Biomass and dispersion of Antarctic Krill across the Scotia Sea as estimated from a multi-ship acoustic and net survey conducted in January-February 2000.

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Abstract

High concentrations of Antarctic krill (*Euphausia superba*), krill predators and krill fishing effort are located in the Scotia Sea (Marr 1963, Laws 1985, Agnew and Nicol 1996). The fishery is regulated under the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR), part of the Antarctic Treaty system. In principle, the Commission of CCAMLR has adopted a feedback approach to management of the krill fishery, by which management measures are adjusted in response to ecosystem monitoring (Constable et al. 2000, Hewitt and Linen-Low 2000). However, such a management scheme remains to be fully developed. In the interim, a complementary approach, which defined and implemented provisions of Article II of the Convention in reference to the Scotia Sea krill stock, was adopted in order to set a precautionary yield. This approach, referred to here as the Generalized Yield Model (GYM), was scaled to an estimate of krill biomass in the Scotia Sea obtained in 1981 (Trathan et al. 1992). Recent reports of the Scientific Committee of CCAMLR have questioned the current relevance of this estimate (e.g. SC-CAMLR-XIV, Annex 4, Para. 4.61) and recommended a new survey.

In January-February of 2000, a collaborative survey for krill across the Scotia Sea was conducted aboard research vessels from Japan, Russia, the UK and the USA using active acoustic and net sampling (Watkins et al. #1 this volume). Survey design and sampling protocols are briefly described here. The procedures used during data analysis are described in more detail, including those used to: 1) review and prepare the raw data for processing; 2) delineate krill from all other acoustic backscatter; 3) convert integrated volume backscattering to krill biomass density; 4) sum krill biomass density over the survey strata; and 5) estimate the variance associated with the estimate of krill biomass.

Mean krill density across the survey area was estimated to be 21.4 g m^{-2} and total biomass was estimated to be 44.3 million tonnes (CV 11.4%). This estimate leads to a revised precautionary yield for krill in the Scotia Sea of 4 million tonnes (CAMLR-XIX). However, it must be cautioned that before the fishery can be permitted to expand to this

level it will be necessary to establish mechanisms to avoid concentration of fishing effort, particularly in proximity to colonies of land-breeding krill predators, and to consider the effects of krill immigrating into the region from multiple sources.

Introduction

A multi-nation, multi-ship survey of the Scotia Sea was conducted during the austral summer of 1999/2000 (Watkins et al. #1 this volume). The survey was conducted in support of the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR), part of the Antarctic Treaty system. The survey was thus referred to as the CCAMLR-2000 Survey. One of the primary objectives of the CCAMLR-2000 Survey was to estimate the biomass of Antarctic krill (*Euphausia superba*) in the Scotia Sea, specifically FAO Statistical Subareas 48.1, 48.2, 48.3 and 48.4. This paper presents the estimate along with the methods used to derive it.

Article II of the Convention mandates a precautionary approach to the management of resources and the Scientific Committee of CAMLR has adopted the Generalized Yield Model (GYM) as a tool to implement this provision (Constable et al. 2000). A simulation approach is used to determine the proportion (γ) of the unexploited biomass (B_0) that can be caught each year within defined risk criteria. The allowable catch, referred to as the precautionary yield (Y), is thus defined as:

$$Y = \gamma B_0$$

The factor γ is set by comparing the statistical distributions of exploited versus unexploited population biomasses using specific management criteria. In the case of Antarctic krill three criteria were established that reflect language in Article II. The first is to ensure that population size remains large enough to produce a stable number of recruits. Accordingly, the probability that the population biomass falls to less than 20% of its unexploited median level should be less than 10%. The second is to ensure that relationships between harvested and dependent species are maintained. Accordingly, the median population biomass should be at least 75% of its unexploited median level. The third is to prevent changes to the ecosystem that cannot be reversed over 20 or 30 years. Accordingly, risks are to be evaluated over a 20-year time period.

Risks are evaluated by simulating hundreds of population trajectories using values of abundance, recruitment, growth and mortality drawn from appropriate statistical distributions. This procedure incorporates both natural variability as well as uncertainty in parameter estimates. An age-structured population model is used to generate distributions of population biomasses, both unexploited and exploited at various fishing levels. The first criterion is examined by comparing the distribution of lowest population biomasses over the period of each population trajectory, and noting the value of γ at which 10% of this distribution is below 20% of the median unexploited population biomass. The second criterion is examined by comparing the distribution of population biomasses at the end of each population trajectory, and noting the value of γ at which the median of this distribution is 75% of the median unexploited population biomass. The third criterion is met by extending the trajectories over 20 years. The lowest value of γ is accepted as the most precautionary. This value together with an estimate of B_0 is used to set the precautionary yield for krill.

Two important parameters in this analysis are B_0 and its associated variance. These values are used to generate a distribution of population biomasses from which an initial biomass is drawn for each population trajectory. Once a value of γ is set, it is applied against B_0 in order to calculate the precautionary yield. Initially, an estimate of krill biomass was generated from acoustic data collected during the first international BIOMASS experiment (FIBEX)[1] in 1981 (Trathan et al. 1992), the only large-scale acoustic survey in this region prior to 2000. Exploitation had historically been low relative to the size of the fished resource such that an estimate of the standing stock was assumed to approximate (B_0). Recent reports of the Scientific Committee of CCAMLR

[1] In the early 1980's the Scientific Committee for Antarctic Research (SCAR) organized the BIOMASS Program (Biological Investigations of Antarctic Systems and Stocks). FIBEX (First International BIOMASS Experiment) was a multi-national multi-ship effort to conduct large-scale acoustic surveys over large areas of the Southern Ocean. See also El-Sayed, S.Z. (ed). 1994. *Southern Ocean ecology: the BIOMASS perspective*. Cambridge Univ. Press: 399 p.

have questioned the current relevance of this estimate (e.g. SC-CAMLR-XIV, Annex 4, Para. 4.61) and recommended a new survey.

The motivations for conducting a new survey were threefold. The first was the recognition of several technical improvements since the conduct of the FIBEX survey in the assessment of krill biomass using active acoustic methods (Everson et al 1990, Greene et al 1991, Hewitt and Demer 1991). The second was the recognition that the FIBEX survey area was substantially less than the known habitat of krill in the Scotia Sea. And the third was the recognition that the krill population in the Scotia Sea may not be stable. Recently published evidence suggests that krill reproductive success may be dependent on multi-year changes in the physical environment (Loeb et al 1997, Naganobu et al. 1999, Nicol et al 2000, White and Peterson 1996, Brierley et al. 1999). During periods of equator-ward excursions of the southern boundary of the Antarctic Circumpolar Current (ACC), the development of winter-time sea ice is more extensive, populations of *Salpa thompsoni* (a pelagic tunicate postulated to be a competitor with krill for access to the spring-time phytoplankton bloom) are displaced offshore, and both krill reproductive output and survival of their larvae are enhanced. During periods of pole-ward excursions of the southern boundary of the ACC, the development of wintertime sea ice is less extensive, salps are more abundant closer to shore and krill reproductive success is depressed. These interactions may be confounded by a warming trend observed in the Antarctic Peninsula over the last 50 years (Vaughan and Doake 1996). The intention was to anchor the estimate of precautionary yield with the most recent and most accurate assessment of Antarctic krill in the Scotia Sea that was possible. Because historical harvest rates have continued to remain low relative to the size of the fished resource, it was again assumed that an estimate of the current standing stock was equivalent to the unexploited biomass (B_0).

Plans for the survey developed over a period of five years through a series of working papers, discussions at the meetings of the Scientific Committee of CCAMLR and its working groups, and more formal workshops (SC-CAMLR-XIV, Annex 4, paragraphs 4.62-4.67; SC-CAMLR-XV, Annex 4, paragraphs 3.72-3.75; SC-CAMLR-

XVI, Annex 4, paragraphs 8.121-8.129; SC-CAMLR-XVII, Annex 4, paragraphs 9.49-9.90; SC-CAMLR-XVIII, Annex 4, paragraph 8.1-8.74 and appendix D). The final survey design and protocols for data collection are described by Watkins et al. #1 (this volume).

The survey was conducted during January and February 2000 using the R/V *Kaiyo Maru* (Japan), the R/V *Atlantida* (Russia), the RRS *James Clark Ross* (UK), and the R/V *Yuhzmorgeologiya* (a Russian research vessel under charter to the US) (see also Table 1). A workshop was subsequently held during two weeks in May-June 2000 in order to process the acoustic data and estimate B_0 and its associated variance. The Report of the B_0 Workshop was published as SC-CAMLR-XIX, Annex 4, Appendix G. Much of the information presented here is drawn from that report.

In the following sections the survey design and sampling protocols are briefly outlined, the acoustic data processing methods are described in more detail, the survey results are presented (as they relate to estimates of B_0 and its variance), and the application of these estimates to the determination of a precautionary yield for krill in the Scotia Sea is discussed.

Survey design and data collection protocols

The defining physical feature of the Scotia Sea is its southern boundary along the Scotia Ridge, extending from the South Shetland Islands east and north through the South Orkney Islands, the South Sandwich Islands and South Georgia (Figure 1). This ridge influences the direction and intensity of the ACC. Antarctic krill appear to move eastward through the Scotia Sea via the ACC, although the relative importance of passive transport versus active migration is uncertain. Likely sources of immigrants to the Scotia Sea are the Bellingshausen Sea to the west and the Weddell Sea to the south. Differences in mitochondrial DNA sequences suggest that krill from these regions may be genetically distinct (Zane et al. 1998). Within the Scotia Sea, zones of water convergence, eddies and gyres are loci for krill concentrations (Witek et al. 1988, Makarov et al. 1988). Krill spawn in the vicinity of the South Shetland and South Orkney Islands. Although they are abundant further to the north and east near South Georgia, they do not spawn there in great numbers and few larvae are found (Fraser 1936). Consumption of krill throughout the Scotia Sea by baleen whales, crabeater and fur seals, pygoscelid penguins and other sea birds, squid and fish is estimated to be between 16 and 32 million tonnes per annum (Everson and de la Mare 1996). Although higher in previous years, annual harvests of krill since 1992 have averaged approximately 100,000 tonnes[2]. Fishing effort has been concentrated near the shelf breaks along the north side of the South Shetland, South Orkney and South Georgia archipelagos (Agnew and Nicol 1996).

