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ABSRACT

The temporal pattern of Chilean blue whale SEP calls recorded between 2003 and 2015 off Juan Fernandez Island, compared with the pattern of calls detected at acoustic stations north and south, confirms the increasing body of evidence suggesting that SEP blue whales feed in southern cooler waters during the austral summer off the coast of Chile and migrate to tropical waters further north to breed. The similarity between the seasonal pattern of the Chilean blue whale calls and the Australian blue whale calls, suggests that despite being from different acoustic populations, the migration patterns of sub-Antarctic blue whales in the south eastern Indian Ocean are similar to those in the south eastern Pacific.

INTRODUCTION

Phenology, the study of annually recurring life cycle events such as the timing of migrations, can provide a particularly sensitive indicator of responses to climate change (Hughes, 2000; Bradshaw & Holzapfel, 2006). Changes in phenology are important to ecosystem function because the level of response to change may vary across functional groups and the decoupling of phenological relationships has important ramifications for trophic interactions, like altering food-web structures, and leading to eventual ecosystem-level changes (Edwards & Richardson, 2004). Blue whales, like many baleen whales, migrate from their feeding grounds to calve and mate in warmer waters at lower latitudes.

The blue whales of the Southern Hemisphere form genetically, phenotypically and behaviourally distinct lineages. Although there are only two recognised sub-species, the pygmy blue whale (*Balaenoptera musculus brevicauda*) that is never found south of in the Subantarctic zone; and the Antarctic or true blue whale (*B. m. intermedia*) that summers in the Antarctic Zone (Rice, 1998), there are ten region-specific blue whale call types, referred to as 'acoustic populations' (McDonald 2006; Frank and Ferris 2011). Seven of these acoustic populations, the Antarctic, Australian, Chilean, Madagascan, New Zealand, Solomon, and the Sri Lankan, are blue whales in the Southern Hemisphere. The population of blue whales feeding off Chile, has been proposed to belong to a third subspecies, the Chilean blue whale (Branch *et al*., 2007).

Chilean blue whales have traditionally been observed during the austral summer (December, January and February) and autumn (March, April and May) in southern Chilean waters (Gilmore, 1971; Cummings and Thompson, 1971a, b; Hucke-Gaete *et al*., 2004;

Cabrera *et al*., 2005; Galletti Vernazzani *et al*., 2012). Recently, blue whale sightings (Abramson and Gibbons, 2010; Försterra and Häussermann, 2012) and acoustic detections (Buchan *et al*. 2015) have been reported off southern Chile extending into the austral winter (June, July and August). Photo-identification surveys over nine-years show individual Chilean blue whales have a high degree of site-fidelity to specific regions such as the Isla de Chiloé (Galletti Vernazzani *et al*., 2012).

Here we describe the seasonal presence of Chilean blue whales in the waters off Chile between 2003 and 2015. We use the presence of acoustic signals, the South East Pacific (SEP) calls, as a proxy for the presence of Chilean blue whales. We analysed 61,178 h of year-round passive-acoustic data from bottom-mounted acoustic loggers located off the coast of central Chile within the south eastern Pacific Ocean. We examine the difference in temporal pattern of SEP calls at our site to acoustic stations north and south. We also examine how the seasonal pattern of the Chilean blue whale calls compares with the pattern of call detections of another sub-Antarctic blue whale, the Australian blue whale, recorded at similar latitudes across ocean basins.

METHODS

Study area

We used the underwater hydrophone array located off Juan Fernandez Island, also known as Robinson Crusoe Island, at 33.4° S, 78.9° E, situated approximately 750 km west of Santiago, Chile in the south eastern Pacific Ocean. The hydrophone array was situated on the north side of Juan Fernandez Island.

