



Seasonal acoustic presence of blue and fin whales in the Mascarene waters (southwestern Indian Ocean)

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Abstract

In the southwest Indian Ocean (SWIO), the Mascarene region has been identified as an Important Marine Mammals Area, yet the seasonal use of these waters by large baleen whales remains poorly resolved. We analysed passive acoustic data from 16 Ocean Bottom Seismometers deployed from October 2012 to November 2013 across latitudinal and longitudinal transects around Réunion Island and off eastern Madagascar. Songs of fin whales (*Balaenoptera physalus*), Antarctic blue whales (*B. m. intermedia*), and SWIO/Madagascar pygmy blue whales (*B. m. breviceauda*) were manually annotated from spectrograms to quantify hourly acoustic presence per day. Fin whales showed the highest acoustic presence among the three studied taxa, with seasonal presence lasting up to 8 months (April–December) and clear north–south patterns in the onset and end of acoustic presence. Antarctic blue whales were detected less frequently, primarily during austral autumn and winter, with records extending north to 16°S and secondary peaks in October–November consistent with southward movement after wintering farther north. Madagascar pygmy blue whales showed a pronounced bimodal acoustic presence (mid-October–mid-January; March–July/August) and a strong longitudinal structuring, with greater acoustic presence in the western part of the study area. The spatial distribution differed markedly between these two periods, revealing distinct migration pathways through the region during northward and southward movements. Taken together, these results identify the Mascarene waters as a shared seasonal habitat for fin whales, Antarctic blue whales, and Madagascar pygmy blue whales, while highlighting distinct seasonal and spatial patterns among taxa. Given the intense shipping activity in the region, continued and expanded acoustic monitoring is needed to assess long-term whale habitat use, characterize underwater noise, and evaluate its potential influence on the use of these waters, thereby informing future conservation measures.

Keywords distribution, migration, baleen whales, endangered species, southwest Indian Ocean

Introduction

The Mascarene Archipelago lies in the tropical latitudes of the southwestern Indian Ocean (SWIO), between 700 and 1500 km east of Madagascar. It comprises three main volcanic islands—Réunion, Mauritius, and Rodrigues—and includes several underwater seamounts and banks. The waters surrounding Réunion and Mauritius, together with the La Pérouse seamount and the southern part of the Nazareth Bank (up to Saint Brandon shoals), have been identified as an Important Marine Mammal Area (IMMA). A total of 26 cetacean species have been recorded in these waters (Dulau-Drouot et al. 2008, Laran et al. 2017, Webster et al. 2020) (<https://www.marinemammalhabitat.org/portfolio-item/mascarene-islands-associated-oceanic-features/>). In addition, the Mascarene Archipelago lies within the Indian Ocean Sanctuary established by the International Whaling Commission in 1979, following a proposal from the Republic of Seychelles to protect large baleen whales from commercial whaling. The sanctuary has since been reviewed and extended on three occasions, the most recent occurring in 2002.

The diverse oceanographic conditions of the Mascarene waters provide favourable feeding and breeding habitats for a variety of cetacean species. For example, the western insular slope of Mauritius is recognized as an important breeding and feeding habitat for sperm whales (*Physeter macrocephalus*) in the southwestern Indian Ocean (Huijser et al. 2020, Chambault et al. 2021, Sarano et al. 2021, Webber et al. 2023, Barteneva-Vitry et al. 2025). In addition, the coastal waters, seamounts, and banks of the Mascarene region are recognized as a major breeding ground for humpback whales (*Megaptera novaeangliae*) (Dulau-Drouot et al. 2012, Dulau et al. 2017).

Despite the high diversity of cetacean species recorded in the Mascarenes and the recognized role of the area as a cetacean habitat, understanding of the spatiotemporal distribution of these populations remains limited, particularly for large baleen whales. Humpback whales are the main exception, having been comparatively better studied in the region (Boer De et al. 2003, Dulau-Drouot et al. 2008, Kiszka et al. 2009). This knowledge gap largely results from the fact that most available data on cetacean presence in Mascarene waters were obtained through coastal visual

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surveys conducted mainly along the west coast of the island (Dulau-Drouot et al. 2008, 2012, Estrade and Dulau 2020, Webster et al. 2020). As most baleen whales inhabit offshore pelagic waters, have elusive diving behaviour, and usually travel alone or in small groups, the probability of visually detecting them is low. Large-scale aerial surveys covering oceanic waters were conducted in the area, but they were performed during austral summer for ideal weather conditions, and thus outside the expected seasonal occurrence of baleen whales in the region (Branch et al. 2007, Dulau-Drouot et al. 2012, Samaran et al. 2013, Leroy et al. 2016, Dulau et al. 2017, Laran et al. 2017, 2018, Dréo et al. 2019).

Understanding the full spatiotemporal distribution of these migratory populations is crucial for their conservation. Most large baleen whale populations were severely depleted during twentieth-century industrial whaling, and many are only slowly recovering. They now face threats from climate change, ship strikes, or increasing anthropogenic noise levels (Leaper and Miller 2011). Among them are southern blue whales, which lost more than 99% of their pre-whaling population (Branch et al. 2004). Of the two blue whale subspecies inhabiting the Southern Hemisphere, the Antarctic blue whale (*Balaenoptera musculus intermedia*) is classified by the International Union for Conservation of Nature (IUCN) Red List as Critically Endangered (Cooke 2018a), whereas the pygmy blue whale (*B. m. brevicauda*) is classified as Endangered, under the classification of the blue whale species as a whole (Cooke 2018b). Similarly, the fin whale (*B. physalus*), which was also heavily targeted by whalers, was listed as Endangered until 2018 and is now listed as Vulnerable by the IUCN. Despite this conservation concern, fin whale distribution and occurrence in the Indian Ocean remain poorly documented (Cooke 2018c).

The southern Indian Ocean has been identified as a key habitat for blue and fin whales (Stafford et al. 2011, Samaran et al. 2013, Leroy et al. 2016, 2018). Tropical to sub-Antarctic waters are used year-round by at least three populations of pygmy blue whales that do not migrate as far south as Antarctica. These waters also provide migratory and wintering habitats for both fin whales and Antarctic blue whales, with likely breeding areas at lower latitudes (Samaran et al. 2013, Leroy et al. 2016, 2018, Cerchio et al. 2024). In the southwestern Indian Ocean, Antarctic blue whales, pygmy blue whales, and fin whales are known to be seasonally present in the Mozambique Channel, the Madagascar Southern Plateau, and waters south of 26°S (Kasuya and Wada 1991, Mikhalev 2000, Best et al. 2003, Samaran et al. 2013, Leroy et al. 2016, 2018, Dréo et al. 2019, Cerchio et al. 2024, 2025). However, records from the Mascarene waters remain scarce. Fin whales have only occasionally been sighted around Mauritius (Corbett 1994) and Réunion Island (Globice Réunion, unpublished data) since the observations reported by Kasuya and Wada (1991). Blue whale records, however, remain limited to historical catches and a few isolated sightings around Madagascar and the Seychelles (Branch et al. 2007), and Réunion Island (Globice Réunion, unpublished data).

Passive acoustic monitoring (PAM) has been increasingly used over the past two decades to study the presence of large baleen whales (Mellinger et al. 2007). These animals are vocally active, as males use stereotypic and identifiable songs as a sexual display to communicate over long distances. Songs are species- and population-specific (McDonald et al. 2006), making PAM a powerful method to study the acoustic presence of large baleen whales over long-term recordings. Accordingly, PAM has proven useful for studying blue and fin whale presence and movements in the

southwestern Indian Ocean. For instance, a large hydrophone array deployed across the southern Indian Ocean, partly overlapping the present study area but extending farther south and east, continuously monitored low-frequency ocean sounds from 2009 to 2023 (Royer 2009). This network improved knowledge of Antarctic and pygmy blue whale distribution in sub-Antarctic and temperate waters, and provided preliminary information on fin whale occurrence (Leroy et al. 2016, 2018, Torterotot et al. 2020). Similarly, autonomous recorders deployed along the west coast of Madagascar documented the seasonal occurrence of Antarctic blue whales, pygmy blue whales and fin whales in the eastern Mozambique Channel (Cerchio et al. 2020, 2024), while corroborating results were later reported east of Mayotte (Dréo et al. 2025). Blue whales are also known to occur farther north around the Chagos Archipelago (Stafford et al. 2004, 2011, Leroy et al. 2021). However, major geographic gaps remain between these study areas, particularly in the Mascarene region, where the presence and seasonal occurrence of blue and fin whales remain poorly documented.

