

ARTICLE



Distribution of Arnoux's beaked whales (*Berardius arnuxii*)

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Funding information

Netherlands Ministry of Agriculture, Nature and Food Quality (LNV), Grant/Award Number: WOT-04-009-047.04; Polarstern Expedition Grant, Grant/Award Number: AWI_PS129_05

Abstract

Arnoux's beaked whales (*Berardius arnuxii*) are generally considered to be uncommon to rare, and likely to prefer deep oceanic waters of the Southern Hemisphere. During many top-predator surveys in the Southern Ocean since 1988 we did not sight the species. However, in April 2022 we encountered three groups in the marginal sea-ice zone of the Weddell Sea. This study provides detailed descriptions of the sighted animals and their environment and report on unpublished sightings of this species from 1986 to 1998. A search of published information on the distribution of the species revealed 108 documented sightings with a total of 1,125 individuals. In combination these sources of information for the Southern Ocean, suggest a frequent occurrence in ice-covered waters, often close to the continental coast and edges of fast ice and ice-shelves. North of 60°S, in the temperate regions of the Southern Hemisphere, the species was also regularly sighted near continents, even far inshore, in fjords surrounded by land.

KEYWORDS

Antarctica, Arnoux's beaked whale, *Berardius arnuxii*, continental shelf, marine mammal survey, sea-ice, Southern Ocean, SOWER-IWC, Ziphiidae

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1 | INTRODUCTION

The Arnoux's beaked whale (*Berardius arnuxii*) has been described as an uncommon to rare species, with an estimated distribution southward from approximately 40°S to the Antarctic continent. Detailed habitat information is not available, but the species is assumed to occur mostly in deeper oceanic waters, like other beaked whales (Brownell & Taylor, 2021; Carwardine, 2020; Jefferson et al., 2015; MacLeod, 2014; Shirihaï, 2007).

Since 1988, Wageningen Marine Research has been involved in systematic quantitative top predator surveys in the Southern Ocean. In eleven earlier expeditions conducted from 1988 to 2018 in different seasons in the Lazarev Sea, Weddell Sea, and Bellingshausen Sea no Arnoux's beaked whales were observed. However, in our most recent, twelfth expedition, the species was observed three times during helicopter surveys. This expedition (PS129) was conducted in the Weddell Sea in March–April 2022 (Hoppema, 2022). Sharing this information with colleagues led to the recovery of unpublished documentation for sightings of Arnoux's beaked whales from 1986 to 1998 in Drescher Inlet, also in the Weddell Sea. As emphasized by all major sources, knowledge regarding this species can be considered poor. Therefore, this study aims to combine our data with a thorough review of other known observations to improve our understanding of the distribution and habitats of Arnoux's beaked whales.

2 | MATERIAL AND METHODS

2.1 | New and previously unpublished observations

Our long-term surveys of top predators in the Southern Ocean have been conducted within interdisciplinary studies of carbon fluxes in the Antarctic marine ecosystem (Joint Global Ocean Flux studies, e.g., Van Franeker et al., 1997). All expeditions were on board the icebreaking research vessel *Polarstern* with the objective to quantify the biomass and food requirements of the warm-blooded top predator community, including both marine birds and mammals. Standard ship-based surveys were conducted on all expeditions, and when possible, these were supplemented with surveys from helicopters. A detailed description of the methods, including methodological references, was given in Van Franeker et al. (2010). In short, ship-based surveys were conducted from outdoor observation posts installed on the roof of the bridge of *Polarstern*, which allows an unobstructed forward view of over 180° from a deck height of approximately 20 m. From this deck, birds and mammals were recorded in standard 10-min, 300 m wide band transect counts. In addition, marine mammals were recorded at all distances by line transect distance sampling methods (Buckland et al., 2001), in which estimated radial distance and angle from track line were used to calculate effective strip widths for the species using the R package “Rdistance” (McDonald et al., 2023). For each 10-min period, information on sea ice was visually recorded as the estimated average ice cover and dominant floe size within the band transect during the observation period. Bottom depth and environmental parameters were taken from the ship's computer systems.

Helicopter surveys only used band transect methods for both birds and mammals during time-blocks defined by waypoints recorded 2–4 min apart. In fast moving platforms like helicopters, the combined bird and mammal survey does not allow the recording of data for mammals by line transect distance sampling methods. Helicopter altitude was maintained at 300 feet with a speed of 80 knots, within the guidelines of the Antarctic Pack Ice Seal program APIS (SCAR-GSS, 1996). Visually assessed ice cover and ice conditions within the band transect were recorded in association with each waypoint. Bottom depths for waypoint positions were assessed using the AWI software program PERPLEX V (Rohardt, 2016) which uses GEBCO depth data with one minute resolution.

Uncommon bird or mammal species outside the surveyed transect strip or seen during opportunistic observations, are included in our *Polarstern* survey database as nonquantitative records that can be used for descriptive distributional analyses. When needed, e.g., to confirm identification of uncommon species, the predesigned linear helicopter survey track was sometimes interrupted in order to circle the animal(s) for a better identification and

assessment of group size, and when possible, supported by photography or video. During these interruptions, the altitude of the helicopter was often reduced but radial distance was maintained at 300 feet or more.

