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Seasonal occurrence of fin whale song off Juan Fernandez, Chile

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ABSTRACT: Fin whales *Balaenoptera physalus* were the species of baleen whale most widely caught by commercial whaling fleets off the Chilean coast and are globally classified as Endangered. However, very little is known about the present distribution and seasonal movements of fin whales off the coast of Chile. Passive acoustic data collected at the HA03 station of the Preparatory Commission for the Comprehensive Nuclear Test Ban Treaty Organization off the Juan Fernandez Archipelago (JFA) between 2007 and 2016 were analyzed. The temporal occurrence of fin whale song was examined using automatic detection via spectrogram cross-correlation of song notes and by calculating the average acoustic power in the frequency bands of fin whale song. Fin whale song off JFA was composed of regular 17 Hz notes associated with high-frequency components at 85 Hz, with singlet phrasing at a dominant primary inter-note interval of 14.4 s and a secondary interval of 30.8 s. There was a clear seasonal pattern in acoustic presence that was consistent across all years: low or no song during the austral summer and a peak in song occurrence in austral winter. A propagation loss model estimated the detection range at this site to be 186 km. Where the fin whales that are heard off JFA spend the summer months remains an open question. Possible locations include the Western Antarctic Peninsula and/or off northern-central mainland Chile. Further studies should be pursued to better understand the distribution and seasonal movements and to support the conservation of this Endangered species.

KEY WORDS: Fin whale · *Balaenoptera physalus* · Juan Fernandez · Chile · Southeast Pacific · Passive acoustic monitoring

1. INTRODUCTION

Fin whales *Balaenoptera physalus* were the species of baleen whale most widely caught by commercial whaling fleets off the Chilean coast, comprising 46.9% of all catches, totaling 4512 individuals between 1929 and 1983 (Aguayo-Lobo et al. 1998). Most catches off the Chilean coast were concentrated in central and northern Chile around 35° S, 32° S, and 19° S (Aguayo-Lobo et al. 1998). Although this species has been assessed as Endangered worldwide by the International Union for Conservation of Nature (IUCN) (Reilly et al. 2013), as well as by Aguayo-Lobo et al. (1998) in Chilean waters, very

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little is known about the distribution or seasonal movements of fin whales off the coast of Chile or through the southeast Pacific.

Fin whales off Chile are thought to be part of a population that migrates to the Southern Ocean (Clarke et al. 1978); however, no recent studies have examined this migration in detail. Sightings of fin whales have occurred off central Chile (approximately 33° to 40° S), but also off northern and southern Chile, the Juan Fernandez Archipelago (JFA), and Easter Island (Aguayo-Lobo et al. 1998 and references therein). Off coastal northern-central Chile, in the waters surrounding Isla Chañaral, which form part of the coastal islands that make up the Humboldt Penguin National Reserve (~29°S), high summertime aggregations of fin whales have been reported feeding off Humboldt Current krill *Euphausia mucronata* (Capella et al. 1999, Perez et al. 2006, Toro et al. 2016). Outside of these summertime sightings of fin whales, the question of where fin whales spend the rest of the year remains unknown.

Passive acoustic monitoring (PAM) is a widely used method to examine the temporal and spatial distribution of large whales throughout the world's oceans, including for fin whales (e.g. Watkins et al. 2000, Stafford et al. 2009, Širović et al. 2015). Male fin whales are known to produce song in loud repetitive sequence of notes around 20 Hz (hereafter referred to as 20 Hz notes; Watkins et al. 1987, Charif et al. 2002, Croll et al. 2002, Širović et al. 2007). Associated with the ~20 Hz note, fin whales in some areas produce a high-frequency component (HFC). Off the western Antarctic, this occurs around 85 Hz (recorded in 2014; Baumann-Pickering et al. 2015) and 89 Hz in 2003 (Širović et al. 2009), and off the eastern Antarctic around 99 Hz (Širović et al. 2009), suggesting that these HFC may serve as possible population identifiers (Gedamke & Robinson 2010). Fin whales also produce high-frequency notes, sometimes with, and sometimes without, a 20 Hz note; in the North Atlantic, these occur around 135 to 140 Hz (Simon et al. 2010, Castellote et al. 2012).

Another fin whale song characteristic which might be a population identifier — albeit a dynamic one — is the duration of the intervals between 20 Hz notes, the inter-note interval (INI), which is sometimes also referred to as the inter-pulse interval. Hatch & Clark (2004) found that INI was the most distinguishing characteristic among regional songs. The 20 Hz notes can occur in singlets, doublets or triplets (Širović et al. 2017 and references therein) with varying INIs. Depending on location, INIs vary from 9 to 34 s (Thompson et al. 1992, Hatch & Clark 2004, Delarue et al. 2009, Castellote et al. 2012, Oleson et al. 2014, Širović et al. 2017). Seasonal changes in INIs have been reported: In the northeast Pacific, INIs were found to be shorter in summer and increase progressively over the winter but are then reset annually (Oleson et al. 2014, Širović et al. 2017); in the western North Atlantic, INIs were short (9.6 s) in late summer to early winter and long (15.1 s) in spring (Morano et al. 2012). Lastly, annual increases in INI have been reported in the northeast Pacific at a rate of 0.54 s yr^{-1} over a decade (Weirathmueller et al. 2017).

