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INTERNATIONAL WHALING COMMISSION

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ABSTRACT

This report presents an overview of the progress to date on the humpback whale detection component of the Arabian Sea Humpback Whale Acoustic Research program off Oman. Three archival acoustic recorders were deployed at sites in two regions for approximately one year each, in Hallaniyats Bay during 2011/2012, and the Gulf of Masirah during 2012/2013. Performance of recorders varied among deployments, but despite some challenges due to equipment failures we succeeded in documenting spatiotemporal patterns in the presence of humpback whales in a large dataset. Several key findings broaden our understanding of the Arabian Sea humpback whale population off Oman. There appears a strong seasonal component to the use of song by this population, primarily from November through May, which is congruent with the Northern Hemisphere breeding cycle and singing season. Throughout this period, singing was heard in both Hallaniyats Bay and the Gulf of Masirah, separated by approximately 400km, indicating that the population utilizes both of these regions. However, there was a much stronger presence in Hallaniyats Bay, with song heard nearly 24 hours/day during the peak months, and song detected simultaneously at multiple sites across the Bay. Previous boat-based survey data indicated similar trends, however, given limitation in the duration of this fieldwork the current acoustic dataset provides a more reliable indication of this population's breeding related activity. This suggests that the Hallaniyats Bay might serve as a more important habitat for breeding activity than the monitored region of the Gulf of Masirah. There also appeared to be a subtle northward shift in distribution of detections as the singing season progressed, both within Hallaniyats Bay, and from Hallaniyats Bay to the Gulf of Masirah, suggesting a seasonal shift in distribution for singing males. During the summer and autumn months, very little song was detected, however sparse detections indicate that whales are present in both regions during at least some of this period. It is recommended that similar acoustic monitoring be conducted in all range states of the population to elucidate spatiotemporal distribution throughout the Arabian Sea.

INTRODUCTION

Historical and Soviet whaling records indicate that Arabian Sea humpback whales (ASHW) are likely distributed throughout the Arabian Sea at least from Yemen to India (Mikhalev, 1997, Mikhalev, 2000, Slijper *et al.*, 1964, Brown, 1957). However, the most recent evidence for their continued presence in the Arabian Sea is derived from studies off the coast of Oman (Baldwin *et al.*, 1999, Minton *et al.*, 2010, Minton *et al.*, 2011, Willson *et al.*, 2015). Currently listed as "Endangered" in the IUCN red list (Minton *et al.*, 2008), ASHW are a globally unique non-migratory population, have a very low population abundance estimate of 82 individuals (95% CI 60-111 (Minton *et al*., 2011)), and are genetically distinct and isolated from all other populations in both hemispheres (Pomilla *et al*., 2014). The Scientific Committee of the International Whaling commission has prioritized the research and conservation of this unique population (e.g. IWC, 2006).

The small size and demographic isolation of this population is of increasing conservation concern, given the many identified threats, including ship strikes, entanglements in fishing gear, coastal development and noise pollution, which cumulatively may limit recovery (Willson *et al*., 2015, Baldwin *et al*., 2015). Recently a workshop that brought together scientists from most ASHW range states and international experts concluded that the ASHW population is "at great risk of extinction and that research should be undertaken immediately to inform conservation measures" (Minton *et al*., 2015). The workshop stressed the need for a regionally collaborative research and conservation program, including scientific surveys to estimate population size and current distribution, collection of further information on biology and ecology, and working with different industries to identify and reduce adverse human impacts on these whales (Minton *et al*., 2015).

Due to the highly vocal nature of humpback whale social behavior, which includes singing during the breeding season for many hours without pause and phonating social sounds throughout the year, Passive Acoustic Monitoring (PAM) for song and social sounds is a highly effective method for assessing distribution across broad spatial and temporal scales (Clark and Clapham, 2004, Cerchio *et al* 2010, 2014, Murray *et al* 2014). By placing bottom-fixed PAM recorders throughout the suspected range of a population, or at targeted areas of conservation concern (i.e., near port developments or areas where industry is active), and collecting long-term acoustic data (on the order of months or years), a detailed record of the presence of whales on an hourly or daily basis can be obtained throughout the year. This information can then be directly applied to assessing risks and developing mitigation strategies, as well as contributing to a biological understanding not otherwise obtainable. In addition, valuable data can be gathered on the presence, temporal and spatial distribution of other species, such as pygmy blue whales, Bryde's whales (potentially two forms), sperm whales and delphinids in general. The information provided by analyses of long-term monitoring datasets is immediately applicable to conservation strategy planning and assessment of potential impacts of anthropogenic activities (such as coastal or offshore development), without the need for more costly boat surveys, which also cannot achieve the same range of extensive temporal effort in difficult offshore waters.

PAM has particular conservation value for ASHW because boat surveys in Oman have been limited to relatively small temporal windows due to seasonal weather conditions and other logistic constraints (Willson *et al*. 2014). Significant gaps exist in the current understanding of the temporal distribution of this population, especially during the southwest monsoon season between the months of July and September (Minton *et al*., 2011, Corkeron *et al*., 2011, Minton *et al*., 2010).

Here we present a preliminary analysis of a two-year acoustic dataset collected off the coast of Oman in the Hallaniyats Bay of the Dhofar region from 2011/2012 and the Gulf of Masirah in the vicinity of Duqm from 2012/2013 (See Figure 1). The primary aim is to document spatial and temporal distribution of humpback whales in the region throughout the year. Accordingly, the acoustic data collection from 2011-2013 was specifically designed to investigate temporal and spatial distribution during the monsoons and times of year when no previous survey effort has been conducted.

METHODOLOGY

Archival recorders and deployment characteristics

Three autonomous archival acoustic recorders, Wildlife Acoustics model SM2M (www.wildlifeacoustics.com), were deployed in 2011/2012 in the Hallaniyats Bay region, the site of previous boat surveys focusing on the population of Arabian Sea humpback whales (Fig 1). Three deployment sites were determined by the team based upon known distribution of whales from previous surveys, logistical considerations of reaching the sites by small boat, and depth profiles that would allow deployment and retrieval by SCUBA. The sites are referred to as: Hal 1 – Hasakiyah, furthest east at 30m depth; Hal 2 – Ras al Hamrah, furthest to the north at 33m depth; and Hal 3 – Ras al Hasik, furthest to the south at 16m depth (Fig 1C). Distance between deployment sites ranged from 20km to 31km. Given these distances and reduced sound propagation in the shallow water shelf habitat, it was considered that each recorder had independent listening space, and that it was unlikely that a singing humpback whale would be detected on more than one recorder.

From November 2011 to October 2012, three separate deployments were conducted, with varying recording parameters and durations (Table 1). The first two deployments from November 2011 to March 2012 recorded continuously at sample rates of 16kHz (8kHz recording bandwidth) and 32kHz (16kHz recording bandwidth), respectively. The third deployment was duty cycled to record 10min every 30min (10min on / 20min off) at 22kHz, in order to have a longer recording endurance from March until October 2012.