The survey area extended across the Scotia Sea and included the continental shelves, oceanic regions, the major frontal zones associated with the ACC and the principal areas of fishing activity (Figure 1a). The survey design consisted of seven strata (four large-scale strata and three meso-scale strata, Figure 1b) with randomly spaced parallel transects within each stratum. The mean density on a transect within a stratum, as determined from acoustic sampling of krill, was considered to be a representative sample of the mean density of the stratum (Jolly and Hampton 1990). Each vessel also obtained net samples and profiles of oceanographic parameters on stations conducted near local apparent noon and midnight each day of the survey.

Strata areas were estimated as:

Large-scale strata	
Antarctic Peninsula (AP)	473,318 km^2
Scotia Sea (SS)	1,109,789 km^2
East Scotia Sea (ESS)	321,800 km^2
Meso-scale strata	
South Shetland Islands (SSI)	48,654 km^2
South Orkney Islands (SOI)	24,409 km^2

[2] Harvest statisics for Antarctic krill are maintained by the CCAMLR Secretariat, P.O Box 213, North Hobart 7002, Tasmania, Australia. email: ccamlr@ccamlr.org; website: www.ccamlr.org

South Georgia (SG)	25,000 km^2
South Sandwich Islands (Sand)	62,274 km^2

All ships collected active acoustic data using Simrad EK500 echosounders (with firmware version 5.3, modified to generate 1 msec pulse duration for 200 kHz) connected to hull-mounted 38, 120 and 200 kHz transceivers. Table 2 lists transceiver and transducer specifics for each ship. Samples of volume backscattering strength (S_V) were collected every 0.71 m from each of the transducer faces to 500 m below the surface. Pings were fired simultaneously on all frequencies and the interval between pings was 2 sec. Pulse duration for all three frequencies was 1 msec. Data output telegrams from the EK500 echosounder were logged using SonarData's EchoLog software. Although acoustic data was logged on all ships continuously throughout the survey, transect data was only collected between the hours of local apparent sunrise and sunset. Nominal vessel speed was set at 10 knots. See Watkins et al. #1 (this volume) for additional details regarding the acoustic sampling protocols.

Acoustic system calibrations were undertaken before and after the survey. Initial calibrations were conducted in Stromness Bay, South Georgia. The second calibration was undertaken on completion of the survey in Stromness Bay by the personnel aboard the *Atlantida* and in Admiralty Bay, King George Island by personnel aboard the other three vessels. In addition, acoustic data were collected aboard each ship along fixed shallow water transects in Stromness Bay and Admiralty Bay.

All calibrations were undertaken using the standard sphere method (Foote et al. 1987, Foote 1990). The primary calibration spheres were 38.1 mm diameter tungsten carbide spheres from the same manufacturing lot, bored and fitted with monofilament loops. Standard copper spheres 60.0, 23.0 and 13.7 mm diameter, provided by each vessel, were also used for calibration.

Temperature and salinity at the calibration sites were similar and within the range of the major portion of the CCAMLR-2000 Survey area. In two instances inclement weather slightly prejudiced the quality of the results. For the R/V *Atlantida* the second calibration and for the R/V *Kaiyo Maru* the first calibration were considered to be the better of the two. For the R/V *Yuzhmorgeologiya* and the RRS *James Clark Ross* the mean values of the two calibrations were used. Calibration specifics for each ship are listed in Table 3. Additional details are to be found in the B_0 Workshop Report, Tables 8, 9, 10 and 11 (SC-CAMLR-XIX, Annex 4, Appendix G).

Krill were directly sampled using a Rectangular Midwater Trawl with an 8 m^2 mouth opening (RMT-8, Baker et al. 1973) near local apparent noon and midnight each day. The RMT-8 was fished obliquely down to 200 m and up to the surface, at a rate of 0.7-0.8 m of wire out per sec and 0.3 m of wire in per sec, while the survey vessel maintained a speed of 2.5 ± 0.5 knots. Each net was equipped with a flow meter in order to estimate the volume of water filtered, and a time-depth recorder with a real time display, in order to follow the trajectory of the net. Standard lengths and maturity stages were determined for every krill if the catch was less than 100 animals, or a subsample of at least 100 animals if the catch was larger. See Watkins et al. #1 (this volume) and Siegel et al. (this volume) for additional details regarding net sampling protocols.

Data processing methods

For the purpose of estimating krill biomass and the associated variance, data processing followed five steps:

1. Data preparation, including consideration of the appropriate values for sound velocity, absorption coefficients, wavelengths, two-way beam angles, depth of surface exclusion layer, bottom definition and offset, and procedures for elimination of non-transect data and allowance for noise.

2. Delineation and integration of volume backscattering attributed to krill. The method use to accomplish this was based on the expected difference in mean volume backscattering at 120 kHz versus 38 kHz (Watkins and Brierley 2000).

Volume backscattering attributed to krill was then summed over a depth range and averaged over a distance interval (integrated).

3. Conversion of integrated backscattering area attributed to krill to areal krill biomass density. The method used to accomplish this was to develop a series of conversion factors equal to the quotient of the weight of an individual krill (expressed as a function of length) and its backscattering cross-sectional area (expressed as a function of length) summed over the sampled length frequency distribution (Hewitt and Demer 1993).

4. Summation of areal krill biomass densities over the survey area (B_0). The method used to accomplish this was as proposed by Jolly and Hampton (1990) where the mean density over each transect is assumed to be a representative sample of the mean density in the stratum.

5. Estimation of the variance associated with an estimate of B_0. The method used was a ratio estimator of variance as proposed by Jolly and Hampton (1990). Additional sources of uncertainty were investigated by Demer (this volume).

Each of these steps is briefly described in the following sections.

1. Data preparation. SonarData's EchoView Version 2 software was used to assemble and annotate echograms from the ping-by-ping acoustic data. This allowed for an adjustment of parameters set in the echosounders during the data collection.

Prior to the survey historical profiles of seawater temperature and salinity across the Scotia Sea were examined. Averages, weighted in favor of those depths where krill were most often observed, were calculated and the corresponding sound velocity determined as 1449 m/sec. Examination of profiles obtained during the survey indicated that a value of 1456 m/sec would be more appropriate. Although this change had a very minor affect, the data were processed using the new value.

The following values of absorption coefficient were used during conduct of the CCAMLR-2000 Survey: 0.010 dB/m at 38 kHz, 0.026 dB/m at 120 kHz and 0.040 dB/m at 200 kHz. Using the equations of Francois and Garrrison (1982), the following revised values, appropriate to the actual survey conditions, were used during data processing: 0.010 dB/m at 38kHz, 0.028 dB/m at 120 kHz and 0.041 dB/m at 200 kHz.

The slight change in the accepted value of sound velocity required a recalculation of the wavelength. Using the nominal resonant frequency of the transducers the following values were determined for wavelength and used during data processing:

200 kHz:	1,456/200,000	=	0.00728 m
120 kHz:	1,456/119,050	=	0.01223 m
38 kHz:	1,456/37,880	=	0.03844 m

The equivalent two-way beam angle for each transducer, as provided by the manufacturer for a nominal sound speed of 1473 m/s, was adjusted for a sound velocity of 1449 m/s by the *James Clark Ross* and the *Atlantida* and used during CCAMLR-2000 Survey. No such adjustments were made for the *Kaiyo Maru* and the *Yuzhmorgeologiya* prior to the survey. The values were not adjusted during data processing and are listed in Table 2 along with transceiver and transducer specifics for each ship.

A surface exclusion layer depth of 15 m had been applied to data from the *Yuzhmorgeologiya* and the *Atlantida*, and 20 m for data from the *James Clark Ross* and the *Kaiyo Maru* based on previous experience. Because krill may occur near the surface, even during daylight hours, reconstructed echograms were reviewed and adjustments were made to include near-surface biological scatter or exclude surface noise spikes. This was carried out by a combination of changing the overall depth of the surface exclusion layer or editing small fragments of the surface exclusion layer around individual targets. Table 4 lists surface exclusion layer depths for each transect by ship.

Bottom as detected by the echosounder was visually verified from the re-constructed echograms and adjusted, if necessary, to ensure that bottom echoes were excluded from the integrated layer. The lower vertical limit of integration was set to 500 m or 2 m above the detected bottom where shallower.

No adjustment for noise was made during data collection activities (i.e. Noise Margin was set to zero under the EK500 Operation Menu). During data processing time-varied volume backscattering strength due to noise was estimated and subtracted from the echograms. Initial estimates of noise were made for each transect and frequency during the survey. During subsequent inspection of echograms several noise levels were modified. This was accomplished by comparing echograms made with the original data and those of pure noise using similar values for the absorption coefficient and the display threshold for volume backscattering strength. The noise level was adjusted until the "rainbow effect" on each display matched; another 2 dB was then added in order to arrive at a conservative adjustment for noise. The final values used are listed in Table 4. The noise adjustment was made after averaging S_V data into 5 m (vertical distance) by 50 ping (horizontal distance) bins (see Step 2).

Finally, reconstructed echograms were annotated to include in subsequent analyses only those data collected along the designated transects. Excluded were data collected between transects, during station times and the period between local apparent sunset and local apparent sunrise.

2. Delineation and integration of volume backscattering attributed to krill. The frequency dependence of the target strength of krill was used to delineate volume backscattering attributed to krill from all other volume backscattering.