The RHUM-RUM (Réunion Hotspot and Upper Mantle Réunion's Unterer Mantel) observatory is a network of Ocean Bottom Seismometers equipped with hydrophones (OBS/H) deployed across the southwestern Indian Ocean around Réunion Island to investigate the mantle structure and seismological activity associated with the Réunion hotspot (Barruol and Sigloch 2013, Barruol et al. 2017) (Fig. 1). The instruments were deployed from September/October 2012 up to November 2013 and recorded continuously at sampling rates of 50 or 62.5 Hz depending on the site. Although this observatory was not originally designed to monitor marine mammals, these sampling frequencies allowed the recording of the low-frequency sounds produced by blue and fin whales, or at least the lower-frequency components of their songs.

The utility of this observatory for studying large baleen whales was previously demonstrated by Dréo et al. (2019), who used six sites located south of Réunion Island to investigate whale seasonality using long-term spectrogram analyses. Building on this opportunistic dataset, we analysed acoustic recordings from 16 OBS selected to cover latitudinal and longitudinal transects centred on Réunion Island, as well as along a latitudinal transect off the east coast of Madagascar (Fig. 1). Our objective was to improve understanding of the temporal and spatial occurrence and movements of Antarctic blue whales, pygmy blue whales, and fin whales in the Mascarene region. Increasing knowledge on how these species use this region is necessary to inform mitigation strategies, particularly in an area experiencing intense large-vessel traffic.

Materials and methods

The RHUM-RUM OBS network

The network consisted of 57 OBS deployed from October 2012 to November 2013 covering 4 million square kilometres (2000 × 2000 km) of the western Indian Ocean (Fig. 1), spanning 16–34°S and 48–70°E, at depths ranging from 2002 to 5430 m. Each OBS was equipped with a three-component seismometer and a hydrophone, recording low-frequency sounds at sampling rates of 50 or 62.5 Hz depending on the site, thus encompassing part of the frequency range of the blue and fin whale vocalizations. The RHUM-RUM data are currently hosted as open-access data through

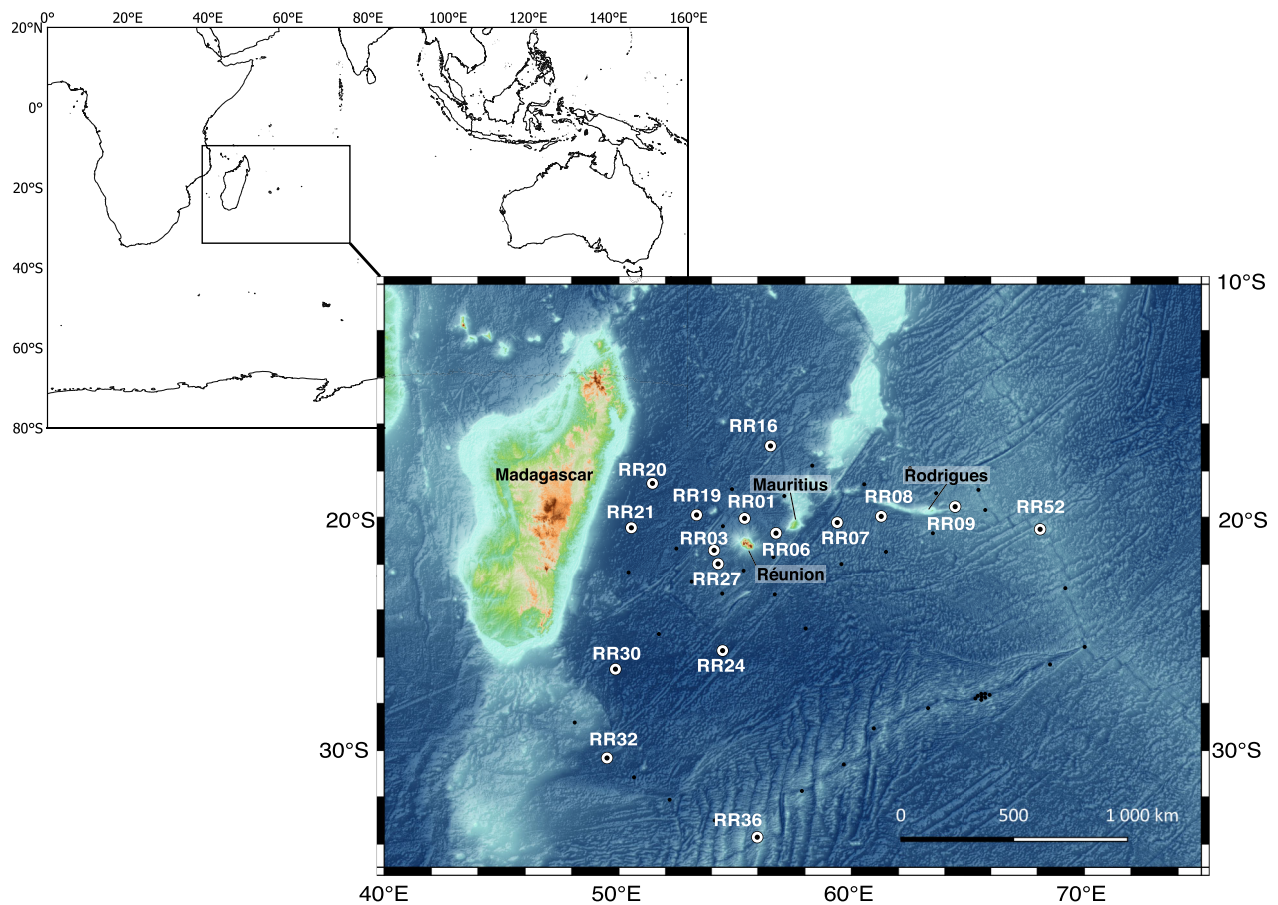


Figure 1. Map of the Mascarene Islands (Réunion, Mauritius, and Rodrigues) showing the RHUM-RUM OBS array. Open circles with a central dot indicate the OBS selected for this study, whereas filled dots correspond to the remaining OBS stations of the array.

the RESIF French national seismic archive centre (<https://seismology.resif.fr>). Additional technical details are provided in Stähler et al. (2016).

To investigate the presence of these species across the Mascarene region, 16 OBS were selected based on their geographic distribution and recording duration. The selected OBS included 13 sites distributed along a latitudinal (17°S–34°S) and longitudinal (50°E–68°E) transect centred on Réunion Island. Réunion Island was used as the central reference point because it lies near the centre of a large portion of the RHUM-RUM OBS array and represents a key area for cetaceans, with 26 species identified to date. In addition, four OBS located along a latitudinal transect off the east coast of Madagascar were included to complement this investigation of blue and fin whale movements in the southwestern Indian Ocean (Fig. 1 and Table 1). Distances between selected OBS ranged from approximately 160 to 700 km, except for RR03 and RR27, which were separated by about 70 km.

Acoustic data analysis

The spectrograms of the acoustic data were manually annotated in Raven Pro 1.6 (Cornell Lab of Ornithology) to assess the hourly presence of whale songs. The spectrogram parameters used were 512-point FFT, 50% overlap, and Hann window. As the OBS sampling frequencies were limited to 50 or 62.5 Hz (Nyquist frequen-

cies of 25 and 31 Hz, respectively), only part of the frequency content of blue and fin whale songs was recorded. The full vocalizations are described below for reference, while species and subspecies identification was based on the characteristic temporal and spectral features remaining within the bandwidth (frequencies within the grey bars in Fig. 2a–c).

Antarctic blue whale

The song displays a characteristic Z-shape on spectrograms (Fig. 2a), with a tone around 27 Hz lasting about 10 s, followed by a short downsweep to a second tone around 18 Hz lasting another 10 s. This song is repeated approximately every 60 s.

SWIO/Madagascar pygmy blue whale

The song is composed of two units (Fig. 2b). The first unit lasts about 14 s and starts with a deterministic chaos segment lasting around 4.75 s, followed by a tonal harmonic sound whose maximum energy occurs in the fifth harmonic at 35.3 Hz (i.e. $F_0 = 7.04$ Hz). The second unit starts 28 s later and consists of a noisy pulsed sound of 3.30 s, followed by a harmonic-like signal whose main energy band is centred around 25 Hz. This unit lasts 23.63 s (Leroy et al. 2021).

Table 1. Selected recording sites of the RHUM-RUM array used in this study.