Data collection

Acoustic data were collected from July 2003 to December 2015, excluding 2006, and 2010-2013 (Table 1). The recording system, part of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization, consisted of three autonomous hydrophones moored to the seafloor and suspended at roughly 1000 m depth. The hydrophones recorded continuous ocean sound, at a sampling rate of 250 Hz, providing relatively flat response (± 1 dB) to the upper frequency limit of 120 Hz. Recordings were made continuously except for minor gaps when maintenance or hardware malfunctions occurred. The hydroacoustic station was destroyed by a tsunami in 2010 and was rebuilt in 2014 and as a result there is a four year gap, from 2010 to 2013, in the recordings. The recordings from 2006 were excluded because the station was offline for maintenance for the majority of this year.

Call detection

Chilean blue whale SEP call types were automatically detected using the automated energy ratio method. The Chilean blue whale produces two call types, the SEP1 (Fig. 1A) and SEP2 calls (Fig. 1B). Previous studies have shown there are no temporal differences in the occurrence of these two call types (Buchan *et al*., 2015), so our SEP detector was not developed to distinguish between the SEP1 and SEP2 call types. The SEP call detector targeted the high-intensity band of the first part of the calls, between 19 and 21 Hz, and triggered a detection when energy in this band was higher than a 0.2 threshold between 12 and 30 seconds (Fig. 1). The bandwidth of the detector was designed to account for a potential shift of approximately 0.14–0.16 Hz per year over the time of the study, as documented for other blue whale acoustic populations (McDonald *et al*., 2009). The SEP call detector was run for each year in Ishmael (V.1.80) (Table 1). Positive detections were checked manually, using Raven Pro 1.4 with spectrogram parameters: 550 points Fast Fourier Transform (FFT), 50% overlap, Hanning window (Mellinger 1994), and confirmed as either SEP1, SEP2 call, or not a SEP call.

RESULTS

A total of 1,380 positively identified SEP calls were detected from the 61,178 h of recordings. The number of calls identified was highly variable between years (Fig 2.). The highest number of calls, 627, was detected in 2003 despite only having 6 months of data available. Only 3 calls were detected in 2015, while the other years ranged between 49-265 detections.

The peak number of calls detected each year occurred mostly from April- June with the exception of 2003 and 2005 when the peaks were in December and February, respectively (Fig 2.). There was an abrupt decrease in detections immediately after the peak. No calls were detected between August and December for any years except 2003 when calls were detected in September, November, and December. The detections show a clear seasonal pattern with the peak in detected calls occurring during the austral autumn.

DISCUSSION

The overall patterns of SEP call detections, from this study and Buchan *et al*. (2015), suggest latitudinal movement of blue whales off the Chilean coast (Fig. 3). With this work, we detected Chilean SEP calls in early winter, whereas further north in the eastern tropical Pacific (ETP) Chilean blue whales are detected through winter (Fig. 3). This increases the body of evidence suggesting that SEP blue whales feed in southern cooler waters during the austral summer off the coast of Chile and migrate to tropical waters further north to breed in winter. After the breeding season they begin to make their return migration during late spring and early summer. Buchan *et al.* (2015) present SEP acoustic data in the Chiloense Ecoregion (CER) in southern Chile and the ETP. Their study revealed high numbers of SEP detections in the CER during late summer/autumn. The peak in detections in the CER occurred in April (Fig. 3). The ETP showed weaker seasonal patterns for SEP detections with calls detected throughout the entire year. Our study site shows an intermediate pattern to the CER and ETP as Juan Fernandez Island is situated in between those two areas. Juan Fernandez is situated closer to the CER and as a result the seasonal pattern is similar, but with a later autumn peak. The data presented in our study coupled with Buchan *et al.* (2015) provides further evidence to support seasonal north-south migration of blue whales.

The detections of SEP blue whale calls were variable between years. The highest number of detections was in 2003 although data was available for only six months of that year. In that year, calls were detected during November and December which did not occur in any of the subsequent years. A possible explanation for lack of detections, presumably also indicative of lack of calling, could be that during these months the whales are migrating south back to their feeding grounds with their newborn calves. This points to one of the weaknesses of the acoustic monitoring; ‘non-vocal’ individuals will not be detected, although they may have been present in the area.