The criterion used during data analyses was based on the frequency-specific expected target strength of krill over the size range encountered during the survey at 38 and 120 kHz. Regions of the reconstructed echograms were thus attributed to krill when the difference in mean volume backscattering strength at 120 kHz and that at 38 kHz was greater than 2 dB and less than 16 dB.

Comparisons of single samples of S_V were too variable to allow contiguous regions of the echograms to be delineated as krill. It was therefore necessary to average S_V over bins of finite vertical and horizontal dimensions. It was expected that the size of the bins would necessitate a tradeoff. If they were too small, the variability between S_V samples would cause the continuous nature of krill swarms and layers apparent on the echograms to be lost. If the bins were too large, the power to delineate krill was diminished because backscatter from both krill and non-krill scatterers would be averaged together. Experimentation with bin size on selected echograms indicated little change in integrated energy attributed to krill when bin size is set larger than some minimal dimensions and smaller than very large regions of the echograms. Bin size was set at 5 m vertical dimension and 50 pings horizontal direction (approximately 500 m at 2 sec pig interval and 10 knot survey speed), but comparable results could have been obtained if the bin size was half or double these dimensions.

Steps 1 and 2 of the data processing were implemented using SonarData's EchoView Version 2 software. For each transect adjustments to parameters set in the echosounders during the survey (as described above) were entered and ping-by-ping echograms were regenerated. Surface exclusion layers were set and adjusted where appropriate. Bottom detection was verified and modified where appropriate. Non-transect portions of the echogram were blocked out and removed from further consideration.

The echograms were then resampled using 5 m (vertical) by 50 ping (horizontal) bins. Time-varied noise echograms were created and subtracted from the resampled echograms. For each transect the 38 kHz noise-free resampled echogram was then subtracted from the 120 kHz noise-free resampled echogram. Portions of the 120 kHz noise-free resampled echogram were masked to exclude regions where the difference between the mean volume backscattering strength at 120 kHz and that at 38 kHz was less than 2 dB or greater than 16 dB. The masked noise-free resampled 120 kHz echogram was then integrated from the bottom of the surface exclusion layer to 500 m (2 m above the bottom if shallower than 500 m) and averaged over 1852 m horizontal distance intervals. These procedures as implemented in the EchoView software are set out in Appendix B.

The output from the analyses outlined above was a series of integrated backscattering areas attributed to krill, one value for each n. mile of acoustic transect. These values are in units of m^2 of backscattering area per square nautical mile of sea surface and are referred to as Nautical Area Scattering Coefficients (NASC), following the definition of s_A established by Simrad.

3. Conversion of integrated backscattering area to biomass density. The conversion factor (CF) was defined as the quotient of the weight of an individual krill (W) and its backscattering cross-sectional (σ) area summed over the length (L) frequency distribution:

$$CF = \frac{W(L)}{\sigma(L)}\left(\frac{g}{m^2}\right)$$

The areal biomass density of krill (ρ) is thus computed as the integrated backscattering area for each interval multiplied by the CF:

$$\rho = NASC \text{ x } CF$$

A weight-length relationship was derived from data collected aboard the Kaiyo Maru when working in Subarea 48.3 during the CCAMLR 2000 Survey using the following general form:

$$W(L) = aL^b$$

Where L is expressed in mm and W is expressed in g. Other published weight-length relationships that were considered included:

a	b	L (mm)	Source
0.925×10^{-6}	3.550	-	FIBEX 1

1.800 x 10^{-6}	3.383	-	FIBEX 2
2.236 x 10^{-6}	3.314	30-48	*Kaiyo Maru*, CCAMLR 2000 Survey
3.850 x 10^{-6}	3.200	26-59	Morris et al. (1988)
2.050 x 10^{-6}	3.325	23–60	Siegel (1992)

Backscattering cross-sectional area is defined as a function of target strength (TS):

$$\sigma(L) = 4\pi 10^{TS(L)/10} \ (m^2)$$

where the TS/length relationship at 120 kHz was that adopted for krill by CCAMLR in 1991 (SC-CAMLR-XII, Annex 5, Para. 4.24 – 4.30), which was derived from general relationship published by Greene et al. 1991:

$$TS(L) = -127.5 + 34.85\log(L)$$

Thus:

$$\sigma(L) = 4\pi 10^{(-127.5+34.85\log(L))/10}$$

$$= 4\pi 10^{-12.75} L^{3.485}$$

Substituting these relationships into the expression for CF and adjusting for units:

$$CF = \frac{0.002236(L)^{3.3314} x10^{-3}}{4\pi 10^{-12.75} L^{3.485}} \left(\frac{g}{m^2}\right)\left(\frac{1n.mile^2}{1852^2 m^2}\right)$$

$$= 0.2917L^{-0.171}$$

The final expression for CF is calculated by summing over the length frequency distribution:

$$CF = 0.2917\sum f_i(L)^{-0.171}$$

where $\sum f_i = 1$.

Cluster analysis performed on the net samples of krill collected over the CCAMLR 2000 Survey area indicated three geographically distinct regions (Siegel et al. this volume). Small krill (1-2 year old, 26 mm modal length) were mapped in the eastern portion of the Scotia Sea in a broad tongue extending from the southern part of the survey area between the South Orkney and South Sandwich Islands north to the eastern end of

South Georgia; very large krill (4-6 year old, 52 mm modal length) were mapped in the western Scotia Sea and Drakes Passage; a third cluster of large krill (3-5 year old, 48 mm modal length, but also including several samples of intermediate size krill) was mapped in the inshore waters adjacent to the Antarctic Peninsula and extended across the northeastern part of the survey area (Figure 2).

Conversion factors for each of these clusters were calculated and are listed in Table 5. Transects were subdivided where they crossed cluster boundaries and *NASC* values from portions of the transects in each cluster were multiplied by the appropriate *CF* in order to generate a series of areal krill biomass densities.

4. Summation of krill biomass density over the survey area. The mean density over each transect was assumed to be representative of the mean density of the stratum. The mean density of each stratum was thus calculated as the weighted average of all transects within each stratum, where the weighting was proportional to the length of each transect:

$$\overline{\rho}_k = \frac{1}{N_k}\sum_{j=1}^{N_k} w_j \overline{\rho}_j$$

where $\overline{\rho}_k$ is the mean areal krill biomass density in the kth stratum, N_k is the number of transects in the kth stratum, and w_j is the normalized weighting factor for the jth transect as defined below, and $\overline{\rho}_j$ is the mean areal krill biomass density on the jth transect as defined below.

For several reasons ships deviated from the planned transects. Such deviations included random effects caused by strong winds and ocean currents, and larger systematic deviations caused by avoidance of icebergs. To correct for these larger deviations, an expected change in latitude per nautical mile of transect, Δlat, was calculated for each transect in the survey design. The actual latitude made good, $\Delta l\hat{a}t$, was derived by differencing the latitudes of the beginning and end of each interval. An interval weighting W_I was calculated as:

$$W_I = \frac{|\Delta lat| - |(\Delta lat - \Delta l\hat{a}t)|}{|\Delta lat|}$$

If the deviation from the standard track line for a particular interval was greater than 10% (i.e. if $W_I < 0.9$), then the 1 n mile integral was scaled by W_I, otherwise $W_I = 1$.

The sum of the interval weightings along each transect was used to weight the transect means to provide a stratum biomass, such that:

$$L_j = \sum_{i=1}^{N_j} (W_I)_i$$

where L_j is the length of the *j*th transect, $(W_I)_i$ is the interval weighting of the *i*th interval, and N_j is the number of intervals in the *j*th transect. The normalized weighting factor for the *j*th transect (w_i) was defined as:

$$w_j = \frac{L_j}{\frac{1}{N_k}\sum_{j=1}^{N_k} L_j} \quad \text{such that} \quad \sum_{j=1}^{N_k} w_j = N_k$$

The mean areal krill biomass density over all intervals on the jth transect ($\overline{\rho}_j$) was defined as:

$$\overline{\rho}_j = \frac{1}{L_j}\sum_{i=1}^{N_j} (NASC)_i (CF)_i (W_I)_i$$

where $(NASC)_i$ is the integrated backscattering area for the *i*th interval and $(CF)_i$ is the conversion factor for the *i*th interval.

Total biomass over the survey area was calculated as:

$$B_0 = \sum_{k=1}^{N} A_k \overline{\rho}_k$$

where A_k is the area of the *k*th stratum and N is the number of strata in the survey. Mean density over the survey area is thus calculated as:

$$\bar{\rho} = \frac{\sum_{k=1}^{N} A_k \bar{\rho}_k}{\sum_{k=1}^{N} A_k}$$

See Appendix B for formulae used to estimate mean areal krill biomass density and its variance over intervals, transects, strata and the total survey area.

5. Estimation of variance.

The variance of the mean areal krill biomass density in the *k*th stratum was calculated as:

$$Var(\bar{\rho}_k) = \frac{N_k}{N_k - 1} \frac{\sum_{j=1}^{N_k} w_j^2 (\bar{\rho}_j - \bar{\rho}_k)^2}{\left(\sum_{j=1}^{N_k} w_j\right)^2} = \frac{\sum_{j=1}^{N_k} w_j^2 (\bar{\rho}_j - \bar{\rho}_k)^2}{N_k (N_k - 1)}$$

The contribution of the *k*th stratum to the overall survey variance of B_0 was defined as:

$$VarComp_k = A_K^2 Var(\bar{\rho}_k)$$

so that the overall survey variance of the mean areal krill biomass density calculated as:

$$Var(\bar{\rho}) = \frac{\sum_{k=1}^{N} A_k^2 Var(\bar{\rho}_k)}{\left(\sum_{k=1}^{N} A_k\right)^2} = \frac{\sum_{k=1}^{N} VarComp_k}{\left(\sum_{k=1}^{N} A_k\right)^2}$$

and the overall survey variance of B_0 was calculated as:

$$Var(B_0) = \sum_{k=1}^{N} VarComp_k$$

See Appendix B for formulae used to estimate mean areal krill biomass density, and its variance, over intervals, transects, strata and the total survey area.