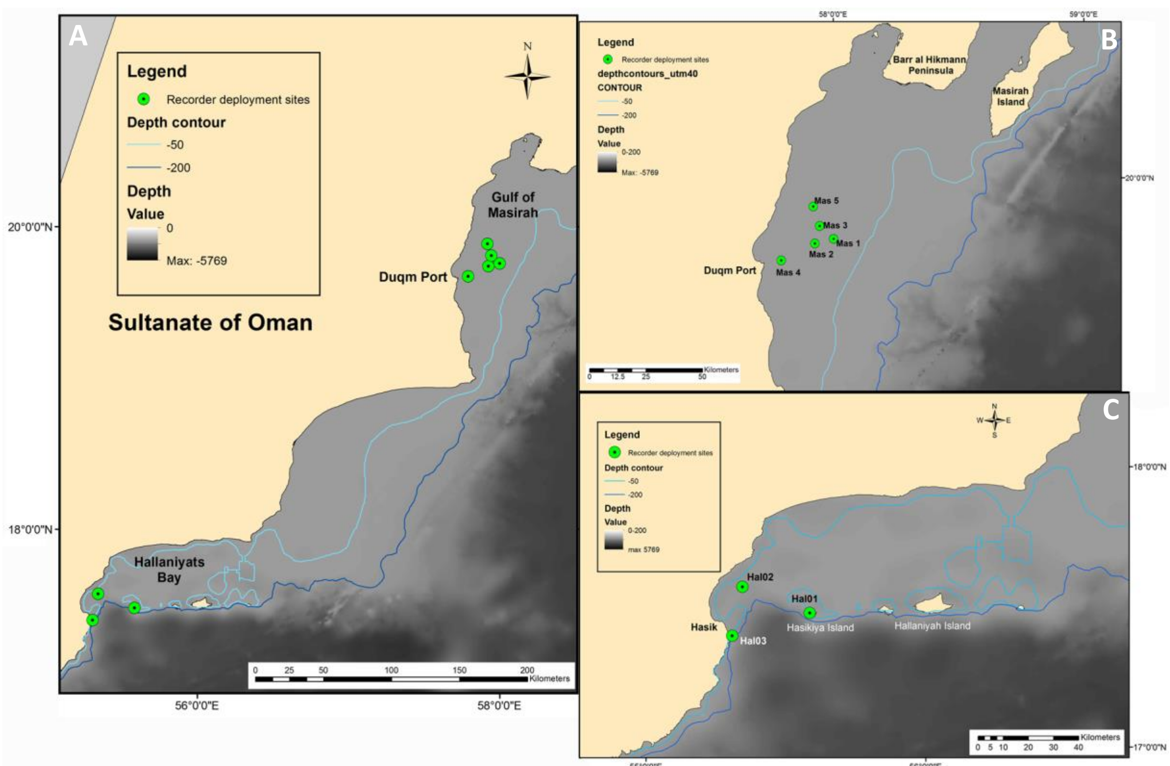


Figure 1. Study region off the cost of Oman (A), showing positions of deployed recorders in the Gulf of Masirah / Duqm site (B) and the Hallaniyats Bay site (C).

During 2012/2013 the recorders were deployed in the Gulf of Masirah near the port of Duqm, with the intention of documenting presence of whales at this more northern part of the Oman range, and with consideration of the port development occurring at Duqm (Baldwin *et al*., 2015). Two deployments were conducted with different spatial arrangements and deployment sites. The first deployment from November 2012 to April 2013 was placed in a triangle formation at sites referred to as Mas 1 at 27m depth, Mas 2 at 24m depth and Mas 3 at 25m depth, with 8km spacing between each unit and ranging from approximately 20km to 27km from the mainland coast near Duqm. It is likely that a whale vocalizing within the space defined by these sites would have been detected on multiple recorders, and therefore they had overlapping listening spaces. Recordings were made on a duty cycle different than in Hallaniyats Bay, recording 15min every 30min (15min on / 15min off).

After this deployment, the units were redeployed in a different spatial arrangement covering a greater range, maintaining one unit at Mas 2, and deploying the others at new sites, Mas 4 at 23m depth, and Mas 5 at 24m depth, between April 2013 and Mar 2014. Distance between sites ranged from 16km (Mas 2 to Mas 4, and Mas 2 to Mas 5) to 27km (Mas 4 to Mas 5); given these distances it was considered that each recorder had independent listening space, and that it was unlikely that a singing humpback whale would be detected on more than one recorder.

Table 1. Sampling design indicating sites, recording parameters, the dates of each deployment, and the expected duration of recording calculated from parameters. Sites Hal 1, 2 and 3 refer to deployments at three sites in Hallaniyats Bay that acquired data between November 2011 and October 2012. Sites Mas 1, 2, 3, 4, and 5 refer to deployments at five sites in Gulf of Masirah that acquired data between November 2012 and August 2013. See Figure 1 for positions of all sites.

Deployment	Sites	Duty Cycle Min on/off	Sample Rate	Deploy Date	Retrieve Date	Days Deployed	Expected Data Days
Hallaniyats Bay							
Deploy 1	Hal 1, 2, 3	Continuous	16kHz	11/23/2011	2/20/2012	90	90
Deploy 2	Hal 2, 3	Continuous	32kHz	2/24/2012	3/26/2012	32	32
Deploy 3	Hal 2, 3	10/20	22.05kHz	3/29/2012	10/21/2012	207	168
Gulf of Masirah							
Deploy 1	Mas 1, 2, 3	15/15	22.05kHz	11/22/2012	4/13/2013	143	143
Deploy 2	Mas 2, 4, 5	15/15	16kHz	4/14/2013	3/4/2014	325	211

Acoustic detection analysis

Data files were downloaded from the units after each deployment recovery, and were converted from the Wildlife Acoustics proprietary ".wac" compression format to aiff sound files using the software program Kaleidoscope (Wildlife Acoustics Inc.). The resulting sound files were viewed as continuous spectrograms through Raven Pro v1.5 (Cornell University; Bioacoustics Research Program). Originally we planned to implement an automated detection procedure (Helble 2012); however, the ubiquitous presence of a vocalization from a chorusing fish species in the same frequency band and with the temporal characteristics of humpback whale vocalizations (Appendix Fig 1), would have resulted in very poor detector efficacy (a small proportion of positive target detections). Thus detection analysis by manual browsing proved to be more time efficient and effective.

With the objective of documenting the presence/absence of humpback whale vocalizations in each hour of each deployment, spectrograms were examined for humpback whale song or social sounds. Spectrograms were set to span a frequency band of 0-1,000 Hz irrespective of sample rate and bandwidth of recording, as this band encompasses the majority of humpback whale song signals and standardized detection across the variety of sampling bandwidths. A time duration of 10 minutes was viewed on a single screen in a four-line spectrogram (2.5min per line), with a 4,096-point FFT, Hann window and 50% overlap. As a result, sounds recorded at a sample rate of 16kHz, 22.05kHz and 32kHz had, respectively, a 256ms, 186ms and 128ms Hann window, a 3.91Hz, 5.38Hz and 7.81Hz frequency resolution, and a 128ms, 92.9ms and 64ms time resolution.

Temporal sampling varied across the deployments from continuous recording, to duty cycled recording either 10min every 30minutes (10min on, 20min off) or 15min every 30min (15min on, 15min off) (Table 1). In order to standardize assessment of the presence of humpback whales across recording schemes, we examined ten minutes starting at the beginning and half-hour point of every recorded hour, which was the maximum sample common to all recording sites and deployments. Each 10-minute recording period was logged as either containing humpback whale song or social sounds or as being void of humpback vocalizations. The resulting dataset contains presence/absence data for two 10-minute samples from every hour of recording from every recording site (i.e., 1/3 of the cumulative deployment period). This amounted to the manual browsing of 33% of continuous recording data, 67% of 15min on/15min off data, and 100% of 10min on/20min off data. We deem this sampling scheme to be more than sufficient for detecting song given that humpback whales characteristically sing for hours continuously; by examining two 10-minute windows separated by 20min, we are confident that we would detect song in every hour in which it was audible at the recording site. Given the more transient nature of humpback whale social sounds, an exhaustive analysis of all data would have been more rigorous for detection of humpback whales when singing was not present; however, as revealed by the analysis (see results) the periods when song was not heard were already duty cycled at 10min every 30 min (Hallaniyats) or 15min every 30min (Masirah), so we believe the impact of subsampling the continuous data to be minimal. Once detections were verified, data was summarized into hourly presence/absence information for humpback whales for the entire deployment period. To illustrate the temporal distribution of whale detections at each recording sight, each day was scored for the total number of hours in which humpback whales were detected.

