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An estimate of error for the CCAMLR 2000 survey estimate of krill biomass

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Abstract

Combined sampling and measurement error is estimated for the CCAMLR 2000 acoustic estimate of krill abundance in the Scotia Sea. First, some potential sources of uncertainty in generic echo-integration surveys are reviewed. Then, specific to the CCAMLR 2000 survey, some of the primary sources of measurement error is explored. The error in system calibration is evaluated in relation to the effects of variations in water temperature and salinity on sound speed, sound absorption, and acoustic-beam characteristics. Variation in krill target strength is estimated using a distorted-wave Born approximation model fitted with measured distributions of animal lengths and orientations. The variable effectiveness of two-frequency species classification methods is also investigated using the same scattering model. Most of these components of measurement uncertainty are frequency-dependent and covariant. Ultimately, the total random error in the CCAMLR 2000 acoustic estimate of krill abundance is estimated from a Monte Carlo simulation which assumes independent estimates of krill biomass are derived from acoustic backscatter measurements at three frequencies (38, 120, and 200 kHz). The overall coefficient of variation ($10.2 \leqslant CV \leqslant 11.6\%$; 95% CI) is not significantly different from the sampling variance alone ($CV = 11.4\%$). That is, the measurement variance is negligible relative to the sampling variance due to the large number of measurements averaged to derive the ultimate biomass estimate. Some potential sources of bias (e.g., stemming from uncertainties in the target strength model, the krill length-to-weight model, the species classification method, bubble attenuation, signal thresholding, and survey area definition) may be more appreciable components of measurement uncertainty.

1. Introduction

In the austral summer of 2000, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) sponsored a survey—the CCAMLR 2000 Survey—to estimate the biomass (B_0) and distribution of Antarctic krill in an area close to the Antarctic Peninsula (FAO statistical area 48; Trathan et al., 2001). The multi-national, multi-ship survey included: (1) multi-frequency echo sounders having their acoustic-beam axes aimed vertically downwards (Forbes and Nakken, 1972); (2) the application of echo integration

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methods to data collected along transects (MacLennan and Forbes, 1986; Simmonds et al., 1992); (3) the conversion of integrated echo energy to biomass density (Hewitt and Demer, 1993; Stanton, et al., 1994); and (4) the interpolation (or extrapolation) of the density estimates to the area sampled by the transect lines (Foote and Stefansson, 1993; Jolly and Hampton, 1990; Simmonds, et al., 1992). Each of these components can affect the overall accuracy and precision of the survey estimates (Demer, 1994; Taylor and Kuyatt, 1993). An estimate of the total random error in B_0 is necessary to quantify change in the standing stock of krill, and to set the fishery catch limits. The remainder of the introductory section summarizes the survey methods as they pertain to the subsequent measurement uncertainty analysis.

1.1. Echo sounder measurements

Four research vessels (*Kaiyo Maru*, *Atlantida*, *James Clark Ross*, and *Yuzhmorgeologiya*) from four nations (Japan, Russia, the UK, and the USA, respectively) were involved in the CCAMLR 2000 Survey. Significant efforts were made to use identical equipment and protocols on each participating ship (Demer, 1998). Simrad EK500 echo sounders (Bodholt et al., 1989) were used, each fitted for synchronous transmissions at three frequencies (38, 120 and 200 kHz) every 2 s.

1.1.1. Sound speed and absorption

The mean sound speed ($\bar{c}$; ms^{-1} and mean absorption coefficients ($\bar{\alpha}_{38\,\text{kHz}}, \bar{\alpha}_{120\,\text{kHz}}$, and $\bar{\alpha}_{200\,\text{kHz}}$; dB km^{-1}) were estimated for use throughout the entire survey area from measurements of salinity and temperature versus depth (r) from surveys conducted the previous year (austral summer 1998/99; see Fig. 1 for station locations). Using conversion algorithms from Mackenzie (1981) and Francois and Garrison (1982), respectively, values of c, $\alpha_{38\,\text{kHz}}, \alpha_{120\,\text{kHz}}$, and $\alpha_{200\,\text{kHz}}$ were first calculated for each station at 10 m depth increments. Because krill reside mostly in the upper 150 m (Miller and Hampton, 1989), weighted means (weight $= 1/r^2$) were calculated for each of these variables. For example,

$$\bar{c} = \frac{\sum_{i=1}^{N} c(r_i)/r_i^2}{\sum_{i=1}^{N} 1/r_i^2}, \tag{1}$$

where r_i is the mid-point of the ith depth bin and $N = 50$ is the total number of 10 m bins from 10 to

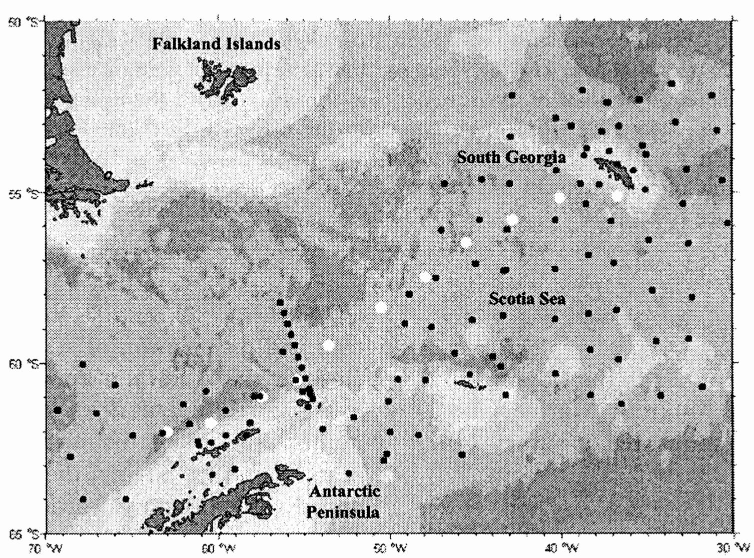

Fig. 1. Stations sampled for salinity and temperature versus depth by the UK and the USA during 1998/99 (11 stations; white dots), and the UK, Japan, and USA during the CCAMLR 2000 Survey (140 stations; black dots).

