Received: 12 December 2023 | Accepted: 22 July 2024

DOI: 10.1111/mms.13167

NOTE

Marine Mammal Science

The first record of the southbound movements of satellite-tagged pygmy blue whales (*B. m. brevicauda*) from Savu Sea (Indonesia) to the subantarctic waters

Putu Liza Kusuma Mustika[1,2,3] | I Made Jaya Ratha[2,3] | Edy Setyawan[4] | Muhammad Offal Prinanda[2] | Rusydi Rusydi[5] | Februanty Suyatiningsih Purnomo[6] | Imam Fauzi[7]

[1]College of Science and Engineering, James Cook University, Douglas, Queensland, Australia

[2]Reef Check Indonesia, Denpasar, Bali, Indonesia

[3]Cetacean Sirenian Indonesia, Jakarta, Indonesia

[4]Elasmobranch Institute Indonesia, Denpasar, Bali, Indonesia

[5]Muhammadiyah University Kupang, Kupang, Nusa Tenggara Timur, Indonesia

[6]The Indonesia Climate Change Trust Fund, Jakarta, Indonesia

[7]National Marine Conservation Area Agency (Balai Kawasan Konservasi Perairan Nasional – BKKPN), Kupang, Nusa Tenggara Timur, Indonesia

Correspondence
Putu Liza Mustika, College of Science and Engineering, James Cook University, Room 19-102, JCU Bebegu Yumba Campus, Douglas, Queensland 4811, Australia.
Email: putu.liza@jcu.edu.au

Funding information
Indonesia Climate Change Trust Fund, Grant/Award Number: ICCTF: 003/SPK/PPK-06-14/PH-ICCTF/08/2020

Pygmy blue whales (*Balaenoptera musculus brevicauda*) are known to conduct annual migrations between the southern and western waters of Australia to the Banda Sea via the Savu Sea in Indonesia (Double et al., 2014; Möller et al., 2020). However, the journey back to Australian waters is rarely documented, often due to limited battery life of satellite tags deployed in Australian waters or inadequate funding to conduct satellite tracking studies originating in the Indonesian waters.

The pygmy blue whale subspecies is one of the four known subspecies of blue whales (*B. musculus*); the other ones are the Northern blue whale (*B. m. musculus*), the Antarctic blue whale (*B. m. intermedia*), and the Northern

Indian Ocean blue whale (*B. m. indica*) (Branch et al., 2007; Leslie et al., 2020; Samaran et al., 2013). A possible fifth subspecies has been observed off Chile (Branch et al., 2007; Leslie et al., 2020; Samaran et al., 2013), but it has not been officially recognized. The Australian population of pygmy blue whales has been shown to conduct regular migrations between the southern and western waters of Australia, the Savu Sea, Timor Sea, and Banda Sea (Double et al., 2014; Möller et al., 2020), while some videos uploaded in September 2016 and November 2018 suggest that the Banda Sea might be an important nursing ground for this subspecies (Pindito, 2016, 2018). In the Timor Sea, the Timor Trough south of Timor-Leste was identified as a likely feeding area for pygmy blue whales during the late austral winter and early austral spring (Burton et al., 2023).

Between 2009 and 2021, 37 pygmy blue whales were tagged in western or southern Australian waters (Double et al., 2014; Möller et al., 2020; Owen et al., 2016; Thums et al., 2022). All tagged whales exhibited the northbound migration towards the Indonesian waters (Double et al., 2014; Möller et al., 2020). Most of the whales migrated to the Banda Sea via the Savu Sea or Timor Sea, although one whale was not recorded to migrate to the Banda Sea and migrated to south Java instead (Möller et al., 2020).

The satellite tagging data suggest that the southbound migration back to the Australian waters started in mid-September 2020 (Thums et al., 2022). Nonetheless, only four satellite tracks were available for the return journeys of the whales to the tagging sites: ID98135 from Double et al. (2014), ID123229 and ID123233 from Möller et al. (2020), and ID 182657 from Thums et al. (2022).

