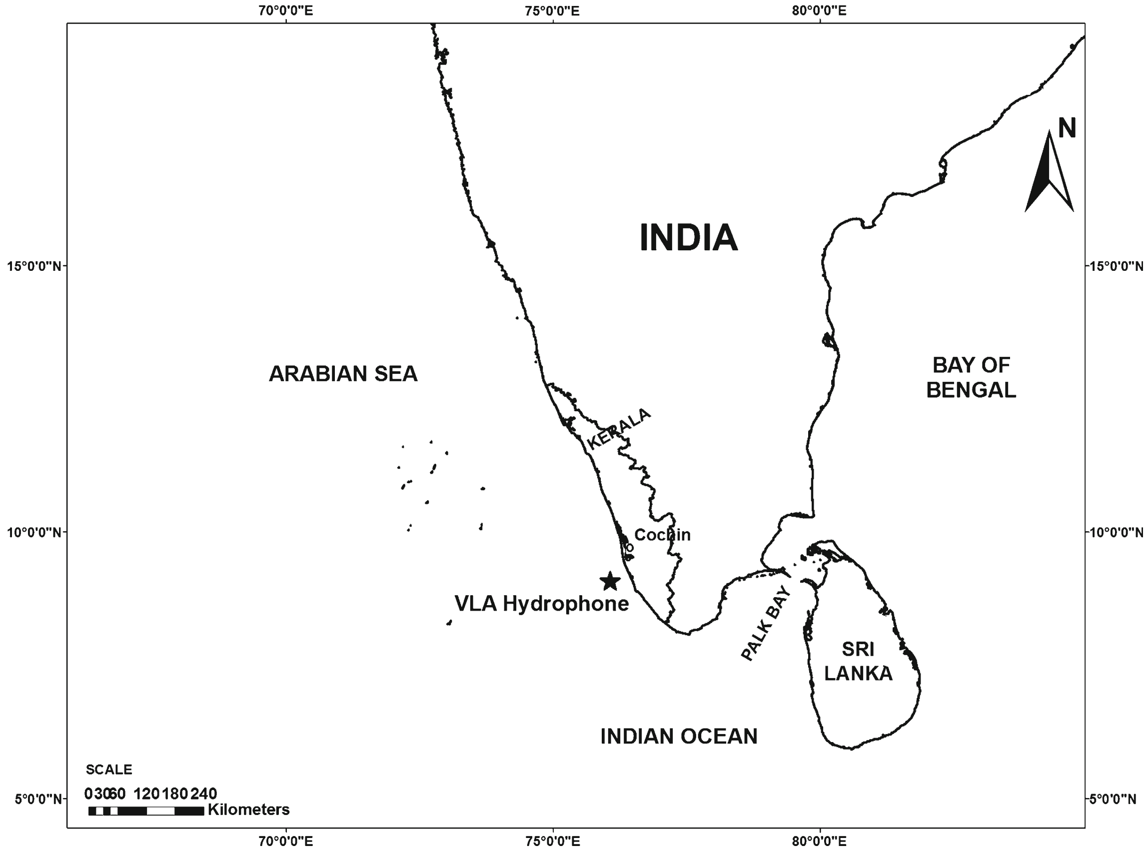

Figure 1. Geographic location of VLA moored in shallow waters of SEAS. VLA Hydrophone is depicted as ★.

using codes in MATLAB from each sound unit: duration, minimum f_0 (minf_0), maximum f_0 (maxf_0), starting f_0 (startf_0), ending f_0 (endf_0) and f_0 trend (trendf_0). In the case of startf_0 and endf_0 of the signal, the first and last 10% of the resulting signal was considered for contour signal overall. The f_0 trend was calculated as the ratio between startf_0 and endf_0. These have been the standard variables to characterize the sound units of humpback whales (Girola 2011; Stimpert *et al.* 2011).

2.3 *Whale sound detection*

The acoustic characteristics derived from the data recorded by the hydrophone have enabled the identification of the humpback whale sound pattern. The basic entity of each sound was assigned as a unit type. Different unit types were distinguished from one another by the contours in the spectrogram. A sequence of different unit types comprised a phrase. Several distinct phrase types were usually found in a whale's repertoire, each characterizing a different theme. As reported by Payne and McVay (1971), important sources of information include the frequency components; temporal characteristics such as time between sound units and adjacent phrases by longer silent duration, the overall duration of phrases, and phrase repetition within themes.

Seven different sound unit types were identified, based on the spectrographic analysis and coded with the alphabets P, Q, R, S, A, B and C, to describe the phrase and theme types. Two theme types were identified, Theme-I and Theme-II. Repetition of similar phrases 'PQRS' constitute Theme-I (PQRSPQRS), whereas similar phrases 'ABC' constitute Theme-II (ABCABC).

2.4 *Background noise data analysis*

Records were excluded from the analysis if vessels were audible in the background noise. Wind-dependent noise was always present in the recorded sample when there was no visually tracked vessel in the area. The sound units produced by humpback whales were more clearly distinguished than the background noise. The recorded background noise samples were extracted before and after the humpback whale call, i.e. silent periods, by applying Welch's averaged periodogram power spectral density method for each sample to calculate the mean noise spectrum level (dB re 1 $\mu Pa^2 Hz^{-1}$).

2.5 *Sea surface temperature in the SEAS*

The daily average sea surface temperatures (SST) for the study period in the shallow waters of the SEAS (VLA location) were extracted from satellite-based AVHRR on NOAA from INCOIS Live Access Server (*http://las.incois.gov.in*).

3. Results

In this study, a total of 1208 data sets were recorded in the period January to May 2011. Among these, only 10 data sets resembled the humpback whales' sound. Four sets of Theme-I and 6 sets of Theme-II have been identified. Theme-I consisted of sound units PQRSPQRS and Theme-II consisted of ABCABC. A total of 74 sound units were found to have occurred covering the above types, on the analysis of 10 data sets.