Although the temporal (seasonal, inter-annual) variation in fin whale singing behavior is clearly dynamic and only now becoming better understood, examining fin whale song in time and space has proven to be a useful approach for achieving a broad understanding of presence/absence and seasonal residence patterns of vocal animals (Širović et al. 2004, 2009, Stafford et al. 2009, Morano et al. 2012, Weirathmueller et al. 2013, Sciacca et al. 2015). In the Southern Ocean, fin whale song occurrence is between February and May, during the austral summer and autumn (Širović et al. 2004). In the Northern Hemisphere, fin whale song is recorded from boreal autumn through spring usually peaking during the boreal winter (Watkins et al. 2000, Stafford et al. 2009, Simon et al. 2010, Nieukirk et al. 2012, Weirathmueller et al. 2017). An exception is the Mediterranean Sea, in which song peaks between spring and summer months (Sciacca et al. 2015). Fin whale song seasonality has not been determined for any sites in the South Pacific.

The Preparatory Commission for the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO; www.ctbto.org) has an International Monitoring Station called HA03, located ~670 km west of mainland Chile, on Robinson Crusoe Island, part of the JFA. HA03 has 6 hydrophones that collect acoustic data for the primary purpose of detecting underwater explosions. In this study, we examine passive acoustic data from a single hydrophone collected at the HA03 station to determine the temporal variation of fin whale 20 Hz song occurrence in order to gain an understanding of the seasonal distribution of fin whales off Juan Fernandez in the southeast Pacific. We also provide an estimate of detection range to determine the geographic area acoustically monitored by the HA03 station. Although our aim here is not to provide a detailed description of song characteristics, we examine the presence of HFC, INI, and any possible changes in frequency of song notes and HFC over time. This is the first report of fin whale vocalizations and seasonal occurrence from this region.

2. MATERIALS AND METHODS

2.1. Acoustic data from the Juan Fernandez Archipelago

Passive acoustic data (42 704 h) were collected continuously at a 250 Hz sample rate by a bottom-mounted hydrophone at 813 m depth at the HA03 station off JFA (Fig. 1). These data were made available from the CTBTO through the Chilean Nuclear Energy Commission in Santiago, Chile. Acoustic data from a single hydrophone, i.e. the North Station Node 1 at 33° 27′ 28.8″ S, 78° 56′ 2.8″ W, were used for this analysis. Data from 2007–2009 and 2014–2016 were analyzed; no data were available between 27 February 2010 and 22 April 2014 due to a tsunami that hit the Chilean coast and the JFA on 27 February 2010 destroying the HA03 station, which was eventually repaired in April 2014. Prior to the 2010 tsunami, the hydrophone used had a sensitivity of 561.81 µPa per digital count; after the tsunami, the replacement hydrophone had a sensitivity of 558.9 µPa per digital count.

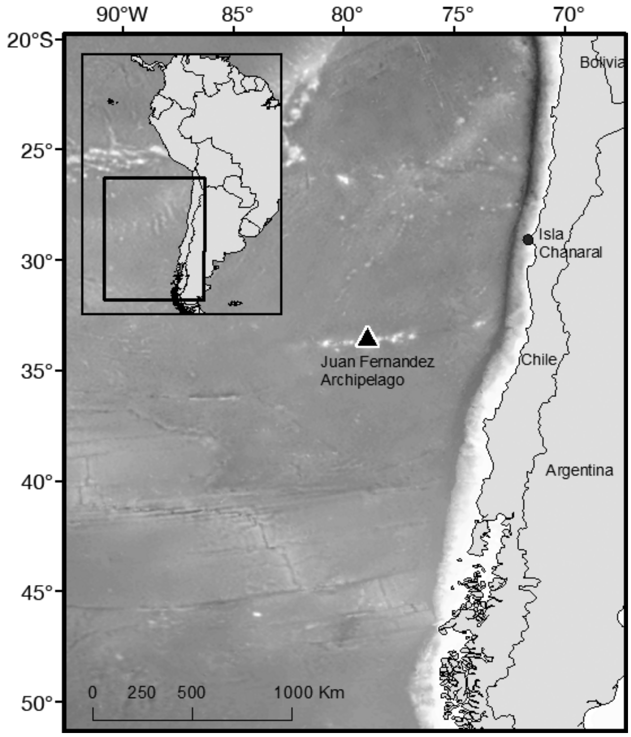

Fig. 1. Study area and location (black triangle) of CTBTO HA03 station off Juan Fernandez

2.2. Median power spectral density analysis

Each year of data was first examined using median power spectral density (PSD) plots made using PAMGuide (Merchant et al. 2015) to gain a broad view of the acoustic environment and examine the frequencies at which acoustic power occurred, including the frequency bands where we expected fin whale calls to occur: around 20 Hz and around 89 Hz or 99 Hz (Širović et al. 2009). PSD analysis provides the acoustic power expressed in sound pressure level in 1 Hz frequency bands (dB re: 1µPa^2 Hz^{-1}); the 50% percentile (median) of the PSD was then calculated and plotted, identifying peaks in acoustic power around 17 Hz, assumed to be fin whales; 24 Hz, assumed to be southeast Pacific blue whales (Buchan et al. 2014, 2015); and 86 Hz assumed to be fin whales (Fig. 2). The frequencies of these peaks were used to inform the subsequent analyses described below. Median PSD per year allowed us to visually determine the frequency bands of interest for the 17 Hz notes and 85 Hz HFC, i.e. 16–22 Hz and 84–86 Hz, respectively.