Table 1
Average sound speed and absorption values calculated both pre- and post-cruise from data collected at the 1998/99 and CCAMLR 2000 stations shown in Fig. 1

	Temperature (°C)	Salinity (psu)	$\bar{c}$ (m s^{-1})	$\bar{\alpha}_{38\,\mathrm{kHz}}$ (dB km^{-1})	$\bar{\alpha}_{120\,\mathrm{kHz}}$ (dB km^{-1})	$\bar{\alpha}_{200\,\mathrm{kHz}}$ (dB km^{-1})
Pre-cruise						
10–250 m mean	0.5	34.1	1452	10.2	26.2	40.1
10–500 m mean	1.1	34.3	1457	10.1	27.5	40.1
10–500 m weighted mean	0.4	33.8	*1449*	*10.1*	*26.1*	*40.2*
Post-cruise						
10–500 m weighted mean	1.9 (1.2)	34.0 (0.2)	1456 (5.0)	10.4 (0.1)	27.9 (1.2)	41.4 (1.0)
weighted harmonic mean	**1.4 (1.2)**	**34.0 (0.2)**	**1456 (5.1)**	**10.4 (0.1)**	**27.7 (1.2)**	**41.3 (1.0)**

Averages were calculated over the ranges 10–250 m and 10–500 m. Also, weighted means (weight = 1/range^2) were calculated for the 10–500 m ranges (shown in italic). These latter pre-cruise values were used throughout the CCAMLR 2000 Survey. Note that the post-cruise weighted means, and the more accurate harmonic means (shown bold) are similar, and higher than the survey constants by approximately one standard deviation (values shown in parentheses).

500 m. These values of $c, \alpha_{38\,\mathrm{kHz}}, \alpha_{120\,\mathrm{kHz}}$, and $\alpha_{200\,\mathrm{kHz}}$ remained constant throughout the cruise (Table 1).

1.1.2. Equivalent two-way beam angle

Considering first-order effects, the nominal equivalent two-way beam angles (ψ) were reduced for the survey by a factor approximately equal to the square of the ratio of $\bar{c}$ (= 1449 ms^{-1}) and the sound speed during Simrad's transducer calibrations (nominally 1473 ms^{-1}). That is, the survey protocols specified that the values used for ψ were 0.14 dB less than the values in Simrad's transducer specifications.

1.1.3. System calibration

System calibrations for each frequency were performed before and after the CCAMLR 2000 Survey in protected bays on South Georgia and King George Island, respectively. Standard targets were identically prepared 38.1 mm diameter tungsten carbide spheres with 6% cobalt binder. Theoretical target strength (TS) values were referenced from Foote (1990a). According to Foote (1983b) and Foote and MacLennan (1984a, b), calibrations with the standard sphere method are precise to $\sim\pm 2\%$. The precision of the EK500 transceivers reduces the calibration precision from ± 2 to $\pm 7\%$, depending upon the receiver bandwidth (Simrad, 1993).

The initially very precise system calibrations probably degraded over time and space, due to changes in temperature and salinity throughout the survey. Variations in temperature affect the transducer characteristics (Brierley et al., 1998; Demer, 1994; Demer and Hewitt, 1992), and variations in $\bar{c}, \alpha_{38\,\mathrm{kHz}}, \alpha_{120\,\mathrm{kHz}}$, and $\alpha_{200\,\mathrm{kHz}}$ increase the uncertainty in models of sound propagation and thus measurements of echo energy. To evaluate these effects, measurements of temperature, salinity, c, and α versus r were made throughout the survey.

1.1.4. Diel vertical migration

Krill migrate vertically, generally moving from depth during the day, to the surface at night (Everson, 1982; Godlewska and Klusek, 1987). Miller and Hampton (1989) estimated that about 40% of the krill biomass could be concentrated in the upper 5 m at night. Demer and Hewitt (1993) estimated that krill surveys conducted in the Elephant Island area and irrespective of the time of day could be negatively biased by an average of 49.5%. Consequently, the CCAMLR 2000 Survey was conducted exclusively during daylight hours.

1.2. Echo integration

So that all possible data were retained, measurements of volume backscattering strength (Sv) and TS were recorded above a minimum value of -100 dB. For effective multiple-frequency data analyses (Demer et al., 1999; Greenlaw et al., 1980), the insonified volumes at each frequency were designed similarly, as far as physically and financially possible. That is, most of the transducers had 7° beam widths, were effectively collocated, and the echo sounders were modified for 1 ms pulse durations at all three frequencies (atypical for 200 kHz operation).

1.2.1. Species classification

A two-frequency method (Madureira et al., 1993; Watkins and Brierley, 2002) was used to identify and delineate acoustic backscatter from krill and other sources. After averaging Sv at 120 and 200 kHz ($Sv_{120\,kHz}$ and $Sv_{38\,kHz}$) over cells 50 pings wide (~500 m) by 5 m depth, differences in mean volume backscattering strengths (ΔMVBS = ($Sv_{120\,kHz} - Sv_{38\,kHz}$) between 2 and 16 dB were used to indicate krill. The integrated echo energy from krill aggregations (s_a; $m^2\,km^{-2}$) was assumed to be equivalent to the sum of energies that would have been received from the same number of individuals in isolation (Foote, 1983a; Johannesson and Mitson, 1983). However, the relationship between s_a and the true animal density (ρ_n) is affected by many factors which are understood to varying degrees (MacLennan and Forbes, 1984). For a group of identical animals that are randomly distributed within the beam, an estimate of the animal density ($\hat{\rho}_n$; animals per m^2) is proportional to s_a or volume backscattering coefficients integrated between depths r_1 and r_2 and averaged over some trackline distance (MacLennan and Simmonds, 1992). Following Simrad (1993)

$$\hat{\rho}_n = \frac{4\pi r_0^2}{\hat{\sigma}} \left\langle \int_{r_1}^{r_2} \left(\frac{\hat{p}_r 32\pi^2 \hat{r}^2 10^{2\hat{\alpha}\hat{r}}}{\hat{p}_t \hat{g}_0^2 r_0^2 \hat{\lambda}^2 \hat{c}\hat{\tau}\hat{\psi}} \right) dr \right\rangle, \qquad (2)$$

where p_t is the transmit power (W), p_r is the receive power (W), g_o is the calibrated on-axis system gain (Blue, 1984; Foote et al., 1987), r is the range (m), r_0 is the reference distance (1 m), λ is the acoustic wavelength of the transmitted pulse (m), c is the sound speed ($m\,s^{-1}$), α is the absorption coefficient ($W\,m^{-1}$), ψ is the equivalent beam angle (Foote, 1990c; Simmonds, 1984a, b) and σ is the backscattering cross-sectional area representative of the animals in the surveyed area at the time of the survey (m^2; Chu et al., 1993; Foote et al., 1990b; Greene et al., 1991; Greenlaw et al., 1980; Hewitt and Demer, 1991). The mean is designated by < >.