Here we report the results of the first two Australian pygmy blue whales satellite-tagged in their wintering area: (1) a full migration between Indonesia and the southern waters of Australia, and (2) a southbound movement from Indonesia to the subantarctic waters. We deployed satellite tags on two pygmy blue whales during a survey from November 5 to 19, 2021, near Semau Island in the Savu Sea, East Nusa Tenggara, Indonesia (Figure 1) with the *Pindito*, a 40-m liveaboard vessel. The research team only approached single animals and specifically avoided mother and calf pairs. The team approached the whales with the *Pindito*'s zodiac boat. No length measurements were taken of the two whales. However, based on the photographic comparison between the whales and the Zodiac boat (5.5 m), we estimated the whales' lengths to be 18–19 m.

We attached SPLASH10-302 and SPLASH10-373 satellite tags (Wildlife Computers, Redmond, WA) to the two pygmy blue whales in this study (Table 1). The SPLASH10-373 tag was deployed on Whale#1 on November 16, 2021, while the SPLASH10-302 was deployed on Whale#2 on November 19, 2021, in the Savu Sea Marine Park (Figure 1, Table 1).

We programmed both tags to collect ARGOS locations and transmit these locations every time the tagged whales came to the sea surface, as well as to collect depth (m) and ambient sea temperature (°C) every 10 min. We binned depth data into 14 bins: 0–5, 6–20, 21–50, 51–100, 101–200, 201–300, 301–400, 401–500, 501–600, 601–700, 701–800, 801–1,000, 1,000–1,500, and >1,500 m. The temperature data were also binned into 14 bins with the upper limits of 5, 10, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, and > 30°C.

Data collected by the satellite tags were transmitted to Wildlife Computers data portal via the ARGOS satellite network. The ARGOS location data, specifically, were obtained irregularly, depending on when and how long the tagged whales spent time on the surface. Given the irregularity of ARGOS position data, we fitted a state-space model (SSM) on these ARGOS position data to estimate the most likely tracks of movements of each tagged whale. The SSM was done using the "aniMotum" package (Jonsen et al., 2023) in R (R Core Team, 2022). We fitted a time-varying move persistence model with a 24-hr time step to generate the most likely locations every 24 hr. We calculated movement velocities of tagged whales using the "move" package (Kranstauber et al., 2021) based on the most likely locations as predicted using SSM. We used move persistence indices, ranging from 0 to 1, to examine the likely behaviors of the tagged whales during the tracking period (Florko et al., 2023; Jonsen et al., 2019). Indicative of area-restricted search (ARS) behaviors (Florko et al., 2023), a low move persistence index (≤0.75) represents the likelihood of foraging or resting, while a high move persistence index (>0.75) indicates transiting or traveling behaviors (Jonsen et al., 2019).

Immediately after being tagged, the two satellite-tagged pygmy blue whales traveled from the Savu Sea Marine Park (Indonesia) towards the western waters of Australia (Figure 2). Whale#1 cruised close to the coasts of Western

