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**Original Article**

# Abundance and distribution of fin and humpback whales at the South Orkney Islands in the austral summers 2011–2025

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## Abstract

Information on cetacean population status is vital for determining fisheries management strategies, especially where they overlap spatiotemporally and target the same organism. This study aims to quantify distribution and abundance of fin (*Balaenoptera physalus*) and humpback whales (*Megaptera novaeangeliae*) near the South Orkney Islands, an area in the Southern Ocean with the highest catches of Antarctic krill (*Euphausia superba*). Ship-based observational data were collected during the austral summers from 2011 to 2025. Most fin whale sightings were over the northern shelf-break and deeper offshore regions, with an annual density between 0.01 and 0.29 individuals per km$^{-2}$ (corresponding to a summer abundance range of 648–18 083 individuals). Humpback whales were mainly sighted north of the islands but more on-shelf, with annual densities between 0 and 0.07 individuals per km$^{-2}$ (average 590 individuals, with a summer abundance range of 0–4486 individuals). Summer abundances varied substantially, with fin whales increasing significantly (0.02 individuals per km$^{-2}$ per year, *P*-value 0.03), while no monotonic increase was detected for humpback whales. This study demonstrates that the South Orkney Islands constitute a key area for fin whales during the summer season, where they play a significant role as major consumers of krill. There is further need for knowledge about cetacean krill consumption, as well as to map their annual presence in this area and to describe how krill density, biomass, and distribution vary throughout the season. This understanding is crucial to determine how whales contribute to nutrient cycling through their feeding activities, and for contributing to fisheries management regulations.

*Keywords:* Antarctic krill; cetaceans; density estimates; Southern Ocean; visual survey

## Introduction

The unregulated Southern Ocean whaling industry during the 20th century over-exploited all baleen whale species and sperm whales (*Physeter macrocephalus*) (Seyboth et al. 2023). Fin whales (*Balaenoptera physalus*) were the most heavily exploited, with close to 750 000 taken in the Southern Ocean (Rocha et al. 2014). Due to data sparsity, uncertainty still prevails regarding post-whaling population structure and abundance of some of these species, but some now exhibit measurable signs of recovery and increased abundance (Johnston et al. 2011, Zerbini et al. 2019, Baines et al. 2022, Herr et al. 2022, Viquerat et al. 2022, Biuw et al. 2024). However, the current guild composition is still very different compared to the period before whaling. It has shifted from being dominated by large baleen whales to a more diverse mix of the recovering populations and increased numbers of smaller cetacean species (e.g. Mikhalev , Biuw et al. 2024, Savoca et al. 2024).

In the Southern Hemisphere, most large baleen whale species migrate from their winter breeding grounds in subtropical and temperate waters to the Antarctic for the austral summer where extensive feeding takes place for up to 6–7 months (Dawbin 1966). Some species show occasional year-round presence in the Southern Ocean (Thomisch et al. 2016, Shabangu et al. 2017) and others may skip southward migration (Andrews-Goff et al. 2018, Schall et al. 2021). Although 7 species of baleen whales and 12 species of toothed whales occur regularly in the Southern Ocean south of the Polar Front, no cetaceans are regarded as endemic to the Antarctic (Costa and Crocker 1996).

Antarctic krill (*Euphausia superba*), constitutes the main food resource for many cetacean species feeding south of the Polar Front in the Southern Ocean. This is especially true for blue (*B. musculus*), fin, humpback (*Megaptera novaeangeliae)*, sei (*B. borealis*), and Antarctic minke (*B. bonaerensis*) whales (Richardson et al. 2012, Burkhardt et al. 2021).

Krill is also an important international fishery resource; regarded as one of the most under-exploited fisheries in the

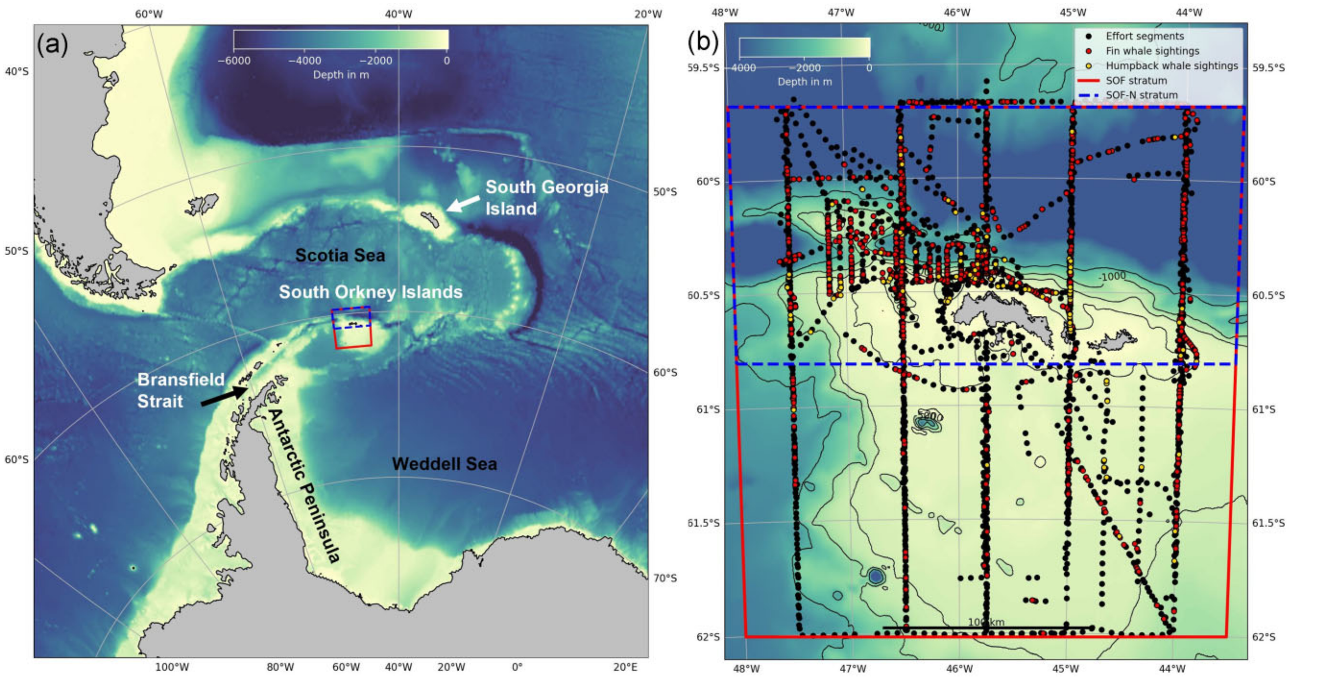


**Figure 1.** Study area (a) and survey stratum (b), bathymetry data are extracted from GEBCO (Weatherall et al. 2021). The depth contours in panel (b) are −2000, −1000, −500, and −200 m. The meaning of the different line styles (e.g. dashed lines, dotted lines) and color categories is explained in a separate legend panel included within the figure. Abbrevations: SOF (South Orkney Fixed stratum), SOF-N (northern South Orkney Fixed stratum).

