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RESEARCH

# At-sea distribution of marine predators around South Georgia during austral winter, with implications for fisheries management

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## Abstract

The sub-Antarctic island of South Georgia is surrounded by highly productive waters, supporting dense aggregations of Antarctic krill (*Euphausia superba*), a vital food source for globally important seabird and marine mammal populations. These waters also support a commercial fishery for Antarctic krill. Regular monitoring of key krill predator species is undertaken at South Georgia to detect any changes in the ecosystem in response to harvesting activities. This monitoring provides essential data but is focused on land-breeding animals during the austral summer, whilst the krill fishery operates exclusively in winter. Here, we report the results of at-sea surveys to investigate abundance and distribution of krill-dependent predators from winter 2010 and 2011, which represented a "poor" krill year and "good" krill year, respectively. Correspondingly in 2011 higher numbers of krill predators were observed; notably Antarctic fur seals (*Arctocephalus gazella*) across the northern shelf. Spatial overlap between fur seals and the krill fishery occurred mainly within the krill fishery hotspot to the north-east, highlighting the potential for locally high levels of competition. Cetaceans were observed during both survey years, but in low numbers compared to recent studies. Gentoo penguins (*Pygoscelis papua*) were the most frequently observed penguin species, showing an inshore distribution and almost no overlap with the krill fishery. Diving-petrels (*Pelecanoides* spp.) were the most abundant flying seabirds, observed across all transects, with particularly high densities to the south in early winter 2010. In conclusion, this survey provides valuable baseline data on the distribution of South Georgia's predators during the winter months.

**Keywords** Krill · South Atlantic · Fur seals · Diving-petrels

## Introduction

The island of South Georgia, part of the UK Overseas Territory of South Georgia and the South Sandwich Islands (SGSSI), is located in the Atlantic sector of the Southern Ocean. It is situated to the south of the Antarctic Polar Front, in the path of the Antarctic Circumpolar Current. The waters surrounding the island are highly productive with large aggregations of Antarctic krill (*Euphausia superba*) concentrated over the shelf and shelf-break (Fielding et al. 2014; Atkinson et al. 2001) providing a vital food source for other fauna that inhabit these waters, including: baleen whales (Baines et al. 2021; Cavan et al. 2019), seals (Bamford et al. 2021; Trathan et al. 2022), penguins (Waluda et al. 2017; Trathan et al. 2022; Ratcliffe et al. 2021) and fish (Zhu & Zhu 2022; Trathan et al. 2014; Main et al. 2009).

These highly productive waters have provided opportunities for commercial exploitation since the islands were discovered in the late seventeenth century. Antarctic fur seals (*Arctocephalus gazella)* and southern elephant seals (*Mirounga leonina)* were the first species to be targeted for the commercial value of their fur and oil respectively (Bonner 1958; Carrick et al. 1962). Throughout the early to mid-twentieth century, attention turned to the exploitation of whales, which were quickly over-exploited (Headland 1984), and exploitation of finfish commenced towards the end of the twentieth century (Kock 1992). Following the historical near-extirpation of whale and seal populations from over-exploitation, increasing commercial interest in

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the krill fishery in the 1970s led to the establishment of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), which adopted an ecosystem approach to management of fisheries in the Southern Ocean (Constable et al. 2000). Fisheries at South Georgia operate under CCAMLR Conservation Measures (CMs), which are legally binding agreements between Members, enforced under CCAMLR Member state's national legislation.

In South Georgia waters (CCAMLR Subarea 48.3) there are currently three fisheries in operation: pelagic trawl fisheries targeting mackerel icefish (*Champsocephalus gunnari*) and Antarctic krill, and a longline fishery targeting Patagonian toothfish (*Dissostichus eleginoides*). The mackerel icefish fishery is sporadic, and currently, of little commercial interest, with catches of less than two tonnes per annum since 2016 (with the exception of 2017 when 110 tonnes was landed) (CCAMLR 2023a). Both the toothfish and krill fisheries provide the most commercial interest, generating revenue to the Government of South Georgia and the South Sandwich Islands (GSGSSI). All fisheries are required to adhere to certain restrictions imposed by both CCAMLR and GSGSSI to mitigate and minimise their environmental impacts. To minimise the direct (incidental mortality) and indirect (e.g. competition) impacts of the fisheries on South Georgia's high density of breeding predators in the austral summer, these two fisheries only operate during winter (Collins et al. 2021; Trathan et al. 2014). Whilst CCAMLR CMs establish catch limits and other regulations, GSGSSI provides additional domestic measures, many of which were established as part of the South Georgia Marine Protected Area (MPA) (GSGSSI 2019). To ensure the MPA continues to reflect known scientific understanding, the MPA objectives and management are reviewed every five years. For example, GSGSSI implemented an extension to the coastal no-take zone (NTZ) in 2018 from 22.22 km (12 nm) to 30 km as a measure to protect land-based krill predators and at the same time extended the summer closed period (Trathan et al. 2014; Ratcliffe et al. 2021).

To detect significant changes in critical components of the ecosystem and to distinguish changes due to the harvesting of commercial species from changes due to environmental variability, CCAMLR established an Ecosystem Monitoring Programme (CEMP) in 1987 (Agnew 1997; CCAMLR 2014). The CEMP's primary focus is Antarctic krill and the animals that depend on it (e.g. gentoo penguins and fur seals) which are used as bio-indicators of local krill availability (Trathan et al. 2021; CCAMLR 2013; Reid et al. 2005; Tarling et al. 2009). CCAMLR standard methods are implemented at two South Georgia CEMP sites (Bird Island and Maiviken) to monitor population metrics such as breeding success, mean fledgling weight and dietary composition (Reid et al. 2005; Trathan et al. 2021). However, a significant limitation of this monitoring is the focus on the austral summer, when predators such as fur seals and gentoo penguins return to land to breed, whilst the krill fishery operates exclusively in winter.

A broad guild of predators feed on krill in South Georgia waters in the summer months, including seabirds (albatrosses, prions and petrels), penguins, Antarctic fur seals and baleen whales (Croxall et al.1985, 1997; Trathan and Hill 2016) and the distribution of predators around Bird Island has been shown to be strongly influenced by the distribution of krill swarms (Veit and Everson 1993). In the winter months, when the krill fishery operates around South Georgia, many of these land-based predators (e.g. macaroni penguins (*Eudyptes chrysolophus*), fur seals and black-browed albatross (*Thalassarche melanophris*)) forage much further afield (Boyd et al. 1998; Waluda et al. 2010) The predators that do stay in South Georgia waters are likely to be present in reduced numbers. It is therefore important to understand which krill-dependent predators forage in the krill fishing grounds when the fishery is open, to obtain data on these potentially susceptible species, especially their distribution and abundance.

Winter is an important time for predators to replenish their body mass and condition before the following breeding season. The body mass of returning female rockhopper penguins (*Eudyptes chrysocome filholi*) on Marion Island is significantly related to breeding success (Crawford et al. 2006), whilst long-term data sets from South Georgia show a potential effect of winter-feeding conditions on gentoo penguin nest numbers (Trathan et al. 2021). After winters of poor krill availability female Antarctic fur seals in poor body condition have been observed aborting pups on the beaches of South Georgia (pers obs.). Whilst the impact of the Subarea 48.3 krill fishery is expected to be reduced by the dispersal of many predators, feeding conditions including krill biomass and competition with the fishery are likely to be important for those predators that do stay in South Georgia waters.

Here, we report on ship-based surveys of marine mammals and seabirds during the austral winters (April-August) of 2010 and 2011. The surveys were designed to examine the overlap between krill-dependent predators and the main area used by the krill fishery. The surveys also provide valuable data on the at-sea winter distribution of not only South Georgia's land-breeding predators (seals, seabirds and penguins) but also of cetaceans. Whilst the surveys are focused on krill predators, the results will also be of interest to the toothfish fishery, particularly the abundance of birds susceptible to long-line bycatch. Finally, surveying was conducted prior to the eradication of rodents (2012–2015; Martin and Richardson 2019) and reindeer (*Rangifer* *tarandus* (2012–2014)) from South Georgia, which will allow subsequent comparison with winter species data collected post-eradication, potentially highlighting the recovery of vulnerable bird species.

## Methods

### Survey design and effort

The South Georgia fisheries patrol and logistics vessel, *MV Pharos SG,* was used to conduct a series of transects during May to August 2010 (four surveys), and April to August 2011 (five surveys) (Table 1). Four survey blocks were chosen, relating to the level of effort undertaken by the krill fishery; 'western' and 'north-eastern' (fished), 'northern' (subject to lower fishing effort) and 'southern' (rarely fished) (Figs. 1 & 2; see also Trathan et al. 2021)). Longline fishing effort is distributed on the shelf-break all around the island (Brigden et al. 2017) and all survey blocks also coincide with longline fishing effort.

