Two unit analysis of Sri Lankan pygmy blue whale song over a decade

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Originally uploaded to JASA on 28 August 2018, Revision uploaded to JASA on 26 November 2018

Running title: Two units in blue whale song

ABSTRACT

Sri Lankan pygmy blue whale song consists of three repeated units: 1) low frequency pulsive unit, 2) frequency modulated (FM) upsweep, and 3) long tonal downsweep. The Unit 2 FM unit has up to three visible upsweeps with energy concentrated at approximately 40 Hz, 50 Hz, and 60 Hz, while the Unit 3 (~100 Hz) tonal downsweep is the most distinct unit lasting 20-30 sec. Spectral characteristics of the Unit 2 and Unit 3 song elements, along with ocean sound levels, were analyzed in the Indian Ocean from 2002-2013. The peak frequency of the tonal Unit 3 calls decreased from approximately 106.5 Hz to 100.7 Hz over a decade corresponding to a 5.4% decrease. Over the same time period, the frequency content of the Unit 2 upsweeps did not change as dramatically with only a 3.1% change. Ambient sound levels in the vocalization bands did not exhibit equivalent patterns in amplitude trends. Analysis showed no increase in the ambient sound or compensated peak amplitude levels of the tonal downsweeps, eliminating the presence of a Lombard effect. Here it's proposed that each song unit may convey different information and thus may be responding to different selective pressures.

KEY WORDS

Sri Lankan pygmy blue whale, song, ambient sound, selection

I. INTRODUCTION

Animal songs are relatively complex, often species-specific signals that are given in the context of intra- or intersexual selection (Tyack, 2000; Beecher and Brenowitz, 2005). Different song types in a repeated display are often seen as parts of the overall display giving an indication of a singer's fitness. However, many song types consist of more than one unit, each of which can have a different function. For example, European starlings (Eens *et al.*, 1993) and greater white-lined bats (Davidson and Wilkinson, 2004) have more tonal units in their songs when singing to females than when singing to males. In chaffinches, the end flourish of songs is more important for mate attraction (Riebel and Slater, 1998) while the trill functions in competition between males (Leitao and Riebel, 2003). In canaries, females only show a copulation solicitation display to so called 'sexy syllables', which have a more complex structure than other units of the song (Vallet and Kreutzer, 1995). When units have different functions as illustrated above, changes in unit structure over time are often not the same among units because the selection pressures driving change or maintaining stability can be different (Janik and Slater, 2003). Such changes can therefore be used as an indicator of functional diversity in units.

Multiple species of baleen whales produce song. Whale song ranges from simple repeated single units as observed in fin whales (Watkins *et al.,* 1987) to more complex, hierarchical song structure as observed in humpback song (Payne and McVay, 1971; Winn and Winn, 1978). Blue whale song is of intermediate complexity and typically thought to be produced by males (Oleson *et al.,* 2007). The exact behavioral function of any baleen whale song remains unknown, but it is generally agreed that song functions in both intra- and intersexual selection within the context of mating (Tyack, 2000).

Blue whale song structure also provides information useful for characterizing population distribution and delineation worldwide. Song is a reliable population identifier because the song structure has shown to be stable over decades for many populations (McDonald *et al.,* 2009). Where traditional genetics, morphology, and osteology studies have not succeeded in producing a clear picture of blue whale population structure, song is a reliable population identifier that appears to be stable over time and has provided another indicator of structure and behavioral grouping. Yet, the internal characteristics of the song units themselves have not been stable over time. There has been a worldwide decline in the tonal frequencies of portions of blue whale songs for at least 7 different populations across all oceans (McDonald *et al.,* 2009; Gavrilov *et al.,* 2011, 2012). McDonald *et al.* (2009) described a decrease in the most salient unit of the Sri Lankan pygmy blue whale song from 116 Hz in 1984 to 106 Hz in 2002. The theories posed in an effort to explain the observed worldwide decrease in tonal song components included: cultural conformity and directional synchrony, response to changing environmental sound levels, increasing body size post whaling, changing ocean sound absorption and propagation related to global warming, post whaling abundance increases, sexual selection, and biological interference; however, none of the proposed hypotheses fully explained the observed trends (McDonald *et al.,* 2009; Gavrilov *et al.,* 2011).

Sri Lanka pygmy blue whales are vocally and biogeographically distinct from other pygmy blue whale and true blue whale subpopulations in that they are largely resident in the northern Indian Ocean and appear to constitute a unique acoustic population (Alling *et al.,* 1991; McDonald *et al.,* 2006; Stafford *et al.,* 2011; Samaran *et al.,* 2013). Stereotyped and repeated phrases of Sri Lankan pygmy blue whale song consist of three components: 1) a low frequency pulsive unit, 2) a frequency modulated (FM) upsweep unit, and 3) a long tonal downsweep unit

(Figure 1). Energy in the pulsive Unit 1 component peaks at approximately 30 Hz and can often not be reliably detected above the background noise. The Unit 2 FM component has up to three visible upsweeps with energy concentrated at approximately 40 Hz, 50 Hz, and 60 Hz. The Unit 3 (~100 Hz) tonal downsweep is the most distinct of the call units and lasts 20-30 sec. This salient Unit 3 song component has been used in previous studies as an indicator of whale presence to gain a better understanding of the Sri Lanka pygmy blue whale distribution and behavioral ecology (e.g. Samaran *et al.,* 2013). Year-round acoustic presence of the Sri Lanka pygmy blue whale in the northern Indian Ocean, as indicated by the detection of the Unit 3 component, has been observed in recordings from the island of Diego Garcia (north and south) and to the northeast of Amsterdam Island (Stafford *et al.,* 2011; Samaran *et al.,* 2013).

In this study, we investigated multiple Sri Lankan song units in two dimensions: time and frequency structure. We simultaneously consider Unit 2 and Unit 3, as opposed to the one most salient unit (Unit 3) assessed in previous studies, to allow us to look for differential changes in elements. Unit 1 was not included in this analysis because it was not consistently visible above the background noise. We hypothesize that if different units of blue whale song have different functions, we could expect divergent changes in units over time related to different selection pressures.