Our most recent top predator survey was conducted as part of the Eastern Weddell Sea Observation System (EWOS) pilot study during expedition PS129 on board *Polarstern*. Observations started south of the South African Exclusive Economic Zone (EEZ) on March 6, 2022, and then continued southward along the 0° meridian to the edge of the Antarctic shelf ice. From there, studies were conducted in the coastal area and then across the Weddell Sea towards the Antarctic Peninsula, where the surveys ended on April 21, 2022 (Hoppema, 2022; Figure 1). In addition to the observations during PS129 in 2022 we queried colleagues working in Drescher Inlet to ascertain whether they had any unpublished observations.

2.2 | Review of other documented observations

To improve the knowledge on distribution and habitat of Arnoux's beaked whales, we supplemented our data with a review of all available records of the species. With the help of many international colleagues, we surveyed data from published literature, and records in OBIS-SEAMAP (Halpin et al., 2006), <https://www.HappyWhale.com>, <https://www.observation.org>, and <https://www.inaturalist.org>. As not all records were properly documented or unique, only records supported by

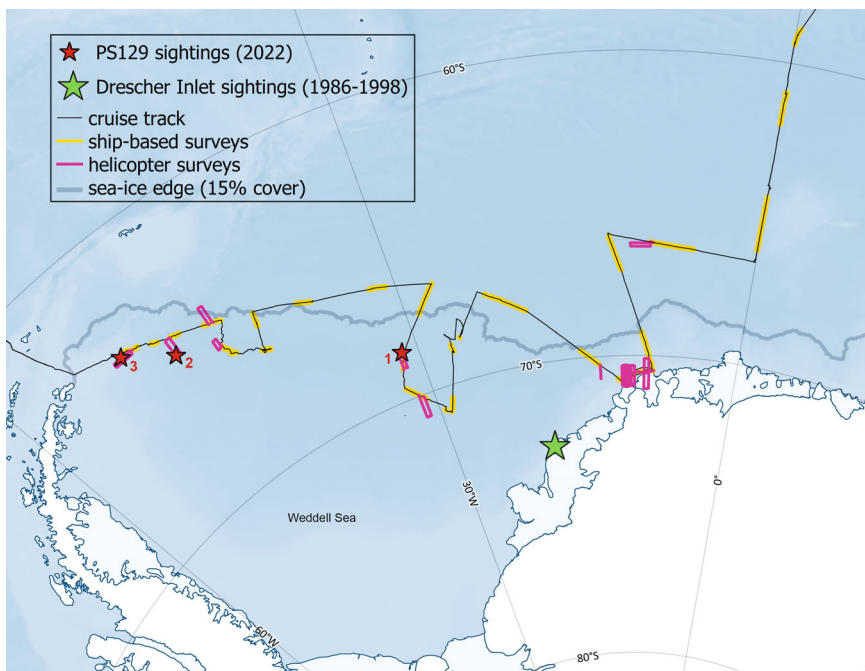


FIGURE 1 Cruise track of *Polarstern* PS129 in March and April 2022 and location of Drescher Inlet. Yellow (thicker) portions in the black cruise track indicate the stretches where dedicated ship-based surveys were made. Ship-based observations had actually started immediately south of the South African Exclusive Economic Zone. Helicopter top predator surveys are shown by pink lines. The positions at which the Arnoux's beaked whales (*Berardius arnuxii*) were sighted in 2022 are indicated with red stars, with group number as used in Table 1. The green star shows the location of Drescher Inlet, for which we provide five (seasons of) previously unpublished sightings in 1986, 1990, 1992, 1995, and 1998. The light blue area shows the shelf ice between continental Antarctica (in white) and the highly variable seasonal sea-ice zone. The meandering thick gray line indicates the sea-ice extent by the position of the 15% sea-ice cover on April 16, 2022 as assessed from satellite data, for this figure downloaded from <https://www.meereisportal.de> (Grosfeld et al., 2016; Spreen et al., 2008).

photographs or by sufficiently detailed texts on identification were included. Records identified as duplicates as judged by date, time, group sizes, photographs or texts were rejected.

In addition, we received permission to extract data from the IWC International Decades of Cetacean Research (IDCR) and Southern Ocean Whale and Ecosystem Research Program SOWER (International Whaling Commission [IWC], 2023; Matsuoka et al., 2003). The IDCR/SOWER program (henceforth SOWER) ran annually during summers from 1978/1979 to 2009/2010 and focused on the area south of 60°S with a population survey of the Antarctic minke whale (*Balaenoptera bonaerensis*) as its main objective. Most ships that participated in the surveys could not operate in sea ice. Records in the SOWER database lack photographic or other details to confirm species identification. However, as IWC surveys are conducted by experienced marine mammal observers, all records have been considered as being “documented,” including a single record listed as “probably Arnoux’s.” As in the other data sets, a check for duplicate records in SOWER was conducted and a few duplicates were removed. Observations in the SOWER database lacked direct information on bottom depth or ice conditions, but as for helicopter flights, these could be estimated using the PERPLEX program. For a few positions too close to the continental coast or ice shelf PERPLEX provided no information; in those cases, the depth was estimated from the NOAA website <https://www.ngdc.noaa.gov/gazetteer/>. For all records, satellite-derived information on ice cover was taken from the database of the NASA NSIDC (National Snow and Ice Data Center, https://nsidc.org/data/smmr_ssmi; DiGirolamo et al., 2022), which maintains a daily record on sea-ice cover since 1978, derived from several passive microwave instruments, and provides estimated ice cover at a grid cell size of 25 × 25 km. For all available whale records, the distance between the geographical position of the observation to the sea-ice edge was calculated under the assumption that the sea-ice edge is defined by the position of the 15% ice concentration contour (Comiso, 2006). For the data analyses we focused on the number of whales rather than on the number of groups.