2.3. Fin whale acoustic power over time

To examine fin whale song occurrence over time for each year of data, we examined the average power around the 17 Hz and the 85 Hz frequency bands. Based on the median PSD plot (Fig. 2), we defined the fin whale bands of interest as being 16–22 Hz for the 17 Hz note and 84–86 Hz for the 85 Hz HFC. These ranges should account for any possible frequency shift within the year and also avoid the 24 Hz southeast Pacific blue whale frequency band. We confirmed the frequency range of interest around 17 Hz and 86 Hz by measuring the peak frequencies of 100 individual fin whale song pulses around 17 Hz and 100 song pulses around 86 Hz, using Raven Pro 1.4 (Bioacoustics Research Program 2014). Pulses were selected from different pulse trains spread over a week of data. The 17 Hz pulses were found to range between 16.6 and 24.4 Hz with an average center frequency of 18.9 ± 2.6 Hz. The 86 Hz pulses were found to range between 83.0 and 87.5 Hz with an average center frequency of 85.3 Hz ± 0.8 Hz, which supports the choice of fin whale bands at 16–22 Hz for the 17 Hz note and 84–86 Hz for the 85 Hz HFC.

From the PSD output data (hourly average of acoustic power in 1 Hz frequency bands), we examined fin whale acoustic power in the 16–22 Hz band over time in a stepwise manner for each hourly bin: we (1) calculated average acoustic power per 1 Hz frequency band over the 16 to 22 Hz bands ('16–22 Hz band'); (2) calculated average acoustic power

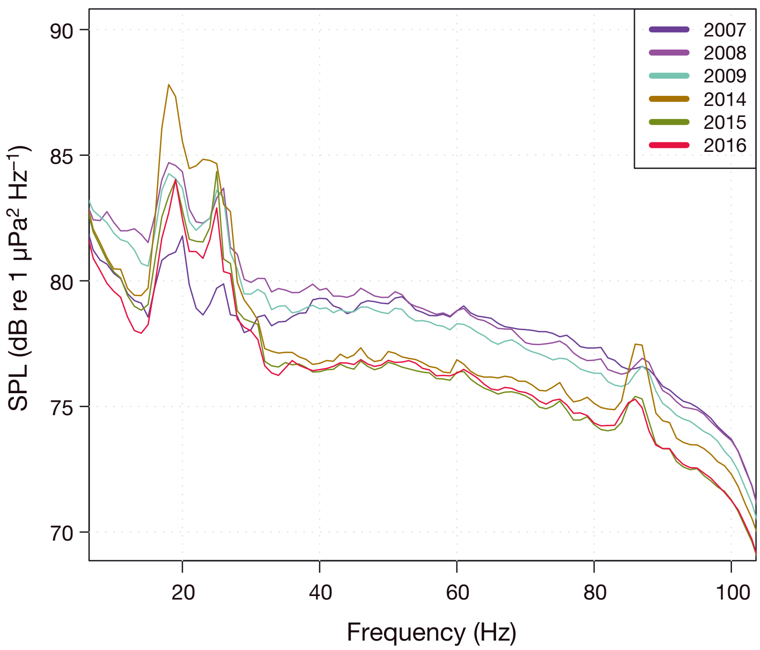

Fig. 2. Median (50% percentile) of the power spectral density expressed as sound pressure level in dB re: 1μPa^2 Hz^{-1}, per year of acoustic data (2007–2009 and 2014–2016) off Juan Fernandez, Chile. Note the peaks at around 17 Hz (fin whales), 24 Hz (southeast Pacific blue whales) and 86 Hz (fin whales)

per 1 Hz frequency band in the 10 and 35 Hz frequency bands ('ambient noise band'); (3) subtracted the ambient noise band (i.e. the average of the 10 and 35 Hz bands) from the 16–22 Hz band to obtain fin whale power in the 16–22 Hz band for each hour. The 10 and 35 Hz bands were chosen as ambient noise bands because they are outside the frequencies where fin or blue whale songs can be expected and therefore can be considered representative of background noise levels around the 17 Hz note band of interest. The same steps were taken to examine the fin whale acoustic power in the 84–86 Hz band: we (1) calculated average acoustic power per 1 Hz frequency band over the 84–86 Hz bands ('84–86 Hz band'); (2) calculated average acoustic power per 1 Hz frequency band in the 70 Hz and 100 Hz frequency bands ('ambient noise band'); (3) subtracted the ambient noise band (i.e. the average of the 70 and 100 Hz bands) from the 84–86 Hz band to obtain fin whale acoustic power in the 84–86 Hz band for each hour. Here, 70 and 100 Hz bands were considered representative of background noise near the 85 Hz note band of interest (e.g. Nieukirk et al. 2012). Monthly fin whale acoustic power in the 16–22 Hz band and the 84–86 Hz band were then calculated and plotted over time for each year of the study period.