1.2.2. Target strength

Krill TS $= 10\log(\sigma/4\pi)$ depends upon the acoustic frequency (Chu et al., 1992), animal size, shape, and density, sound speed, and its orientation within the acoustic-beam (Stanton 1989a, b). Estimates of TS are derived from models based on scattering physics (e.g., Chu et al., 1993; Stanton et al., 1993) or linear regressions of empirical TS data and crustacean lengths (e.g. Greene et al., 1991; Wiebe et al., 1990). Although the Greene et al. (1991) model has been corroborated by in situ measurements of *Euphausia superba* (Hewitt and Demer, 1991), and has been adopted by CCAMLR (Trathan et al., 1992), it does not account for TS variability due to animal density, sound speed, shape and orientation, and acoustic wavelength. Demer (1994) demonstrated the potential errors in using linear models of TS versus animal length (L) to approximate scattering from zooplankton (a highly non-linear phenomenon). Additionally, several investigators have shown that animal behavior has a dominant effect on the TS of zooplankton (Demer and Martin, 1995; Greenlaw et al., 1980; Stanton, 1989a). For example, Everson (1982) observed an 8 dB difference between the daytime and nighttime Sv of krill aggregations and attributed this to diel changes in orientation. McGehee et al. (1998) offered a TS model based on the distorted-wave Born approximation (DWBA) that explicitly accounts for acoustic frequency, animal shape, orientation, and material properties. The DWBA was validated using measurements of live krill in a tank, but only near broadside incidence.

The Greene et al. (1991) model was used to estimate mean *TS* for the CCAMLR 2000 Survey. To convert $\hat{\rho}_n$ to an estimate of biomass density ($\hat{\rho}$; $g\,m^{-2}$), another model (see Hewitt et al., 2004) provided estimates of wet weight per animal (w; g per animal):

$$\hat{\rho} = \hat{\rho}_n \hat{w}. \qquad (3)$$

1.3. Measurement error

Application of this theory necessitates estimates of all the variables in Eqs. (2) and (3) (e.g., estimated $x = \hat{x}$), each introducing some uncertainty (Demer, 1994). More realistically, these variables are represented by their respective probability density functions (PDFs). Because most of these variables are covariant, an analysis of all the individual components of measurement uncertainty is daunting.

Considering some of these potential sources as independent variables, Tesler (1989) and MacLennan and Simmonds (1992) estimated the systematic and random components of uncertainty for generic echo integration surveys (Table 2). According to Tesler (1989), the primary sources of survey bias are system calibration (±12 to ±26%) and the values assumed for TS (±26 to ±41%). Although MacLennan and Simmonds (1992) stated that the calibration bias is relatively inconsequential (±2%), they agreed that TS could be a significant source of error (0 to ±50%) in addition to species identification (0 to ±80%; see Greenlaw and Johnson, 1983; Holliday et al., 1989; Stanton et al., 1994), vertical migration (0 to ±40%; see Demer and Hewitt, 1993 Everson, 1982; Godlewska and Klusek, 1987), and possibly bubble attenuation (0 to −90%; see Dalen and Lovik, 1981).

Although it is correct to consider the uncertainties associated with system calibration, species identification, TS, and animal behavior as systematic for point measurements, the magnitudes and signs of the associated biases are often variable over the time- and space-scales of a survey. Thus, they contribute random errors to the biomass estimate. Moreover, each of these sources of uncertainty manifest different errors for biomass estimates derived from acoustic backscatter at different acoustic frequencies. For example (1) system calibrations performed on separate transceiver-transducer pairs are temperature dependent to varying degrees (Brierley et al., 1998; Demer, 1994), and are subject to different sound absorption values (Francois and Garrison, 1982) (2) the relative sensitivity of acoustic backscatter to krill orientation is dependent on the relationship between the animal size and the acoustic wavelength (i.e. whether Rayleigh, Mie, or Geometric scattering; Demer and Martin, 1995) and (3) the transmit power, ambient noise, bubble attenuation, receive sensitivity and thus detection probabilities of each echo sounder frequency are unique. Support for the latter point is given in Section 2.4.

Table 2
Uncertainty in generic echo integration surveys for aquatic biomass estimation

Source of error	Tesler (1989)		MacLennan and Simmonds (1992)	
	Random	Systematic	Random	Systematic
Physical calibration	—	±12–±26	±2	±5
Transducer motion	±3	—	—	0–−30
Bubble attenuation	—	−12	—	0–−90
Hydrographic conditions	*	*	±2–±5	0–±5
Target strength	—	±26–±41	±5	0–±50
Species identification	*	*	—	0–±80
Random sampling	*	*	±10–±40	—
Fish migration	*	*	—	0–±40
Diurnal behavior	*	*	0–−25	—
Avoidance reactions	*	*	—	uncertain
Integrator error	±5	—	*	*
Attenuation coefficient	—	±5	*	*
Time-varied gain	—	±10	*	*
Equivalent beam angle	±14–±20	—	*	*

The magnitudes of systematic and random sources of error (%) were estimated by Tesler (1989) and MacLennan and Simmonds (1992). Some categories were not explicitly considered by the authors (*) and some effects were considered negligible (—).