For the purpose of generating maps of the dispersion of krill across the survey area, estimates of mean areal krill biomass density were interpolated onto a grid, whose dimensions were 2º of longitude by 1º of latitude, and then contouring the grid values. Interpolation was accomplished by Krigging assuming a linear model of variance between points as a function of distance.

Results

Estimates of areal krill biomass density by transect, strata and survey are listed in Tables 6 and 7. Highest densities of krill were encountered in the island strata, ranging from 25.8 g m^{-2} (CV 26.4%) near the South Sandwich Islands to 150.4 g m^{-2} (CV 55.5%) near the South Orkney Islands; densities in the oceanic strata ranged from 11.2 g m^{-2} (CV 19.3%) off the Antarctic Peninsula to 24.54 g m^{-2} (CV 15.3%) in the western Scotia Sea; total krill biomass over the survey area was estimated at 44.3 million tonnes (CV 11.4%).

Although the highest biomasses of krill were estimated for the oceanic strata, the highest biomass densities were mapped along the Scotia Ridge (Figure 3), in areas where the fishery has operated in previous years (Figure 1a). An area of moderately high krill biomass density was mapped to the south and east of South Georgia in water greater than 2000 m depth. Approximately two-thirds of the estimated krill biomass in Subareas 48.1, 48.2, 48.3 and 48.4 is located in areas where fishing has not occurred. Anecdotal evidence suggests that extensive fishing in the large-scale strata has not occurred because biomass densities are low and/or the location of fishable concentrations is not predictable.

The variances reported are based on transect to transect sampling variability. Additional sources of uncertainty associated with the characterization of TS, the probability of detection, and the efficiency of the algorithms used for delineation of backscatter attributed to krill were evaluated by Demer (this volume). Total error was evaluated by estimating krill biomass from acoustic backscatter for each of the three frequencies, and assuming that the identified errors affect each of these estimates independently. Results from a Monte Carlo simulation of this process indicate that the mean of the total error distribution is not significantly different from the estimated sampling variability (i.e. the measurement variance would be negligible relative to the sampling variance if averaged over many surveys).

Discussion

The estimate of B_0 and its associated variance derived from the CCAMLR 2000 Survey were used to set γ at 0.091 (SC-CAMLR-XIX, Annex 4, Para. 2.96 – 2.113, Table 1 reprinted here as Table 8). The precautionary yield (Y) for krill in Subareas 48.1, 48.2 , 48.3 and 48.4, where $\gamma Y = B_0$, was set at 4 million tonnes.

Before the fishery can expand to this level, however, it will be necessary to establish mechanisms to avoid concentration of fishing effort near colonies of land-breeding krill predators. In the absence of detailed information regarding dispersion and movement of krill throughout their habitat, demand by krill predators, and variability in recruitment and the factors that control it, an earlier form of the GYM was adopted in order to establish the original precautionary yield (Butterworth et al. 1991, 1994). The current form of the GYM still assumes a freely distributed krill population, homogeneously distributed predation pressure and randomly determined recruitment. The effects of uncertainty with regard to input parameters are included, but spatial and temporal trends in krill demographics, predator demand and fishing pressure are not. Several CCAMLR members are conducting research studies and long-term monitoring in order to provide some of this information (Agnew 1997), but until a more complete management scheme is in place the model will remain the primary tool for regulating the fishery.

One approach to refining the management scheme is to modify the GYM so as to allow some of the input parameters to be spatially explicit. In this manner spatial variations in predator demand, resulting in spatial variations in krill mortality, could be incorporated. Similar considerations could be made for recruitment and transport. The GYM would still treat the krill population in Subareas 48.1, 48.2, 48.3 and 48.4 as a single stock, but allowances would be made for variability in population parameters across the Scotia Sea. Results from the CCAMLR 2000 Survey suggest, however, that krill may be transported into the Scotia Sea from two sources (Siegel et al. this volume, Watkins et al. #2 this volume) and that the assumption of a single stock may be invalid.

A complementary approach, currently being investigated by CCAMLR, is the establishment of smaller management units (SC-CAMLR-XX, Para. 6.15 – 6.19). Constable and Nicol (submitted) suggested that a first step in this approach could be to divide the larger Subareas into non-overlapping land-breeding krill predator foraging areas. This was thought to be tractable because the principal archipelagoes, where breeding colonies of krill predators are located, are separated by distances larger than the predator foraging ranges. Information regarding predator foraging areas and prey demand would be complemented with information regarding the immigration and emigration of krill through the areas and information regarding the tactical behavior of the fishery within these areas. These data could then be used to more rationally divide the precautionary yield among these smaller management units.

The establishment of smaller management units as a method for disbursing the harvest also assumes the existence of a single stock. However, monitoring within the units would allow for information feedback, and consequent adjustments to allocation of yield among the units as well as characterization of input parameters to the population model. Identification and monitoring of key processes regulating the krill-centric ecosystem (Hewitt and Linen-Low 2000) would thus contribute to both the long-term and interim goals of CCAMLR.

Smaller management units may also be used in an experimental fashion. For example, certain units could be closed to fishing while the fishing level in other units may be allowed to approach γ (Constable and Nicol submitted). Suitable monitoring schemes could be established to provide the data necessary to test key assumptions and predictions.

Deposition of data

Copies of all data files, including raw ping-by-ping echosounder output telegrams (EK5 files), echogram annotation files (EV files), various integration output files (CSV files) and summary tables (MS Excel files), are maintained at the CCAMLR Secretariat in Hobart, Australia. See *Rules For Access and Use of CCAMLR Data*, available on the CCAMLR Web Site: www.ccamlr.org

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Table Captions

Table 1. Summary of survey and calibration activities undertaken by vessels during the CCAMLR 2000 Survey. Large-scale strata: AP – Antarctic Peninsula, SS – Scotia Sea , ESS – Eastern Scotia Sea. Mesoscale strata: SSI – South Shetland Islands, SOI – South Orkney Islands, SG – South Georgia, Sand – South Sandwich Islands.

Table 2. Ship-specific transducer specifications and transceiver settings. Values in parentheses were those used during data processing.

Table 3. Calibration specifics for each ship.

Table 4. Surface exclusion layer depths and noise levels (dB) for each transect by ship. Atl – R/V *Atlantida*; JCR – RRS *James Clark Ross*; KyM – R/V *Kaiyo Maru*; Yuz – R/V *Yuzhmorgeologiya*.

Table 5. Factors for converting integrated backscattering area (NASC in units of m^2 of backscattering area per n. mile2 of sea surface) to areal krill biomass density (ρ in units of g/m^2).

Tables 6. Mean areal krill biomass densities (ρ) and associated variances by transect and stratum. See Appendix B for description of labels and formulae.

Table 7. Mean areal krill biomass density (ρ) and standing stock (B_0), and associated variances, by stratum and for the entire survey. See Appendix B for description of labels and formulae.

Table 8. Input parameters to the GYM for evaluating γ based on the estimated coefficient of variance (CV) of B_0 and the timing of the CCAMLR 2000 Survey for krill in Seubareas 48.1, 48.2, 48.3 and 48.4.

Figure Captions

Figure 1. Island groups and bathymetry of the Scotia Sea (shading indicates 500 m, 1000 m, and 3000 m isobaths). **a.** Survey strata outlined in green relative to historical fishing activity (red squares) and major ocean frontal zones (blue lines; from north to south, the Sub-Antarctic Front, the Polar Front, the Southern ACC Front, and the southern ACC Boundary). **b.** Survey transects color coded, where violet indicates those transects occupied by the Japanese R/V *Kaiyo Maru*, yellow indicates the Russian R/V *Atlantida*, blue indicates the British RRS *James Clark Ross*, and red indicates the US chartered R/V *Yuzhmorgeologiya*. Arrows indicate direction of major currents.

Figure 2. Composite krill length-frequency distributions and the geographic distribution of stations for each cluster (from Siegel et al. this volume).

Figure 3. Dispersion of krill biomass density over the survey area.

Appendices

Appendix A. EchoView procedures and virtual variables, where raw variables are designated as: Q1 – 38 kHz raw data and Q2 – 120 kHz raw data.

Appendix B. Descriptors for labels in Tables 6, 7 and 8, where *i* is used to index intervals along a transect, *j* is used to index transects within a stratum, and *k* is used to index strata.

Table 1. Summary of survey and calibration activities undertaken by vessels during the CCAMLR 2000 Survey. Large-scale strata: AP – Antarctic Peninsula, SS – Scotia Sea , ESS – Eastern Scotia Sea. Mesoscale strata: SSI – South Shetland Islands, SOI – South Orkney Islands, SG – South Georgia, Sand – South Sandwich Islands.

	Vessel			
	Atlantida	*Kaiyo Maru*	*James Clark Ross*	*Yuzhmorgeologiya*
Survey				
Survey strata	ESS, Sand	AP, SS, SSI	AP, SS	AP, SS, SG, SOI
CCAMLR subareas	48.4	48.1 48.2 48.3	48.1 48.2 48.3	48.1 48.2 48.3
Start date	17 January	11 January	18 January	13 January
End date	1 February	2 February	10 February	4 February
Number of large-scale transects	3	6	7	6
Transect names	SSA SSB SSC	SS03 SS06 SS09 AP12 AP15 AP18	AP13 AP16 AP19 SS01 SS04 SS07 SS10	AP11 AP14 AP17 SS02 SS05 SS08
Number of meso-scale transects	10	8	0	8
Transect names	Sand01-10	SSI01-08		SG01-04 SOI01-04
Calibration				
Pre-survey				
Date	14 January	9 January	16 January	12 January
Location	Stromness Bay	Stromness Bay	Stromness Bay	Stromness Bay
Post-survey				
Date	5 February	4 February	11 February	7 March
Location	Stromness Bay	Admiralty Bay	Admiralty Bay	Admiralty Bay

Table 2. Ship-specific transducer specifications and transceiver settings during data collection. Values in parentheses indicate adjusted values used during data processing.

