Spatial and temporal variability of Antarctic krill: implications for stock assessment

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Acoustic estimates of Antarctic krill biomass measured in four surveys around Elephant Island during the American Antarctic Marine Living Resources 1990 (AMLR90) cruises were analyzed to examine spatial and temporal variability in absolute biomass. Each survey took 5-6 days to complete, and survey mid-points were separated by 15-17 days. The depth-integrated biomass data were highly positively skewed. The biomass frequency distributions diverged progressively over time from that measured in the first survey, with greatest change occurring between survey 2 and 3. The coefficients of variation over each survey for 30 s length records (order 100 m) ranged from 85 to 247%, indicating intense patchiness. Analysis of the fractal dimension of krill biomass revealed patterns that were consistent between surveys and indicated that a horizontal integration interval smaller than 100 m would be necessary to resolve much of the structure in krill spatial variability. In addition to spatial patchiness we found strong temporal variability between surveys at scales on the order of 2 weeks. Our findings indicate that the krill distributions around Elephant Island are highly variable. We suggest that data assimilation models, incorporating repeated fine-scale sampling of physical variables and acoustic back-scattering, be employed to quantify changes in krill distribution and abundance through time in regions characterized by such high variability. We conclude: (1) that sampling with resolutions finer than 100 m is necessary to determine the characteristic scales of spatial patchiness in krill distributions; and (2) the application of biophysical data assimilation models would facilitate more accurate stock assessment of krill. We suggest that traditional survey methods could be improved by introducing long-range moored sonar arrays or towed bodies to operate in conjunction with ship surveys. We present estimates of the feasibility of detecting krill aggregations at up to 1-2 km range using a side-looking sonar operating at 20-40 kHz.

Key words: acoustics, Antarctic krill biomass, spatial distributions, stock assessment.

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Introduction

Euphausia superba, the Antarctic krill, is a keystone species in the food web of the Southern Ocean (Laws, 1985). Its high abundance has prompted considerable interest in its potential as a major invertebrate fisheries resource. Between 1986 and 1991, commercial fishing, mainly by the Soviets and Japanese, harvested 450 000 t per year, declining to 350 000 t of krill per year (Kailoa *et al.*, 1993; CCAMLR, 1990a). Accurate assessment of krill standing stock is essential to developing a rational management strategy for this resource, especially as

pressure increases for an expansion of the fishery (Nicol, 1991). Acoustic survey methods have been used extensively by a number of nations attempting to assess the standing stocks of Antarctic krill in various regions of the Southern Ocean (Anon., 1986; Miller and Hampton, 1989). Two major types of problems have confounded these efforts, the first concerning acoustic methodology, the second concerning the design of field programs for stock assessment. Acoustic methodological problems have ranged from the use of inaccurate sound-scattering models for krill to the use of acoustic systems that often were operated at inappropriate frequencies and/or were

uncalibrated (Greene et al., 1991). Although the definitive work on krill sound-scattering models has yet to be done, new models have been developed which should substantially reduce the errors in acoustic estimates of krill abundance (Everson et al., 1990; Greene et al., 1991; Chu et al., 1992). Likewise, new acoustic instrumentation and improved training of acoustic system operators should further reduce the uncertainties that have plagued acoustic studies of krill in the past.

Here, we focus our attention on the second major type of problem, the design of field programs for stock assessment, and what we can learn from previous acoustic studies of krill to improve the design of future stock-assessment programs in the Southern Ocean. Specifically, we will examine how the spatial and temporal variability of krill distributions can confound efforts at stock assessment which rely on traditional survey methods.

The root of the problem lies in our ignorance of underlying patterns in the spatial and temporal variability of krill distributions. It has been difficult to extract the characteristic scales of patchiness from existing acoustic data for two reasons. First, there is the confounding of spatial and temporal scales. Acoustic data are usually collected along a series of transect lines through a field which is assumed stationary for the purpose of analysis, but is often strongly advective. Second, acoustic surveys typically have been designed to estimate biomass in regional blocks, rather than to examine smaller-scale distributional patterns. As was emphasized by Stommel (1963), no field experimental plan "can encompass all the scales and periods; each plan must provide a definite significance level within a limited part of the spectrum". We argue here that it is time to introduce a program of scale-dependent field experiments to krill research in the Southern Ocean. We support this argument by examining the variability in krill biomass measured during surveys conducted during the AMLR90 cruises around Elephant Island in the Scotia Sea.

