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# 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

**Keywords.** Acoustic parameters; breeding habitat; humpback whale; phrases; sound units; thematic structure

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  $\mu$ Pa, 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  $\mu$ Pa (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.

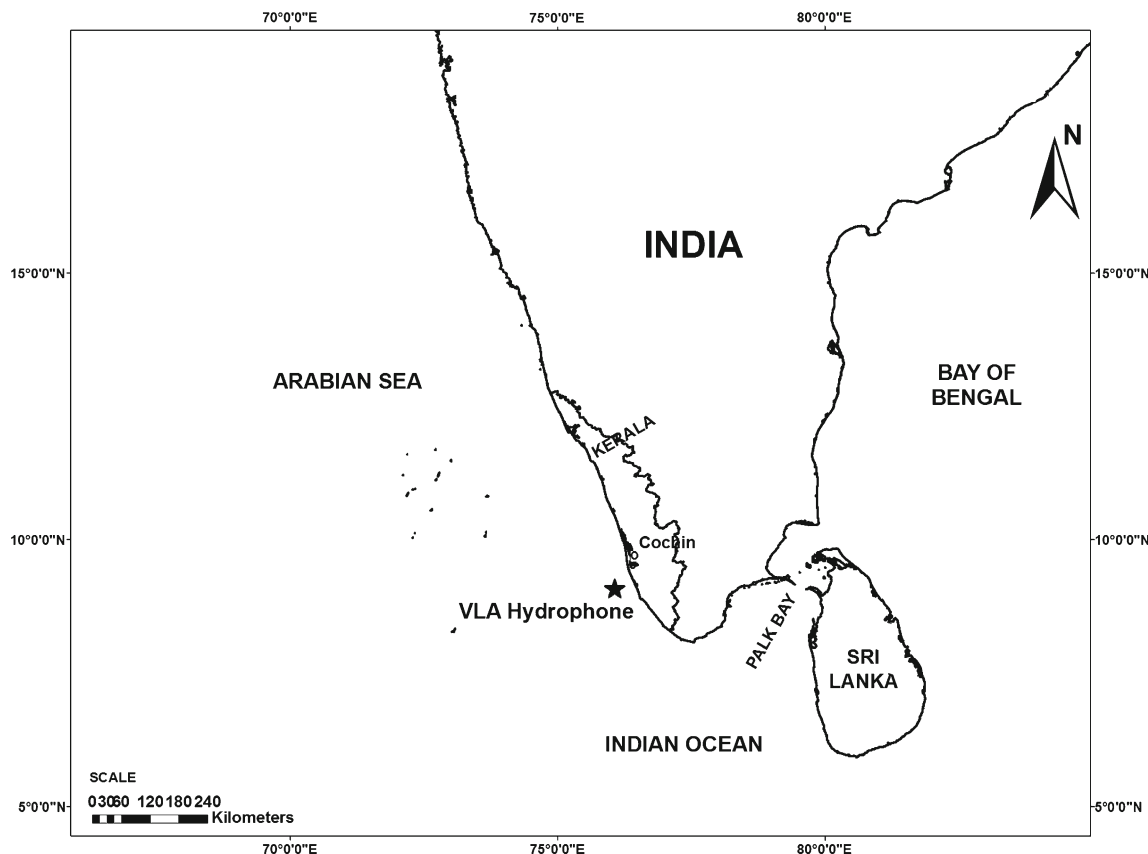
## 2. Methods

### 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 ( $\mu$ Pa) by applying the pre-amplifier gain and receiving sensitivity ( $-170$ dB) 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 ( $\text{dB re } 1 \mu\text{Pa}^2\text{Hz}^{-1}$  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  $f_0$  ( $\text{min}f_0$ ), maximum  $f_0$  ( $\text{max}f_0$ ), starting  $f_0$  ( $\text{start}f_0$ ), ending  $f_0$  ( $\text{end}f_0$ ) and  $f_0$  trend ( $\text{trend}f_0$ ). In the case of  $\text{start}f_0$  and  $\text{end}f_0$  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  $\text{start}f_0$  and  $\text{end}f_0$ . 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 ( $\text{dB re } 1 \mu\text{Pa}^2\text{Hz}^{-1}$ ).

