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Seasonal acoustic presence of blue, fin, and minke whales off the Juan Fernández Archipelago, Chile (2007–2016)

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Abstract

The southeast Pacific (SEP) contains the home ranges of several migratory large whale species, determined largely based on research in coastal waters. These whales' pelagic seasonal residency is unknown. The Juan Fernández Archipelago (JFA) is an offshore island in the SEP where passive acoustic monitoring (PAM) data collection is ongoing at the HA03 hydroacoustic station (sample rate of 250 Hz) maintained by the Preparatory Comprehensive Nuclear-Test-Ban Treaty Organization. Six years (2007–2009 and 2014–2016) of PAM data from HA03 were examined for the acoustic presence of Antarctic, Chilean (southeast Pacific 1, southeast Pacific 2), and southeast Indian Ocean blue whale song types; the fin whale 20-Hz song; and minke whale vocalizations. The weekly presence or absence of these six vocalization types was annotated manually by an expert analyst and then averaged across all years. For each vocalization type, the number of weeks per month with presence was averaged over all years. Consistently, we found austral wintertime presence of Antarctic blue, fin, and minke whales; and the year-round presence of Chilean blue whales. Southeast Indian Ocean blue whales were also detected, but very rarely. We discuss the possible seasonal movements of each species or acoustic group in the offshore SEP. This is the first year-round multispecies study of baleen whale in the offshore SEP and provides valuable information for understanding the migrations of endangered baleen whales in this region, highlighting the importance of offshore areas as hotspots for baleen whale biodiversity.

Keywords Baleen whales · Southeast Pacific · Seamounts · Passive acoustic monitoring · Bioacoustics

Introduction

Chile contains four marine provinces that encompass eight marine ecoregions, which are biogeographic classifications established to encourage ecologically representative protected areas, sensu Spalding et al. (2007). Of these, the offshore Archipelagos of Juan Fernández and Desventuradas constitute a single ecoregion within a single marine province, reflecting the unique ecological characteristics of these offshore islands (Spalding et al. 2007). This region has also been identified as a global hotspot of endemism and biodiversity (Friedlander et al. 2016). Offshore archipelagos and seamounts are known to provide critical feeding habitat for migratory and pelagic animals (e.g., Pitcher et al. 2007). These remote areas often present particularly difficult monitoring, conservation management, and enforcement challenges due to their location in offshore open ocean areas (e.g., Probert et al. 2007).

The southeast Pacific and eastern tropical Pacific contain the home ranges of several large whale species. Historical whaling data indicate the presence of eight different species of baleen whales, and sperm whales (e.g., Aguayo-Lobo et al. 1998). Today, scientific information on the distribution of large whales is largely based on visual sightings of whales in coastal waters: blue (*Balaenoptera musculus* spp.), fin (*B. physalus*), and humpback (*Megaptera novaeangliae*) whales occur in relatively high austral summer aggregations and have been the target of numerous studies off coastal Chile (reviewed in Hucke-Gaete et al. 2018). More rarely, southern

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right whales (*Eubalaena australis*) are sighted, generally in austral winter (Aguayo-Lobo et al. 1998; Galletti-Vernazzani et al. 2014; Jacobs et al. 2019). Sei (*B. borealis*) and minke whales (*B. acutorostrata* spp.) have also been reported, generally in the austral summer (Aguayo-Lobo et al. 1998; Acevedo et al. 2006; Häussermann et al. 2017).

The offshore distributions of all these species in the southeast Pacific are virtually unknown. Given the difficult logistics and high costs of offshore research, offshore areas have often been overlooked by research groups that study baleen whales in coastal waters. Passive acoustic monitoring (PAM) is the only method that offers continuous year-round observations of cetacean presence in areas where boat work is unfeasible. Since 2003, the Preparatory Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) has been collecting PAM data at an International Monitoring System hydroacoustic station called HA03 off the Juan Fernández Archipelago (JFA) located approximately 670 km west of mainland Chile (Fig. 1). This station collects low-frequency (< 125 Hz) passive acoustic data at six hydrophones (two triads) with the primary purpose of detecting nuclear underwater explosions in the world's oceans. These data can also serve to listen for large whale species that vocalize below 125 Hz, i.e., blue, fin, minke, and sei whales (e.g., Cummings and Thompson 1971; Watkins 1981; Mellinger et al. 2000; Baumgartner and Frantantoni 2008). The aim of this study was to examine the seasonal acoustic presence of different species of blue, fin, and minke whales in the offshore southeast Pacific, off JFA. Southern right and humpback whale vocalizations overlap but also exceed this frequency range (Jacobs et al. 2019; Stimpert et al. 2012; Thompson et al. 1986). Although sei whale vocalizations are within the frequency range examined, too little is currently known about their vocalization characteristics in this region to determine their acoustic occurrence with confidence.

