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Distribution and biomass estimation of Antarctic krill (*Euphausia superba*) off the South Orkney Islands during 2011–2020

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Antarctic krill is a key species in the Southern Ocean and subject to the most extensive fishery in the Antarctic. The Norwegian Institute of Marine Research has conducted acoustic-trawl monitoring of krill off the South Orkneys annually since 2011 in collaboration with the krill fishing industry. Average krill biomass within the 60000 km^2 survey area ranged from 1.4 to 7.8 million tonnes in the period 2011–2020, strongly supporting that this is among the regions in the Scotia Sea with consistently highest krill densities. There were no significant ($p \approx 0.18$, non-parametric Mann–Kendall test) monotonic trends in estimated krill biomass over the 10 years. The highest krill densities were associated with the shelf edge and submarine canyons on the north side of the South Orkneys. Our comparison with the CCAMLR 9.3% reference exploitation rate suggests that management of the krill fishery in the South Orkneys region is precautionary. The monitoring is run on fishing vessels, so e.g. acoustic frequencies applied could not always be in compliance with the standard CCAMLR methodology. Estimated deviance in krill backscatter when comparing 38 kHz to the standard 120 kHz ranged from −1.1% to 12.8%. Our results show that industry-based surveys are cost-efficient approaches to high-quality monitoring of krill.

Keywords: acoustics, bathymetry, CCAMLR, industry-based survey, LSSS, acoustic-trawl survey.

Introduction

Antarctic krill (*Euphausia superba*) (hereafter krill) are extremely abundant in the Southern Ocean (Atkinson *et al.*, 2009), and are also by far the most harvested resource in Antarctic waters. During the past decade, commercial landings have more than doubled and are now exceeding 450000 tonnes per year (CCAMLR, 2021). The fishery is mainly constrained to the Scotia Sea in the South Atlantic sector of the Southern Ocean, more specifically to shelf areas off the South Shetland Islands and Bransfield Strait, the South Orkney Islands, and South Georgia.

Krill is preferred and often essential prey for a range of fish, pinnipeds, cetaceans, and seabirds (Trivelpiece *et al.*, 1987; Kock *et al.*, 1994; Reid and Arnould, 1996; Croxall *et al.*, 1999; Friedlaender *et al.*, 2006). The key ecosystem role of krill and increasing commercial interest were the main reasons for the founding of the Commission for the Conservation of Marine Living Resources (CCAMLR), which is responsible for the management of the krill fishery. CCAMLR has established a precautionary catch level for krill in the Southern Ocean at 5.61 million tonnes (CCAMLR, 2010a) based on a krill yield model in combination with the abundance estimate from an international acoustic krill monitoring survey conducted in the Scotia Sea in 2000 (Hewitt *et al.*, 2002). However, due to incomplete knowledge about the potential local effects of the harvest, especially upon krill-dependent predators, the current total allowable catch (trigger level) is set at 620000 tonnes (Hill *et al.*, 2016). This level reflects the historical maximum krill catch the system has sustained, without evident harmful impact. The total allowable catch is distributed among four CCAMLR fisheries subareas (CCAMLR Subarea 48.1: the South Shetland Islands and Bransfield Strait; Subarea 48.2: the South Orkney Islands; Subarea 48.3: South Georgia; and Subarea 48.4: the South Sandwich Islands; CCAMLR Conservation Measure 51-07, https://www.ccamlr.org/en/organisation/convention-area). Of the four subareas, the South Orkney Island Subarea has developed to be the most important fishing area in terms of both biomass of harvested krill and the number of participating vessels (CCAMLR, 2021).

Comprehensive krill abundance monitoring surveys in the Scotia Sea like the one providing the fundament of the precautionary catch level have only been undertaken on two occasions 19 years apart (Watkins *et al.*, 2004; Krafft *et al.*, 2021). Given the large effort involved in conducting such surveys, frequent recurrence cannot be expected. Regional surveys, on the other hand, can provide regular updates about krill abundance, distribution, and population characteristics. There has been annual krill monitoring in Subarea 48.3 since 1996 carried out by the British Antarctic Survey (BAS; UK) (Fielding *et al.*, 2014; Trathan *et al.*, 2022), and krill monitoring in Subarea 48.1 has previously been carried out by the US Antarctic Marine Living Resources program as part of multidisciplinary efforts near the South Shetland Islands (Reiss *et al.*, 2008, 2017).

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Table 1. Overview of survey vessels, dates, acoustic frequencies available, coverage, and frequencies used for the swarm detection (for acoustic identification of krill) and acoustic integration for biomass estimates.

Year	Vessel	Survey dates	Frequencies available	South stratum	North stratum	Shelf edge stratum	Frequency for swarm detection	Frequency for integration
2011	FV Saga Sea	4–8 February	38, 120	X*	X*		120	120
2012	FV Juvel	26–29 January	70, 120	X*	X*		120	120
2013	FV Saga Sea	25–29 January	38 120		X**		38	120
2014	FV Saga Sea	24–30 January	38 120	X	X		38	38
2015	FV Juvel	9–12 February	38, 70	X**	X	X	38	38
2016	FV Saga Sea	10–15 February	38, 120	X	X		120	120
2017	FV Saga Sea	6–11 February	38, 120	X	X		120	120
2018	FV Juvel	4–10 February	38, 70, 120	X	X		120	120
2019	RV Kronprins Haakon	30 January–4 February	18, 38, 70, 120, 200, 333	X	X	X	120	120
2020	FV Saga Sea	5–10 February	38, 120	X	X	X	38	38

*Transects slightly shorter than those for later years.
**Coverage limited due to sea ice.

Starting in 2011, the Institute of Marine Research (IMR; Norway) has carried out annual surveys in Subarea 48.2 off the South Orkney Islands. These are acoustic-trawl surveys using fishing vessels as research platforms (Hill *et al.*, 2016; Watkins *et al.*, 2016; Krafft *et al.*, 2018). The vessels are equipped with scientific trawls and calibrated quantitative echo sounders allowing for acoustic abundance estimates according to scientific standards (Watkins *et al.*, 2016). Nonetheless, different acoustic frequencies have been available, so data collection could not be done in full compliance with the CCAMLR recommendation for krill monitoring surveys (CCAMLR, 2017). In addition, the standard computer program for processing acoustic data implemented in CCAMLR could not be used. Therefore, we needed to adapt alternative processing methods and analyses to the data in order to attain a coherent time series, and then evaluate whether it is comparable to other CCAMLR survey series.

An aim of this study was therefore to consolidate the acoustic-trawl survey data from the first 10 years of the continued IMR krill monitoring program (2011–2020). We evaluate the uncertainty introduced by using non-standard data collection and processing methods. We then use the resulting dataset to assess annual variability in krill abundance and distribution off the South Orkney Islands and investigate whether there are trends in abundance. Finally, we use the results to appraise whether the krill fishery in CCAMLR Subarea 48.2 is precautionary on a regional scale.

Material and methods

Survey area, design, and coverage

The ten annual surveys described here have been conducted from late January to early February in the years 2011–2020 (Table 1). The survey timing is chosen early in the fishing season to minimize the potential impact of commercial fishing on krill abundance before the survey, but late enough that the risk of sea-ice coverage in the survey area is acceptable. The survey follows a random stratified parallel transect design and a randomly set starting point. The starting point was set in the first year and then maintained throughout to avoid the potential variable annual impact of non-random geographical features such as bathymetry on the estimated krill distribution and abundance.

The present survey grid consists of a south and a north stratum each including five transects along the longitudes 47.5°W, 46.5°W, 45.75°W, 45°W, and 44°W (Figure 1). The south stratum area is 32142 km^2 and comprises most of the shelf area south of the South Orkney Islands, while the north stratum area is 28218 km^2 and covers the fishing areas along the shelf to the north of the islands, as well as areas east and west of the shelf, which are potentially important drift paths for krill (Murphy *et al.*, 2004). During the first year of monitoring, a sixth transect was visited to the west of T1 and the north–south limits were at 60°S and 61.75°S, respectively. In 2012, the north–south transects were extended north to 59.67°S, and the westernmost transect was removed. In 2014, the southernmost waypoints were moved south to 62.00°S. Since 2014, the design has remained the same. The survey grid takes 4–5 days to complete under normal operational conditions with monitoring both day and night (Table 1).