Themes were associated with individual sound units grouped into the phrase type. The phrases for Theme-I and Theme-II were PQRS and ABC, whose spectrograms and spectral levels are shown in figures 2 and 3, respectively. Theme-I constituted repeated sequence of similar phrases 'PQRSPQRS' (figure 4), whereas Theme-II constituted 'ABCABC' (figure 5). Themes-I and -II were static themes; their phrase structure remained consistent with each consecutive repetition. Table 1 shows the temporal variability of the humpback whale sounds in the SEAS. Units were separated by intervals of silence of 0.5–1.55s and 2.35–2.55s within the phrase for Theme-I and Theme-II respectively; similarly, adjacent phrases were separated by longer silent duration of 2.01 s for Theme-I and 4.18 s for Theme-II. The average phrase and theme durations were 10.01 s and 22.52 s for Theme-I, whereas they were 9.68 s and 24.87 s for Theme-II. The average repetition of the phrase was 2 within the themes. The summary statistics for all parameters of f_0, and the frequency range of each sound unit are listed in table 2. The sound units produced by humpback whales were more clearly distinguished as the levels that were higher by 25dB than the background noise (figure 2).

In phrase PQRS, unit P is an upsweep harmonic groan sound, with a mean f_0 starting at 269.63±4.46 and ending at 370.12±5.76 Hz (n=9, range=227–2260 Hz) over 1.87 s

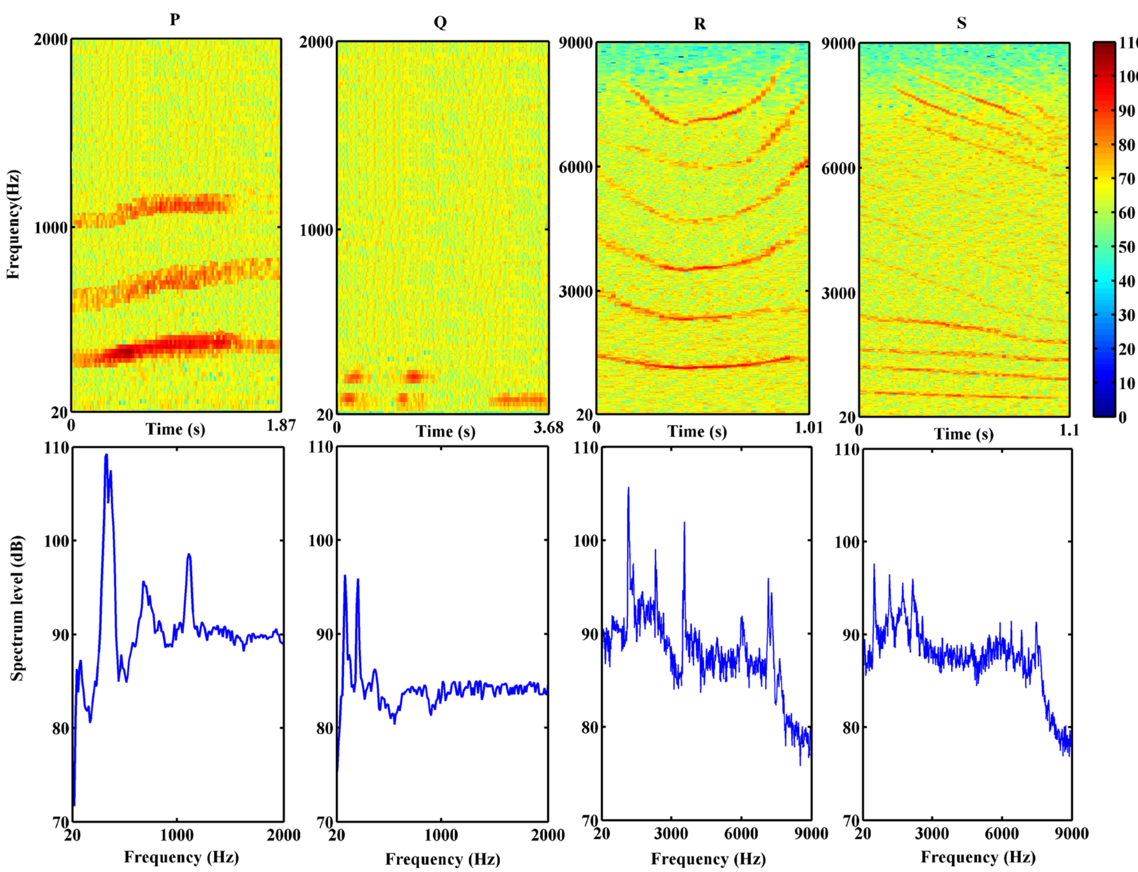

Figure 2. Spectrogram and spectrum of sound units (P, Q, R, S) produced by humpback whale basic phrase in the SEAS. Alphabets denote coded unit types.