Materials and methods

The CTBTO passive acoustic data were made available by the Chilean Nuclear Energy Commission (CCHEN) and a vDEC contract with the CTBTO. We examined passive acoustic data

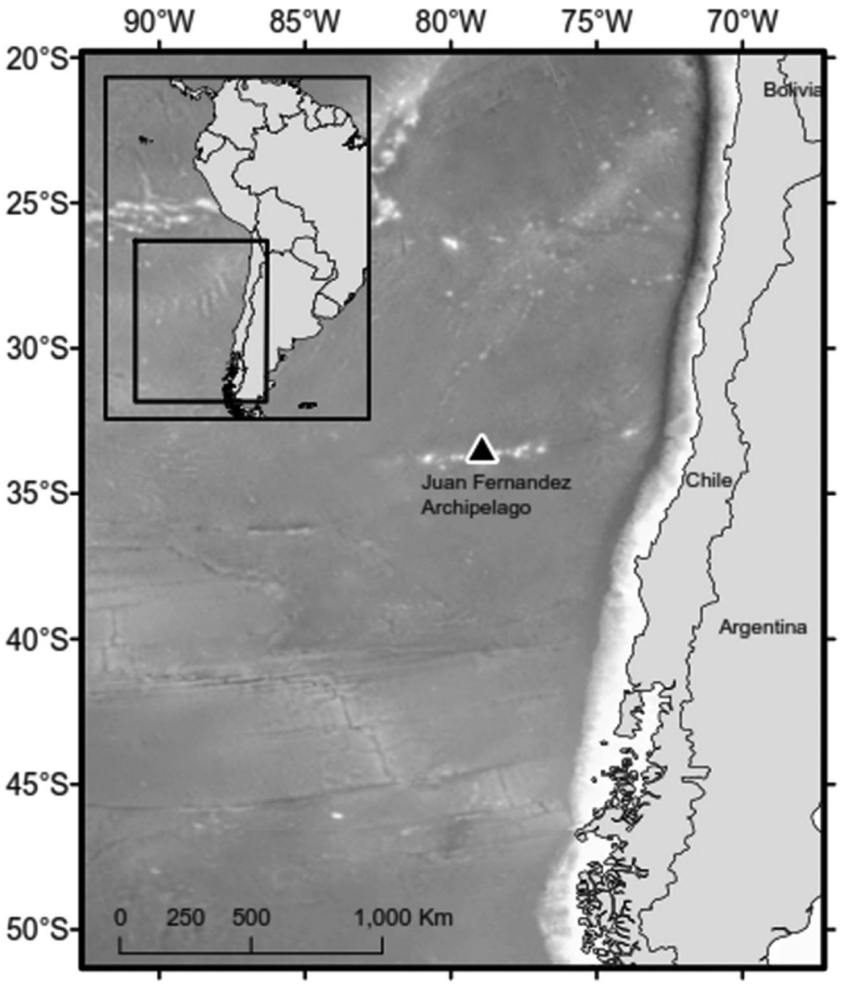

Fig. 1 Map of study area; the white triangle indicates the CTBTO HA03 station off the Juan Fernández Archipelago, Chile (map produced with ArcMap version 10.0)

(42,704 h) collected continuously between 2007 and 2009 and 2014–2016 at a 250-Hz sample rate from a single hydrophone (CTBTO HA03 station North Node hydrophone 1 at S33° 27′ 28.9, W78° 56′ 2.9), moored at a depth of 813 m in total water column depth of 1538 m (Fig. 1). No data were available between 27 February 2010 and 22 April 2014 due to the tsunami that hit the Chilean coast and the JFA on 27 February 2010 destroying the HA03 station, which was eventually repaired in April 2014. Here, we used data from all of 2007, 2008, and 2009; May to December 2014; and all of 2015 and 2016.

To examine seasonal and interannual trends in acoustic presence of baleen whales off JFA, we examined the weekly presence or absence of blue whale song types, fin whale songs, and minke whale vocalizations. The division of the 6-year time series in weekly bins was done for operational reasons, providing sufficient temporal resolution to adequately examine seasonal trends while making efficient use of analyst time. Data were divided up into weekly chunks (week 1 = day 1 to day 7 of the month; week 2 = day 8 to day 14; week 3 = day 15 to day 21; week 4 = day 22 to the end of month). Acoustic data files were visually examined as spectrograms (512-point FFT, 80% overlap, Hann window, 0–125 Hz frequency range) of 3600 s page length using Raven Pro 1.5 (Bioacoustic Research Program 2012). Presence was determined by the visual identification and classification of one or more vocalizations of a species of baleen whale by an experienced analyst; the total number of vocalizations was not counted.