In addition, the small shelf edge stratum at 2368 km^2 inside the north stratum has been covered with a denser transect grid during three of the years subject to weather conditions and available vessel time. The shelf edge stratum covers the locations with the highest historical krill catches. The acoustic sampling effort is higher than that in the main strata, with average transect spacing of the north–south oriented parallel lines of ~15.6 nautical miles, but otherwise the design is the same. This small stratum takes about 24 h to complete. (The start and end points of all transects are found in Supplementary Appendix A.)

Survey area coverage (Figures 1 and 5) was complete in all years except for 2013 and 2015, when the coverage was severely hampered by sea ice south of the islands.

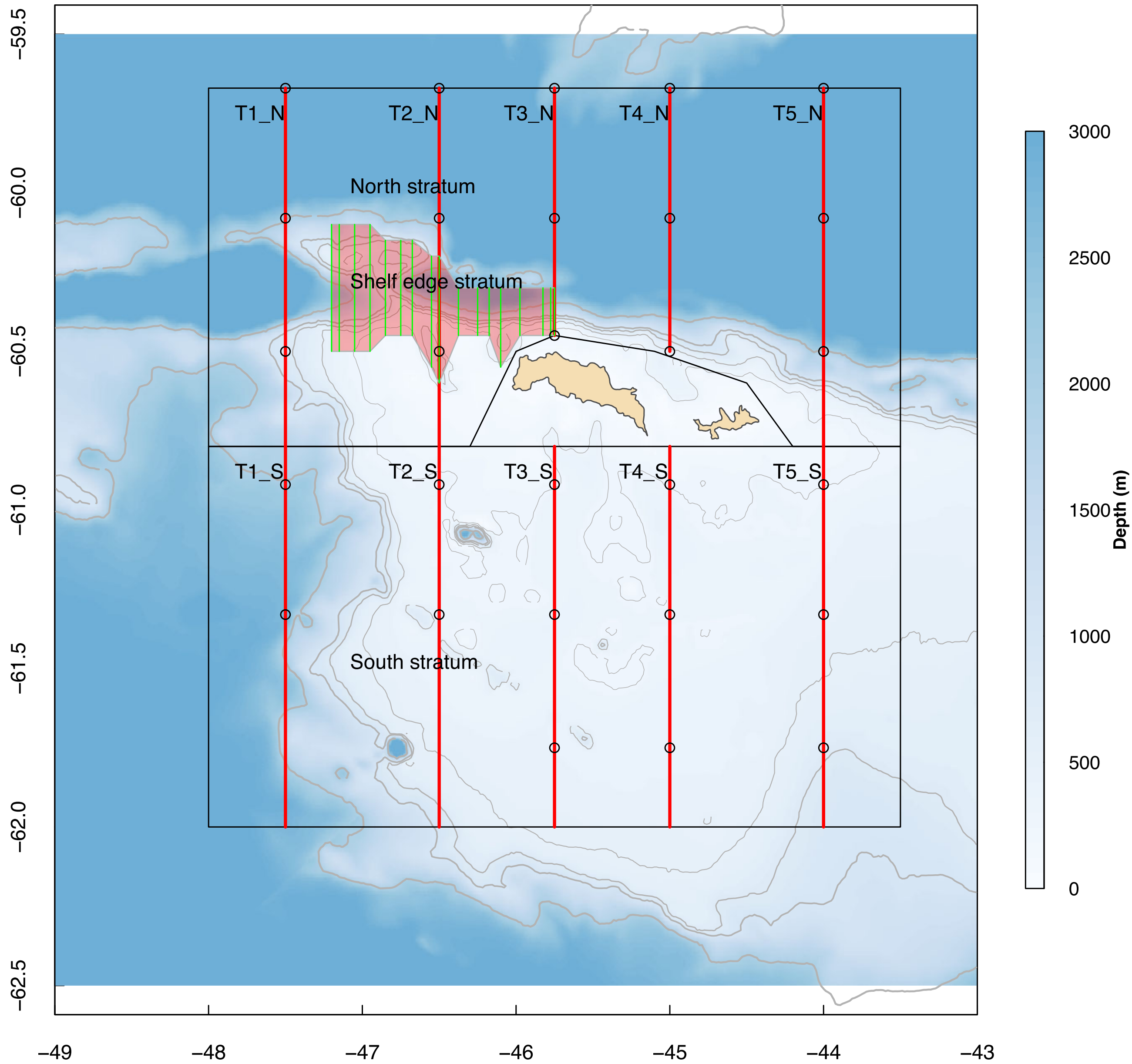

Figure 1. Strata and transects for the Norwegian Institute of Marine Research South Orkney Island survey from 2011 to 2020. The dots mark the positions for trawl sampling, which are fixed. Note that the south-western part of the coverage area is within a protected area where trawling is not allowed.

Vessels

The survey has been conducted in collaboration with the Norwegian krill fishing industry using the fishing vessels "Saga Sea" (Aker Biomarine ASA) and "Juvel" (Olympic Seafood AS; later Aker Biomarine ASA) (Table 1). The monitoring survey is a mandatory part of the Norwegian license to access the krill fishery in the Southern Ocean. In 2019, the Norwegian research icebreaker RV "Kronprins Haakon" (KPH) surveyed as part of the large-scale international krill monitoring effort in CCAMLR area 48 (Krafft *et al.*, 2021).

Acoustic data collection

The fishing vessels were equipped with Simrad ES60 echo sounders, and the research vessel KPH used Simrad EK80 echo sounders. The available frequencies differed between vessels and are listed in Table 1. The ship's ES60 General Purpose Transceivers (GPTs) were replaced with scientific EK60 GPTs for all frequencies when available. All frequencies were calibrated as per normal procedures for sphere-based echo sounder calibration (Demer *et al.*, 2015). The calibrations were carried out in Antarctic waters except in 2011 when it was carried out off Punta del Este (Uruguay; Table 2). During surveys, the echo sounder was operated with a ping interval of 1 s. Occasionally, ping interval requirements could not be met due to the system settings and a larger interval was used (up to 2 s). In the processing, the acoustic absorption coefficients were set to 10 and 27.7 dB km^{-1}, respectively, for 38 and 120 kHz in accordance with Hewitt *et al.* (2004). Pulse length was set to 1.024 ms and power to 2000 and 250 W for 38 and 120 kHz, respectively. We set the sound speed to values in the range 1450–1456 m s^{-1} based on CTD-casts at the calibration site. Nominal vessel speed was 5.1 m s^{-1} during the