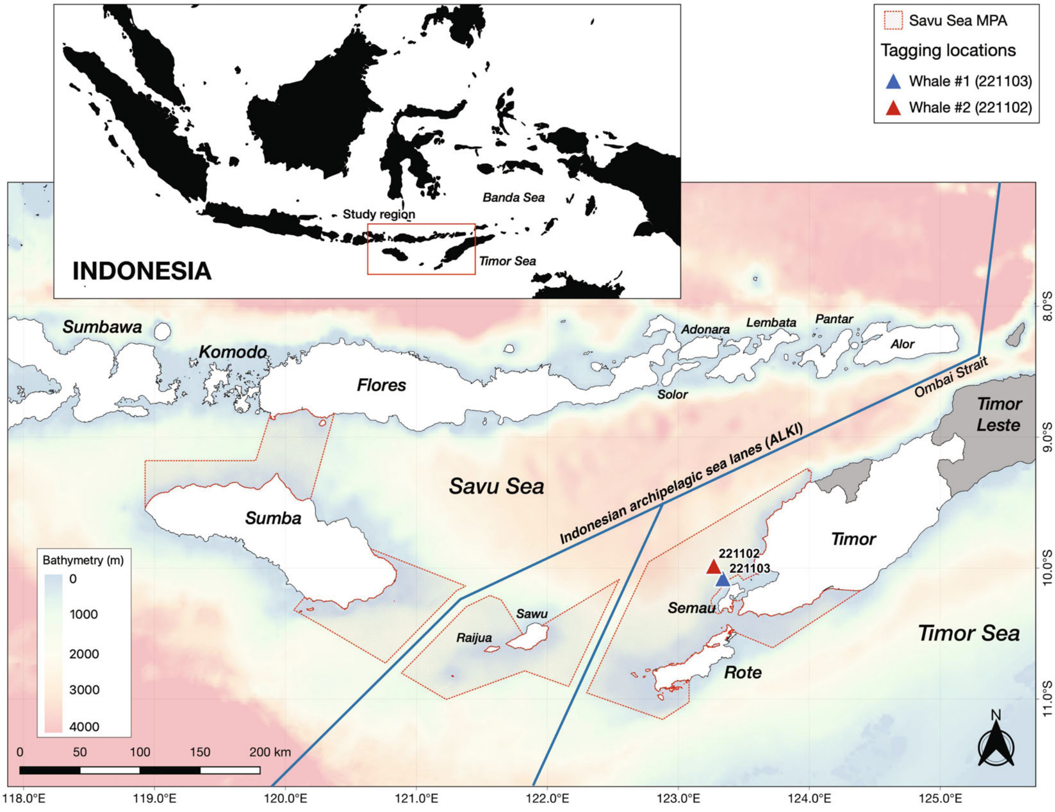

FIGURE 1 The tagging deployment locations in the Savu Sea Marine Protected Area, Indonesia. The gaps westward of Raijua Island and eastward of Sawu Island were created to accommodate shipping lanes (the Indonesian Archipelagic Sea Lanes or Alur Laut Kepulauan Indonesia/ALKI, the blue lines).

Australia. The closest point, recorded on November 27, 2021, was approximately 50 km from the northern tip of the North West Cape (21.29°S, 114.09°E). From there, Whale#1 resumed the journey southwards and turning eastwards off Augusta (Western Australia) on December 7, 2021, reaching the closest estimated point to Australian coast with a distance of <30 km, towards the southern waters of Australia. On December 30, 2021, at 39.11°S, 123.43°E (about 500 km south of Esperance, Western Australia), Whale#1 stopped moving eastwards and started moving southwards and southeastwards. For the following 3.5 months (until April 16, 2022), Whale#1 moved through the waters between 37°S–49°S and 103°E–123°E, south of the Great Australian Bight, just outside of Australia's Economic Exclusive Zone (EEZ). This region is located in the Southern Subtropical Convergence Zone, between the Subtropical Front and the Subantarctic Front (Figure 2). On March 13, 2022, Whale#1 reached the westernmost point of its track and then headed north, leaving the Subtropical Front on April 16, 2022. Between 29 April and May 9, 2022, the whale explored the waters of Shark Bay, Western Australia before continuing its journey towards Indonesian waters. The whale's last location was on June 1, 2022, at 11.84°S, 121.3°E, just before it entered the Savu Sea. Overall, Whale#1 was tracked for 198 days, with a total distance of 13,683 km and an average velocity of 69.1 km/day (Table 1).

In contrast, the travel direction of Whale#2 was more linear than Whale#1 (Figure 2). After tagging, Whale#2 cruised along the western edge of Australian waters before continuing southwest towards Heard and McDonalds Islands. Whale#2 was tracked for 59 days from November 19, 2021, to January 16, 2022 (Table 1). The last satellite transmission was located 500 km in the northeast of the Kerguelen Islands and Heard and McDonalds Islands, just

TABLE 1 Details of satellite tag deployments on two pygmy blue whales (*B. m. brevicauda*) in the Savu Sea, Indonesia.