### 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>).

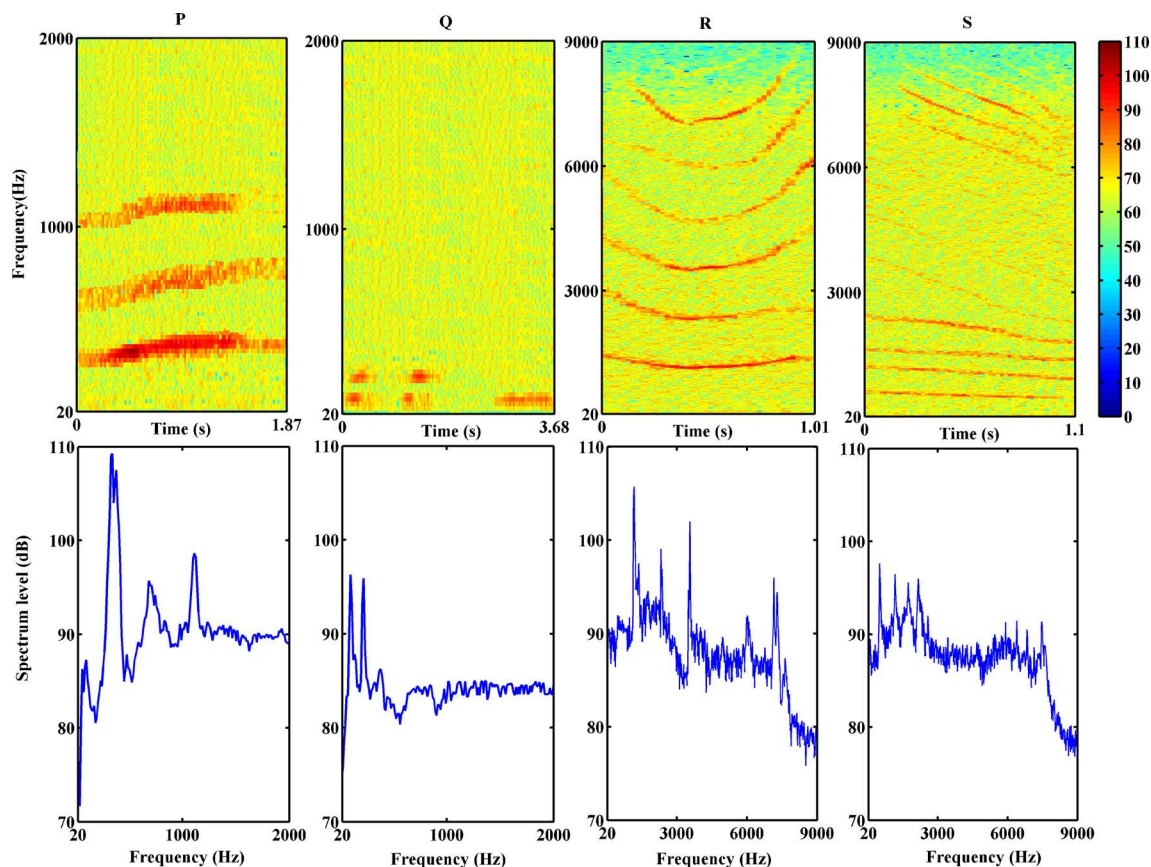
### 3. Results

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.