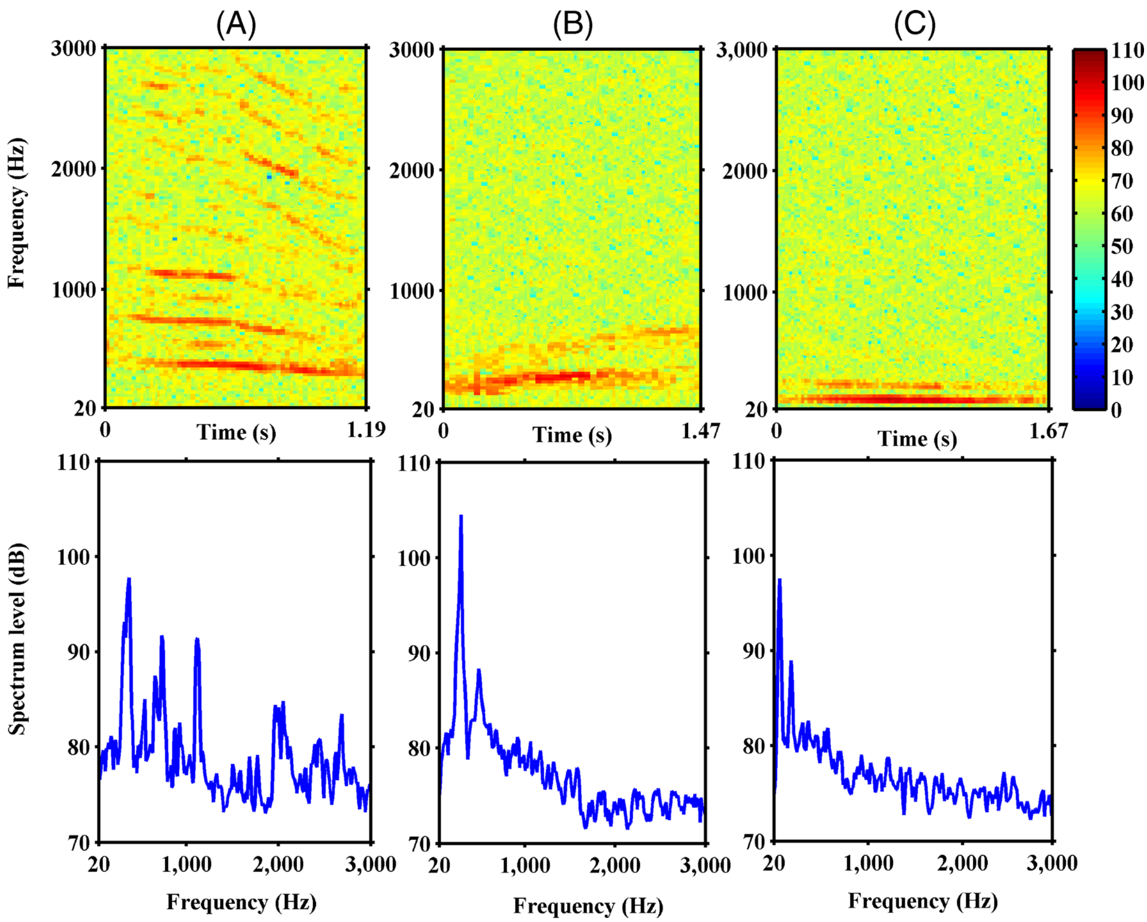

Figure 3. Spectrogram and spectrum of sound units (A, B, C) produced by humpback whale basic phrase in the SEAS. Alphabets denote coded unit types.

(table 2) followed by Q, a series of repeated gulp jumping sounds. This unit Q is a low frequency downsweep, beginning at 114.15±3.59 and ending at 100.24±2.85 Hz, and lasting about 3.68 s on average (n=8, range=96–128 Hz). Units R and S are swept upward and downward tonal sounds respectively, with strong high frequency harmonics. Sound R is a short (1.01s) unit type, swept up, starting at 1180.24 ±9.77 and ending at 1308.43±6.94 Hz (n=10, range=1095–8810 Hz), followed by S, swept down from 575.21±7.36 to 437.42±7.44 Hz (n=11) over 1.10s with a frequency range of 390–8570 Hz.

In phrase ABC, unit A, is the strongest harmonic downsweep, starting at 375.74±5.83 and ending at 265.70±4.89 Hz (n=12, range=207–2954 Hz) during 1.19 s call duration followed by B and C. The B type sound is an upsweep, which is swept up from 235.08±3.45 to 317.26±2.43 Hz (n=12, range=195–781 Hz) over 1.47s, whereas unit C, is a low frequency downsweep starting at 142.21±3.34 and ending at 112.23±3.09 Hz (n=12, range=98–270 Hz) lasting about 1.67 s. The f_0 trend decreases due to the contemporary increase in ‘startf_0’ and decreasing of ‘endf_0’. At the same time ‘Minf_0’ decreases and ‘Maxf_0’ increases for each sound unit type (table 2). Upsweep calls produced a more spectral level compared to the downsweep calls (figures 2 and 3).

Whale signatures of high intensities (lower frequencies) are likely to be detected at longer ranges than low intensity sounds. Humpback whales produce songs at frequencies of 300–10000Hz with the estimated mean source level of up to 174 dB at 1 m (Frankel 1994 in Au *et al.* 2001b). In order to estimate the range at which humpback whales produce sound, a transmission loss model KRAKEN (Porter 1992) based on the normal mode theory was implemented for the site in order to obtain the loss in level as the sound propagated over a range of 50 km. Estimates such as the received level, source level and transmission loss for specific harmonics give an idea about the range of humpback whales. Considering the received noise levels,