The pattern of call detections for the sub-Antarctic blue whales from the Indian Ocean, as well as the Australian blue whale call, is similar to that seen for the Chilean blue whale call (Fig.4) (Stafford *et al*., 2011; Balcazar *et al*., 2015). We show that despite being from different acoustic populations the migration patterns of blue whales in the south eastern Indian Ocean are similar to those in the south eastern Pacific. In contrast, the seasonal calling patterns of the Antarctic blue whale, which has been established as a different subspecies, are completely different from the patterns seen in this study (Tripovich *et al*. 2015; Balcazar *et al*., 2015).

Our approach is a conservative count, it does not account for calls that may have been masked by background noise or missed during high density calling periods, where calls overlapped.

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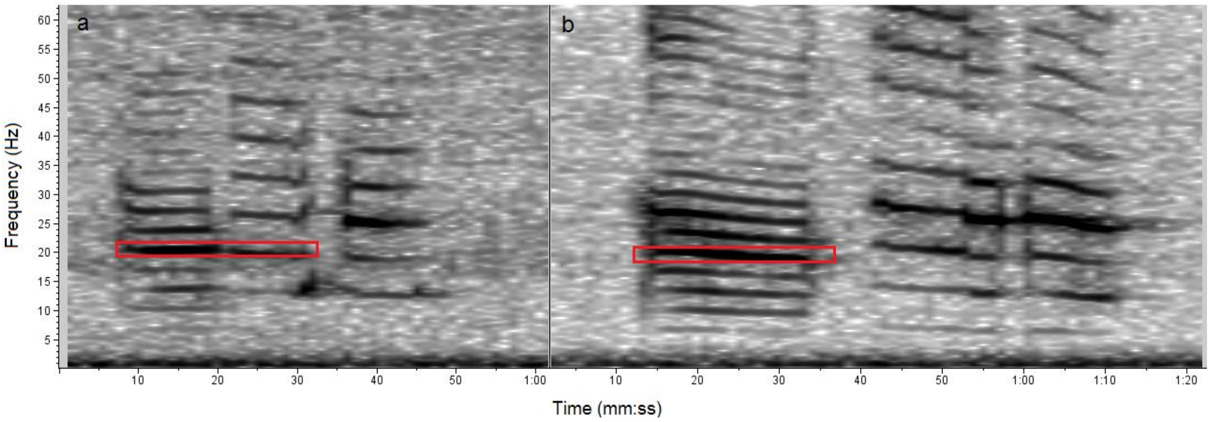

Figure 1. Southeast Pacific blue whale calls: (a) SEP1 and (b) SEP2 calls. The red box identifies the part of the call used in the detector. Spectrogram parameters are 550 points Fast Fourier Transform, 50% overlap, Hanning window.