The aim of the survey was to undertake two 60 km transects in each block during each of the austral winter months (May to September), however, due to weather conditions and vessel logistics, effort varied for each survey (Table 1). May 2010 produced the highest survey effort of 142.3 km$^2$, with the lowest survey effort (53.6 km$^2$) in July 2010. The north-eastern block (usually fished), had the highest overall survey effort of 288.7 km$^2$, whilst the southern block (rarely fished) had the lowest overall survey effort (61.4 km$^2$) for all surveys conducted. Total survey effort in 2011 (453.8km$^2$) was greater than in 2010 (356.4km$^2$) (Table 1).

### Predator observations

Surveying was conducted from the bridge deck of the *MV Pharos SG*, at a height of approximately 10 m above sea level, on the side of the vessel with the best viewing conditions on the day. Three observers worked across the surveys. Survey methods were based on the UK Seabirds-at Sea Team (SAST) methodology (Tasker et al. 1984) and encompassed continuous recording of seabirds and marine mammals on the surface of the water within a 300 m wide strip transect, in a 90º arc from bow to beam. In addition to the continuous strip transect, a second count of flying birds was made using a 'snapshot' technique. The timing of the snapshot was dictated by the speed of the vessel and occurred whenever the vessel travelled 300 m. Any flying birds within the transect at the time of the snapshot were recorded as 'in transect.' The final densities reported here are number of animals per km$^2$.

All animals observed on surveys were identified to species level where possible. Species which are difficult to identify at sea to species level i.e. prions (*Pachyptila* spp.), diving-petrels (*Pelecanoides* spp.) and *Mesoplodon* beaked whales were identified to genus level. Seabirds obviously associating with the survey vessel were omitted from the analysis.

In addition to seabird and marine mammal data, routine environmental and positional data were collected during surveys. Surveys were ordinarily conducted in sea states of 6 or less (Beaufort scale). On two occasions surveying conditions were recorded as poor by the observer. On transect 7 in May 2010 wind and sea state increased during surveying and conditions were recorded as very poor by the observers on the second half of the transect. In August

**Table 1** Monthly survey effort (km$^2$) along each survey transect in 2010 and 2011

| | Western block (Fished) | | Northern block (Low fishing effort) | | North-eastern block (Fished) | | Southern block (Rarely fished) | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Transect 1 | Transect 2 | Transect 3 | Transect 4 | Transect 5 | Transect 6 | Transect 7 | Transect 8 | |
| May 2010 | 18.44 | 18.05 | 17.84 | 17.56 | 17.57 | 17.96 | 17.09 | 17.78 | 142.29 |
| June 2010 | 13.36 | 13.74 | 12.74 | 12.24 | 13.53 | 14.30 | 12.88 | 13.65 | 106.44 |
| July 2010 | 12.89 | 13.87 | / | / | 13.53 | 13.35 | / | / | 53.62 |
| August 2010 | 13.53 | 13.57 | / | / | 13.71 | 13.28 | / | / | 54.09 |
| April 2011 | / | / | 17.83 | 17.62 | 17.62 | 17.79 | / | / | 70.87 |
| May 2011 | 16.53 | 16.96 | 16.60 | 16.41 | 17.71 | 17.76 | / | / | 101.96 |
| June 2011 | 15.61 | 15.63 | 13.93 | 15.14 | 16.50 | 16.26 | / | / | 93.06 |
| July 2011 | 17.41 | 18.53 | 17.58 | 17.64 | 17.50 | 17.75 | / | / | 106.41 |
| August 2011 | 16.25 | / | 16.37 | 16.29 | 16.37 | 16.26 | / | / | 81.54 |
| Total | 124.0 | 110.34 | 112.89 | 112.91 | 144.03 | 144.71 | 29.97 | 31.43 | 810.27 |

No survey effort is indicated by "/". "Fished", "Rarely fished" and "Low fishing effort" refers to the activity of the krill fishery in each survey block

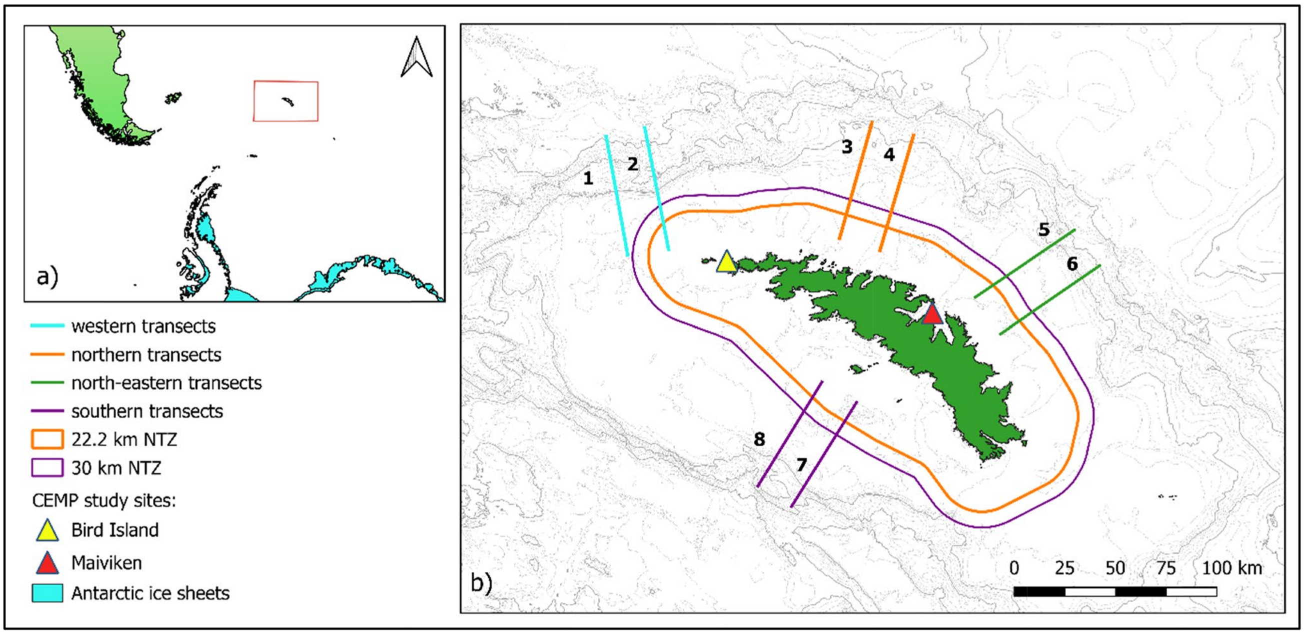



**Fig. 1** **a** Location of South Georgia in relation to the South American and Antarctic continents. **b** Winter survey transects around South Georgia shown in the four survey blocks, with individual transects labelled by number (see Table 1 for details). Current 30 km no-take zone (NTZ) shown in purple, pre 2018 NTZ (22.22 km; 12 nm) shown in orange. Note, all transects were designed to be orthogonal to the shelf-break. CEMP sites are shown by coloured triangles

2010 marginal visibility was recorded on transect 5 for approximately 30 min.

## Krill fishery data

Krill fishery catch data (including tonnes caught, location, dates) for Subarea 48.3 during winter 2010 and 2011 was obtained from the CCAMLR Secretariat (Data request 626). Krill catch data for Subarea 48.3 was plotted as raw data in QGIS and mapped in 25 km$^2$ blocks (5 km × 5 km) to create a heatmap of fishing effort over the two survey winters (2010 and 2011) to show location of fishing effort in proximity to survey transects and predator observations.

## Fishery activity

During 2010 and 2011 the krill pelagic trawl fishery in Subarea 48.3 was permitted to operate during the period from May 1st until October 30th (see Trathan et al. 2014). In 2010, the fishery caught 8,834 tonnes, with only 2 vessels operating over a period of approximately one month (11/05/10 to 09/06/10) (Fig. 2a). In 2011, the catch was 55,801 tonnes, with six vessels operational over a period of three and a half months (04/06/11 to 16/09/11) (Fig. 2b). The catch in 2011 was above the long-term mean (2000–2022) of 44,437 tonnes (CCAMLR 2023b; Fig. 2c). Fishing activity was primarily to the north-east of South Georgia, overlapping with transects 5 and 6 (north-eastern block). There was also an area of activity to the west of South Georgia in 2011, overlapping with transect 1 (western block). Krill fishery activity did not overlap with transect 2 to the west of South Georgia, or with the northern and southern transects.

