CCAMLR

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Commission pour la conservation de la faune et la flore marines de l'Antarctique
Комиссия по сохранению морских живых ресурсов Антарктики
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Evaluation of Antarctic krill biomass and distribution off the South Orkney Islands 2011-2015

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Evaluation of Antarctic krill biomass and distribution off the South Orkney Islands 2011-2015

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Abstract

Annual acoustic trawl surveys for krill monitoring have been carried out by the Institute of Marine research, Norway near the South Orkney Islands since 2011. The survey has been conducted early in the fishing season (January/February), using two different krill fishing vessels as platforms. The vessels were equipped with similar Simrad echo sounder systems suitable for quantitative assessments, but the frequencies operated varied between vessels and years. In addition, the survey coverage has varied between years in particular due to ice. In order to allow for comparison of distribution and abundance of krill near the South Orkneys among years, we here attempt to generate a coherent series of krill density estimates from the 5 years of surveys. We follow the CCAMLR protocol for biomass estimation as far as practically possible, given that we work with unconventional sets of frequencies for target strength estimation and target identification. In order to avoid variability due to differences in coverage, we also define a stratum within the survey area on the north side of the islands with full coverage in all years except 2013. The results show that except from the year 2015, krill densities were high, in the range 100-300 g/m^2 based on the 120 kHz recordings, and a total estimated biomass of ca. 8 million tons of krill within the stratum in the peak year 2014. There were also consistently higher values of acoustic backscatter on the north side of the islands where the fisheries occur, than on the south side. Values were particularly high in the north-west shelf area associated with underwater canyons. In 2012, and particularly in 2015, low proportions of the acoustic backscatter were allocated to krill. The low proportions are probably caused by shortcomings in the krill identification techniques when other pairs of frequencies than combinations of 38, 120 and 200 kHz are used.

Introduction

Antarctic krill (*Euphausia superba*) have a circumpolar distribution and are extremely abundant in the Southern Ocean . They are preferred and often essential prey for a range of fish, pinnipeds, cetaceans and seabirds , and are subject to a commercial harvest which has been increasing during the past decade . The fishery is managed by the Commission for Conservation of Marine Living Resources (CCAMLR), and the harvest is constrained to the western sector of the South Atlantic, more specifically near the South Shetland Islands (CCAMLR subarea 48.1), the South Orkney Islands (subarea 48.2) and South Georgia (subarea 48.3) (https://www.ccamlr.org/en/organisation/convention-area). The precautionary catch level of 5.61 million tons has been calculated based on a joint international acoustic krill abundance estimation survey conducted in the Scotia Sea in 2000 providing a total biomass of 60.3 million tons . However, due to a lack of knowledge about the local impact of the fisheries on krill dependent predators, the current limit to krill catch is set at 620 000 tons, a number which is based on historical catches.

Even though comprehensive krill surveys in the Southern Ocean have only been undertaken on two occasions , there is regular krill meso-scale monitoring near some of the most important areas for fishing. There has been annual krill monitoring in subarea 48.3 since 1996 carried out by the British Antarctic Survey (BAS; UK). They conduct a ~4-day survey in December-February in a 133 by 80 km rectangle across the shelf break to the north west of the South Georgia ('Western core box') . Krill monitoring in 48.1 has been carried out annually since 1988 by the United States - Antarctic Marine Living Resources program (US-AMLR; US) as part of multidisciplinary efforts near the South Shetland Islands . Starting in 2011, the Institute of Marine Research (IMR; Norway) has carried out annual surveys in subarea 48.2 near the South Orkney Islands in collaboration with the fishing industry.

Krill abundance estimation from the meso-scale surveys is done by use of hydroacoustics, which provides data with high spatial and temporal resolution. For derivation of krill abundance estimates from acoustic recordings, the portions of the acoustic backscatter originating from krill must first be identified and allocated to krill, and then the allocated backscatter must be converted from backscatter to biomass. The backscatter to biomass conversion is possible if the mean target strength of individual krill can be estimated accurately. Since scattering from individual krill is highly non-linear, the conventional linear regression between logarithm of body length and acoustic target strength which is typically used for fish, can be misleading for krill (Stanton et al. 1993; 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 . The Distorted Wave Born Approximation model (DWBA) is today normally recognised as the most proficient model for target strength prediction , and CCAMLR have adopted the Stochastic Distorted Wave-Born Approximation (SDWBA) in their protocol for biomass estimation . Following the CCAMLR protocol, the model is not only used to estimate target strength based on a given set of parameters defining krill morphology, structure and behaviour, but also indirectly to identify and separate krill from other scatterers in the acoustic data set. The identification is based on the assumption that the mean acoustic response of krill differs in a predictable manner between different frequencies . The SDWBA can estimate the expected response of krill at a given frequency, which again is used to calculate the difference in response between a given pair of frequencies, and thereby identify frequency based krill identification ‘windows’ within a given length range of krill. The method is more objective than expert evaluation of echogram appearance, and has been validated for some pairs of frequencies, in particular 38 and 120 . In CCAMLR, 38, 120 and 200 kHz have been adopted as reference frequencies in the protocol.

The Southern Ocean krill fishing vessels are typically running acoustic equipment with one or several of the standard CCAMLR acoustic frequencies and can be used to carry out a krill monitoring survey . Involving effort from the fishing fleet is likely a requirement in order to attain sufficiently frequent abundance evaluation for a feedback management system. The IMR has been applying fishing vessels for annual acoustic krill monitoring since 2011, and here, we consolidate the information from the five years of surveying. The survey has been carried out with two different krill fishing vessels, different instrumentation and variable coverage. The aim of this work was to establish a coherent time series of krill abundance and distribution based on the collected data..