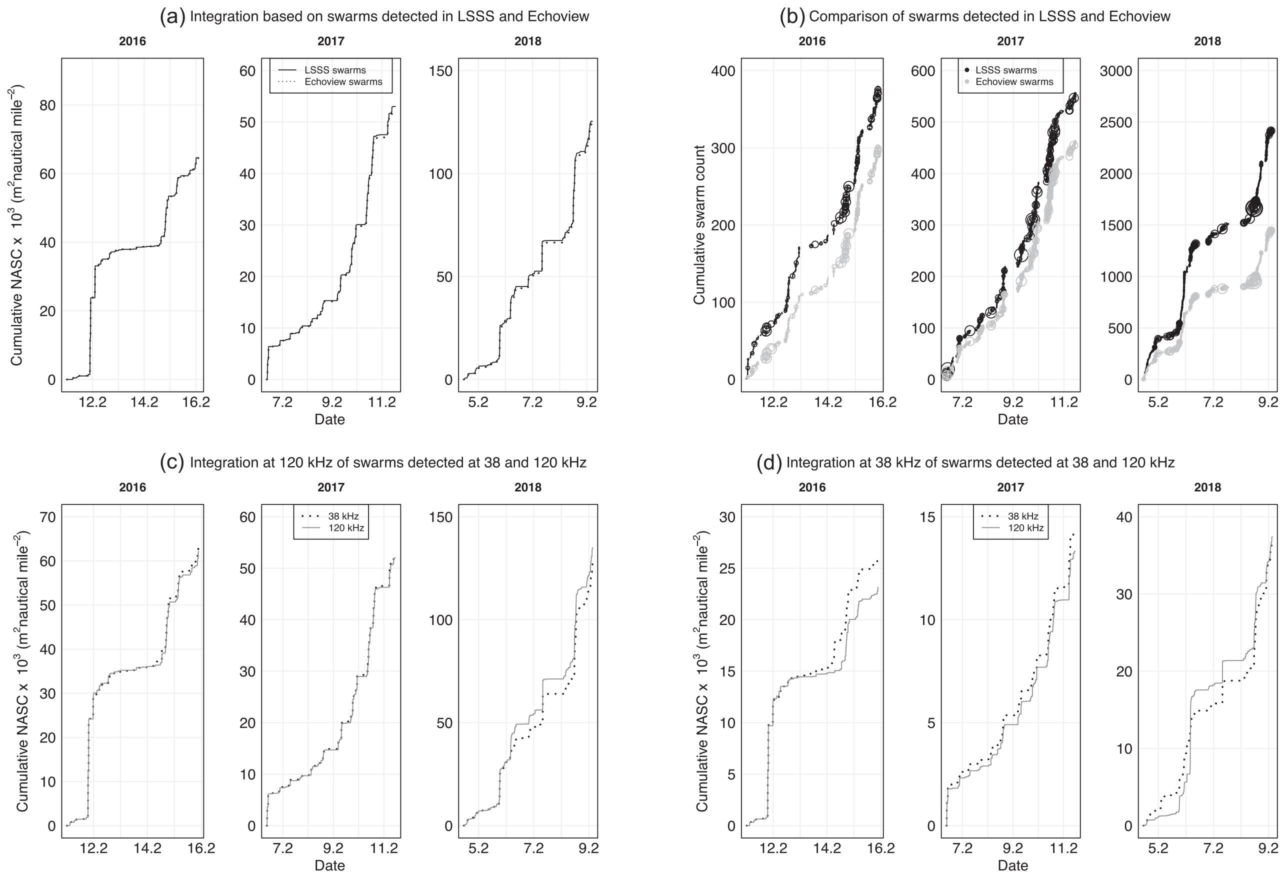

Figure 2. (a) Cumulative NASC integrated in Echoview from swarms delineated in LSSS (solid line) and Echoview (dashed line). The differences in cumulative sums are 0.2, 1.2, and 1.3%, respectively, for the years 2016, 2017, and 2018. (b) Cumulative swarm count using the LSSS (black dots) and the Echoview (grey dots) swarm-based templates over the course of the survey years 2016–2018. The size of each circle corresponds to the swarm NASC. The integration here is done with the Echoview template. The differences in number of detected swarms between LSSS and Echoview are 25, 20, and 66% for the survey years 2016, 2017, and 2018, respectively. (c) Cumulative NASC at 120 kHz from swarms detected at the 38 kHz (black dashed lines) and 120 kHz (grey solid lines). Both sets of swarms are integrated on the 120 kHz data for the survey years 2016–2018 using LSSS. (d) Cumulative NASC at 38 kHz of swarms detected at 38 kHz (black dashed lines) and 120 kHz (grey solid lines). Both sets of regions are integrated on the 38 kHz data for the survey years 2016–2018 using LSSS.

survey. Acoustic data were set to be logged to 750 m depth on all available frequencies, but only data up to 250 m (or just above the seabed where more shallow) were processed for the krill biomass estimation.

Biological data collection

Trawl hauls were carried out at predefined positions spaced 20 or 25 nautical miles apart along the transects, using a Macroplankton trawl with a nominal mouth-opening of 36 m^2 and a mesh size of 7 mm from the trawl-opening to the codline (Krafft *et al.*, 2018). Trawl doors were used to spread the trawl when the survey was carried out on board "Juvel" in 2012 and KPH in 2019, otherwise the trawl mouth was spread by a 6-m wide beam [see Krafft *et al.* (2018) for a drawing of the trawl and rigging]. In 2013, the scientific trawl was not available, and a commercial trawl was used for sampling. This trawl had a 400 m^2 mouth-opening and an inner net mesh size of 16 mm on the side walls from mouth to cod line. The mesh size of the codend was 11 mm. On each station, the trawl, equipped with a depth sensor (Marport™, Reykjavik, Iceland), was lowered from the surface to 200 m depth (or ~20 m above the seafloor if the water was shallower than 200 m) and then hauled at ~1.0 m s^{-1}. A subsample of approximately 200 individuals was taken from the catch for length measurements. Krill body length was measured (± 1 mm) from the anterior margin of the eye to the tip of telson excluding the setae, according to the "Discovery method" used in Marr (1962).

Acoustic data processing

Acoustic discrimination of krill

To derive krill abundance estimates from acoustic recordings, the portions of the acoustic backscatter originating from krill must first be recognized and allocated to krill. CCAMLR recommends a protocol of automated steps to enable reproduction of results and avoid the subjectivity of manual scrutiny (CCAMLR, 2017). The current standard according to the recommendation is to use predicted differences in krill frequency response between 38 and 120 kHz and between 120 and 200 kHz to distinguish krill from other scatterers for biomass estimation purposes. However, data from all of these frequencies are not always available and an alternative approach applying detection and delineation of swarms (swarm-based approach) according to a set of criteria for discrimination of krill has been developed (CCAMLR, 2017). CCAMLR has implemented the standard swarm-based approach for krill

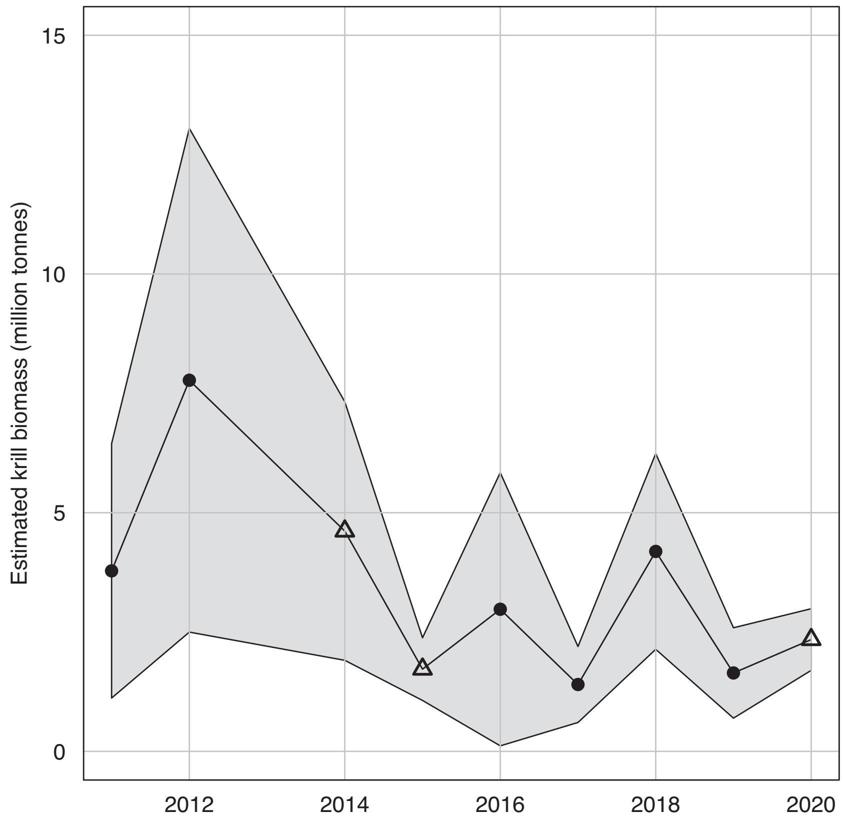

Figure 3. South Orkney Islands krill biomass estimates for 2011–2020. The shaded area marks the 95% confidence interval (±1.96∗SE) around the mean based on the Jolly and Hampton estimator using the transects as the primary sampling unit. Years with swarm detection and integration done at 38 kHz are marked with triangles. The other estimates are based on 120 kHz data. The 2013 estimate is not included due to poor survey coverage.

discrimination on 120 kHz data using an Echoview work template, which includes noise removal filters, a swarm detection filter, and an integration module (CCAMLR, 2017). The Echoview swarm detection and delineation algorithm, which is applied in the CCAMLR swarm-based approach, is based on a body of published work (e.g. Barange, 1994; Coetzee, 2000).

In this work, we adopt the swarm-based approach and we implement swarm detection using the Large Scale Survey System (LSSS) computer program (Korneliussen *et al.*, 2016). Since the use of LSSS deviates from standard implementation, we compared the output of LSSS (LSSS version 2.8.0) to the output when using the CCAMLR Echoview template (Echoview version 8.0). In addition, we did the swarm detection on 38 kHz data in 4 out of the 10 survey years, and integration on 38 kHz data in 3 of the years as 120 kHz was either unavailable or the data were too noisy to be used (see Table 1). We therefore compared swarm detection at 38 and 120 kHz to evaluate the potential effect of applying the swarm-based approach to different frequencies. For the comparisons of swarm detection in different computer programs and at different frequencies, we used the surveys from the years 2016, 2017, and 2018. These were all years with full survey coverage, with both 38 and 120 kHz echo sounders available and with different distributions of krill swarms. More details of set-up and processing are found in Supplementary Appendix B.