Site	Latitude	Longitude	Start recording date	End recording date	Number of recording days	Sampling frequency (Hz)	Depth (m)
RR01	-20.0069	55.423	14-Oct-2012	6-Nov-2013	388	50	4298
RR03	-21.3732	54.1294	4-Oct-2012	31-Oct-2013	392	50	4340
RR06	-20.6550	56.7639	2-Oct-2012	31-Oct-2013	394	50	4216
RR07	-20.1945	59.4058	29-Sep-2012	24-Oct-2013	390	50	4370
RR08	-19.9259	61.2907	29-Sep-2012	23-Oct-2013	389	50	4190
RR09	-19.4924	64.4485	30-Sep-2012	25-Oct-2013	390	50	2976
RR16	-16.8976	56.5335	3-Oct-2012	27-Oct-2013	389	50	4426
RR19	-19.8500	53.3805	8-Oct-2012	30-Oct-2013	387	50	4901
RR20	-18.4774	51.4600	5-Oct-2012	31-Oct-2013	391	50	4820
RR21	-20.4217	50.5599	7-Oct-2012	31-Oct-2013	389	50	4782
RR24	-25.6805	54.4881	21-Oct-2012	10-Aug-2013	293	50	5074
RR27	-21.9657	54.2889	7-Oct-2012	19-Jul-2013	285	50	4277
RR30	-26.4861	49.8917	10-Oct-2012	8-Oct-2013	363	50	5140
RR32	-30.2903	49.5555	12-Oct-2012	6-Oct-2013	359	50	4670
RR36	-33.7018	55.9578	14-Oct-2012	18-Nov-2013	400	62.5	3560
RR52	-20.4722	68.1094	19-Oct-2012	25-Nov-2013	402	62.5	2880

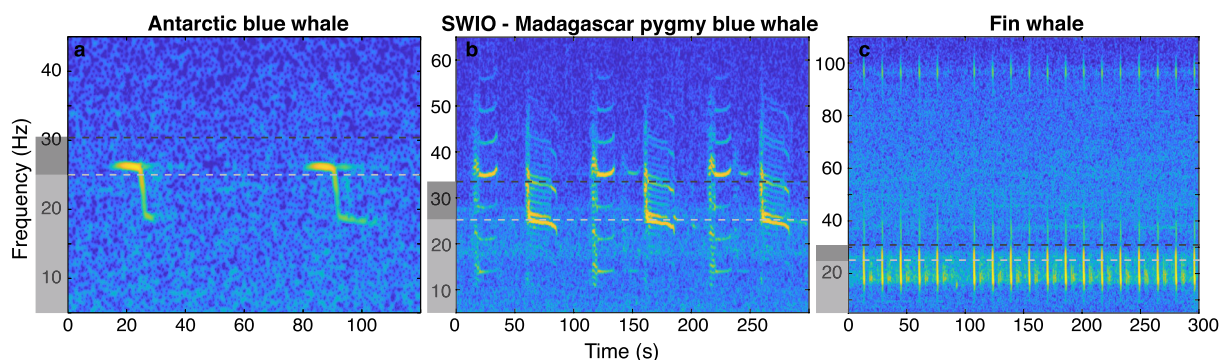


Figure 2. Stereotyped songs of (a) Antarctic blue whale, (b) South-Western Indian Ocean/Madagascar pygmy blue whale, and (c) fin whale. The grey highlighting and the corresponding dashed line show the recorded bandwidth: up to 25 Hz (light grey, $F_s = 50$ Hz) for most of the recorders, and up to 31 Hz (medium grey, $F_s = 62.5$ Hz) for RR36 and RR52.

Fin whale

The song consists of sequences of regularly repeated stereotyped downsweeps lasting less than 1 s (Fig. 2c). These repeated signals, known as ‘20-Hz pulses’, downsweep from around 30 to 15 Hz, with peak energy around 20 Hz. They are often associated with an upper pulse in the 80–100 Hz range that may vary among populations.

A positive detection corresponded to the visual identification of at least one distinguishable vocalization above the ambient noise level within a given hour, even at low signal-to-noise ratios. Acoustic presence of each song type was manually logged using the Raven Pro annotation tool to generate a presence/absence metric per hour, which was subsequently pooled by day.

Results

In total, the 16 selected OBS provided more than 6000 days of acoustic recordings that were manually analysed for low-frequency baleen whale vocalizations. The three song types corresponding to fin whales, Antarctic blue whales, and SWIO/Madagascar pygmy blue whales (hereafter referred to as ‘Madagascar pygmy blue whales’) were detected at all sampled sites, all showing strong seasonality and overlapping periods of occurrence.

Fin whales

The RHUM-RUM OBS/H acoustic data revealed a strong acoustic presence of fin whales through the detection of their characteristic 20-Hz pulse at all sampled sites (Fig. 3), with an average of 43% (SD = 8%, range = 25%–57%) of the recording days containing at least one hour with fin whale songs. The lowest value (25%) corresponded to the site RR27 where the recording effort stopped shortly after fin whale songs first appeared, leading to an underestimation of acoustic presence at this site. Fin whale acoustic presence was highly seasonal and occurred during periods of up to 8 months, starting in April and ending as late as December (depending on the site). No songs were recorded from January to the end of March, during austral summer.

Along a **latitudinal transect** near the longitude of Réunion Island (approximately 55°E), fin whale acoustic presence in 2013

started earliest at the southernmost site (RR36, ~33.7°S), where songs were first detected around 29 March 2013, and progressively later toward the north, reaching RR01 (~20°S) approximately 1500 km farther north on 13 June 2013 (Figs 3a and 4a). RR16 (~16.9°S), the northernmost site of the gradient, was however an exception to this overall trend, as song occurrence started about three weeks earlier (24 May 2013) than at RR01, located 350 km further south. The end of song occurrence in 2013 was difficult to estimate because it occurred after the recorders stopped. Based on the beginning of the recordings in October 2012, song presence appeared to extend until late October or November, depending on the site. Overall, at RR36 (the southernmost site), song presence spanned from late March to mid-November, and was slightly sparser than at more northern sites (on average 12.8 positive hours per day of acoustic presence vs 18.4 for RR16). A particularly strong acoustic presence of fin whale songs was also noted in November 2012 at RR24 (Fig. 3a).

Along the **east coast of Madagascar**, we also observed a latitudinal gradient in the onset of fin whale acoustic presence during 2013, with occurrences beginning at the end of March at RR32 (~30.3°S) and 2.5 months later at RR20 (~18.5°S), approximately 1,320 km farther north (Fig. 3b). Similarly, the end of the 2012 acoustic season appeared gradual, ending in early November at RR20 and later in November in RR32. However, some sporadic acoustic presence persisted into December at RR20 and RR21. The acoustic presence was also higher at the two northernmost sites RR20 and RR21, compared to the southern sites RR30 and RR32 (on average 11.1 positive hours per day of acoustic presence at RR32 vs 19.7 at RR21). Prominent song presence was also observed in November 2012 at all these sites, compared to the other sampled sites, except RR24.

Along a **longitudinal transect** near the latitude of Réunion Island (approximately 20°S), fin whale acoustic presence in 2013 began almost simultaneously across sites separated by approximately 1825 km, with the acoustic season starting in early June (Fig. 3c and 4b), and persisting at least until late October (then the recorder stopped). In 2012, at the beginning of the recording period, fin whale 20-Hz pulses were recorded until late October or mid-November but with relatively sparse daily occurrence. On the western side of the gradient (RR21, RR19, and RR01; 50.6–55.4°E), detections continued sporadically until mid-December, with the latest detection on 22 December at RR21 (~50.6°E), the westernmost site.