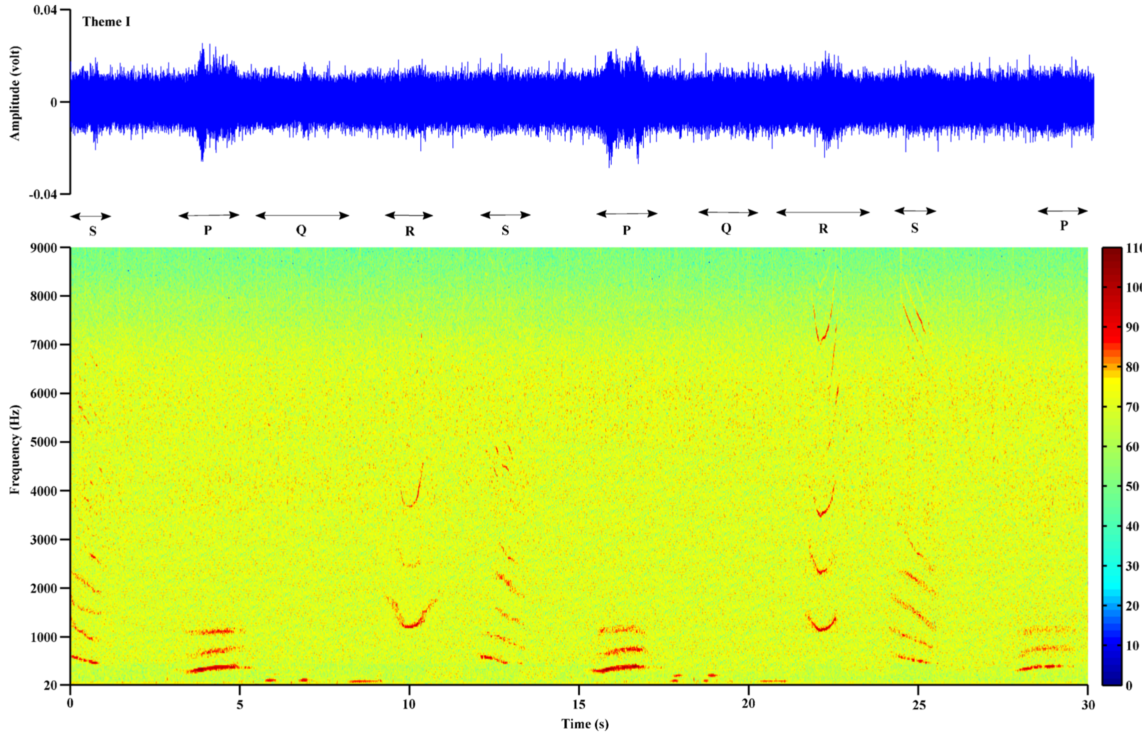

Figure 4. Waveforms and spectrograms of the humpback whale Theme-I in the SEAS.

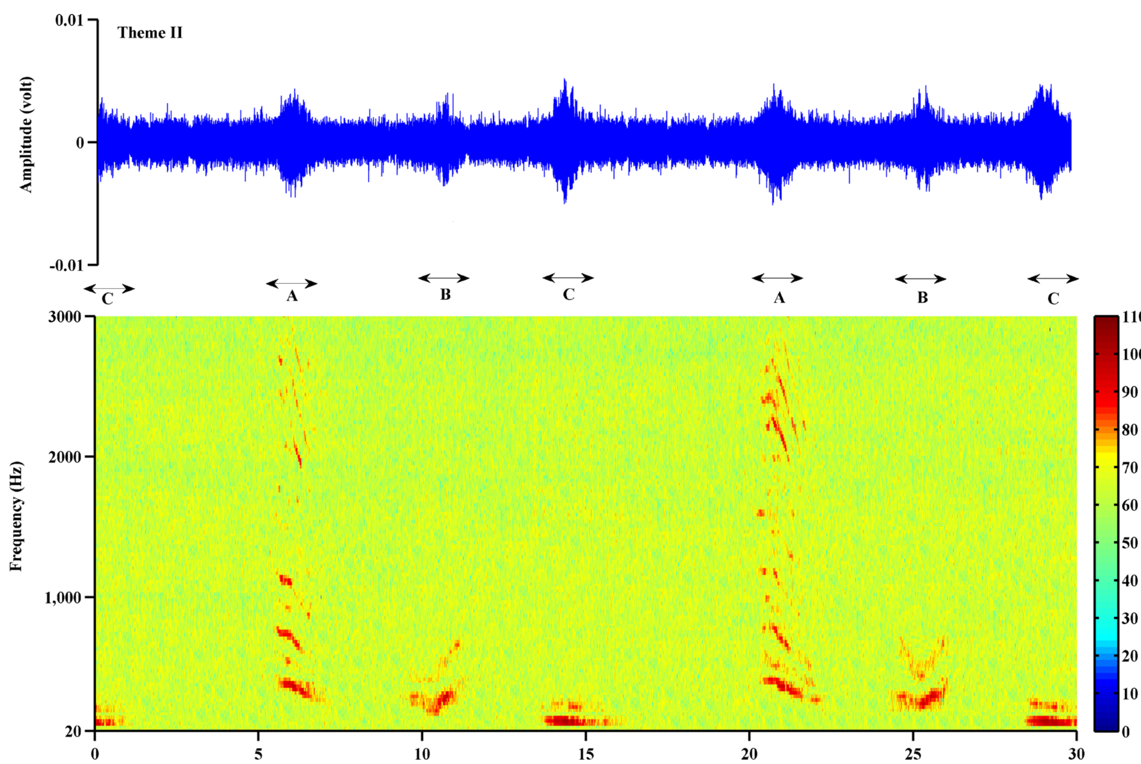

Figure 5. Waveforms and spectrograms of the humpback whale Theme-II in the SEAS.

Table 1. The temporal variability of the humpback whale sounds recorded in shallow waters of the SEAS

Theme number	Units	Phrases			Theme
	Intervals of silence (s)	Average duration (s)	Average repetition	Silence duration (s)	Average duration (s)
Theme-I	0.5–1.55	10.01	2	2.01	22.52
Theme-II	2.35–2.55	9.68	2	4.18	24.87

the themes PQRS and ABC are expected to originate at a range of 25–35 km.

The detection range of the hydrophone array in the frequency range (370–7200 Hz), considering source level of 174 dB, ambient noise level (80–94 dB in the considered band) and transmission loss (output from KRAKEN model), is a maximum of 50 km.