RESULTS

Sample characteristics

The performance of the recorders varied from expectations among the different deployments, with some deployments providing data at, near or exceeding expected recording duration and others manifesting technical failures that yielded reduced data (Table 2, Fig 2). Of greatest consequence, in Hallaniyats Bay, the unit deployed at site Hal 1 had a catastrophic failure during Deployment 1 due to an internal electrical short partway through the deployment. Thereafter it was not available for redeployment, resulting in no data from Hal 1 for Deployments 2 and 3. In the Gulf of Masirah, all three units during Deployment 1 performed as expected; however, during Deployment 2 the units performed inconsistently and for less than the expected duration, with the last data day recorded in August 2013, well before the mid-November expectation, and Mas 2 experiencing an unexplained gap in recording between mid-May and mid-July. Considering only days for which data were collected in all 24-hour blocks, the total sample included 651 complete data days in Hallaniyats Bay and 718 complete data days in Gulf of Masirah. As a visual overview of the entire sample, Figure 2 displays a temporal chart of all deployments at all sites, indicating when the units were deployed, when data were recorded, when failures resulted in no data collection, and the programmed duty cycle for the collected data.

Humpback whale detections

Humpback whale vocalizations were detected at all sites at some point during all deployments, and were predominantly song. The signal-to-noise ratio (SNR) for detected song varied markedly (Fig 3), from cases where complete phrases and details of all units were obvious and clear, to cases

Table 2. Description of acquired data for each deployment at each site, accounting for only complete days of data for which presence/absence of humpback whales was scored for all 24 hours of the day. See Table 1 for description of site names and Figure 1 for positions of sites.

	Deployment 1				Deployment 2				Deployment 3			
Site	First Day Data	Last Day Data	Days Data	Duty Cycle Min on/off	First Day Data	Last Day Data	Days Data	Duty Cycle Min on/off	First Day Data	Last Day Data	Days Data	Duty Cycle Min on/off
Hal 1	11/24/2011	1/19/2012[1]	48[1]	Continuous								
Hal 2	11/24/2011	2/18/2012	87	Continuous	2/25/2012	3/25/2012	30	Continuous	3/30/2012	9/25/2012	180	10/20
Hal 3	11/24/2011	2/2/2012	71	Continuous	2/25/2012	3/25/2012	30	Continuous	3/30/2012	10/20/2012	205	10/20
Mas 1	11/23/2012	4/12/2013	141	10/20								
Mas 2	11/23/2012	4/12/2013	141	10/20	4/15/2013	8/13/2013	73[2,3]	15/15				
Mas 3	11/23/2012	4/12/2013	141	10/20								
Mas 4					4/15/2013	7/28/2013	105[3]	15/15				
Mas 5					4/15/2013	8/9/2013	117[3]	15/15				

[1] The Unit deployed at Hal 1 experienced a catastrophic failure due to electrical shorting and stop recording entirely on 1/31/2011. Signal interruptions starting on 12/14/2011 caused the loss of complete hours of data on 21 days resulting in only 48 complete days of data between the indicated dates during Deployment 1. Thereafter the unit was not functional and thus there were no Deployments 2 or 3 at Hal 1.

[2] Mas 2, Deployment 2 experienced an unexplained gap in recording from 5/23/2013 to 7/9/2013, resulting in only 73 complete days of data.

[3] Mas 2, 4 and 5, Deployment 2, stopped recording well short of anticipated 211 days due to suspected failure of logging unit circuitry.

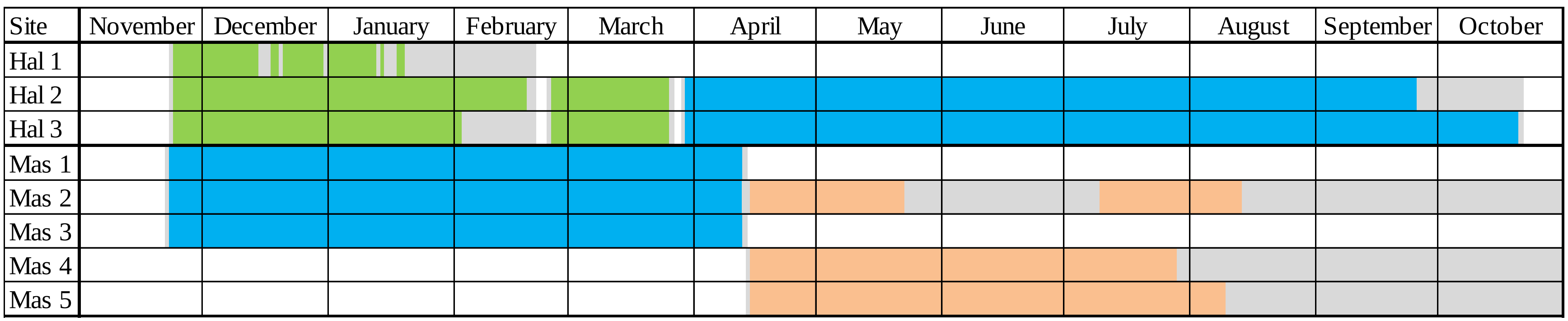


Figure 2. Temporal map of available recordings from deployments off Oman. The entire recording period for Hallaniyats Bay (Hal 1, 2 and 3) and Gulf of Masirah (Mas 1, 2, 3, 4 and 5) are aligned by month of the year, despite the former being sampled in 2011/2012 and the latter in 2012/2013. Days for which there were complete days recorded are color coded for recording schedule: green being continuous, blue duty-cycled 10min on and 20min off, and orange duty-cycled 15min on and 15min off. Grey indicates periods for which the unit was deployed but either no data were recorded, or an incomplete day (<24hrs) was recorded.

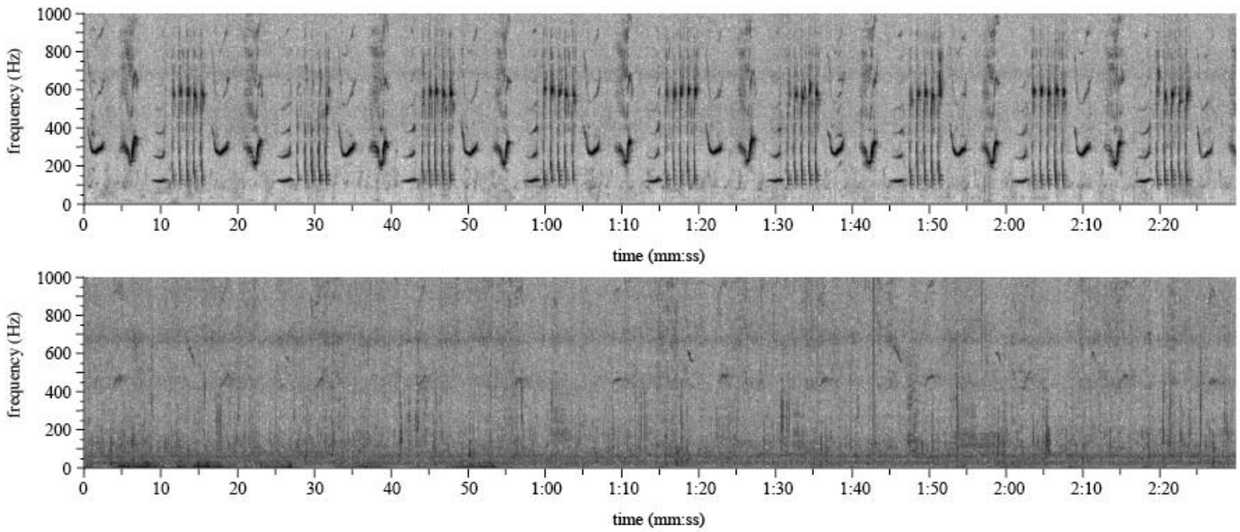


Figure 3. Example spectrograms of humpback whale song detected during browsing of recorder data, illustrating the range in signal quality, with a high quality, high signal-to-noise ratio exemplar (top panel), and a low quality, low signal-to-noise ratio exemplar (lower panel). Spectrograms are displayed with a 1000Hz bandwidth and 2.5min length, as each line was displayed during the browsing.