Transceiver	Specification/Setting	*Atlantida*	*James Clark Ross*	*Kaiyo Maru*	*Yuzhmorgeologiya*
1 (38 kHz, Split beam)	Transducer type	ES38B	ES38B	ES38B	ES38-12
	Transducer depth (m)	5.0	5.7	5.8	7.0
	Transmitted power (W)	2000	2000	2000	1000
	Pulse length (ms)	1.0	1.0	1.0	1.0
	Absorption coef. (dB/m)	0.010	0.010	0.010	0.010
	Sound speed (m/sec)	1449 (1456)	1449 (1456)	1449 (1456)	1485 (1456)
	Wavelength (m)	0.03868 (0.03844)	0.03868 (0.03844)	0.03868 (0.03844)	0.03868 (0.03844)
	Two-way beam angle (dB)	-21.2	-20.8	-20.9	-15.9
	S_v transducer gain (dB)	23.43 (23.32)	25.49 (25.51)	27.06	22.43 (22.36)
	TS transducer gain (dB)	23.76 (23.50)	25.60	27.32	22.64 (22.51)
	Angle sens. along	21.9	21.9	21.9	12.5
	Angle sens. athw.	21.9	21.9	21.9	12.5
	3 dB beamw. along (°)	7.1	7.0	6.8	12.2
	3 dB beamw. athw. (°)	7.1	7.1	6.9	12.2
2 (120 kHz, Split beam)	Transducer type	ES120-7	ES120	ES120-7	ES120-7
	Transducer depth (m)	5.0	5.70	5.8	7.0
	Transmitted power (W)	1000	1000	1000	1000
	Pulse length (ms)	1.0	1.0	1.0	1.0
	Absorption coef. (dB/m)	0.026 (0.028)	0.026 (0.028)	0.026 (0.028)	0.026 (0.028)
	Sound speed (m/sec)	1449 (1456)	1449 (1456)	1449 (1456)	1485 (1456)
	Wavelength (m)	0.01225 (0.01223)	0.01225 (0.01223)	0.01225 (0.01223)	0.01225 (0.01223)
	Two-way beam angle (dB)	-20.9	-18.4	-20.6	-20.4
	S_v transducer gain (dB)	23.23 (24.49)	20.26 (20.20)	24.74	25.37 (25.26)
	TS transducer gain (dB)	23.29 (24.66)	20.26 (20.18)	24.83	25.56 (25.37)
	Angle sens. along	15.7	15.7	21.0	21.0
	Angle sens. athw.	15.7	15.7	21.0	21.0
	3 dB beamw. along (°)	7.3	9.3	7.1	7.3
	3 dB beamw. athw. (°)	7.3	9.3	7.1	7.3
3 (200 kHz, Single beam)	Transducer type	200_28	200_28	200_28	200_28
	Transducer depth (m)	5.0	5.70	5.8	7.0
	Transmitted power (W)	1000	1000	1000	1000
	Pulse length (ms)	1.0	1.0	1.0	1.0
	Absorption coef. (dB/m)	0.040 (0.041)	0.040 (0.041)	0.040 (0.041)	0.040 (0.041)
	Sound speed (m/sec)	1449 (1456)	1449 (1456)	1449 (1456)	1485 (1456)
	Wavelength (m)	0.00735 (0.00728)	0.00735 (0.00728)	0.00735 (0.00728)	0.00735 (0.00728)
	Two-way beam angle (dB)	-20.3	-20.8	-20.5	-20.5
	S_v transducer gain (dB)	24.83 (23.26)	22.78 (22.91)	25.76	26.12 (25.96)
	TS transducer gain (dB)	24.50 (23.47)	23.07 (23.12)	25.78	26.12 (25.96)
	3 dB beamw. along (°)	7.1	6.9	7.1	7.1
	3 dB beamw. athw. (°)	7.1	7.1	7.1	7.1

Table 3. Calibration specifics for each ship.

R/V *Atlantida*	First Calibration	Second Calibration	First Calibration	Second Calibration	First Calibration	Second Calibration
Date	13-Jan-00	05-Feb-00	13-Jan-00	05-Feb-00	13-Jan-00	05-Feb-00
Location	Stromness Bay	Stromness Bay	Stromness Bay	Stromness Bay	Stromness Bay	Stromness Bay
Transducer	ES38B	ES38B	ES120-7	ES120-7	200_28	200_28
Water depth (m)	56	53	54	53	54	53
Sound speed (m/s)	1 457	1 460	1 457	1 460	1 457	1 460
Alpha (dB/km)	10	10	28	28	41	41
Transmit power (watts)	2 000	2 000	1 000	1 000	1 000	1 000
Pulse duration (m/s)	1	1	1	1	1	1
Bandwidth (kHz)	3.8 (10%)	3.8 (10%)	1.2 (1%)	1.2 (1%)	2.0 (1%)	2.0 (1%)
2-way beam angle (dB)	-21.2	-21.2	-20.9	-20.9	-20.3	-20.3
Sphere type	60.0 mm CU	38.1 mm WC	23.0 mm CU	38.1 mm WC	13.7 mm CU	38.1 mm WC
Range to sphere (m)	17.1	14.5	15.0	15.9	14.7	15.5
Calibrated S_v gain (dB)	23.43	23.32	23.23	24.49	24.83	23.26
Selected S_v gain (dB)		23.32		24.49		23.26
Calibrated TS gain (dB)	23.76	23.50	23.29	24.66	24.50	23.47
Selected TS gain (dB)		23.50		24.66		23.47
RRS *James Clark Ross*						
Date	16-Jan-00	12-Feb-00	16-Jan-00	12-Feb-00	16-Jan-00	12-Feb-00
Location	Stromness Bay	Admiralty Bay	Stromness Bay	Admiralty Bay	Stromness Bay	Admiralty Bay
Transducer	ES38B	ES38B	ES120	ES120	200_28	200_28
Water depth (m)	54	264	54	264	54	264
Sound speed (m/s)	1 458	1 455	1 458	1 455	1 458	1 455
Alpha (dB/km)	10	10	27	27	41	41
Transmit power (watts)	2 000	2 000	1 000	1 000	1 000	1 000
Pulse duration (m/s)	1	1	1	1	1	1
Bandwidth (kHz)	3.8 (10%)	3.8 (10%)	1.2 (1%)	1.2 (1%)	2.0 (1%)	2.0 (1%)
2-way beam angle (dB)	-20.8	-20.8	-18.4	-18.4	-20.8	-20.8
Sphere type	38.1 mm WC	38.1 mm WC	38.1 mm WC	38.1 mm WC	38.1 mm WC	38.1 mm WC
Range to sphere (m)	27.7	29.9	28.2	29.73	28.2	28.7
Calibrated S_v gain (dB)	25.49	25.53	20.26	20.09	22.78	23.04
Selected S_v gain (dB)		25.51		20.20		22.91
Calibrated TS gain (dB)	25.60	25.60	20.26	20.15	23.07	23.16
Selected TS gain (dB)		25.60		20.18		23.12

Table 3. Calibration specifics for each ship (cont).

R/V *Kaiyo Maru*	First Calibration	Second Calibration	First Calibration	Second Calibration	First Calibration	Second Calibration
Date	09-Jan-00	04-Feb-00	09-Jan-00	04-Feb-00	09-Jan-00	04-Feb-00
Location	Stromness Bay	Admiralty Bay	Stromness Bay	Admiralty Bay	Stromness Bay	Admiralty Bay
Transducer	ES38B	ES38B	ES120-7	ES120-7	200_28	200_28
Water depth (m)	80	58	80	58	80	58
Sound speed (m/s)	1 453	1 453	1 453	1 453	1 453	1 453
Alpha (dB/km)	10	10	28	27	41	40.5
Transmit power (watts)	2 000	2 000	1 000	1 000	1 000	1 000
Pulse duration (m/s)	1	1	1	1	1	1
Bandwidth (kHz)	3.8 (10%)	3.8 (10%)	1.2 (1%)	1.2 (1%)	2.0 (1%)	2.0 (1%)
2-way beam angle (dB)	-20.9	-20.9	-20.6	-20.6	-20.5	-20.5
Sphere type	38.1 mm WC	38.1 mm WC	38.1 mm WC	38.1 mm WC	38.1 mm WC	38.1 mm WC
Range to sphere (m)	30.6	30.0	30.0	29.9	30.5	30.1
Calibrated S_v gain (dB)	27.06	27.09	24.74	24.30	25.76	25.74
Selected S_v gain (dB)		27.06		24.74		25.76
Calibrated TS gain (dB)	27.32	27.35	24.83	24.55	25.78	25.77
Selected TS gain (dB)		27.32		24.83		25.78
R/V *Yuzhmorgeologiya*						
Date	12-Jan-00	07-Mar-00	12-Jan-00	07-Mar-00	12-Jan-00	07-Mar-00
Location	Stromness Bay	Admiralty Bay	Stromness Bay	Admiralty Bay	Stromness Bay	Admiralty Bay
Transducer	ES38-12	ES38-12	ES120-7	ES120-7	200_28	200_28
Water depth (m)	88	75	88	75	88	75
Sound speed (m/s)	1 450	1 450	1 450	1 450	1 450	1 450
Alpha (dB/km)	10	10	26	26	40	40
Transmit power (watts)	1 000	1 000	1 000	1 000	1 000	1 000
Pulse duration (m/s)	1	1	1	1	1	1
Bandwidth (kHz)	3.8 (10%)	3.8 (10%)	1.2 (1%)	1.2 (1%)	2.0 (1%)	2.0 (1%)
2-way beam angle (dB)	-15.9	-15.9	-20.4	-20.4	-20.5	-20.5
Sphere type	38.1 mm WC	38.1 mm WC	38.1 mm WC	38.1 mm WC	38.1 mm WC	38.1 mm WC
Range to sphere (m)	30.0	38.0	29.2	37.6	29.0	37.6
Calibrated S_v gain (dB)	22.43	22.29	25.37	25.16	26.12	25.80
Selected S_v gain (dB)		22.36		25.26		25.96
Calibrated TS gain (dB)	22.64	22.37	25.56	25.17	26.12	25.80
Selected TS gain (dB)		22.51		25.37		25.96

Table 4. Surface exclusion layer depths and noise levels (dB) for each transect by ship. Atl – R/V *Atlantida*; JCR – RRS *James Clark Ross*; KyM – R/V *Kaiyo Maru*; Yuz – R/V *Yuzhmorgeologiya*.