Methods

The AMLR90 survey was designed as four repeated ship transects each defining a grid with a scale of 200×200 km centered on Elephant Island (60–62°S, 52.5–58°W). Each survey was conducted as rapidly as possible and was of equal duration. Surveys were conducted from 6 to 11 January, 21 to 26 January, 7 to 13 February, and 21 to 27 February. The trackline steamed during each survey differed due to weather conditions. The interval between the mid-points of surveys was 15 to 17 days. Although the surveys were conducted over the same region we do not in any way regard them as replicates.

Acoustic data presented here were collected at 200 kHz using a V-fin mounted transducer towed at 6–10-m depth between hydrographic stations. Length–frequency data for ensonified krill populations were derived from bongo-net sampling, and used to estimate target strength for input into the echo-integration calculations (Macaulay et al., 1984; Anon., 1986; Daly and Macaulay, 1988; M. C. Macaulay in AERG 1990). Data were integrated for each 30-s interval along the trackline, to 250 m depth or bottom, depending on which was encountered first.

Results

Spatial and temporal patterns in krill biomass

Krill distributions around Elephant Island exhibited strong spatial and temporal variability, changing markedly between the four surveys. The depth-integrated biomass of krill measured along each of the survey tracks was highly variable. The location of biomass concentrations was not consistent between surveys, and, for the most part, depth-integrated biomass was very low (Fig. 1).

We used spectral analysis on blocks of data selected from regions where penguins were present to determine if any characteristic scales (frequencies) explained more of the variance in depth-integrated krill biomass. Penguin foraging was part of a larger predator–prey study, and we examined areas with penguins to determine if there was horizontal patchiness detectable in the depth-integrated krill biomass data. We assumed that predators might aggregate in areas which had particular horizontal scales of variability in prey biomass, but this was not evident in our data. There was no indication that a greater proportion of the variance in krill biomass could be associated with any characteristic spatial scale. Variance increased at higher frequencies. The spatial scales examined ranged from 0.3 to 10.0 km (frequencies of 0.1 to 3.3 cycles km^{-1}), overlapping with the small-scale (high-frequency) range of previous studies (Weber et al., 1986; Levin et al., 1988; Morin et al., 1988). Spectra obtained by Levin et al. (1988) also exhibited indications of increasing noisiness at higher frequencies. We examined the autocorrelation structure of data from each survey, but no useful information was gained from these analyses.