In presentation of results, care was taken to differentiate between the SOWER records and all others (including our own), listed as “incidental” records. This is because SOWER cruises were restricted to mid-summer (late December to February) and had a strong focus on open water between 60°S and the sea ice. Furthermore, the SOWER records come from dedicated whale-surveys with professional observers. All other records presented, including our own, were labeled “incidental” because they had no such spatial or temporal restrictions, and originated from a wide range of sources, mostly not from professional whale surveys, and therefore had to be confirmed by photo or other information to be accepted as a “documented record.”

3 | RESULTS

During the ship-based surveys on PS129, no Arnoux’s beaked whales were observed. However, during the helicopter surveys, three separate groups of Arnoux’s beaked whales were encountered consisting of four, five, and eight individuals.

TABLE 1 Details of Arnoux’s beaked whale (*Berardius arnuxii*) sightings during helicopter surveys conducted on expedition PS129 in April 2022. All three observations concerned a single group, with Ind(n) providing the number of individuals, and with details for UTC date and time, latitude and longitude in decimal degrees derived from waypoints marked on handheld GPS, bottom depth, and local ice-cover as visually assessed during the observation.

Group	Ind (n)	Date (2022)	Time (UTC)	Latitude	Longitude	Bottom depth (m)	Ice cover (%)	Notes
1	4	April 11	12:58	−68.4416	−31.4994	4,600	95	In transect; Figure 2
2	5	April 19	18:24	−64.8078	−47.9162	4,152	10	Out of transect; Figure 3
3	8	April 21	14:37	−63.7172	−51.2116	2,296	85	Out of transect; Figure 4

All three sightings were in areas of stable sea ice, south of the ice-edge (defined by 15% ice cover), with long open leads and/or patches of open water. During each of these sightings, the helicopter survey was temporarily interrupted in order to confirm species identification and number of individuals (Figure 1, Table 1). All three observations were documented by photographs and/or video which illustrate the species characteristics, their habitat, and their behavior (Figures 2, 3, 4, and additional photographs and links to videos in the Supplemental Material). In all three groups, the animals were quietly logging or slowly swimming in parallel position at or just below the surface, sometimes diving under ice.

In addition to the aforementioned sightings during PS129 (2022), we provide full details of previously unpublished observations of Arnoux's beaked whales, made in the 1980s and 1990s during a multiyear study of



FIGURE 2 Three of the Arnoux's beaked whales (*Berardius arnuxii*) of the first group (Table 1), preparing to dive under ice (photo A. Meijboom).



FIGURE 3 One of the Arnoux's beaked whales (*Berardius arnuxii*) of the second group of five animals (Table 1), in a lead in already fairly heavy autumn ice (photo B. Feij).



FIGURE 4 Two of the Arnoux's beaked whales (*Berardius arnuxii*) of the third group (Table 1), moving slowly. Especially the front animal shows the important character combination of the long straight back from forehead to fin above the water line, plus the underwater visibility of the light colored long and slender beak (photo S. Kühn).

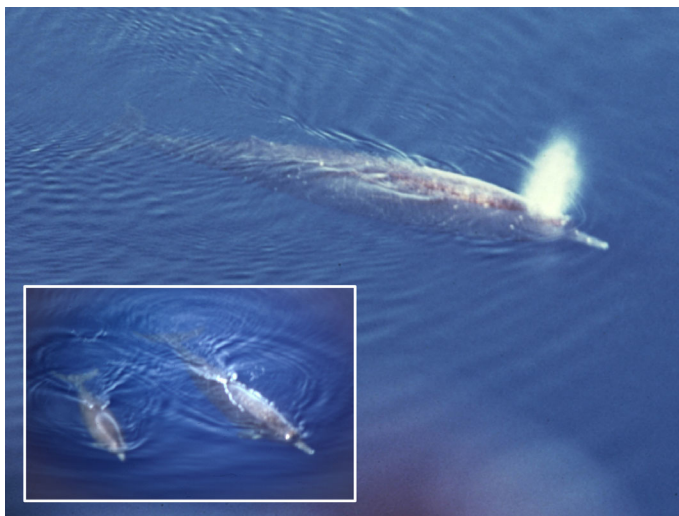


FIGURE 5 A group of at least three Arnoux's beaked whales (*Berardius arnuxii*) was seen in the polynya in front of the fast ice of Drescher Inlet, in November 1986. This included a mother with calf (inset). Scans of slides were provided by Peter Reijnders and Wilhelm Hagen. Groups of Arnoux's beaked whales were observed on multiple occasions along the fast ice of Drescher Inlet in 1990, 1992, 1995, and 1998 (Table S1 and Figures S2–S6).