Ship	Transect	Surface Layer (m)	Noise (S_v re 1 m)		
			38 kHz	120 kHz	200 kHz
Yuz	SG01	20	-123.00	-123.00	-123.00
Yuz	SG02	20	-124.00	-120.00	-121.00
Yuz	SG03	20	-125.00	-124.00	-124.00
Yuz	SG04	15	-137.00	-129.00	-124.00
Yuz	SS02	20	-137.00	-123.00	-124.00
Yuz	SS05	15	-135.00	-125.00	-123.00
Yuz	SS08	15	-131.00	-125.00	-123.00
Yuz	SOI01	15	-126.00	-120.00	-119.00
Yuz	SOI02	15	-126.00	-122.00	-123.00
Yuz	SOI03	15	-129.00	-122.00	-122.00
Yuz	SOI04	20	-135.00	-127.00	-122.00
Yuz	AP11	20	-129.00	-120.00	-123.00
Yuz	AP14	15	-129.00	-120.00	-125.00
Yuz	AP17	20	-121.00	-120.00	-117.00
Atl	Sand01	15	-127.00	-136.50	-135.00
Atl	Sand02	15	-127.00	-136.50	-135.00
Atl	Sand03	15	-127.00	-136.50	-135.00
Atl	Sand04	15	-127.00	-136.50	-135.00
Atl	Sand05	15	-127.00	-136.50	-135.00
Atl	Sand06	15	-127.00	-136.50	-135.00
Atl	Sand07	15	-127.00	-136.50	-135.00
Atl	Sand08	15	-127.00	-136.50	-135.00
Atl	Sand09	15	-127.00	-136.50	-135.00
Atl	Sand10	15	-127.00	-136.50	-135.00
Atl	SSa	15	-127.00	-136.50	-135.00
Atl	SSb	15	-127.00	-136.50	-135.00
Atl	SSc	15	-127.00	-136.50	-135.00
JCR	SS01	20	-150.00	-124.00	-110.00
JCR	SS04	15	-150.00	-124.00	-112.00
JCR	SS07	20	-150.00	-124.00	-112.00
JCR	SS10	20	-150.00	-124.00	-110.00
JCR	AP13	20	-150.00	-124.00	-110.00
JCR	AP16	20	-150.00	-124.00	-110.00
JCR	AP19	20	-152.00	-124.00	-110.00
KyM	SS03	20	-136.40	-136.40	-134.40
KyM	SS06	20	-147.40	-136.40	-138.10
KyM	SS09	20	-141.90	-136.80	-138.40
KyM	AP12	20	-147.00	-135.70	-135.10
KyM	AP15	20	-148.10	-136.20	-136.10
KyM	AP18	20	-147.40	-136.60	-136.80
KyM	SSI01	20	-140.90	-136.60	-134.40
KyM	SSI02	20	-138.90	-136.60	-133.40
KyM	SSI03	20	-144.90	-136.60	-133.40
KyM	SSI04	20	-141.90	-136.60	-135.40
KyM	SSI05	20	-144.90	-136.60	-134.40
KyM	SSI06	20	-146.90	-136.60	-135.40
KyM	SSI07	20	-149.90	-136.60	-135.40
KyM	SSI08	20	-152.90	-136.60	-135.40

Table 5. Factors for converting integrated backscattering area (NASC in units of m^2 of backscattering area per n. mile2 of sea surface) to areal krill biomass density (ρ in units of g/m^2). Factors for 120 kHz were derived as explained in the text. Factors for 38 and 200 kHz were derived by evaluating the Greene et al. (1991) equation at these frequencies, where $TS_{38} = -132.44 + 34.85 \log(L)$ and $TS_{200} = -125.23 + 34.85 \log(L)$.

	Cluster 1	Cluster 2	Cluster 3	Clusters 2+3	Clusters 1+2+3
120 kHz					
FIBEX 1	0.1481	0.1523	0.1536	0.1526	0.1508
FIBEX 2	0.1656	0.1583	0.1557	0.1576	0.1609
CCAMLR-2000	0.1636	0.1517	0.1477	0.1506	0.1560
Morris et al. (1988)	0.1931	0.1703	0.1630	0.1684	0.1785
Siegel (1992)	0.1556	0.1449	0.1414	0.1440	0.1487
38 kHz					
FIBEX 1	0.4672	0.4805	0.4847	0.4815	0.4757
FIBEX 2	0.5224	0.4993	0.4913	0.4971	0.5075
CCAMLR-2000	0.5163	0.4786	0.4661	0.4753	0.4921
Morris et al. (1988)	0.6092	0.5372	0.5142	0.5311	0.5630
Siegel (1992)	0.4909	0.4573	0.4461	0.4543	0.4693
200 kHz					
FIBEX 1	0.0888	0.0914	0.0921	0.0915	0.0904
FIBEX 2	0.0993	0.0949	0.0934	0.0945	0.0964
CCAMLR-2000	0.0982	0.0910	0.0886	0.0904	0.0936
Morris et al. (1988)	0.1158	0.1021	0.0977	0.1010	0.1070
Siegel (1992)	0.0933	0.0869	0.0848	0.0864	0.0892

Tables 6. Mean areal krill biomass densities (ρ) and associated variances by transect and stratum. See Appendix B for description of labels and formulae.

Transect						Stratum Krill Density		
Name	Length (n miles)	Weighting Factor	Krill Density		Variance Component	Mean (g/m^2)	Variance	CV (%)
			Measured (g/m^2)	Weighted (g/m^2)				
AP11	95.99	0.67	12.83	8.59	1.13	11.24	4.70	19.29
AP12	194.66	1.36	15.58	21.17	34.79			
AP13	133.00	0.93	11.79	10.94	0.26			
AP14	76.59	0.53	18.06	9.65	13.29			
AP15	108.14	0.75	22.88	17.27	77.18			
AP16	90.29	0.63	13.22	8.33	1.56			
AP17	156.60	1.09	10.57	11.55	0.54			
AP18	228.75	1.60	5.30	8.46	89.92			
AP19	205.40	1.43	3.61	5.18	119.59			
SS01	431.22	1.23	20.38	25.14	26.28	24.54	14.07	15.28
SS02	416.33	1.19	47.53	56.60	749.40			
SS03	364.24	1.04	26.11	27.19	2.66			
SS04	312.13	0.89	30.94	27.62	32.67			
SS05	397.78	1.14	25.49	29.00	1.17			
SS06	402.48	1.15	13.93	16.03	149.20			
SS07	379.43	1.09	30.16	32.73	37.17			
SS08	271.53	0.78	21.40	16.62	5.96			
SS09	346.36	0.99	10.43	10.33	195.34			
SS10	175.13	0.50	8.29	4.15	66.27			
SSA	326.60	1.07	8.18	8.75	11.29	11.32	23.10	42.46
SSB	199.88	0.65	1.97	1.29	37.44			
SSC	389.24	1.28	18.75	23.91	89.85			
SSI01	37.87	1.09	17.73	19.35	476.09	37.73	97.94	26.23
SSI02	35.11	1.01	27.65	27.96	103.96			
SSI03	38.34	1.10	61.30	67.71	677.62			
SSI04	28.67	0.83	14.48	11.96	368.57			
SSI05	31.56	0.91	25.83	23.48	117.00			
SSI06	32.88	0.95	29.89	28.32	55.08			
SSI07	35.14	1.01	95.76	96.94	3 451.40			
SSI08	38.13	1.10	23.78	26.12	234.93			
SOI01	38.71	1.22	12.20	14.93	28 615.52	150.37	6966.86	55.51
SOI02	32.65	1.03	221.61	228.84	5 412.21			
SOI03	29.61	0.94	361.59	338.62	39 127.21			
SOI04	25.51	0.81	23.65	19.08	10 447.39			
SG01	38.47	1.03	70.75	72.94	1 051.46	39.30	146.24	30.77
SG02	39.48	1.06	17.34	18.34	539.47			
SG03	39.07	1.05	42.35	44.34	10.24			
SG04	32.26	0.86	24.95	21.57	153.74			
Sand01	42.27	1.13	27.69	31.25	4.77	25.76	46.15	26.37
Sand02	38.89	1.04	20.88	21.69	25.60			
Sand03	38.35	1.02	20.89	21.39	24.83			
Sand04	36.60	0.98	22.11	21.60	12.72			
Sand05	39.33	1.05	18.09	19.00	64.81			
Sand06	36.28	0.97	85.63	82.94	3 363.21			
Sand07	27.21	0.73	28.11	20.42	2.93			
Sand08	37.09	0.99	10.47	10.37	229.21			
Sand09	39.57	1.06	6.86	7.24	398.80			
Sand10	38.96	1.04	20.83	21.67	26.23			

Table 7. Mean areal krill biomass density (ρ) and standing stock (B_0), and associated variances, by stratum and for the entire survey. See Appendix B for description of labels and formulae.