1.4. Sampling error

The CCAMLR 2000 Survey was conducted using randomly spaced parallel-line transects. Following the method proposed by Jolly and Hampton (1990), each transect provided a single sample of $\hat{\rho}$. Within a stratum, mean biomass density $\hat{\bar{\rho}}$ was weighted by the number of averaging intervals along each transect. The total biomass ($\hat{B}$; Mt) was estimated by multiplying $\hat{\bar{\rho}}$ by the estimated total survey area ($\hat{A}$; m^2). The coefficient of variation (CV; %), usually used to summarize the variance in $\hat{B}$, was derived from the ratio of the standard deviation of $\hat{B}$ (SD($\hat{B}$)) and $\hat{B}$. The equations used for the CCAMLR 2000 analysis are tabulated by Hewitt et al. (2004). Calculated in this way, the CV only accounted for the sampling variance. The aim of this study is to estimate the total error in the CCAMLR 2000 krill biomass estimate—i.e. a combination of both the measurement and sampling errors.

2. Methods

Some of the potential sources of measurement uncertainty in the CCAMLR 2000 Survey were explored in a variety of ways. The actual environmental values affecting sound propagation were compared to the constants selected before the survey. The validity of the empirical TS model adopted from Greene et al. (1991) was explored relative to a physics-based DWBA model. Expected values for ΔMVBS were also derived and compared using the two aforementioned scattering models and krill length distributions measured during the survey. Relative detection sensitivities of the echo sounders aboard each ship, at each frequency, were quantified using the respective system parameters. Each of these studies identified potential errors that are frequency dependent, generally covariant and thus difficult to quantify. Ultimately, the total error in the CCAMLR 2000 estimate of B_0 was estimated from a Monte Carlo simulation which assumed that independent estimates of krill biomass were derived from acoustic backscatter measurements at each of the three frequencies (38, 120, and 200 kHz).

2.1. Sound speed and absorption

At the conclusion of the CCAMLR 2000 Survey, weighted mean values of $c, \alpha_{38\,\mathrm{kHz}}$, $\alpha_{120\,\mathrm{kHz}}$, and $\alpha_{200\,\mathrm{kHz}}$ were re-estimated using Eq. (1) and 10 m averages of temperature and salinity for each of the 140 CCAMLR 2000 stations (Fig. 1). The results (Table 1) are more representative of the actual survey conditions.

As sound propagation is affected by the values of c and α only between the transducer and the scatterers and the mean values of c and α are dependent upon the propagation time spent in each incremental depth, these variables are more accurately calculated as harmonic means ($\bar{c}_h$, and $\bar{\alpha}_h$; Weinberg, 1971), weighted by the PDF of krill density versus depth. That is, the sound speed and absorption coefficients are best calculated by weighting the depth dependent variables $c(r_i)$ and $\alpha(r_i)$ by the incremental time (Δt_i; s) spent in the ith depth bin ($\Delta r_i = r_i r_{i-1}$; m) and the krill distribution probability $P(\Delta r_i)$ in each Δr_i. For example

$$c_{h_i} = (r - r_0)\left[\sum_{i=1}^{N} \frac{1}{g(r_i)} \mathrm{Ln}\left(1 + \frac{g(r_i)}{c(r_i)}\Delta r_i\right)\right]^{-1}, \quad (4)$$

$$\bar{c}_h = \frac{\sum_{i=1}^{N} P(\Delta r_i) c_{h_i}}{\sum_{i=1}^{N} P(\Delta r_i)}, \quad (5)$$

where $g(r_i)$ is the gradient dc/dr in Δr_i, and r and r_0 are the maximum and minimum depths, respectively. A Rayleigh distribution (R(r_i, 40 m)) was used to closely approximate a PDF of the vertical krill distribution $P(\Delta r_i)$. For comparison with the survey constants, the harmonic means for sound speed and absorption are tabulated and plotted (Table 1 and Fig. 2).

2.2. Target strength

Krill TS was predicted using the DWBA model solved with a generic krill shape (McGehee et al., 1998), and $g = 1.0357$ and $h = 1.0279$ (Foote, 1990b; Fig. 3). Note that the scattering directivity of krill increases dramatically with animal length

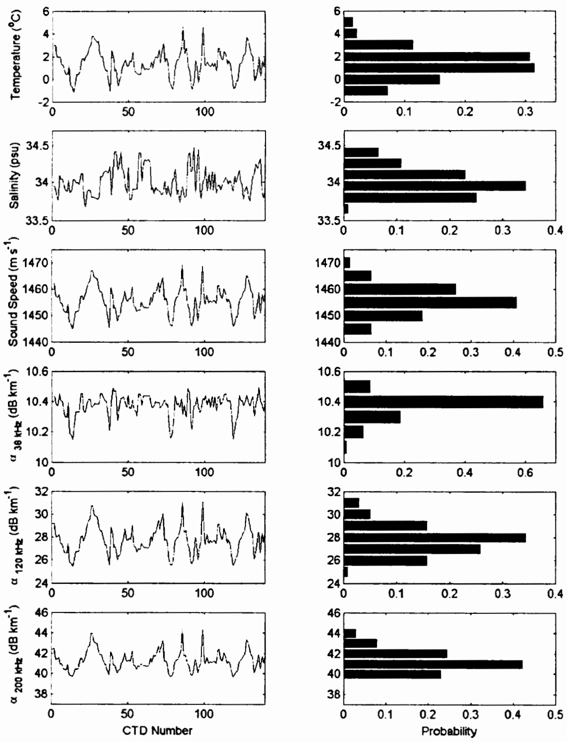

Fig. 2. Temperature, salinity, and harmonic means of sound speed and absorption (α) at each survey frequency, averaged with a Rayleigh weighting-factor ($\boldsymbol{R}$ (r, 40 m)) and plotted for each of the 140 CCAMLR 2000 CTD stations.