Changes in the frequency distribution of krill biomass

We used univariate statistics and quantile plots to compare the frequency distribution of depth-integrated krill biomass from each survey. The data from all four surveys were positively skewed, with survey 3 showing the highest skew (Table 1). Distributions were not
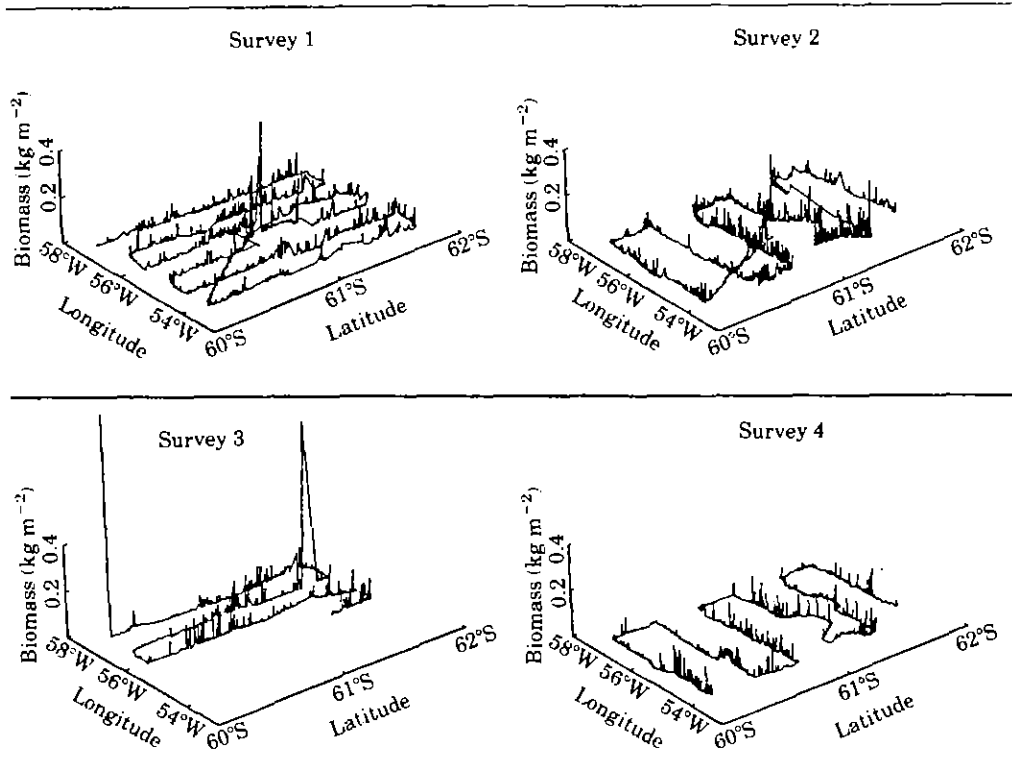
Figure 1. Depth-integrated biomass of *Euphausia superba* measured by acoustics along the ships track in four surveys around Elephant Island (islands are not shown). Survey 1 was conducted from 6 to 11 January 1990; survey 2 from 21 to 26 January; survey 3 from 7 to 13 February; and survey 4 from 21 to 27 February. Krill biomass integrated over the upper 250 m of the water column, and averaged over horizontal intervals of 75 to 130 m, ranged from 0.004 to 0.8 kg m^{-2}, or over two orders of magnitude.

Table 1. Univariate statistics for each of four acoustic surveys around Elephant Island. N=number of data points; CV, coefficient of variation=standard deviation/mean. Means, medians, and maximum values are in kg m^{-2}. Variances were estimated by the classical method rather than by geostatistical methods such as kriging (Anon., 1991), and should mainly be used to compare between surveys.

	Survey 1	Survey 2	Survey 3	Survey 4
N	4667	7042	2624	9694
Skewness	8.3	2.99	20.55	3.51
Kurtosis	148.6	20.11	533.03	16.38
S.D.	0.018	0.018	0.031	0.013
CV	100.5%	85.6%	247.1%	112.3%
Min	0.004	0.004	0.003	0.001
Mean	0.0181	0.0212	0.0127	0.0114
Median	0.013	0.016	0.008	0.008
Max	0.493	0.292	0.935	0.126

greatly influenced by high values, as shown by the fact that means were only 1.3 to 1.6 times the median values for the surveys. Coefficients of variation within each survey were high (Table 1), with survey 3 showing the greatest variability (CV=247%). Variances were estimated by the classical method rather than using a geostatistical method such as kriging. This can have a large effect on the magnitude of the variance estimate

(Anon., 1991), and we use the CVs mainly to show differences between surveys. The quantile plots show that survey 1 and survey 2 had similar frequency distributions, which differed from survey 3 and survey 4 (Fig. 2a). The steeper slope of survey 3 and 4 shows that there was a greater proportion of small data values relative to surveys 1 and 2. By comparing the quantiles of each survey against survey 1 it can be seen that there was a
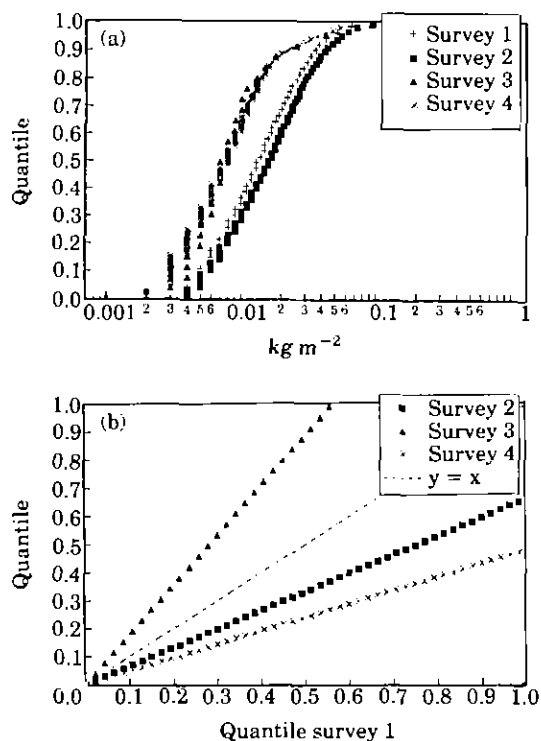
Figure 2. Comparison of the frequency distribution of depth-integrated biomass from four acoustic surveys around Elephant Island. (a) Quantile plots for each survey. x-Axis is logarithmic. (b) Quantiles for each of surveys 2, 3, and 4 plotted against the quantiles for survey 1 to show evolution of the frequency structure.