Whale ID	PTT number	Tag type	Tag deployment locations		Tag deployment date	Last transmission date	Tracking duration (days)	Total dist. traveled (km)	Min–max velocity (km/day)	Average velocity (km/day)	Deepest dive (m)
			Latitude	Longitude							
Whale#1	221103	SPLASH10-373	10.07720°S	123.34061°E	Nov 16, 2021	Jun 1, 2022	198	13,683.1	2.5–260.3	69.1	456 ± 4
Whale#2	221102	SPLASH10-302	10.04976°S	123.18714°E	Nov 19, 2021	Jan 16, 2022	59	5,953.9	4.9–166.6	100.9	312 ± 4

Note: total dist. traveled = total direct distance traveled by the tagged whale over water during tracking period; deepest dive = the deepest depth the tagged whale achieved during the tracking period (m) ± its accuracy.

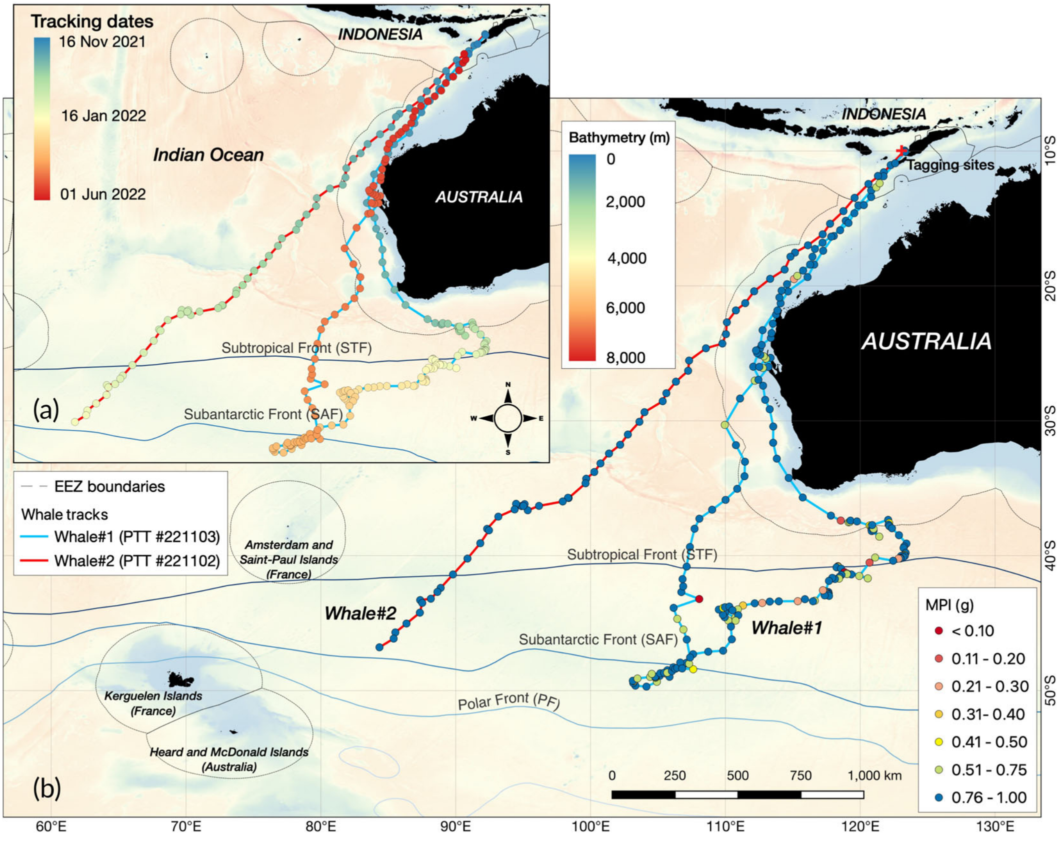

FIGURE 2 The movement tracks of two satellite tagged pygmy blue whales. (a) Whale tracks based on dates; the color dots represent tracking dates; (b) whale tracks based on the move persistence index ranging from 0 to 1 (Florko et al., 2023; Jonsen et al., 2019).

to the north of the Subantarctic Front (46.5°S, 84.9°E). This position was the westernmost location in this study (Figure 2). While being tracked, Whale#2 reached a total distance of 5,953 km with an average velocity of 100.9 km/day.