Material and methods

Surveys and area

The five surveys which have been carried out to this date have been conducted in late January or early February in the years 2011-2015 using FV ‘Saga Sea’ (Aker Biomarine AS) and FV ‘Juvel’ (Olympic Seafood AS) as platforms (Table 1). The rationale behind the timing is to lower the risk of ice coverage hindering the survey and at the same time cover the population before the annual fisheries potentially have started to impact abundance, distribution and behaviour. The survey follows a design with parallel transect lines, and a random starting point set the first time and then kept to avoid annual variation due to bathymetric influences on the krill distribution. The survey grid originally comprised six parallel transect lines going from 60°S to 61.75°S at the longitudinal waypoints 44°W, 45°W, 45.75°W, 46.5°W, 47.5° and 48.5°W (Fig. 1). In 2012, the north-south transects were extended north to 59.67°S in order to incorporate more of the northern off-shelf area through to be interesting, and the westernmost transect line was removed to keep effort constant. In 2014, the southernmost waypoints were prolonged to 62.00°S, in order to monitor parts of the MPA defined on the southside of the South Orkneys. The survey normally takes 4-5 days to conduct (Table 1).

The South Orkney Islands have a narrow shelf with conspicuous underwater canyons on its northside, where almost all of the fisheries takes place, and a broader shelf on the southside of which parts are included in a Marine Protected Area (MPA). Surface ocean currents from the Weddel Sea enter the South Orkney shelf from south-west, and circle around the shelf counter clockwise. In connection with the bathymetric structures there are likely small-scale hydrographical features of importance for krill flux and retention, but these are little known. The South Orkney islands host high numbers of penguins, in particular chinstrap penguins, and Antarctic fur seals which are dependent upon krill for food .

Acoustic data collection

The vessels have been equipped with Simrad ES60 echosounders, but the available frequencies have varied from year to year and are listed in Table 1. The original ES60 General Purpose Transceivers (GPTs) have been replaced with scientific EK60 GPTs for all frequencies prior to the surveys. All frequencies have been calibrated according to standard sphere calibration . Calibration has been carried out in Antarctic waters except in 2011 when it was carried out off Punta del Este (Uruguay) (Table 1). The echo sounder was operating with a ping repetition rate of 1 second^{-1}. Occasionally, ping interval requirements could not be met due to the system settings and a higher interval was then chosen (between 1 and 1.5 second^{-1}). Nominal vessel speed was 10 knots. The transceiver settings are specified in Table 2. Acoustic data were logged down to 750 m on all available frequencies, but only data down to 250 m were processed for the krill biomass estimation.

Biological data collection

Trawl hauls were conducted at predefined positions spaced 20 or 25 nmi apart along the transect lines depending on the year, using a trawl with a mouth-opening of 38m^2 and a stretched mesh size of 3 mm (measured from knot to knot) from the trawl-opening to the rear end and trawl doors of 7.5 m height were used when the survey was carried out on board ’Juvel’ ain 2012, otherwise it was mounted on a beam. In 2013, the scientific trawl was not available, and the commercial trawl on board was used for sampling. This trawl had a 400 m^2 mouth-opening and a mesh size of 16 mm on the side panels from the mouth opening to the cod end. The mesh size of the cod end was of 11 mm. On each station the trawl was lowered from surface to 200 m depth (or ~ 20 m above bottom if the water was shallower than 200 m) and then hauled at 2.5-3 knots. Body length was measured (± 1 mm) for *E. superba* from the anterior margin of the eye to the tip of telson excluding the setae, according to the "Discovery method" used in .

Acoustic data processing

Noise removal

In general, the surveys were carried out under relatively calm weather conditions so undesired backscatter due to wave generated air bubbles within the upper water layers were minor in the recordings. Noise caused by signal interference from other instruments or disturbances on the electrical circuit system has also been limited within our range of operation and in most cases not necessary to take into consideration during pre-processing. There are three exceptions as shown in Table 1 where filters were applied. In the first case (filter 1), a combination of filters was used on the 120 kHz in the range 100-250 m. In the second case (filter 2), the same combination of filters was used as in 1), but for the entire sampling range. Further details about the noise removal algorithms are provided in the appendix. Noise removal and echo integration was done with the software Large Scale Survey System (LSSS) .

Identification and discrimination of krill targets

The method for target discrimination as described in the CCAMLR protocol for krill biomass estimation requires data from the frequencies 38, 120 and 200 kHz , while our data were collected using different combinations of 38, 70 and 120 kHz (Table 1). However, we assumed that different targets have predictable frequency dependent volume backscattering strength (S_v; dB re m^{-1}) within a specified range of krill body lengths. Following this assumption, targets which fall within a specific range of ΔS_v-values (for instance $S_{v,70} - S_{v,38}$ for the 70 and 38 kHz frequency pair) will be identified as *E. superba*. The method was applied on sample bins of 50 pings horizontal*5 m vertical resolution. The minimum and maximum ΔS_v-values defining the krill identification 'window' were calculated from Stochastic Distorted Wave Born Approximation (SDWBA) full model runs, as implemented in the SDWBApackage2010 , and was based on the krill length frequency distribution from the trawl samples where the 2.5 % highest and 2.5 % lowest values from a cumulative probability distribution were excluded . The model was implemented and parameterised according to the CCAMLR protocol with a fixed mean krill orientation of -20° and standard deviation of 28 (CCAMLR, 2010). After the discrimination, the retained Nautical Area Scattering Coefficient (NASC)-values were averaged for each nautical mile.