Table 3. Summary of data browsed and detections of humpback whales. For each hour-block, two 10min sample periods were examined at the start and half of the hour. The number of hours with humpback whale vocalizations detected in either 10min period is indicated, along with the percentage of hour-blocks with detections for each deployment.

Site	Hour-blocks browsed	Hours with Detections	Percent
Hallaniyats Bay			
Hal 1	1540	1033	67%[1]
Hal 2	4013	2249	56%
Hal 3	3621	1500	41%
Subtotal	9174	4782	52%
Gulf of Masirah			
Mas 1	3409	173	5%
Mas 2	4355	229	5%
Mas 3	3412	271	8%
Mas 4	1262	112	9%
Mas 5	1812	235	13%
Subtotal	14250	1020	7%
Grand Total	23424	5802	25%

[1]Note that this percentage is skewed by the fact that this unit stopped recording in January 2012, during the peak period of song detection for other recorders. As such, this unit was not functioning during the times when other recorders detected lower frequency of song.

where only one or two units in each phrase could be faintly detected but the stereotyped repetitive nature of song allowed it to be diagnosed. This variation was due predominantly to the distance of the singer from the recorder, but also likely affected by the propagation characteristics in the area of each site. Social sounds were documented on very few occasions, interspersed in periods when humpback song was also detected, and only in Gulf of Masirah recordings: at site Mas 2 during two days in late April and two days in mid-May; at Mas 3 during one day in early April; and at Mas 5 during two days in mid-May and one day in early June. A one hour-block was scored as humpback whales 'present' if vocalizations could be detected by the analyst (CM) during either 10-minute sample period within the hour, irrespective of its SNR. Thus detections represent a wide range of acoustic qualities, SNRs and distances of the animals from the unit. Propagation characteristics likely varied at the different sites, such that detection ranges also likely vary; since all recorders were deployed in relatively shallow water (ranging from 16 to 33m) the variation may not be dramatic (e.g., as compared to shallow vs. deep water propagation). However, possible differences in detection range should be considered as a caveat is the following assessment and interpretation of observed differences among sites.

A total of 43,848 10min samples were scanned, representing 23,424 hour-blocks, and resulting in 5,802 hour-blocks with humpback whale detections across all sites and deployments (Table 3). Included in these totals are only days for which there was a complete sample of all 24 hour-blocks. Incomplete days with fewer hours due to lack of recorded data during some hours are excluded to maintain consistency across analyzed days. This summary highlights a distinct difference in the number of detections between the two regions, with 52% of hours examined in the Hallaniyats Bay sites indicating presence of vocalizing humpback whales, as opposed to only 7% of hours examined in the Gulf of Masirah sites. Differences were also apparent among sites within each region, with detections in Hallaniyats sites consistently high and ranging from 41-67%, and in Masirah sites consistently low, ranging from only 5-13% of hours.

As an overview of detections in the two regions, data from each were lumped into a composite depiction of daily and hourly presence (Fig 4 and 5). For this assessment, if a whale was detected in a given hour-block at any of the three sites at which units were simultaneously deployed, that hour was scored as having a whale present (essentially "in the region" as a whole). The stark contrast between Hallaniyats Bay and Masirah is immediately obvious, with whales present (and vocalizing) in the Hallaniyats Bay during most hours between November 2011 and May 2012 (Fig 4). Conversely, in the Gulf of Masirah, presence of vocalizations is comparatively sparse, but relatively consistent from mid-December 2012 until early June 2013.

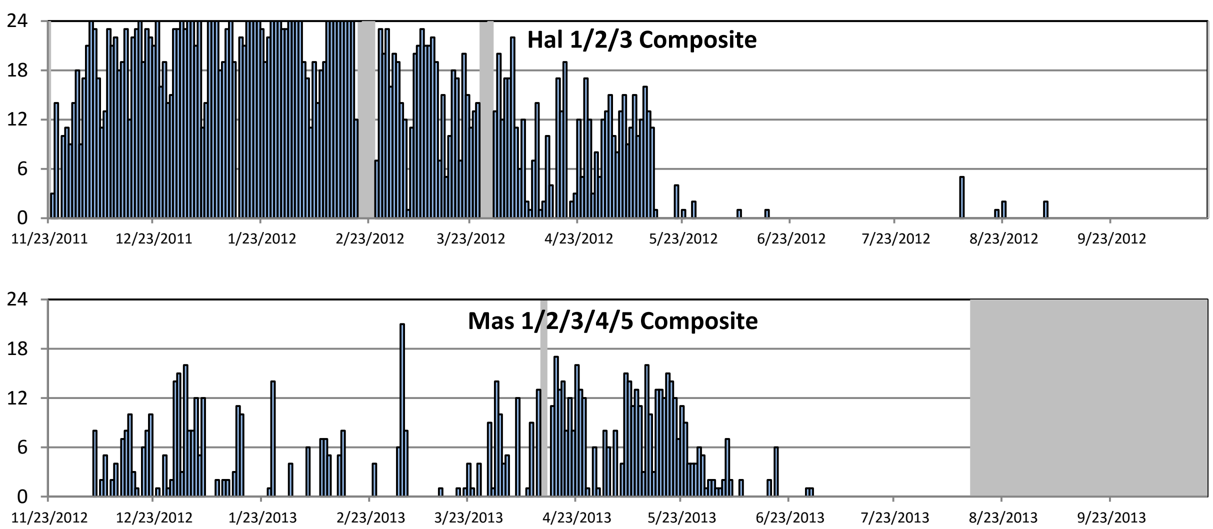


Figure 4. Daily occurrence of humpback whale vocalizations as shown by composite histograms for all sites in Hallaniyats Bay (Hal 1, 2 and 3) and Gulf of Masirah / Duqm (Mas 1, 2, 3, 4 and 5), showing the number of hours in a given day in which humpback whales were detected during complete days for which recordings were available. Since these sites within each region were not close enough to record the same whales, the composite histogram combining the data from all sites represents a general indication of presence in the region as a whole. Grey indicates no data.