During the 198 days of tracking, Whale#1 showed various behaviors as indicated by the move persistence index (Figure 2). Whale#1 showed a high move persistence index along the track between the Savu Sea and the south of Western Australia, suggesting a travelling behavior. On December 10, 2021, after approximately 3 weeks of traveling, Whale#1 started to show area restricted search (ARS; Möller et al., 2020) behaviors as indicated by the low move persistence index (≤0.75; Jonsen et al., 2019), which suggests foraging and/or resting behaviors (Florko et al., 2023; Möller et al., 2020). During the following four months until April 14, 2022, Whale#1 mostly exhibited the ARS behaviors between 37°S–49°S and 103°E–123°E, outside of Australia's EEZ, between the Subtropical Front and the Subantarctic Front. On the way back to Indonesia, Whale#1 generally showed traveling behavior as indicated by the high move persistence index. This whale demonstrated ARS behaviors around Shark Bay and areas in the north of Exmouth. Contrary to Whale#1, Whale#2 consistently demonstrated traveling behavior as indicated by the high move persistence index (>0.75; Jonsen et al., 2019) for 59 days before the tag stopped transmitting on January 16, 2022.

Whale#1 spent more than 85% of its time at depths of 0–50 m (Figure 3a) while Whale#2 spent almost 75% of its time at depths of 0–20 m (Figure 3b). Both whales spent about 10% of their time at depths of 51–100 m and up

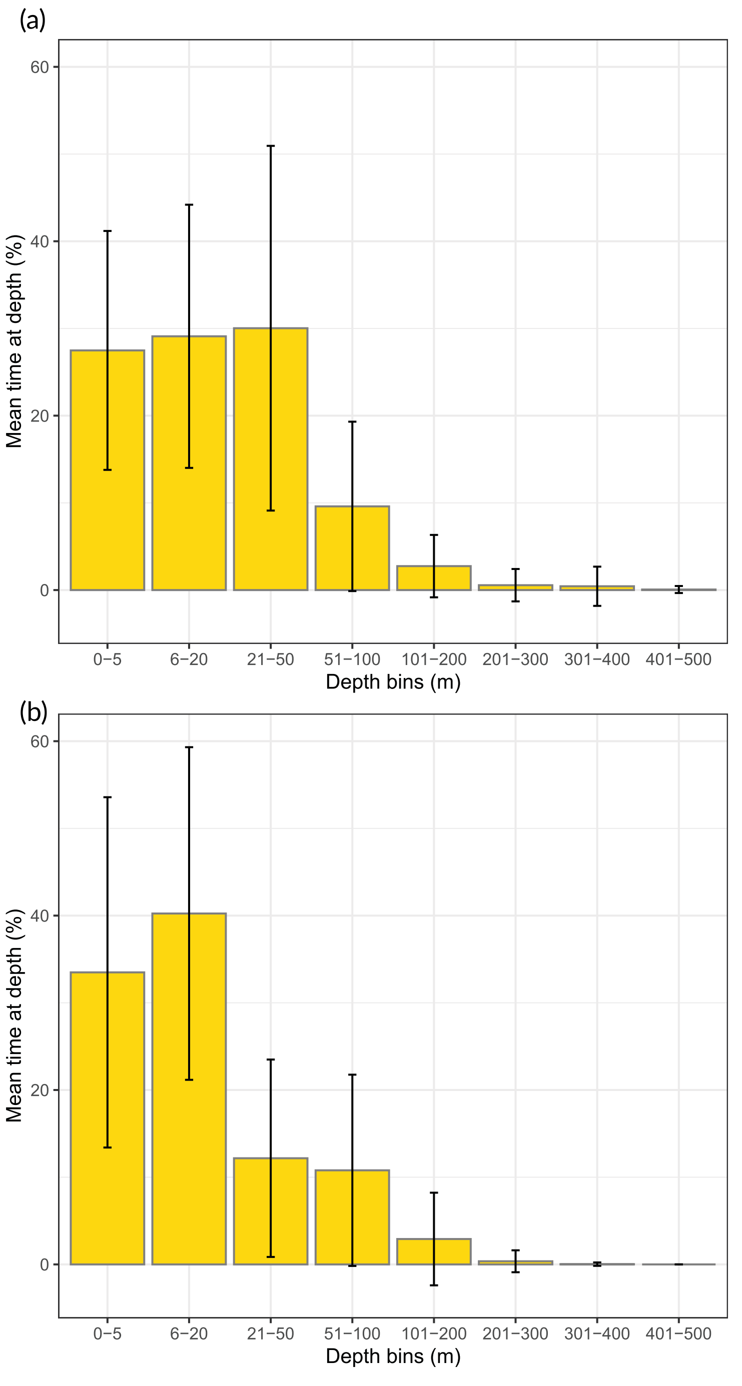

FIGURE 3 Mean time at depths based on user-defined bins for Whale#1 (a) and Whale#2 (b). Error bars show the standard deviation of the mean.