2.4. Automatic detection of fin whale song notes over time

An alternative method for examining fin whale song occurrence over time was also used, which involved counting individual 17 Hz song notes using an automatic detection method based on spectrogram cross-correlation (Mellinger & Clark 2000). Spectrogram cross-correlation measures the similarity between an acoustic signal and a template, or kernel, of the target signal, both of which are represented as a spectrogram. Detection occurs when the time-frequency features of the input signal closely match those of the template and exceed a detection threshold based on a correlation score between the template and the detected signal (Mellinger & Clark 2000). XBAT (Extensible Bioacoustic Tool; Bioacoustics Research Program 2012) was used to carry out automatic detection, and spectrograms were made with a 512 point FFT, 25% overlap, and a Hann window. The detector template was a single 17 Hz song note selected from the acoustic data (Fig. 3). The detector was configured to prevent any esoverlapping detections to avoid double detections of the same sound.

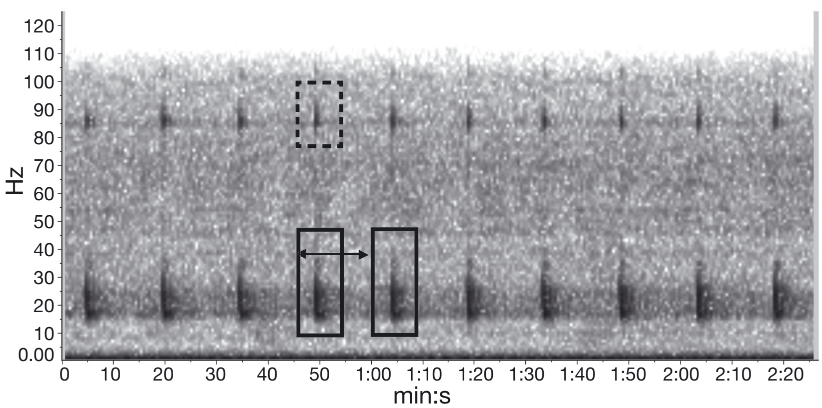

Fig. 3. Spectrogram of 17 Hz (solid box) and 85 Hz (dashed box) notes of a fin whale song sequence. Spectrogram parameters: FFT: 256 samples, 25% overlap, Hann window. Note: The solid black boxes mark the data template used for automatic detection of 17 Hz notes using spectrogram cross-correlation. The double arrow shows how the inter-note interval was determined, i.e. the duration between the beginning of 2 consecutive detections

To assess the detector performance, all detections with a minimum correlation score of 20% from a randomly selected 1.6% (668 h) subset of the entire 2007–2016 data set were examined manually by an experienced analyst to visually check for true positives (correct detections) and false positives (false detections). Detections with scores below 20% were extremely numerous and largely false, and therefore were discarded *a priori* to make efficient use of analyst time. From this, detector precision was determined for correlations above 20%; in principle, the higher the correlation score, the greater the match between the detected signal and the template (as per Roch et al. 2011). Precision is the percentage of all target signals identified by the analyst (true and false positives) that are correctly identified by the automatic detector (true positives). Precision was determined by manually reviewing 96 393 individual 17 Hz notes. When choosing the detection threshold, priority was given to a low false positive rate and a high true positive rate, with a trade-off producing a very high false negative rate, higher detector precision and lower detector recall. Fig. 4 shows precision vs. recall at a range of detection scores (20 to 80%); a threshold of 55% correlation was ultimately chosen. At 55% detection score, 88.4% of detections were true positives, 11.6% were false positives, the precision was 0.88, and the recall was 0.38%. Precision was assessed seasonally for all years: autumn precision was 95.4%; winter precision was 88.3%; spring precision was 66.7%. There were no detections that met our criteria during summer. Precision was also assessed before and after the 2010 tsunami and subsequent instrument change: for the 2007–2009 period, precision was 96.4%; for the 2014–2016 period, precision was 87.7%. All raw detections at or above 55% detection score were analyzed; these were not corrected for seasonal differences or pre-/post-tsunami differences in detector performance.