4. Discussion and conclusion

Humpback whales have been extensively studied in several areas (Winn and Reichley 1985; Clapham 1996), but relatively little is known about their distribution and breeding activity in the Arabian Sea. The distribution of humpback whales in the Arabian Sea is known from whaling records (Wray and Martin 1983; Mikhalev 1997), as well as observations from merchant vessels and winter surveys off the coast of Oman. Sighting and survey records have suggested that humpback whales are mostly concentrated in the shallow nearshore areas of the coast, particularly in the Gulf of Masirah and Kuria Muria Bay regions (Minton 2004), while sighting and stranding have suggested a population range including the Balochistan coast of Pakistan, Iran, Iraq (Al Robaae 1974; Braulik *et al.* 2010), Yemen, Northern Gulf of Aden, western India and Sri Lanka (Brown 1957; Mikhalev 2000; Minton *et al*. 2008; Reeves *et al*. 1991; Slijper *et al.* 1964; Yukhov 1969). Whitehead (1985) recorded humpback whale songs off the coast of Oman, which indicate that this population coincided with the Northern Hemisphere breeding cycle, with calving taking place between January and May (Mikhalev 2000; Minton *et al*. 2008), and peaking in early March. Reeves *et al*. (1991) described the records of humpback whales in the Arabian Sea, and claimed that sightings in this area were frequent during spring, summer and winter. Ross (1981) reported the presence of humpback whales in September and October, off Oman's Masirah Island. During February and March, singing was detected in the Dhofar region, suggesting breeding activity (Minton *et al.* in press). Mikhaliev (1995) presented detailed biological and other information regarding 242 humpback whales illegally caught by Soviet whaling operations between 1965 and 1966. From the examination of embryos and the discovery of lactating females he concluded that the breeding season coincided with that of the Northern Hemisphere humpbacks.

Table 2. Summary of acoustic parameters measured for each sound unit recorded in the SEAS

Unit type	P Upsweep Groan	Q Low gulps jumping	R Tonal upsweep	S Tonal downsweep	A Downsweep	B Upsweep	C Downsweep
Duration (s)	(n=9) **1.87** 0.03	(n=8) **3.68** 0.09	(n=10) **1.01** 0.04	(n=11) **1.10** 0.06	(n=12) **1.19** 0.02	(n=12) **1.47** 0.07	(n=12) **1.67** 0.05
Frequency range (Hz)	227–1160	96–128	1095–8810	390–8570	208–2954	195–781	98–270
Max f_0 (Hz)	**416.12** 2.66	**128.48** 2.87	**1404.45** 5.82	**698.76** 6.19	**463.87** 4.25	**341.38** 2.71	**158.90** 3.51
Min f_0 (Hz)	**227.35** 2.23	**95.84** 1.81	**1095.47** 3.63	**390.43** 2.19	**207.90** 2.96	**195.28** 3.45	**98.07** 2.04
Start f_0 Hz)	**269.63** 4.46	**114.15** 3.59	**1180.24** 9.77	**575.21** 7.36	**375.74** 5.83	**235.08** 3.45	**142.21** 3.34
End f_0 (Hz)	**370.12** 5.76	**100.24** 2.85	**1308.43** 6.94	**437.42** 7.44	**265.70** 4.89	**317.26** 2.43	**112.23** 3.09
Trend f_0 (ratio)	**1.37** 0.02	**0.87** 0.02	**1.10** 0.01	**0.76** 0.01	**0.70** 0.02	**1.34** 0.02	**0.79** 0.03

Mean parameters are in bold, standard deviations (SD) are listed for each variable. f_0=fundamental frequency (Hz), n=number of sound unit of particular type. Frequency range defines the minimum and maximum energy values of the sound.

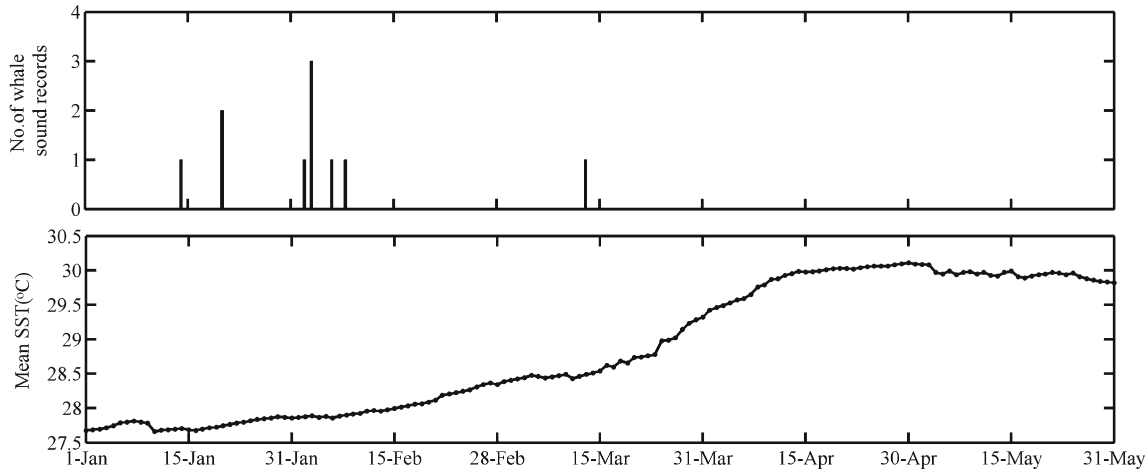

Figure 6. Humpback whale sounds recorded and mean SST during the study period.

The aforementioned comparison provides strong evidence of the breeding activity of the humpback whales in the Arabian Sea. The recent International Union for Conservation of Nature (IUCN) Red List designates the Arabian Sea population of humpback whales as 'endangered'. It also provides further indication that this population is well known to be vulnerable to entanglement in fishing gear (Volgenau *et al.* 1995; Johnson *et al.* 2005) and gillnets (Salm *et al.* 1993; Papastavrou 1995), and requires continued research and conservation efforts, in order to assess the possible threats more accurately.