to 3% of their time at depths of 101–200 m (Figure 3a). The maximum dive depth of Whale#1 was 456 ± 4 m, occurring on December 21, 2021, at 38.13°S, 120.99°E, 420 km in the south of Western Australia, while the maximum recorded dive depth for Whale#2 was 312 ± 4 m, occurring on December 17, 2021, at 31.78°S, 102.19°E, nearly 1,300 km to the west of Western Australia (Table 1).

Despite the incomplete data transmission, we were able to examine 93 out of 198 tracking days and 33 out of 59 tracking days for the diving behaviors of Whale#1 and Whale#2, respectively. The daily diving depths of Whale#1 varied during the tracking period. During the first few days of the tracking period, Whale#1 mostly dived to depths of 0–20 m (Figure 4a). From mid to end of December 2021, this whale dived quite frequently beyond the depths of 200 m south of Western Australia, between Australia's EEZ and the Subtropical Front. From early January 2022 to early February 2022, the whale dived more frequently to between 50 m and 100 m, around the Subtropical Front. As the whale moved southwestwards to areas around the Subantarctic Front, the whale dived more frequently to shallower waters (21–50 m). Like Whale#1, Whale#2 mostly dived to shallower depths of 0–20 m deep from November 2021 to mid-January 2022 (Figure 4b). In mid-December 2021, after reaching the 30°S, Whale#2 started to dive deeper than 200 m more frequently.

After 13,600 km of travel, the transmission of Whale#1 ended in the waters south of the Savu Sea where it was tagged six months prior. To our knowledge, this journey would be the second longest migration journey of a blue whale, second after the journey of a blue whale tagged in the waters of South Australia with 15,120 km journey in 271 days (Möller et al., 2020). The shallow dives and high average velocity of Whale#2 suggests that it had not arrived at its destination in the summering ground when the satellite transmission stopped (Table 1). The Whale#2 trajectory supports the hypothesis that the home range of the Australian population of pygmy blue whales might include the Kerguelen Plateau (Samaran et al., 2010, 2013), but it is inconclusive due to the sample size of one.