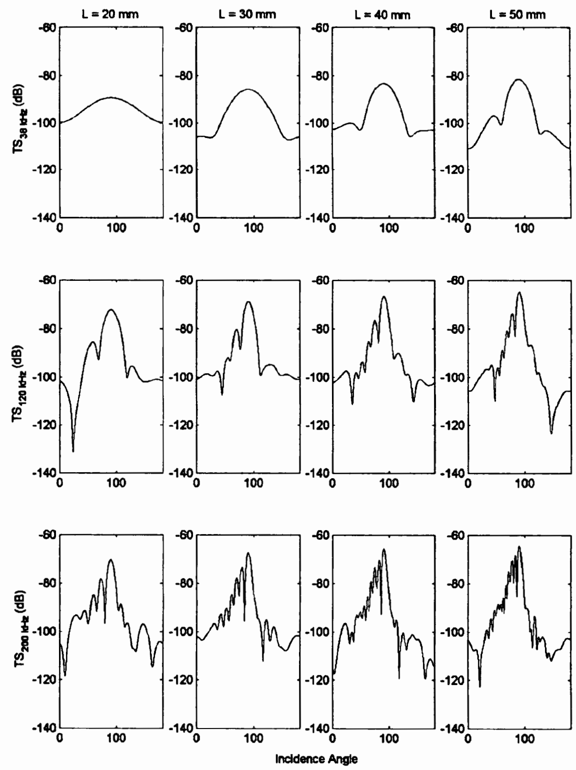

Fig. 3. Target strength (TS) calculated from the DWBA model (McGehee et al., 1998), using a generic krill shape, and $g = 1.0357$ and $h = 1.0279$.

and frequency (90° = normal or dorsal incidence). In fact, the model predicts TS to change by 10 – 40 dB versus animal orientation angles, sometimes not too distant from normal incidence. However, McGehee et al. (1998) noted that their TS data from live *Euphausia superba* only matched the model on the main lobe; TS measurements at steeper angles were elevated relative to predictions.

Using the RMT8 net samples from each ship, three clusters of krill length–frequency distributions were identified for different portions of the CCAMLR 2000 survey area (Siegel et al., 2004). Cluster one (C1) comprised small krill with a narrow length distribution centered at 26 mm, Cluster 2 (C2) had a broad and somewhat bimodal length distribution peaking at 46 mm and Cluster 3 (C3) comprised large krill having a positively skewed length distribution centered at 52 mm. The DWBA model was therefore calculated with the general range of krill lengths (20–55 mm), and plotted versus acoustic frequency and incidence angle (Fig. 4). The model indicates that a wide range of TS (approximately 5–30 dB, depending upon incidence angle) is expected for this range of animal sizes.

Choosing a very narrow distribution of angles about normal incidence (N (90°, 3°)), TS distributions were estimated for each length-frequency distribution (Fig. 5). For comparison, the TS distributions estimated from the Greene et al. (1991) model using the same length-frequency distributions are also plotted.

2.3. Species classification

Again using the DWBA model (generic shape; $g = 1.0357$, $h = 1.0279$; density $= N$ (600 m^3, 150 m^3); and a distribution of krill orientations

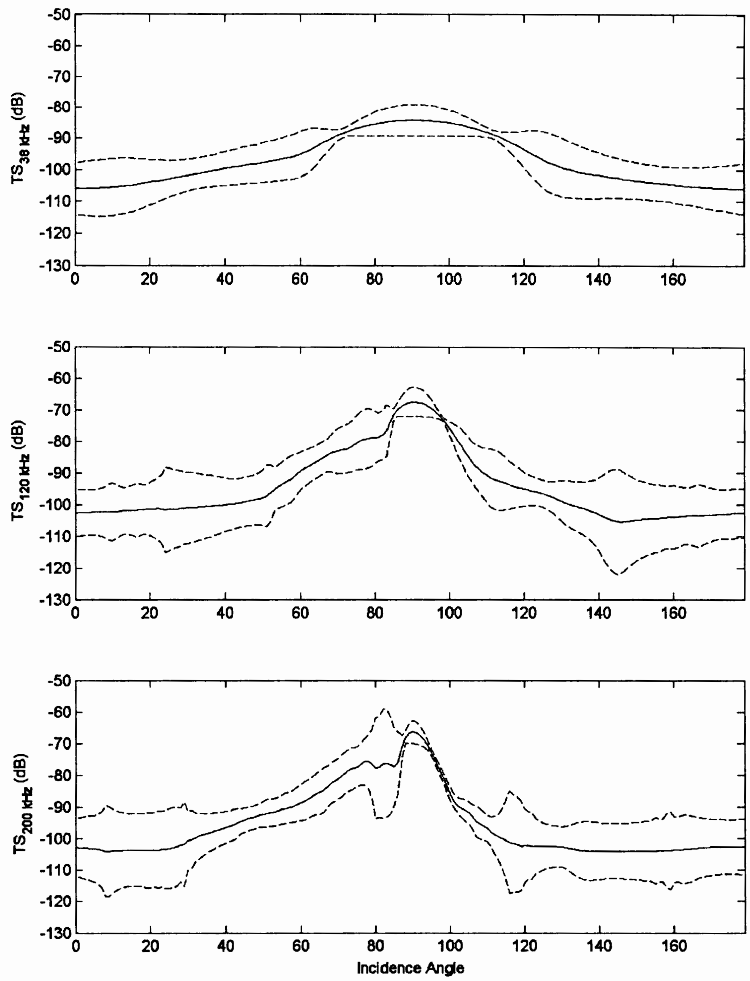

Fig. 4. Mean krill target strength (TS ± 2 SD) as predicted by the DWBA model for variable krill lengths ($L = 20$–55 mm) versus incidence angle at acoustic frequencies of 38, 120, and 200 kHz.

from Kils (1981; N (45.3°, 30.4°)), Sv was predicted for each frequency and each size cluster (Fig. 6). The objective was to estimate the expected distributions of Sv and ΔMVBS at the survey frequencies, for the size distributions of krill in the area (Fig. 7).

2.4. Detection probability

The transmit power, ambient noise, bubble attenuation, receive sensitivity, and thus the PDF of krill detection versus depth, are unique for each echo sounder and frequency. Detection probabilities were explored for the echo sounders aboard each ship by calculating the signal-to-noise ratio (SNR; dB) versus range for various levels of Sv:

$$\mathrm{SNR} = P_t + S_v + 2G_0 + \psi + 10\log 32\pi^2\lambda^2 c\tau - 20\log r - 2\alpha r - P_n, \quad (6)$$

using the values, units, and average background noise levels recorded during the CCAMLR 2000 Survey listed in Table 3. The results for each frequency for each ship are plotted in Fig. 8.