Passive acoustic monitoring has been suggested as an effective and low cost technique for the conservation of marine mammals, to identify their existence over longer time scales rather than the earlier methods with traditional sighting surveys (Mellinger *et al*. 2007; Baumgartner and Mussolini 2011). Specific acoustic monitoring programs have been discussed earlier for several cetacean species. Studies included the presence of sperm whales in the Gulf of Alaska during the winter, when boat based surveys cannot be conducted (Mellinger *et al.* 2004), to study the night foraging behaviour of beaked whales (Johnston *et al*. 2008), and extended breeding period of humpback whales on their feeding grounds (Clark and Clapham, 2004). The present study verified the efficiency of long term passive acoustic measurement to remotely detect and characterize the analysis of humpback whale sounds in the SEAS. Findings from this work confirmed that the passive acoustic technique could be used to noninvasively identify the humpback whales' breeding habitat.

The variability in the songs of humpback whales is of great interest to bioacousticians. The recordings of humpback whale songs off Oman in January 1982, and the Gulf of Mannar, Sri Lanka, during February and March 1982 (Whitehead, 1985) are similar to one another, but different from those of the North Atlantic and North Pacific Ocean. Songs from the West Indies and Cape Verde Islands, on both sides of the Atlantic, are similar, but different from the songs off Hawaii and Mexico (Payne and Guinee 1983; Winn *et al*. 1981), which are themselves similar to each other. In all oceans, certain rules govern the dynamics of the song, as described by Payne and McVay (1971). The humpback whales change their song at the breeding ground in response to the environmental conditions, such as ambient sounds, eddies, temperature or salinity differences (Parsons *et al*. 2008).

Time series passive acoustic measurements were made in the SEAS, and the recording of the humpback whale sounds in this region is indeed the first of its kind. The results represent the detailed characteristics of different sound units produced by humpback whales in the SEAS and they agree with those of Payne *et al*. (1983), who illustrated similar repeated sound units constituting a phrase, and phrases grouped into themes. The maximum number of sounds produced by humpback whales was recorded during mid-January to mid-March, with a peak in February (figure 6), where the mean SST was ~28°C. The temperatures in this study area are within the range reported in other areas (24–28°C; Dawbin 1966; Herman and Antinoja 1977; Whitehead and Moore 1982). The absence of sound records after mid–March can be explained by the increase of SST in the SEAS.

The findings suggest that the SEAS is a breeding ground used by humpback whales, which produce repeated patterns of individual sound units within themes during winter. These characteristics relate to the functions of the humpback whale songs. Further research is required from different breeding areas within an ocean basin in order to understand the song of humpback whales.

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References

Abileah R, Martin D, Lewis S D and Gisiner B 1996 Long-range acoustic detection and tracking of the Hawaii-Alaska migration; in *MTS/IEEE Oceans 96* (Ft. Lauderdale) pp 373–377

Afsal VV, Yousuf KSSM, Anoop B, Anoop AK, Kannan P, Rajagopalan M and Vivekanandan E 2008 A note on cetacean distribution in the Indian EEZ and contiguous seas during 2003-07. *J. Cetac. Res. Manage.* **10** 209–215

Al Robaae K 1974 *Tursiops aduncus* bottle nosed dolphin: a new record for Arab Gulf; with notes on Cetacea of the region. *Bull. Basrah Nat. Hist. Mus.* **1** 7–16

Au W, Darling J and Andrews K 2001a High frequency harmonics and source level of humpback whale songs. *J. Acoust. Soc. Am.* **110** 2770

Au WWL, Frankel A, Helweg A and Cato DH 2001b Against the humpback whale sonar hypothesis. *IEEE J. Ocean. Eng.* **26** 295–300

Au WWL, Mobley J, Burgess WC, Lammers MO and Nachtigall PE 2000 Seasonal and diurnal trends of chorusing humpback whales wintering in waters off western Maui. *Mar. Mamm. Sci.* **16** 530–544

Au WWL, Lammers MO, Pack AA and Herman L 2004 Vertical array measurements of humpback whale songs. *J. Acoust. Soc. Am.* **115** 2520–2521

Au WW, Pack AA, Lammers MO, Herman LM, Deakos MH and Andrews K 2006 Acoustic properties of humpback whale songs. *J. Acoust. Soc. Am.* **120** 1103–1110

Baby KG 2009 Stranding of baleen whale (*Balaenoptera Sp.*) at thalikulam landing center; Thrissur District, Kerala. Marine fisheries information service, CMFRI, Cochin, *Technical and Extension Series* 201, p 30.

Baumgartner MF and Mussolini SE 2011 A generalized baleen whale calls detection and classification system. *J. Acoust. Soc. Am.* **129** 2889–2902

Braulik GT, Ranjbar S and Owfi F 2010 Marine mammal records from Iran. *J. Cetac. Res. Manage.* **11** 49–64

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

Cato DH 1991 Songs of the humpback whales: the Australian perspective. *Mem. Queensland Mus.* **30** 277–290

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

Cholewiak D 2008 Evaluating the role of song in the humpback whale (*Megaptera novaeangliae*) breeding system with respect to intra-sexual interactions; PhD thesis, Cornell University (Ithaca, NY)

Chittleborough RG 1958 Dynamics of two populations of the humpback whale, *Megaptera novaeangliae* (Borowski). *Aust. J. Mar. Freshwat. Res.* **16** 33–128

Clapham P 1996 The social and reproductive biology of humpback whales: an ecological perspective. *Mammal Rev.* **26** 27–49

Clapham PJ and Mead JJ 1999 *Megaptera novaeangliae. Mamm. Species* **604** 1–9

Clark CW and Clapham PJ 2004 Acoustic monitoring on a humpback whale (*Megaptera novaeangliae*) feeding ground shows continual singing into late spring. *Proc. Biol. Sci.* **271** 1051–1057.