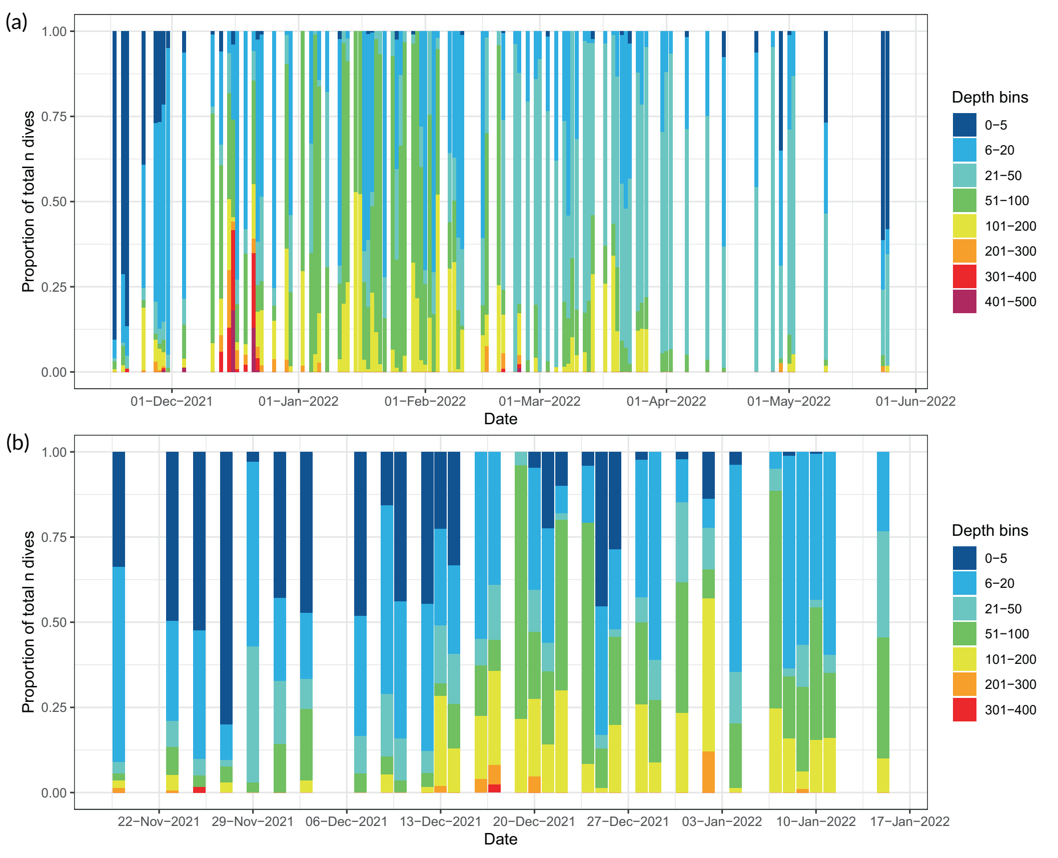

FIGURE 4 Proportion of the total number of dives per day at each depth bin for Whale#1 (a) and Whale#2 (b). Blank stacked bars represent days when transmitted data were unavailable.

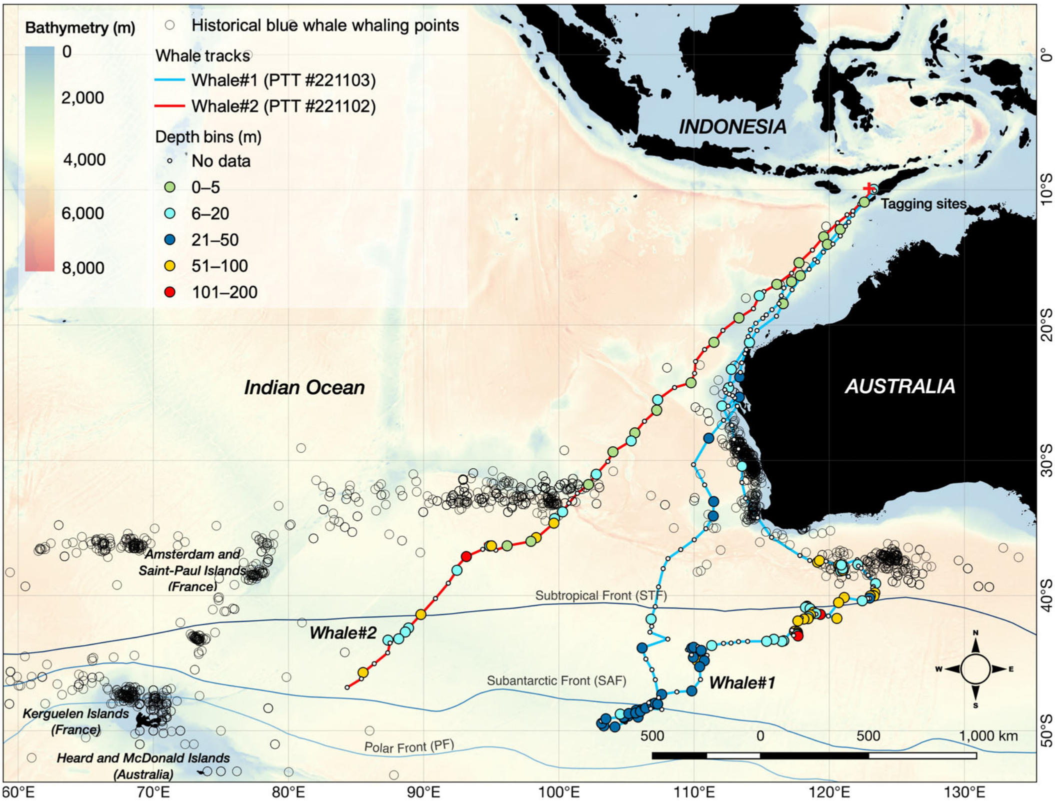

FIGURE 5 Dive depth variability for Whale#1 and Whale#2 and the historical blue whale whaling points. For the dive depth, each dot represents a dive bin (meter) with the highest proportion per day based on Figure 4 data.