## Spatial overlap between the krill fishery and predators

To calculate spatial overlap with predators the krill fishery area was defined in each month using the same grid of 5 km×5 km squares across the South Georgia area in QGIS as the fishery heatmap. Any grid-square containing krill fishing activity in a chosen month was considered part of the active krill fishery area for that month. Predator observations were assigned to the 5 km×5 km grid square the survey vessel was in when they were recorded. The number of animals inside and outside of the krill fishery area was then calculated per transect and month.

Observations of Antarctic fur seals were used to calculate spatial overlap with the fishery as they are krill-dependent predators (Croxall et al. 1985) with many females thought to remain within 500 km of South Georgia in the winter (Waluda et al. 2010; Bamford et al. 2021). Spatial overlap was also calculated for diving-petrels as the second most common taxa observed. Spatial overlap has been considered for gentoo penguins, as they remain in South Georgia

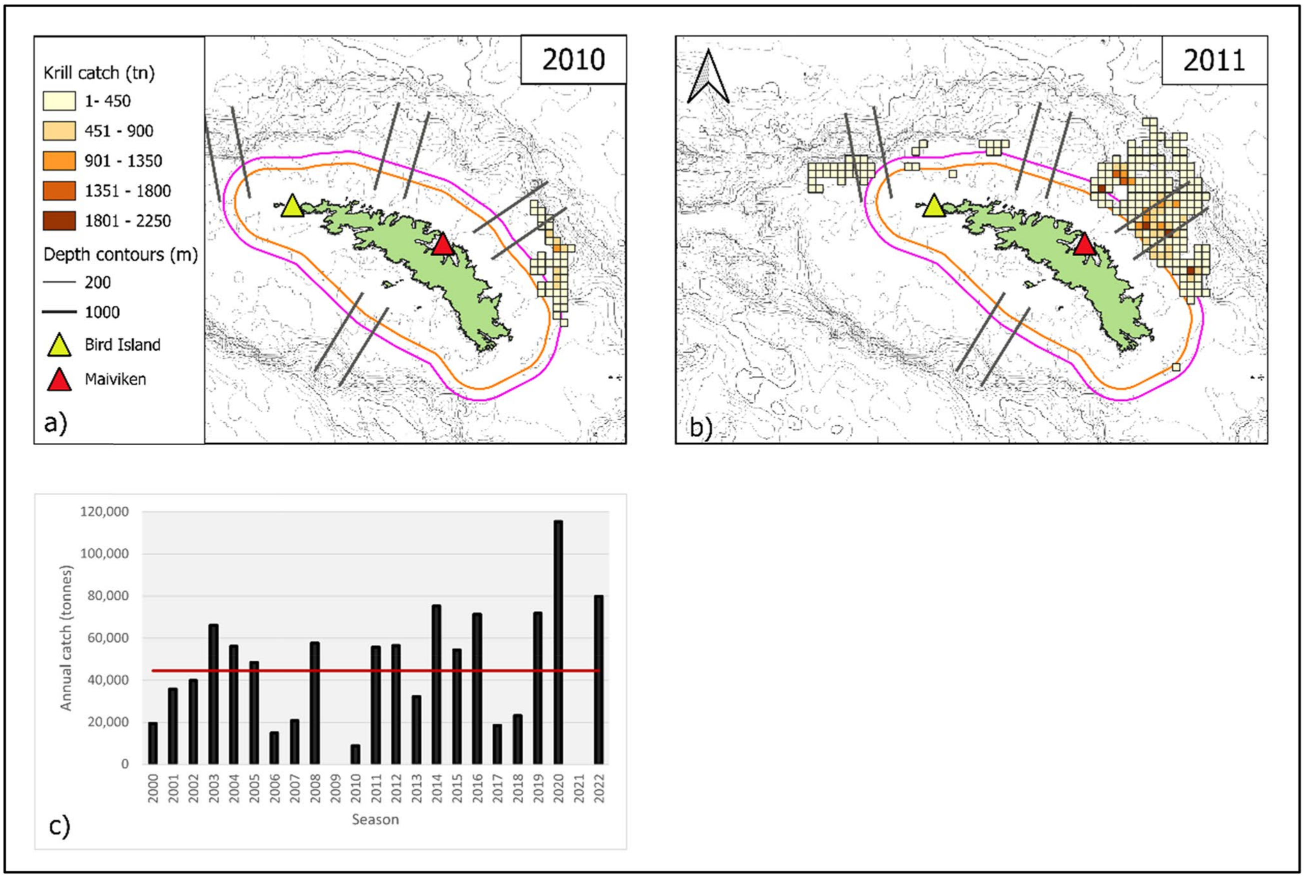



**Fig. 2** Activity of the Subarea 48.3 krill fishery in winter 2010 **a** and winter 2011 **b**. Data is plotted as krill caught (tonnes) per 5 km × 5 km square. Survey transects are shown in grey, with current 30 km no-take zone shown in purple, pre 2018 NTZ (22.22 km; 12 nm) shown in orange. Bird Island and Maiviken are shown by coloured triangles. **c** Annual krill catch in tonnes from Subarea 48.3 from 2000–2022 is shown, with the horizontal red line showing mean annual catch for the period 2000 to 2022 (CCAMLR 2023b). Note that catches in 2009 and 2021 were less than 1 tonne

waters after their breeding season with a relatively inshore distribution during the winter months (Tanton et al. 2004). We note that any overlap with the krill fishery would have been reduced following the extension of the NTZ around South Georgia to 30 km in 2018. Baleen whales have also been considered. Although many whales depart South Georgia in the winter, some are known to remain on the winter feeding grounds (Bamford et al. 2022). Should cetaceans return in large numbers to South Georgia waters they could be competing with the krill fishery for resources.

### Data analysis and mapping

All species distribution maps were produced in QGIS version 3.34.0. R studio was used to produce violin plots.

## Results

### Seabird and marine mammal observations

A total of 5,243 predator observations of 35 ‘species’ were made along transect, totalling 21,288 individuals (Supplementary Material, Table 1). Fur seals (presumed to be *Arctocephalus gazella*) and diving-petrels (*Pelecanoides* spp.) were the most commonly encountered taxa; 11 taxa had over 100 individuals sighted during the course of all surveys (Table 2). Species which were seen in low numbers during the survey include macaroni penguins ($N=2$), white-chinned petrels (*Procellaria aequinoctialis*; $N=40$), black-browed albatross ($N=38$) and grey-headed albatross (*Thalassarche chrysostoma*; $N=36$).

**Table 2** Number of individuals sighted (of the most frequently observed taxa) on the survey transects run in 2010 and 2011, displayed as transect totals. Total numbers observed across the survey are highlighted in bold

| Species | Western block (Fished) | | Northern block (Low fishing effort) | | North-eastern block (Fished) | | Southern block (Rarely fished) | | |
|---|---|---|---|---|---|---|---|---|---|
| | T1 | T2 | T3 | T4 | T5 | T6 | T7 | T8 | Total |
| Fur seals* | 1,040 | 1,884 | 1,450 | 727 | 2,525 | 2,076 | 8 | 13 | **9,723** |
| Diving-petrels * | 871 | 1,506 | 941 | 510 | 266 | 633 | 564 | 2,958 | **8,249** |
| Blue petrel* | 75 | 66 | 55 | 47 | 455 | 197 | 38 | 34 | **967** |
| Cape petrel* | 41 | 33 | 23 | 36 | 75 | 205 | 4 | 1 | **418** |
| Gentoo penguin* | 11 | 25 | 77 | 31 | 123 | 34 | 6 | 2 | **309** |
| Prion species* | 22 | 23 | 13 | 11 | 57 | 111 | 5 | 7 | **249** |
| King penguin | 20 | 27 | 14 | 11 | 40 | 122 | 10 | 0 | **244** |
| Antarctic tern* | 1 | 3 | 24 | 14 | 94 | 68 | 3 | 3 | **210** |
| Antarctic fulmar* | 19 | 34 | 11 | 9 | 42 | 54 | 0 | 1 | **170** |
| Black-bellied storm-petrel* | 5 | 13 | 16 | 13 | 17 | 8 | 1 | 33 | **106** |
| Kerguelen petrel* | 26 | 30 | 10 | 6 | 17 | 5 | 6 | 1 | **101** |

*Indicates species as krill consumers (Croxall et al. 1985)

## Fur seals

Fur seals were observed across the survey, with monthly and inter-annual variation (Figure 3). The number of fur seals sighted was much higher in 2011 ($N = 7{,}911$) than 2010 ($N = 1{,}812$), with larger groups of fur seals also more commonly observed. The largest aggregation of seals in both 2010 and 2011 was in the north-eastern block, but this comprised 70 individuals in August 2010, compared to 500 individuals in July 2011.