Darling JD and Berube M 2001 Interactions of singing humpback whales with other males. *Mar. Mammal Sci* **17** 570–584

Darling JD 1983 Migration, abundance and behavior of Hawaiian humpback whales (*Megaptera novaeangliae*) (Borowski); PhD dissertation, University of California at Santa Cruz (Santa Cruz, CA) pp 1–147

Darling JD, Nicklin ME and Nicklin CP 2006 Humpback whale songs: do they organize males during the breeding season? *Behaviour* **143** 1051–1101

Dawbin WH 1966 The seasonal migratory cycle of humpback whales; in *Whales, dolphins and porpoises* (ed) KS Norris (Berkeley & Los Angeles: University of California Press) pp 145–170

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

Friedl WA and Thompson PO 1981 Measuring acoustic noise around Kahoolawe island; NOSC, San Diego, CA, *Tech. Rep.* 732.

Frumhoff P 1983 Aberrant songs humpback whales (*Megaptera novaeangliae*) clues to the structure of humpback songs; in *Communication and behavior of whale* (ed) R Payne (Boulder, CO: Westview Press) pp 81–127

Girola E 2011 *Quantifying year around changes in a humpback whale (Megaptera novaeangliae) song sound using multivariate statistics and artificial neural networks* University of St. Andrews

Guinee LN, Chu K and Dorsey EM 1983 Changes over time in the songs of known individual humpback whales (*Megaptera novaeangliae*); in *Communication and behavior of whale* (ed) R Payne (Boulder, CO: AAAS Selected Symposium 76, Westview Press) pp 59–80

Herman LM and Antinoja RC 1977 Humpback whales in the Hawaiian breeding waters: population and pod characteristics. *Sci. Rep. Whales Res. Inst. (Tokyo)* **29** 59–85

Johnson A, Salvador G, Kenney J, Robbins J, Kraus S, Landry S and Clapham P 2005 Fishing gear involved in the entanglements of right and humpback whales. *Mar. Mammal Sci.* **21** 635–645

Johnston DW, Robbins J, Chapla ME, Mattila DK and Andrews KR 2008 Diversity, habitat associations and stock structure of odontocete cetaceans in the waters of American Samoa, 2003–06. *J. Cetac. Res. Manage.* **10** 59–66

Jurasz M and Jurasz VP 1979 Feeding modes of the humpback whale, Megaptera novaeangliae, in southeast Alaska. *Sci. Rep. Whales Res. Inst. (Tokyo)* **31** 69–83

Kumaran PL 2002 Marine mammal research in India-a review and critique of the methods. *Curr. Sci.* **83** 1210–1220

Levenson C 1969 Behavioral, physical, and acoustic characteristics of humpback whales (*Megaptera novaeangliae)* at Argus Island; Naval Oceanographic Office Informal Report No. 69-54

Levenson C 1972 Characteristics of sounds produced by humpback whales (*Megaptera novaeangliae*); NAVOCEANO Tech. Note No. 7700- 6-72 (Naval Oceanographic Office, Washington, DC)

Levenson C and Leapley WT 1978 Distribution of humpback whales (*Megaptera novaeangliae)* in the Caribbean determined by a rapid acoustic method. *J. Fish. Res. Board Can.* **35** 1150–1152

Mathew AP 1948 Stranding of a whale *Megaptera nodosa* on the Travancore coast in 1943. *J. Bombay Nat. Hist. Soc.* **47** 732–733

Mednis A 1991 An acoustic analysis of the 1988 song of the humpback whale, *Megaptera novaeangliae*, of Eastern Australia. *Mem. Queensland Mus.* **30** 323–332

Mellinger DK, Stafford KM and Fox CG 2004 Seasonal occurrence of sperm whale (*Physeter macrocephalus*) sounds in the Gulf of Alaska, 1999-2001. *Marine Mammal Sci*. **20** 48–62

Mellinger DK, Stafford KM, Moore SE, Dziak RP and Matsumoto H 2007 An overview of fixed passive acoustic observation methods for cetaceans. *Oceanography* **20** 36–45

Mikhaliev YA 1995 Humpback whales of the Arabian Sea; Working document submitted to the International Whaling Commission Scientific Committee

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

Mikhalev YA 2000 Whaling in the Arabian Sea by the whaling fleets Slava and Sovetskaya Ukraina; in *Soviet whaling data (1949-1979)* (eds) AV Yablokov, VA Zemsky and DD Tormosov (Moscow: Centre for Russian Environmental Policy) pp 141–181

Minton G, Collins T, FIndlay K *et al.* (In press) Seasonal distribution, abundance, habitat use and population identity of humpback whales in Oman. *J. Cetac. Res. Manage* (Special Issue).

Minton G 2004 Ecology and Conservation of Cetaceans in Oman, with particular reference to humpback whales (*Megaptera novaeangliae*). Millport: University of London, University Marine Biological Station.

Minton G, Collins T, Pomilla C, Findlay K, Rosenbaum H, Baldwin R and Brownell RL 2008 *Megaptera novaeangliae* (Arabian Sea sub-population), in *2009 IUCN Red List of threatened species* (eds) IUCN [http://www.iucnredlist.org/details/132835].

Muthiah C, Mohammed S, Bhatkal G and Melinmani B 1988 On the stranding of a Humpback Whale in the North Kerala coast; Marine Fisheries Information Service, Sightings and strandings database on Marine mammal conservation Network of India. *Techn. Ext. Ser.* **85** p12

Norris TF 1995 The effects of noise on the singing behavior of humpback whales (*Megaptera novaeangliae)*; MS thesis, Moss Landing Marine Laboratories, California State University

Papastavrou V 1995 Soviets attacked mystery whales. *BBC Wildl.* **13** 34

Papastavrou V 1991 A note on recent sightings and standings of cetaceans in Oman: Ra's Sawad1 to Rakhyut; in *Cetaceans and Cetacean Research in the Indian Ocean Sanctuary* (eds) S Leatherwood and G P Donovan (Marine Mammal Technical Report Number 3, UNEP, Nairobi, Kenya) p 287