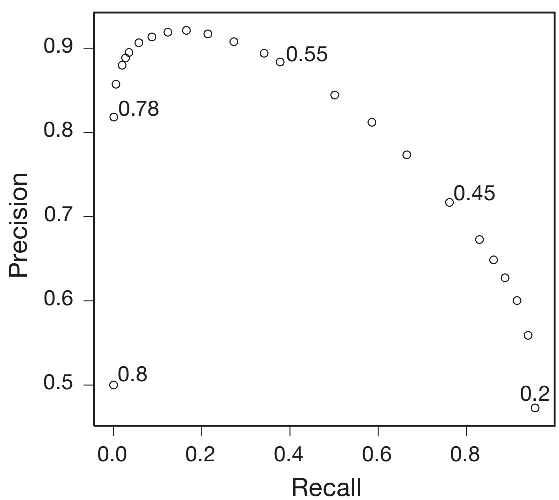

Fig. 4. Performance of automatic detector of 17 Hz fin whale pulses via spectrogram cross-correlation at detection threshold scores between 0.20 and 0.80 (numbers indicate detection score of points). Precision and recall values are based on the manual review of 96 393 fin whale 17 Hz pulses. The 0.55 threshold was chosen for the detector applied to the entire data set

The detector was then applied to the entire dataset, and the number of detections per month was divided by the number of hours of PAM effort to get song note rates (i.e. 17 Hz note detections per hour of PAM effort) for each month plotted as a histogram.

2.5. Inter-note interval estimate

An estimate of INI was done using 17 Hz note detections. Detection via spectrogram cross-correlation occurs when features of the input signal match those of a template (Mellinger & Clark 2000), which in this case contained the target signal (a single 17 Hz note) but also a portion of time before and after the target signal (see Fig. 3). The target signal in the template aligns with the peak correlation with the detected target signal in the time domain. This means that all peak detections of target signals occur at the same time from the start of the detection event. We assumed that the time period between the start of consecutive true positive detections can be taken as an estimate of the duration between 2 consecutive target signals. Therefore, the time from the start of detection i to the start of detection $i + 1$ was equivalent to the time from the center of the detected signal i to the center of signal $i + 1$. INI was calculated as the duration between the begin time of successive detections (Fig. 3). We took all the 42 317 visually checked true positive detections (see Section 2.4) across all years of data to estimate INI. We then plotted these INIs as a histogram for INIs between 0 and 60 s. Caveats include that it is unlikely that all consecutive pulses in a pulse train were successfully detected (given the detection score of 55%), and it was also possible that 2 consecutive detections were actually from 2 different but overlapping pulse trains. Therefore, the interval between 2 consecutive detections may not always accurately reflect the interval between 2 consecutive notes in a single pulse train, which can introduce error into the INI estimate. However, because of the large sample size used, this approach nevertheless provided a satisfactory first assessment of INI.

2.6. Detection range of fin whale 17 Hz notes at the HA03 station

To determine the detection range of fin whale song notes at the HA03 North Station Node 1 hydrophone, a range-dependent acoustic model (RAM; Collins 1993) was run using the HARCAM envelope (Hodgson and RAM Composite Acoustic Model) propagation loss tool (© Ocean Acoustic Developments 2017; http://oad.tv). For this, the figure of merit (FOM) was first determined, which is the allowable propagation loss that a signal can suffer and still be detected 50 % of the time, calculated as: FOM = SL − NL + DI − DT, where SL is the source level assumed to be 189 ± 4 dB re: 1µPa at 1 m over 20 Hz (from Širović et al. 2007); NL is noise level assumed to be 80 dB re: 1µPa at 1 m based on Lawrence (2004); DI is a directivity index, assumed to be zero for an omnidirectional hydrophone sensor; DT is the detection threshold, assumed to be 12 dB re: 1µPa at 1 m based on Ainslie (2010). This produces a FOM of 97 dB, meaning that detection is possible 50 % of the time when the propagation loss of the signal is less than the FOM, i.e. <97 dB.

The RAM in HARCAM models the propagation loss of fin whale 17 Hz notes with the following assumed inputs: geographical position = 33° 27′ 28.8″ S, 78° 56′ 2.8 W; month = July; source depth = 10 m (taken from Stimpert et al. 2015); omnidirectional hydrophone deployment depth = 813 m; source frequency = 20 Hz; FOM = 97 dB. Water column temperature and salinity data were obtained from the World Ocean Atlas 2013 (www.nodc.noaa.gov/OC5/woa13/); bathymetric data from the General Bathymetric Chart of the Oceans V3 (GEBCO; www.gebco.net); water-sediment interface data from HFEVA (High Frequency Environmental Acoustics Sediment Model); Sediment type and thickness were provided by WADER (http://oad.tv). All data were compiled by Ocean Acoustic Developments. Because the seasonal variation in oceanographic conditions was minimal, causing only a very small variation in sonic layer depth (only between 10 and 56 m depth throughout the year), the sonic layer is essentially transparent for 20 Hz signals, and therefore different seasonal propagation models were not determined and water column input data for the month of July were used.