Target strength prediction and conversion to biomass

The retained NASC allocated to krill were converted to biomass density (g m^{-2}) using full SDWBA model runs to estimate backscattering cross-sectional areas (σ) for all 1 mm krill length groups present in the sample according to the formula:

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

The predicted target strengths were used to calculate weighted conversion factors (CF) from NASC-values to biomass density:

$$CF = \left[\sum f_i \cdot W(TL_i)\right] / \left[\sum f_i \cdot \sigma(TL_i)\right]$$

where f is the frequency of occurrence of a specific length group (i), σ(TL) is the backscattering cross-sectional area at total length, and W(TL) is weight at total length, which was calculated following Hewitt et al. (2004):

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

Estimation of biomass

Based on the average biomass density for each nautical mile, a weighted biomass density for each transect line could be calculated and the sampling variance from the averages of each transect line according to . In cases of deviance from the original transect line due to ice coverage, the weighting was done according to the length of the original transect line.

Results and discussion

Coverage

The survey coverage for all years is shown in Fig. 1. In 2011 and 2012 the entire survey area was covered. In 2013, the coverage was severely hampered by ice coverage, and in 2015, large parts of the areas south of the islands had to be dropped due to ice coverage (Fig. 1). In 2014, a small region in the south was not covered due to ice. In order to take into account the different coverages when comparing between years we defined a stratum on the north side of the islands which was fully covered all years except in 2013 (See fig. 1).

Krill length distribution

Krill length distribution for all survey years is shown in Fig. 2. While the length distributions in the years 2013-2015 were similar and unimodal with means lengths around 43 mm, the years 2011 and 2012 had bimodal distributions, with a main peak around 50 mm and a smaller around 35 mm in 2011, and a main around 25 mm and a smaller around 45 mm in 2012. In 2012, 43.7% of the sampled krill were juveniles.

Krill density estimates

Krill density estimates for the surveys, both for the entire survey areas and the stratum, are shown in table 4. Most krill density values are high. Notably were krill densities in the stratum for the years 2011 and 2014, around 213 and 301 g/m^2 while the highest krill densities reported from the South Georgia core box during the period 1997-2013 was 137 g/m^2 . Also during the CCAMLR 2000 survey, very high krill densities were found for two of the South Orkney transect lines, 222 g/m^2 and 362 g/m^2, respectively, while no other transect line densities from the CCAMLR 2000 survey exceeded 100 g/m^2 .

The years with low density estimates, particularly 2015, but also 2012, are most likely biased low due to the way the krill identification is implemented in the acoustic data processing. This judgment is based on both the appearance of the echogram recordings, and expected distribution and abundance of krill from trawl hauls and previous investigations. The standard 120-38 frequency pair was not available for these years, and the 70 kHz was used in combination with 38 and 120 kHz, respectively. Potentially the bias is due to poor calibration, but we do not have reason to suspect this in the present case. Alternatively, there is an issue with the implementation of the SDWBA model for frequency combinations including 70 kHz. While the krill identification properties using combinations of 38, 120 and 200 kHz frequencies have been quite rigorously tested and validated, this has not been the case for the 70 kHz.

For the 2011 survey, calibration was carried out off Punta del Este, Uruguay. The performance of echosounder transducers is known to be affected by temperature , and the performance of the echo sounders in the 2011 survey was likely reduced in the survey area compared to the calibration area. No correction for this potential error was applied here.

Distribution

The distribution of acoustic NASC-values are shown in fig. 3. Notably, the area north/north-west of the South Orkney Islands with the conspicuous bathymetric features has persistent high NASC values. Very little of the NASC was allocated to krill in 2015 (Table 4). This is probably an artefact from the krill identification method (see section above), which is supported by the fact that high values in typical krill areas were here not allocated to krill. The performance of the identification is illustrated in fig. 4.

Tables and figures

Table 1. Survey details. The different acoustic processing filters (1 and 2) used are further described in the text and appendix.

Year	Vessel	Dates	Acoustic frequencies used						Calibration site
			38	filter	70	filter	120	filter	
2011	Saga Sea	4-8 February	x				x		Punta del Este
2012	Juvel	26-29 January			x		x		Scotia Bay
2013	Saga Sea	25-29 January	x				x	1	Admiralty Bay
2014	Saga Sea	24-30 January	x	2			x	2	Scotia Bay
2015	Juvel	9-12 February	x		x				Scotia Bay

Table 2. Echo sounder specifications and transducer settings.

	SAGA SEA 2011		JUVEL 2012			SAGA SEA 2013		SAGA SEA 2014		JUVEL 2015	
Echo sounder specification	38 kHz	120 kHz	38 kHz	70 kHz	120 kHz	38 kHz	120 kHz	38 kHz	120 kHz	38 kHz	70 kHz
Transducer type	ES38B	ES120-7	ES38-B	ES70-C	ES120-7C	ES38B	ES120-7	ES38-B	ES120-7C	ES38B	ES70-7C
Transmitted power (W)	2000	250	2000	700	250	2000	250	2000	250	2000	700
Pulse length (ms)	1.024	1.024	1.024	1.024	1.024	1.024	1.024	1.024	1.024	1.024	1.024
Absorption coefficient (dB km^{-1})	10.1	38.4	10.1	23.4	38.4	10	38.4	10.1	38.4	10.1	23.4
Sound speed (ms^{-1})	1456	1456	1450	1450	1450	1453	1453	1450	1450	1450	1450
Sample distance (m)	0.186	0.186	0.186	0.186	0.186	0.186	0.186	0.186	0.186	0.186	0.186
Two-way beam angle (dB)	-20.6	-20.8	-20.6	-21	-21	-20.6	-21	-20.6	-21	-20.6	-21
S_v transducer gain (dB)	25.68	24.72	24.72	26.05	25.9	26.31	24.47	26.58	23.5	26.74	26.1
Angle sensitivity alongship	21.9	21	21.9	23	23	21.9	23	21.9	23	21.9	23
Angle sensitivity athwartship	21.9	21	21.9	23	23	21.9	23	21.9	23	21.9	23
3 dB beamwidth alongship (deg)	6.75	7.34	6.56	7.07	6.84	6.85	6.94	7	6.76	7.49	6.82
3 dB beamwidth athwartship (deg)	6.42	7.07	6.46	6.88	6.94	6.96	6.63	6.37	7.09	7.08	6.55
Sa correction	-0.66	-0.32	-0.53	-0.32	-0.31	-0.69	-0.37	-0.6	-0.34	0.23	-0.33