Weddell seals (*Leptonychotes weddellii*) at Drescher Inlet, Weddell Sea (73°S, 19°W; Figure 1). The first sighting was in November 1986, made from a helicopter while flying over the coastal polynya between *Polarstern* and the camp on the shelf ice (P. Reijnders, K. Zegers, & W. Hagen, personal communication, March 18, 2023; Figures 5 and S2). At least three animals were present, including a mother and calf. The Drescher Inlet seal study was continued over several years and in February 1990, 1992, 1995, and 1998 the whales were sighted on multiple occasions close to the fast ice directly from the study plot and from the more remote camp location on the shelf-ice (Figures S3–S6).

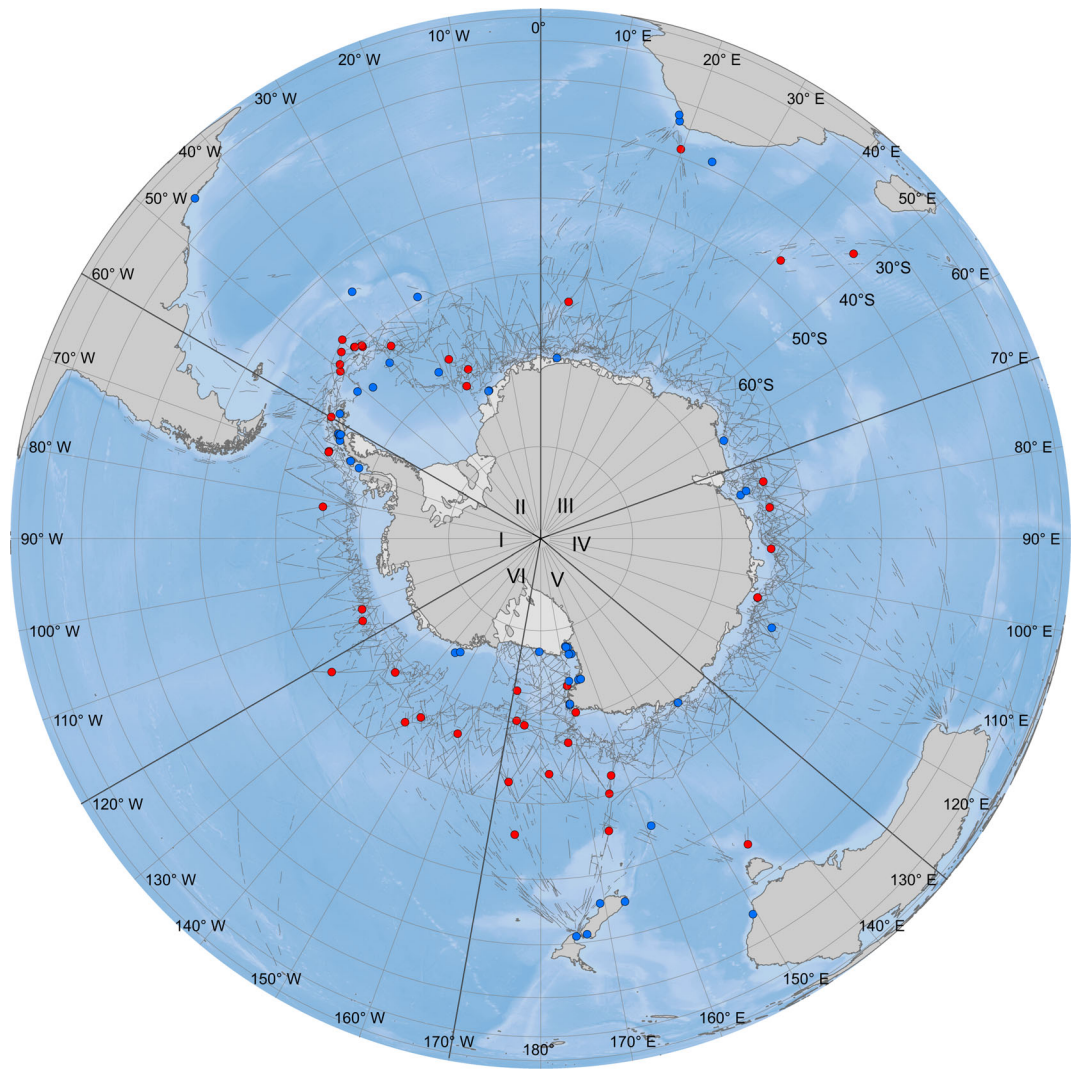


FIGURE 6 Documented live sightings of Arnoux's beaked whales (*Berardius arnuxii*). Blue dots represent incidental sightings from ships, helicopters or coasts as compiled from our own sightings, literature, or online databases. Red dots indicate observations from the 1978/1979–2009/2010 IWC SOWER study including all survey tracks (gray lines) made within that program, illustrating that many vessels involved were unable to enter sea ice. Sighting details of all plotted positions have been included in Table S1. Roman numerals in the map and Table S1 refer to the IWC Management Areas in the Southern Ocean (Donovan, 1991; Leaper & Miller, 2011).