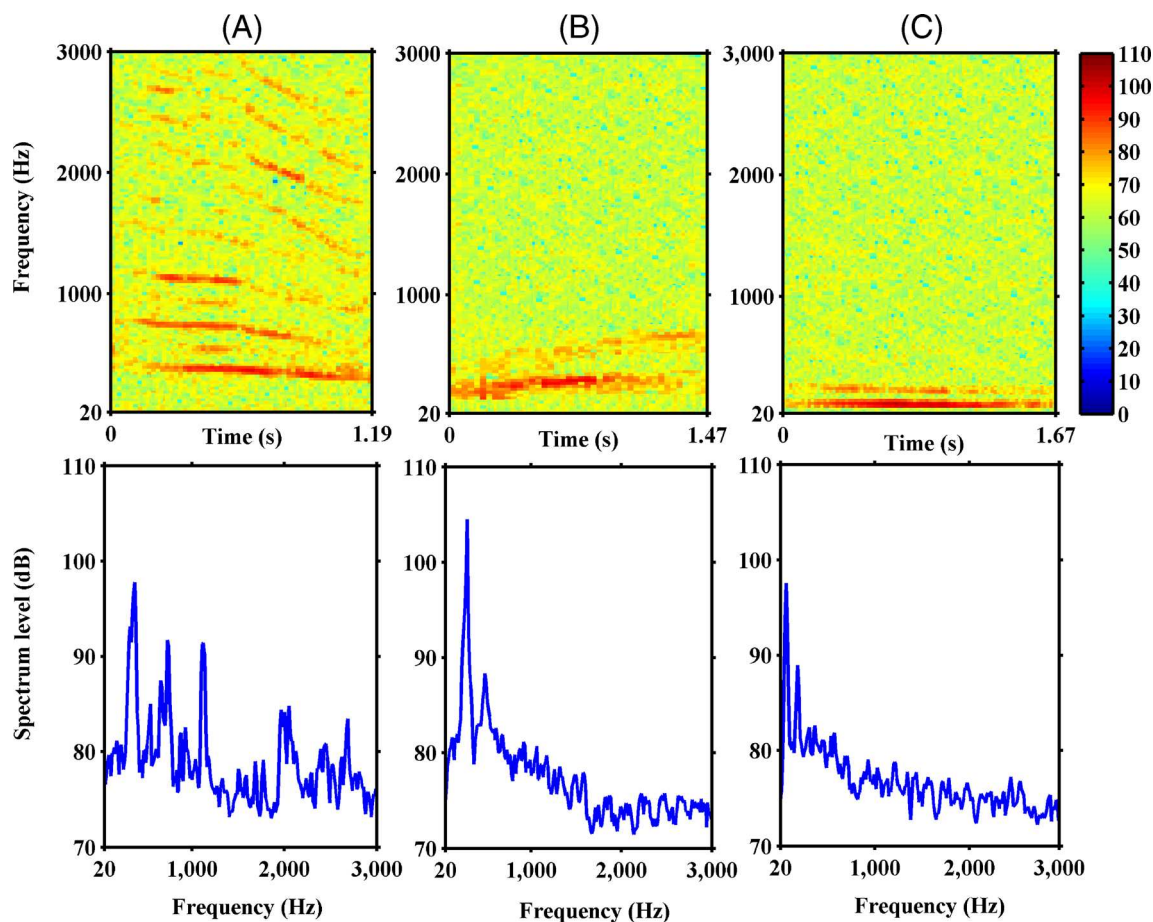
Themes were associated with individual sound units grouped into the phrase type. The phrases for Theme-I and Theme-II were PQRS and ABC, whose spectrograms and

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  $269.63 \pm 4.46$  and ending at  $370.12 \pm 5.76$  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  $114.15 \pm 3.59$  and ending at  $100.24 \pm 2.85$  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  $1180.24 \pm 9.77$  and ending at  $1308.43 \pm 6.94$  Hz ( $n=10$ , range=1095–8810 Hz), followed by S, swept down from  $575.21 \pm 7.36$  to  $437.42 \pm 7.44$  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  $375.74 \pm 5.83$  and ending at  $265.70 \pm 4.89$  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  $235.08 \pm 3.45$  to  $317.26 \pm 2.43$  Hz ( $n=12$ , range=195–781 Hz) over 1.47s, whereas unit C, is a low frequency downswEEP starting at  $142.21 \pm 3.34$  and ending at  $112.23 \pm 3.09$  Hz ( $n=12$ ,

range=98–270 Hz) lasting about 1.67 s. The  $f_0$  trend decreases due to the contemporary increase in ‘start $f_0$ ’ and decreasing of ‘end $f_0$ ’. At the same time ‘Min $f_0$ ’ decreases and ‘Max $f_0$ ’ 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,