Parsons ECM, Wright AJ and Gore MA 2008 The nature of humpback whale (*Megaptera novaeangliae)* song. *J Mar. Anim. Ecol.* **1** 22–31

Payne R 1978 Behavior and vocalization of humpback whales (*Megaptera novaeangliae*); in U.S. Department of Commerce, NTIS: Report on a workshop on problems related to humpback whales (*Megaptera novaeangliae*) in Hawaii (eds) PB Norris KS, Reeves RR. pp 280–794:56–78

Payne R and Guinee LN 1983 Humpback whale (*Megaptera novaeangliae*): songs as an indicator of "stocks"; in *Communication and behavior of whales* (eds) R (Boulder, CO: AAAS Selected Symposium 76 Westview Press) pp 333–358

Payne K and Payne R 1985 Large scale changes over 17 years in songs of Humpback whales in Bermuda. *Z. Tierpsychol.* **68** 89–114

Payne RS and McVay S 1971 Songs of humpback whales. *Science* **173** 585–597

Payne K, Tyack P and Payne R 1983 Progressive changes in the song of humpback whales (*Megaptera novaeangliae*): a detailed analysis of two seasons in Hawaii; in *Communication and behavior of whale* (eds) R Payne (Boulder, CO: AAAS Selected Symposium 76 Westview Press) pp 9–57

Porter MB 1992 The KRAKEN normal mode program; No.NRL/MR/5120-92-6920. Naval Research Laboratory, Washington, DC

Rasmussen K 2006 *Comparison of two distinct populations of humpback whales (Megaptera novaeangliae) off Pacific Central America* (Moss Landing Marine Laboratories, San Francisco State University, San Francisco, CA: MS thesis) p 90

Reeves RR, Leatherwood S, Papastavrou V 1991 Possible stock affinities of humpback whales in the northern Indian Ocean; in *Cetaceans and Cetacean Research in the Indian Ocean Sanctuary* (eds) S Leatherwood and GP Donovan, (Marine Mammal Technical Report Number 3, UNEP, Nairobi, Kenya) pp 259–269.

Ross JP 1981 Recent marine mammal sightings in the Sultanate of Oman. Workshop to Plan a Programme of Scientific Research on Cetaceans in the Indian Ocean Sanctuary; Zeist, Netherlands, 28 September-1 October (unpublished).

Salm RV, Jensen RAC and Papastavrou VA 1993 *Marine fauna of Oman: cetaceans, turtles, seabirds and shallow water corals; A Marine Conservation and Development Report* (Gland, Switzerland: IUCN).

Scheidat M, Castro C, Denkinger J, González J and Adelung D 2000 A breeding area for humpback whales (*Megaptera novaeangliae*) off Ecuador. *J. Cetac. Res. Manage.* **2** 165–172

Silber GK 1986 The relationship of social vocalizations to surface behavior and aggression in the Hawaiian humpback whale (*Megaptera novaeangliae*). *Can. J. Zool.* **64** 2075–2080

Slijper EJ, Van Utrecht WL and Naaktgeboren C 1964 Remarks on the distribution and migration of whales, based on observations from Netherlands ships. *Bijdr. Dierkd.* **34** 3–93

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

Thompson TJ 1981 Temporal characteristics of humpback whale (*Megaptera novaeangliae*) songs. Ph.D. dissertation, University of Rhode Island.

Thompson POW, Cummings WC and Kennison SJ 1977 Sound production of humpback whales, *Megaptera novaeangliae*, in Alaskan waters. *J. Acoust. Soc. Am.* **62** 1–182

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

Tyack P and Whitehead H 1983 Male competition in large groups of wintering humpback whales. *Behaviour* **83** 132–154

Vivekanandan E and Jeyabaskaran R 2012 *Marine mammal species of India; CMFRI (Central Marine Fisheries Research Institute)* (Kochi: St. Francis Press) pp 15–55

Volgenau L, Kraus SD and Lien J 1995 The impact of entanglements on two substocks of the western North Atlantic humpback whale (*Megaptera novaeangliae). Can. J. Zool.* **73** 1689–1698

Watkins WA, Daher MA, Repucci GM, George JE, Martin DL, DiMarzio NA and Gannon DP 2000 Seasonality and distribution of whale calls in the North Pacific. *Oceanography* **13** 62–67

Whitehead H and Moore MJ 1982 Distribution and movements of West Indian humpback whales in winter. *Can. J. Zool.* **60** 2203–2211

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

Winn HE and Reichley NE 1985 Humpback whale (*Megaptera novaeangliae*) In: *Handbook of marine mammals* (eds) SH Ridgway, R Harrison, The Sirenians and Baleen Whales. *Academic Press*, London and Orlando, pp 241–73.

Winn HE, Thompson JT, Cummings WC, Hains J, Hundnall J, Hays H and Steiner W 1981 Songs of the humpback whales; Population comparison. *Behav. Ecol. Sociobiol.* **8** 41–46

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

Winn HE, Perkins PJ and Poulter TC 1970 Sounds of the humpback whale; in *Proceedings of the Seventh Annual Conference on Biological SONAR* (Menlo Park, CA: Stanford Research Institute) pp 39–52

Winn HE, Edel RK and Taruski AG 1975 Population estimates of the humpback whale (*Megaptera novaeangliae*) in the West Indies by visual and acoustic techniques. *J. Fish. Res. Board Can.* **32** 449–506

Wray, P and Martin KR 1983 Historical whaling records from the western Indian Ocean; *Rep. Intl. Whaling Commission* **5** 213–41

Yukhov VL 1969 Observations of cetaceans in the Gulf of Aden and the northwestern part of the Arabian Sea; in *Marine mammals* (eds) VA Arsenev, BA Zenkovich and KK Chapskii (Akademmi Nauk: Moscow) [Original in Russian, this article translated by S. Pearson, National Marine Mammal Lab., Seattle, USA] pp 327–328

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