Fur seal density in 2010 was low across the winter, peaking in August at 11.2 per km$^2$, with similar densities seen on transects to the west (transect 1 = 20 per km$^2$) and the north-east (transect 6 = 19.3 per km$^2$). No surveying was conducted to the north in August. In 2011 fur seal density was relatively high in June (27.3 per km$^2$) with the highest transect densities to the north (transect 3 = 59.7 per km$^2$) and north-east (transect 6 = 58.4 per km$^2$) of South Georgia. Density then peaked in July at 34.5 per km$^2$. The highest transect density was to the north-east (transect 5 = 85.5 per km$^2$) followed by the west (transect 2 = 43.3 per km$^2$) of South Georgia. Density in August 2011 was lower than the preceding months, but still slightly higher than in August 2010 (Supplementary material; Table 2).

Overall, the highest fur seal densities by transect were observed in the survey blocks to the north-east and to the west of South Georgia (Supplementary material; Table 2). Transects to the south of the island were only surveyed in May and June 2010, but fur seal densities here were much lower than in the three northern survey blocks (Fig. 3).

Spatial overlap of fur seal observations with krill fishery activity was calculated per transect and month. However, to compare overlap between years and survey blocks a sub-set of this data has been used for all species overlap calculations. Data from the southern transects has been excluded, as these were not surveyed in 2011. Months where the krill fishery was not active have also been excluded. All of the north coast transects were surveyed when the krill fishery was active, with the exception of transect 2 in August 2011 (Table 3).

In total 31.76% of fur seals observed on the north coast overlapped with the krill fishery area when it was active. This varied markedly between years, with 1.67% of fur seals observed on the north coast spatially overlapping with the krill fishery in 2010, compared to 35.21% in 2011. Spatial overlap occurred primarily in June, July and August 2011 in the north-eastern survey block. In total 59.91% of fur seals observed to the north-east overlapped with the krill fishery area. Overlap also occurred to the west in August 2011 on transect one. There was no spatial overlap in the survey block to the north of South Georgia, with no fishing taking place in this region.

## Cetaceans

Cetacean numbers were low throughout the survey, but indicative of a winter presence. Along transect 33 individual cetaceans were observed, comprising seven species, with five individuals sighted in 2010 and 28 in 2011 (Fig. 4). Fin whales (*Balaenoptera physalus*) were the most commonly observed cetaceans ($N = 13$), followed by humpback whales (*Megaptera novaeangliae*) and hourglass dolphins (*Lagenorhynchus cruciger*) (both $N = 6$) (Table 4). Only one cetacean was observed on

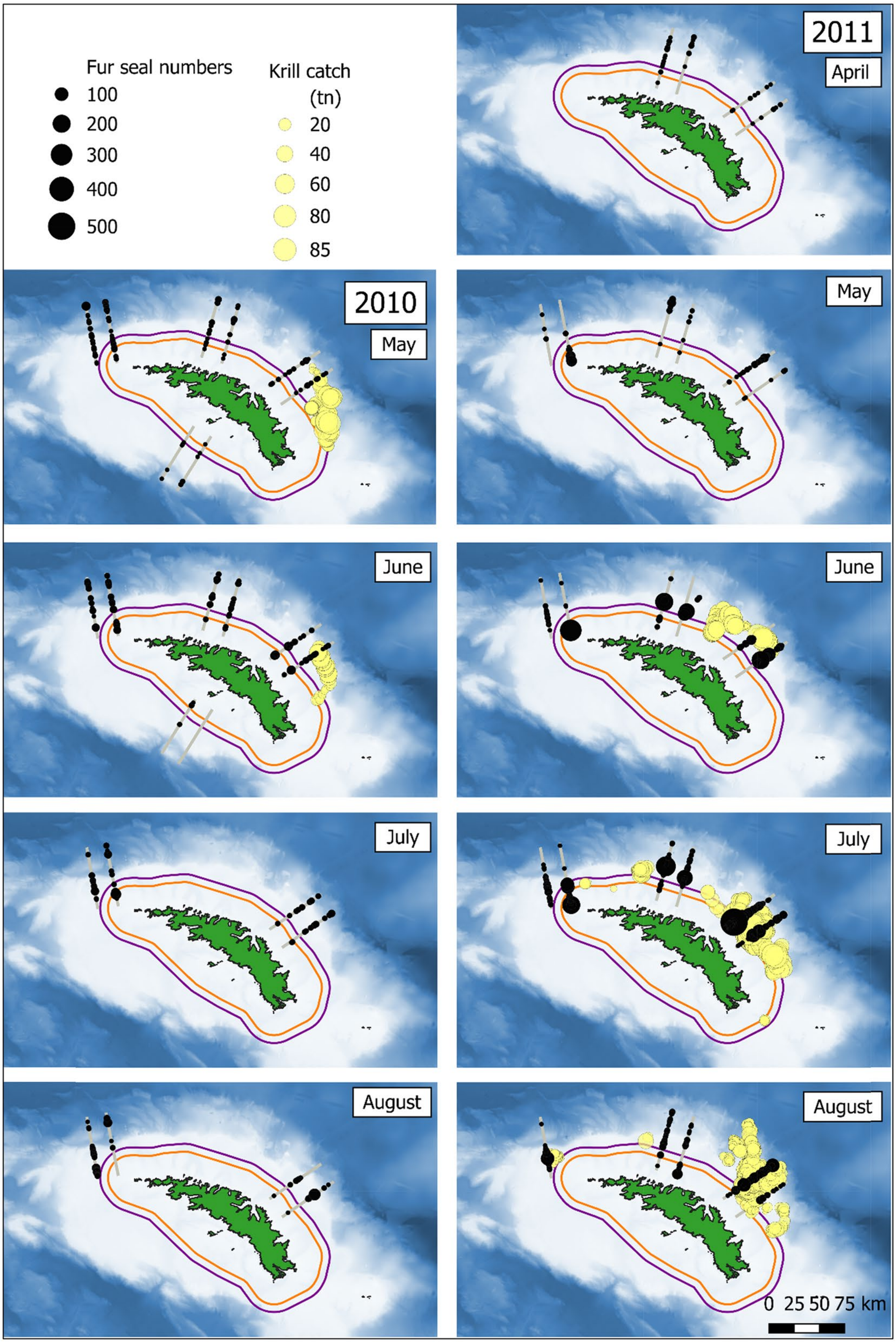



**Fig. 3** Seasonal distribution of fur seals on survey transects in winter 2010 and 2011. Transects shown in grey, current 30 km no-take zone (NTZ) in purple and pre-2018 (22.22 km; 12 nm) NTZ in orange. Activity of the krill fishery shown in pale yellow circles, with size representing catch in tonnes

the southern transects, however, survey effort here was considerably less than on the northern transects.

Ninety one percent of the baleen whales were observed in 2011 and all were observed on the north coast transects, with the majority in the northern survey block ($N=16$ out of 22). One southern right whale (*Eubalaena australis*) overlapped with the krill fishery area in July 2011 to the north-east of South Georgia.

### Gentoo penguins

Gentoo penguins were the most commonly observed penguin species, with 309 individuals recorded in 69 observations (Fig. 5a). A total of 80 gentoo penguins were recorded in 2010 and 229 individuals in 2011. Gentoo penguins were observed at the highest densities on transects in July and August 2011, in the north-eastern and northern blocks (Supplementary material; Table 6). Gentoo penguins were most commonly seen on the inshore end of survey transects, with 85.8% of total penguins within 30 km of land, but inter-annual variation was observed (Fig. 5b). Gentoo penguins were also recorded in higher densities when surveys were conducted inshore, off the transect lines, which are not accounted for in these numbers. During surveying 244 king penguins (*Aptenodytes patagonicus)* and two macaroni penguins were observed.

Spatial overlap between gentoo penguin observations and krill fishery activity was minimal and occurred on the north-eastern transects in 2011. On transect 6 in July one penguin was observed in the krill fishery area, with two penguins observed in the krill fishery area on transect 5 in August.

### Small burrowing petrels

With 8,249 sighted, diving-petrel species were the most commonly observed seabird taxa during the surveys (Table 1). Diving-petrels are difficult to separate unless in the hand (Payne and Prince 1979), so this category of 'at-sea' observations includes both common (*Pelecanoides urinatrix*) and South Georgia (*P. georgicus*) diving-petrels. In contrast to most other species, greater numbers were sighted in 2010 ($N=5{,}753$) than in 2011 ($N=2{,}496$) (Table 4).