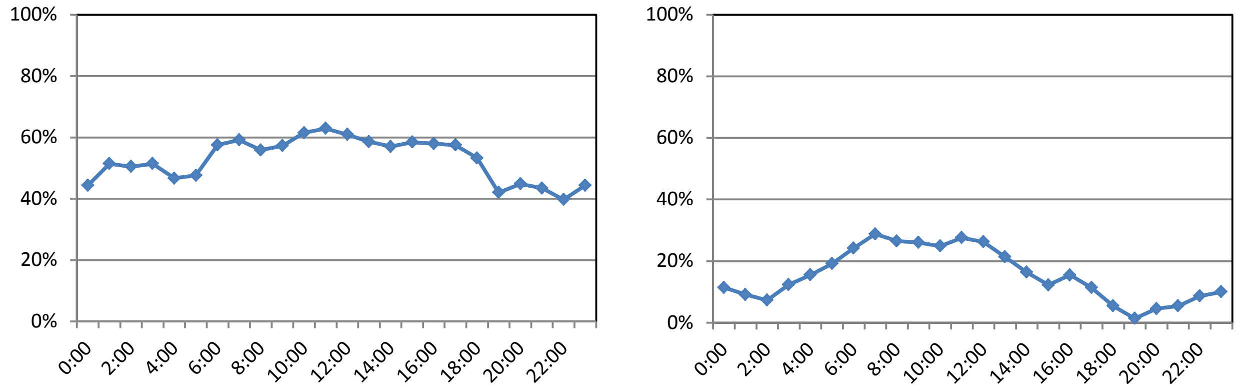
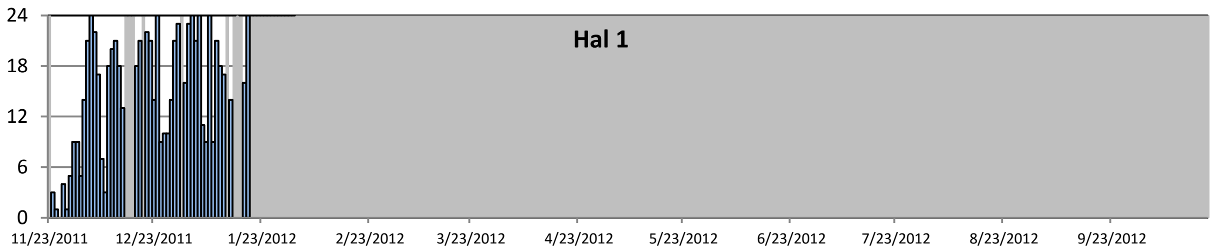


Figure 5. Hourly occurrence of humpback whale vocalizations as shown by composite plots for all sites in Hallaniyats Bay on the left (Hal 1, 2 and 3) and Gulf of Masirah / Duqm on the right (Mas 1, 2, 3, 4 and 5), showing the percentage of hour-blocks for each hour in which humpback whales were detected; these presented data are restricted to the predominant period when whales were detected, between 23 November and 30 June in each region (n = 215 for Hallaniyats and n = 220 for Masirah), excluding 30 Jun to 20 Oct when few whales were detected at either site.

There are several notable differences between the regions. There was a complete lack of detections in Masirah in late November and early December, when there was strong presence in Hallaniyats, and peak presence in Masirah from mid-April to late May when presence of vocalizing whales was declining in Hallaniyats. The difference is also evident in the percentage of each hour with detections, which was consistently and markedly higher in Hallaniyats Bay (Fig 5). For assessment of diel variation, the data was restricted to the period from 23 November to 30 June when the majority of detections were made in either region, in order to not deflate the percentage of hours with detections by including the period after 30 June when few whales were detected at either site. There is a slight diel trend evident in singing activity in both the Hallaniyats Bay and Gulf of Masirah, with a rise in singing activity in the middle of the day during daylight hours and less documented singing activity during night hours.

Within the regions, evaluation of temporal variation in presence is hampered by recording unit failures and changes of recording locations; however, interesting trends are evident in the data that was successfully collected. At each of the three sites in the Hallaniyats Bay, there is a ramp up in singing activity from the start of the deployments on 24 November, with steadily increasing numbers of hours with song for the next two to four weeks (Fig 6). This suggests that there may have been little singing present before the period, which is reinforced by the entire absence of singing during October in Hal 3 (the only site for which October data was available). After late May, very little singing was detected in Hallaniyats Bay and entirely absent from Hal 3. However the detection of song at Hal 2 during six days in the summer and early autumn months indicates that whales were present in the region during this period, and just may not have been vocalizing as frequently as other months.

There were no detections in the Masirah for the first 2 weeks of deployment, followed by a slight ramp up of activity from mid-December to mid-January (Fig 6); thereafter there is intermittent presence of vocalizing whales at Mas 1/2/3 through to mid-March. But the numbers of hours/day never reach the activity levels evident at Hallaniyats during the same time of year. During the second deployment in Masirah, evaluation is hindered by the recording failures, but there appears to be somewhat more activity at the most northern recorder Mas 5, particularly compared to the southern recorder Mas 4 (Fig 6), the latter being nearest to Port Duqm. There are few detections after early June, and none during July and little monitoring available in August.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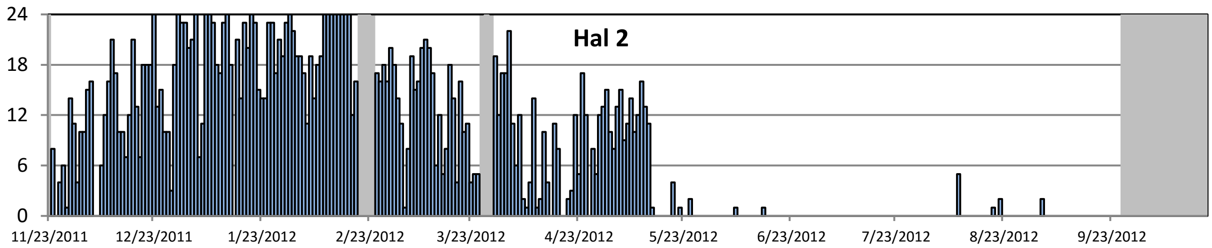
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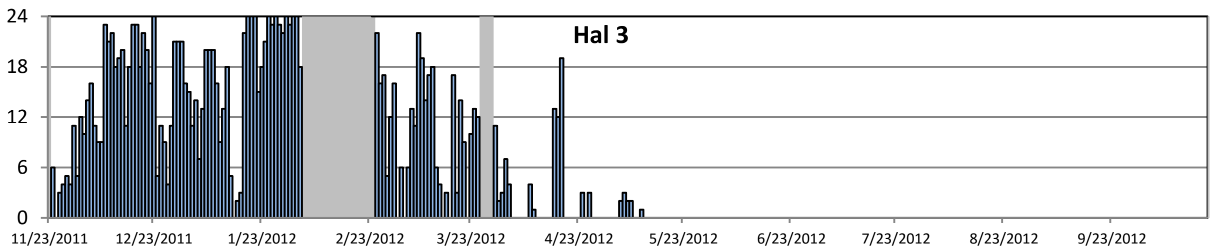
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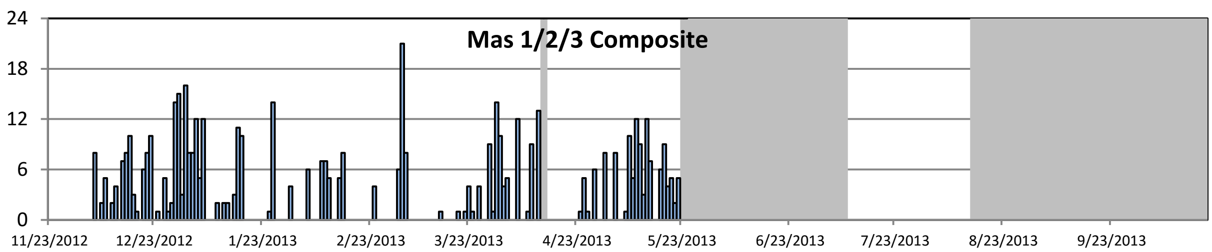
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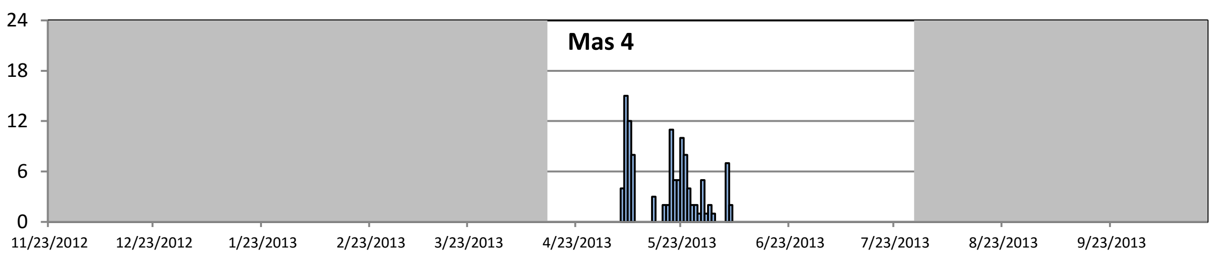
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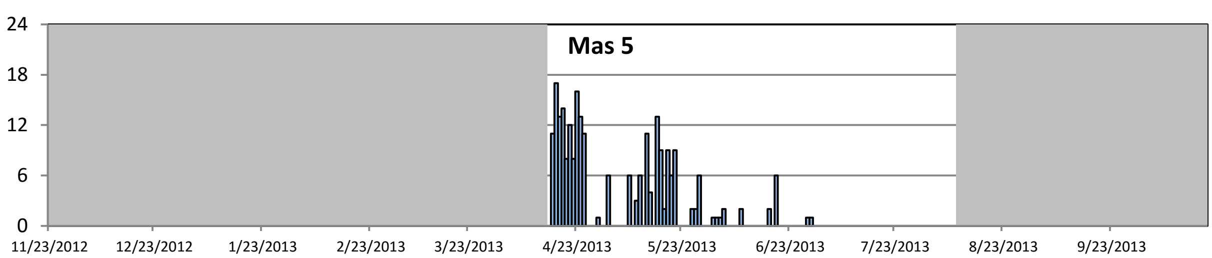
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Figure 6 (Previous page). Hourly occurrence of humpback whale vocalizations at each site, showing the number of hours in a given day in which humpback whales were detected during complete days for which recordings were available. Grey indicates no data. Site Mas 1, 2 and 3 were combined into a composite histogram (see Appendix Figure 2).