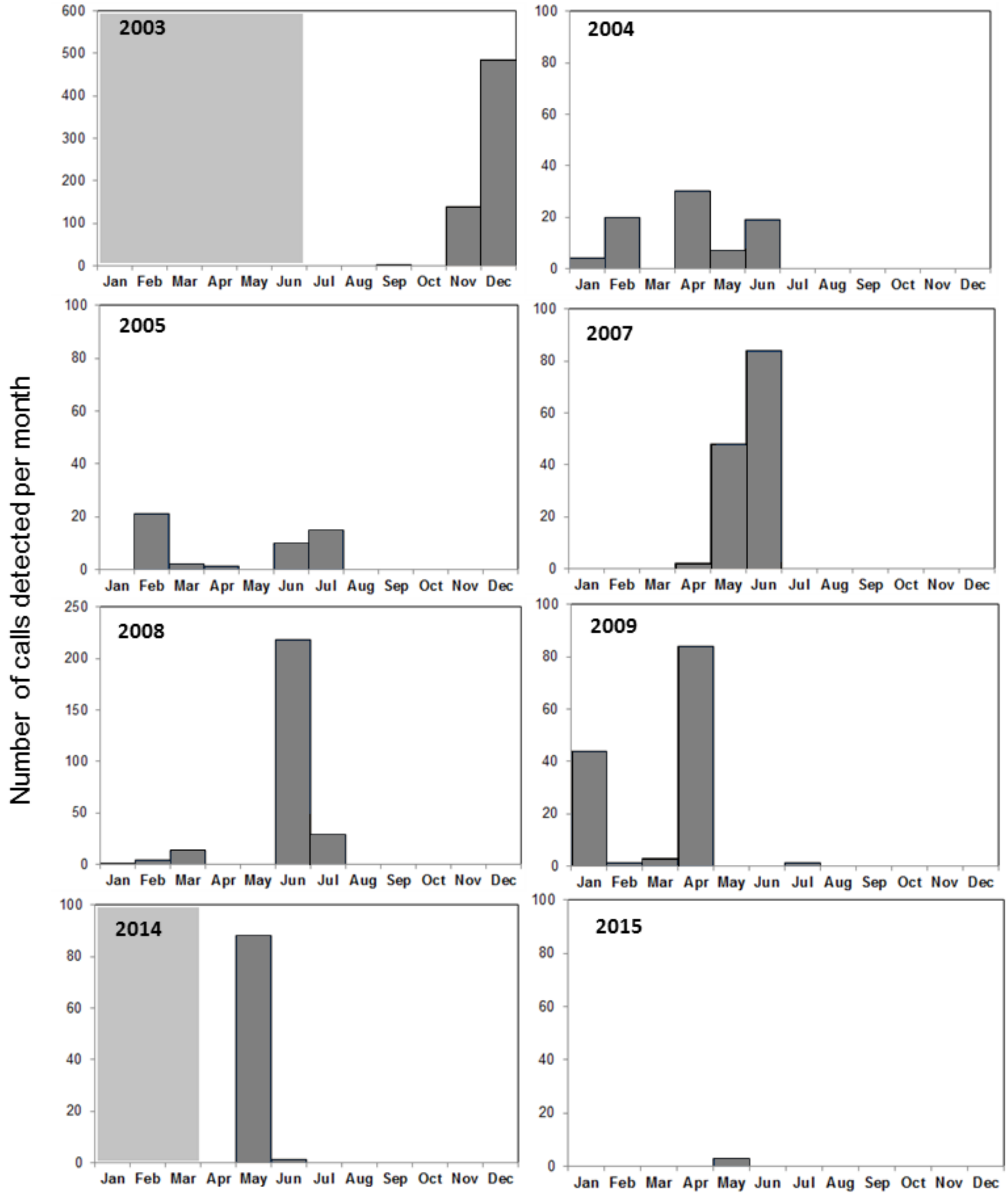

Figure 2. The number of Chilean blue whale call detections each month with data from 2003 to 2015 at Juan Fernandez Island. Chilean blue whale SEP1 and SEP2 calls were combined. Greyed out months indicate when data was not available.