Biomass estimation of krill

After the discrimination of krill, the backscatter allocated to krill was converted to biomass. The backscatter to biomass conversion requires accurate estimates of the mean target strength of individual krill. Since scattering from individual krill is highly non-linear, the conventional linear regression between logarithm of body length and acoustic target strength, typically used for fish, can be inaccurate (Stanton *et al.*, 1994; Demer and Martin, 1995). Instead, models of krill target strength use physical representations of the krill body under a given set of parameters taking into account krill body composition and/or behaviour (Stanton and Chu, 2000). The Distorted Wave Born Approximation acoustic scattering model (DWBA) (Stanton and Chu, 2000; Demer and Conti, 2005) with stochastic enhancements (SDWBA) (Conti and Demer, 2006; CCAMLR, 2010b; Calise and Skaret, 2011) has been adopted by CCAMLR for biomass estimation. Following the CCAMLR protocol, the model is used to estimate target strength based on a given set of parameters defining krill morphology, structure, and behaviour (see Table 3 in Krafft *et al.*, 2021 for parameter settings used).

Target strength prediction and conversion to biomass

The nautical area scattering coefficients (NASC, m^2 nautical $mile^{-2}$) (MacLennan *et al.*, 2002) allocated to krill were converted to biomass density ($g\,m^{-2}$) using full SDWBA model runs to estimate the spherical scattering cross-section (σ_{sp}) for all 1-mm krill length groups present in the sample according to the formula

$$\sigma_{sp} = 4\pi 10^{TS/10} \qquad (m^2 \text{ per krill}).$$

The predicted spherical scattering cross-sections were used to calculate weighted conversion factors (CF) from NASC

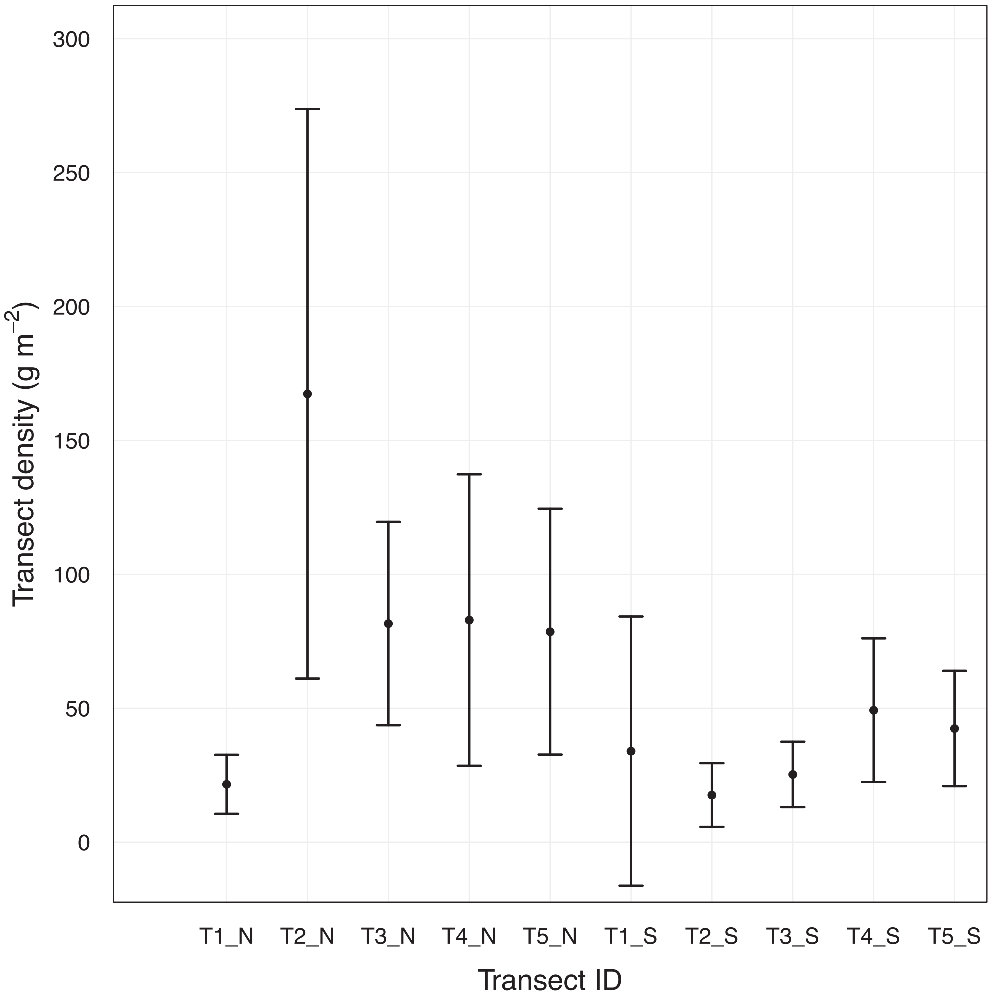

Figure 4. Mean krill density per transect in 2011–2020 with bars indicating 95% confidence bands (±1.96∗SE). The overview of transects is shown in Figure 1.

values to biomass density:

$$\mathrm{CF} = \left[\sum f_i \cdot W\left(TL_i\right)\right] / \left[\sum f_i \cdot \sigma_{sp}\left(TL_i\right)\right],$$

where f is the frequency of occurrence of a specific length group (i), TL_i is the total length of the specific length group (i) in mm, $\sigma_{sp}(TL_i)$ is the spherical scattering cross-section area at total length TL_i, and $W(TL_i)$ is wet weight at the specific length group (i) in gram, which was calculated following Hewitt *et al.* (2004):

$$W\left(TL\right) = 2.236 \cdot 10^{-6} \cdot TL^{3.314} \ \ (\mathrm{g}).$$

The krill acoustic scatter was then converted to its biomass density (ρ) using the following equation:

$$\rho = \mathrm{NASC} \cdot CF \cdot 1852^{-2} \qquad \left(\mathrm{g\ krill\ per\ m^2}\right).$$

Our methodology thus approximately follows CCAMLR standards, with the main difference being the acoustic frequency used as the basis for swarm delineation and biomass estimation in some of the years (Table 1).

Estimation of biomass

Based on the average biomass density for each echo-integration interval, a biomass density for each transect could be calculated weighted according to the length of the transect, and a sampling variance was estimated for each stratum and for the north and south strata combined based on the averages of each transect according to Jolly and Hampton (1990). The original transect length was always used for the weighting even if there was deviation in the track due to ice coverage.

In order to evaluate whether there was any trend in the biomass estimates over time, a Mann–Kendall non-parametric trend test for autocorrelated data modified according to Hamed and Rao (1998) as implemented in the "mmkh" function in the R package "modifiedmk" (Patakamuri and O'Brien, 2021), was used.

Estimation of exploitation rate

We used the annual biomass estimates to calculate a krill exploitation rate for the surveyed area based on the approach used in Hill *et al.* (2016). The exploitation rate is there simply estimated as total catch in CCAMLR Subarea 48.2 divided with estimated biomass in our survey area. Following Hill *et al.* (2016), we also calculated a subarea exploitation rate as maximum allowed subarea catch (trigger catch) at 0.279 million tonnes divided by subarea biomass estimated as survey area biomass scaled up with a factor of 3.17. The scaling of 3.17 corresponds to the biomass estimate for the entire Subarea 48.2 derived from the CCAMLR 2000 survey (24.6 million tonnes) divided by maximum esti-