Diving-petrels were present across all survey blocks but particularly abundant to the south of the island on transect 8 (Fig. 6); with a very high density (180.9 per km$^2$) recorded on this transect in June 2010. Transect 2 (to the west) had the highest density of diving-petrels on the north coast (Supplementary material; Table 3). The two southern transects were only surveyed in May and June 2010. Despite reduced survey effort in this region these southern transects accounted for 42.7% of all diving-petrels observed across the whole survey. Diving-petrels were present at the lowest densities on the two transects to the north-east.

In the months the krill fishery was active 6.6% of diving-petrel observations on the north coast overlapped with krill fishery activity. In 2010 this figure was 0.19% and in 2011 this figure was 14.81%. Overlap was almost entirely in the north-eastern survey box, with 43.58% of diving-petrels observed here overlapping with krill fishery activity in the months the fishery was active.

Blue petrels were the second most commonly observed seabird taxa, with 967 recorded during the surveys (Table 1; Fig. 6). Numbers sighted were higher in 2011 ($N=679$) than in 2010 ($N=288$). Blue petrels were observed across the surveys, but recorded in the highest densities on the two north-eastern transects in August 2011 (transect 5–23.1 per km$^2$) and June 2011 (transect 6 = 7.8 per km$^2$) (Supplementary material; Table 4).

### White-chinned petrel, black-browed and grey-headed albatrosses

Forty white-chinned petrels were observed during the surveys, one in 2010 and 39 in 2011. All observations were in April, May and June, with no sightings in July or August. Across both winters 38 black-browed albatrosses were observed, seven in 2010 and 31 in 2011, with sightings spread across all months. Thirty-six grey-headed albatrosses were observed, 24 in 2010 and 12 in 2011. Sightings were primarily in April and May, with two birds observed in June (Table 4). The winter distribution of these seabirds is significant as these species are susceptible to bycatch in longline fisheries (Collins et al. 2021).

## Discussion

Whilst the marine predators of South Georgia have been well studied in the summer months (e.g. Trathan et al. 2021), data on their winter distribution is limited (Black 2005) and comes mainly from tagging studies (Bamford et al. 2021; Ratcliffe et al. 2015; Staniland et al. 2012; Tanton et al. 2004). The addition of 'at-sea' data is valuable, as it can also account for populations/individuals from outside of the tagged South Georgia populations which use this area in the winter and other predators that are not constrained by land, such as cetaceans. The current study provides at-sea distribution data from the winter period when South Georgia's krill and Patagonian toothfish fisheries operate, with these fisheries restricted to winter to protect predators during the summer breeding period (Trathan et al. 2014; Collins et al. 2021). South Georgia's fisheries have the potential to interact with predators both directly (bycatch or incidental mortality), and indirectly (resource competition) during the winter months.

### Krill fishery

Antarctic krill are the primary prey for many of South Georgia's marine predators, including Antarctic fur seals (Reid 1995; Reid and Arnould 1996) gentoo and macaroni penguins and flying seabirds (Croxall et al. 1985), but krill abundance is highly variable in space and time. The South Georgia region is subject to "good" and "poor" krill years (Fielding et al. 2014), with the breeding performance of many of the land-based predators reduced in poor krill years (Croxall et al. 1999; Trathan et al. 2022).

During the two years surveyed here (2010 and 2011), there were contrasting levels of summer krill abundance and winter catch by the fishery. Fielding et al. (2014) analysed summer krill abundance from acoustic surveys undertaken to the north-west of South Georgia (in the "Western Core Box") over a 17-year time series, identifying summer 2009/10 as a period of low mean krill density (15.05 g $m^{-2}$), followed by a below average catch in the winter fishery of 8,834 tonnes (CCAMLR data). During 2010/11, mean krill density was higher in the austral summer (59.00 g $m^{-2}$) (Fielding et al. 2014) and fishery catches in the following winter were above average at 55,801 tonnes (CCAMLR data). These contrasting krill abundance values are reflected in the predator observations during these surveys, with higher numbers of fur seals, blue petrels, prion species, Antarctic terns, gentoo penguins, baleen whales, white-chinned petrels and black-browed albatrosses observed in 2011. This pattern was not seen with diving-petrels, cape petrels, Antarctic fulmars, black-bellied storm petrels or Kerguelen petrels, with higher numbers observed in 2010.

The South Georgia (CCAMLR Subarea 48.3) krill fishery is active along the northern shelf of South Georgia, but primarily focused on the shelf and shelf-break to the north-east (Fig. 2). Data from 2002 to 2018 shows that 75% of the Subarea 48.3 krill catch was taken from this north-eastern area (Trathan et al. 2021). Data from 2010 and 2011 shows a focus on this north-eastern area, with a larger spatial footprint of the fishery in 2011 than 2010. Whilst the CCAMLR krill catch limit is set in a precautionary manner, at the time of the surveys the CCAMLR catch limit of 279,000 tonnes was not allocated into smaller areas. Since 2021, the catch has been limited to 115,000 tonnes in each of three areas (East, West and Pelagic-Offshore). Despite this spatial allocation, the fishery continues to concentrate to the north-east of South Georgia and the total Subarea 48.3 catch has exceeded 70,000 tonnes in four of the last five seasons (CCAMLR 2023b). The majority of krill predators during this survey were observed in the highest numbers in the north-eastern survey block, even accounting for the extra survey effort in this region. The presence of an intensively fished hotspot to the north-east therefore has the potential to increase competition with South Georgia's krill eating predators.

### Antarctic fur seals

Antarctic fur seals are krill-dependent predators (Reid 1995; Reid and Arnould 1996), breeding on South Georgia during the summer months, with adult males dispersing from breeding sites from December/January onwards (Boyd et al. 1998) and females and juveniles departing from March/April onwards (Warren et al. 2006; Staniland et al. 2012; Bamford et al. 2021). Sightings data from the winter surveys presented here show fur seals to be present across the northern shelf of South Georgia during the winter, with seasonal and inter-annual variability in their distribution. Higher numbers of fur seals were observed in 2011 than in 2010, with densities higher in June, July and August, perhaps suggesting that fur seals forage elsewhere in April and May. Previous work by Boyd et al. (1998) reported that some males head south to the South Orkneys in December/January. Similarly, tagging and modelling studies suggest that whilst many females remain in the waters around South Georgia (within approx. 500 km) in the post-breeding period (Waluda et al. 2010; Bamford et al. 2021) some tagged animals visited the edge of the Antarctic sea ice and the Patagonian Shelf in the winter (Boyd et al. 2002, Staniland et al. 2012).

During these surveys fur seal densities were highest to the north-east and to the west of South Georgia, with the lowest densities observed on the southern transects. Whilst surveys of the southern transects were restricted to two months and just in 2010, only 21 seals were observed in total, suggesting low usage of the southern area at the time. Using habitat models based on tracking data Bamford et al. (2021) predicted high female fur seal occurrence across the northern shelf and shelf-break in winter 2003, a year when seals were more coastally distributed, with seals in 1999 associated with the northern and southern shelf areas, but also offshore regions. From tagging work at Bird Island Staniland et al. (2012) indicated that female fur seals remained within South Georgia waters during the winter and foraged to the west of Bird Island, although foraging area may be highly dependent on tagging location.

The high degree of spatial overlap between fur seals and the krill fishery to the north-east of South Georgia in winter 2011 (June–August) highlights a potential for competition. Overall, 31.76% of fur seals observed on the north coast in these surveys overlapped spatially with the krill fishery in the months it was active. Overlap was 1.67% in 2010, when fewer seals were observed and the krill fishery had a smaller footprint, compared to 35.21% in 2011, when there

**Table 3** Percentage of fur seals observed on the north coast spatially overlapping with the activity of the krill fishery in Subarea 48.3 by transect and month. Seal observations have been compared to the corresponding krill fishery area in each month to calculate spatial overlap. Bold text shows total overlap per transect in the months the krill fishery was active. *Indicates this figure is an overestimate, due to T2 not being surveyed in August 2011. "/" Indicates no surveying occurred

| Season | Western block | | Northern block | | North-eastern block | |
|---|---|---|---|---|---|---|
| | T1 | T2 | T3 | T4 | T5 | T6 |
| May-10 | 0 | 0 | 0 | 0 | 0 | 13.04 |
| Jun-10 | 0 | 0 | 0 | 0 | 0 | 11.22 |
| Jun-11 | 0 | 0 | 0 | 0 | 0 | 53.68 |
| Jul-11 | 0 | 0 | 0 | 0 | 70.07 | 80.78 |
| Aug-11 | 63.96 | / | 0 | 0 | 62.41 | 53.52 |
| Overall transect | **21.16** | **0** | **0** | **0** | **59.89** | **59.94** |
| Survey block | 7.11* | | 0 | | 59.91 | |