world (FAO 2005, Garcia and Rosenberg 2010). It has potential to contribute around 10% of all future marine landings (Trathan et al. 2022), which would add significantly to future global food security by providing a source of protein and essential nutrients supporting human and animal diets (Tang et al. 2024). The Antarctic krill fishery is managed under the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) established under the Antarctic Treaty System to prevent potential ecosystem perturbance through overfishing and is enacted by a multinational Commission (www.ccamlr.org). Due to large knowledge gaps regarding the role of krill in the Southern Ocean marine ecosystem and potential effects caused by fishery activities, interim catch limits for the Scotia Sea region were set at 620 000 tons (termed as the "trigger level") by CCAMLR in 1991 to avoid potential conflicts with predators dependent on krill as prey. The total annual catch in the Scotia Sea region ranges from 100 000 to ∼500 000 tons (CCAMLR Secretariat 2025), taken from a krill stock which comprises a biomass of approximately 60 million tons (CCAMLR 2010, Krafft et al. 2021).

Given the low trigger level relative to the estimated biomass and high productivity of krill (Atkinson et al. 2009), there is increasing pressure to raise catch levels in the krill fishery (Nicol et al. 2012). Potentially larger catches have also increased concerns regarding the impact that an expanding fishery could have on the ecosystem, particularly at small scales, if much of the harvesting concentrates within localized regions and at critical time periods for krill-dependent predators (e.g. Schiermeier 2010, Flores et al. 2012, Watters et al. 2013, Krüger et al. 2020, 2020). Overfishing is not the only cause for concern over krill stocks; potential cumulative pressures from ongoing environmental changes, such as sea ice decline (Stammerjohn et al. 2008), temperature rise (IPCC 2023, Kawaguchi et al. 2024), increased pollutant levels (Schiavone et al. 2009), ocean acidification (Orr et al. 2005), and changes in oceanic circulation (Fyfe and Saenko 2006, Böning et al. 2008) may also cause declines in overall krill abundance and changes in their distribution with potentially far-reaching consequences to the rest of the ecosystem.

As fin and humpback whale populations appear to be undergoing significant recoveries with increased abundances in the Southern Ocean (e.g. Johnston et al. 2011, Zerbini et al. 2019, Baines et al. 2022, Herr et al. 2022, Johannessen et al. 2022, Biuw et al. 2024), there is an urgent need for improved knowledge about their population sizes, spatiotemporal distribution, foraging strategies, and the degree of interaction with fishing activities. This is important for evaluating risks and identifying relevant preventive measures to maintain a co-existence between these large-bodied krill predators and the commercial krill fishery (Krafft et al. 2022, Trathan et al. 2024).

The South Orkney Islands (Fig. 1) represent the most important commercial krill fishing ground in the Southern Ocean in terms of the total annual catches of krill (CCAMLR Secretariat 2025). The Scotia Sea and Antarctic Peninsula region are also experiencing rapid climate change effects, including shifts in sea ice cover, ocean temperature increases, and changes in the distribution and abundance of marine species (Cavanagh et al. 2021). Information about abundance, distribution, and krill consumption rates is crucial for facilitating the development of sustainable, ecosystem-based management of the krill fishery.

The aim of this study is to evaluate annual variation in summer distribution and abundance of fin and humpback whales in the South Orkney Islands region. We use visual sightings data systematically collected between late January and early February from 2011 to 2025. Additionally, we aim

**Table 1.** Vessels used during the surveys in 2011–2025, with observation platform heights and survey periods (YYYY.MM.DD).

| Year | Vessel and observation platform height above Sea level (m) | Start date of survey | End date of survey |
|---|---|---|---|
| 2011 | FV Saga Sea (14 m) | 2011.02.04 | 2011.02.08 |
| 2012 | FV Juvel (14 m) | 2012.01.26 | 2012.01.29 |
| 2013 | FV Saga Sea | 2013.01.25 | 2013.01.29 |
| 2014 | FV Saga Sea | 2014.01.24 | 2014.01.30 |
| 2015 | FV Juvel | 2015.02.06 | 2015.02.12 |
| 2016 | FV Saga Sea | 2016.02.10 | 2016.02.15 |
| 2017 | FV Saga Sea | 2017.02.06 | 2017.02.11 |
| 2018 | FV Juvel | 2018.02.04 | 2018.02.10 |
| 2019 | RV Kronprins Haakon (23 m) | 2019.01.22 | 2019.02.18 |
| 2022 | CV Antarctic Provider (23 m) | 2022.02.08 | 2022.02.17 |
| 2023 | CV Antarctic Provider | 2023.01.28 | 2023.02.28 |
| 2024 | CV Antarctic Provider | 2024.02.01 | 2024.02.08 |
| 2025 | CV Antarctic Provider | 2025.01.26 | 2025.02.13 |

**Table 2.** Survey strata location and area.

| Stratum | Longitudinal boundaries | Latitudinal boundaries | Area in km$^2$ | Area in km$^2$ excluding land |
|---|---|---|---|---|
| SOF | −48° and −43.5° | −62° and −59.67° | 63 495 | 62 650 |
| SOF-N | −48° and −43.5° | −60.8° and −59.67° | 31 368 | 29 676 |

to study the possible relationship between whale distribution and abundance with the biomass and distribution of krill, as well as other environmental variables.