progressive evolution of the frequency structure over time (Fig. 2b). Deviations from the original distribution increased with time, but the direction of the deviations was not consistent. The large differences in standard deviation and coefficients of variation between survey 2 and survey 3 was associated with the largest difference in biomass between surveys (Table 1). This suggests that important processes affecting the spatial distribution of krill were occurring at temporal scales shorter than the interval between surveys.

A simple calculation illustrates this point. The geostrophic flow around Elephant and Clarence Island has a south-west–north-east axis and exhibits horizontal shear, with higher velocities on the north-east side of the islands (Capella *et al.*, 1992). Surface flow in this region is about 0.03 m s^{-1} (Capella *et al.*, 1992), suggesting advection on the order of 40 km during the 15–17 days separating surveys. In addition, krill can swim at 0.13–0.15 m s^{-1} (Kanda *et al.*, 1982). This rate of movement could transport a swarm 170–190 km during the 15–17-day interval separating surveys, indicating that swarms have the potential to move in and out of the entire survey grid between surveys. Thus, it is reasonable to speculate that entirely different populations of krill may

have been assessed during each survey. In fact, changes in the size and developmental stage structure of krill samples collected with bongo nets (Loeb and Siegel, 1992) suggest that different populations probably were sampled during the four surveys.

Fractal pattern

Fractal geometry, or the geometry of structures with a scaling symmetry, can provide information on the sampling scales necessary to resolve spatial patchiness of krill swarms. A descriptor of spatial variability that has proven useful in the absence of patterns of periodic variability (detectable by spectral analysis) is the Haussdorf dimension, D, derived from the Cantor set (Berge *et al.*, 1984; Schuster, 1988). Defined as:

$$D = -\frac{\log \dfrac{N\,(l)}{N\,(l')}}{\log \dfrac{l}{l'}}.$$

D is a measure of how similarly distributed a variable is when viewed at two levels of resolution. For example, a 10-km stretch of ocean is cut up into 10 blocks 1 km long, and it is observed that seven of these blocks contain krill ($N(l)=7$; $l=1$ km). The same stretch of ocean is then cut up into 100 blocks 100 m long and it is observed that 55 of these blocks contain krill ($N(l')=55$; $l'=100$ m). In this case, the Haussdorf dimension, $D=0.895$.

At resolutions larger than the largest physical separation of krill swarms, $D=1$. At resolutions smaller than this, $D<1$. In a system where D is constant, (i.e. regardless of the resolution of observation the variable is similarly distributed in space), the system is said to be self-similar.

Figure 3 shows the Haussdorf dimension plotted against block level for the four surveys. Block level, n, is converted to a lengthscale (in meters), l, by:

$$l = \frac{819200}{2^n}.$$

$D=1$ for surveys 3 and 4 for block lengths greater than 12 (800 m), suggesting that the largest gap between detectable krill concentrations was between 6.4 km and 12.8 km. For surveys 1 and 2 the largest gap was between 3.2 km and 6.4 km. For all surveys, D decreased with increasing resolution. None of the krill distributions were found to be self-similar above the smallest resolution (100 m). One possible interpretation of this result is that the finer the scales observations were made on, the scarcer the abundance of krill appeared. The fractal analysis shows that at smaller scales there are more intervals in which krill do not occur. In other
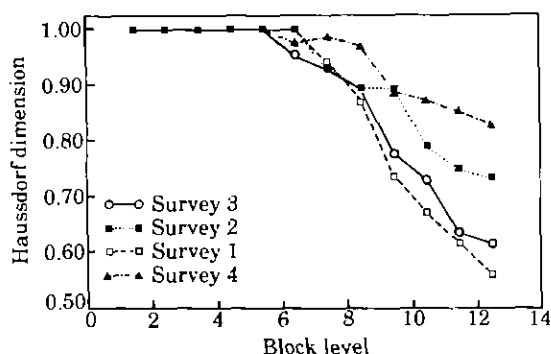
Figure 3. Haussdorf dimension, D, plotted against block level, n, for the four acoustic surveys. Block length $1 = 819200/2^n$ (meters).

words, the structure becomes more full of holes. In survey 2 there was a suggestion that D may asymptote to some non-zero value.

At very fine resolutions (the length of an individual krill) one would expect D to become constant. If it were known that D was constant at some scale above this finest possible resolution, then calculations of swarm biomass might be relatively simple: a geometric structure with the same fractal dimension could be integrated for its solid volume to estimate biomass. It remains for experiments to be conducted at scales finer than several hundred meters to clarify this point.

Discussion

Implications for stock assessment surveys

The intense spatial and temporal variability in krill biomass, combined with apparent changes in the populations being sampled, suggest that the oceanographic regime around Elephant Island is highly dynamic, and a more sophisticated research program will be necessary in regions like this to assess changes in krill distribution and abundance through time. Two issues must be resolved in developing a regional research program for krill stock assessment: (1) what are the spatial scales of interest?; (2) what are the assets available to such a program? It should be noted that these issues are not independent – the larger the region of interest, the greater the assets must be to yield scientifically meaningful results.

As a first example of the scalar issues confronted when designing a stock assessment program, consider the limitations inherent to ship survey methods. Single-ship surveys can accurately assess changes in krill distribution and abundance through time over relatively small spatial scales. The absolute size of an appropriate survey grid will depend on the local oceanographic regime, the desired grid resolution, and the ship's speed. Determining an appropriate size will typically require an iterative

process of incrementally increasing grid size until results indicate that the assumption of a stationary field is violated beyond reason (i.e. the distributional data can no longer be assumed synoptic). Multiple-ship surveys can expand the areal coverage of a survey region in an approximately linear manner (as done in the BIOMASS program), but this leads to at least an additive increase in the financial and logistical demands placed on the field program. Given the present-day costs associated with oceanographic research cruises in the Southern Ocean, it appears that we have reached a crossroads at which we must rethink our entire strategy for krill stock assessment. In the remainder of this paper we will suggest some approaches to the problem that may appear novel to most fisheries scientists and biological oceanographers, but should look at least vaguely familiar to those knowledgeable of current methods in physical oceanography.

New modeling approaches

The approaches that we suggest are based on the following premise: given the financial and logistical constraints of conducting multiple-ship surveys in the Southern Ocean, it is impossible to rely on ship data alone to assess krill distributions over large areas both synoptically and with high spatial resolution. Therefore, we believe that successful assessments of krill in the future will be based on sophisticated computer modeling efforts, emphasizing data assimilation techniques (e.g. Haidvogel and Robinson, 1989; Ishizaka, 1990) coupled with properly designed, multi-disciplinary field programs.

The sophisticated computational methods necessary for conducting this type of research are presently being developed (Hofmann, 1993). Data assimilation techniques have long been applied to atmospheric circulation models in meteorology for the purpose of weather forecasting (Daley, 1991) and have only recently been introduced to oceanography. For oceanographic applications, these techniques require a well-specified ocean circulation model with the appropriate biological processes embedded within it. Such models can be developed for a region provided that the boundary conditions are correctly specified. Field data are used initially to develop the model, and subsequently are assimilated into the model to keep numerical solutions approximating real-world observations. The models are useful for predicting spatial distributions of variables through time where and when the coverage of field measurements is discontinuous. Obviously, the resolution and accuracy of the model solutions are ultimately limited by the quality of the available field data. Short-term fluctuations in krill biomass on the order of 3–4 times in 40 days around the South Shetland Islands indicate that krill exist in a highly advective regime in this region, resulting in temporal variability which may be

intensified by the food-searching activity of swarms (Ichii *et al.*, 1991). A major difficulty in applying data-assimilation techniques lies in adequately defining the boundary conditions in such regions, and further research is required. To date there are no studies integrating acoustic data into data-assimilation models, but we consider this approach will lead to important advances, despite the fact that the methods are computationally complex.