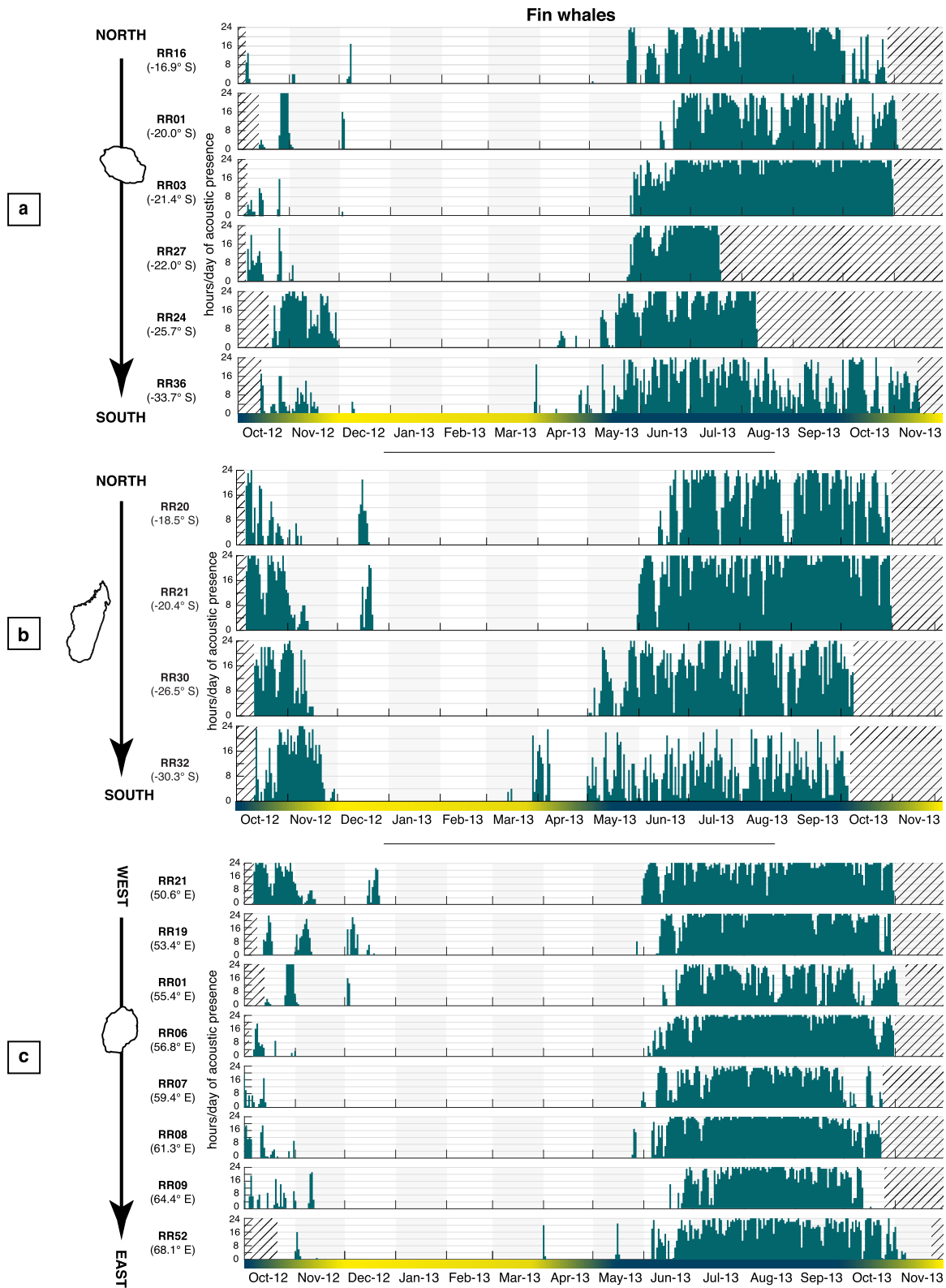


Figure 3. Hourly acoustic presence of fin whales per day along (a) a latitudinal transect centred on Réunion Island; (b) a latitudinal transect off the east coast of Madagascar; (c) a longitudinal transect centred on Réunion Island. The colour bar indicates the season: blue = austral winter (June–September), yellow = austral summer (December–March), green = interseason (April–May and October–November). Dashed areas represent periods with no recordings, shaded bars delineate months.

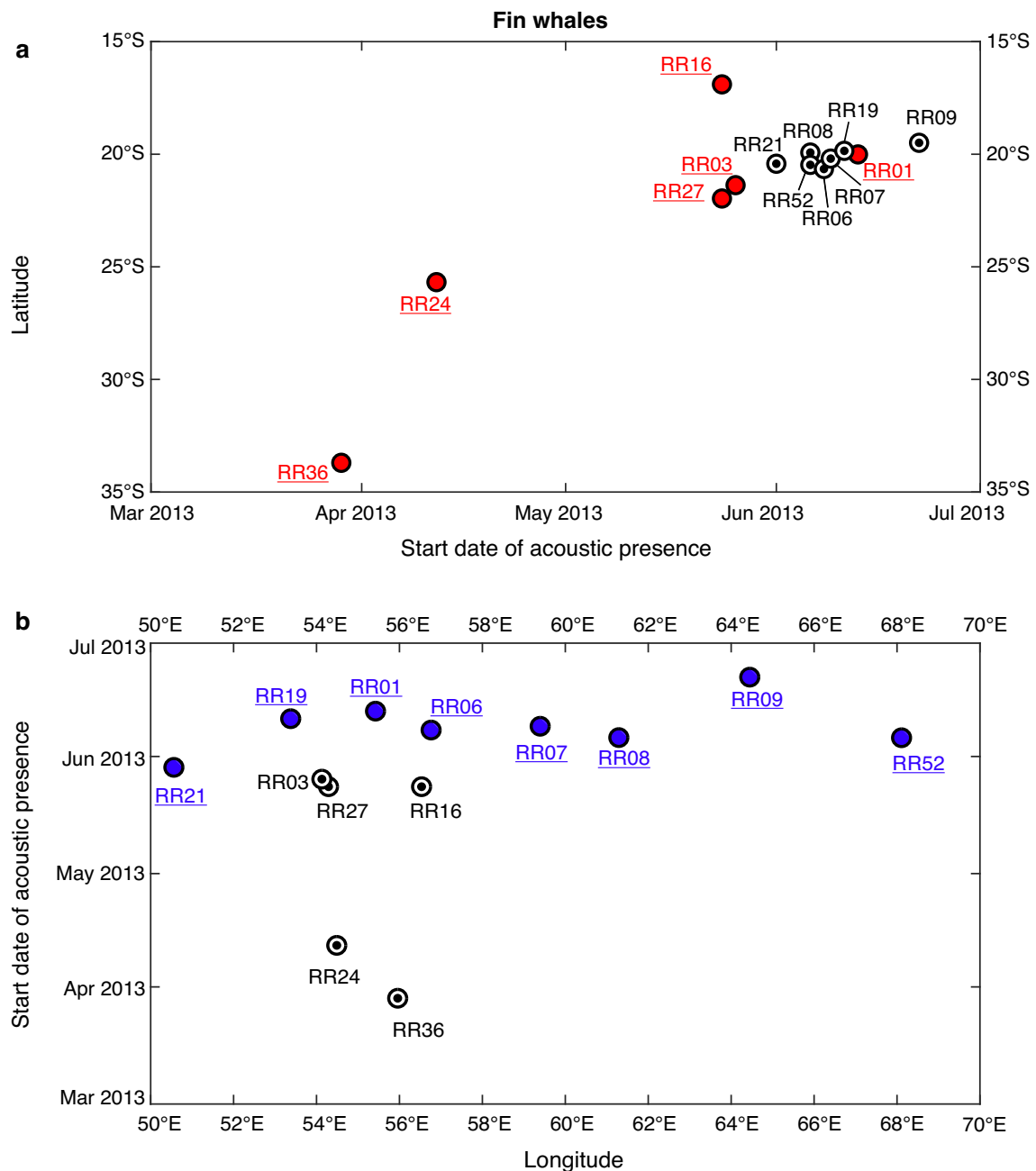


Figure 4. Start date of fin whale acoustic presence for the 2013 season (a) by site latitude. Red filled circles with underlined labels indicate sites belonging to the latitudinal transect centred on Réunion Island (~55°E), whereas open circles with black central dots indicate OBS located outside this transect; (b) by site longitude. Blue filled circles with underlined labels indicate sites belonging to the longitudinal transect centred on Réunion Island (~20°S), whereas open circles with black central dots indicate OBS located outside this transect.

Antarctic blue whales

Antarctic blue whale songs were detected at all the sampled sites, although with much lower occurrence than fin whale songs (Fig. 5). On average, acoustic presence of Antarctic blue whales was detected on 13% of recording days (SD = 6%, range = 4%–28%). For most sites sampled along the latitudinal and longitudinal transects centred on Réunion Island, the daily pattern of acoustic presence was sparse, with a few days of strong presence (up to 24 h/day) followed by one or more days of absence (Fig. 5a and c). For the majority of sites, no song was detected from mid-

spring to early autumn (October to April), except on the western side of the transect and along the east coast of Madagascar, where songs were detected in November (Fig. 5b and c).