## Materials and methods

The Institute of Marine Research (IMR) in Norway has conducted annual surveys around the South Orkney Islands since 2011 (Krafft et al. 2018, Skaret et al. 2023, Freer et al. 2025). These surveys are designed as acoustic trawl surveys for systematic monitoring of distribution, abundance, and population characteristics of Antarctic krill, and take place around late January to late February (Table 1). Data could not be collected due to the COVID-19 global pandemic in 2020 and 2021. The surveys follow a grid of five predetermined latitudinal transects (Fig. 1 b) included in the South Orkney Fixed stratum "SOF" (Krafft et al. 2021), covering an area of 63 495 km$^2$. In 2013 and 2015 the sea ice edge was so close to the South Orkney Islands that only the northern part of the stratum could be surveyed. For those years, we used the SOF-N stratum (31 368 km$^2$) that covers the shelf break north of 60.8°S, identical to the strata used for krill biomass estimation in Skaret et al. (2023). Table 2 summarizes the location and area of the two strata (SOF and SOF-N).

Marine mammal observations were carried out by 1–2 dedicated observers (one at a time) during daylight hours (06:00–22:00 local time), whenever the visibility was not severely impacted by fog, glare, or sea state. The observers were familiarized with relevant taxonomic literature and had undergone practical training; some observation teams participated in multiple surveys. The observer was located on the bridge (see Table 1 for observation platform height above sea level) and continuously scanned either the starboard or port forward quarter, depending upon conditions (sun, glare, etc.). While primary sightings relied on the naked eye, binoculars were used for species identification. Observations were recorded while the vessel was in transit between and along the transects, with a nominal speed of 10 knots. The vessel GPS track and logged effort were recorded with a PC running custom software (DOI 10.5281/zenodo.10228669), and for each observation the type of cue, species identification, time, location, radial distance, angle relative to the bow, and number of individuals were recorded.

Sufficient data (>60 sightings, Buckland et al. 2001) for obtaining robust and consistent density and summer abundance estimates were only available for fin and humpback whales. Standard line transect distance sampling methods (Buckland et al. 2001) were used to analyze the fin and humpback whale sightings data using the *Distance* and *mrds* packages (Thomas et al. 2010, Miller et al. 2013, 2019) in R (R Core Team 2022). We fitted a series of half-normal detection functions with a truncation distance of 4000 m to the observations, comparing models with different sets of the covariates, with survey year, vessel, or species as available covariables. Survey year and species as co-variates gave the most suitable detection function ($\Delta$AIC = 44.6), which likely relates to the different visibility conditions and individual observers participating over the survey years. The effective strip width (corresponds to area covered by detection function) was on average 275 m narrower for humpback whales compared to fin whales. The detection function for fin and humpback whales is displayed in Fig. 2, while Table 3 displays the effective strip widths for the different years and species. The fitting algorithm of hazard rate models exhibited instabilities during fitting and resulted in unrealistic detection functions, whereas the half-normal detection functions fitted well to the data.

We used the distance sampling function *dht* to estimate the spatially averaged whale species density for each survey to generate a time series. In addition, we also performed density surface modeling (DSM) using the R package *dsm* (Miller et al. 2013) to map the temporally averaged (over all surveys between 2011–2025) spatial distribution of fin and humpback whales. For these analyses, we divided the vessel tracks into ~5 km effort segments, where the average segment location was calculated from the vessel track, and where vessel ID, survey year, seafloor depth, slope angle, and aspect where added as covariates, based on the GEBCO-2020 bathymetry grid (Weatherall et al. 2021). Each fin and humpback whale sighting were assigned to its corresponding effort segment and survey stratum using individual segment labels. All locations