Baleen whales produce acoustic signatures that are species specific. Additionally, blue whale songs vary regionally such that their songs have been proposed as "acoustic population" delineators. Six vocalization types were identified based on the previously described acoustic signatures of the following Southern Hemisphere species and song types: Antarctic blue whale regional song type (AA; Rankin et al. 2005; Fig. 2a); Chilean or southeast Pacific 1 blue whale song type (SEP1; Cummings and Thompson 1971; Buchan et al. 2014; Fig. 2b); Chilean or southeast Pacific 2 blue whale song type (SEP2; Buchan et al. 2014; Fig. 2c); Southeast Indian Ocean (SEIO) blue whale song type (McCauley et al. 2001; Fig. 2d); fin whale "20-Hz" song (Širović et al. 2009; Fig. 3a); minke whale vocalizations (Schevill and Watkins 1972; Fig. 3b). The non-song downsweep vocalizations of blue whales (e.g., Oleson et al. 2007) and fin whales (Širović et al. 2013) were not examined.

Based on the weekly presence/absence time series, the total number of different vocalization types, i.e., different whale species or acoustic population, was averaged across all years (± standard deviations) to examine how the community composition changed over time. Then, for each vocalization type, the number of weeks per month with presence was determined for the entire 6-year time series and was also averaged over all years to obtain a monthly mean (± standard deviations).

Results

Over the 6 years of available acoustic data (2007–2009, 2014–2016), the acoustic presence of the number of species/song types of large whales off JFA was consistently higher during the austral winter, compared with the austral summer, with a peak during June and July, and a minimum during December and January (Fig. 4). For most of the year, at least three different species/song types are present around JFA with four to five present for several months in austral winter. The exception is SEIO, which is unsurprising given how unexpected it was in the acoustic data. Clearly, the JFA is an important habitat for large whales in the SE Pacific Ocean during much of the year.

This seasonal pattern was also true for individual species/song types. Figure 5 shows the complete time series of number of weeks per month with presence for each vocalization type, and Fig. 6 shows the average of this over all 6 years. AA blue whales (Figs. 5a and 6a), fin whales (Figs. 5e and 6e), and minke whales (Figs. 5f and 6f) occurred acoustically during more weeks per month in the austral winter than the austral summer across all 6 years of data. SEP1 presence (Figs. 5b and 6b) was low but relatively constant throughout 9 months of the year (January through September), and absent during October, November, and December of all 6 years analyzed. SEP2 (Figs. 5c and 6c) was present during all months of the year without showing a clear seasonal pattern. SEIO blue whale song was heard unsurprisingly only very occasionally in the months of May and October (Figs. 5d and 6d).

Discussion

This is the first multispecies study of baleen whale acoustic presence in the southeast Pacific. The temporal variation in the presence of the six vocalization types examined reveals the seasonal residency of four blue whale acoustic groups, as well as fin whales and minke whales. The individual acoustic behavior for these species is largely unknown and therefore it is impossible to say whether the seasonal pattern of presence/absence is also influenced by seasonal changes in individual vocalization or song production rates. The propagation conditions at this sites for the calls reported here are unknown, except for fin whales where a previous study found a maximum detection range of 97 km at the HA03 North Node 1, assuming the whale was singing at 5 m depth, or 324 km for a whale singing at 20 m depth (Buchan et al. 2019). Based on this, it is possible that the whale vocalizations detected at HA03 could have been produced by animals vocalizing several hundreds of kilometers away, which is important to bear in mind for the interpretation of results. Changes in ambient noise levels will certainly influence the detection range. Noise levels at JFA were found to vary by year by up to 6 dB in the