3. RESULTS

3.1. Median power spectral density analysis

The median PSD plot identified peak acoustic power produced by fin whales at 17 and 85 Hz (Fig. 2). Note that the peak at 24 Hz that can be attributed to southeast Pacific blue whales (e.g. Buchan et al. 2015). The PSD plot indicates no frequency shift in the 17 Hz note over the study period, but a slight shift in the frequency of the 85 Hz HFC was apparent, from 87 Hz in 2007 to 85 Hz in 2016, i.e. a rate of −0.22 Hz yr^{-1}. The PSD plot revealed a clear difference in overall noise levels between 2007, 2008, 2009 which all displayed high ambient noise conditions around −20 dB re: $1µPa^2$ Hz^{-1} at 30 Hz; 2016 had intermediate noise conditions around −35 dB re: $1µPa^2$ Hz^{-1} at 30 Hz; and 2014 and 2015 had low noise conditions around −45 dB re: $1µPa^2$ Hz^{-1} at 30 Hz. Under the high and intermediate noise conditions, the peaks at 17 and 85 Hz are less pronounced than under low noise conditions.

3.2. Fin whale song rates and acoustic power over time

A total of 1 241 958 fin whale 17 Hz notes were detected in the CTBTO's Juan Fernandez HA03 passive acoustic data between 2007 and 2009 (636 250) and between 2014 and 2016 (605 708). Monthly detection rates, across years, ranged between 0 and 94 detections per hour of effort (bars in Fig. 5).

The seasonal pattern in acoustic power (at both 17 and 85 Hz) (lines in Fig. 5) and in monthly 17 Hz note detections was consistent across years: very few or no detections during December, January, February, and March, i.e. the austral summer; and higher detections between June (the onset of winter) and September (early spring), with a clear peak in August, i.e. during the austral winter.

3.3. INI and detection range

The INI histogram shows a bimodal distribution, with a primary peak centered at 14.4 s and a secondary peak at 30.8 s. The dominant INI was 14.4 s, but this ranged from 13.4 to 16.4 s (Fig. 6).

From the HARCAM propagation loss modelling, the detection range of the fin whale song notes at the hydrophone was 186 km for a whale singing at 10 m

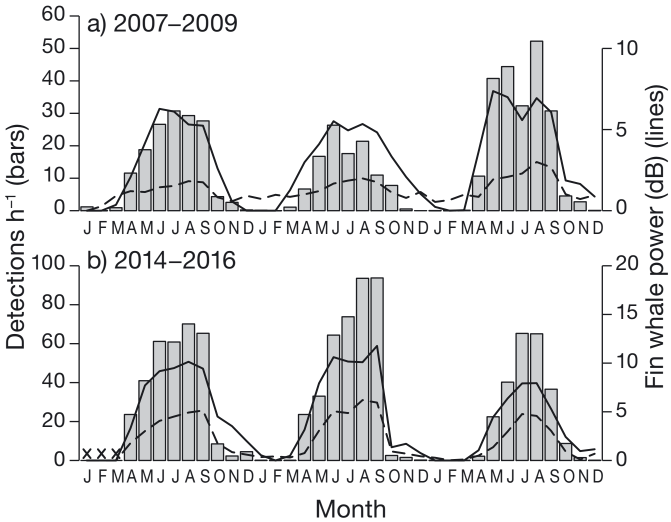

Fig. 5. Monthly fin whale song rates from automatic detections of 17 Hz notes (detections per hour of passive acoustic monitoring effort; bars) and fin whale acoustic power (dB re: $1\mu Pa^2\ Hz^{-1}$) in the 16–22 Hz frequency band (solid line) and in the 84–86 Hz frequency band (dashed line) off Juan Fernandez, Chile, during (a) 2007–2009 and (b) 2014–2016. Detections were not corrected for seasonal difference in detector performance (see Section 2). Crosses mark lack of data for these months. Note the different *y*-axis scales

depth. This range decreases to 97 km when the whale is singing at 5 m depth and increases to 324 km when the whale is singing at 20 m depth.

4. DISCUSSION

4.1. General characteristics of fin whale song off Juan Fernandez

Fin whale song at the CTBTO Juan Fernandez HA03 station was composed of regular 17 Hz notes associated with short notes at ~85 Hz and singlet phrasing at a dominant INI of ~14.4 s. Although the 17 Hz note is within the general frequency range reported for fin whales (Stafford et al. 1999, Širović et al. 2004, Castellote et al. 2012, Weirathmueller et al. 2017), it is lower than reports in the literature. The 85 Hz note was similar to that noted for HFC for the Western Antarctic Peninsula from 2014 (Baumann-Pickering et al. 2015); this value was 89 Hz in 2003. The possible rate of frequency decrease (–0.22 Hz yr^{-1}) that we have observed over our 6 yr study period suggests that the 89 and 85 Hz high pulses may be representative of the same population. A frequency decrease over decadal timescales has recently been documented for fin whales in the northeast Pacific and the southern Indian Ocean (Weirathmueller et al. 2017, Leroy et al. 2018).

The INIs reported here were within the general range of INIs in the literature (Stafford et al. 1999, Širović et al. 2004, 2017, Castellote et al. 2012, Morano et al. 2012, Oleson et al. 2014, Weirathmueller et al. 2017). The primary mode at 14.4 s is similar to the 13 s INI reported off the Western Antarctic Peninsula in 2003–2004 (Širović et al. 2004). At present, there are no other INIs reported in the literature from other areas in the Southern Hemisphere.