DISCUSSION

Implications for seasonality of breeding and feeding activity

A striking aspect of the data presented here is the clear seasonal trend of increasing levels of song from November through March, and a trailing off of detections to almost no vocalizations in either study area from June onward. These timings are consistent with previous studies indicating that Arabian Sea humpback whales adhere to a Northern Hemisphere breeding cycle. Data on pregnancy rates, embryo size, and stomach contents collected during illegal Soviet whaling in the 1960's indicated a calving season between early January and late May, with a peak in early March (Mikhalev, 1997, Mikhalev, 2000). This is congruent with the peaks in song detection in this dataset, as song is a male breeding display and can be considered an indicator of breeding behavior (e.g. Clapham, 1996, Clapham, 2000, Darling and Berube, 2001, Darling *et al*., 2006). Earlier boat-based surveys off the coast of Oman during which short recordings were made at regular intervals also detected song regularly in the Hallaniyats Bay in February and March, but not in the Gulf of Masirah in October and early November (Minton *et al*., 2011), although song was recorded in Masirah in October 2006 (ESO, unpublished data). The absence of song in September and early November in this dataset is consistent with these earlier findings (noting that none of the recorders were collecting data in October).

From an evolutionary perspective, the synchrony of ASHW with the Northern Hemisphere populations' breeding cycle is notable. Genetic evidence indicates that ASHW are derived from a Southern Hemisphere population (either the southwest or southeast Indian Ocean populations), with an estimated colonization and divergence time of ca. 70,000 years ago, and subsequent apparent isolation (Pomilla, Amaral *et al*., 2015). In response to this colonization the population adapted to a non-migratory life history, making it unique among humpback whale populations globally. Clearly there is no potential for the typical latitudinal migrations of other Northern Hemisphere populations to high latitude regions for feeding. Stomach contents from whaling data (Mikhalev, 1997, Mikhalev, 2000) and direct observations of feeding off Oman (Minton *et al*. 2011) indicate that the population has adapted to monsoon driven patterns of productivity (Brock & McClain 1992, Brock *et al.* 1992), with apparent feeding year-round, and lacking the period of fasting that Northern Hemisphere populations undergo while on low-latitude winter/breeding grounds. Despite these life history adaptations in migratory and feeding biology, the population not only maintains a seasonal breeding cycle, but presumably switched to a boreal winter breeding season after previously following an austral winter season (since it was derived from a Southern Hemisphere population). This suggests a strong selective pressure for seasonal breeding, and possibly an abiotic trigger, such as day length, for breeding physiology (e.g., testes growth, hormonal changes, estrus) and subsequent behavioral responses (e.g., singing, male competition).

It remains impossible to know if there were whales present near the recorders during periods when no song was detected, or whether they were in the region but not singing. The presence of isolated bouts of song in June, August and September in Hallaniyats Bay and June in Gulf of Masirah indicates that some whales were present during some periods, and may have been there throughout the year. Detection of social sounds could have been an indicator of presence, but the extremely low prevalence of social sounds in this sample limits how informative the absence of social sounds can be considered for Oman. Social sounds have been documented with greater frequency of occurrence in humpback whale feeding and breeding grounds, such as southeast

Alaska (Cerchio & Dahlheim 2001), the Gulf of Maine (Murray *et al*. 2014), the east coast of Australia (Dunlop *et al*. 2007, Rekdahl *et al*. 2013) and the coast of north Angola (Rekdahl *et al*., in review), and can be considered a reliable indication of humpback whale presence or absence in those regions. However, for this Oman dataset, the absence of social sounds in the months outside the breeding season does not necessarily indicate an absence of humpback whales. Observations during several October/November seismic surveys and dedicated cetacean surveys between 1997 and 2015 indicated that humpback whales are certainly present at that time (Minton *et al*., 2010, Minton *et al*., 2011, Willson *et al*., 2015, Baldwin, 2000). High levels of primary productivity (Brock and McClain, 1992, Brock *et al*., 1992) and direct observations of high densities of sardines and probable feeding behavior in the Gulf of Masirah at this time of year indicates that this location may serve as a prime feeding ground for this population (Minton *et al*., 2011). Song has been documented during boreal summer months on several northern hemisphere feeding areas (e.g. Clark and Clapham, 2004, Eriksen *et al*., 2005, Magnúsdóttir *et al*., 2014, Mattila *et al*., 1987), however it is greatly reduced from the level of breeding ground activity and tends to ramp up in the autumn before migration begins. This is consistent with the pattern observed in Hallaniyats Bay and the Gulf of Masirah during June to September.