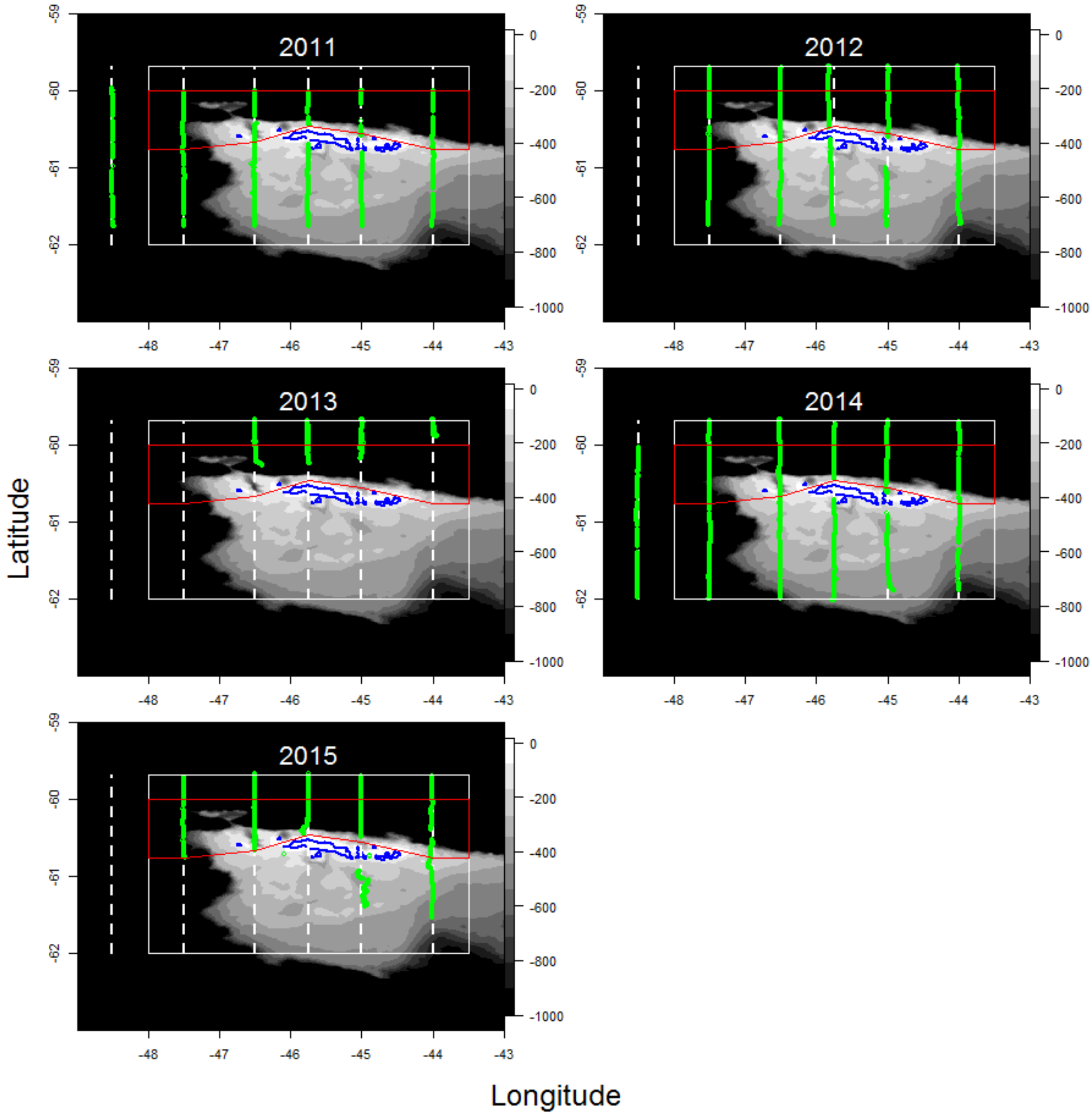

Figure 1. Survey coverage during 2011-2015. Green dots mark parts of transect covered. White dashed line marks full length of all transect lines occupied during the 5-year period. Area in red: post-stratum with coverage in 2011, 2012, 2014 and 2015. Area in white: total survey area as of 2015.