Seal observations have been compared to the corresponding krill fishery area in each month to calculate spatial overlap

*Indicates this figure is an overestimate, due to T2 not being surveyed in August 2011

"/"Indicates no surveying occurred

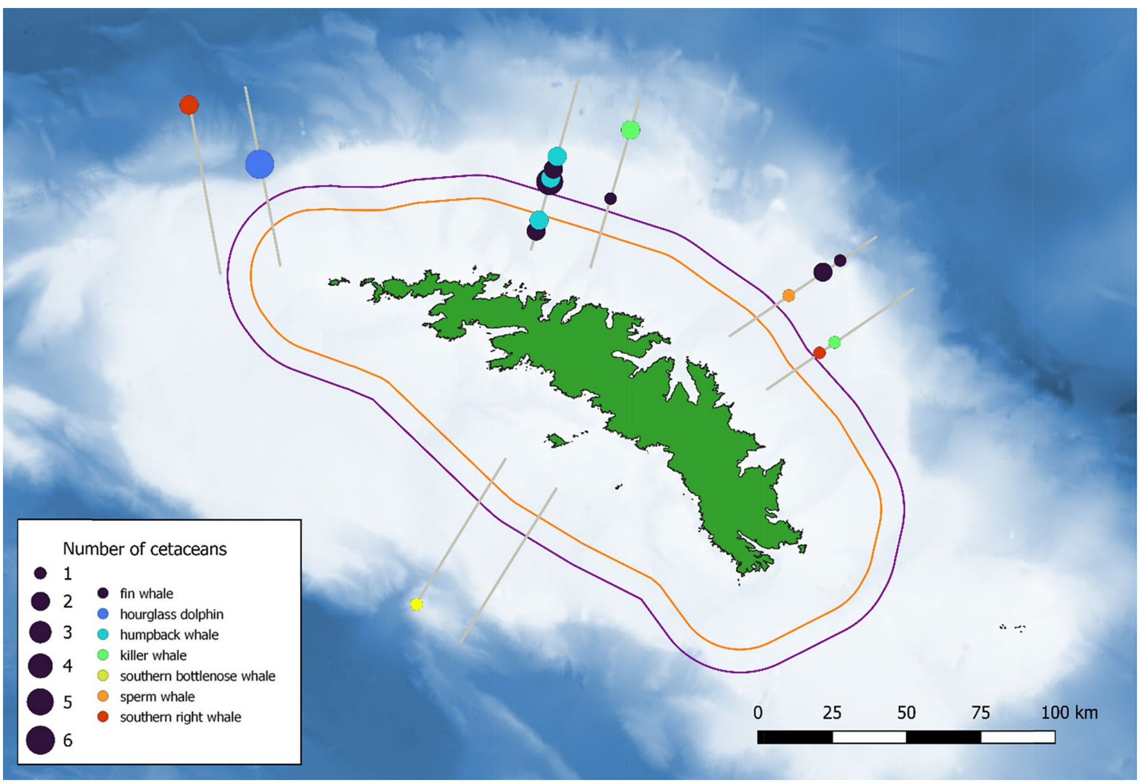



**Fig. 4** Cetacean observations around South Georgia in winter 2010 and 2011, survey transects shown in grey. Current 30 km no-take zone (NTZ) shown in purple and pre-2018 NTZ (22.22 km; 12 nm) shown in orange. $N = 33$ individuals from 16 observations

were higher numbers of seals and the fishery had a larger spatial and temporal footprint. Spatial overlap in the north-eastern survey box was 59.91%, with the only other overlap to the west in August 2011. Bamford et al. (2021) considered the whole South Georgia area and at a > 50% modelled likelihood of fur seal occurrence, found the Subarea 48.3 krill fishery (1999–2019) to spatially overlap with 7.5% of the predicted area used by fur seals in years of greater seal dispersion and up to 21.9% in years when seals were more coastally distributed.

The population of fur seals at Maiviken, a colony on the mainland close to the north-east fishing hotspot, has been

**Table 4** Seasonal observations of selected species (common names) around South Georgia on survey transects in winter 2010 and 2011

| Species | 2010 | | | | 2011 | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| | May | June | July | August | April | May | June | July | August | |
| Fur seals | 289 | 571 | 347 | 605 | 58 | 537 | 2,537 | 3,676 | 1,103 | 9,723 |
| Fin whale | 0 | 0 | 0 | 0 | 7 | 2 | 4 | 0 | 0 | 13 |
| Hourglass dolphin | 0 | 0 | 0 | 0 | 0 | 6 | 0 | 0 | 0 | 6 |
| Humpback whale | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 0 | 0 | 6 |
| Killer whale | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 2 | 3 |
| Southern right whale | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 3 |
| Southern bottlenose whale | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Sperm whale | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| Gentoo penguins | 28 | 24 | 6 | 22 | 32 | 2 | 10 | 116 | 69 | 309 |
| Diving-petrels | 1,533 | 3,528 | 371 | 321 | 491 | 803 | 617 | 439 | 146 | 8,249 |
| Blue petrels | 134 | 81 | 37 | 36 | 9 | 56 | 141 | 57 | 416 | 967 |
| Black-browed albatrosses | 5 | 0 | 0 | 2 | 9 | 5 | 3 | 4 | 10 | 38 |
| Grey-headed albatrosses | 22 | 2 | 0 | 0 | 2 | 10 | 0 | 0 | 0 | 36 |
| White-chinned petrels | 0 | 1 | 0 | 0 | 30 | 3 | 6 | 0 | 0 | 40 |

studied since 2008 as part of the CEMP program, which should allow fishery effects to be detected. Trathan et al. (2021) did not find a significant relationship between the magnitude of the krill catch and either the number or mass of fur seal pups at Maiviken the following January. In a good krill year both the fishery and fur seals appeared to do well. In years with particularly low abundance of krill (e.g. 2009) the fishery is limited, as vessels are not able to catch efficiently and either move to other areas or cease fishing for the season. It is possible therefore that competition may be the strongest in years of medium krill abundance, when the fishery and predators are both competing for limited resources, though this will be more difficult to detect.

## Gentoo penguins

Gentoo penguins are krill-dependent predators (Croxall et al.1985) although across their geographic range their diet can show more flexibility than other krill consuming penguins (Handley et al. 2015). The gentoo penguin breeding season on South Georgia can last from October until March (Trathan et al. 2014) varying between years. Post-breeding gentoo penguins remain in South Georgia waters during the winter, with a relatively inshore distribution (Tanton et al. 2004). The initial 22.2 km (12 nm) NTZ around South Georgia was extended to 30 km in 2018 to provide greater protection for foraging gentoo penguins (Handley et al. 2020; Ratcliffe et al. 2021). During our survey gentoos were predominantly observed on the inshore ends of survey transects, with 85.8% of penguins within 30 km of land, consistent with their primarily coastal winter distribution (Tanton et al. 2004). This may be an underestimate of inshore gentoo numbers, as transects started at least 10 km offshore. A predominantly inshore distribution of gentoo penguins means direct spatial overlap with the krill fishery will be reduced. Very few macaroni penguins ($N=2$) were sighted during surveying, consistent with their dispersal away from South Georgia during the winter months (Green et al. 2005) reducing the potential for competition with the winter krill fishery (Ratcliffe et al. 2015). Low numbers may also partly reflect the fact that penguins are not as easy to detect as flying seabirds and larger mammals during at-sea surveys.

In years with a lower abundance of krill, competition posed by the fishery to krill eating penguins may increase, as they travel further from shore to meet their nutritional requirements (e.g. Croxall et al. 1999; Waluda et al. 2010). Waluda et al. (2010) showed breeding macaroni penguins foraged further from their colonies, dived deeper and switched prey in 2004, a year when krill abundance was low during summer but increased in autumn. Ratcliffe et al. (2021) showed gentoo penguins undertook longer multi-day foraging trips in 2018, when krill availability was low, compared to 2001, when krill density was higher and penguins made short single day foraging trips. In our study 2010 was considered a 'poor' krill year and a higher percentage of gentoo penguins were recorded over 30 km from land (32.5%) than in 2011 (7.9%), however, only 80 individuals were observed in 2010, with sightings still on the inshore end of survey transects. Spatial overlap between gentoo penguins and the krill fishery was very limited during these surveys. No spatial overlap occurred in 2010, when the fishery had a smaller spatial footprint. In 2011 only three of the gentoo penguins observed overlapped with krill fishery activity, all on the north-eastern transects in July and August.