II. METHODS

A decade of data (2002-2013) from the Indian Ocean Comprehensive Nuclear-Test-Ban Treaty International Monitoring Station (CTBTO IMS) at Diego Garcia (6.3421 S, 71.0143 E) was accessed from the AFTAC/US NDC (Air Force Tactical Applications Center/US National Data Center) and analyzed to detect Sri Lankan pygmy blue whale vocalizations. The Diego

Garcia CTBTO IMS (H08) consists of a triad of hydrophones deployed on each side of the island and positioned in the deep sound channel. All data in this study were recorded off the north side of the island from hydrophone N1 which was at a depth of 1248 m. Data were sampled continuously at a 250 Hz sampling rate and 24 bit A/D resolution. The hydrophones were calibrated individually prior to initial deployment in January 2002 and re-calibrated while at-sea in 2011, and there was no measured change in hydrophone sensitivity during the re-calibration of the H08 N1 hydrophone. Hydrophone H08 N1 had a flat (3 dB) frequency response from 8-100 Hz. Information from individual hydrophone response curves was applied to the data to obtain absolute values over the full frequency spectrum (5-115 Hz). Data less than 5 Hz and from 115-125 Hz were not used due to the steep frequency response roll-off at these frequencies.

Phrase Units 2 and 3 (Figure 1) were selected for analysis in this study, as these were the most salient signals consistently recorded at high amplitude and visible above the ambient sound. The maximum estimated range of signal detection for the peak frequencies of the two analyzed units from Diego Garcia North was 600-1000 km depending on frequency and bearing. Seasonal transmission loss was modelled along 360 bearings at 1° resolution using the OASIS Peregrine parabolic equation model for a receiver in the deep sound channel and a source position extending over the upper 300 m of the water column to determine the maximum estimated range of signal detection along each bearing (Miksis-Olds *et al.,* 2015). The estimated range of signal detection in this region is significantly greater than the 50-150 km range estimated by Širović *et al.* (2009) and Samaran *et al.* (2010) required for individual signal classification of pygmy blue whale calls off Antarctica and Crozet Islands, respectively, but it is consistent with blue whale song detection reported by Stafford *et al.* (1998) in the northeast Pacific Ocean and by Harris (2012) in the Indian Ocean. The dominant factor influencing the propagation loss associated with estimated detection range north of Diego Garcia in this study was bathymetry (Miksis-Olds et al., 2015) and is also likely to be the factor limiting detection range in the other referenced studies.

Spectral characteristics of the ~ 100 Hz tonal downsweep (Unit 3) and the 60 Hz FM upsweep (Unit 2), along with long-term patterns of ambient ocean sound, were assessed from weekly plots of average power spectral density (PSD). Weekly average PSDs were used instead of measuring characteristics from individual calls to reduce the effect of short-term variations due to the differences in call characteristics of each whale and are reflective of the characteristics of the regional population. This methodology is consistent with the analysis methods of Gavrilov *et al.* (2012) that documented the steady decrease in vocalization frequency of Antarctic blue whales. Weekly average PSD was calculated to identify frequency peaks and peak sound pressure levels within targeted frequency bands associated with the calling population of Sri Lankan pygmy blue whales at approximately 110-100 Hz and 57-63 Hz (Figure 2). A 3 dB signal-to-noise threshold was implemented within the targeted bands of each unit to identify whale presence and vocal contribution above the background sound. PSD was computed for each 2 hour period with a 15000-point DFT and Hanning window with no overlap, corresponding to an approximate resolution of 0.02 Hz, and averaged over each week.

PSD of ambient ocean sound was averaged weekly over the targeted 7-Hz frequency bands of 100-107 Hz for the tonal Unit 3 component and analogous 56-63 Hz band for the Unit 2 component to capture the full band of whale calls over the decade. Weekly average PSD was also computed in adjacent 93-100 Hz and 107-114 Hz bands around Unit 3 and 49-56 Hz and 63-70 Hz bands around Unit 2 where there were no contributions from whales. A second-order polynomial curve created from points in the adjacent sound bands that did not contain whale call energy was fit to the two targeted bands of the weekly average PSD that contained the peak in whale calling. A polynomial fit allowed a more accurate estimation of ambient sound without whale contributions because the sound pressure level was not flat across the frequency range (Figure 2). The spectral level of ambient sound at the peak calling frequency was interpolated from the fitted curve and is representative of the sound level with no whale contributions. To determine the contribution of sound in the targeted bands from whales alone for each of the song units, the peak level of the weekly average PSD was corrected or compensated for the PSD of ambient sound from the fitted sound level estimate. Recording periods saturated with natural seismic signals from underwater earthquakes were excluded from this analysis. The full spectrum sound levels including the natural seismic signals (5-115 Hz) were computed as part of a previous study (Miksis-Olds *et al.,* 2013).

Frequency peaks from the weekly PSD estimates from Weeks 21 and 22 for each year and both units were included in a linear regression analysis conducted in R software vs. 3.3.1 (R Core Team, 2016) Frequency was the response variable, and year and unit were included as explanatory variables (unit was included as a factor). An interaction term between year and unit was included as part of model selection, conducted using an F-test, to investigate whether the rate of frequency change significantly differed between the two units. Model fit was visually assessed using a quantile–quantile (Q-Q) plot. Model assumptions of linearity, constant error variance, error independence and normality were tested in R software through diagnostic plots and relevant hypothesis tests. Linear regression analyses were also used to assess any trends in the noise level measurements. Two models were fitted: one using the weekly average PSD levels and the other using the compensated (whale-only) peak PSD levels. In each model, PSD level was the response variable, and year and frequency band (56-63 Hz and 100-107 Hz) were included as explanatory variables (frequency band was included as a factor). Data from Weeks 21 and 22 only were used to be consistent with the frequency analyses. Model fit and assumptions were tested in the same way as the frequency analyses.

III. RESULTS

Sri Lankan pygmy blue whale vocal presence, as detected from peaks in the weekly averaged PSDs, was seasonal (Figure 3). The week of peak calling activity was variable within a year across the decade and likely related to oceanographic variability driving whale distribution (Branch *et al.,* 2007a; Stafford *et al.,* 2011). Vocal activity was detected nearly year round at this location. Peak periods of vocal activity (based on the number of hours per week with calls present) averaged over the decade occurred during Weeks 21 and 22 corresponding to the months of May-June in the austral fall.

Annual rate of decrease of both units was estimated from the regression analysis using the average peak frequencies in Weeks 21 and 22 from 2002-2012 to reflect the measured shift during the peak in vocal activity. The QQ plot (not included here) suggested an adequate model fit and all model assumptions were met.