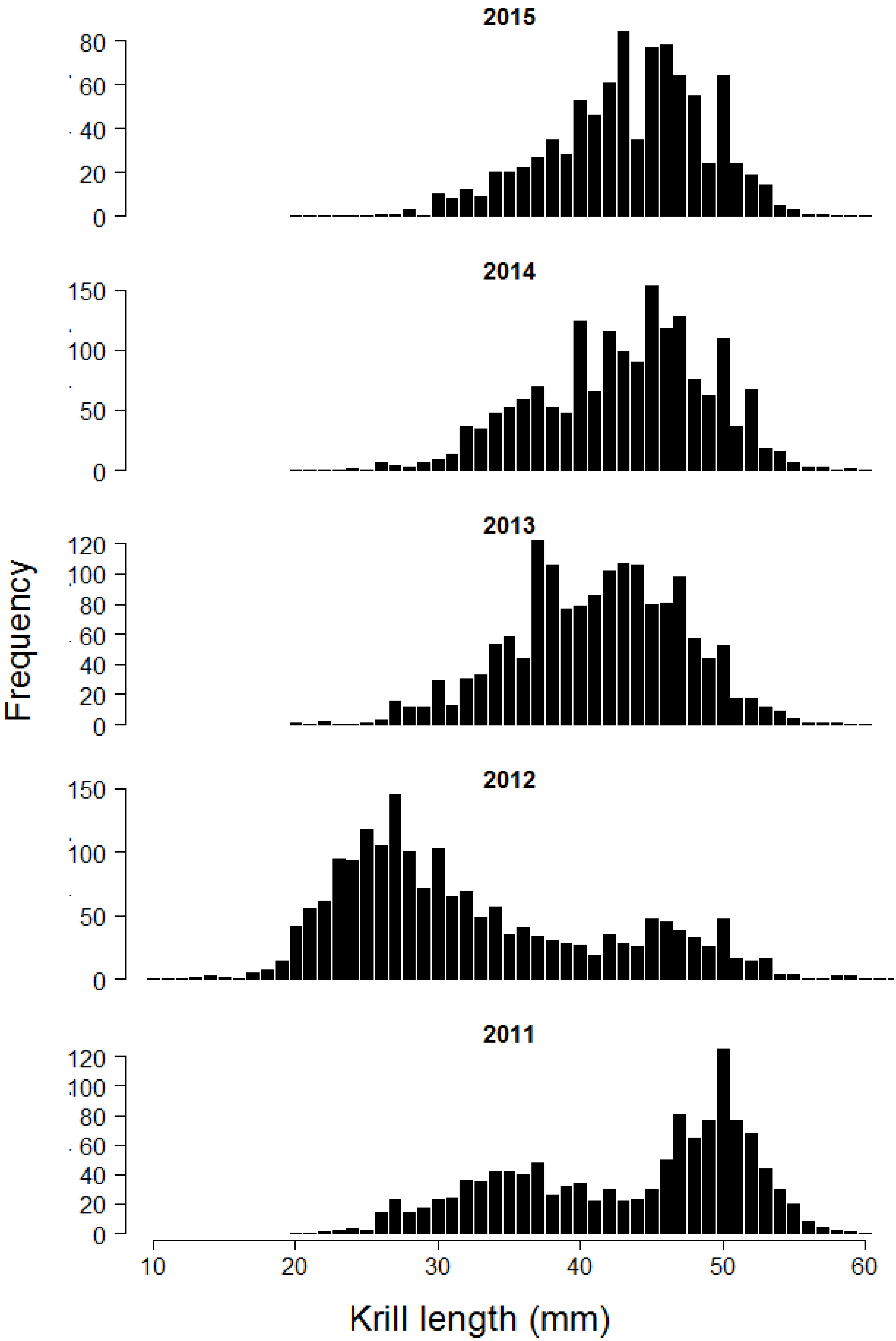

Figure 2. Krill length distribution for all survey years.

Table 3. Summary of biomass estimates. Note that frequencies vary between years.

	Entire area						Stratum							
Year	Freq	Density (g/m^2)	CV	Freq	Density (g/m^2)	CV	Freq	Density (g/m^2)	BM (mill. t)	CV	Freq	Density (g/m^2)	BM (mill. t)	CV
2011	38	69.31	12	120	108.69	18	38	121.79	3.29	17	120	212.75	5.74	28
2012	70	41.49	30	120	86.93	32	70	41.15	1.11	56	120	94.79	2.56	66
2013	38	118.19	26	120	120.28	32								
2014	38	73.69	38	120	148.29	41	38	143.02	3.86	42	120	301.39	8.14	46
2015	38	5.26	51	70	7.10	49	38	7.83	0.21	54	70	10.42	0.28	51