We did not see the apparent complexity recently described for the North Pacific (i.e. singlets, doublets and triplets; Oleson et al. 2014, Širović et al. 2017, Weirathmueller et al. 2017). However, the method we used to estimate INI had drawbacks and was done to provide a first coarse approach to INI estimation, since the aim of this study was not an in-depth examination of singing behavior. Because INI was estimated by calculating the interval between all consecutive detections, it is likely that the detector did not detect all consecutive pulses in a pulse train (particularly with a 55 % detection score applied) and that the detector could have detected 2 pulses very close together from 2 overlapping pulse trains. This means that very large and very small intervals could have been measured between 2 consecutive notes and that this does not reflect the real INI in a single pulse train. We are, however, satisfied with this first estimate given the very large sample size, i.e. >42 000

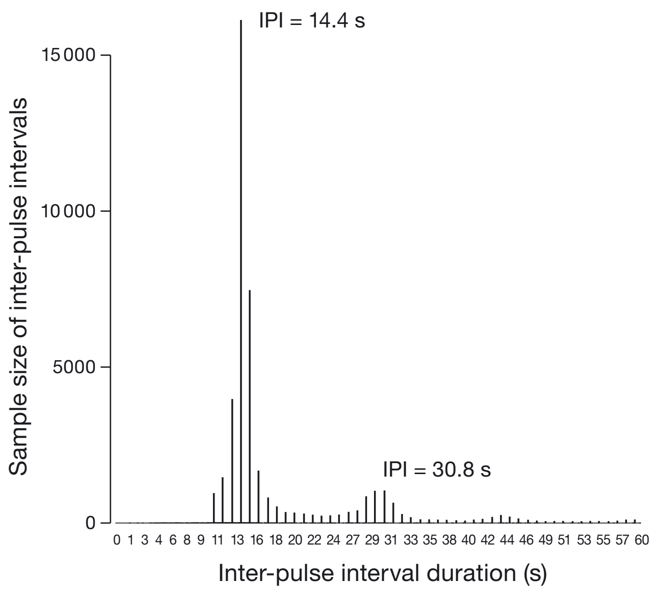

Fig. 6. Inter-note interval (INI) of fin whale song off Juan Fernandez, Chile. INI was calculated as the duration in s between 2 consecutive 17 Hz note detections (inter-pulse interval duration; IPI)

detections. Given that INI may be useful as a population identifier, more detailed work is needed to look at seasonal and intra-annual variation of the INI of fin whale song off JFA.

4.2. Detector performance and ambient noise

There were clear differences in ambient noise levels between years, i.e. high ambient noise in 2007, 2008, and 2009, intermediate in 2016, and lower levels in 2014 and 2015 (Fig. 2). There was an instrument change after the 2010 tsunami which may have led to lower overall received levels due to a known incremental drop in sensitivity and/or instrument type. However, this does not explain the difference between 2014–2015 and 2016. Unknown internal factors (e.g. hydrophone sensitivity) or external factors (e.g. deployment platform noise or ambient noise) between years may explain these changes, but this information is not available.

Changes in noise affected the detection of 17 Hz notes and 85 Hz HFC via spectrogram cross-correlation and acoustic power. In effect, the energy peaks at 17 and 85 Hz were less pronounced under high (2007–2009) and intermediate (2016) noise conditions, compared to low noise conditions (2014 and 2015) (Fig. 2). Recall increased and precision decreased after the known instrument change: false negatives decreased, and false positives increased. This means fewer target signals were missed by the detector and more non-target signals were incorrectly detected by the detector under lower noise conditions (2014–2016). Higher noise can explain why the total number of 17 Hz note detections h^{-1} and fin whale acoustic power were lower in 2007–2009 compared to 2014–2016 (Fig. 5). Noise might also explain why the acoustic power in the 16–22 Hz and 84–86 Hz bands were less well-coupled in 2007–2009 compared with 2014–2015, possibly due to noise affecting the higher-frequency band (Fig. 5). The overall impact of changes in ambient noise level is to change the area over which fin whales can be detected off JFA, both for analysis purposes and for the animals themselves. Changes in ambient noise affect the 'acoustic space' over which animals can communicate (e.g. Hatch et al. 2012). Without more information on the hydrophone deployment, we cannot conclusively say whether this noise is due to internal or external factors. However, although overall detections were lower in 2007–2009 compared to 2014–2015, the same seasonal pattern was clear from the data.

There were also seasonal changes in detector precision, which are most likely due to external environmental factors: in spring, recall was highest and precision was lowest, indicating a lower proportion of false negatives and a higher proportion of false positives, compared to autumn when recall was lowest (higher proportion of false negatives) and precision was highest (lower proportion of false positives). Higher levels of ambient noise might be explained in autumn due to adverse weather during the transition between summer and winter. Noise levels (regardless of their source) and changes in detector performance are important to bear in mind when interpreting the temporal changes in 17 Hz note and 85 Hz HFC occurrence in Fig. 5. However, the close agreement between the individual 17 Hz pulse detections and the fin whale band noise curves gives us confidence in the robustness of the seasonal patterns shown in our data. Because the causes of inter-annual variation in noise remain unresolved, we cannot draw conclusions on the inter-annual changes in animal presence, but rather focus the discussion on the intra-annual variation in fin whale song occurrence and animal presence.