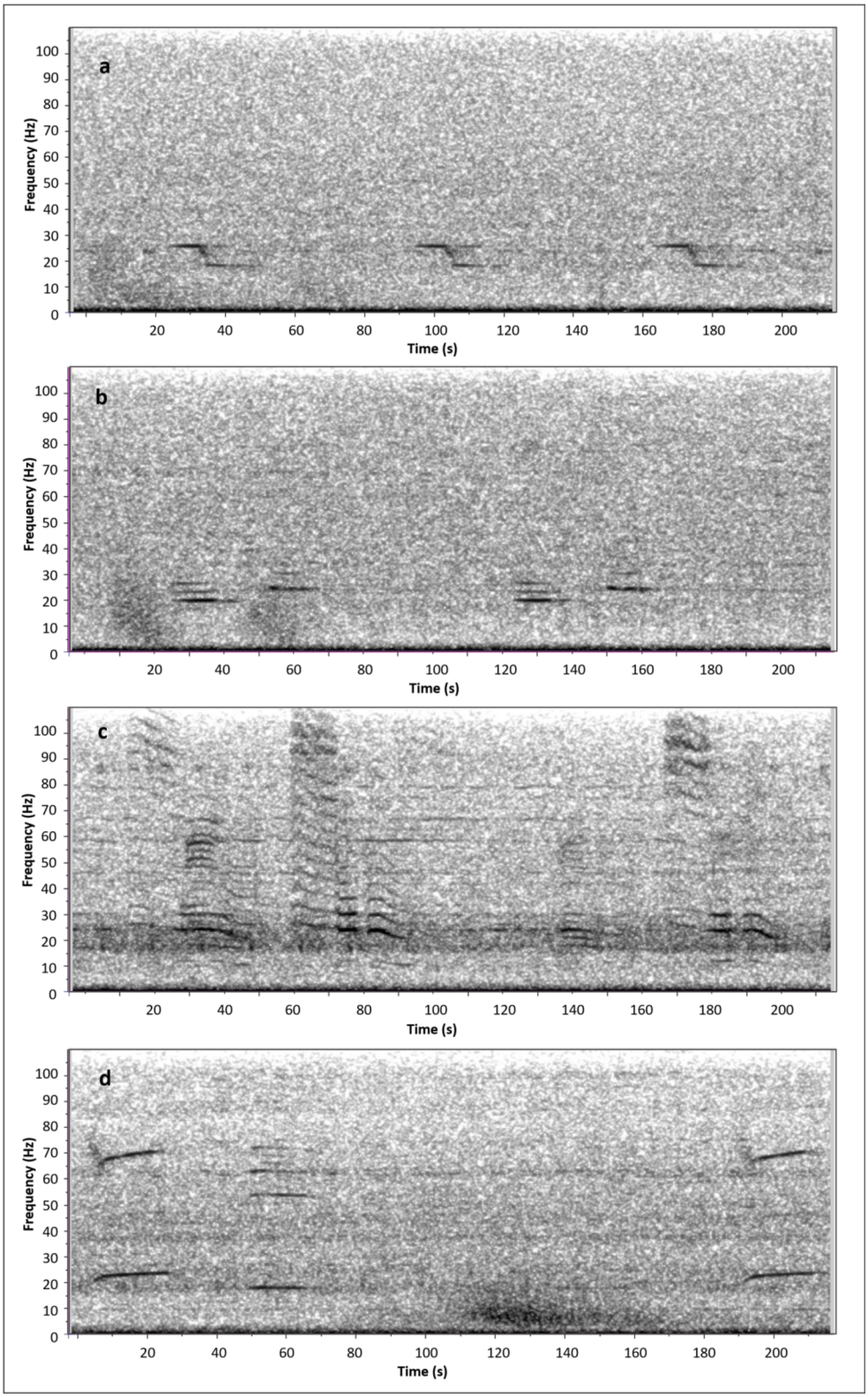

Fig. 2 Regional dialects of blue whale vocalizations recorded off the Juan Fernández Archipelago, Chile: **a** Antarctic song type (AA); **b** southeast Pacific 1 (SEP1) song type; **c** southeast Pacific 2 (SEP2) song type; **d** southeast Indian Ocean (SEIO) song type. Spectrogram visualized with a 512-point Fast Fourier Transform, Hann window, 90% overlap, 0.488 Hz frequency resolution, 0.408 s time resolution, and page length 3600 s

frequency range in which most of the signals discussed here occur (Buchan et al. 2019).

Our results suggest that AA blue, fin, and minke whales may move from the Southern Ocean into this offshore area of the southeast Pacific during the austral winter. For AA blue whales, whose primary feeding ground is the Southern Ocean (Branch et al. 2007), it is unclear how much of the population migrates north during the winter months and what percentage