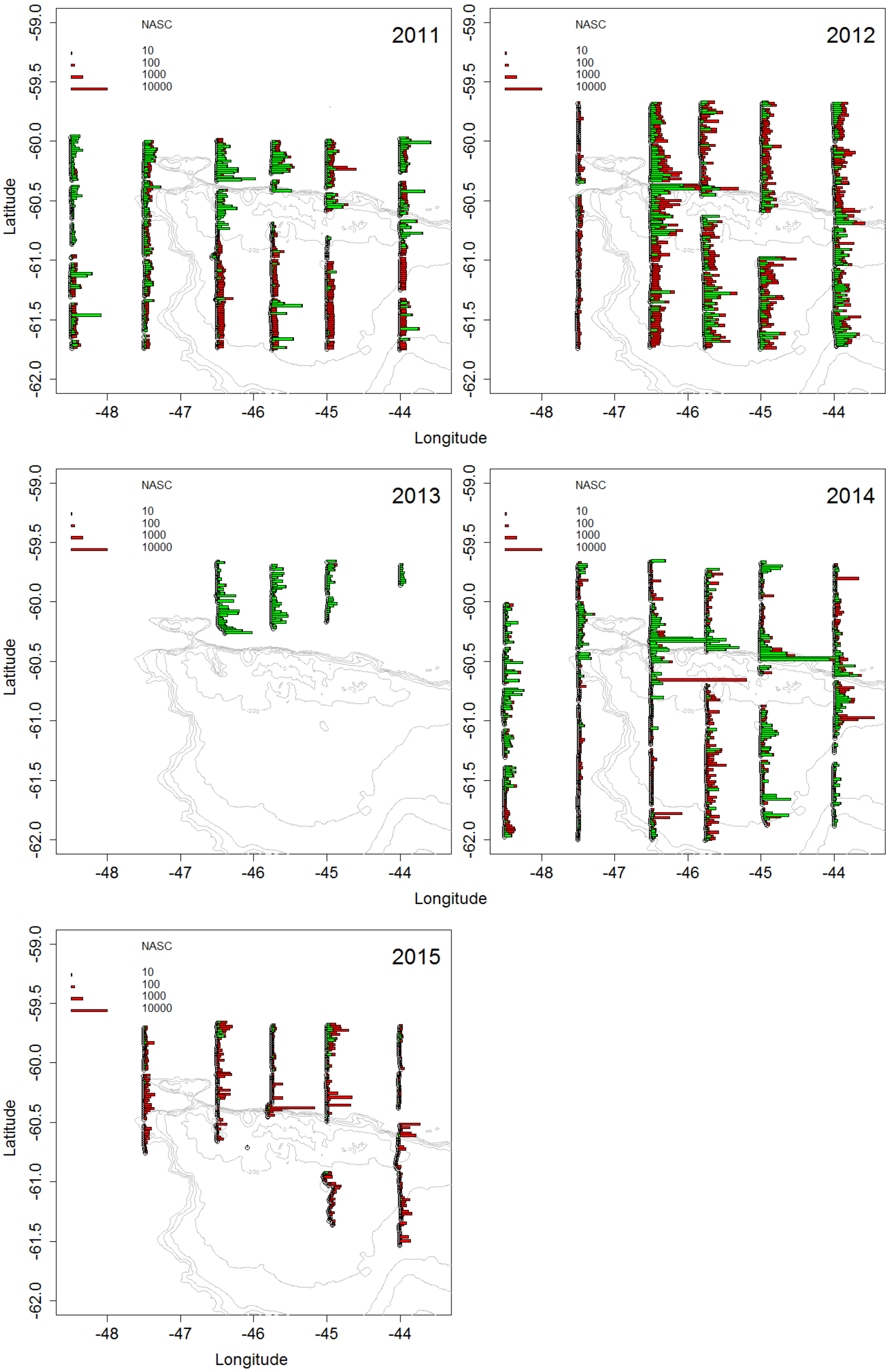
2011
2012
2013
2014
2015
NASC
10
100
1000
10000
Latitude
Longitude
-59.0
-59.5
-60.0
-60.5
-61.0
-61.5
-62.0
-48
-47
-46
-45
-44

Figure 3. Distribution of total NASC (red), and NASC allocated to krill (green) per nautical mile. The length of the bars is proportional to the square root of the NASC. Bathymetric contours are marked from 0-1000 m in steps of 200 m.

Table 4. Summary of total NASC and NASC allocated to krill for the 5 survey years.

		Entire area			Stratum		
Year	Frequency	NASC total	NASC krill	% krill	NASC total	NASC krill	% krill
2011	120	275581	162057	59	151662	103117	68
2012	120	617643	197527	32	282772	84937	30
2013	120	49230	45621	93			
2014	120	551012	329686	60	336363	258348	77
2015	70	90524	4396	5	72353	3997	6