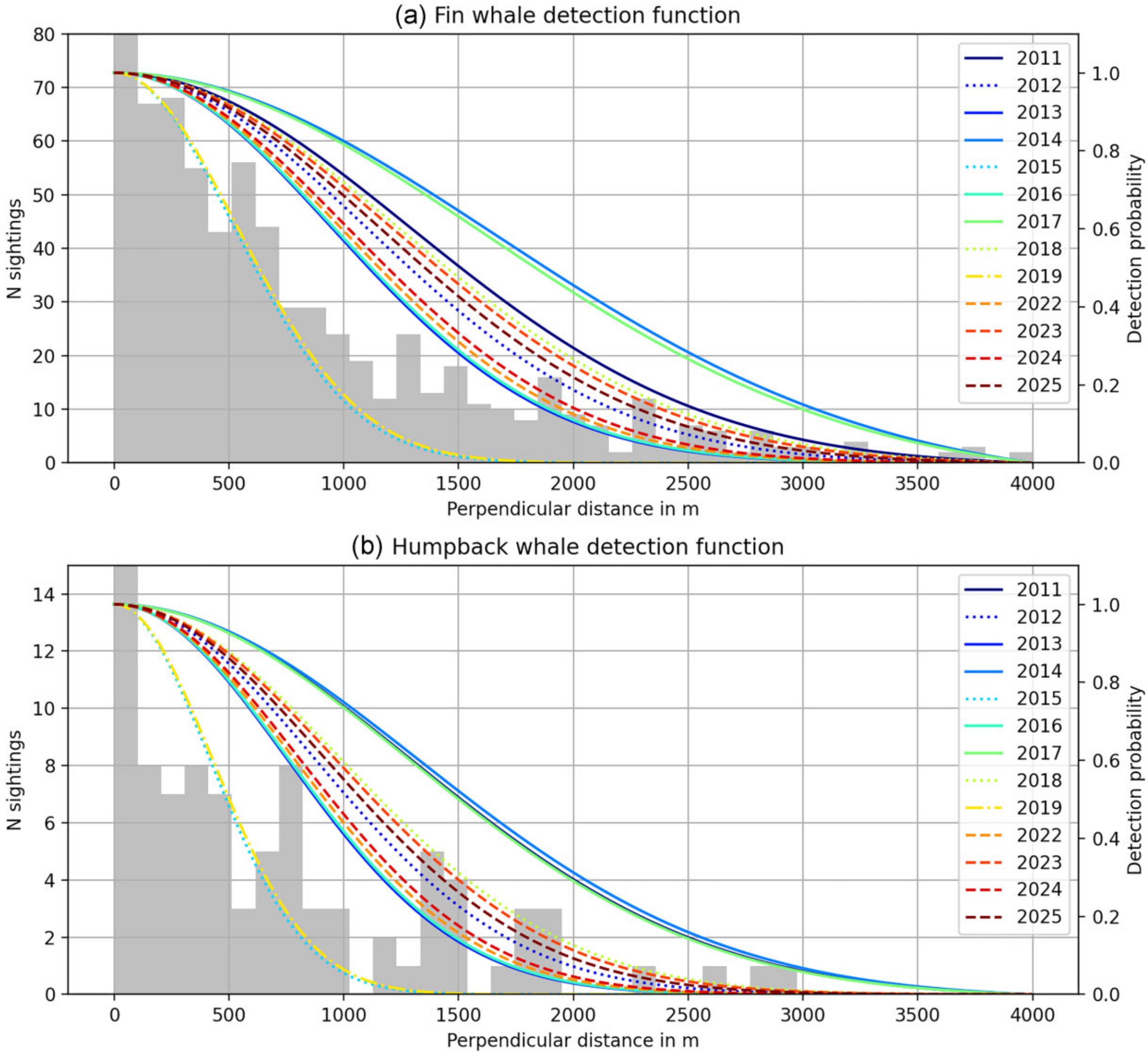


**Figure 2.** Fin (panel a) and humpback (panel b) whale detection function for best-fitting half-normal model including year as covariable. Line color indicates the survey year and line type the survey vessel: solid line: FV Saga Sea, dashed line: CV Antarctic Provider, dotted line: FV Juvel, dot–dash line: RV Kronprins Haakon. Gray bars show histograms for all sightings between 2011 and 2025.

**Table 3.** Estimated parameters of the detection function.

| Covariate (year) | Fin whales—effective strip width in m | Humpback whales—effective strip width in m |
|---|---|---|
| 2011 | 1614 | 1286 |
| 2012 | 1371 | 1091 |
| 2013 | 1181 | 940 |
| 2014 | 2052 | 1656 |
| 2015 | 654 | 520 |
| 2016 | 1193 | 949 |
| 2017 | 1993 | 1604 |
| 2018 | 1547 | 1232 |
| 2019 | 672 | 535 |
| 2022 | 1229 | 978 |
| 2023 | 1508 | 1201 |
| 2024 | 1267 | 1009 |
| 2025 | 1443 | 1148 |

were transformed from latitude and longitude to Universal Transverse Mercator (UTM, zone 23S) coordinates in meters. General additive models (GAMs) were fitted to the observations using the restricted maximum likelihood score with a Tweedie error distribution. The average density surface of fin and humpback whales between 2011 and 2025 was estimated from the best fitting model using a 5 × 5 km grid covering the SOF stratum.

The variation in fin and humpback whale density over time was estimated using a Horvitz–Thompson estimator (Horvitz and Thompson 1952, distance sampling function *dht*) with the same effort and observation datasets and detection function as for the DSM. Estimates were calculated for the northern (SOF-N) and entire SOF stratum (Tables 4, 5 and 6). For years with no humpback whale sightings, the density estimate was set to 0. We found that excluding observation segments that were not on one of the 5 transect lines had no significant effect on the density estimates (Wilcoxon signed-rank test for the density time series with or without data off transect lines: $P$-value = 0.92) and thus we used all available segments for the estimation (Fig. S1). A comparison of the density time series with survey year as covariable, survey vessel as well as a static detection function showed no significant difference between survey year or vessel as covariable (Wilcoxon signed-rank test $P$-value = 0.49) and only a minor offset (0.05 ind.

**Table 4.** Count of observed individuals per species and year.

| Year | Fin whales | Humpback whales | Antarctic fur seals | Antarctic minke whales | Antarctic blue whales | Southern right whales | Orcas | Unknown whales |
|---|---|---|---|---|---|---|---|---|
| 2011 | 61 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2012 | 62 | 0 | 79 | 1 | 0 | 0 | 10 | 0 |
| 2013 | 145 | 5 | 230 | 0 | 0 | 2 | 0 | 45 |
| 2014 | 24 | 21 | 337 | 0 | 0 | 0 | 0 | 8 |
| 2015 | 167 | 33 | 116 | 0 | 0 | 0 | 0 | 5 |
| 2016 | 36 | 7 | 51 | 0 | 0 | 0 | 4 | 0 |
| 2017 | 60 | 14 | 47 | 0 | 0 | 0 | 0 | 1 |
| 2018 | 57 | 11 | 128 | 2 | 0 | 0 | 2 | 1 |
| 2019 | 192 | 7 | 474 | 2 | 3 | 0 | 0 | 77 |
| 2022 | 152 | 0 | 5 | 4 | 0 | 0 | 1 | 67 |
| 2023 | 534 | 25 | 46 | 0 | 0 | 0 | 0 | 166 |
| 2024 | 240 | 16 | 27 | 0 | 0 | 0 | 7 | 98 |
| 2025 | 239 | 54 | 45 | 0 | 0 | 0 | 3 | 47 |

**Table 5.** Summary of density surface model abundance estimates for the SOF stratum using all data from 2011 to 2025.

| | Mean *N* (95% confidence intervals) | CV of detection function | CV from GAM |
|---|---|---|---|
| Fin whales | 6930 (6125–7840) | 0.022 | 0.060 |
| Humpback whales | 590 (445–782) | 0.022 | 0.143 |