Stratum	Nominal Area (km^2)	Mean Density (g/m^2)	Area*Density (tonnes)	Variance Component ($tonnes^2$)
AP (11 – 19)	473 318	11.24	5 319 647.98	1 052 496 388 913.78
SS (01 – 10)	1 109 789	24.54	27 234 964.55	17 326 537 058 061.60
SS (A – C)	321 800	11.32	3 642 035.01	2 391 655 734 991.07
SSI (01 – 08)	48 654	37.73	1 835 720.49	231 845 632 004.71
SOI (01 – 04)	24 409	150.37	3 670 294.56	4 150 849 848 119.59
SG (01 – 04)	25 000	39.30	982 423.23	91 401 915 350.65
Sand (01 – 10)	62 274	25.76	1 603 985.17	178 954 989 453.98
Total	2 065 244		44 289 070.99	25 423 741 566 895.40
Survey				
Mean density	21.44 g/m^2			
Variance	5.96 $(g/m^2)^2$			
CV	11.38 %			
Krill standing stock	44.29 x 10^6 tonnes			
Variance	25 423 741.57 x 10^6 $tonnes^2$			
CV	11.38 %			

Table 8. Input parameters to the GYM for evaluating γ based on the estimated coefficient of variance (CV) of B_0 and the timing of the CCAMLR 2000 Survey for krill in Subareas 48.1, 48.2, 48.3 and 48.4.

Category	Parameter	Estimate
Age structure	Recruitment age Plus class accumulation Oldest age in initial structure	0 7 7
Recruitment (R) and natural mortality (M)	M and R dependent on proportion of recruits in stock where: Proportion of recruits Standard deviation of proportion Age of recruitment class in proportion Data points to estimate proportion	 0.557 0.126 2 17
von Bertalanffy growth	Time 0 L_∞ k Proportion of year from beginning in which growth occurs	0 60.8 mm 0.45 0.25
Weight at age	Weight–length parameter – A Weight–length parameter – B	1.0 3.0
Maturity	L_{m50} Range: 0 to full maturity	32.0–37.0 mm 6 mm
Spawning season		1 December–28 February
Estimate of B_0	Survey time CV	1 February 0.114
Simulation characteristics	Number of runs in simulation Depletion level Seed for random number generator	1 001 0.2 -24189
Characteristics of a trial	Years to remove initial age structure Observations to use in median SB_0 Year prior to projection Reference start date in year Increments in year Years to project stock in simulation Reasonable upper bound for annual F Tolerance for finding F in each year	1 1 001 1 1 November 365 20 5.0 0.0001
Fishing mortality	Length, 50% recruited Range over which recruitment occurs Fishing selectivity with age	30–39 mm 9 mm
Fishing season		1 December–1 March

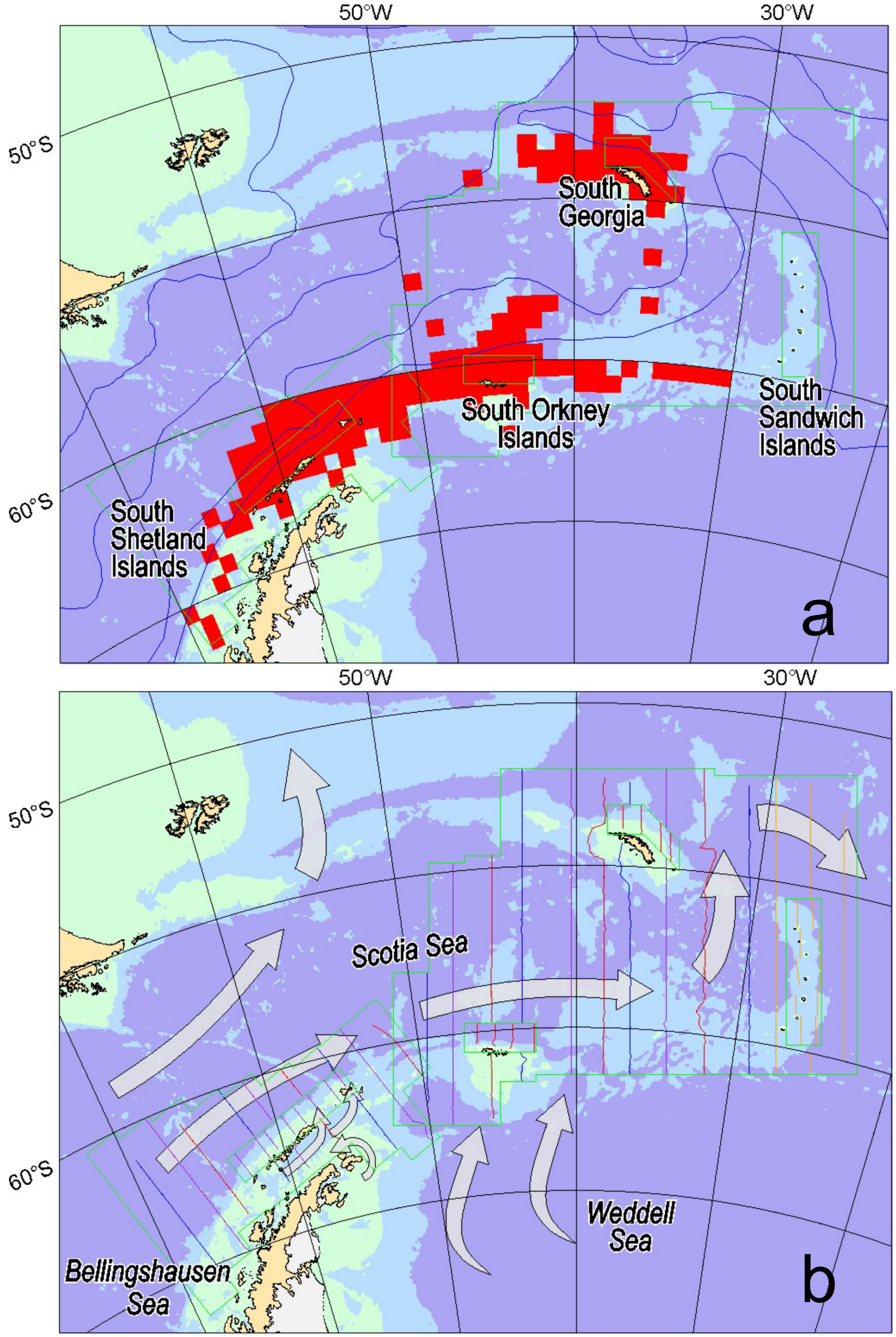

Figure 1. Island groups and bathymetry of the Scotia Sea (shading indicates 500 m, 1000 m, and 3000 m isobaths). **a.** Survey strata outlined in green relative to historical fishing activity (red squares) and major ocean frontal zones (blue lines; from north to south, the Sub-Antarctic Front, the Polar Front, the Southern ACC Front, and the southern ACC Boundary). **b.** Survey transects color coded, where violet indicates those transects occupied by the Japanese R/V *Kaiyo Maru*, yellow indicates the Russian R/V *Atlantida*, blue indicates the British RRS *James Clark Ross*, and red indicates the US chartered R/V *Yuzhmorgeologiya*. Arrows indicate direction of major currents.

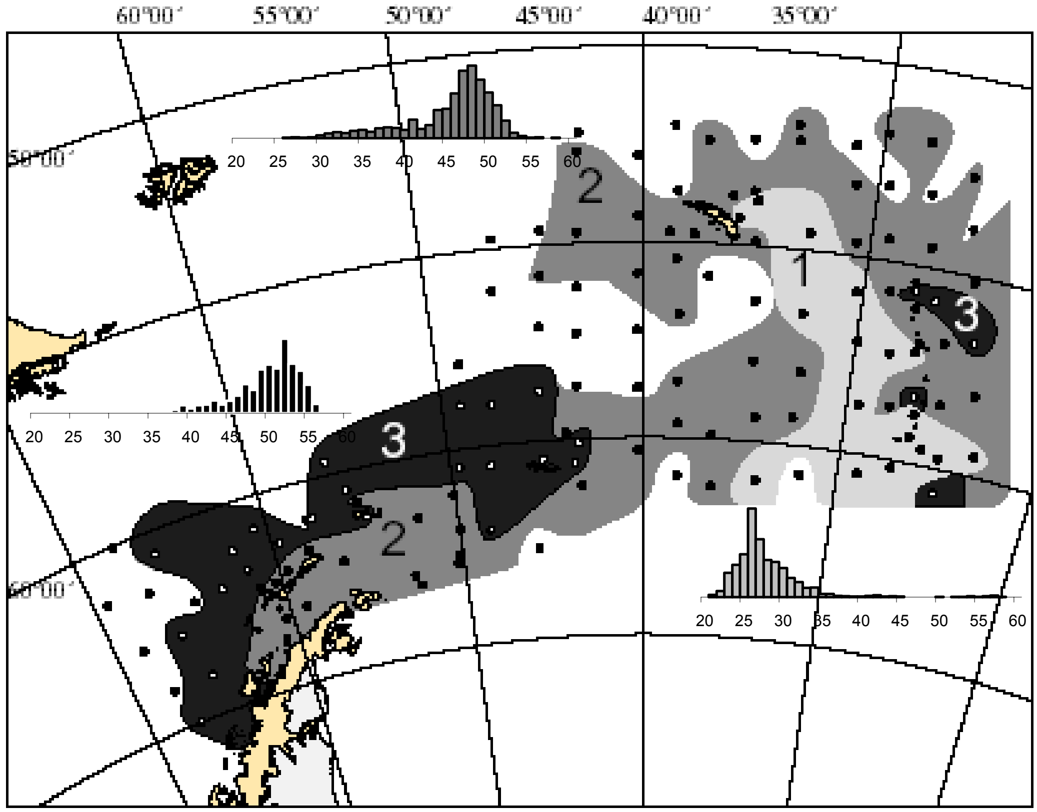

Figure 2. Composite krill length-frequency distributions and the geographic distribution of stations for each cluster (from Siegel et al. this volume).