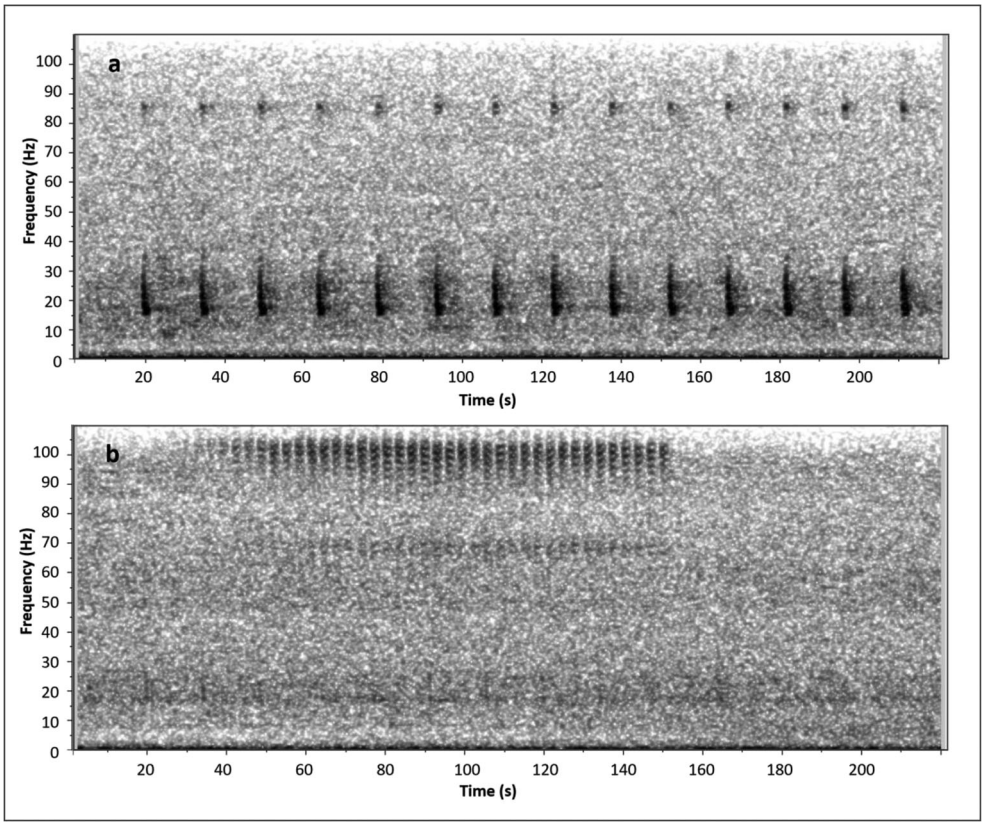

Fig. 3 Spectrograms of **a** fin whale "20-Hz" song and **b** minke whale vocalizations recorded off the Juan Fernández Archipelago, Chile. Spectrogram visualized with a 512-point Fast Fourier Transform, Hann window, 80% overlap, 0.488 Hz frequency resolution, 0.408 s time resolution, and page length 3600 s

remains in the Southern Ocean year round. It is also unclear what percentage of the migrating population uses the various low latitude sites where they have been acoustically reported during the austral winter: the Indian Ocean (Stafford et al. 2004; Samaran et al. 2013), the southeast Pacific (Stafford et al. 1999; Buchan et al. 2018), or the South Atlantic (Samaran et al. 2019). The presence of SEIO blue whales was unexpected given this population's range documented off western Australia and in the Indian Ocean (McCauley et al. 2001; Stafford et al. 2011; Samaran et al. 2013;

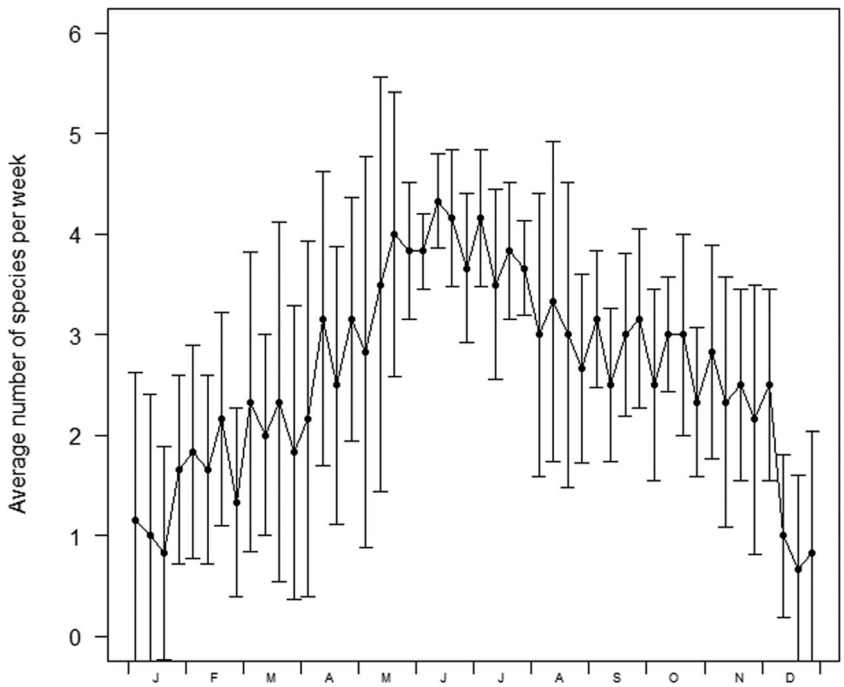

Fig. 4 Acoustic presence of baleen whales shown as the average number (± standard deviation shown by bars) of different vocalization types per week of the year recorded off the Juan Fernández Archipelago, averaged over 2007–2009 and 2014–2016. Vocalization types include southeast Pacific blue whale songs SEP1 and SEP2, Antarctic blue whale song (AA), southeast Indian Ocean blue whale song (SEIO), fin whale song, and minke whale vocalizations