The peak frequency of both units of the Sri Lankan pygmy blue whale call significantly decreased across years ($F_{1,36} = 395.69$, $p < 0.001$). Unit 3 tonal calls peak frequencies measured in Weeks 21 and 22 decreased from 106.5 Hz to 100.7 Hz over a decade corresponding to a 0.54 Hz/year rate of decrease (Figures 4, 5, 6). This is an approximate 13% decrease from 1984 when the peak frequency was reported at 115.5 Hz (McDonald *et al.,* 2009), and a 5.4% decrease over the past decade. Over the same time period, the frequency content of the ~ 60 Hz Unit 2 FM upsweeps measured in Weeks 21 and 22 did not change as dramatically. The regression model predicted a 0.18 Hz/year rate of decrease (Figures 4, 5, 6) corresponding to only an approximate 3.1% decrease over the past decade. The interaction term between year and unit was selected in the model ($F_{1,36} = 92.66$, $p < 0.001$), indicating that the rates of frequency change across years differed significantly between the two units. A series of simple linear regressions showed a weak within-season trend in the Unit 3 call with six of the eleven seasons having a significant progressive decrease at the 95% significance level in tonal frequency over one annual season (Figure 7). However, with the application of the Bonferroni correction for multiple tests (n=11), (applying a significance level of 0.0045= 0.05/11), the only significant seasonal trend was observed in 2005 (Figure 7).

Both weekly noise level measurements displayed a visible seasonal trend in the two targeted frequency bands (56-63 Hz and 100-107 Hz) associated with the migratory presence of vocalizing whales (Figure 8). The frequency decrease observed in the whale call units over the decade did not appear to be related to increasing ambient sound. The linear regression models fitted to the Week 21 and 22 data had adequate fit and the model assumptions were met. The average spectrum level in both frequency bands actually showed a decreasing annual trend over the same decadal time period ($F_{1,41} = 10.238$, $p = 0.003$) (Figure 8a-b), which is consistent with decadal trends over similar frequencies in particular percentiles (Miksis-Olds *et al*., 2013). The maximum spectrum level reflecting the seasonal whale contribution to the ambient sound showed no significant decadal trend ($F_{1,41} = 0.1664$, $p = 0.685$) (Figure 8c-d).

IV. DISCUSSION

In this ten-year dataset from Diego Garcia, the Sri Lankan blue whale song was a prominent feature of the soundscape. Analysis of weekly PSDs revealed calling nearly year-round, peaking in the austral fall (May-June). The advantage of the analysis approach used in this study is that the frequency parameters obtained from weekly PSDs in the annual analysis reflect the vocal activity of the subpopulation as a whole, as opposed to measured call characteristics from individual whales assuming that the weekly PSD peak is not the result of a single singing whale. This eliminated the need for extrapolation of information from individual singers, which can be age-, sex-, and reproductive status-dependent and related to segregation in migration of the general subpopulation (Craig *et al.,* 2003; Stevick *et al.,* 2003). We analyzed two units in the blue whale song and found that the previously reported frequency decrease over time occurs more strongly in the Unit 3 call compared to the Unit 2 call. The Unit 2, ~60 Hz component of the call is more stable over time than Unit 3 at ~100 Hz, showing that the reported decrease in peak frequency in blue whale song does not affect the entire song uniformly.

The timing of singing and the fact that documented baleen whale singers are males implies that at least parts of song are a mating display (Tyack, 2000). The seasonal peak of Sri Lankan pygmy blue whale vocal activity occurs at Diego Garcia between April and June (Stafford *et al.,* 2011; Samaran *et al.,* 2013, this study), which corresponds to the subpopulation's breeding cycle. Although the distribution of the Sri Lankan population extends widely into the southern hemisphere, their reproductive cycle is offset from other southern Indian Ocean populations by six months, aligning with a northern hemisphere breeding cycle (Mikhalev, 2000; Branch *et al.,* 2007b). In addition, in other populations it is blue whale males that produce song (McDonald *et al.,* 2001; Oleson *et al.,* 2007) and peak song production by Sri Lankan pygmy blue whales occurs during the breeding season; it logically follows that song is connected to reproductive behavior as is proposed for other baleen whale species such as humpback whales (reviewed in Herman, 2017) and fin whales (Croll *et al.,* 2002; Oleson *et al.,* 2014).

The most salient feature of this multi-part blue whale song is Unit 3, the long, ~ 100Hz tonal downsweep. Like McDonald *et al.* (2009), who reported a 10 Hz decrease between 1984 and 2002 (Table 1 in McDonald *et al.,* (2009)) we also observed a gradual, almost linear decrease in the frequency of this sound, from 106.5 Hz in 2002 to 100.7 Hz in 2012, or about 0.54 Hz/yr. Unlike other studies examining blue whale calls (e.g. Gavrilov *et al.,* 2012) we did not observe any significant "resetting" of the Unit 3 frequency each year. Unit 2 of the song showed a less dramatic change in frequency over time, potentially making this unit a more stable, attractive cue for passive acoustic monitoring applications such as density estimation.

Many interesting theories about the mechanism driving this continual frequency decrease of blue whale song units have been proposed (McDonald *et al.,* 2009). Changes in the physical and chemical properties of the ocean over time or changes in calling depth hardly affect frequency parameters and can therefore be excluded as possible explanations. Frequency changes to compensate for noise from an anthropogenic source has been observed in other species, but the expected frequency shift in response to increasing ocean noise would be an increase in tonal frequency (McDonald *et al.,* 2009), as observed in belugas (Lesage *et al.,* 1999) and right whales (Parks *et al.,* 2007), rather than a decrease, as observed in blue whale populations. Furthermore, we did not observe an increasing trend in weekly sound pressure levels in blue whale vocalization bands, indicating background noise levels did not increase significantly over the course of this decadal study and did not contribute to a Lombard effect (see also Miksis-Olds *et al.,* 2013; Hotchkin and Parks, 2013). Potential biological interference or masking from other vocalizing marine mammals in the frequency range below 100 Hz is predominantly restricted to other baleen whale species. In the Indian Ocean, this would include vocalizations from fin, humpback, Bryde's, sei, and other blue whale subpopulations (i.e.

Antarctic, Madagascar, Australian) (McDonald *et al.,* 2006, 2009; Ballance and Pitman, 1998; Best *et al.,* 1998). At the Diego Garcia location over the time period examined, there were no other whale calls detected that overlapped the Sri Lankan Unit 3 song component. Hence, biological and anthropogenic noise is not a viable explanation for the observed frequency shift in this subpopulation.