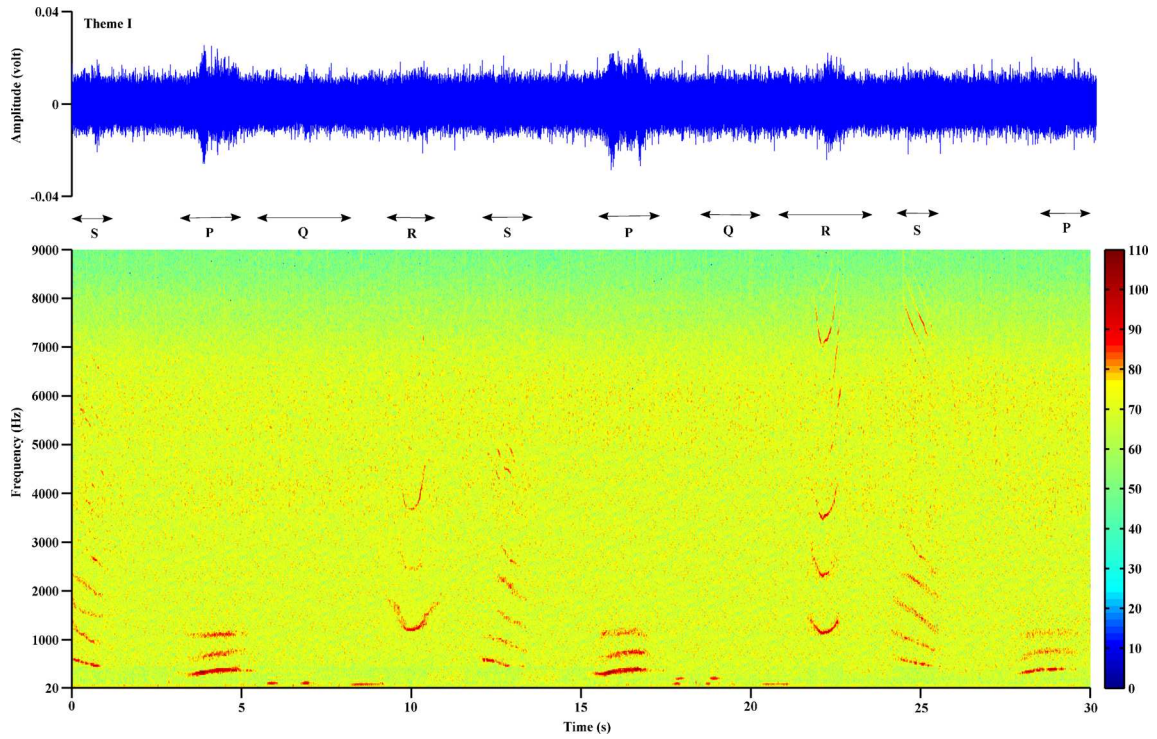


Figure 4. Waveforms and spectrograms of the humpback whale Theme-I in the SEAS.

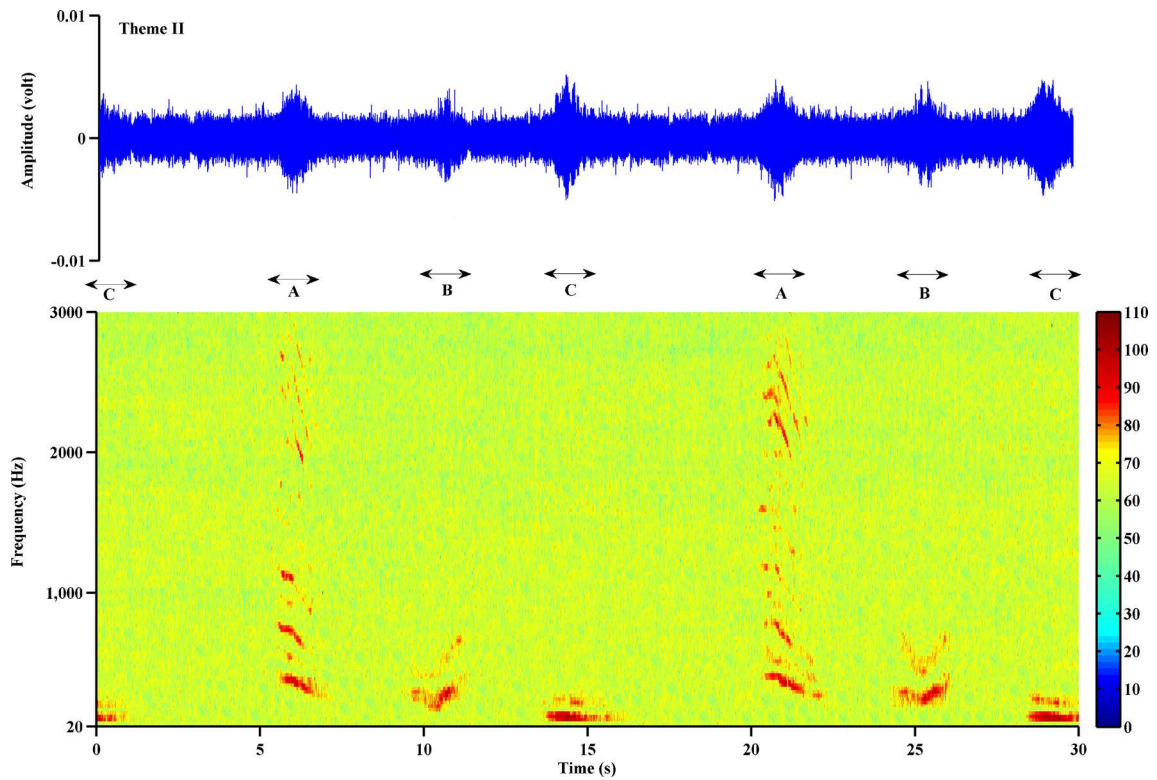


Figure 5. Waveforms and spectrograms of the humpback whale Theme-II in the SEAS.