Competition between the krill fishery and South Georgia's predators, including gentoo penguins, may not be limited to direct spatial overlap. Fishing for krill further offshore may

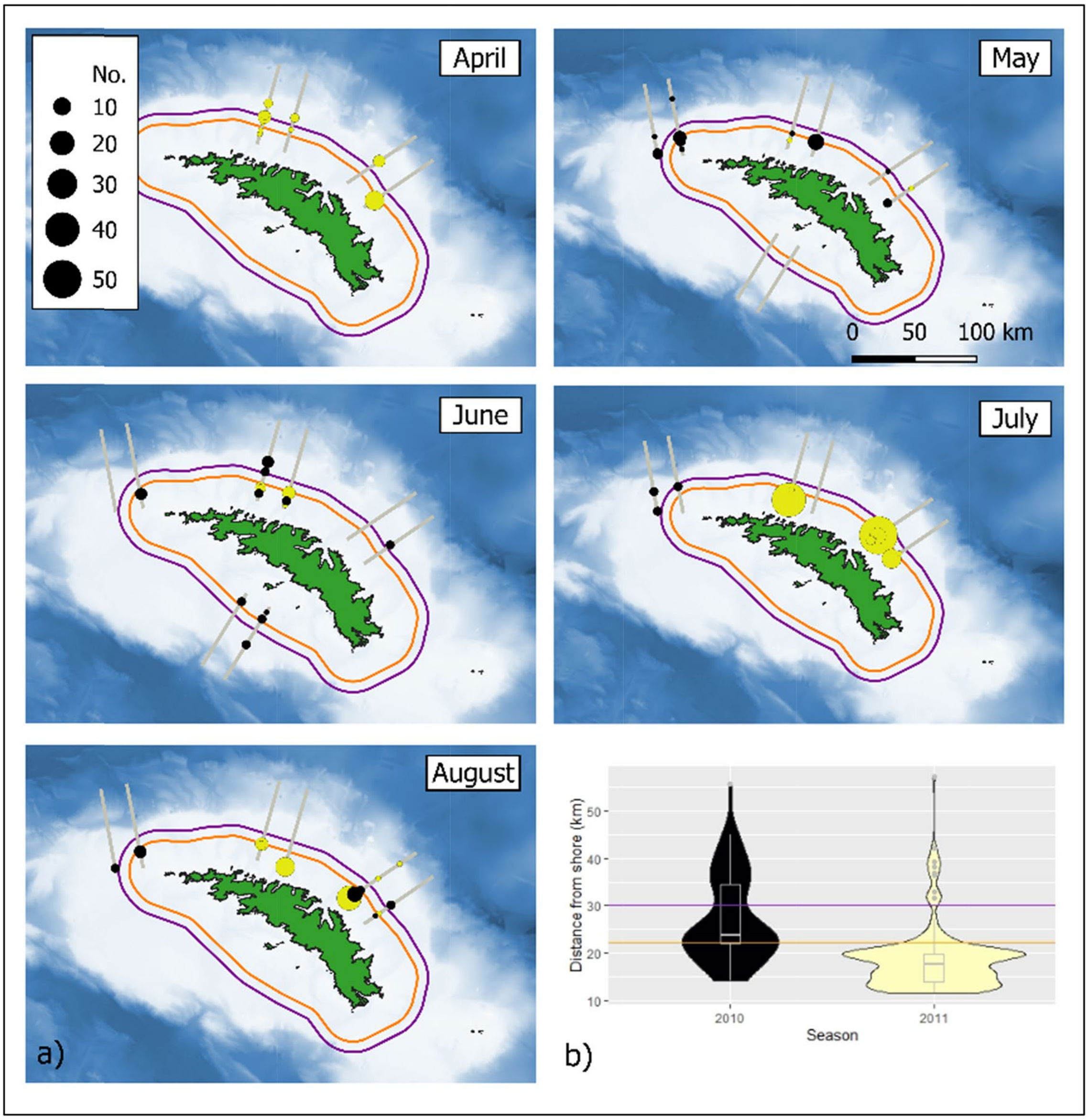



**Fig. 5** **a** Seasonal distribution of gentoo penguins in winter 2010 (black) and 2011 (yellow) from survey transect observations. Survey transects are shown in grey. **b** Violin plot of distance (km) from shore of gentoo penguin observations from South Georgia in winter 2010 ($n=80$, colour = black) and 2011 ($n=229$, colour = yellow) with boxplot inset (thick line = median value). Transects all started 10 km or more from the land. On both plots current 30 km no-take zone (NTZ) is shown in purple and pre-2018 NTZ (22.22 km; 12 nm) is shown in orange

reduce the biomass of krill which would otherwise have been advected in ocean currents onto the shelf where inshore species are feeding. Trathan et al. (2021) analysed breeding data from the gentoo penguin colonies at Maiviken and Bird Island and found the number of nesting pairs to be the only metric of breeding success showing a possible relationship with the previous fishing season, where low nest numbers followed a less productive winter season. It is difficult to draw conclusions from the relatively small number of gentoo penguins observed during our surveys, but the primarily inshore observations support the effectiveness of the current 30 km NTZ at reducing spatial overlap with the krill fishery.

The current study clearly highlights the north-east shelf and shelf-break as a possible area of concern for competition between the fishery and krill predators, particularly if krill catches increase in the future. The continued monitoring of study colonies of both fur seals and gentoo penguins at Maiviken should be well placed to reflect this, including further analysis of breeding performance in good and bad krill years. In addition, conducting more regular predator surveys at sea is recommended, which would provide very valuable data on the winter distribution of not only seals and penguins, but also krill feeding cetaceans.

## Cetaceans

Cetacean sightings in the current study were relatively low, with only 33 individuals sighted on transect across the two winters. The majority (> 90%) of baleen whales were observed in winter 2011, likely reflecting the greater abundance of krill compared to 2010, supported by higher densities of krill observed during the preceding summer (Fielding, et al. 2014) and higher fisheries catches in the winter (CCAMLR data). All baleen whale observations were on the north coast, with the majority on the transects in the northern survey block. Krill fishery activity is lower in the northern survey block than the north-eastern or western blocks. Only one southern right whale spatially overlapped with the krill fishery, this was to the north-east in July 2011.

Whilst a considerable proportion of the baleen whale population return to breeding grounds at lower latitudes, there is evidence that some individuals remain on the feeding grounds over winter (e.g. Bamford et al. 2022), but there is very limited winter data. Recent work points to the return of humpback and blue whales (*Balaenoptera musculus*) to South Georgia since our surveys took place. For example, visual surveying in summer 2020 recorded 58 blue whale sightings in South Georgia waters (Calderan et al. 2020) and Jackson et al. (2020) noted a marked increase in both sightings and group sizes of humpback whales since 2013. Future surveys looking at the winter distribution of whales in South Georgia waters are now underway (https://www.bas.ac.uk/project/winter-krill-at-south-georgia/) and will provide valuable data, particularly for management of the krill fishery, which has the potential to compete with large baleen whales for resources.

## Toothfish longline fishery

Understanding the distribution of South Georgia's predators is also important for the toothfish fishery, as vulnerable seabirds may interact with the fishing gear, or the vessels themselves. Mitigation measures in South Georgia's fisheries, primarily to protect albatross and petrels, have proved very effective, nearly eliminating bycatch during fishing operations (Collins et al. 2021). These measures include: seasonal closure of the fishery, night setting, weighted lines, bird exclusion devices, restrictions on offal discharge and better hook management (Collins et al. 2021).