The groups would surface simultaneously, and often remained stationary close together directly along the ice, heavily breathing to recuperate from the preceding dive. After some time, the whole group would disappear, regularly swimming towards fast ice or the shelf ice before diving. Group size varied and no written notes remain on numbers of sightings in specific years, dive durations, and surface periods. From photo- and video-documentation it shows that at some stage at least 13 individuals were seen, but on occasion more may have been present.

Following these eight newly documented observations (noted as “this study” in Table S1A), 53 additional documented sightings were retrieved from literature and from the internet (detailed in Table S1A under sources and notes).

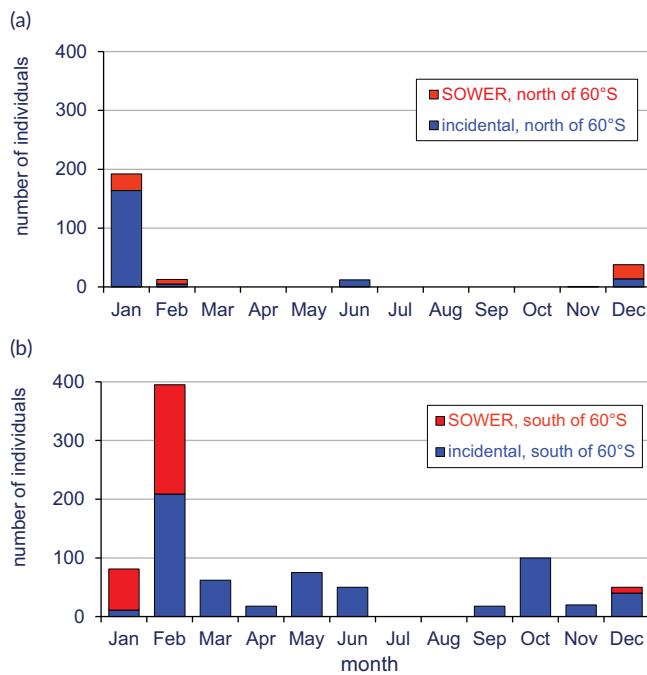


FIGURE 7 Seasonal pattern of observations of Arnoux's beaked whales (*Berardius arnuxii*) in a. temperate regions north of 60°S ($n = 256$), and b. the Southern Ocean ($n = 869$). SOWER surveys were only conducted from late December to February. Incidental sightings include all data without geographical or seasonal restrictions.

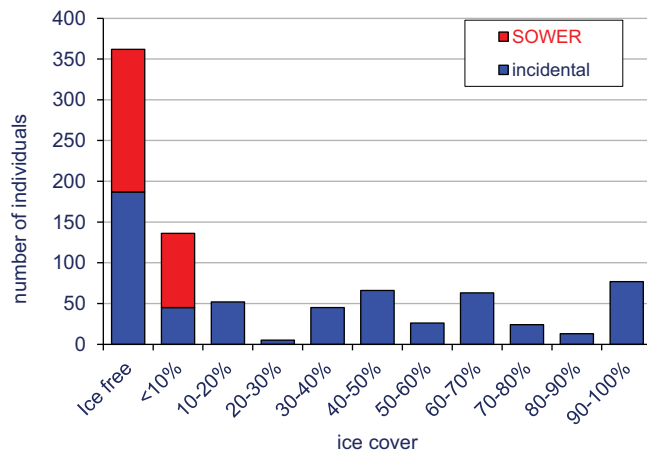


FIGURE 8 Number of observed Arnoux's beaked whales (*Berardius arnuxii*) in the Southern Ocean (south of 60°S) in relation to satellite observed ice cover at position and date of observation ($n = 869$). In more northern ice-free waters, 256 of the overall 1,125 individuals were seen, but these are not included here. Data were binned in 10% ice cover categories. SOWER surveys focused on the area south of 60°S (Figure 6) but mostly avoided sea ice.

Many of these were recent but the earliest one dated from 1955 (Taylor, 1957). Our eight new records plus the 53 internet/literature records add up to a total of 61 incidental records listed in Table S1A. These 61 incidental records encompass sightings of 94 groups with a total number of 799 individual whales.

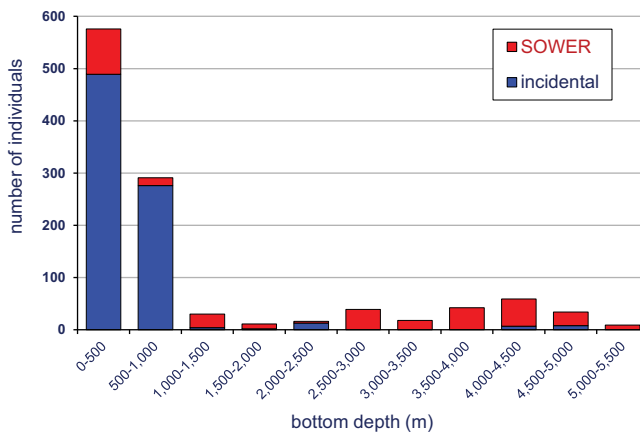


FIGURE 9 Number of observed Arnoux's beaked whales (*Berardius arnuxii*; $n = 1,125$) in relation to bottom depth.

In addition, we were able to extract 47 sightings from the 1978/1979–2009/2010 IWC SOWER database (Table S1B). The SOWER data set holds 47 sightings of groups with a total of 326 individual whales.