Increase in blue whale body size post whaling has also been suggested as a source of decadal frequency decrease because body size sets the lower limit of the frequency of sound production (Bradbury and Vehrencamp, 1998). Accurate historical records of blue whale body size are difficult to obtain due to lack of measurement standards and deliberate misreporting of species during commercial whaling (Best, 1989; Branch *et al.,* 2007c). McDonald *et al.* (2009) hypothesized that present day body size distributions of blue whales have returned to pre-whaling values based on the rationale that blue whales reach sexual maturity and have 95% of their mature body weight at 8 yrs (Lockyer, 1984). If we assume that the present day blue whale body size distribution has remained stable at pre-whaling levels while tonal frequencies of song components continue to decrease, an increase in whale body size post-whaling driving the observed frequency shift is not supported. Sexual selection has also been eliminated as a potential driver of song frequency decrease within blue whale populations as the change we are observing is too fast for genetic sexual selection. McDonald *et al.* (2009) felt the most plausible explanation for the decline in tonal frequencies of blue whale song was that of increasing population size post whaling contributing to a sexually selected tradeoff for singing males between amplitude and frequency. This explanation might be expected to apply equally to all song units, which is not case here with different rates of change. Additionally, to date there is no definitive evidence of decreased amplitude of blue whale calls (Gavrilov *et al.,* 2011), but the acoustic technology in ocean observing systems is evolving and may allow us to fully investigate this theory in the future.

Given the data currently available, what new can we say about this tonal frequency decrease of blue whale vocalizations? The analysis of two stereotyped blue whale song units in this study, compared to the single unit analyses of previous studies (McDonald *et al.,* 2009; Gavrilov *et al.,* 2011), provides additional information critical to developing a plausible theory explaining the mechanistic driver behind the observed trend; however, it should be noted that it is unknown whether the observed tonal decreases are detectable or significant to the blue whales, because so little is known about the hearing capabilities of this species. Because Unit 2 and Unit 3 are changing differently over time, it is possible that different units of blue whale song, particularly Sri Lankan song, might serve different functions and carry different information. Songs or calls of numerous species have multiple parts that apparently serve different functions and change differently over time (Janik and Slater, 2003). In killer whales (*Orcinus orca*), biphonic and monophonic calls vary in diversity and are thought to convey different information such as group and individual identification (Filatova *et al.,* 2012). In white crowned sparrows (*Zonotrichia leucoophrys*), the trill, which encodes dialect identity, changes faster than other units of the song (Nelson *et al.,* 2004). Riebel and Slater (1998) found that the end flourish in chaffinch (*Fringilla coelebs*) song is the part that attracts the females, and hypothesize that the start of the song gives different information, and both parts would therefore be subject to different kinds of selection pressures. The Savannah sparrow (*Passerculus sandwhichensis*) has a relatively simple four-part song with segments that convey different information. During a 30-year study, the introductory notes and buzz segments of Savannah sparrow song changed little over time and are believed to identify the species. The middle segment was quite variable and might distinguish individuals. The fourth segment, the terminal trill, decreased in both. Each segment is therefore likely to communicate different types of information (Williams *et al.,* 2013).

Perhaps Unit 2, the more stable portion of the Sri Lankan blue whale song, conveys information such as species identification or draws attention to the caller before it produces Unit 3 thereby priming listeners to pay attention. The reduced rate of change in Unit 2 in the Sri Lankan population reinforces the fact that simplistic explanations such as change in body size may not be the sole explanation for the song frequency decrease. The observed differential frequency shift of the Unit 3 song component, while the Unit 2 song remained more stable by comparison, suggests possible voluntary and purposeful control of the song units. Parks *et al.* (2007) point out that the upward shift in right whale calls to compensate for increased noise in the environment must be a behavioral change as opposed to a sexually selected response because the long term shift occurred within the known lifespan of individual whales. Similarly here, the continuing decrease is occurring within the lifespan of individual whales. However, in this study increased environmental noise was not identified as a potential driver as in right whales (Parks *et al.,* 2007). There remains the possibility that the decrease in frequency of the Sri Lankan pygmy blue whale Unit 3 call, as well as the tonal frequency decrease observed in other blue whale populations, may be voluntary to increase the range of effective communication.

The high apparent conformity and change in unison within the Sri Lankan population to sing the same song suggests that whales can hear one another within the Indian Ocean and may likely be changing this part of their song via social learning and cultural transmission. Such song synchrony has been observed in other baleen whales such as fin whales (Oleson *et al.,* 2014; Širović *et al.,* 2017), humpback whales (Payne and Payne, 1985; Cerchio *et al.,* 2001) and other populations of blue whales (Gavrilov *et al.,* 2012). However, numerous blue whale populations are in acoustic contact in the Indian Ocean, yet there is no evidence of song hybridization such as that seen in humpback whales (Noad *et al.*, 2000).

One of the most intriguing aspects of the blue whale song unit decrease is that it is happening worldwide (McDonald *et al.,* 2009). McDonald *et al.* (2009) thoroughly explored potential causes for this global decrease in frequency, and predicted a stabilization of frequency as populations continue to recover from exploitation. Recent work by Monnahan *et al.* (2015) estimates that the eastern North Pacific population of blue whales is close to carrying capacity (97% carrying capacity, 95% CI 62%-99%), which provides an ideal opportunity to explore the prediction of McDonald *et al.* (2009) in future years. Frequencies have also continued to decrease in the Sri Lankan, Australian pygmy (Gavrilov *et al.,* 2011) and Antarctic (Gavrilov *et al.,* 2012) populations of blue whales possibly indicating that these populations may have not yet approached carrying capacity and continue to grow. At some point, whale anatomy and physiology cannot continue to support the observed frequency decrease. Investigating other units of song in other populations of blue whales may provide additional insight into this phenomena and overall blue whale song function.

ACKNOWLEDGEMENTS

JLMO and SLN were funded by the Office of Naval Research (Award N000141110619). DH was funded by the Office of Naval Research (Award N000141612364). Thanks are extended to James Neely (AFTAC), Richard Baumstark (AFTAC), Mark Prior (formerly CTBTO), and Andrew Forbes (formerly CTBTO), Mario Zampolli (CTBTO) and Georgios Haralabus (CTBTO) for their assistance in data transfer and transfer of knowledge of CTBTO data. Thanks also to AFTAC and CTBTO for making the data available (CTBTO Virtual Data Exploitation

Centre (vDEC): https://www.ctbto.org/specials/vdec/). Please note that the views expressed in this study are those of the authors and do not necessarily represent the views of the CTBTO Preparatory Commission. Finally, we thank two anonymous reviewers for their time and insightful comments that helped make this a stronger paper. This is PMEL contribution # 4840. Finally, we thank two anonymous reviewers for their time and insightful comments that helped make this a stronger paper.