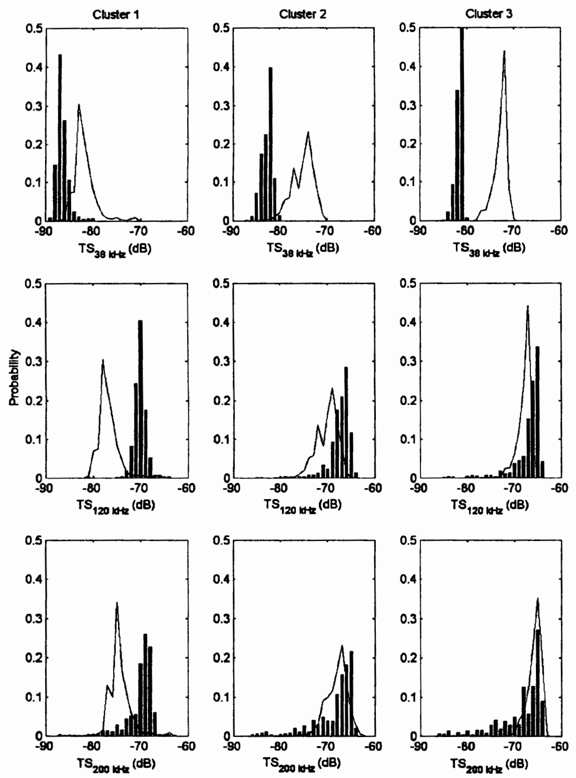

Fig. 5. Target strength (TS) distributions estimated for each length-frequency distribution using the DWBA model and a very narrow distribution of angles about normal incidence (*N*; 90°, 3°) (bars). For comparison, the corresponding TS distributions estimated from the Greene et al. (1991) model are also plotted (lines).

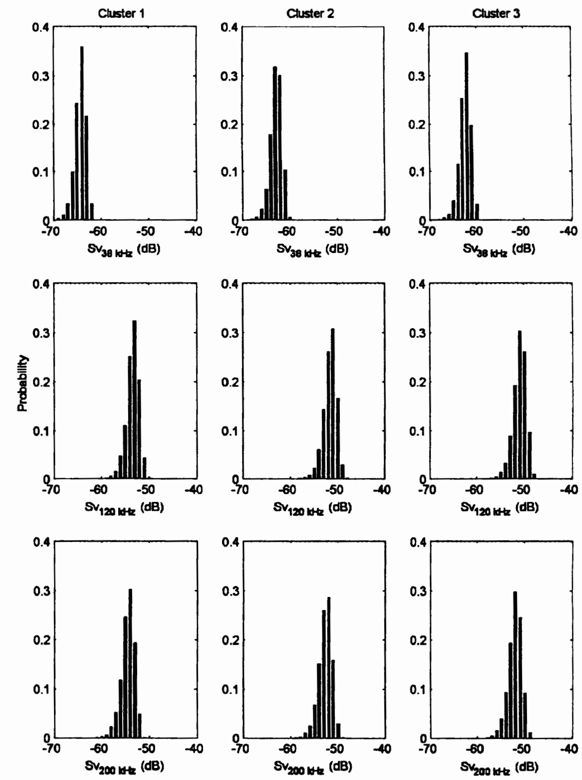

Fig. 6. Volume backscattering strengths (Sv) calculated from the DWBA model (McGehee et al., 1998; generic shape; $g = 1.0357$; $h = 1.0279$; density = $N\,(600\,\mathrm{m}^3, 150\,\mathrm{m}^3)$ and a distribution of krill orientations from Kils (1981; N (45.3°, 30.4°)).

Assuming a worst-case situation where the noise and signal are coherently additive the SNR provides some metric of the percent bias at each detection range and level of Sv:

$$\frac{\text{Noise}}{\text{Signal}} = \left(\frac{1}{10^{\mathrm{SNR}/10}}\right) * 100(\%). \quad (7)$$

From Eq. (7), a 10 dB SNR in Fig. 8 indicates a 10% bias.

2.5. Total random error

Because the components of measurement uncertainty are generally covariant, a Monte Carlo simulation was used to quantify overall variance specific to the CCAMLR 2000 Survey. Assuming each of the three frequencies provided independent estimates of krill biomass, average densities were randomly selected for each interval from one of the three frequencies and a survey biomass was simulated (equations defined in Hewitt et al., 2004). Repeating this process 10 000 times, a PDF of CVs was estimated for the survey biomass. Because the 38 kHz frequency provided an estimate of krill biomass (29.41 million tonnes) that was about 33% less than that for 120 and 200 kHz (44.29 and 44.82 million tonnes, respectively), the interval densities at 38 and 200 kHz were normalized to the 120 kHz estimate $S_{Ai}f_i(W_I)_i^*$ 44.82/29.41 for 38 kHz and $S_{Ai}f_i(W_I)_i^*$ 44.29/44.82 for 200 kHz), and the simulation was repeated. The PDF of CVs was again calculated for the survey biomass.

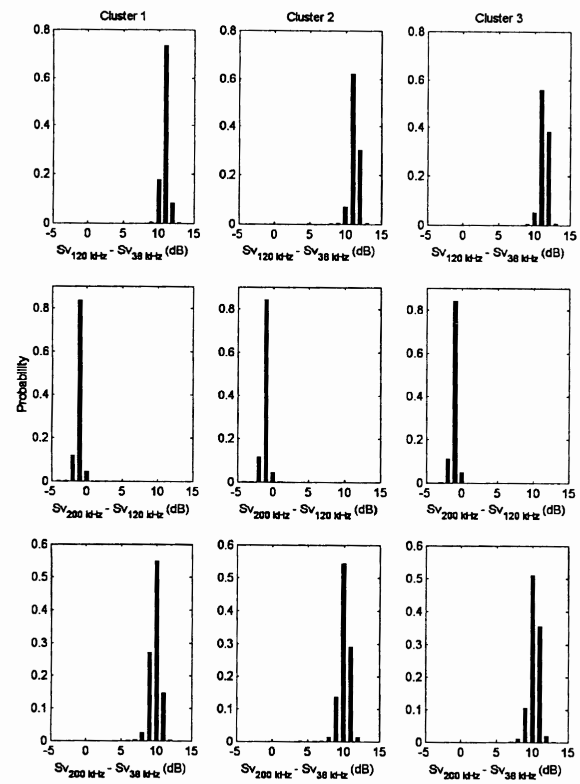

Fig. 7. Volume backscattering strength (Sv) differences calculated from the DWBA model (McGehee et al., 1998; generic shape; $g = 1.0357$; $h = 1.0279$; density = N (600 m^3, 150 m^3) and a distribution of krill orientations from Kils (1981; N (45.3°, 30.4°)).