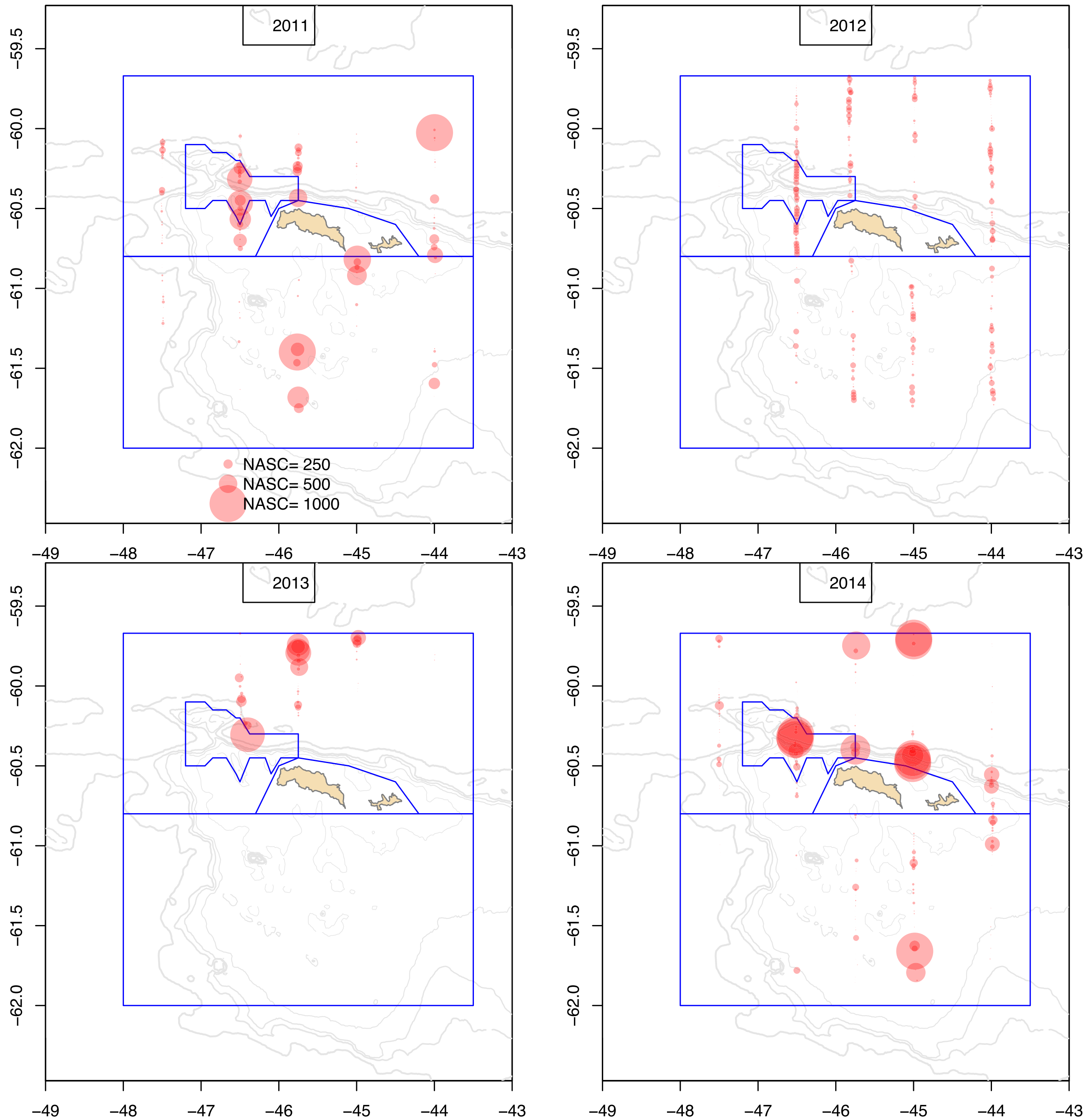

Figure 5. *Continued.*

mate from the present South Orkney survey series (7.77 million tonnes estimated for 2012). Even though the estimation methods used are different for the CCAMLR 2000 survey and the present survey series, they are comparable (Krafft *et al.*, 2021), and the scaling of 3.17 can be viewed as a conservative upscaling of the survey area biomass to subarea biomass (Hill *et al.*, 2016). Results from the more recent large-scale krill monitoring survey in 2019 (Krafft *et al.*, 2021) would have been relevant to use for the upscaling, but subarea biomass estimates are not provided there. We use an exploitation rate of 9.3% per year as a reference point to evaluate whether a given harvesting level is precautionary. This level of exploitation is intended to reserve sufficient production of krill to maintain predator populations (Hewitt *et al.*, 2002; Hill *et al.*, 2016), and was revised by CCAMLR in 2010 (CCAMLR, 2010a).

Results

Comparison and evaluation of acoustic processing methods

The two computer programs for acoustic processing assessed here (LSSS and Echoview), have differing implementations of swarm detection and delineation. Our comparison of NASC integration at 120 kHz based on the swarm detections in the two programs, showed that the cumulative NASC was consistently slightly lower when swarms had been detected with LSSS than with Echoview; 0.2, 1.2, and 1.3% lower for the

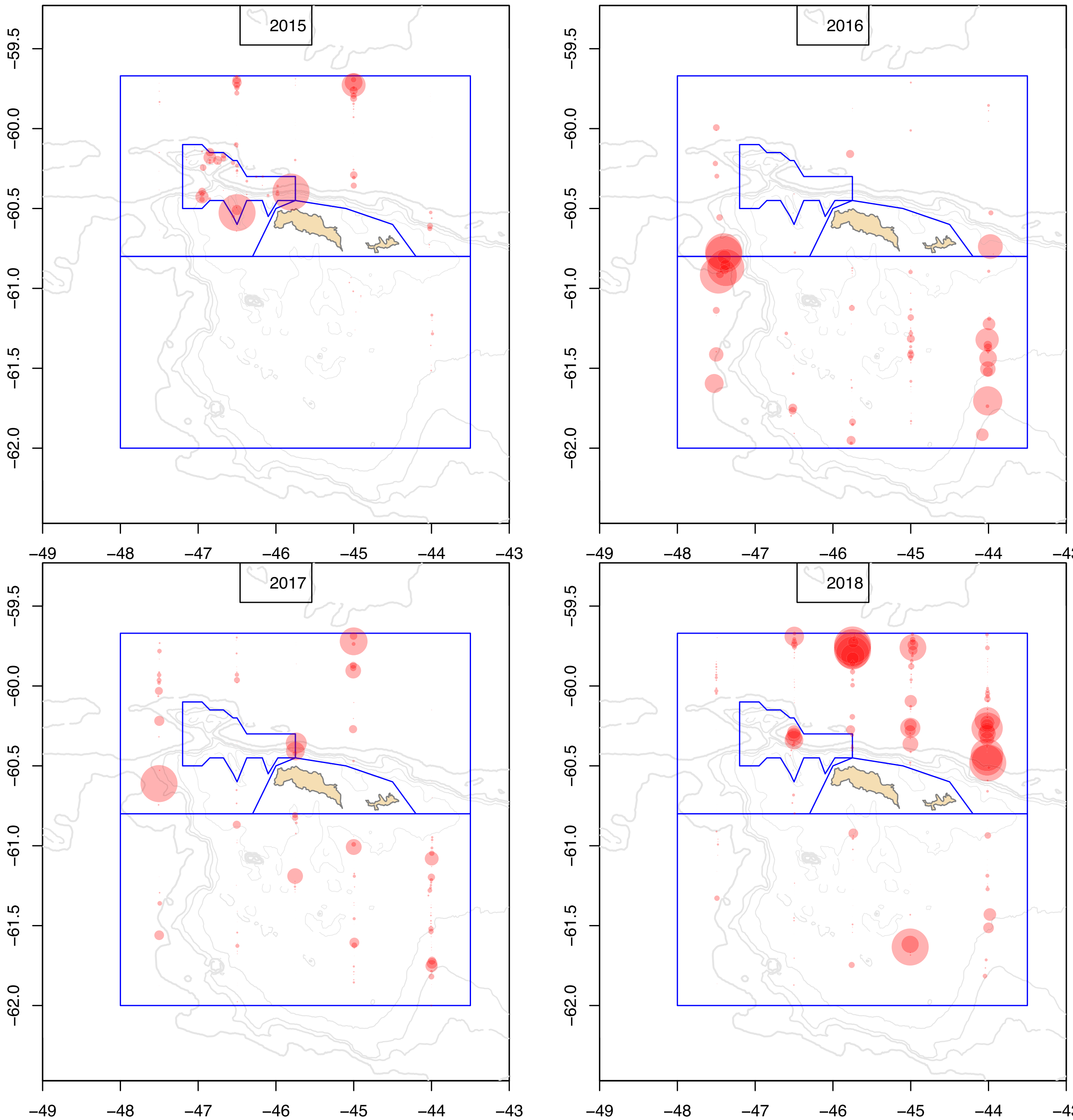

Figure 5. *Continued.*

years 2016, 2017, and 2018, respectively (Figure 2a). In this case, the integration is done in Echoview, so the difference comes from differences in implementation of swarm detection only. But there was also some deviance between the outputs from the two programs due to how integration is done close to excluded echogram regions. The deviance decreased with increasing resolution of the integration, and at 0.1 nautical miles, the cumulative integrated NASC from LSSS was 1.2, 0.2, and 0.5% higher for the years 2016–2018 than integrated NASC from Echoview (Figure A1 in Supplementary Appendix B).