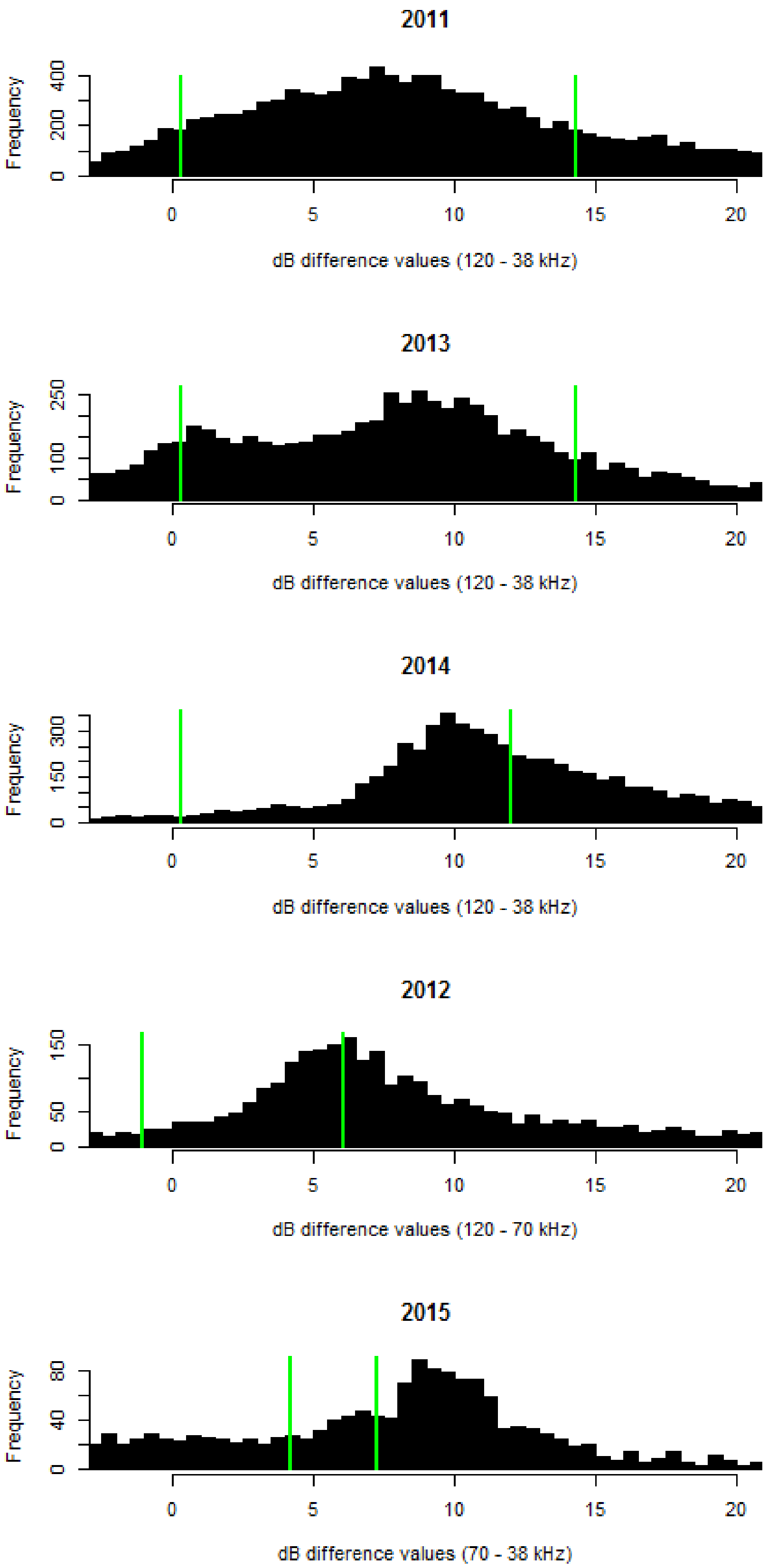

Figure 4. Distribution of dB difference-values, and window (green) derived from target strength estimations from the SDWBA model based on 95 % of the krill length distribution. See text for further details of how the method was applied.

References

Atkinson, A., Siegel, V., Pakhomov, E. A., Jessopp, M. J., and Loeb, V. 2009. A re-appraisal of the total biomass and annual production of Antarctic krill. Deep-Sea Research Part I-Oceanographic Research Papers, 56: 727-740.

Brierley, A. S., Goss, C., Watkins, J. L., and Woodroffe, P. 1998a. Variations in echosounder calibration with temperature, and some possible implications for acoustic surveys of krill biomass. Ccamlr Science, 5: 273-281.

Brierley, A. S., Ward, P., Watkins, J. L., and Goss, C. 1998b. Acoustic discrimination of Southern Ocean zooplankton. Deep-Sea Research Part Ii-Topical Studies in Oceanography, 45: 1155-1173.

Calise, L., and Skaret, G. 2011. Sensitivity investigation of the SDWBA Antarctic krill target strength model to fatness, material contrasts and orientation. Ccamlr Science, 18: 97-122.

CCAMLR 2010. Report of the fifth meeting of the Subgroup on Acoustic Survey and Analysis methods. SC-CAMLR-XXIX/6.

CCAMLR 2014a. Report of the Meeting of the Subgroup on Acoustic Survey and Analysis Methods. SC-CAMLR-XXXIII/4.

CCAMLR 2014b. Report of the thirty-third meeting of the scientific committee. SC-CAMLR-XXXIII.

Conti, S. G., and Demer, D. A. 2006. Improved parameterization of the SDWBA for estimating krill target strength. ICES Journal of Marine Science, 63: 928-935.

Croxall, J. P., Reid, K., and Prince, P. A. 1999. Diet, provisioning and productivity responses of marine predators to differences in availability of Antarctic krill. Marine Ecology Progress Series, 177: 115-131.

Demer, D. A. 2004. An estimate of error for the CCAMLR 2000 survey estimate of krill biomass. Deep-Sea Research Part Ii-Topical Studies in Oceanography, 51: 1237-1251.

Demer, D. A., and Conti, S. G. 2005. New target-strength model indicates more krill in the Southern Ocean. ICES Journal of Marine Science, 62: 25-32.

Fielding, S., Watkins, J. L., Trathan, P. N., Enderlein, P., Waluda, C. M., Stowasser, G., Tarling, G. A., et al. 2014. Interannual variability in Antarctic krill (Euphausia superba) density at South Georgia, Southern Ocean: 1997-2013. ICES Journal of Marine Science, 71: 2578-2588.

Foote, K. G., Vestnes, H. P., MacLennan, D. N., and Simmonds, E. J. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. ICES Cooperative Research Report, 144: 69 pp.

Friedlaender, A. S., Halpin, P. N., Qian, S. S., Lawson, G. L., Wiebe, P. H., Thiele, D., and Read, A. J. 2006. Whale distribution in relation to prey abundance and oceanographic processes in shelf waters of the Western Antarctic Peninsula. Marine Ecology Progress Series, 317: 297-310.

Godø, O. R., Reiss, C., Siegel, V., and Watkins, J. L. 2014. Commercial fishing vessel as research vessels in the Antarctic - requirements and solutions exemplified with a new vessel Ccamlr Science, 21: 11-17.

Hewitt, R. P., Watkins, J., Naganobu, M., Sushin, V., Brierley, A. S., Demer, D., Kasatkina, S., et al. 2004. Biomass of Antarctic krill in the Scotia Sea in January/February 2000 and its use in revising an estimate of precautionary yield. Deep-Sea Research Part Ii-Topical Studies in Oceanography, 51: 1215-1236.

Hewitt, R. P., Watkins, J. L., Naganobu, M., Tshernyshkov, P., Brierley, A. S., Demer, D. A., Kasatkina, S., et al. 2002. Setting a precautionary catch limit for Antarctic krill. Oceanography, 15(3): 26-33.

Jolly, G. M., and Hampton, I. 1990. A stratified random transect design for acoustic surveys of fish stocks. Canadian Journal of Fisheries and Aquatic Sciences, 47: 1282-1291.