The horizontal movements of the two pygmy blue whales overlapped with historical blue whale whaling points (Figure 5) and the satellite tracks of two other great whale species. Whale#1's tracks overlapped with the satellite tracks of the southern right whales (*Eubalaena australis*) tagged at the Australian and New Zealand wintering grounds (Mackay et al., 2020), while Whale#2's tracks overlapped with those of the humpback whales (*Megaptera novaeangliae*) tagged at the waters of Western Australia (Bestley et al., 2019).

This study suggests an extended habitat range of the Australian pygmy blue whales. Nonetheless, since the data are derived from just two individuals, these findings are preliminary in nature and cannot be extrapolated to inform a general migratory pattern from the Savu Sea to the subantarctic waters. Therefore, more satellite tags need to be deployed to southward-migrating pygmy blue whales from these Indonesian seas to confirm whether the subantarctic waters are indeed regular migratory routes of the pygmy blue whales originating from the Banda Sea in Indonesia.

ACKNOWLEDGMENTS

We thank the Edi Frommenwiler and the *Pindito* crew for providing us with significant in-kind support and expertise that enabled us to conduct the boat survey and tag the whales. We thank Zulkarnain Lubis and Muhammad Hilmi of the BKKPN Kupang as members of our field work team. We thank Michael Double of the Australian Antarctic Division for providing us with the historical whaling data based on the International Whaling Commission catch data. We thank Rushan bin Abdul Rahman of the James Cook University Australia for the GIS assistance. We also thank the Editor of Marine Mammal Science and an anonymous reviewer for their very useful feedback in improving this manuscript. This project was funded by ICCTF (the Indonesian Climate Change Trust Fund) Bappenas for the

COREMAP-CTI World Bank program with the contract number ICCTF: 003/SPK/PPK-06-14/PH-ICCTF/08/2020. All tagging activities followed the animal ethics protocol approved by the World Bank as the funding agency of this study. Open access publishing facilitated by James Cook University, as part of the Wiley - James Cook University agreement via the Council of Australian University Librarians.

AUTHOR CONTRIBUTIONS

Putu Liza Kusuma Mustika: Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; writing – original draft; writing – review and editing. **I Made Ratha:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; validation; writing – original draft; writing – review and editing. **Edy Setyawan:** Data curation; formal analysis; methodology; resources; software; validation; visualization; writing – original draft; writing – review and editing. **Muhammad Offal Prinanda:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; writing – review and editing. **Rusydi Rusydi:** Investigation; methodology; writing – review and editing. **Februanty Suyatiningsih Purnomo:** Methodology; project administration; writing – review and editing. **Imam Fauzi:** Supervision; writing – review and editing.

ORCID

Putu Liza Kusuma Mustika https://orcid.org/0000-0001-5157-4635
I Made Jaya Ratha https://orcid.org/0000-0002-1583-0053
Edy Setyawan https://orcid.org/0000-0001-6629-5997
Muhammad Offal Prinanda https://orcid.org/0009-0002-4854-3728
Rusydi Rusydi https://orcid.org/0009-0008-4323-708X
Februanty Suyatiningsih Purnomo https://orcid.org/0000-0001-8683-0491

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How to cite this article: Mustika, P. L. K., Ratha, I. M. J., Setyawan, E., Prinanda, M. O., Rusydi, R., Purnomo, F. S., & Fauzi, I. (2024). The first record of the southbound movements of satellite-tagged pygmy blue whales (*B. m. brevicauda*) from Savu Sea (Indonesia) to the subantarctic waters. *Marine Mammal Science*, e13167. https://doi.org/10.1111/mms.13167