The apparent differences in the documentation of social sounds in comparison to other populations is noteworthy (e.g. Dunlop *et al*. 2007, Rekdahl *et al*. 2013, Murray *et al*. 2014). The paucity in rates of detection of social calling off Oman is likely due to the vast difference in abundance and density of animals between the Arabian Sea and other regions, combined with the sparseness, relatively low amplitude and short propagation range of social sounds as compared to song. With an estimated population of fewer than 100 individuals off the coast of Oman (Minton *et al*., 2011) densities are extremely low in all areas surveyed, which would result in less frequent opportunities to record social vocalizations. Additionally, there may also be less social activity and motivation for social vocalizations than in other regions where populations are one to two orders of magnitude larger, and large feeding or breeding aggregations are not uncommon. The largest humpback whale group size recorded during small boat surveys between 2000-2003 off the coast of Oman was three individuals, with 97% of 146 sightings comprised of single individuals or pairs (Minton *et al*., 2011). Groups of four and five have since been observed but appear to be linked to feeding opportunities (ESO, unpublished data). Competitive groups, characteristic of every other known humpback whale breeding ground (e.g. Clapham, 2000) and documented to be highly vocal among behavioral categories in the breeding ground (Silber, 1986), were never observed off the coast of Oman between 2000-2003 (Minton *et al*., 2011) and only rarely thereafter (ESO, unpublished data). This low mean group size may be a primary contributing factor, given that social vocalizations in other studies were documented to increase with larger group sizes (particularly in groups of three or more) and with social interactions (Silber, 1986, Rekdahl *et al*. 2015).

Spatial distribution and possible seasonal shifts

Previous work has documented the presence of whales in Hallaniyats Bay from January to March, and in Gulf of Masirah during June and October to November (Minton *et al*., 2011, Corkeron *et al*., 2011), but little information existed outside of these periods in either region. The acoustic detections presented here confirm the consistent and constant presence of whales in Hallaniyats Bay from November to May and at least sporadic presence from June to October. In the Gulf of Masirah, the occurrence of song is markedly less than in Hallaniyats Bay, but nevertheless there is consistent presence from December to June. This suggests that although Hallaniyats Bay appears to be more utilized than Gulf of Masirah for breeding behaviors (at least by displaying males), breeding activity appears to be spread throughout the entire sampled region. Genetic determination of sex suggested that the whales in Hallaniyats Bay in January to March were strongly skewed towards males, whereas near parity in the Gulf of Masirah during October/November (Minton *et al.* 2011). Therefore, it is possible that the patterns revealed by acoustic detection of song may reflect the distribution of males more than the population as a whole. However, a male-skewed sex ratio is a common feature of humpback whale breeding grounds globally, so the reported sex ratio in Hallaniyats Bay is not surprising and may reflect the timing of sampling more that spatial distribution (i.e., season and region are confounding factors in the genetic sampling). It should be noted that the observed differences in singing activity between the two regions assumes that detection ranges of vocalizing whales are not significantly different among sites; this assumption will be tested with forthcoming assessments of ambient noise and sound propagation loss. Currently, given the similarity of depth of deployed recorders, coupled with the consistent magnitude in difference in detected singers between regions, we believe the contrast reflects the actual distribution of animals. However, it remains possible that the difference is exaggerated by the closer proximity of deep water to the Hallaniyats Bay Sites Hal 1 and 3 (Figure 1) and a consequent greater detection range in that direction. The greater similarity of bathymetry of Site Hal 2 with the Masirah Sites, also argues that the observed differences between the regions is real.

There was a simultaneous and near constant presence of song recorded at all sites in Hallaniyats Bay during the period when all recorders were collecting data (Fig 6). This indicates that despite the low density of this population, individual whales engaged in typical breeding behavior are dispersed throughout a relatively broad portion of the region simultaneously, as opposed to aggregations moving around the region. This was also evident in the relatively low occurrence of chorusing (i.e., three or more singers within acoustic detection range) observed at any one site, with only one or two whales detected in the vast majority of hour-blocks. This pattern was also noted by field teams during tagging work in 2014, with clear and sustained separation noted between adjacent singers. This is markedly different from other documented breeding habitats during singing season (e.g., Hawaii, Mexico and Angola) where simultaneous detection of three or more singers in relatively close proximity to each other is common (Cholewiak 2008, Cerchio *et al* 2010, 2014).

Considering temporal patterns within regions, singing activity appears to diminish after late February off Hal 3, the most southern site in Hallaniyats Bay, with pulses of activity in March and April and a near complete cessation by May (Fig 6). Conversely at Hal 2, the most northern site in Hallaniyats Bay, there is some variation in March and April but strong and consistent presence from late April to late May, when there is an abrupt decline and near cessation of singing (Fig 6). Also in Gulf of Masirah, despite the lower prevalence of song overall, there is an indication of a seasonal offset with Hallaniyats Bay, particularly at the most northern site Mas 5, exhibiting a peak late in the season in May when activity in Hallaniyats Bay is waning. Therefore, there is some indication of a northern shift during the singing season, with the most northern sites in both regions exhibiting the latest peak in detections for that region, and a shift from Hallaniyats Bay to Gulf of Masirah late in the season.

A seasonal shift of singing males from the Hallaniyats Bay north toward the Gulf of Masirah would be consistent with findings of earlier boat-based surveys (Minton *et al*., 2011). This northward movement is also visible in recently obtained satellite tagging data where all six whales tagged in the Hallaniyats Bay in February-March 2014 and 2015 were seen to move into the Gulf of Masirah in the following weeks (Willson *et al*., 2015). Of these whales, five were known males, and as such, this seasonal shift in distribution may be more linked to male behavior than female behavior. Previous studies also documented a predominance of observations of males in Hallaniyats Bay, while whales biopsied in the Gulf of Masirah neared parity between males and females (Minton *et al*., 2011). Therefore, despite the loss of long-distance latitudinal migration and a seasonal separation of feeding and breeding behavior that is a characteristic of every other population of humpback whales, the ASHW population may still engage in comparatively minor seasonal movements. This pattern may be solely related to changes in spatiotemporal distribution of productivity and prey, or possibly an expression of remnant migratory behavior. These conclusions regarding season shifts should be considered preliminary given limitations inherent in the general sampling regime. Furthermore, it is also important to remember that the deployments in these regions were not simultaneous but in different years. Although it is considered unlikely, the differences between the regions, as well as temporal/seasonal variation in presence may be due to differences between the years rather than a seasonal shift in distribution.

Next Steps and Recommendations

Acoustic monitoring within the range of ASHW was a research priority identified at the Dubai Workshop 2015 (Minton *et al*., 2015; WP provided at this meeting) and reported on at IWC SC66a (2015). The relevant recommendations were generally to "Implement regional research activities that include passive acoustic monitoring at strategic locations, dedicated boat surveys for genetic sampling, photo-identification and collecting data on distribution and numbers, and further analyses of acoustic and genetic data already obtained from Oman and other locations". With specific regard to acoustics, there was a recommendation to "Deploy passive acoustic devices in key locations throughout the suspected current range of ASHWs – with an initial phase in areas of known occurrence and/or concentrations of Soviet catches, and a second phase of deployment to be informed by the opportunistic and dedicated data collection". This study represents the first successful implementation of these recommendations, with a priority being focused on the analysis of existing acoustic data that had been collected off Oman prior to the Dubai workshop. Next steps for processing these data will be:

(i) Further analysis of patterns of spatial and temporal presence of vocalizations including estimation of detection range.
(ii) Assessment of ambient noise and masking potential in the different sampled regions.
(iii) Definition of temporal change in song patterns within the Oman sample, and a geographic variation comparison with songs from humpback whales in the southwest Indian Ocean.