**Table 6.** Density and abundance estimates for each year for the SOF stratum.

| Year | Avg. density SOF [ind. km$^{-2}$] and 95% confidence intervals | Avg. abundance SOF and 95% confidence intervals |
|---|---|---|
| Fin whales | | |
| 2011 | 0.055 (0.033–0.091) | 3440 (2082–5683) |
| 2012 | 0.063 (0.029–0.137) | 3971 (1842–8560) |
| 2013* | 0.187 (0.13–0.268) | 11 689 (8142–16 782) |
| 2014 | 0.010 (0.004–0.025) | 648 (272–1544) |
| 2015* | 0.135 (0.091–0.201) | 8450 (5683–12 567) |
| 2016 | 0.055 (0.029–0.104) | 3460 (1837–6518) |
| 2017 | 0.034 (0.019–0.059) | 2101 (1190–3710) |
| 2018 | 0.059 (0.035–0.099) | 3708 (2223–6186) |
| 2019 | 0.255 (0.182–0.356) | 15 957 (11 428–22 282) |
| 2022 | 0.104 (0.068–0.159) | 6503 (4247–9958) |
| 2023 | 0.289 (0.197–0.423) | 18 083 (12 328–26 525) |
| 2024 | 0.236 (0.172–0.325) | 14 801 (10 755–20 368) |
| 2025 | 0.185 (0.136–0.25) | 11 568 (8544–15 661) |
| Humpback whales | | |
| 2011 | 0.0 | 0 |
| 2012 | 0.0 | 0 |
| 2013* | 0.004 (0.001–0.014) | 240 (64–904) |
| 2014 | 0.010 (0.005–0.022) | 625 (287–1361) |
| 2015* | 0.019 (0.01–0.037) | 1188 (605–2331) |
| 2016 | 0.014 (0.006–0.034) | 907 (383–2149) |
| 2017 | 0.011 (0.004–0.028) | 664 (256–1726) |
| 2018 | 0.006 (0.001–0.034) | 402 (76–2106) |
| 2019 | 0.007 (0.002–0.023) | 448 (140–1428) |
| 2022 | 0.0 | 0 |
| 2023 | 0.021 (0.011–0.041) | 1305 (662–2574) |
| 2024 | 0.015 (0.007–0.031) | 917 (438–1918) |
| 2025 | 0.072 (0.042–0.123) | 4486 (2611–7710) |

Note that in 2013 and 2015, only the northern section of the stratum (SOF-N) was covered (*).

km$^{-2}$) toward higher densities for the static detection function (Wilcoxon signed-rank test *P*-value = 0.03). The major pattern of the density time series remained the same for each detection function (Fig. S2). To test for temporal trends in density, we applied the non-parametric Mann–Kendall test modified for serially correlated data (Hamed and Rao 1998) to the fin whale density timeseries using the r package *modifiedmk* (Patakamuri and O'Brien 2021).

We also tested whether the spatial variation in effort between the years (due to variable weather and daylight conditions) significantly changed the density estimates. The average fin whale DSM density at the effort segment locations were calculated for each year. This time series was then normalized by dividing by the mean density of the entire DSM (SOF stratum), resulting in a correction weight for each year that was applied to the Horvitz–Thompson estimator density time series. A comparison between the weighted and original fin whale density time series is shown in Fig. S3 and showed no major differences between the time series, both showed a significant increase in fin whale density (Mann–Kendall test original $P = 0.049$, weighted $P = 0.020$). A Wilcoxon signed-rank test indicated only a minor offset (0.01 ind. km$^{-2}$, $P = 0.05$) between the weighted and original unweighted Horvitz–Thompson estimator density time series, we thus choose to use original Horvitz–Thompson estimator density time series.

The abundance of krill was measured with vessel mounted Simrad echosounders along the five transects. Each year a combination of 120 with 38, 70, and/or 200 kHz transducers were used to record and scrutinize krill backscatter. The echosounders were calibrated during each survey using the standard sphere method (Foote et al. 1987). The 2011–2020 krill biomass estimates are described in Skaret et al. (2023). Here, we extend the time series to 2025 using the same methodology. The updated time series can be found in Table S1. A detailed description of the echosounders, calibration, and processing can be found in Skaret et al. (2023) and Krafft et al. (2021). To compare the spatial distribution of krill and marine mammals, we calculated the spatial average krill density in the SOF stratum using kriging (spherical variogram) and krill density data from all surveys between 2011 and 2025.

We visually compared our fin and humpback whale and krill density time series to several environmental variables (Table S2). Statistical modeling was omitted due to the briefness of the time series (13 datapoints). The bathymetry data were extracted from the global GEBCO dataset (Weatherall et al. 2021). The Southern Oscillation Index (Ropelewski and Jones 1987) was provided by NOAA (2022). Sea ice concentration in the study area was extracted from remote sensing measurements by the AMSRE and AMSRE-2 satellites (Spreen et al. 2008). We calculated the sea ice edge latitude between 48° 30'W and 43° 30'W by fitting a sigmoid function to the longitudinal average ice concentrations across latitudes.

## Results

Only fin ($N = 1969$) and humpback ($N = 193$) whales were observed in sufficient numbers to obtain density and abundance estimates (Buckland et al. 2001) during the 2011–2025 survey periods. Other identified cetacean species included Antarctic minke whales, blue whales, southern right whales (*Eubalaena australis*), and killer whales (*Orcinus orca*), as well as the pinniped Antarctic fur seal (*Arctocephalus gazella*) (Table S3). Several sightings of cetaceans could also not be identified to species (categorized as "unknown whales"), this could include instances where only few blows or backs were visible for a short period or from a distance, but represents large baleen whales such as fin, blue, humpback, sei, and minke whales. Fin whales were by far the most observed cetacean in the study area in all years (Table S3).

The interannual variation in fin and humpback whale density in the South Orkney Islands stratum is presented in Table 5. Figure 3 shows the variability in density in the context of El- Niño indicators and the location of the sea ice edge. Fin whale density varied between 0.01 and 0.29 ind. $km^{-2}$ over the study period (Fig. 3, panel a and Table 5). During 2013 and 2015, the Antarctic sea-ice was so extensive that only the SOF-N stratum could be surveyed (Fig. 3, panel e). In 2019 and 2023, fin whale densities were highest, and the sea ice situation allowed full survey coverage.

Humpback whale density varied between 0 and 0.07 ind. $km^{-2}$ over the survey years. Humpback whale density was highest in 2025 and exhibited a minor peak between 2013 and 2018, around the strong El- Niño event in 2016 (Fig. 3, panels b, d and Table 5).

The estimated distribution of fin and humpback whales in the study period 2011–2025 around South Orkney Islands is shown in Fig. 4. Fin whale density was highest north of the islands, especially along the shelf break between 44 °W and 47 °W whereas humpback whales were concentrated closer to the islands along the shelf break between 45 °W and 46 °W. In contrast to humpback whales, fin whales were also frequently present in deeper waters north of the shelf break. Average krill density in the study period 2011–2025 was highest along the shelf break north of the islands between 44 °W and 47 °W, similar to the fin and humpback whale distribution (Fig. 4c). The DSM based estimates of fin and humpback whale in the study period are summarized in Table 4.