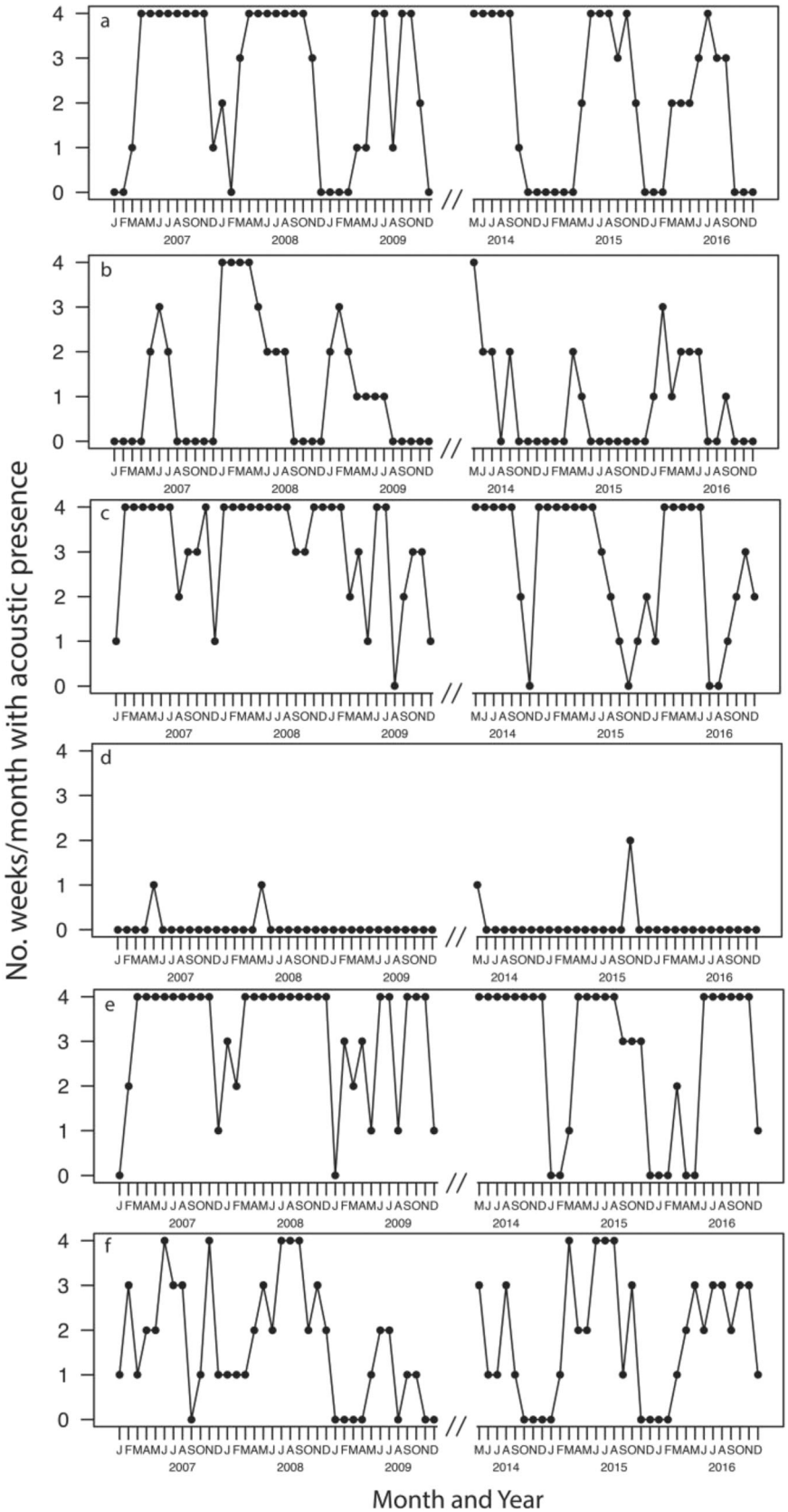

Fig. 5 Number of weeks per month with acoustic presence of **a** Antarctic blue whale song; **b** Southeast Pacific 1 blue whale song; **c** Southeast Pacific 2 blue whale song; **d** Southeast Indian Ocean blue whales song; **e** fin whale song; and **f** minke whale vocalizations between 2007 and 2009 and 2014–2016 of the Juan Fernández Archipelago, Chile

Balcazar et al. 2015). However, SEIO blue whale songs were very rare, detected during 1 week in 2007, 2008, and 2014 and 2 weeks in 2015 (Fig. 5d), suggesting that JFA is probably the very easternmost limit of the SEIO blue whale range. SEIO songs could have been produced by vagrant animals moving well outside their home range. It is also possible, but much less probable, that favorable propagation conditions allowed songs to be heard at the HA03 station across the South Pacific Basin. Given that northern Indian Ocean blue whales have been recorded off Gabon, in the South Atlantic (Cerchio et al. 2010), Southwest Indian Ocean blue whales have been recorded in the Antarctic (Gedamke and Robinson 2010) and Antarctic blue whales are heard in all ocean basins of the Southern Hemisphere, we think it much more likely that the SEIO blue whales we recorded were vagrants as this species can clearly displace itself over great distances.