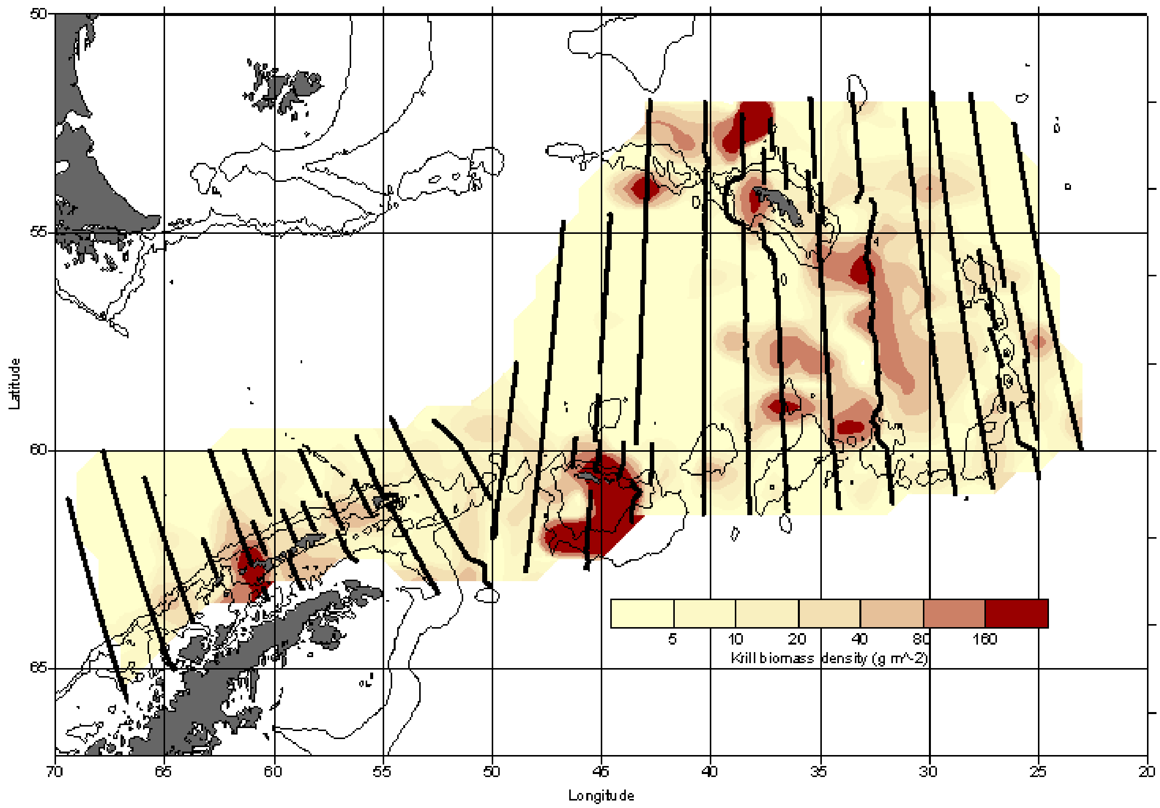

Figure 3. Dispersion of krill biomass density over the survey area.

Appendix A. EchoView procedures and virtual variables, where raw variables are designated as: Q1 – 38 kHz raw data and Q2 – 120 kHz raw data.

Procedures	Virtual Variables				
	Name	Operator	Operand1	Operand2	Other Settings Required
Define inclusions	Surf-bott	Line bitmap	Q1		Surface exclusion to integration stop line
	Good data	Region bitmap	Q1		Bad data regions, INVERT output
	Include	AND	Surf-bott	Good data	
Mask echograms	38-E	Mask	Q1	Include	DO check zero is no data
	120-E	Mask	Q2	Include	DO check zero is no data
Resample masked echograms	38-S	Resample by time	38-E		100 seconds, 0–500 m, 100 samples
	120-S	Resample by time	120-E		100 seconds, 0–500 m, 100 samples
Generate noise	Noise 38	Data generator	38-S		Use noise(s_v)1 m from table; set α = 0.010
	Noise 120	Data generator	120-S		Use noise(s_v)1 m from table; set α = 0.028
	Noise 200	Data generator	200-S		Use noise(s_v)1 m from table; set α = 0.041
Subtract noise from resampled echograms	38-S-C	Linear minus	38-S	Noise 38	
	120-S-C	Linear minus	120-S	Noise 120	
Subtract (120-38)	Dif-S 120-38	Minus	120-S-C	38-S-C	Set display min s_v to 0
Define dB range	Range Dif-S	Range	Dif-S 120-38		Range 2–16
Mask resampled noise-free echograms	Mask 38-S-C	Mask	38-S-C	Range Dif-S	Do NOT check zero is no data, add grid
	Mask 120-S-C	Mask	120-S-C	Range Dif-S	Do NOT check zero is no data, add grid
					Process tab: exclude above = surface exclusion; exclude below = integration stop.

Appendix B. Descriptors for labels in Tables 6, 7 and 8, where *i* is used to index intervals along a transect, *j* is used to index transects within a stratum, and *k* is used to index strata.

Transect Label	Formula/Descriptor
Length	Transect length defined as the sum of all interval weightings $L_j = \sum_{i=1}^{N_j} (W_I)_i$ where L_j is the length of the *j*th transect, $(W_I)_i$ is the interval weighting of the *i*th interval, and N_j is the number of intervals in the *j*th transect.
Weighting Factor	Normalized transect length $w_j = \dfrac{L_j}{\frac{1}{N_k}\sum_{j=1}^{N_k} L_j}$ such that $\sum_{j=1}^{N_k} w_j = N_k$ where w_j is the weighting factor for the *j*th transect, and N_k is the number of transects in a stratum.
Krill Density Measured	Mean areal krill biomass density over all intervals on each transect $\overline{\rho}_j = \dfrac{1}{L_j}\sum_{i=1}^{N_j} (NASC)_i (CF)_i (W_I)_i$ where $\overline{\rho}_j$ is the mean areal krill biomass density on the jth transect, $(NASC)_i$ is the integrated backscattering area for the *i*th interval and $(CF)_i$ is the conversion factor for the *i*th interval.
Krill Density Weighted	Mean areal krill biomass density times the weighting factor $\overline{\rho}_{W\,j} = w_j \overline{\rho}_j$ where $\overline{\rho}_{W\,j}$ is the mean weighted areal krill biomass density on the *j*th transect
Variance Component	$VarComp_j = w_j^2 \left(\overline{\rho}_j - \overline{\rho}_k\right)^2$ where $VarComp_j$ is the weighted contribution of the *j*th transect to the stratum variance

Appendix B (cont.)

Stratum Label	Formula/Descriptor
Mean	Stratum mean areal krill biomass density $\overline{\rho}_k = \frac{1}{N_k}\sum_{j=1}^{N_k} w_j \overline{\rho}_j$ where $\overline{\rho}_k$ is the mean areal krill biomass density in the *k*th stratum (after equation 1, Jolly and Hampton 1990)
Variance	Stratum variance $Var(\overline{\rho}_k) = \frac{N_k}{N_k - 1}\frac{\sum_{j=1}^{N_k} w_j^2(\overline{\rho}_j - \overline{\rho}_k)^2}{\left(\sum_{j=1}^{N_k} w_j\right)^2} = \frac{\sum_{j=1}^{N_k} w_j^2(\overline{\rho}_j - \overline{\rho}_k)^2}{N_k\left(N_k - 1\right)}$ where $Var(\overline{\rho}_K)$ is the variance of the mean areal krill biomass density in the *k*th stratum
CV (%)	Coefficient of variation $CV_k = 100\frac{\left(Var(\overline{\rho}_k)\right)^{0.5}}{\overline{\rho}_k}$ where CV_k is the coefficient of variation for the *k*th stratum

Appendix B (cont.)

Survey Label	Formula/Descriptor
Nominal Area	Area of kth stratum (A_k) estimated at the time of survey design
Mean Density	Mean areal krill biomass density of the kth stratum, $\overline{\rho}_k$
Area*Density	$A_k \overline{\rho}_k$
Variance Component	$VarComp_k = A_k^2 Var(\overline{\rho}_k)$ where $VarComp_k$ is the contribution of the kth stratum to the overall survey variance of B_0
Mean Density	Overall survey mean areal krill biomass density $\overline{\rho} = \frac{\sum_{k=1}^{N} A_k \overline{\rho}_k}{\sum_{k=1}^{N} A_k}$ where N is the number of survey strata. (after equation 2, Jolly and Hampton 1990)
Variance	Overall survey variance of the mean areal krill biomass density $Var(\overline{\rho}) = \frac{\sum_{k=1}^{N} A_k^2 Var(\overline{\rho}_k)}{\left(\sum_{k=1}^{N} A_k\right)^2} = \frac{\sum_{k=1}^{N} VarComp_k}{\left(\sum_{k=1}^{N} A_k\right)^2}$ (after equation 3, Jolly and Hampton 1990)
CV	Overall coefficient of variation of the mean areal krill biomass density $CV_{\overline{\rho}} = 100 \frac{\left(Var(\overline{\rho})\right)^{0.5}}{\overline{\rho}}$
Krill Standing Stock	$B_0 = \sum_{k=1}^{N} A_k \overline{\rho}_k$
Variance	Overall survey variance of B_0 $Var(B_0) = \sum_{k=1}^{N} VarComp_k$
CV	Overall coefficient of variation of B_0 $CV_{B_0} = 100 \frac{\left(Var(B_0)\right)^{0.5}}{B_0}$