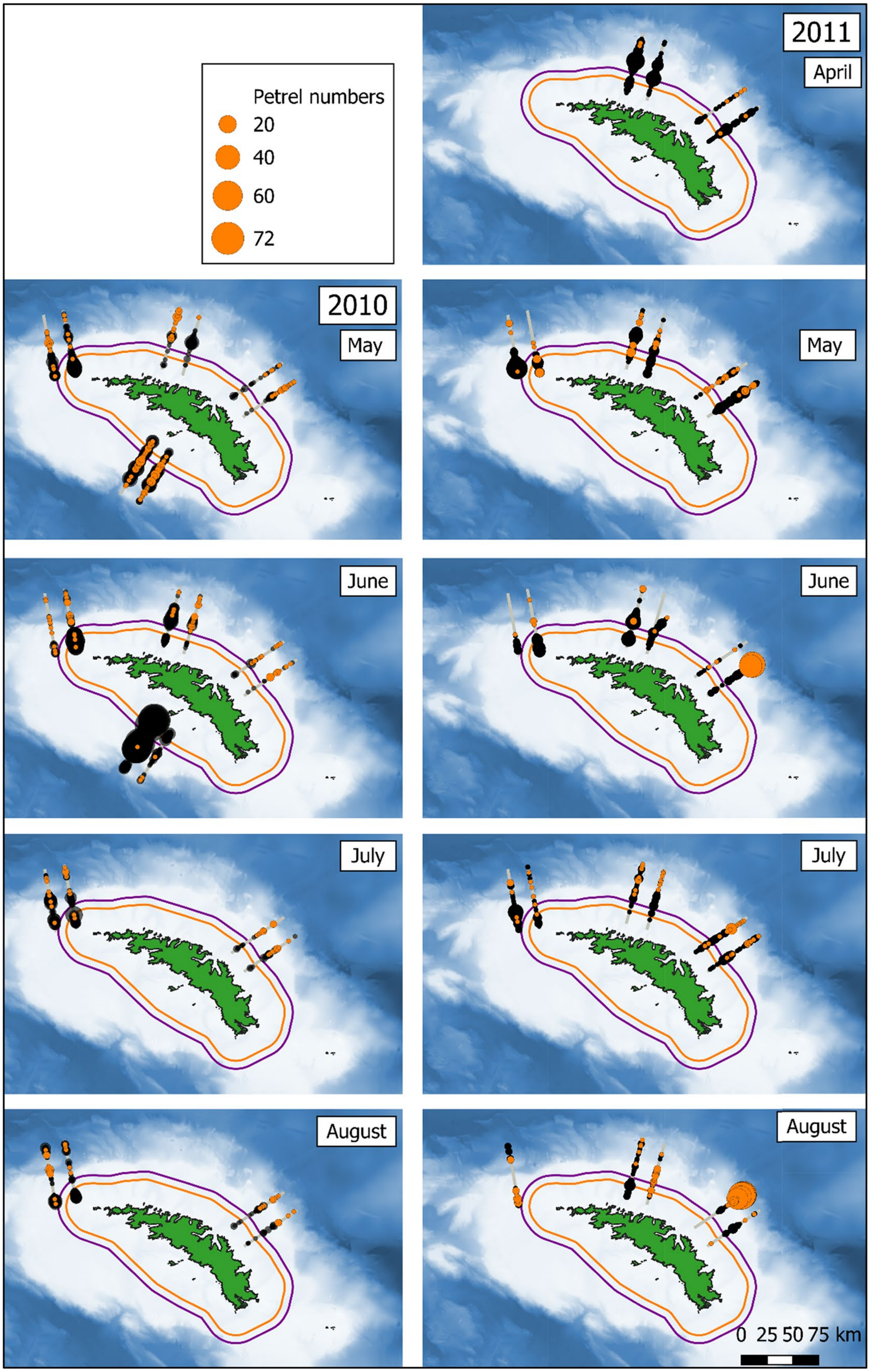
The longline fishery operated from April 26th until August 31st in 2010 and from April 21st to August 31st in 2011. In these two years the fishing season was experimentally and incrementally extended into late April, having previously begun on May 1st (see Collins et al. 2021). The toothfish fishery is limited to depths of 700 to 2,200 m (Trathan et al. 2014), with most effort in waters of less than 1,750 m. Longline effort is distributed around South Georgia and Shag Rocks in this depth range, see Bamford et al. (2024; Fig. 7) for the mapped distribution of the longline fishery around South Georgia 1997–2021. Catch has been approximately 2,000 tonnes per year since 2011 (CCAMLR, 2023c).

## Species vulnerable to bycatch

White-chinned petrels (IUCN 2024a: Vulnerable), black-browed albatross (IUCN 2024b: Least Concern) and grey-headed albatross (IUCN 2024c: Endangered) breed on South Georgia and are susceptible to bycatch in long-line fisheries. The current South Georgia toothfish fishery start (May 1st) has been set to allow the post-breeding dispersal of these vulnerable birds from South Georgia waters (Phillips et al. 2005, 2006; Croxall et al. 2005). Results from this study suggest that few white-chinned petrels and grey-headed albatross overwinter within the South Georgia region, which should mean that direct fisheries interactions will be limited. A potential exception to this is black-browed albatrosses, with observations most common in April and August but spread across all months (Table 4). Numbers observed during the winter were still low when compared to the summer months however (Collins, pers obvs). Overall data from this survey supports the winter dispersal of these vulnerable species.

## Small burrowing petrels

The two diving-petrel species in South Georgia waters were grouped together in observations here. There are distinct differences between the species, with Payne and Price (1987) showing them to utilise different breeding habitats and exhibit different timings to their breeding season on Bird Island. However, tracking of a small number of diving petrels from Bird Island suggests that populations utilise similar areas overwinter, remaining both around South Georgia and also using an area 3,000 km to the east north-east (Navarro et al. 2015) although more winter data is needed. During these surveys diving-petrels (*Pelecanoides* spp.) were the most commonly observed seabird taxa; 8,249 individuals were observed with 3,522 of these on the south coast, largely due to the very high numbers observed on transect 8. The next most abundant small burrowing taxa were blue petrels (967 observed) and prion species (249 observed, with an additional 23 identified fairy prions (*Pachyptila turtur*)). Tracking data from the same project (Navarro et al. 2015) showed blue petrels to utilise Antarctic waters in the Atlantic and Pacific outside of the breeding season, with Antarctic prions using sub-Antarctic waters


Petrel numbers
20
40
60
72
2011
April
2010
May
May
June
June
July
July
August
August
0 25 50 75 km

◂**Fig. 6** Seasonal distribution of diving-petrels (black) and blue petrels (orange) in winter 2010 and 2011 from survey observations. Survey transects are shown in grey, with the current 30 km no-take zone (NTZ) shown in purple and pre-2018 NTZ (22.22 km; 12 nm) shown in orange

to the east of the Patagonian shelf. Data from this survey appears to support the winter dispersal of these taxa.

Diving-petrels were present throughout the winter in all survey blocks, but the southern transects accounted for 42.7% of all diving-petrels observed, despite only being surveyed in two months. The highest densities on the north coast were recorded to the west on transect 2. With the southern transects only occupied for two months in 2010, it is difficult to interpret these observations. However, circumstantial evidence may help explain the observation. Burrowing petrels are particularly susceptible to rodent predation and this apparent disparity between the north and south might be explained by the fact that, in contrast to the north coast, a large area of the south coast, including Annenkov Island, was rodent-free at the time of our study (Martin and Richardson 2019). Additionally, the outlying islands to the west of South Georgia, the closest land to transect 2, were also rodent free.

Blue petrels and prions were observed in much lower numbers across the survey than diving-petrels and particularly high abundances on the south coast were not observed. With South Georgia now considered rodent-free, further surveys of burrowing petrels, including contemporary comparisons between the north and south coast, would be particularly useful.

### Vessel strikes

The high number of diving-petrels observed during surveying, particularly on the south coast in 2010 suggests they may be at high risk of vessel strikes in the winter. The operation and transit of fishing vessels at night means deck lights, navigation lights and sometimes ice lights are required, increasing bird attraction to the ships and increasing the risk of vessel strikes. Coleman et al. (2022) detailed four bird strike events between 2004 and 2021 along the south coast of South Georgia, all involving high numbers of burrowing petrels, with diving-petrels (*Pelecanoide*s spp.) the most common and suffering the highest mortalities. Reporting of bird strikes from vessels is not uniform or complete, but diving-petrels represented 53% of all live bird strikes and 50% of fatal bird strikes reported to GSGSSI between 2017 and 2022 (GSGSSI unpublished data). Current reports are likely to be an underestimate of total bird strikes and a new reporting system is being trialled to encourage and standardise bird strike reporting across all sectors in South Georgia waters (see https://www.darwininitiative.org.uk/project/DPLUS143/).

## Conclusion

In conclusion, this study represents an important step towards understanding the distribution of South Georgia's predators in the winter months, which is critical for identifying any conflict with the Subarea 48.3 fisheries, changes in their winter distributions and understanding the possible future impacts of climate change. The results from this study clearly highlight the north-eastern shelf and shelf break as an area of possible competition between the krill fishery and predators in winter and further work is needed to explore this.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s00300-024-03257-6.

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**Authors contribution** PT, MC and AB designed the study. AB, JA and AW collected the data. KO mapped the data. KO, MG and MC drafted the paper. PH, CW and PT contributed to data interpretation and edited the manuscript. All authors read and approved the final version for publication.

**Data availability** The survey data presented here is available in the Polar Data Centre (https://doi.org/10.5285/a271c430-739f-44a2-9fb0-29404740a625). Krill fishery data came from CCAMLR data request 626.

## Declarations

**Competing interests** The authors declare no competing interests.

**Conflict of interests** None of the authors have any conflicts of interest.

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