This study has identified trends within two discrete study areas representing important ASHW habitats off the coast of Oman. There is a clear need to expand the research effort to other areas of the Arabian Sea suspected to host ASHW. Additional fieldwork and acoustic monitoring is recommended to define the full spatial and temporal extent of humpback whale presence and singing activity in all range states, including previously un-sampled areas off Oman, Iran, Pakistan, India and the Maldives. Furthermore studies should be designed and pursued as a means to understand the potential impacts of emerging noise-producing anthropogenic activities to humpback whale breeding display and communication, such the Duqm port development (Baldwin et al., 2015). As an example of relevant documented impacts, Cerchio *et al*. (2014) found significant reduction in humpback whale singing activity off the coast of Angola in response to occurrence of seismic surveys. Given that song is a breeding display believed to be critical to male reproductive success, and potentially used by females to choose mates (Clapham, 1996, 2000, Cholewiak 2008), disruption of singing off the coast of Oman and other ASHW breeding areas could have severally negative impacts on this already endangered and sparsely distributed population. Completing the recommended work will require the deployment of a network of archival PAM recorders across the habitat and specific acoustic modeling/ maps in areas adjacent to noise sources including shipping channels, dredging areas, port anchorages and petroleum exploration, with a view to measuring the potential impact of these activities and working with government and industry to design appropriate mitigation measures.

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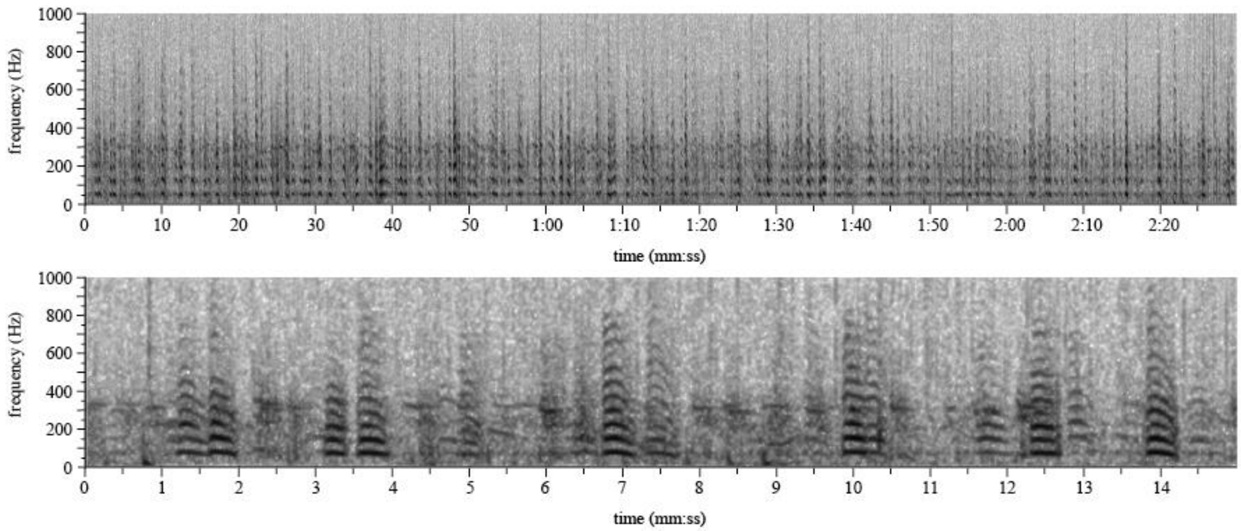
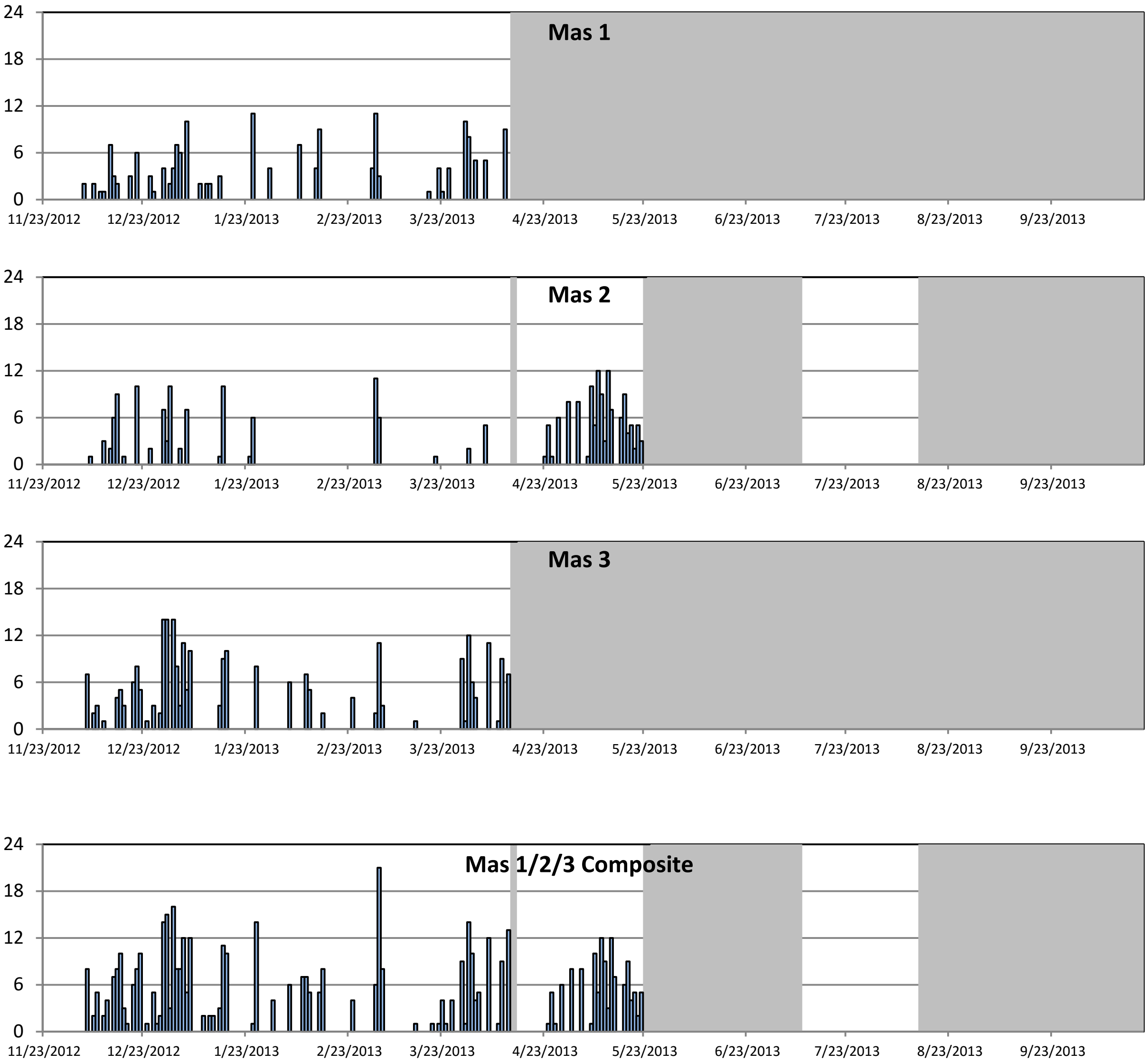
APPENDIX



Appendix Figure 1. Example of a common and ubiquitous signal recorded during the Oman deployments that we believe to be a fish vocalization and chorusing. Spectrograms are presented illustrating the signal in the analysis parameters used for browsing (top row, 1000Hz bandwidth, 2.5sec / spectrogram line) as well as a detail to better illustrate the specific vocalizations (bottom row, 15sec window).



Appendix Figure 2. Hourly occurrence of humpback whale vocalizations at site Mas 1, 2 and 3, showing the number of hours in a given day in which humpback whales were detected during complete days for which recordings were available. Since these sites were close enough to record the same whales, a composite histogram combining the data from the three sites in shown on the bottom row, for which presence was assessed for each hour at any of the three sites. Grey indicates no data.