Results in this paper thus add up to 108 documented records holding information on 141 groups representing at least 1,125 individuals. These records are fully listed in Table S1A (Incidental) and S1B (SOWER) and plotted in Figure 6. The locations of the 61 incidental sightings are shown by blue dots. For these records, it is not possible to provide a qualitative indication of effort. The incidental records tend to concentrate closely around the Antarctic continent and ice shelves. In the open ocean north of 60°S and around the Southern Hemisphere continents, documented sightings of Arnoux's beaked whales are rather rare, although quite a few records of dead beached specimens exist (e.g., Groom et al., 2014; Lichter, 1986; Otley et al., 2012). Several near shore sightings for New Zealand suggest a resident population, that even ventures deep into the fjords (Hudgins & Bachara, 2014). Around Australia, off the coast of New South Wales, aerial tuna surveys revealed 27 sightings with a total of about 150 individual whales from 1981 to 1984, almost all close to the 200 m isobath (Paterson & Parker, 1994). For South Africa, two live sightings have been documented in harbor areas (Rice, 1998; M. Meyer, personal communication, March 17, 2023). A single case of an offshore Arnoux's beaked whale south of South Africa was reported on the internet (Table S1A; S1A-033). Best (2007) mapped other offshore sightings off South Africa, but these lack any detail and are therefore not included in Table S1 or Figure 6. For South America, one live sighting in Brazilian waters has been suggested by Martuscelli et al. (1996), referring to a beached corpse that was supposedly seen earlier at sea accompanied by a live whale of the same species. This is the most northern record in this data set. Carwardine (2020) suggested sightings of Arnoux's beaked whales between Tierra del Fuego and the Antarctic Peninsula, but without supporting details.

The map in Figure 6 shows the locations of all SOWER sightings by red dots. As an indicator of effort in the SOWER program, the map includes light gray transects lines for all surveys conducted during SOWER. Figure S1 provides a map that zooms in on the SOWER study area south of 60°S to increase detail. The tracks show that limited survey data were collected north of the SOWER target area, and that relatively few transects were made into areas with dense sea ice. Although SOWER methods are, in principle, adequate for quantitative analyses of circumpolar densities, only 47 sighting is too small of a sample size and largely lacks information from the sea-ice zone.

To explore the spatio-temporal distribution and habitats of Arnoux's beaked whales, observations were summarized per month, ice cover and bottom depth. To evaluate potential seasonal shifts in distribution, the number of individuals observed in each month of the year, north and south of 60°S, are depicted in Figures 7a and b, respectively. The whales were observed in all months of the year, except for July and August.

SOWER surveys were only conducted from late December to February. The occurrence of Arnoux's beaked whales in relation to the ice cover as derived from satellite data has been summarized for the Southern Ocean in Figure 8. This applies to 869 of the 1,125 individuals (77%) in our data. Farther north in ice free temperate waters, 256 individuals had been observed. Figure 9 shows the number of Arnoux's beaked whales by bottom depth grouped in 500 m depth bins. Most individuals occurred in waters <500 m deep, and numbers reduced quickly towards depth of 1,000 m, although lower numbers of animals were sighted in waters with bottom depths >5,000 m.

4 | DISCUSSION

4.1 | Distribution and abundance

Arnoux's beaked whales have been observed to make long dives, up to 70 min (Hobson & Martin, 1996). Our sightings of Arnoux's beaked whales in the Weddell Sea directly along the fast ice and ice-shelf in 1990, 1992, 1995, and 1998 consistently involved groups of whales recuperating from simultaneous long dives. The species can be highly gregarious, with up to 80 individuals in a single group (Table S1, sighting nr S1B-100) and an overall average number of eight individuals in all documented sightings (Table S1).

In addition to the influence of diving behavior and the number of animals in a group, the frequency of observations in any region is linked to observation effort, observation platform, and environmental conditions (Williams et al., 2014). Direct links between observation effort and sightings listed in Table S1 are usually not possible. The chances of being detected from moving platforms like ships and especially airplanes or helicopters are affected by the exceptional dive capacities of Arnoux's beaked whales (Sucunza et al., 2022). In the Antarctic most surveys by researchers or tourists were conducted from ships. Chances for ship-based sightings may be affected by vessel specific underwater noise from engines (Pirotta et al., 2012), and from operation of sounding systems that may disturb beaked whales up to distances of at least 5.2 km (Cholewiak et al., 2017).

In our dedicated top predator surveys from the ship during 12 *Polarstern* expeditions since 1988 and over all seasons, we never observed this species in over 14,000 10-min survey periods, covering a track length of 42,634 km and strip surface of 13,840 km² south of 40°S (Table S2A). Our methods of combined bird and mammal surveys imply a focus on the nearby narrow transect, which limits chances of detection of more distant animals. Furthermore, colleagues that participated in four dedicated whale surveys on board *Polarstern* have never observed the species from the ship, despite their methods with multiobserver effort continuously searching to the horizon with strong binoculars with the purpose to confirm species identification of animals detected by the naked eye using line transect methods and to quantify animals missed by the naked eye (Geelhoed et al., 2015). Large icebreaking research vessels differ in ship size, speed, engine noises, and sounding systems from smaller slow moving sightseeing tourist vessels, that avoid heavy ice. This might explain the near lack of beaked whale sightings from the large icebreakers, in comparison to the many incidental sightings by tourist vessels. SOWER surveys applied dedicated professional survey methods but used many different vessels and mostly avoided sea ice.