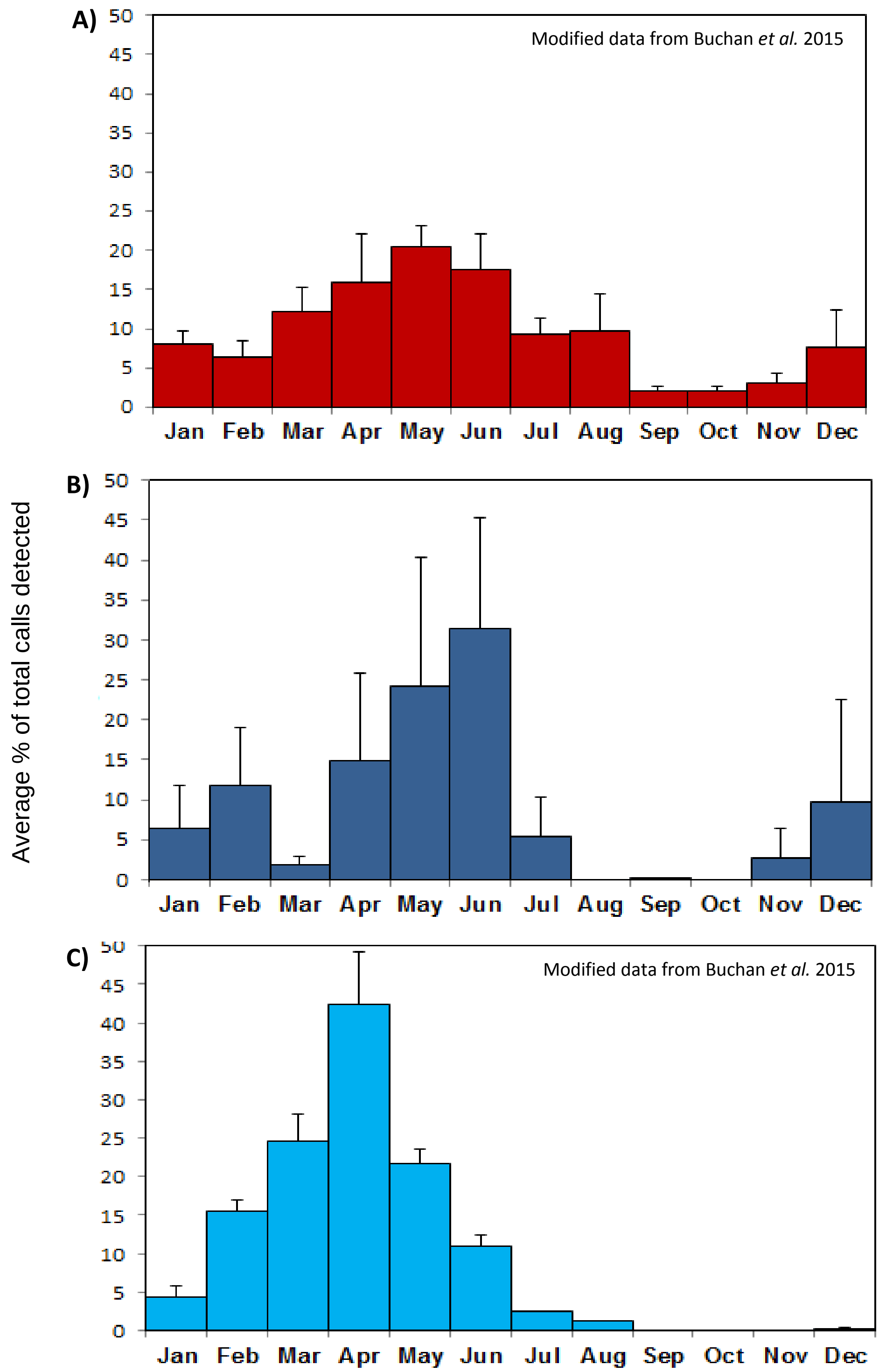

Figure 3. Comparison of the differences in timing when Chilean blue whale calls were detected at three locations in the south eastern Pacific. Represents the average % of calls detected per month: A) within the Eastern Tropical Pacific data pooled from 1996-1999 and 2000-2001 from Buchan *et al.* (2015), B) Juan Fernandez Island (mid Chile) data from 2003-2005, 2007-2009, 2014-2015, and C) Chiloense Ecoregion (southern Chile) data from 2012-2013 from Buchan *et al.* (2015).