3. Results

3.1. Sound speed and absorption

At the conclusion of the CCAMLR 2000 Survey, estimated means for temperature, salinity, c, and α versus r were compared to the 1998/99 data (see Table 1). Of note: (1) the weighted-mean temperature was 1.5 °C warmer than that of the previous year; and (2) correspondingly, the harmonic means for c and α were each approximately one standard deviation higher than the pre-selected survey constants. In both cases, the inaccuracies in sound propagation parameters result in an unquantified negative bias in B_0.

3.2. Equivalent two-way beam angle

During the survey, the minimum sound velocity (harmonic mean) was 1447 m s^{-1} and the maximum was 1468 m s^{-1}. These correspond to equivalent two-way beam angle corrections (relative to Simrad specifications) of −0.16 and −0.03 dB, respectively. Therefore, relative to the survey-constant equivalent two-way beam angles (Simrad specified ψ−0.14 dB), the bias in equivalent two-way beam angles is estimated as −0.02–+0.11. The effect was an almost negligible negative bias in B_0.

3.3. Target strength

The TS predicted by the DWBA and Greene et al. (1991) models are quite similar for larger krill size clusters (C2 and C3) and higher frequencies (120 and 200 kHz; Fig. 5). In contrast, the modal TS predicted for smaller animals (C1) and at low frequency (38 kHz) are 5–8 dB different between the two models. Similarly, the DWBA model indicates virtually the same TS values at 200 and 120 kHz and a large difference (~16 dB) between TS at 120 versus 38 kHz. In contrast, the Greene et al. (1991) model predicts constant differences of 10 log(200/120) = 2.2 dB and 10 log(120/38) = 5 dB, respectively. All this suggests that the Greene et al. (1991) model is not applicable for Rayleigh scattering and that the DWBA model may therefore be better suited for predicting differences in mean volume backscattering strengths (e.g. $Sv_{120\,kHz}$–$Sv_{38\,kHz}$). This finding is supported by the close agreement between the B_0 estimates at 120 and 200 kHz and the 33% lower estimate at 38 kHz, derived using the Greene et al. (1991) TS model.

3.4. Species classification

For C1, C2, and C3, the modes of Sv are −64, −52, and −54; −62, −51, and −52; and −62, −51, and −52 dB, for 38, 120, and 200 kHz, respectively (Fig. 6). The Sv distributions vary little between C2 and C3, and more between clusters C2/C3 and C1 (much smaller animals). Values of ΔMVBS show consistent modes for all three clusters

Table 3
Parameters for determining detection probabilities versus range for each ship and frequency

	Atlantida	*James Clark Ross*	*Kaiyo Maru*	*Yuzhmorgeologiya*
G_{Sv}				
38 kHz (dB)	23.32	25.51	27.06	22.36
120 kHz (dB)	24.49	20.20	24.74	25.26
200 kHz (dB)	23.26	22.91	25.76	25.96
P_n				
38 kHz (dB re 1 W)	−127.0	−150.2	−142.8	−126.5
120 kHz (dB re 1 W)	−136.5	−124.0	−136.5	−122.1
200 kHz (dB re 1 W)	−135.0	−110.5	−135.3	−121.8
P_t				
38 kHz (kW)	2	2	2	1
120 kHz (kW)	1	1	1	1
200 kHz (kW)	1	1	1	1
Ψ				
38 kHz (dB)	−21.2	−20.8	−20.9	−15.9
120 kHz (dB)	−20.9	−18.4	−20.6	−20.4
200 kHz (dB)	−20.3	−20.8	−20.5	−20.5

G_{Sv} is the on-axis system gain, P_n is the ambient noise power averaged over all transects, P_t is the transmit power, and ψ is the equivalent 2-way beam angle. Other parameters were common to all ships.

(Sv_{120}–Sv_{38} = 11 dB; Sv_{200}–Sv_{120} = −1 dB; and Sv_{200}–Sv_{38} = 10 dB; Fig. 7). The distributions of $Sv_{120\,kHz}$–$Sv_{38\,kHz}$ range from 9 to 12, 9 to 13, and 9 to 13 dB for C1, C2, and C3, respectively. Recalling that the CCAMLR 2000 window of ΔMVBS indicating krill was 2–16 dB, it is reasonable to assume that few krill were rejected with the chosen algorithm. On the other hand, the survey limits were sufficiently wide to possibly allow other species to be counted as krill. The latter uncertainty is most certainly frequency dependent.

3.5. Diel vertical migration

Despite the effort to survey only during daylight hours, there was some variation in detection probability versus time-of-day. Fig. 9A shows a non-uniform distribution of total s_a at 120 kHz, normalized to observation effort, versus time-of-day. Peak detections occurred at 0700, 1000, and 2300 GMT or approximately noon, 3 PM, and 4 AM, local time, respectively. A detection minimum occurred between 1500 and 1600 GMT or between approximately 10 and 11 PM local time. The latter suggests that the survey effort may have continued slightly longer than it should have to avoid bias due to diel vertical migration. Total s_a at 120 kHz versus depth for the entire survey describes a Rayleigh-type distribution with 90% of the biomass detected in the upper 100 m (Fig. 9B). Also plotted were the mean and maximum Sv at 120 kHz for krill detected during the CCAMLR 2000 Survey (averaged over interval size; Figs. 9C and D). The distributions of Sv averaged over cells approximately 5 m by 500 m peak at approximately −83 and −80 dB, respectively. In view of the shallow distribution of krill (Fig. 9B) and the expected Sv values for the krill caught during the survey (Fig. 6), the CCAMLR 2000 Survey was generally not noise-limited, except possibly when surveying low density krill aggregations (Fig. 8). However, the detection probabilities are very frequency dependent and worst for the 200 kHz echo sounder on the RRS *James Clark Ross*.

3.6. Total uncertainty

Assuming each of the three frequencies provided independent estimates of krill biomass, combined measurement and sampling errors were quantified with a Monte Carlo simulation (Demer, 1994).