4.3. Fin whale seasonal distribution in the southeast Pacific

Bearing in mind variations in detector performance between seasons, there was a clear temporal pattern in fin whale detections and acoustic power at the HA03 station which showed a consistent seasonal trend of austral winter acoustic presence of fin whales in the waters around the JFA. Although the low recall rate of the 17 Hz note automatic detector could have led to underestimation of detections h^{-1}, both the automatic detection analysis and the acoustic power analysis indicate the same seasonal pattern. The estimated maximum detection range of 324 km was much greater than the detection range for fin whales in the Southern Ocean, on hydrophones deployed at similar depths, which was estimated to be 56 km (Širović et al. 2007). In the present study, then, we may be listening to whales at a greater distance than that reported by Širović et al. (2007). However, we are still monitoring an area within the Southeast Pacific region rather than listening to animals in the Southern Ocean.

The seasonal trend in fin whale acoustic occurrence points towards some group or population of fin whales that consistently spend the winter in the offshore waters of the southeast Pacific within a few

100 km of the JFA. This does not exclude this group of animals from wintering in other offshore areas that have not yet been visually or acoustically monitored. Where these animals spend the rest of the year remains unknown. It is possible that they move out of this area outside winter months; however, it is also possible that these animals are not vocal outside winter months and therefore undetectable using PAM (Stafford et al. 2007). From recent work off northern Chile (S. J. Buchan et al. unpubl. data), high visual sightings of fin whales during spring and early summer months (November-February) do not coincide with acoustic recordings of fin whale vocalizations, suggesting variation in vocalization production over time.

However, the scenario in which fin whales move out of the JFA area in summer coincides with findings by Sepúlveda et al. (2016) using visual monitoring efforts off Isla Chañaral between 2015 and 2016, who recorded high numbers of foraging fin whales primarily during the austral summer months (December and March). Further, a recent study of fin whales instrumented with satellite tags showed 1 male moving south towards JFA in summer (Sepúlveda et al. 2018). This, as well as previous studies (Capella et al. 1999, Perez et al. 2006, Pacheco et al. 2015, Toro et al. 2016), suggests summertime residency of some fin whales on coastal feeding grounds off central and northern mainland Chile. No long-term passive acoustic data are available for these areas. Interestingly, winter sightings have been reported off the coast of mainland Chile, but at much lower rates than during summer months (Pacheco et al. 2015, Sepúlveda et al. 2016). The results of this study and limited sighting data off mainland Chile could point towards a seasonal longitudinal movement of fin whales onshore–offshore in the southeast Pacific, but more temporal and spatial coverage in this region is necessary for conclusive results.

Alternatively, if we assume that the high-frequency note is a population identifier and that a downward frequency shift of the 89 Hz note recorded off the Western Antarctic Peninsula in 2003 has occurred, then it is possible that fin whales off JFA (that produce 85 Hz notes) are part of a population that undertakes a seasonal latitudinal migration between summer feeding grounds off the Western Antarctic Peninsula and wintering grounds in the offshore southeast Pacific (JFA). More recent recordings from the Southern Ocean would be useful to determine whether the 89 Hz note in Antarctica has decreased in frequency or been maintained.

In either case, at present, we have no evidence that the fin whales sighted off the coast of mainland Chile or observed acoustically off the Western Antarctic Peninsula are the same animals as those heard at the JFA HA03 station. Based on the recovery of 4 out of the 11 whale marks deployed into fin whales off Chile in October and November 1958 by commercial whaling fleets in the Drake Passage (presumably operating during the austral summer), we know that some animals do migrate between the coast of Chile and Antarctica (Clarke et al. 1978 and references therein). It is unclear if this is the predominant seasonal movement of the population of fin whales heard off JFA.

It is also possible that there are 2 partially overlapping populations of fin whales in the southeast Pacific, one that forages in the Southern Ocean and one that forages off mainland Chile during summer, and that both spend the winter offshore in the southeast Pacific. For better-studied blue whales, 2 distinct Chilean and Antarctic blue whale populations are known to overlap in this region, based on morphometrics (Branch et al. 2007), genetics (Torres-Florez et al. 2014), and acoustics (Stafford et al. 1999, Buchan et al. 2014, 2015, 2018). A more detailed comparison of fin whale song characteristics from the southeast Pacific and the Southern Ocean could help elucidate this for fin whales.

This study is the first report of fin whale song in the southeast Pacific and reveals large gaps in the current knowledge of fin whale population structure and seasonal distribution in the southeast Pacific. We recommend further coverage of PAM and sighting effort off the coasts of Chile and Peru, as well as offshore islands like Juan Fernandez, and also acoustic and genetic studies in the southeast Pacific and the Southern Ocean to better understand the distribution, seasonal movements, and population structure of this endangered species.

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