Results from the DSM showed that the bathymetry covariates (seafloor depth, slope, and aspect) did not improve the model fit significantly, compared with the a simple model only using locational covariates (Table S4). Among the bathymetry covariates, only depth contributed significantly to explain the variation in whale sightings ($P_{\text{fin}} = 0.048$, $P_{\text{hump}} = 0.007$), predicting an increase in whale density in shallower waters. The smooth functions for depth are shown in Fig. S4. We choose to use only a bivariate smooth of $(x, y)$ in the DSM.

The low number of data points available allowed only a rudimentary multiple regression analysis (Fig. S5) that showed no significant correlation ($P < 0.05$) between the abundance and environmental time series, but fin whale density showed a significant increase with survey year.

The non-parametric Mann–Kendall test used to investigate for monotonic trends in densities of fin and humpback whale and in biomass of krill over the time series (excluding the data from the years 2013 and 2015 with incomplete survey coverage), found for fin whales a $Z$-score of 2.18, $P$-value of 0.03 and a Sen's slope estimated at 0.02 ind. $km^{-2}$ $y^{-1}$. Linear regression ($r^2 = 0.53$) of the same data results in an identical slope estimate of 0.02 (0.00–0.03 95% confidence intervals) ind. $km^{-2}$ $y^{-1}$. For humpback whales, the $Z$-score was 2.42, $P$-value 0.02 and Sen's slope estimated as 0.00 ind. $km^{-2}$ $y^{-1}$. For the krill biomass, the $Z$-score was −0.15, $P$-value 0.88 and Sen's slope estimated as −0.13 million tons $y^{-1}$. The only significant monotonic trend in the density time series was an increase in fin whale density.

## Discussion

The fin whale summer densities reported in this study were high in some years, varied substantially inter annually (between 0.011 and 0.290 individuals per $km^{-2}$) but importantly, showed an increasing trend over the study period from 2011 to 2025, suggesting that fin whales in the Scotia Sea are not currently food limited. Our study also supports previous findings that fin whales in the Southern Hemisphere appear to be undergoing recovery and population growth after a century of exploitation (Herr et al. 2022, Biuw et al. 2024). During some of the survey seasons in this study, especially in more recent years, the average fin whale density was found to be significantly higher, indicating that the South Orkney Islands region is important for feeding fin whales during the austral summer season.

Large abundances and feeding aggregations of fin whales are also reported from the eastern Bransfield Strait, central Scotia Sea, as well as at South Georgia (Herr et al. 2022, Ryan et al. 2023, Biuw et al. 2024). Viquerat and Herr (2017) reported similar fin whale densities from their survey in 2016 as we report for the same survey year (0.059 and 0.055 individuals per $km^{-2}$, respectively). Both the cetacean guild composition and dominance of fin whales at South Orkney Islands differ from other areas in the Atlantic sector of the Southern Ocean described as high cetacean density areas, such as the South Georgia waters, South Sandwich Islands, Bransfield and Gerlache Straits; where most sightings are of humpback whales (Friedlaender et al. 2006, Pallin et al. 2018, Baines et al. 2022, Johannessen et al. 2022).

While the time series indicate no clear annual temporal relationship between fin whales and krill abundance (Fig. 3, and the correlation matrix in Fig. S5), the comparison of the average spatial distribution shows a close association between krill, fin whales and humpback whales (Fig. 4). Fin and humpback whales were most frequently observed north of the South Orkney Islands in association with the shelf break where krill density is found to be highest during the summer season (Krafft et al. 2018, Skaret et al. 2023, Freer et al. 2025). The lack of temporal correlation can be explained by the snapshot nature of line transect surveys and the inherent patchiness of krill and whale distribution, which likely masks any meaningful temporal correlations in the short time series available.

The distribution pattern for humpback whales in the study area was broadly similar to that found for fin whales with most observations made in the northern parts, but humpbacks were more associated with the on-shelf and shelf-edge area. In the western Antarctic Peninsula region, tracked humpback