Along the **latitudinal transect** near the longitude of Réunion Island (~55°E), the main period of acoustic presence of the Antarctic blue whales occurred slightly earlier and lasted somewhat longer at southern sites than at northern ones (from mid-April to late July for RR16, ~16.9°S, *versus* mid-April to late August at RR36, ~33.7°S, located 1,850 km farther south, in 2013). Songs were also detected in October 2013 at RR01 and RR03 (~20°S and 21.4°S),

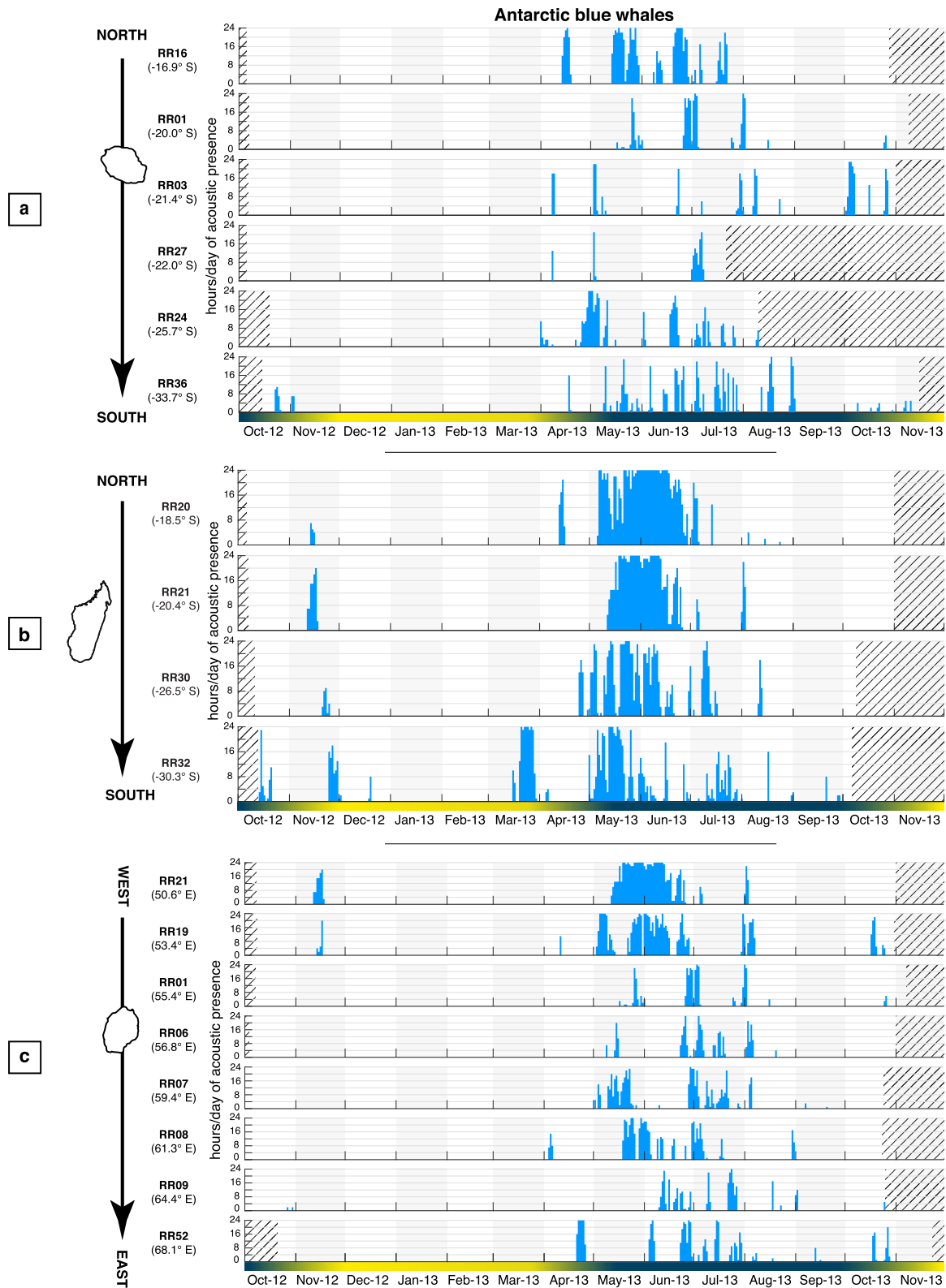


Figure 5. Hourly acoustic presence of Antarctic blue whales per day along (a) a latitudinal transect centred on Réunion Island; (b) a latitudinal transect off the east coast of Madagascar; (c) a longitudinal transect centred on Réunion Island. The colour bar indicates the season: blue = austral winter (June–September), yellow = austral summer (December–March), green = interseason (April–May and October–November). Dashed areas represent periods with no recordings, shaded bars delineate months.

following a month of acoustic absence, as well as in October 2012 and October–November 2013 at RR36 (Fig. 5a).

Off the **east coast of Madagascar**, higher acoustic presence of Antarctic blue whales was recorded at RR20 and RR21 ($\sim 18.5^\circ\text{S}$ and 20.4°S), with high singing activity from May through late June 2013 (Fig. 5b). At RR30 and RR32 ($\sim 26.5^\circ\text{S}$ and 30.3°S), singing activity was generally less concentrated, with fewer hours of acoustic presence per day distributed over a longer period, particularly at RR32. In 2012, Antarctic blue whales were recorded at RR32 in October, late November, and for three days in December, whereas at RR20, RR21, and RR30 detections were restricted to about one week in mid-November, with no detections before or after that period. Along the **longitudinal transect** around the latitude of Réunion Island ($\sim 20^\circ\text{S}$), no consistent longitudinal pattern in acoustic presence was apparent, although acoustic occurrence was generally higher at the western sites (Fig. 5c), consistent with the higher acoustic occurrence observed off the east coast of Madagascar (Fig. 5b). At the eastern edge of the transect, acoustic presence was generally lower in terms of hours per day but extended over a longer period, with detections from mid-April to August 2013 and a few additional days in September. Songs were also recorded in October 2013 at RR19 ($\sim 53.4^\circ\text{E}$) and RR52 ($\sim 68.1^\circ\text{E}$) reaching up to 22 h/day on some days (Fig. 5c).

Madagascar pygmy blue whales

Madagascar pygmy blue whales showed strong seasonal acoustic occurrence at each sampled site (Fig. 6). Overall, they were acoustically present during two distinct periods: from October to early January, and from March to late August, with variability among sites. The proportion of recording days with Madagascar pygmy blue whale song presence ranged from 3% to 61% (mean = 28%, SD = 18%).

All sites along the **latitudinal transect** near the longitude of Réunion Island ($\sim 55^\circ\text{E}$) showed a similar pattern, with sparse acoustic presence in November–December 2012 followed by a more prominent presence from mid-March to late July 2013 (Fig. 6a). During days with detections, acoustic presence was higher at the northernmost site RR16 (mean = 17.6 positive hours per day) than at the southernmost site RR36 (12.3 h/day). Madagascar pygmy blue whale acoustic presence began within four days across all sites spanning approximately 1850 km during March 2013 (Figs 6a and 7a). However, the period of presence ended progressively earlier from south to north: it lasted until early to mid-June at RR36 ($\sim 33.7^\circ\text{S}$), but persisted a full month longer—until late July—at RR16 ($\sim 16.9^\circ\text{S}$) (Figs 6a and 7b).

Along the **east coast of Madagascar**, detection patterns mirrored those observed along the latitudinal transect centred on Réunion Island, with Madagascar pygmy blue whale songs occurring broadly during the same two periods: late October 2012 to mid-January 2013, and March to August 2013 (Fig. 6b). Unlike the more easterly transect, the first period (October–January) was as pronounced as the second, particularly at the northern sites RR20 and RR21. In contrast, sites RR30 and RR32, located approximately 680 to 1100 km farther south, showed a more intermittent acoustic presence, with generally fewer hours of detection per day. Moreover, songs were detected in February at RR32 ($\sim 30.3^\circ\text{S}$), and from early March onward at both RR30 ($\sim 26.5^\circ\text{S}$) and RR32. The main period of acoustic presence also ended earlier at these sites,

around late June, with only a few detections persisting in late July and early August.