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FIGURE CAPTIONS

Figure 1. Sri Lankan pygmy blue whale call recorded from the CTBTO IMS station at Diego Garcia. The Unit 1 pulsive (1), Unit 2 frequency modulated upsweep (2), and Unit 3 tonal downsweep (3) components are labelled. (color online)

Figure 2. Weekly average spectrum from Week 3 in year 2004 recorded from the CTBTO IMS station at Diego Garcia. The arrows indicate the spectral peaks corresponding to the two salient components (60 Hz Unit 2 and ~ 100 Hz Unit 3 from Figure 1) of the Sri Lankan pygmy blue whale call analyzed as part of this study. The red line shows the polynomial curve fit to a portion of the PSD for the 60 Hz Unit 2 target frequency band spanning 56-63 Hz. (color online)

Figure 3. Annual time series and decade average of hourly vocal presence detected per week. Average decadal vocal activity peaked during Weeks 21-22, and data from these two weeks were used in further power spectral density trend analyses. (color online)

Figure 4. Long term spectral average from the Diego Garcia H08 N1 location in the Indian Ocean. The decadal spectral image was constructed using a 1-hour window and 0.25 Hz resolution. A decrease in the Sri Lankan blue whale call is observed over time in the 110-100 Hz range. (color online)

Figure 5. Peak frequency of Sri Lankan whale vocalizations determined from weekly PSD sound averages. The blue circles are the weekly peaks measured throughout the season when whales were vocally present. The trend line is related to the red circles that are peak frequency from Weeks 21 and 22 of each year. The greyed regions designate the 95% confidence intervals for the trend. (color online)

Figure 6. Power spectral density of ambient ocean sound averaged over Week 22 (28 May – 3 June) in 2002, 2008, and 2012. The indicated peaks reflect the tonal peak of Sri Lankan blue whale calls. (color online)

Figure 7. Within season average rate of frequency change of the ~ 100 Hz Unit 3 song unit. The * denotes significant frequency decreases over a single season (p-value < 0.05 for annual linear regression analysis) for six of the eleven years analyzed. The ** denotes the single year showing a significant seasonal decrease after the application of a Bonferroni correction (p-value< 0.0045). (color online)

Figure 8. Average and compensated maximum spectrum levels in the 56-63 Hz (a, c) and 100-107 Hz (b, d) frequency bands. The blue circles are the weekly PSD levels throughout the full dataset. The trend line was fitted to data from Week 21 and 22 of each year (red circles). The greyed regions designate the 95% confidence intervals for the trend. Band compensated spectrum levels reflect the contribution of whales alone corrected for the PSD of ambient sound from the fitted sound level estimate. (color online)

Figure 1.

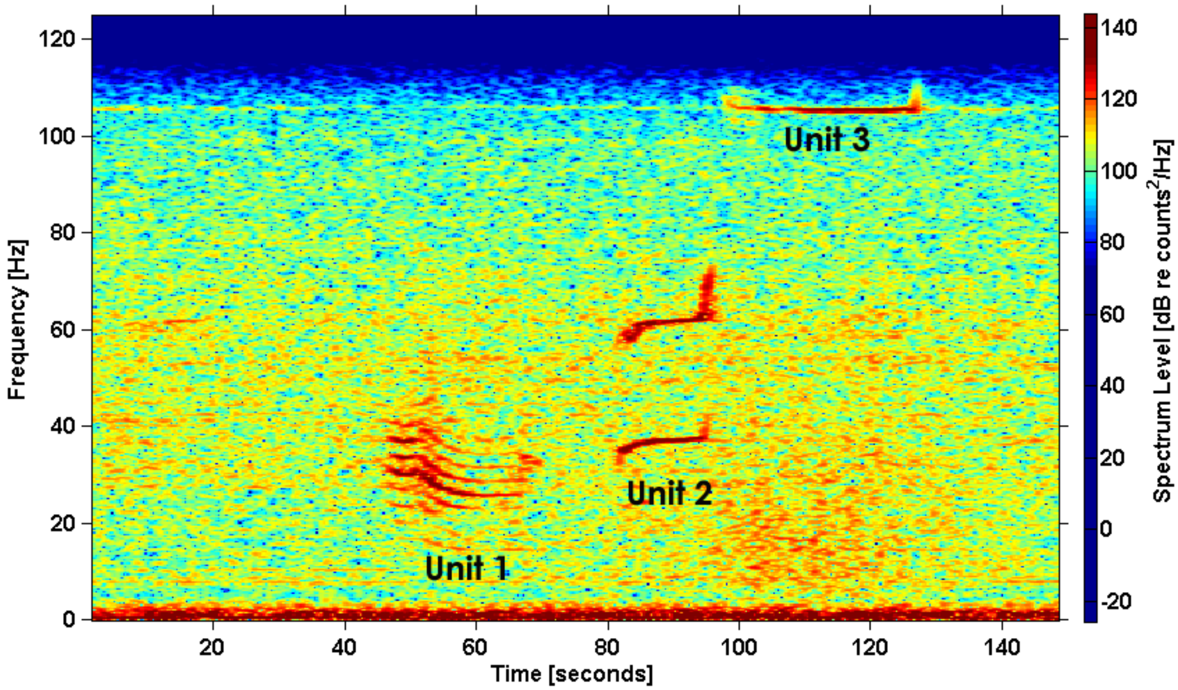

Unit 1
Unit 2
Unit 3
Frequency [Hz]
Time [seconds]
Spectrum Level [dB re counts^2/Hz]

Figure 2.