**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)
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

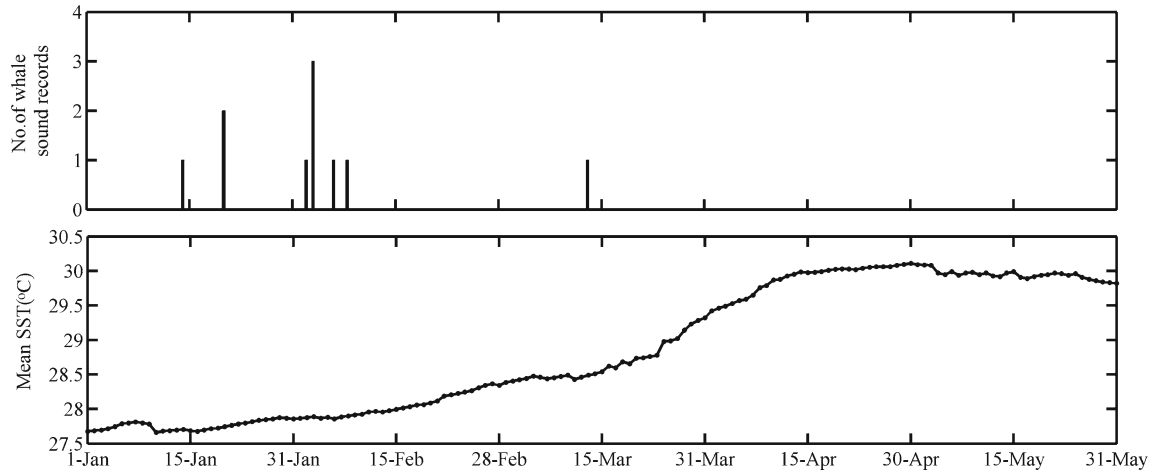
Humpback whales have been extensively studied in several areas (Winn and Reichley 1985; Clapham 1996), but relatively little is known about their distribution and breeding activity in the Arabian Sea. The distribution of humpback whales in the Arabian Sea is known from whaling records (Wray and Martin 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). Mikhalev (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) <b>1.87</b> 0.03	(n=8) <b>3.68</b> 0.09	(n=10) <b>1.01</b> 0.04	(n=11) <b>1.10</b> 0.06	(n=12) <b>1.19</b> 0.02	(n=12) <b>1.47</b> 0.07	(n=12) <b>1.67</b> 0.05
Frequency range (Hz)	227–1160	96–128	1095–8810	390–8570	208–2954	195–781	98–270
Max $f_0$ (Hz)	<b>416.12</b> 2.66	<b>128.48</b> 2.87	<b>1404.45</b> 5.82	<b>698.76</b> 6.19	<b>463.87</b> 4.25	<b>341.38</b> 2.71	<b>158.90</b> 3.51
Min $f_0$ (Hz)	<b>227.35</b> 2.23	<b>95.84</b> 1.81	<b>1095.47</b> 3.63	<b>390.43</b> 2.19	<b>207.90</b> 2.96	<b>195.28</b> 3.45	<b>98.07</b> 2.04
Start $f_0$ (Hz)	<b>269.63</b> 4.46	<b>114.15</b> 3.59	<b>1180.24</b> 9.77	<b>575.21</b> 7.36	<b>375.74</b> 5.83	<b>235.08</b> 3.45	<b>142.21</b> 3.34
End $f_0$ (Hz)	<b>370.12</b> 5.76	<b>100.24</b> 2.85	<b>1308.43</b> 6.94	<b>437.42</b> 7.44	<b>265.70</b> 4.89	<b>317.26</b> 2.43	<b>112.23</b> 3.09
Trend $f_0$ (ratio)	<b>1.37</b> 0.02	<b>0.87</b> 0.02	<b>1.10</b> 0.01	<b>0.76</b> 0.01	<b>0.70</b> 0.02	<b>1.34</b> 0.02	<b>0.79</b> 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 Antinaja 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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