Concerning top predator surveys using helicopters, we have conducted such surveys on seven different *Polarstern* cruises between 2001 and 2022, covering 2,883 waypoint counts over a linear distance of 41,428 km and transect band surface of 11,483 km² (Table S2B). For safety reasons, helicopter surveys were largely restricted to ice-covered areas. Arnoux's beaked whales were only observed during the recent 2022 cruise. Scheidat et al. (2011) conducted dedicated whale surveys from helicopter on two *Polarstern* cruises in the Weddell Sea and around the Antarctic Peninsula, which followed dedicated cetacean line-transect methods and covered a total of 26,000 km linear distance. During these, only a single group of four Arnoux's beaked whales was observed in December 2006 near the ice edge of the central Weddell Sea (Figure S7).

We cannot quantify observation effort by the many other bird and mammal surveys in and around the Southern Ocean and the Southern Hemisphere continents. However, in the Weddell and Lazarev Seas, during ship-based and aerial studies of ice seals over many years, South African surveyors have not sighted Arnoux's beaked whales (M. Bester, personal communication, June 20, 2023). Similarly, between Australia and east Antarctica, during many years of Australian ship-based top predator surveys, only once has a single Arnoux's beaked whale been spotted (E. Woehler, personal communication, June 11, 2023). None have been seen during Australia's many ship-based and aerial surveys of ice seals (C. Southwell, personal communication, November 14, 2023). It may also be noted that the trained marine mammal observers in the SOWER program surveyed about 216,000 nautical miles (over 400,000 km) in the area south of 60°S and detected 320 groups of blue whales (*Balaenoptera musculus*) with a total 400 individuals (Branch, 2007; IWC, 2023). The blue whale, certainly in those years, was considered relatively rare. The SOWER analyses for the Arnoux's beaked whale south of 60°S add up to no more than 43 groups of Arnoux's beaked whales, with a combined number of only 295 individuals.

Despite all uncertainties on detectability, disturbance, and observation effort, the combined data tend to confirm that Arnoux's beaked whales are rather uncommon.

4.2 | Seasonal movements

From the perspective of potential seasonal migration between the Southern Ocean and the more northerly areas, the data show no evidence of substantial seasonal movements (Figure 7). In the Southern Ocean, Arnoux's beaked whales have been sighted in all months of the year (except for July and August, but such is not surprising considering the near absence of ship-based and aerial tourist and research effort in mid-winter). Furthermore, field trips from stations to scarce areas of open water will be infrequent. In more northern latitudes records are almost restricted to mid-summer but similar to the south, reduced observation activities outside the summer season will play a role. The contribution of SOWER data to the graphs is limited, as SOWER surveys were conducted only from late December to January and mainly south of 60°S. The data show that in summer the species can be present in the south as well as farther north.

4.3 | Sea ice

As evidenced by photographs and descriptive texts there appears to be a clear link between Arnoux's beaked whales and sea ice (Table S1, column ice details). Among 51 incidental records in the Southern Ocean (south of 60°S), only four were in open water well away from sea ice, whereas 47 (92%) were linked to ice. In fact, no less than 33 of the records (65%) were close to fast ice, shelf ice, glacier fronts, or rocky shores with partial ice cover. Satellite-derived data on presence of sea ice in relation to numbers of Arnoux's beaked whales in the Southern Ocean (Figure 8) show that 69% of the individuals in incidental observations (416 out of 603) occurred in 25 × 25 km blocks where satellites had recorded sea ice. However, this is an underestimate, as several sightings where the satellite recorded no ice, were known to be linked to sea-ice (compare columns ice detail and ice cover in Table S1). For sightings in the SOWER surveys, 34% of individuals (91 out of 266) were seen in satellite blocks with sea ice, in spite of the fact that most SOWER vessels had to avoid sea ice. No observation-linked ice details are available for the SOWER records. When looking at the distance between sightings and the position of the ice edge derived from satellite data, incidental as well as SOWER records tended to concentrate around the ice edge (Figure S11). Frequent occurrence of Arnoux's beaked whales in association with sea ice could possibly be linked to availability of food or to calmer water conditions within the sea ice. Calm surface water conditions could facilitate breathing during the recovery periods after deep dives, when the whales tend to rest with little movement in a horizontal body position. Open water might also represent a higher risk to

Arnoux's beaked whales for predation by orcas (*Orcinus orca*; Fearnbach et al., 2019). More observations are needed to fully understand Arnoux's beaked whale behavior in relation to sea ice.