The two computer programs detected large swarms similarly, but LSSS generally detected numerically more swarms than Echoview; 25, 20, and 66% more swarms for the years 2016, 2017, and 2018, respectively (Figure 2b). In LSSS, neighbouring swarm segments are not linked like they are in Echoview. By reducing the vertical swarm linking distance in Echoview from 5 to 0.5 m for the 2018 data (horisontal linking distance could not be altered much without resulting in discontinuities at the ping boundaries), the number of swarms detected increased with 32%, so this differing implementation in the two computer programs is likely the main contributor to the differences in numbers of swarm counted.

In our survey time series, swarm detection needed to be done at 38 kHz in 4 of the years, and integration in 3 of the years (see Table 1). Since 120 kHz is the frequency recommended by CCAMLR to use for krill monitoring, a

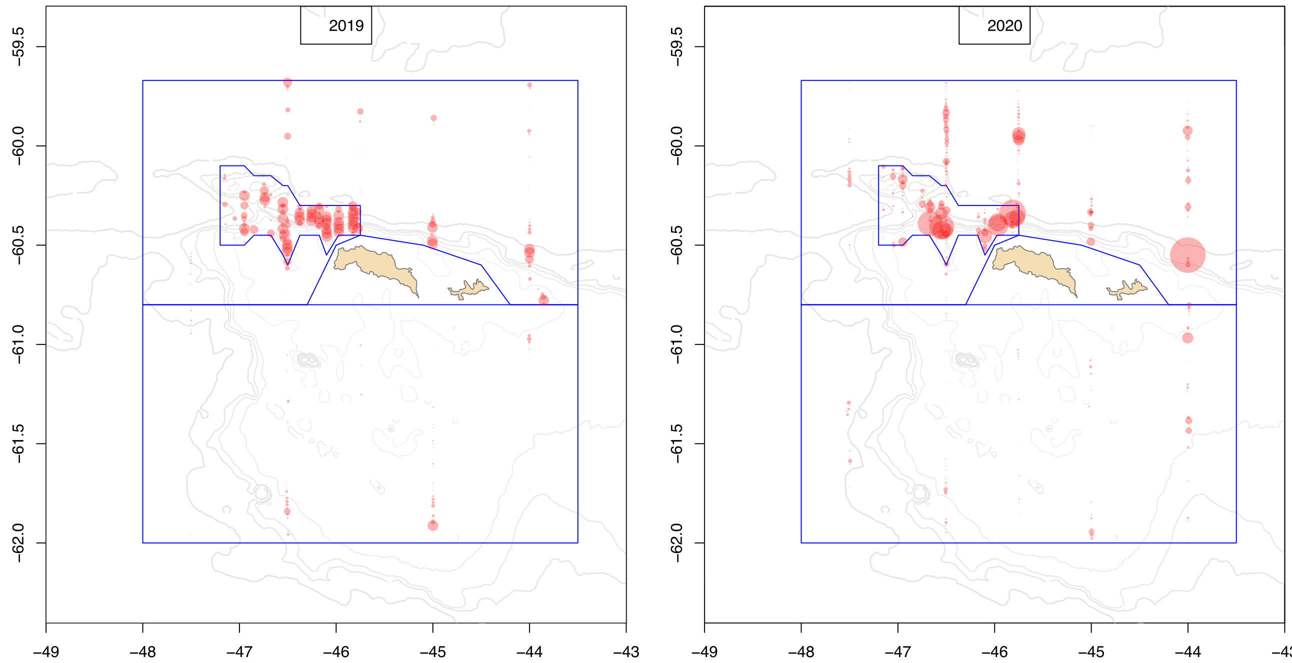

Figure 5. NASC distribution for the 10 survey years. Circle size is proportional to NASC (m^2 nautical mile^{-2}) over 1 nautical mile integration distance with a cut-off at NASC = 1000. All values are based on 38 kHz data for easy comparison except for 2012 and 2019, where they are based on 120 kHz data but scaled with the ratio of the conversion factor between 38 and 120 kHz. Blue lines mark strata borders. The coverages in 2013 and 2015 were reduced due to sea-ice coverage.

Table 2. Overview of calibration sites and results.

Year	Vessel	Calibration site	Echo sounder	S_v transducer gain (dB re 1 m^{-1})		S_a correction	
				38 kHz	120 kHz	38 kHz	120 kHz
2011	FV Saga Sea	Punta del Este, Uru	Simrad EK60	25.68	24.72	− 0.66	− 0.32
2012	FV Juvel	Scotia Bay, SOI	Simrad EK60		25.9		− 0.32
2013	FV Saga Sea	Admiralty Bay, SSI	Simrad EK60	26.31	24.47	− 0.69	− 0.37
2014	FV Saga Sea	Scotia Bay, SOI	Simrad EK60	26.58	23.5	− 0.6	− 0.34
2015	FV Juvel	Scotia Bay, SOI	Simrad EK60	26.74		0.23	
2016	FV Saga Sea	Scotia Bay, SOI	Simrad ES60	26.24	24.2	− 0.69	− 0.3
2017	FV Saga Sea	Scotia Bay, SOI	Simrad ES60	25.52	23.94	− 0.7	− 0.41
2018	FV Juvel	Scotia Bay, SOI	Simrad EK60	25.87	26.97	− 0.61	− 0.33
2019	RV Kronprins Haakon	Admiralty Bay, SSI	Simrad EK80	27.07	26.89	0.03	0.01
2020	FV Saga Sea	Scotia Bay, SOI	Simrad ES60	26.26	24.35	− 0.7	− 0.38

comparison between swarm detection and integration between the two frequencies was needed here. When integration was done at 120 kHz, swarms detected at 38 kHz resulted in 1.6 and 0.8% higher cumulative NASC for the years 2016 and 2017, respectively, than swarms detected at 120 kHz (Figure 2c). For 2018, the cumulative NASC was 5.8% lower for swarms detected at 38 kHz than for swarms detected at 120 kHz. When integration was done at 38 kHz, the cumulative NASC of regions detected at 38 kHz was 12.8 and 7.6% higher for 2016 and 2017, and 1.1% lower for 2018 than regions detected at 120 kHz (Figure 2d). When swarm detection is done at 38 kHz, there is a risk that it may include scatterers, which are strong at 38 kHz but weak at 120 kHz, for instance fish or diving predators (see Supplementary Appendix B and Figure A2 for more details).

Estimates of krill density and biomass

Estimated mean density for the entire survey area ranged from a low of 23.2 g m^{-2} in 2017 to 128.8 g m^{-2} in 2012 corresponding to biomass estimates of 1.4 to 7.77 million tonnes (Table 3). There were no trends in the krill density estimates over the time series ($p \approx 0.18$), but considerable annual variability (Figure 3). The sampling variance based on the Jolly and Hampton estimator (Jolly and Hampton, 1990) and expressed as Coefficient of Variation (CV) was around 0.3 for 6 of the 9 years with combined estimates. The corresponding confidence intervals around the mean values for these years are large (Table 3). For 2016, the CV was 0.49 and for 2015 and 2020, it was 0.19 and 0.14, respectively.

Overall, the north stratum had higher krill densities than the south stratum with an average density of 93 g m^{-2} compared to 32 g m^{-2} in the south (Table 3). In all years except

Table 3. Krill density and biomass estimates by strata.