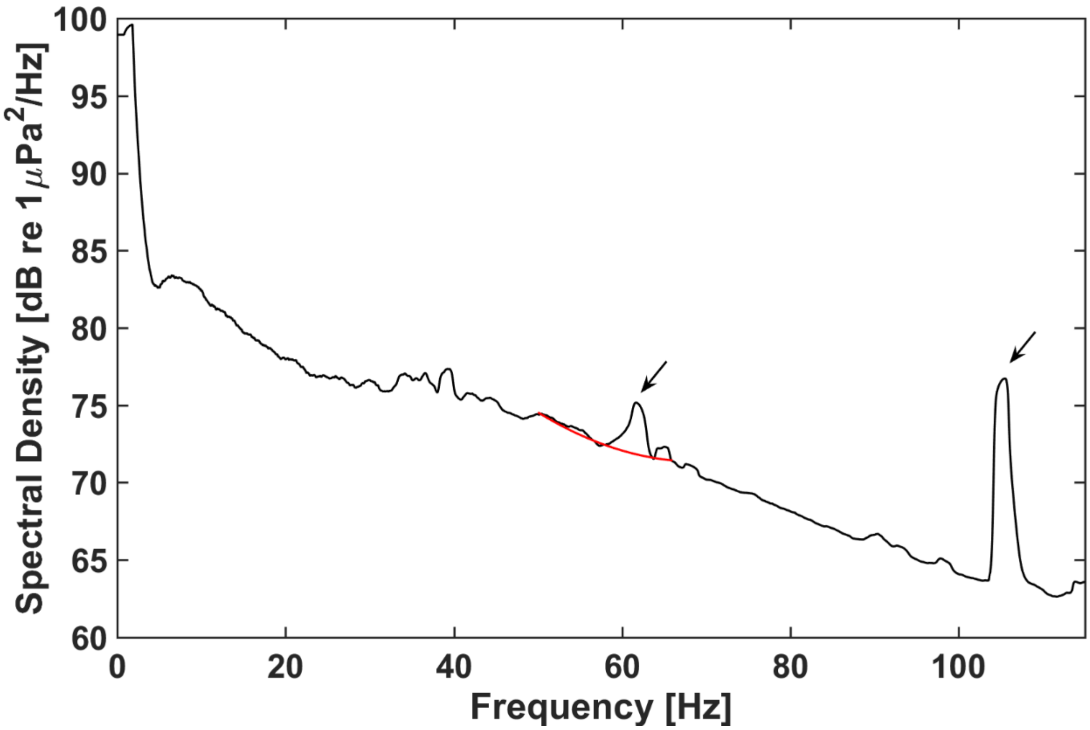
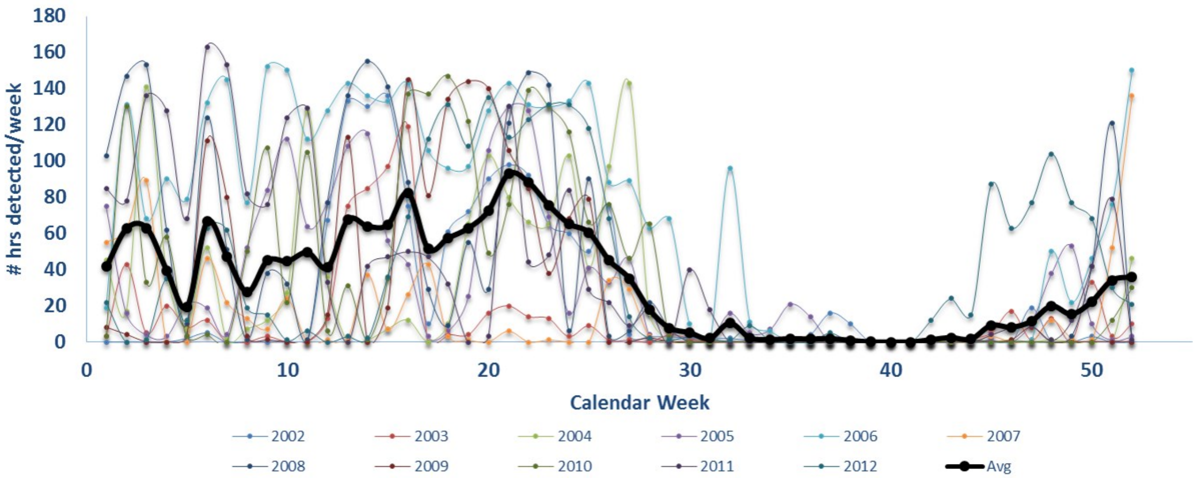
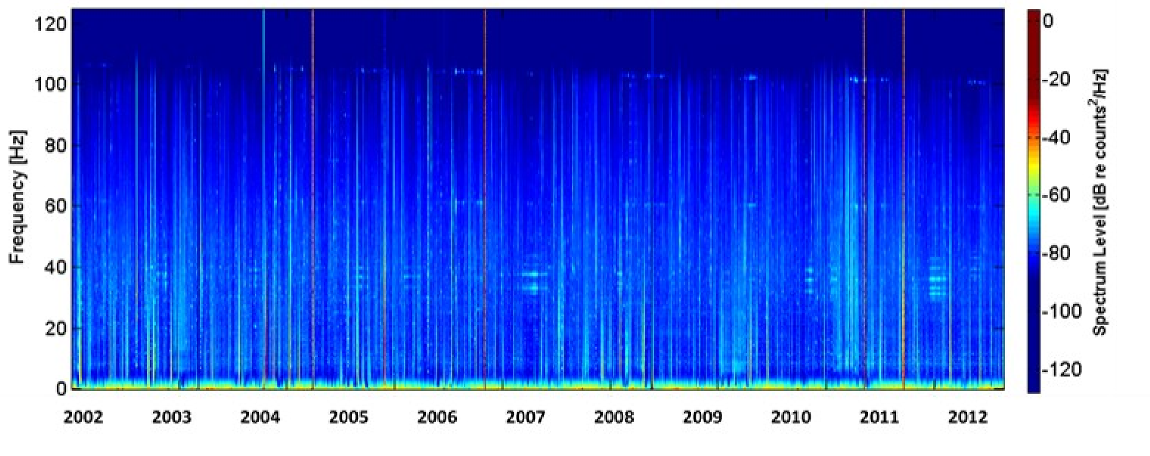

Spectral Density [dB re 1μPa²/Hz]
100
95
90
85
80
75
70
65
60
0
20
40
60
80
100
Frequency [Hz]

Figure 3.



hrs detected/week
180
160
140
120
100
80
60
40
20
0
0
10
20
30
40
50
Calendar Week
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Avg

Figure 4.



Frequency [Hz]
0
20
40
60
80
100
120
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Spectrum Level [dB re counts^2/Hz]
0
-20
-40
-60
-80
-100
-120

Figure 5.