Along the **longitudinal transect** around the latitude of Réunion Island ($\sim 20^\circ\text{S}$), site location had a clear effect on Madagascar pygmy blue whale acoustic presence. In November–December 2012, acoustic presence decreased markedly from west to east, being highest at RR21 ($\sim 50.5^\circ\text{E}$), followed by RR19 ($\sim 53.4^\circ\text{E}$), and limited to only a few hours per day at RR01 and RR06 ($\sim 55.4^\circ\text{E}$ and 56.8°E , located approximately 215 and 360 km east of RR19, respectively), while no songs were detected east of 57°E (RR07, RR08, and RR09), the closest of which was separated from RR06 by at least 635 km (Fig. 6c).

During the March–August 2013 period, the duration and daily acoustic presence decreased eastward. This presence extended from March to August at RR21 ($\sim 50.6^\circ\text{E}$), whereas sites farther east showed a gradually later onset (Fig. 8a), earlier end of acoustic presence (Fig. 8b), and fewer hours of acoustic presence (Fig. 6c) along the west-to-east transect (50°E to 68°E).

Discussion

The Mascarene waters: a shared area

Our study provides a large-scale characterization of the seasonal and spatial patterns of fin and blue whale acoustic presence across the Mascarene region. Using an extensive hydrophone array spanning broad latitudinal and longitudinal transects, we show that fin whales, Antarctic blue whales, and SWIO/Madagascar pygmy blue whales occur across these oceanic waters during austral autumn and winter, while exhibiting distinct seasonal and geographic patterns. Fin whales and Antarctic blue whales occurred across much of the longitudinal extent of the study area, from 50°E to 70°E , whereas Madagascar pygmy blue whales were more concentrated in its western sector (west of 59°E). The latitudinal patterns further revealed seasonal shifts in acoustic presence consistent with migratory movements through the region. Together, these findings identify the Mascarene waters as a shared oceanic habitat for fin whales, Antarctic blue whales, and Madagascar pygmy blue whales, and provide new insights into their seasonal movements across the southwestern Indian Ocean.

Despite the relatively limited duration of our recordings, the seasonal and spatial patterns observed here are broadly consistent with acoustic observations collected over more than a decade across the southwestern Indian Ocean (Leroy et al. 2016, 2018, Torterotot et al. 2020, Cerchio et al. 2024). This consistency suggests that the patterns documented here are not restricted to the year of our study. The substantial acoustic presence recorded in the offshore waters east of Madagascar, together with comparable seasonal patterns reported west of Madagascar (Cerchio et al. 2024), further highlights the broad use of waters surrounding Madagascar and the Mascarenes by these large baleen whales.

Fin whales

Fin whale songs were recorded for up to 8 months of the year and represented the most prominent low-frequency whale vocalization across the recording sites surrounding the Mascarenes. Previous acoustic studies had documented fin whale presence across a broad area of the southern Indian Ocean (Leroy et al. 2018) and

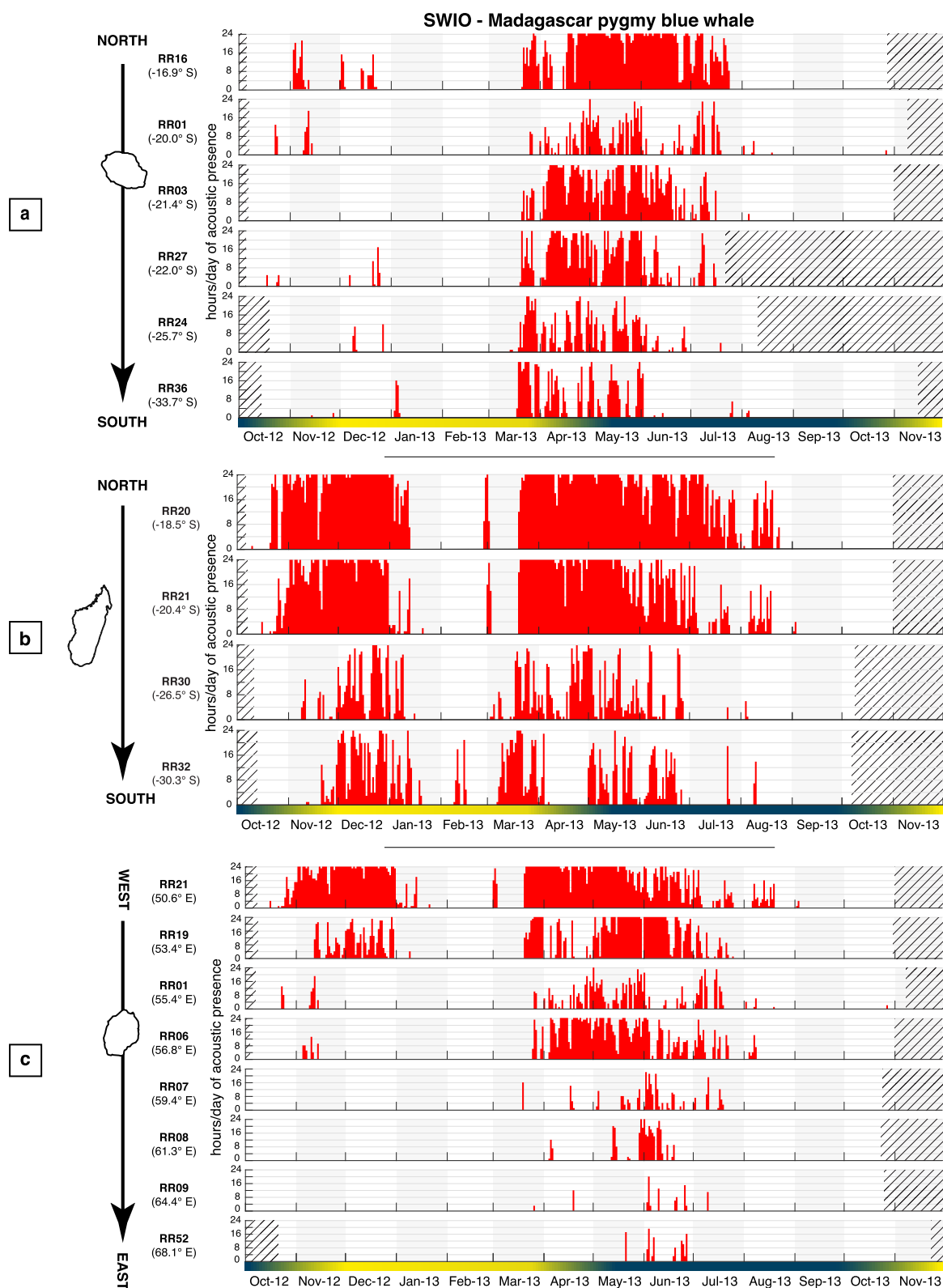


Figure 6. Hourly acoustic presence of Madagascar pygmy blue whales per day along (a) a latitudinal transect centred on Réunion Island; (b) a latitudinal transect off the east coast of Madagascar; (c) a longitudinal transect centred on Réunion Island. The colour bar indicates the season: blue = austral winter (June–September), yellow = austral summer (December–March), green = interseason (April–May and October–November). Dashed areas represent periods with no recordings, shaded bars delineate months.

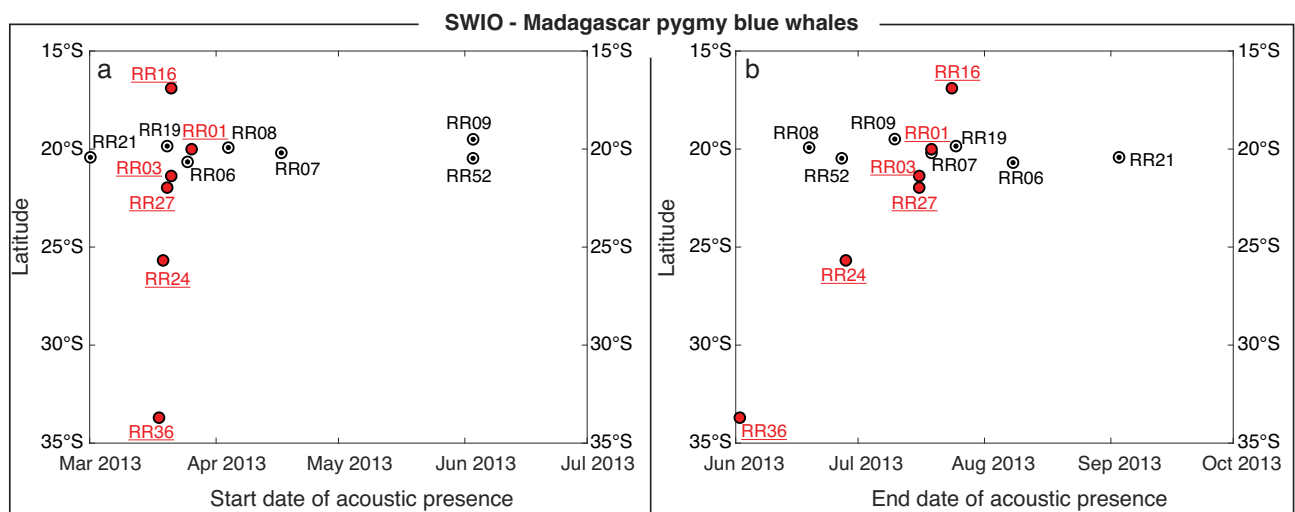


Figure 7. Start (a) and end (b) dates of Madagascar pygmy blue whale acoustic presence by site latitude for the austral autumn to spring period of 2013. Red filled circles with underlined labels indicate sites belonging to the latitudinal transect centred on Réunion Island ($\sim 55^{\circ}\text{E}$), whereas open circles with black central dots indicate OBS sites located outside this transect..