Year	Stratum	Density (g/m^2)	CV	Mean BM (mill. tonnes)	BM 2.5% cl	BM 97.5% cl	CF 38 kHz	CF 120 kHz
2011	Combined	62.6	0.36	3.78	1.12	6.45		
2012	Combined	128.8	0.35	7.77	2.50	13.05		
2014	Combined	76.5	0.30	4.62	1.91	7.32		
2015	Combined	28.5	0.19	1.72	1.07	2.38		
2016	Combined	49.3	0.49	2.98	0.12	5.84		
2017	Combined	23.2	0.29	1.40	0.61	2.20		
2018	Combined	69.4	0.25	4.19	2.14	6.24		
2019	Combined	27.2	0.29	1.64	0.70	2.59		
2020	Combined	38.8	0.14	2.34	1.70	2.99		
2011	North	111.5	0.43	3.15	0.52	5.78	1.36	0.43
2012	North	195.8	0.47	5.52	0.43	10.62	1.73	0.28
2013*	North	181.3	0.61	5.12	0.00	11.21	1.59	0.30
2014	North	135.5	0.35	3.82	1.24	6.41	1.47	0.35
2015	North	40.1	0.30	1.13	0.48	1.79	1.49	0.34
2016	North	24.2	0.45	0.68	0.08	1.29	1.38	0.41
2017	North	18.7	0.42	0.53	0.10	0.95	1.47	0.34
2018	North	120.7	0.30	3.41	1.42	5.39	1.37	0.42
2019	North	46.0	0.36	1.30	0.38	2.21	1.36	0.42
2020	North	58.1	0.17	1.64	1.08	2.20	1.35	0.44
2011	South	19.7	0.34	0.63	0.21	1.06	1.46	0.36
2012	South	70.0	0.31	2.25	0.87	3.63	1.81	0.27
2014	South	24.6	0.51	0.79	0.00	1.59	1.62	0.29
2015*	South	18.4	0.04	0.59	0.54	0.64	1.63	0.29
2016	South	71.4	0.62	2.29	0.00	5.09	1.48	0.34
2017	South	27.2	0.39	0.87	0.20	1.54	1.62	0.29
2018	South	24.4	0.32	0.78	0.29	1.28	1.71	0.26
2019	South	10.7	0.37	0.34	0.09	0.60	1.50	0.33
2020	South	21.8	0.23	0.70	0.38	1.02	1.56	0.31
2015	Shelf edge	31.6	0.24	0.07	0.04	0.11	1.49	0.34
2019	Shelf edge	217.6	0.29	0.52	0.22	0.81	1.36	0.42
2020	Shelf edge	62.0	0.17	0.15	0.10	0.19	1.35	0.44

*Reduced survey coverage due to sea-ice.
The 2.5 and 97.5% confidence limits are calculated as 1.96*standard error using the Jolly and Hampton estimator. 2.5% confidence limits lower than 0 were set to 0. CF denotes factors used for converting NASC values to biomass density at 38 and 120 kHz (see text in the section "Material and Methods" for details). In the combined estimate, north and south strata with their associated conversion factors are combined.

2016 and 2017, the krill density was higher in the north stratum than in the south, and the five highest average krill densities in the time series were from the north stratum. Estimated krill density in the north stratum was significantly correlated with the krill density in the combined strata (Spearman's rank correlation, $p < 0.001$), while biomass in the south stratum was not ($p = 0.29$).

The estimates from the 3 years of coverage in the small shelf edge stratum showed krill densities ranging from 32 to 218 g m^{-2}. The estimated krill densities for 2015 and 2020 were similar to the densities in the north stratum, while the density in the shelf edge stratum in 2019 was almost five times higher than in the north stratum.

Distribution of krill acoustic recordings and length distributions

The mean survey time-series NASC value per transect highlights that transect T2_N covered the region with highest krill densities (Figure 4). This transect crosses the conspicuous bathymetric features in the middle of the main target area for the fisheries. But the confidence interval for krill density is large in this transect reflecting the great inter-annual variability in krill NASC distribution (Figure 5). In general, the transects in the north crossing the shelf had higher mean krill densities and wider confidence intervals than the transects in the south. The exception was transect T1_N, which is to the west of the shelf break, and had generally low krill densities.

The krill length distributions typically had a mode with a peak between 40 and 50 mm (Figure 6). This mode dominated in 2013, 2014, 2015, 2018, and 2020. The other years had a more bimodal length distribution with a second smaller mode with a mean between 30 and 40 mm apparent in 2011, 2016, 2017, and 2019. The survey result from 2012 is an anomalous, with a very clear mode of small sized krill with a mean body length of between 20 and 30 mm. The length distribution modes were similar in the north and south strata, with exception of the years 2018 and 2020, but the smaller individuals generally made up a higher proportion in the south.

Krill exploitation

The krill regional exploitation rates are shown in Table 4. The rates are on the precautionary side (<9.3% of total regional krill biomass) for all years when looking at actual catch and survey area, and for all but one year when fishing at trigger level and considering subarea scale.

Discussion

Krill density and biomass in the South Orkney region

The results from the first 10 years of monitoring the krill biomass in the South Orkney waters show that there are consistently high krill densities in this region during the austral

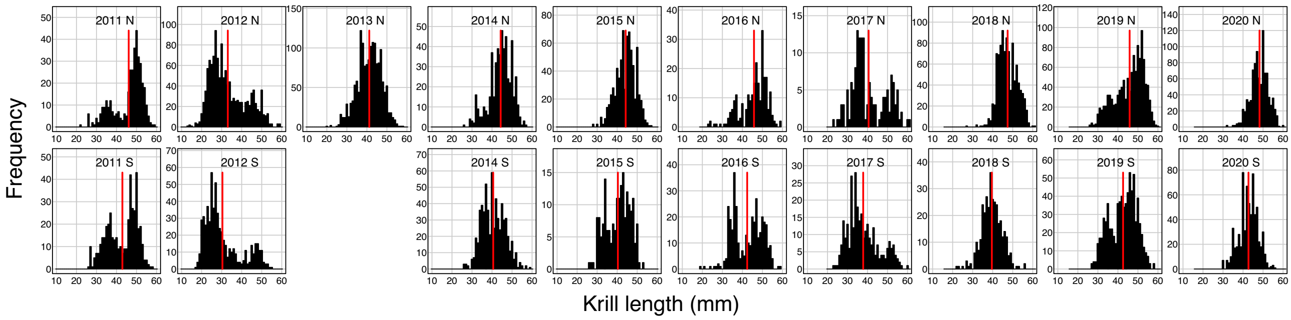

Figure 6. Overview of krill length distribution for the survey years, split into the north ("N") and south strata ("S"). The south stratum was not covered in 2013. Vertical red line marks mean krill length.

Table 4. Regional exploitation compared to estimated available krill.

Year	BM combined strata (tonnes)	Catch (tonnes)	Exploitation stratum area (%)	Exploitation subarea (%)
2011	3.78	0.12	2.3	3.1
2012	7.77	0.03	1.1	0.4
2014	4.62	0.07	1.9	1.6
2015	1.72	0.02	5.1	1.0
2016	2.98	0.03	3.0	1.2
2017	1.40	0.07	6.3	4.9
2018	4.19	0.14	2.1	3.3
2019	1.64	0.16	5.4	9.9
2020	2.34	0.18	3.8	7.6

The exploitation per stratum area is actual catch for a given year divided by the krill biomass that was estimated for that year. Exploitation per subarea is the trigger level catch for 48.2 (0.279 million tonnes) divided by biomass of krill in the CCAMLR Subarea 48.2 (stratum biomass scaled up). Both metrics were introduced in Hill *et al.* (2016).

summer. The results support the outcomes of the CCAMLR 2000 large-scale survey (Hewitt *et al.*, 2004) and the large-scale survey in area 48 in 2019 (Krafft *et al.*, 2021), indicating that the South Orkney region has among the highest concentrations of krill in the Scotia Sea. It is however, notable that the South Orkney estimate based on the CCAMLR 2000 survey (319.4 g m^{-2}; Krafft *et al.*, 2021) is 63% higher than the highest estimate in our time series suggesting that this was a year with unusually high krill concentrations in the region. The estimates of mean krill biomass density in our South Orkney survey vary annually ranging from a low of 23.2 to a high of 128.8 g m^{-2} over the 10 years. This observed variability is low compared to what has been observed in the BAS regional surveys off South Georgia with mean annual krill density estimates ranging from 2.74 to 137.03 g m^{-2} (Fielding *et al.*, 2014) and in the three strata of the AMLR South Shetland Island survey with estimates for Elephant Island stratum ranging from 0.8 to 66.8 g m^{-2}, South stratum from 0.1 to 80 g m^{-2} and West stratum from 0.1 to 54.3 g m^{-2} [Reiss *et al.*, 2008; biomass density calculated from strata areas given in Table 7 in Krafft *et al.* (2021)]. The results show that the South Orkney region can be viewed as a krill hotspot consistently holding a substantial krill biomass, which makes the area important to both natural krill predators (Lynnes *et al.*, 2004; Casaux *et al.*, 2016) and the krill fishing industry (Sushin, 1998; Kawaguchi *et al.*, 2009; Krafft *et al.*, 2015; Warwick-Evans *et al.*, 2018).