The results for fin whales are in line with a more detailed study of fin whale seasonal acoustic occurrence at this same study site by Buchan et al. (2019). Like blue whales, fin whales were generally thought to migrate between Antarctic

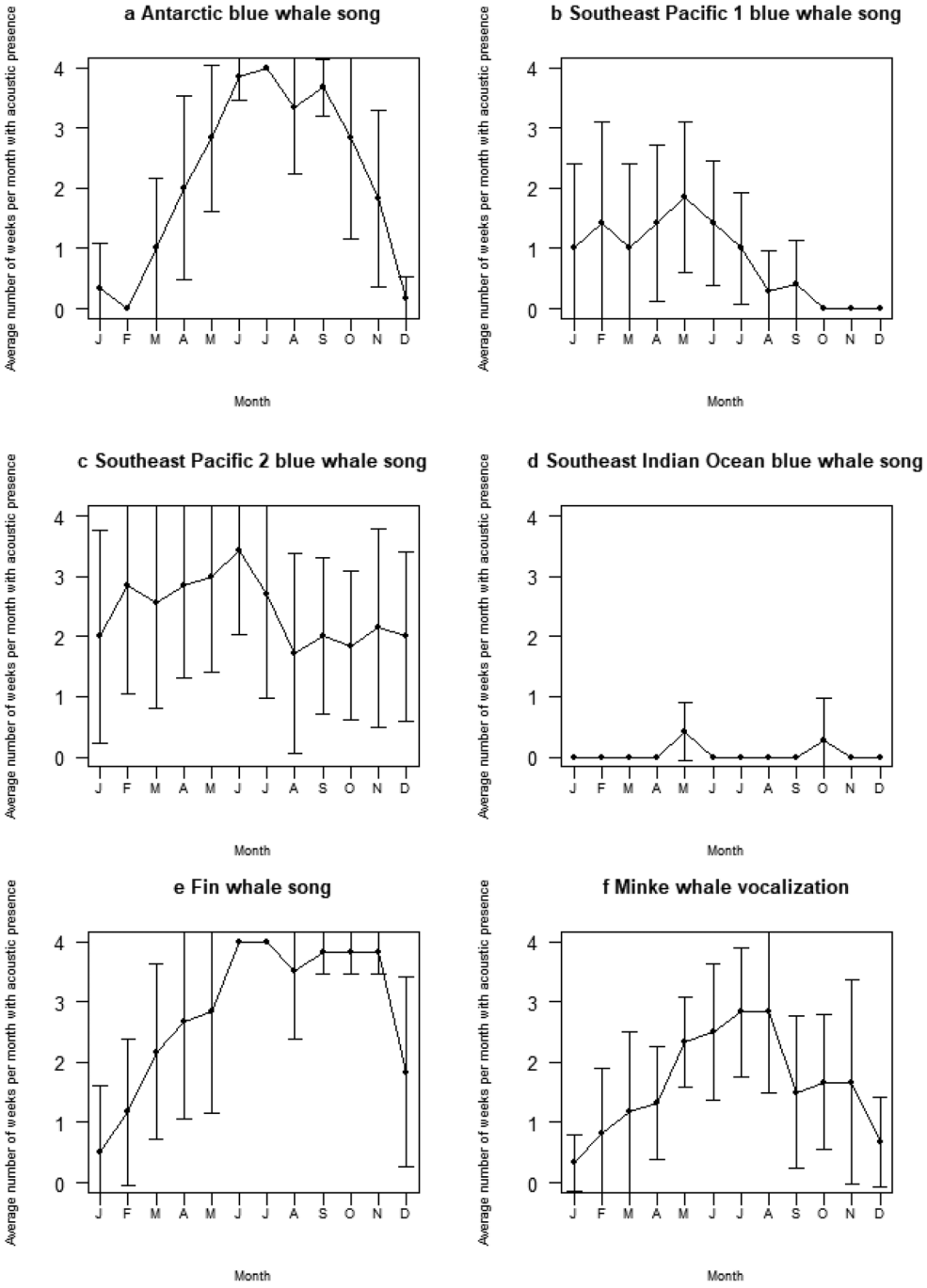

Fig. 6 Average number of weeks per month with acoustic presence (± standard deviations shown by bars) of **a** Antarctic blue whale songs (AA); **b** Southeast Pacific 1 blue whale songs (SEP1); **c** Southeast Pacific 2 blue whale songs (SEP2); **d** Southeast Indian Ocean blue whale song (SEIO); **e** fin whale song; **f** minke whale vocalizations

feeding grounds and breeding grounds further north (Kellogg 1929). However, geographic variation in fin whale songs are not as clear as in blue whales, so it is difficult to say at this stage whether the fin whales heard off JFA migrate from the Antarctic (Kellogg 1929) or along the coast of Chile (Capella et al. 1999; Pérez et al. 2006; Toro et al. 2016; Sepúlveda et al. 2018). Regardless, the strong seasonal pattern in acoustic presence found in this study suggests that some AA blue whales and fin whales from an unknown population consistently use this offshore area of the southeast Pacific as a wintering ground.