Kock, K. H., Wilhelms, S., Everson, I., and Groger, J. 1994. Variations in the composition and feeding intensity of Mackerel icefish *Champsocephalus gunnari* at South Georgia (Antarctic). Marine Ecology Progress Series, 108: 43-57.

Korneliussen, R. J., Ona, E., Eliassen, I., Heggelund, Y., Patel, R., Godø, O. R., Giertsen, C., et al. 2006. The large scale survey system—LSSS. Proceedings of the 29th Scandinavian Symposium on Physical Acoustics, Ustaoset, 29 January to 1 February 2006: 6 pp.

Lawson, G. L., Wiebe, P. H., Stanton, T. K., and Ashjian, C. J. 2008. Euphausiid distribution along the Western Antarctic Peninsula - Part A: Development of robust multi-frequency acoustic techniques to identify euphausiid aggregations and quantify euphausild size, abundance, and biomass. Deep-Sea Research Part Ii-Topical Studies in Oceanography, 55: 412-431.

Madureira, L. S. P., Ward, P., and Atkinson, A. 1993. Differences in backscattering strength determined at 120 and 38 kHz for 3 species of Antarctic macroplankton. Marine Ecology-Progress Series, 93: 17-24.

Marr, J. 1962. The natural history and geography of the Antarctic krill (Euphausia superba Dana). *In* Discovery reports vol 32, pp. 33-464. National Institute of Oceanography, Cambridge University Press, Cambridge.

Nicol, S., Foster, J., and Kawaguchi, S. 2012. The fishery for Antarctic krill - recent developments. Fish and Fisheries, 13: 30-40.

Poncet, S., and Poncet, J. 1985. A survey of penguin breeding populations at the South Orkney Islands British Antarctic Survey Bulletin: 71-81.

Reid, K., and Arnould, J. P. Y. 1996. The diet of Antarctic fur seals Arctocephalus gazella during the breeding season at South Georgia. Polar Biology, 16: 105-114.

Reiss, C. S., Cossio, A. M., Loeb, V., and Demer, D. A. 2008. Variations in the biomass of Antarctic krill (Euphausia superba) around the South Shetland Islands, 1996-2006. ICES Journal of Marine Science, 65: 497-508.

Stanton, T. K., and Chu, D. Z. 2000. Review and recommendations for the modelling of acoustic scattering by fluid-like elongated zooplankton: euphausiids and copepods. ICES Journal of Marine Science, 57: 793-807.

Trivelpiece, W. Z., Trivelpiece, S. G., and Volkman, N. J. 1987. Ecological segregation of Adelie, Gentoo, and chinstrap penguins at King George Island, Antarctica. Ecology, 68: 351-361.

Watkins, J., Reid, K., Ramm, D., Zhao, X., Cox, M., Skaret, G., Fielding, S., et al. Submitted. The use of fishing vessels to provide acoustic data on the distribution and abundance of Antarctic krill and other pelagic species. Submitted for fisheries science.

Watkins, J. L., and Brierley, A. S. 2002. Verification of the acoustic techniques used to identify Antarctic krill. ICES Journal of Marine Science, 59: 1326-1336.

Watkins, J. L., Hewitt, R., Naganobu, M., and Sushin, V. 2004. The CCAMLR 2000 Survey: a multinational, multi-ship biological oceanography survey of the Atlantic sector of the Southern Ocean. Deep-Sea Research Part Ii-Topical Studies in Oceanography, 51: 1205-1213.

Appendix. Noise removal

The noise removal algorithms were run using the Large-Scale Survey Software (LSSS) in the following order and with the following settings:

Spike filter 1: Range: 10-100 m; TotalDelta: 10; VerticalDelta: 10; VerticalMedianSearchHeight: 30 m; WindowMedianSearchHeight: 7 m.
Spike filter 2: Range: 90-250 m; TotalDelta: 14; VerticalDelta: 14; VerticalMedianSearchHeight: 30 m; WindowMedianSearchHeight: 7 m.
Spot noise filter: Range: 10-250 m; Delta: 10.
Bubble noise filter 1: Range: 10-100 m; TotalDelta: 14; VerticalDelta: 14; VerticalMedianSearchHeight: 30 m; WindowMedianSearchHeight: 7 m.
Bubble noise filter 2: Range: 90-250 m; TotalDelta: 10; VerticalDelta: 10; VerticalMedianSearchHeight: 30 m; WindowMedianSearchHeight: 7 m.
Smoothing filter 1: MinPing: 0; MaxPing: 100; HorizontalWidth: 100 m;
VerticalWidth: $1e^{-15}$ m.
Noise quantification: TimeStepBufferMaxSize: 50; HistogramInitialisationCellCount: 2000; HistogramInitialisationSampleCount: 1000; HistogramMinimumSampleCount: 25000; HistogramSmoothFactor: 100.
Noise remover: MaxBufferSize: 10
Spike filter 3: Range: 10-100 m; TotalDelta: 20; VerticalDelta: 20; VerticalMedianSearchHeight: 35 m; WindowMedianSearchHeight: 7 m.
Spike filter 4: Range: 80-250 m; TotalDelta: 15; VerticalDelta: 15; VerticalMedianSearchHeight: 35 m; WindowMedianSearchHeight: 7 m.
Smoothing filter 2: MinPing: 0; MaxPing: 20; HorizontalWidth: 15 m;
VerticalWidth: 1 m.
Smoothing filter 3: MinPing: 0; MaxPing: 100; HorizontalWidth: 25 m;
VerticalWidth: 2.5 m.

Descriptions of parameters can be found in the LSSS help file.