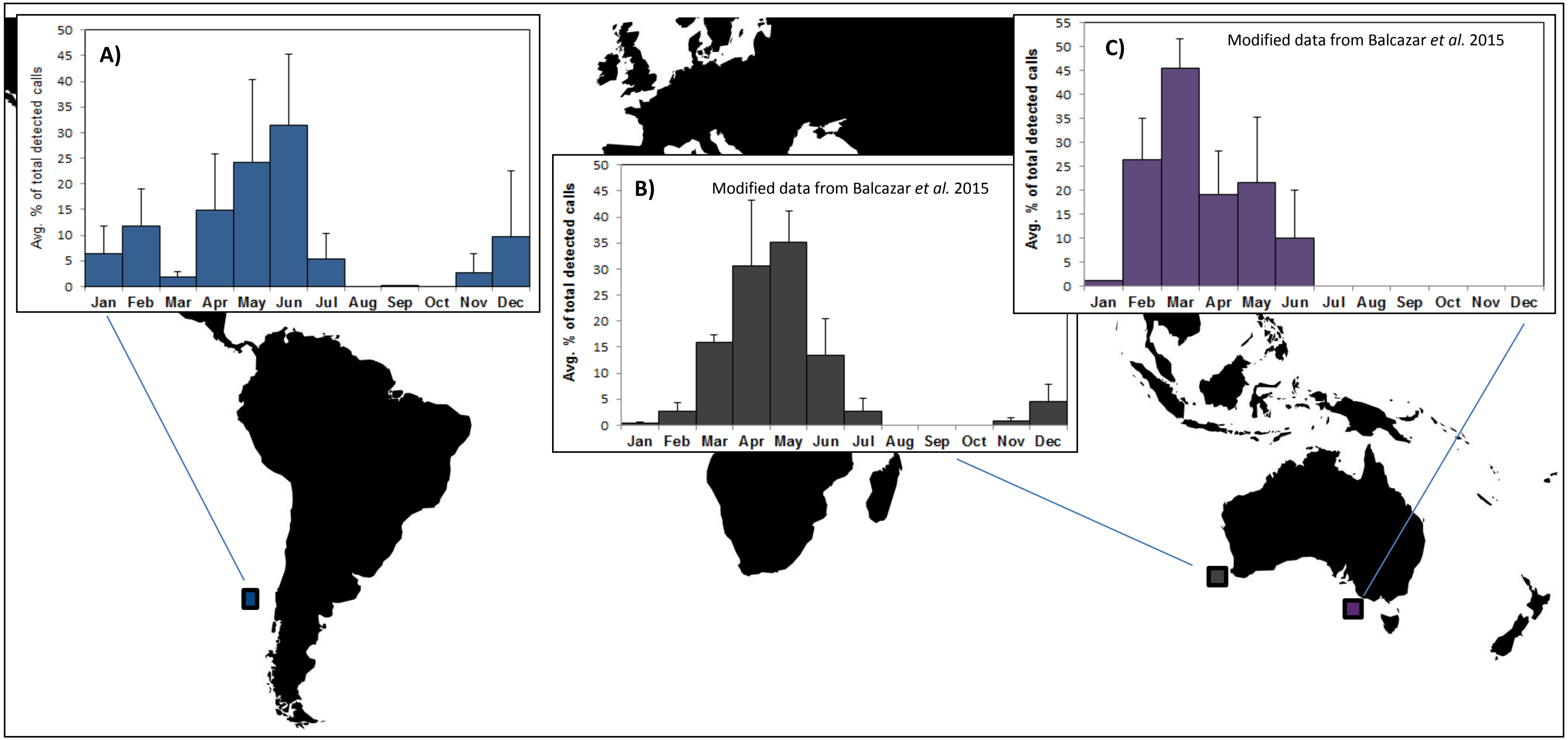

Figure 4. Longitudinal comparison of temperate blue whale seasonal distribution across the Southern Hemisphere. A) Chilean blue whale call recorded at Juan Fernandez Island averaged across 8 years, between 2003 and 2015 and Australian blue whale calls from B) the Perth Canyon and C) Bass Strait using modified data from Balcazar *et al.* (2015). Bars represent means with standard error bars.

Table 1. Summary of the underwater acoustic data available recorded at Juan Fernandez Island; hours = number of hours data were available.

Year	Recording months	Hours
2003	July-December	4208
2004	January-December	8668
2005	January-December	7868
2007	January-December	8441
2008	January-December	8757
2009	January-December	8431
2014	April-December	6068
2015	January-December	8737