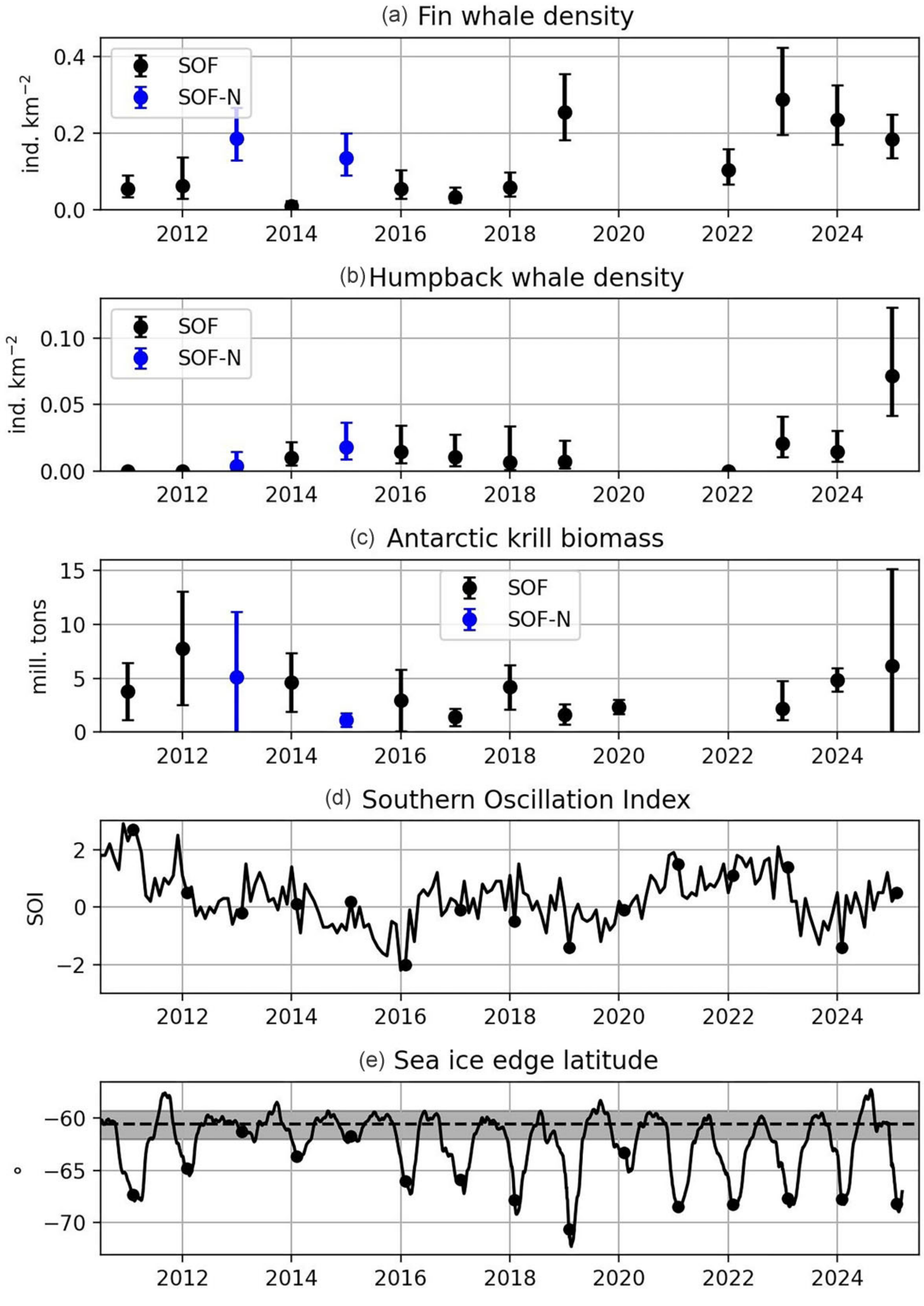


**Figure 3.** Comparison of whales density timeseries and environmental variables. The dots and lines mark the point estimate and 95% confidence interval for the SOF-N stratum due to incomplete coverage of the entire stratum in 2013 and 2015. (a) Fin whale density, the lines mark the point and the shaded areas the 95% confidence intervals (b) humpback whale density, the lines mark the point estimate and the shaded areas the 95% confidence intervals. (c) Antarctic krill biomass from acoustic surveys, the lines mark the point estimate and the shaded areas the 95% confidence intervals. (d) Southern Oscillation Index as monthly averages. Dots mark values at the first of February. (e) The line marks the sea ice edge latitude (between −48.5 and −43.5 °S, 20 day rolling mean), the gray shaded area the latitude boundaries of the SOF stratum and the dashed line the latitude of the South Orkney islands. Dots mark values at the first of February.

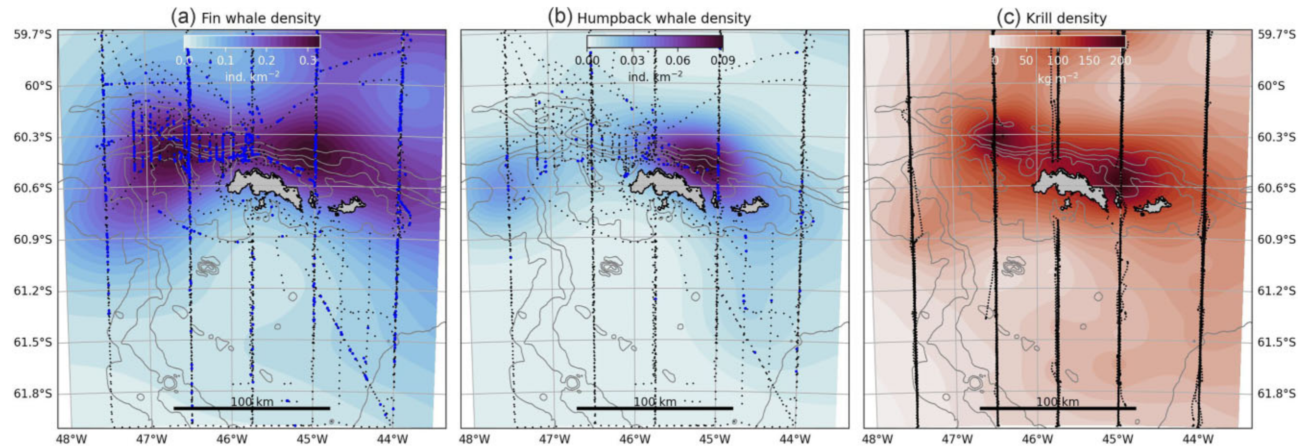


**Figure 4.** Density surface model (DSM) for fin whale (panel a) and humpback whale (panel b) sightings between 2011 and 2025 are shown alongside average krill density for the same period (kriging average of data from Skaret et al. (2023)). For the DSM easting (*x*) and northing (*y*) coordinates on a UTM grid were used as response variables in combination with the detection function. Dots indicate 5 km long observation effort segments in panels a and b, and 1 nm long acoustic transect segments in panel c. Sighting locations for each species are marked with distinct symbols in panels a and b. Depth contours at −2000, −1000, −500, and −200 m are shown in all panels using consistent line styles.

whales have shown a preference for habitats proximal to sea ice, but avoiding bays with sea ice (Friedlaender et al. 2021). In the Scotia Arc, the main feeding ground of humpback whales was associated with the polar front (Zerbini et al. 2011, Horton et al. 2020) likely as a function of krill availability in the area (Murphy et al. 2007). Herr et al. (2016) investigated connections between the modeled distributions of cetaceans and the euphausiid species *E. superba*, *E. crystallorophias*, and *Thysanoessa macrura*. The predicted distributions suggest a complex relationship rather than a straightforward correlation; however, it indicated that fin whales were feeding in an area dominated by *T. macrura*, while humpback whales were found in areas of higher *E. superba* biomass. Future studies could investigate potential relationships between baleen whales and density and distribution of euphausiids species present at the South Orkney Islands. Taxonomic data from net samples collected along the acoustic transects from the survey years 2011–2025, identified *E. superba* to be the dominant euphausiid species, followed by -*T. macrura* and with only sporadic occurrences *of* -*E. frigida*, -*E. triacantha*, and -*T. gregaria* (e.g. Krafft et al. ).

In some years at the South Orkney Islands, humpback whales were not sighted and their apparent absence in the study area coincided with El Nino Southern Oscillation (ENSO) events, a hemispheric-scale climatological phenomenon (Chen et al. 2024) that occurs on average every 2–7 years. However, our time series is still relatively short and few extreme ENSO events occurred in this period. It will be important to maintain this time series to provide a means to monitor how climatological events may impact cetaceans as the climate continues to change (IPCC 2023).