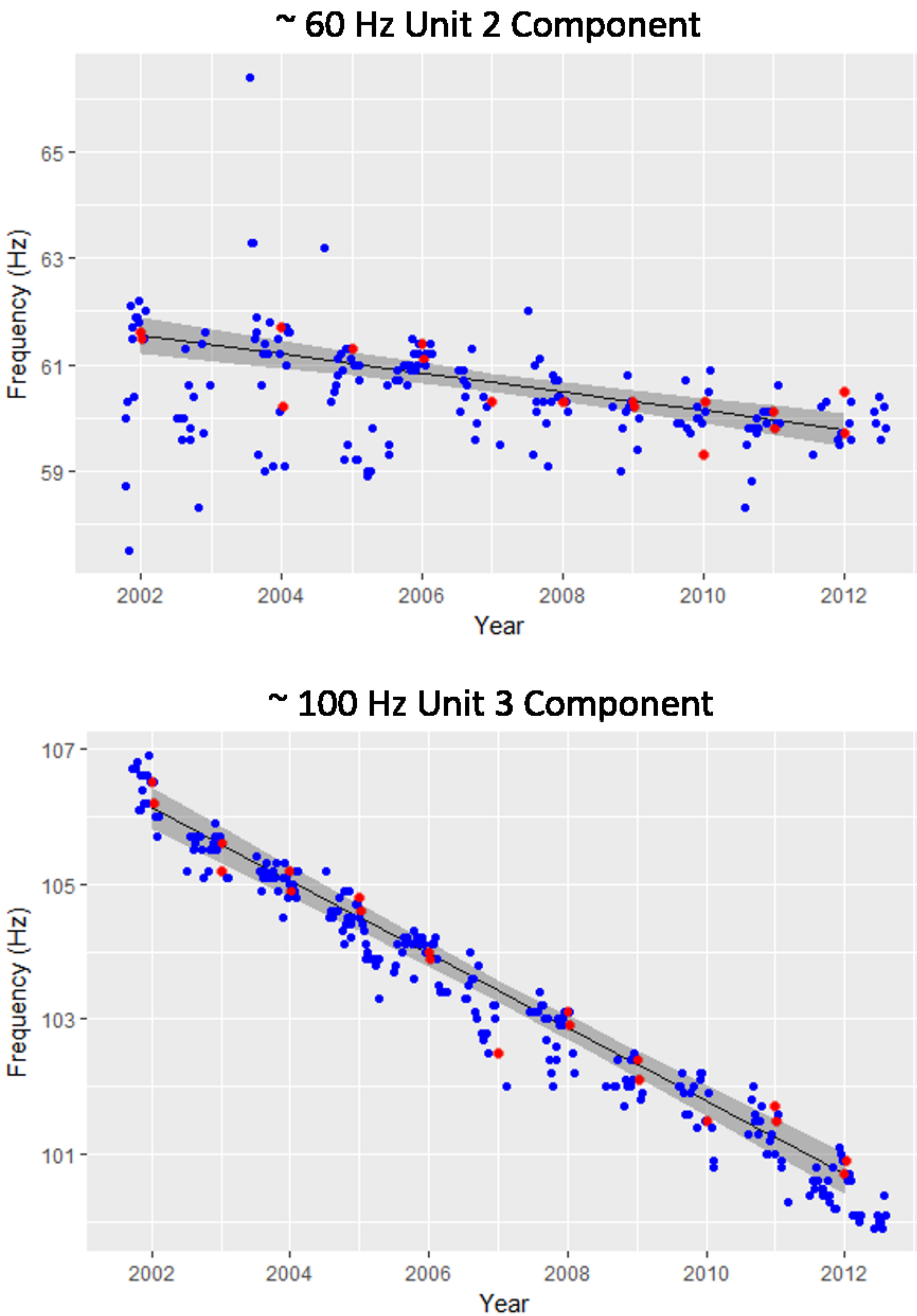

~ 60 Hz Unit 2 Component
Frequency (Hz)
65
63
61
59
2002
2004
2006
2008
2010
2012
Year
~ 100 Hz Unit 3 Component
Frequency (Hz)
107
105
103
101
2002
2004
2006
2008
2010
2012
Year

Figure 6.

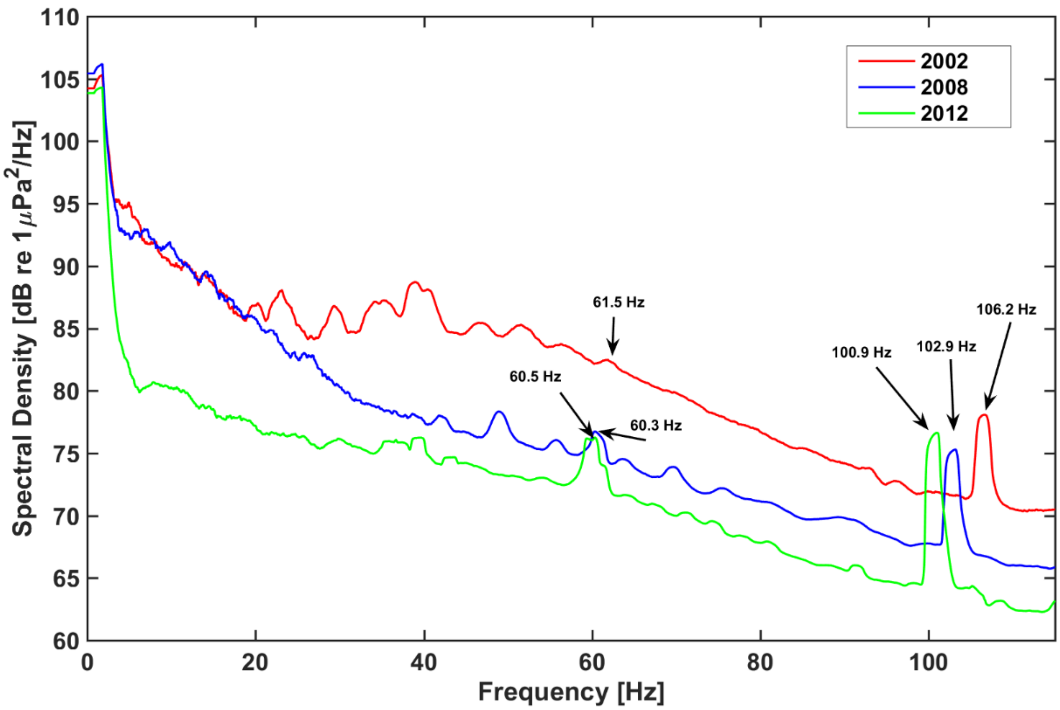

2002
2008
2012
61.5 Hz
106.2 Hz
100.9 Hz
102.9 Hz
60.5 Hz
60.3 Hz
Spectral Density [dB re 1μPa²/Hz]
Frequency [Hz]
110
105
100
95
90
85
80
75
70
65
60
0
20
40
60
80
100

Figure 7.