The field data must include both physical and biological measurements. Physical oceanographers have come to rely on satellite remote sensing (Abbott and Chelton, 1991) and grids of moored, remotely interrogated instruments (Lindstrom and Nowlin Jr, 1989) to provide them with the data sets they require for developing ocean circulation models. Biological oceanographers are just beginning to collect their data sets in a comparable fashion (Dickey, 1988, 1991). Instruments that can be deployed on moorings and can quantitatively measure the acoustic back-scatter from krill are presently operational (Greene and Wiebe, 1990). New moored instruments that will also be able to provide krill size information are under development (Ehrenberg *et al.*, 1989). As these and other acoustic instruments become incorporated into standard mooring deployments, long time series of truly synoptic krill measurements will become a reality. Undoubtedly, the spatial resolution of the data will be coarser than we would like, but at least these measurements could provide a coarse to meso-scale time-series context for the finer-scale data provided by ship surveys.

Viability of long-range sonar

Filling in the gaps in areal coverage is not a trivial problem and should not be ignored, especially given the small-scale spatial variability we observed. One approach to this problem will involve the development of field methods that can remotely sense krill distributions both continuously and synoptically over large areas of ocean. Satellite and aircraft remote-sensing methods are of little value at present since electromagnetic radiation does not penetrate the ocean sufficiently to detect and quantify krill distributions at depth. Low-frequency, long-range acoustic methods, originally developed by the military for antisubmarine warfare, may provide a major technological advance to future efforts in krill stock assessment. Revie *et al.* (1974) and Weston and Andrews (1990) describe the use of a 1–2 kHz mooring-based SONAR that could detect and track fish schools at distances up to 65 km. The positions of schools were tracked over several days, with a research vessel subsequently directed to the schools for high-frequency, higher-resolution acoustic surveys. Extensions of this concept to mooring-based SONAR arrays and towed SONAR arrays (e.g. modeled after

"GLORIA", Rusby *et al.*, 1973) could greatly expand the scope of our field measurements. We suggest that shorter-range systems operating over 1–2 km at frequencies between 20–40 kHz could be used to track krill swarms at a distance. Higher-frequency systems would have to be employed to resolve details within swarms.

In support of the concept of long-range sonar, we present some calculations in the Appendix to illustrate the viability of using long-range sonar with a frequency of 20 kHz to detect swarms of krill at 1 km range. Target strengths of krill in this frequency range have been estimated both empirically and from theoretical models. At 38 kHz the target strength (TS) of krill was measured between [−86, −80] dB (Foote *et al.*, 1990). The bent cylinder model described by Chu *et al.* (1992) also predicts a $TS \simeq -80$ dB for a 40-mm krill at 40 kHz, and a $TS \simeq -90$ dB for a 40-mm krill at 20 kHz. If we assume the density of krill in swarms or schools is [10^2, 10^3] animals m^{-3}, then the volume back-scattering strength of an aggregation can be estimated from the TS (see Appendix). In the appendix we use estimates of the acoustic system parameters, the beam pattern parameters, biological parameters, and TVG parameters to calculate the magnitude of the signal detected at the tranducer from krill swarms. Since our goal is to detect krill swarms, we do not need a very narrow beam to achieve satisfactory horizontal resolution. At 1 km, a 6° beam will have a resolution of $\simeq 105$ m, which is sufficient to detect large krill aggregations. We can also use a pulse duration of 3 ms because we are less concerned with horizontal resolution. From the calculations in the Appendix, we conclude that a 20 kHz system operating over a range of 1 km is a practical option to detect krill swarms with densities greater than or equal to $10^3 \, m^{-3}$.