Over the years of our study, the north-facing shelf and shelf break of the South Orkney Islands emerged as the key habitat for both fin and humpback whales. There are several submarine canyons and troughs along the slope from the shelf break to abyssal depths of around 3000–4000 m (Dickens et al. 2014). These are likely important for retention of krill advected along the shelf and slope region from areas further west and south-west, or via deeper currents from the Weddell Sea region flowing east and turning north in a counterclockwise fashion around the South Orkney plateau (Gordon et al. 2001, Heywood et al. 2004). The interaction between bathymetry and current patterns lead to predictable areas of krill concentration and retention hotspots during the summer season (Nicol et al. 2012, Krafft et al. 2015, 2018, Warwick-Evans et al. 2018, Skaret et al. 2023, Freer et al. 2025). Unsurprisingly these hotspots are also the center of the commercial krill fishery in the area (CCAMLR Secretariat 2025) and overlap with the cetacean distribution observed in this study.

The acoustic monitoring data from 2011 to 2025 shows high annual variability in krill biomass, but still without displaying any clear monotonic or cyclic trends. This variability may reflect annual changes, but likely indicate that the South Orkney Islands area represents a dynamic oceanographic system with a high degree of krill flux pulsing through the area (Kasatkina et al. 1997, Klevjer 2019, Young et al. 2023). Such instances of temporal variation in krill distribution and biomass can also be found near South Georgia, linked with interactions with ocean currents (Krafft et al. 2021, Trathan et al. 2022). Future research should focus on quantifying krill flux to better understand fishery–predator–prey interactions, particularly the degree of krill consumption by whales in relation to actual biomass in the South Orkney Islands region. Additionally, understanding large-scale spatial variation in krill is essential for improving management of the fishery (Trathan et al. 2022).

Based on Biuw et al. (2024), the summer fin whale population in the South Orkney Islands region consumes between 4043 and 7605 tons of krill daily, which is 4–8 times more than the average daily commercial catch rate of 962 tons during January–February (2011–2023; see Table S5).

However, the literature reveals a considerable variation in the estimated krill consumption by fin whales (e.g. Goldbogen 2010, Goldbogen et al. 2010, Savoca et al. 2021, 2024). Also, a recent study by Åsvestad et al. (2024), based on passive acoustic monitoring (PAM) of marine mammals reported that the whale species composition at South Orkney Islands varied both seasonally and annually, but with fin whales arriving earlier than humpbacks during the summer season. Traditional use of PAM provides a useful tool for monitoring year-round distribution and habitat use of marine mammals. However, it has limitations in quantifying the abundance of species due to its inability to identify individual animals and has challenges in distinguishing overlapping calls from multiple individuals. Deploying multiple PAMs placed in a grid or array can improve spatial coverage and increase the likelihood of detecting and distinguishing individual calls, thereby enhancing the accuracy of abundance estimates (e.g. Gibb et al. 2018, Tougaard et al. ). Additional data providing quantitative analyses of within-season abundance trends would allow for the estimation of per-season consumption rates (as discussed by Johannessen et al. 2022) and their contribution to nutrient cycling through their feeding activities (Gilbert et al. 2023). The current Ecosystem Monitoring Program run by CCAMLR (CEMP) does not include cetaceans, focusing only on key life-history parameters of only selected land-based predators that are monitored to detect changes in their performance. Cetaceans are neglected in this regard, but they will become even more important than they already are if these populations continue to grow even further (e.g. Trathan 2023, Trathan et al. 2024), suggesting that any new management strategy for the Antarctic krill fishery should consider cetaceans as a monitored taxa.

## Conclusions

The abundance estimates we present in this study support the contention that the South Orkney Islands area constitutes a key area for fin whales during the summer season. Humpback whales are also present in smaller numbers in the South Orkney Islands region in January and February although they appear to be absent in some years. To convert our findings into robust science-based advice for sustainable management of the krill fishery requires further work to understand cetacean krill consumption requirements as well as the role of flux in krill availability and the spatiotemporal dynamics of cetaceans throughout their summer feeding season. The krill fishery has developed into a sizeable industry and the recovery of large-bodied marine mammal krill predators constitutes an important factor to consider when further developing an appropriate sustainable fishery management framework.

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## Author contributions

Bjørn A. Krafft (Conceptualization [equal], Data curation [equal], Funding acquisition [lead], Investigation [equal], Methodology [equal], Project administration [lead], Resources [equal], Validation [equal], Writing – original draft [lead], Writing – review & editing [lead]), Sebastian Menze (Data curation [equal], Formal analysis [lead], Methodology [equal], Software [equal], Validation [equal], Visualization [equal], Writing – original draft [equal], Writing – review & editing [equal]), Georg Skaret (Data curation [equal], Investigation [equal], Methodology [equal], Writing – original draft [equal], Writing – review & editing [equal]), Ludvig A. Krag (Data curation [equal], Investigation [equal], Methodology [equal], Writing – original draft [equal], Writing – review & editing [equal]), Martin Biuw (Formal analysis [equal], Methodology [equal], Supervision [equal], Validation [equal], Writing – original draft [equal], Writing – review & editing [equal]), Ulf Lindstrøm (Writing – original draft [equal], Writing – review & editing [equal]), Phil Trathan (Data curation [equal], Methodology [equal], Supervision [equal], Writing – original draft [equal], Writing – review & editing [equal]), Leif Nøttestad (Conceptualization [equal], Methodology [equal], Writing – original draft [equal], Writing – review & editing [equal]), Heidi Ahonen (Writing – original draft [equal], Writing – review & editing [equal]), Nat Kelly (Validation [equal]), and Andrew Lowther (Writing – original draft [equal], Writing – review & editing [equal])

## Supplementary data

Supplementary data is available at *ICES Journal of Marine Science* online.

The following supplementary material is available at ICESJMS online: Figs S1–S5 illustrate calculations included in the density estimates and density and distribution relationships to environmental variables, Tables S1–S5 with results from the marine mammal sightings, acoustic krill time series 2011–2023, the annual Southern Oscillation Index and sea ice extent, and reported commercial catch levels from Subarea 48.2 during January–February 2011–2023.

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## Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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