The first 10 years of acoustic monitoring of krill during the same time of year and with much the same coverage showed clear annual variability but no significant trends. There is a question that how suited our survey results are to reveal an actual trend unless it is very strong, given the high sampling variance and the assumed high temporal variability in abundance associated with krill flux (Kasatkina *et al.*, 1997; Cutter Jr *et al.*, 2022). The comparison between our estimates from the small-scale shelf edge stratum and large-scale area indicated the strong heterogeneity in distribution. For two out of 3 years, the estimate from the shelf edge stratum corresponded well with the larger scale survey, but in one of the years, biomass levels were significantly above the large-area estimates. This result supports that biomass level estimates for krill rely heavily on sampling effort and location, i.e. outcome depends not primarily on the size of the area surveyed, but whether or not the high density swarms are included (Brierley *et al.*, 2006; Fielding *et al.*, 2014). If krill biomass is mostly concentrated in a few, large swarms, the probability of intersecting one of these is low.

Krill distribution

We found that krill density was generally higher in the north stratum covering the shelf edge on the north side of the South Orkney Islands than in the south stratum. The highest densities were found in the north transect T2_N, which is a section through the submarine canyon Monroe Trough to the northwest of Coronation Island (see Figure 1). The results strongly support that krill in this region concentrate along the shelf break and associated submarine canyons. This phenomenon has been reported for krill in several previous studies from other regions in Antarctica (Trathan *et al.*, 2003; Santora and Reiss, 2011; Bernard *et al.*, 2017). Krill aggregation in the submarine canyons is often explained by retention from e.g. fronts or eddies, and/or lack of offshore advection (Santora *et al.*, 2012). The same mechanisms that lead to krill aggregating likely also enhance local productivity and therefore increase food availability for krill (Santora and Reiss, 2011). Such krill hotspot locations are also likely of great importance for krill-dependent predators (Santora and Reiss, 2011), and provide fishing grounds with predictable high concentrations of krill for the fishery (Murphy *et al.*, 1997; Sushin, 1998; Krafft *et al.*, 2015).

The observation that krill densities were low in the north stratum compared to the south stratum in a few of the years suggests that flux and advection out of the area is also an important mechanism in the spatial dynamics. Kasatkina *et al.* (1997) described krill flux in the South Orkney shelf area and found an important outflux path towards the north-east. Sushin (1998)also described a fishing vessel following a krill aggregation towards the north-east for 5 days, suggesting that an offshore migration or advection towards the north-east is an important transport mechanism for krill in this area. There is, however, a huge potential for exploring flux and advection of krill further in this area using a combination of opportunistic acoustic data from the krill fishing vessels (Niklitschek and Skaret, 2016), mooring data (Klevjer, 2019; Klevjer and Skaret, 2019), and the current acoustic survey data set.

Is krill fishery in Subarea 48.2 precautionary?

Krill abundance estimates are necessary when evaluating whether a krill fishery is precautionary or not, and Hill *et al.* (2016) used regional time series to assess this. In their evaluation, the South Orkney Islands were only represented with 3 years of data, which were available at the time. Here, we use updated estimates to add 6 more years (2015–2020) of data to the evaluation. Our results show that the regional fishery is precautionary at its present level in all observation years and at trigger level in all years except one where it is slightly above. The evaluation only considers risk of depletion for the krill stock, and not risk of local events, e.g. local depletion of a krill-dependent predator due to poor feeding conditions. Many studies address risk to krill-dependent predators induced by the fisheries (e.g. Hinke *et al.*, 2017; Watters *et al.*, 2020), but there is currently no management consensus in CCAMLR as to what is a bad event for a given predator, and what is an acceptable risk of such an event to occur (Hill, 2013; Hill *et al.*, 2016; Godø and Trathan, 2022).

Representativeness of the krill abundance estimates

The surveys off the South Orkney Islands are conducted in collaboration with the krill fishing industry and use fishing vessels as monitoring platforms (Watkins *et al.*, 2016; Krafft *et al.*, 2018). The vessels were equipped with quantitative echo sounders that were calibrated and logged data, but due to unavailable acoustic frequencies and in some cases unwanted interference noise, it was not possible to be in full compliance with the standard CCAMLR methods for collection and processing of acoustic data (CCAMLR, 2017). Notwithstanding, we applied the recommended swarm-based approach (CCAMLR, 2017; Krafft *et al.*, 2021) for krill target allocation and integration at 120 kHz for 7 of the 10 survey years. The approach was implemented in LSSS, which is a different computer program from Echoview—the computer program used in the CCAMLR implementation. Our comparisons between the two programs showed that the output differed due to unique software implementations, but that they had minimal impact on the biomass estimation. The difference in swarm count was significant, however, and is likely dependent on how the delineation of swarms is implemented in the two computer programs. This must be kept in mind when comparing swarm features between areas with different data processing. For the years 2014, 2015, and 2020, we needed to rely on the 38 kHz data for both target identification and integration due to either noise issues or lack of an operational 120 kHz echo sounder. Our evaluation indicated that the swarm detection and integration in these cases is positively biased, likely due to non-krill targets, such as diving air-breathing predators or fish (Fielding *et al.*, 2012), being identified as krill. It should be noted that up to 12.8% bias we observed by comparing results from the years 2016–2018 is well within the 95% confidence interval estimated from sampling variance. The potential bias due to different scattering properties of krill at 38 and 120 kHz is not evaluated here. For the 2011 survey, calibration was carried out off Punta del Este, Uruguay, where the water temperature was approximately 20°C higher than that for typical Antarctic calibrations. The sensitivity of echo sounder transducers is known to be affected by temperature (Brierley *et al.*, 1998; Demer and Renfree, 2008) and the 2011 survey estimate is therefore likely an underestimate (Brierley *et al.*, 1998). Diel vertical migration of krill could also potentially bias our estimates, since krill might be distributed in the surface acoustic dead zone (Demer and Hewitt, 1995; Krafft *et al.*, 2021) or below the lowest integration depth of 250 m (Schmidt *et al.*, 2011).

Conclusion

This paper presents the results from the first 10 years of acoustic data from the primarily industry-based IMR krill survey off the South Orkney Islands. The survey has established new knowledge about krill densities and spatial distribution between years in the region (in addition to the present paper, see e.g. Krafft *et al.*, 2018), and our evaluation shows that the krill fishery in the South Orkneys region is precautionary with regards to what are currently the agreed management objectives for krill. However, with the management system currently in place for krill with a fixed trigger level, the survey results have limited applied value for the assessment since there is no update of TAC at any regular time interval. There is an aim in CCAMLR to move towards a feedback management system that has more flexible regulations in both time and space than the present system, and that reflects the fishery-induced risk for krill-dependent predators at relevant scales (Constable, 2011; CCAMLR, 2019). However, CCAMLR is a consensus organization, and consequently, it is a time-consuming process to agree on changes to an operational management system with associated aims and acceptable risk levels (Constable, 2011). When such an alternative management system is not defined, it is also challenging to evaluate the adequacy of different survey designs to inform management decisions. An efficient monitoring to inform krill management might need to combine large-scale and small-scale approaches, and also use non-transect data from fishing vessels and autonomous platforms to increase coverage in space and time (Niklitschek and Skaret, 2016; Zhao *et al.*, 2022). However, whichever shape a future krill management system will take, regular monitoring of krill abundance is likely to play an important role, and a collaboration between the science and the industry is becoming an important instrument to achieve this. The established krill monitoring time series presented here is an example of data that are based almost entirely on an industry platform, and contributions from the krill fishing industry have in recent years become an integral part of the monitoring of Antarctic krill for assessment and management purposes (Watkins *et al.*, 2016; Krafft *et al.*, 2021; Godø and Trathan, 2022; Zhao *et al.*, 2022). With the huge costs involved with surveying in remote Antarctic waters, there is a great cost efficiency in using vessels that are already at the site. In addition, increased collaboration between industry and science on krill monitoring improves mutual understanding between the parties, which is likely to be beneficial for krill management in the longer term.

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Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Conflict of interest statement

There is no conflict of interest related to this work.

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Author contributions

Conceptualization: GS and BAK; data collection: all authors; formal analysis: GS and GJM; funding acquisition and project administration: BAK; visualization: GS; writing—original draft: GS; and writing—review and editing: all authors.

Data availability

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

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