4.4 | Bottom depth

Out of 799 individuals recorded in incidental sightings, 489 (61%) were seen in situations where the water was <500 m deep, and no fewer than 96% occurred in waters shallower than 1,000 m (Figure 9). For SOWER sightings the situation was different, as only 27% of individuals were seen in waters shallower than 500 m, and 31% in waters shallower than 1,000 m. This is not surprising as SOWER efforts were largely limited to deeper waters of the Southern Ocean north of the ice edge. For incidental and SOWER sightings combined, 51% of animals were seen in waters shallower than 500 m, and 77% in waters shallower than 1,000 m. Boebel et al. (2009) suggested that sightings of Arnoux's beaked whales around the Antarctic tended to be associated with shallow regions, coastal waters, continental slopes or seamounts and other areas with steep-bottomed slopes. The mean depth of the Antarctic continental shelf is 460 m (Amblas & Dowdeswell, 2018). In sightings north of the Southern Ocean, 194 of 256 individuals (76%) were seen in waters shallower than 500 m. As a matter of fact, 183 (71%) were seen within the 250 m isobath. With three quarters of individuals observed above bottom depths <1,000 m, it may be concluded that Arnoux's beaked whales commonly occur in shallower waters.

4.5 | Conclusions

In spite of problems with detectability and observer effort, the low detection rate of Arnoux's beaked whales in many dedicated ship-based and aerial surveys suggests that the species may be relatively uncommon. This is the case even in or near the Antarctic seasonal ice zone, which appears to be a favored area throughout the year. No clear evidence is available that the species tends to migrate northwards during the Antarctic winter.

A remarkable proportion of observations included groups of whales in close association with the Antarctic fast ice, or directly along the shelf ice. In Drescher Inlet it was regularly observed that, after rest periods at the surface, the whale groups started swimming and diving towards the fast ice and ice shelf, suggesting feeding under fast ice or maybe even under the ice shelf. The remarkable diving capacities of the species may allow the Arnoux's beaked whale to forage in under-ice habitats out of reach for other top predators. This hypothesis is supported by the sightings in leads deep in the fast ice of the western peninsula (Hobson & Martin, 1996), and by observations from the Ross Sea (Ponganis et al., 1995). On the other hand, whales tend to occur in shallower waters also farther north in temperate waters, where no extreme dive durations are needed. Without documentation of survey effort, the relative rarity of sightings over the vast areas of deep ocean represents no proof of absence of the species there. However, also in these oceanic areas, considerable sighting effort has been made from the large number of scientific and tourist cruises commuting to and from Antarctica. Overall, for the Southern Ocean, the combined records indicate a year-round circum-Antarctic distribution linked to shallower areas and to sea ice, specifically the edge of fast ice or shelf ice.

This paper contributes to the understanding of the distribution of this understudied species. A problem that cannot be solved is that long-duration diving species such as the Arnoux's beaked whale can be easily missed even in dedicated predator surveys with quantifiable effort. Acoustic devices on ice-shelves, ship-hulls, and moorings (Barlow, 2021; Boebel et al., 2008; Pirodda et al., 2012) as well as more frequent helicopter surveys, may enhance our understanding of the distribution, population size, and potential seasonal movements of the fascinating Arnoux's beaked whale.

ACKNOWLEDGMENTS

We are grateful for the support of the captain and crew of R/V *Polarstern* during expedition PS129. Special thanks to the helicopter crew (Harold Jager, Jonas Christensen, Dave Stenssen and Timo Hecken) for their work during surveys.

The PS129 top predator survey was conducted under permit RWS-2021/39434, drafted in accordance with the Dutch implementation of the Madrid Protocol and additional measures, and the Dutch Law and Policies concerning Antarctica (Dutch Protection of Antarctica Act). We want to thank Marthan Bester, Olaf Boebel, John Cooper, Janine Dunlop, Steve Geelhoed, Wilhelm Hagen, Thomas Jefferson, Michael Meyer, Petra Plötz, partner of the late Joachim Plötz, Marinka van Puijenbroek, Ben Raymond, Peter Reijnders, Peter Ryan, Meike Scheidat, Colin Southwell, Hans Verdaat, Eric Woehler, and Koos Zegers for searching their archives on more details of earlier sightings, providing access to images and footage or other support. Antarctic research by Wageningen Marine Research is supported by the Netherlands Ministry of Agriculture, Nature and Food Quality (LNV) which funded this research under its Statutory Research Task Nature & Environment WOT-04-009-047.04. Support during *Polarstern* expedition PS129 was provided by Expedition Grant-no. AWI_PS129_05. We would like to thank the International Whaling Commission for granting permission to use the IDCR/SOWER sighting data, and also the Government of Japan for its scientific and financial contributions to the IDCR/SOWER program over the years. Finally, we thank the anonymous reviewers and the editor for very useful comments.

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Bram Feij: Conceptualization; investigation; writing – original draft; writing – review and editing. **Susanne Kühn:** Conceptualization; investigation; writing – original draft; writing – review and editing. **André Meijboom:** Investigation; visualization; writing – original draft; writing – review and editing. **Jan Andries van Franeker:** Data curation; funding acquisition; methodology; writing – original draft; writing – review and editing. **Horst Bornemann:** Writing – review and editing. **Nat Kelly:** Data curation; investigation; visualization; writing – review and editing. **Fokje L. Schaafsma:** Conceptualization; funding acquisition; project administration; writing – original draft; writing – review and editing.

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How to cite this article: Feij, B., Kühn, S., Meijboom, A., van Franeker, J. A., Bornemann, H., Kelly, N., & Schaafsma, F. L. (2024). Distribution of Arnoux's beaked whales (*Berardius arnuxii*). *Marine Mammal Science*, e13158. <https://doi.org/10.1111/mms.13158>