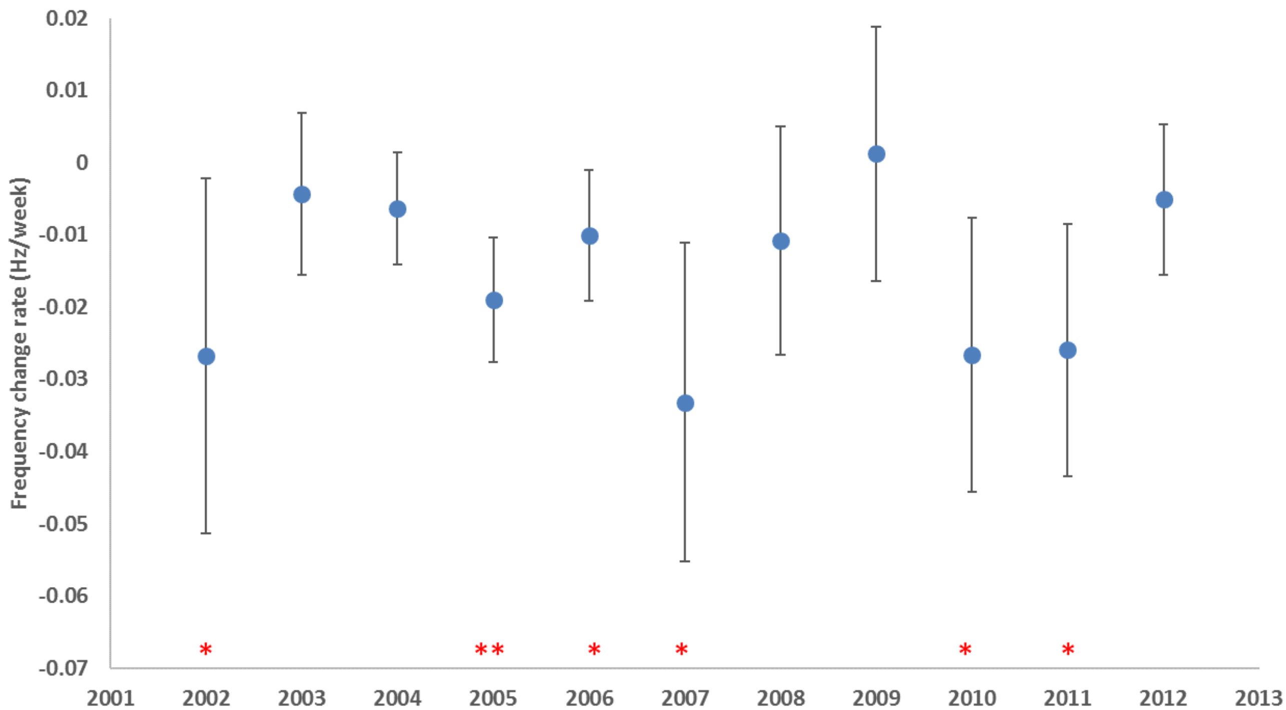
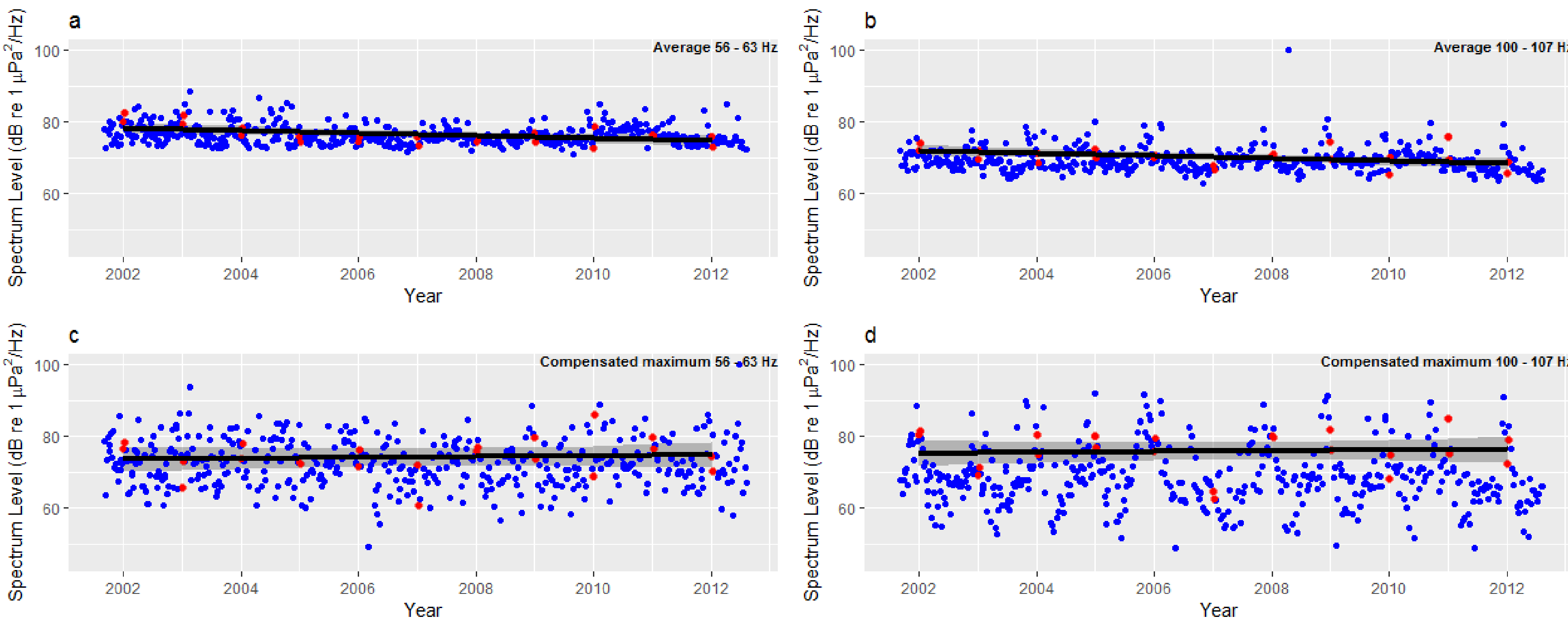

Frequency change rate (Hz/week)
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
*
**
*
*
*
*

Figure 8.


a
Average 56 - 63 Hz
b
Average 100 - 107 Hz
c
Compensated maximum 56 - 63 Hz
d
Compensated maximum 100 - 107 Hz
Spectrum Level (dB re 1 µPa²/Hz)
100
80
60
2002
2004
2006
2008
2010
2012
Year