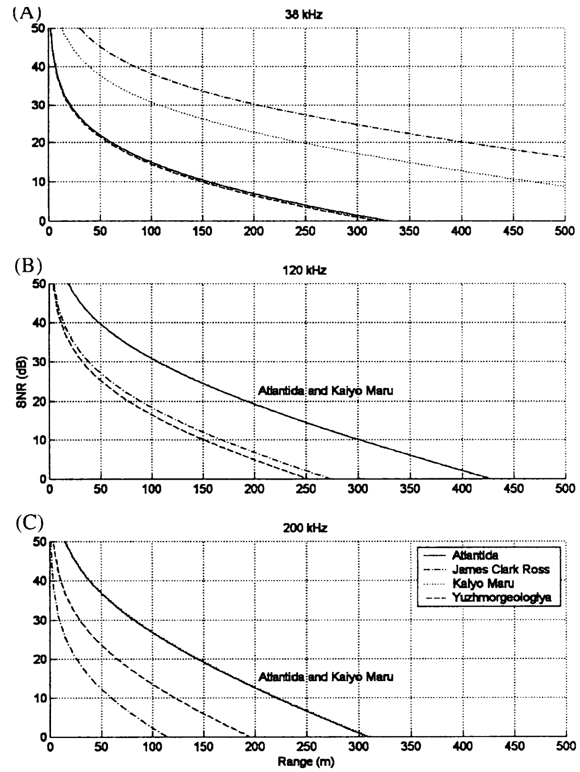

Fig. 8. Signal-to-noise ratio (SNR) versus range for research vessels *Atlantida* (—), *James Clark Ross* (—.), *Kaiyo Maru* (…), and *Yuzhmorgeologiya* (—) at: (A) Sv = −70 dB for 38 kHz; (B) Sv = −60 dB for 120 kHz; and (C) Sv = −60 dB for 200 kHz. See Table 3 for background noise levels and other parameters used.

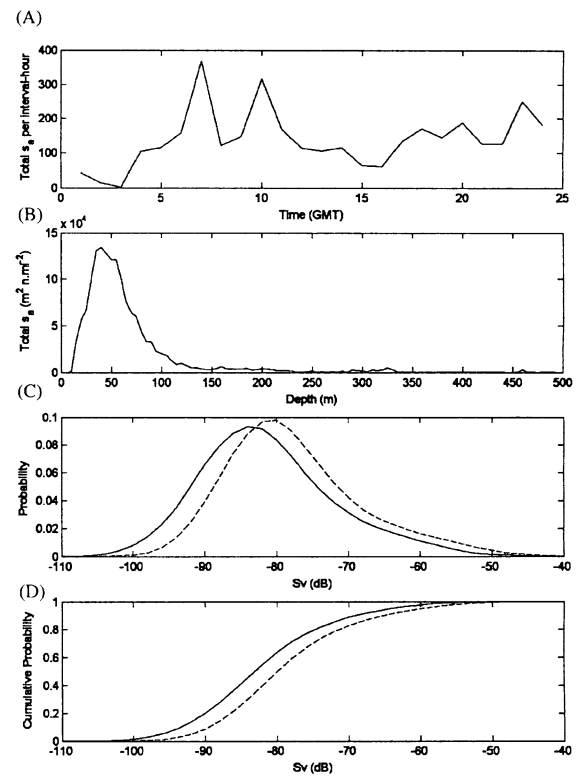

Fig. 9. Total integrated volume backscattering coefficient (s_a), normalized to observation effort, versus time-of-day (A); total s_a versus depth (B); and (C and D) the distribution of mean (solid) and maximum (dashed) volume backscattering strength (Sv) for krill detected during the CCAMLR 2000 Survey (averaged over interval size).

Results indicate an overall variance: CV of B_0 = 11.3%, SD = 0.42%. When mean biomass values are normalized to that of 120 kHz, the overall variance is smaller: CV of B_0 = 10.9%, SD = 0.37%.

4. Discussion

During the CCAMLR 2000 Survey, the weighted mean temperature was 1.5 °C warmer than that of the previous year, and harmonic mean values c and α, and ψ were therefore higher than the survey constants. The combined effect is a small negative bias in B_0.

The Greene et al. (1991) model may provide accurate TS(L) values for larger krill at 120 and 200 kHz, but appears to yield erroneously high values at 38 kHz and thus causes an appreciable negative bias in B_0 at that frequency. The two-frequency method employed to delineate krill from other scatterers appeared quite effective, but is more likely to contribute a positive bias to B_0, if any.

Despite efforts to survey only during daylight hours, there is some evidence that diel vertical migration of krill may have also contributed a minor negative bias to B_0. The tendency for krill to reside mostly in the upper 100 m of the water column kept most echo sounders from being noise limited and subject to thresholding. However, for low density krill aggregations, a small negative bias could have resulted at 200 kHz for the RRS *James Clark Ross*.

Clearly, numerous components of an echo-integration survey can contribute uncertainty to the estimate of biomass. Individually, the magnitudes of these components of uncertainty are in reasonable agreement with the values estimated by Tesler (1989) and MacLennan and Simmonds (1992) (Table 2). However, most of the components of uncertainty are frequency-dependent and covariant. Consequently, a practical and robust way to estimate the overall error in the survey estimate is introduced here. This method includes a simulation that assumes each frequency provides an independent estimate of biomass.

5. Conclusion

The error in B_0 is essential for measuring change in the standing stock of krill (Hewitt and Demer, 1994), and for setting fishery catch limits. The overall CV, accounting for measurement and sampling error (10.2–11.6%; 95% CI), is not significantly different from the sampling CV (11.4%). That is, the measurement variance is negligible relative to the sampling variance due to the large number of measurements averaged to derive the ultimate biomass estimate.

Some potential sources of bias (e.g. stemming from uncertainties in sound propagation parameters, TS, species classification, bubble attenuation, thresholding, area definition, conversion of number density to biomass density, etc.) may be more significant components of measurement uncertainty and should be investigated further. TS appears to be the largest of these components of measurement uncertainty. Almost all of the potential biases in B_0 considered here are negative, with the exception of species classification. Therefore, judging from this analysis, the CCAMLR 2000 estimate of B_0 is quite precise and possibly a bit conservative.

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