Much less is known about minke whales in this region. As for fin whales, robust regionally distinct acoustic dialects are less well documented, so it is unclear where the minke whales that are heard off JFA spend the rest of the year. However, the minke whale vocalizations recorded off JFA are similar to the vocalizations attributed to Antarctic minke whales (*B. bonaerensis*), known as the "bio-duck" (Risch et al. 2014). Given the seasonal pattern and moderate acoustic presence off JFA, the results of this study at the very least suggest a fairly consistent seasonal passage of minke whales through this area and possible links to an Antarctic population.

Chilean blue whales (both SEP1 and SEP2 song types) did not show a seasonal pattern and were present year round in this area. Year-round acoustic presence of Chilean blue whales is also found in the eastern tropical Pacific (8°S 95°W) (Stafford et al. 1999; Buchan et al. 2015). The JFA is relatively close, 630 nm to the northeast, of what is considered the primary feeding ground for Chilean blue whales in coastal Chilean Patagonia (Hucke-Gaete et al. 2004; Buchan and Quiñones 2016; Galletti Vernazzani et al. 2017; Bedriñana-Romano et al. 2018). In Chilean Patagonia, however, SEP1 and SEP2 occur seasonally with a strong seasonal peak during the austral summer (Buchan et al. 2015). Seasonal presence on their coastal feeding ground, and year-round acoustic presence in offshore areas in the eastern tropical and southeast Pacific (i.e., JFA), may be explained by different propagation characteristics at these different sites since the deep offshore deployment sites will allow a much greater detection range than a coastal deployment site since low-frequency signals will interact with the bottom in shallow areas (where shallow is relative to the wavelengths of the whale calls, i.e., 75 m for a 20-Hz signal) and therefore not propagate as far (Wenz 1962). This can only be resolved by propagation models for each deployment site where SEP blue whale songs are heard and should be a priority for future work. Alternatively, and the explanation that seems mostly likely, is that these differences are due to the partial migration of Chilean blue whales, previously suggested by Buchan et al. (2015). In this case, most of the population migrates and aggregates in coastal Chile to feed during the austral summer and then disperses and spends winter offshore in the southeast and eastern tropical Pacific; a small percentage of the population spends the entire year in the offshore southeast and eastern tropical Pacific.

It remains unclear whether JFA is an area of transit along a migration route, a short-term foraging site, or a foraging hotspot for large whales. Certainly, productive seamounts near the JFA could provide feeding opportunities and the high number of species heard there during many months of the year support this. Offshore archipelagos and seamounts are known to be important feeding habitat for cetaceans, including baleen whales (e.g., Kaschner 2007; Morato et al. 2008; Visser et al. 2011). Off the Azores, for example, Visser et al. (2011) found that blue, fin, sei, and humpback whales feed seasonally off euphausiids and proposed that baleen whales use this mid-latitude archipelago as a feeding site along their migration route to summer feeding grounds. The habitat use of large whales remains unknown due to the logistical and economic challenges of observing these animals visually, acoustically, or via telemetry in this vast oceanic region.

In conclusion, this study reveals the seasonal presence of Antarctic blue, fin, and minke whales and the year-round presence of Chilean blue whales off the JFA, in the offshore southeast Pacific. This advances our understanding of the seasonal movements of these endangered species in this remote region. This study highlights the importance of offshore areas in the southeast Pacific as hotspots for multiple baleen whale species. The Chilean Government recently created both the Nazca and Desventuradas Marine Park (300,000 km^2) in 2016 and the "Mar de Juan Fernández" Multiple Use Marine Protected Area (11,000 km^2) in 2017, which are important steps forward in the conservation of the seamount ecosystems of the Juan Fernández and Desventuradas marine province and ecoregion. PAM may offer a cost-effective means of monitoring baleen whale distribution and highlighting the biodiversity of these top predators in these protected areas over time. Future research should focus on greater spatial and temporal coverage in this extensive offshore area, understanding the propagation conditions in the southeast Pacific, examining possible regional differences in fin and minke whale vocalizations that could indicate population identity of the animals heard of JFA, and lastly, examination of sei whale acoustic presence in this area.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All applicable international, national, and/or institutional guidelines for the care and use of animals were followed by the authors. This article does not contain any studies with animals performed by any of the authors. This article does not contain studies where permits for sampling are required.

Sampling and field studies No fieldwork or sampling was carried out in this study.

Data Availability The datasets generated during and/or analyzed during the current study are available through a contract agreement with Comprehensive Nuclear-Test-Ban Organization (https://www.ctbto.org/).

Authors' contribution All authors contributed to study conception, design, and data analysis. All authors commented on all previous versions of the manuscript and read and approved the final manuscript.

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