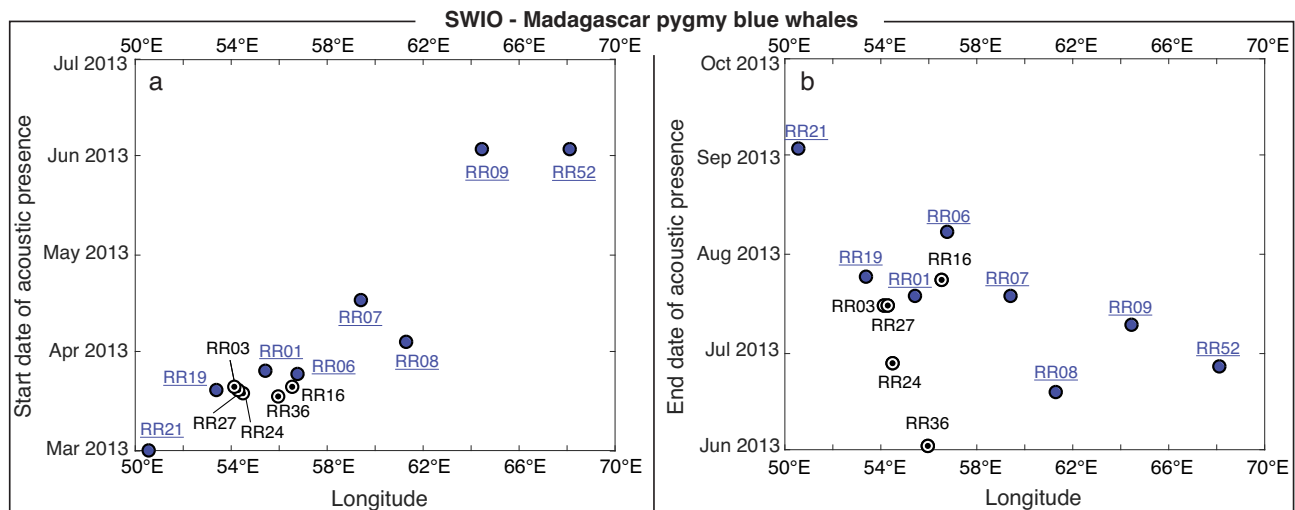


Figure 8. Start (a) and end (b) dates of Madagascar pygmy blue whale acoustic presence by site longitude for the austral autumn to spring period of 2013. Blue filled circles with underlined labels indicate sites belonging to the longitudinal transect centred on Réunion Island ($\sim 20^{\circ}\text{E}$), whereas open circles with black central dots indicate OBS located outside this transect.

at several sites in the Mascarene region (Dréo et al. 2019). Our fine-scale analysis builds on these earlier observations by providing a more detailed picture of the timing and geographic variation of fin whale acoustic presence across the Mascarene region. In particular, acoustic presence showed a gradual onset and end along a south-to-north transect, consistent with the migratory patterns previously described for this species (Mackintosh 1966), and extended as far north as 16°S .

In the data analysed here, no fin whale songs were recorded at our sampled sites from mid-December to mid-March. This absence of acoustic detections does not necessarily imply the absence of fin whales, as individuals may have remained present without producing detectable songs. Indeed, studies combining visual and acoustic observations have shown that fin whales can be present while 20-Hz song activity is low or absent (Burkhardt et al. 2021). No visual survey data are available from the Mascarene region dur-

ing this period to independently assess fin whale presence. Nevertheless, given that the Mascarene waters are not known as a fin whale feeding area, it is possible that at least part of the population vacates the region during the austral summer and migrates toward higher-latitude feeding grounds. Some individuals might nevertheless make shorter or partial migrations, as suggested for fin whales in other ocean basins (Mizroch et al. 2009). In the southwestern Indian Ocean, year-round fin whale acoustic presence has been reported around sub-Antarctic Marion Island (Shabangu et al. 2024), indicating that fin whales can occur acoustically at these higher latitudes throughout the year. Such individual variation in migratory strategies could also account for the sporadic acoustic detections before and after the main period of acoustic presence.

Supporting the hypothesis of a seasonal movement toward higher latitudes, the period of acoustic absence in the Mascarene region overlaps with the occurrence of fin whales in Eastern

Antarctica, where visual surveys combined with passive acoustics conducted in January–February 2006 documented their presence between 30°E and 80°E (Gedamke and Robinson 2010). This temporal correspondence is consistent with the possibility that at least some fin whales using the Mascarene region migrate to Antarctic feeding grounds during the austral summer, although satellite tagging, photo-identification, or other approaches would be required to demonstrate connectivity between these areas. Whether fin whales occurring in the Mascarene region and at higher latitudes belong to the same population remains unknown. As fin whale song characteristics can help distinguish acoustic populations (Koot 2008, Širović et al. 2017, Aulich et al. 2019, Archer et al. 2020, 2022), comparative analyses of song structure across the Mascarene and sub-Antarctic datasets could help assess connectivity within the southwestern Indian Ocean.

Fin whales use the Mascarene waters from austral autumn to austral spring, with substantial acoustic presence across the broad longitudinal range covered by our array. Recent studies in the tropical Mozambique Channel provide an opportunity to place this widespread acoustic presence in a broader regional context. At ~13°S, fin whale songs were recorded between July and September near Nosy Be (13°S, 48°E) (Cerchio et al. 2024), with similar detections reported near Mayotte (13°S, 45.5°E), 270 km to the west (Dréo et al. 2025). Both studies reported strong interannual variability, a shorter period of acoustic presence, and lower occurrence than observed in the Mascarene region, suggesting that these tropical latitudes in the Mozambique Channel may lie near the northern boundary of the species' core distribution. Farther south, at 23.5°S, Cerchio et al. (2024) reported an earlier onset of acoustic presence, although occurrence remained substantially lower than at similar latitudes in the Mascarenes. Taken together, these observations suggest that fin whales may make greater use of waters east than west of Madagascar.

Fin whale breeding grounds remain poorly known, and the species has been suggested to disperse into pelagic open-ocean habitats during the winter breeding season (Edwards et al. 2015, Herr et al. 2022). The prolonged winter acoustic presence documented here suggests that the pelagic waters surrounding the Mascarenes may constitute an important wintering habitat and potentially form part of the species' breeding range in the southwestern Indian Ocean. Furthermore, the substantial acoustic presence recorded at our northernmost sites, up to 16°S, demonstrates that fin whale occurrence extends into the 20°N–20°S region described by Edwards et al. (2015) as an 'equatorial hiatus'. Our observations therefore suggest that this apparent hiatus may partly reflect the limited data historically available from tropical oceanic waters rather than a strict distributional boundary.

Antarctic blue whales

Antarctic blue whales were also detected acoustically in the surveyed area during austral autumn and winter, across both the longitudinal and latitudinal transects in the Mascarene waters. Their acoustic presence was relatively sparse compared with that of fin whales and Madagascar pygmy blue whales, but the observed seasonal pattern is consistent with previous acoustic observations from subtropical and sub-Antarctic regions of the western Indian Ocean (Samaran et al. 2013, Leroy et al. 2016, Torterotot et al. 2020). These studies identified these regions as key winter-

ing habitats for Antarctic blue whales, and our findings extend this conclusion to the Mascarene region.

Recent observations from the Mozambique Channel showed substantially greater Antarctic blue whale acoustic presence at 23°S than at 13°S, suggesting a decrease in occurrence toward the northern part of this western sector (Cerchio et al. 2024). The authors proposed that the southern channel may represent a prime breeding habitat, whereas the northern channel could approach the limits of the species' winter distribution.