The technology for carrying out such an innovative and ambitious approach to the krill stock-assessment problem could be developed within a few years. The potential of long-range sonar for fisheries assessment using fixed transducer arrays and towed bodies was known since the early 1970s (see the summary in Mitson, 1983), but the idea has yet to be effectively implemented. While the data-assimilation models are a recently-developed technique, they are being used with increasing success by physical oceanographers and modelers. The initial capital investment would be relatively high, but the long-term (>5 years) costs would likely be comparable to those incurred if we continue to do business as usual with only conventional ship-based surveys. There can be little doubt that the quality of data will improve substantially if these new approaches are pursued. Finally, we want to reemphasize that different approaches to stock assessment operate effectively on different spatial scales. Therefore, since the problems associated with krill stock assessment range over many scales, a variety of approaches should be encouraged.

Acknowledgments

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Appendix

Calculations supporting the claim that krill swarms should be detectable by long-range sonar at 1 km range using a 20 kHz system.

Acoustic system parameters

SRT = -170 receiver sensitivity, dB re 1 V/(μPa)

SL = 232 source level, dB re 1 μPa for 5 kW input power

f20 = 20 000 acoustic frequency, Hz

To predict sound speed, c (m/s), from Leroy (1969):

T = 0 mean temperature, deg. C
S = 35 mean salinity, ppt
Z = 50 mean depth of krill swarms, m

$$c = 1492.9 + 3 \times (T - 10) - 0.006 \times (T - 10)^2 - 0.04 \times (T - 18)^2 + 1.2 \times (S - 35) - 0.01 \times (T - 18) \times (S - 35) + \frac{Z}{61}$$

$c = 1.45 \times 10^3$

$\lambda = \dfrac{c}{f20}$ acoustic wavelength, m $\lambda = 0.073$

$\tau = 3 \times 10^{-3}$ pulse duration, s

R = 1000 range, m $10 \log \left[c \dfrac{\tau}{2} \right] = 3.4$

Acoustic beam pattern

θ = 6 beamwidth in degrees

L = $57.3 \times \lambda \times \theta^{-1}$ dimension of the active face of the transducer, m L = 0.692

$a = \dfrac{L}{2}$ radius of the active face of the transducer, m

$10 \log \Psi = 20 \log \left[\dfrac{\lambda}{2} \times \pi \times a \right] + 7.7$ equivalent two-way beam width, dB/steradian

$10 \log \Psi = -20.4$

Biological parameters

N = 10^3 krill density in swarms, m^{-3}

TS20, target strength of krill @ 20 kHz = -90 dB

SV20 = $10 \log(N) + $ TS20

SV20, back-scattering volume of a swarm = -60 dB

TVG parameters

α, absorption coefficient @ 20 kHz = 11 dB/km

β, absorption coefficient = $\dfrac{\alpha}{8.69}$ nepers/km

t0, optimum start time for TVG = $1.94 \cdot 10^{-3}$ s

t = 0.5 s

Ideal TVG function (MacLennan, 1987):

$$a_1 = 20 \log \left[\frac{c}{1000} \times (t - t0) \times \exp \left[\beta \times c \times \frac{t}{2000} \right] \right]$$

Assuming krill are within 1000 m range, at the speed of sound the two-way travel time is 2000/1500 = 1.33 s. Setting t = 1.33, gain is estimated as:

$$a133 = 20 \log \left[\frac{c}{1000} (1.33 - t0) \times \exp \left[\beta \times c \times \frac{1.33}{2000} \right] \right]$$

$$a133 = 16.3$$

$$20 \log(R) + 2\alpha \times \frac{R}{1000} = 82$$

Relationship between voltage output of the TVG amplifier and SV from Do (1987):

20logV_TVG = SV20 + SL + SRT + 10logφ +

$$10 \log \left[c \times \frac{\tau}{2} \right] + 20 \log(a133) - 20 \log(R) + 2\alpha \times \left[\frac{R}{1000} \right]$$

$$20logV\_TVG = -28.77$$

mV20 = 10logV_TVG

$$\mu V = mV20 \times 1000 = 36$$

This level of signal should be detectable.