Torterotot et al. (2020) suggested that sites near 24°S could represent the northern boundary of Antarctic blue whale distribution in the western Indian Ocean because of the lower song occurrence recorded there. In contrast, our array extended farther north and demonstrates that Antarctic blue whales occur up to at least 16°S. Moreover, the secondary detection peak observed in October–November at several sites is consistent with whales passing these locations during their southward spring migration, suggesting that at least some individuals had wintered farther north.

Antarctic blue whale songs have indeed been detected as far north as the Chagos Archipelago (~7°S, 71°E), supporting the hypothesis that the wintering and possibly breeding range of Antarctic blue whales can occasionally extend to these low latitudes (Stafford et al. 2004, Leroy et al. 2016). However, long-term monitoring showed acoustic presence in only four years between 2002 and 2018 (Truong 2023), suggesting that the species does not systematically migrate to such low latitudes but may only do so under favourable environmental conditions.

Madagascar pygmy blue whales

The acoustic presence of the Madagascar pygmy blue whales showed a bimodal annual pattern in the region, with detections spanning a combined total of up to ten months of the year. The two main periods extended from mid-October to mid-January and from March to July/August, consistent with patterns reported from the Mozambique Channel and Mayotte across multiple years (Cerchio et al. 2024, Dréo et al. 2025).

The nearly synchronous onset of acoustic presence in March across sites spanning ~1870 km along the latitudinal transect does not reveal a clear direction of arrival. However, acoustic presence subsequently ended progressively later toward the north, consistent with a northward migration through the region. This interpretation is also supported by acoustic tracking within the RHUM-RUM array (Dréo et al. 2019). During this period, acoustic presence was concentrated in the western part of our array and was very limited east of ~57°E. Together with detections in the Mozambique Channel (Cerchio et al. 2024, Dréo et al. 2025), these observations suggest a broad northward migration encompassing the Mascarene region and both sides of Madagascar.

From the end of August to early October, Madagascar pygmy blue whales were nearly absent acoustically from our array, as well as from monitored sites around western Madagascar and Mayotte (Cerchio et al. 2024, Dréo et al. 2025), leaving their distribution during this period unresolved. Occasional detections farther north, around the Chagos Archipelago (Stafford et al. 2011), indicate that some individuals can reach lower latitudes, but available data are insufficient to determine the main distribution of the population during this period.

The second period of acoustic presence, from mid-October to mid-January, showed a different spatial pattern. This acoustic

presence was strongest in the western part of our array, with high acoustic presence off eastern Madagascar, moderate presence at RR19 (53.4°E), only sparse detections at RR01 and RR06 (55.4°E and 56.8°E), and no detections farther east. Together with contemporaneous detections in the Mozambique Channel (Cerchio et al. 2024, Dréo et al. 2025) and historical catches off northeastern Madagascar in December (Best et al. 2003), the progressively later onset toward southern sites along eastern Madagascar, is consistent with a southward movement on both sides of Madagascar. These observations suggest that the spatial pathways used during northward and southward migration may differ. The sustained acoustic presence around 30°S from mid-November to March, near the productive Madagascar Plateau where blue whales have previously been observed feeding (Best et al. 2003), further suggests that some individuals may use this area as a summer feeding ground.

At higher latitudes, Madagascar pygmy blue whale songs have also been recorded in sub-Antarctic waters during both austral summer and winter (Torterotot et al. 2020), indicating that the population does not conform to a simple, synchronous north-south migration.

Taken together, available observations suggest substantial heterogeneity in migratory behaviour, potentially involving partial migration, differences in migration timing or destination among individuals, and interannual variability. A comprehensive synthesis of existing acoustic observations across the southwestern Indian Ocean would provide an important first step toward resolving these large-scale migration patterns and identifying remaining gaps in the annual distribution of this population.

Considerations on acoustic detectability

Interpreting these patterns and comparing them across sites and studies also requires accounting for the limitations inherent to PAM, particularly the variable detection ranges of whale songs under different environmental conditions. The precise detection range of blue and fin whale songs remains subject to considerable uncertainty due to the complexity of underwater sound propagation and uncertainties associated with source-level variability and environmental propagation conditions. For the OBS array used in this study, Dréo et al. (2019) estimated a detection range of approximately 100 km for the full Antarctic blue whale song, using hydrophones with a 62 Hz sampling frequency that captured the entire frequency band of the song. Other studies have reported greater ranges, up to 200 km (Širović et al. 2007, Samaran et al. 2010), but with sensors deployed within the SOFAR channel. For Australian pygmy blue whales, estimated detection ranges on OBS range between 60 and 80 km (Gavrilov et al. 2018), while for fin whale songs, values from 56 km (Širović et al. 2007) to around 100 km (Aulich et al. 2019) on deep-water hydrophones have been reported. Detection ranges are strongly influenced by environmental conditions surrounding the hydrophone (bathymetry, latitude, season) as well as by ambient noise, source-level and depth of the vocalizing whales (Helble, D'Spain, Campbell et al. 2013, Helble, D'Spain, Hildebrand et al. 2013, Širović et al. 2015). These parameters remain poorly constrained and small variations in their values have considerable impacts on detection range estimates. Given the variability in source-level measurements reported in the literature (see table 2 in Bouffaut et al. 2021), detection range estimation still requires refinement, which is beyond

the scope of the present study. In our analyses, only the lower part of the Antarctic blue whale Z-call was used for the detection, because the Nyquist frequency was below that of the first unit. The first unit is the louder component, and under low signal-to-noise ratio (SNR) conditions, it is often the only element visible, with a chorus of distant songs forming a continuous line on the spectrogram at its peak frequency. Detecting only the second unit therefore implies that the Antarctic blue whale songs identified in our dataset correspond to those with higher received levels, and thus likely originate from whales located relatively close to the recorders. Fin whale songs, in contrast, occupy a broader energy band between 15 and 30 Hz, enabling the detection of both individual low-SNR songs and fin whale chorus. For Madagascar pygmy blue whale songs, the second unit was used for detection as the first one lies above the Nyquist frequency. However, for this song type, the second unit is the most powerful one (Bouffaut et al. 2021). Hence, the detection ranges for the three song types might differ and have an impact on their relative detectability. This could explain the sparser song presence observed for the Antarctic blue whales. Nevertheless, the temporal patterns of acoustic presence differed substantially among sites for all three song types, suggesting limited overlap in detections between OBS.

Conclusion

The post-whaling abundance and distribution of blue and fin whales in the southwestern Indian Ocean remain poorly documented, especially for fin whales (Edwards et al. 2015). Our results demonstrate that the Mascarene waters constitute a shared seasonal habitat for fin whales, Antarctic blue whales, and Madagascar pygmy blue whales, with all three taxa occurring in the region during austral autumn and winter. Together with previous acoustic studies across the southwestern Indian Ocean (Samaran et al. 2013, Leroy et al. 2016, 2018, Dréo et al. 2019, Torterotot et al. 2020, Cerchio et al. 2024, 2025), these findings confirm the recurrent use of this region by large baleen whales and reinforce its relevance for their regional conservation.

Although the cessation of whaling has allowed whale populations to begin to recover, they remain exposed to anthropogenic pressures across both their feeding and wintering ranges. In the Mascarene region, major shipping lanes connecting Asia and southern Africa generate intense large-vessel traffic (Plot et al. 2025), exposing whales to risks from ship strikes and underwater noise. Continued and expended acoustic monitoring is therefore needed to assess the long-term use of the Mascarene region by large baleen whales and determine whether the seasonal and spatial patterns documented here persist over time. Additional hydrophones would also help characterize regional shipping noise and its potential influence on the use of these waters, providing information relevant to the identification of areas where mitigation measures may be needed.

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Author contributions

Emmanuelle C. Leroy (Conceptualization [lead], Formal Analysis [lead], Investigation [lead], Methodology [lead], Validation [lead], Visualization [lead], Writing – original draft [lead], Writing – review & editing [equal]), Salvatore Cerchio (Validation [equal], Writing – review & editing [equal]), Violaine Dulau (Validation [equal], Writing – review & editing [equal]).

Conflicts of interest

None declared.

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Data availability

The RHUM-RUM data set (<http://dx.doi.org/10.15778/RESIF.YV2011> (Rhum-rum dataset)) is hosted and served by the French RESIF data centre (<http://seismology.resif.fr> (RESIF)) under the FDSN network code YV.

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