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Hydroacoustic surveys of the distribution and abundance of krill: Prydz Bay region - FIBEX, ADBEX II and SIBEX II, MV *Nella Dan*

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HYDROACOUSTIC SURVEYS OF THE DISTRIBUTION AND ABUNDANCE OF KRILL: PRYDZ BAY REGION - FIBEX, ADBEX II AND SIBEX II, MV *NELLA DAN*

by

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ABSTRACT

Hydroacoustic surveys of the distribution and abundance of krill, *Euphausia superba* Dana, were undertaken in the Prydz Bay region, Antarctica. Three surveys were carried out south of 60°S within an area of 1.28×10^6 km^2 between 55°E and 95°E, during the austral summer months of 1980-81, 1983-84 and 1984-85. The surveys included a total of 25 transects and covered a distance of 22 500 km over the three seasons. The surveys formed part of the Australian contribution to the international BIOMASS program.

The results of the surveys and a discussion of the theory and methods employed including sources of error in the echointegration technique are presented. Quantitative data are presented on the abundance (biomass) of krill in the Prydz Bay region as a whole and the weight density of krill along each cruise track is presented in graphical form. These data demonstrate a patchy density distribution with surface densities reaching a maximum of over 100 g/m^2 along the coastal margin.

Estimates of biomass for the entire study region of 1.28×10^6 km^2 were 1.6, 3.5 and 3.7 million tonnes for the 1980-81 (FIBEX), 1983-84 (ADBEX II) and 1984-85 (SIBEX II) cruises respectively. It could not be concluded, however, that there had actually been changes in the abundance of krill in the region over the period between the surveys because of the wide confidence limits on the abundance estimates.

The precision with which changes in abundance can be detected can be improved by underway identification of target species, better calibration and improved survey design. More accurate estimates of biomass also require more accurate target strength measurements.

[illegible]ACOUSTIC SURVEYS OF THE DISTRIBUTION AND ABUN[illegible] PRYDZ BAY REGION: FIBEX, ADBEX II AND SIBEX II [illegible]

by

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ABSTRACT

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1. INTRODUCTION

Krill, *Euphausia superba* Dana, is a major fisheries resource. Its harvest commenced in 1974 and reached a peak in 1982 with a landed catch of 528 000 t. Approximately 148 000 t were taken in Food and Agricutural Organisation/Convention for the Conservation of Antarctic Marine Living Resources (FAO/CCAMLR) Statistical Area 58 which includes most of the waters adjacent to the Australian Antarctic Territory, northwards to 50°S. Since then the total catch has decreased slightly and in the 1987 season it weighed 376 527 t of which 29 557 t were from area 58 (Scientific Committee AMLR 1986). The krill fishery ranked sixteenth in the world in 1982 and fortieth in 1983 in terms of the catch of a single species (FAO 1984).

Despite the importance of the krill fishery there is a paucity of knowledge on which to base sound conservation and management practices. When the fishery commenced very little was known of the distribution of krill, and there were neither direct nor accurate data on the abundance and annual production of krill and the physical and biological factors controlling these parameters. Concern was expressed among the scientific community at this fundamental lack of data on krill and other living resources of the Southern Ocean, and as a result the international Biological Investigations of Marine Antarctic Systems and Stocks (BIOMASS) program was developed under the auspices of the Scientific Committee on Antarctic Research (SCAR) and the Scientific Committee on Oceanic Research (SCOR) (Anonymous 1977). The objective of this program was to gain a deeper understanding of the structure and dynamic functioning of the Antarctic marine ecosystem as a basis for the future management of potential resources.

The First International BIOMASS Experiment (FIBEX) took place in 1980-81. Although krill is circumpolar in distribution, work was limited to Bransfield Strait and the Prydz Bay region where known concentrations of krill existed and harvesting had already occurred. The program was directed toward obtaining accurate data on the magnitude of the standing stock of krill using quantitative hydroacoustic surveys and research scale trawling.

Australia participated in the program using the ice strengthened research vessel MV *Nella Dan*, operating in the Prydz Bay region in the vicinity of the Australian Antarctic stations Davis and Mawson. Japan, South Africa and France also operated in the same region. Australia continued the hydroacoustic program in 1983-84 with the Antarctic Division BIOMASS Experiment number 2 (ADBEX II) and again in 1984-85 during the Second International BIOMASS Experiment, phase II (SIBEX II).

The hydroacoustic data obtained by nations participating in FIBEX were analysed collectively at workshops in Hamburg (Anonymous 1981) and Frankfurt in 1984 (Anonymous 1986). The standing stock of krill for the Prydz Bay region was calculated at the second workshop to be approximately 1.6 million tonnes (Anonymous 1986). A detailed analysis of the data sets was left to the individual nations to undertake.

This report presents the results of a detailed analysis of the Australian data obtained on the FIBEX, ADBEX II and SIBEX II hydroacoustic surveys. It is intended that it should be a guide to the analysis of echointegrator data as well as an analysis of the data obtained. A catalogue of raw data files and FORTRAN programs developed for the preparation and analysis of the data is provided at Appendix I.

2. THEORETICAL BACKGROUND

Echointegration is a method of stock assessment using acoustics in which the energy of the backscattered echo is summed or integrated over a period of time. The following provides a brief introduction to the theory and introduces the mathematical terms used in the text. A more detailed outline of the theory is provided by Johannesson and Mitson (1983).

The echosounder transmits acoustic pulses into the water column and displays the returned signal as an echogram on a chart or monitor screen. After each transmission a 'time varied gain' amplifier (TVG) compensates for the spreading and absorption of the acoustic beam. The returned signal from a given target is thus independent of its distance from the transducer.

Volume backscatter strength (S_V) is defined as the proportion of incident acoustic energy reflected back towards the transducer (backscattered) by targets within a unit volume of water.

$$S_V = 10 \log \frac{I_r}{I_o} \quad (\text{dB re.}1\mu\text{Pa})^{*} \qquad (1)$$

where I_r = backscattered acoustic intensity from unit volume,
I_o = incident acoustic intensity.
Ir and Io are measured 1 m from the reflecting volume.

The volume backscatter strength, S_V, is related to the voltage, V, measured across the echosounder transducer by the logarithmic equation:

$$S_V = \text{VRT} - (\text{SL} + \text{SRT}) - 10 \log \frac{c\tau}{2} - 10 \log\psi + (20 \log r + 2\alpha r) \qquad (2)$$

where, S_V = volume backscatter strength (dB re.1µPa),
VRT = measured voltage across transducer (dB re.1 volt)
= 20 logV,
SL = source level (dB),
SRT = transducer sensitivity as a receiver (dB re. 1 volt μPa^{-1}),
c = sound velocity (set to 1500 m/s),
t = pulse length (ms),
ψ = equivalent beam width of transducer (steradian),
$(20 \log r + 2\alpha r)$ = compensation for absorption and spreading loss where targets are spread as a layer in the water column (dB),
r = distance from transducer to target volume (m) and
α = absorption coefficient of sound in water (m^{-1})

(Johannesson and Mitson 1983)

The quantities (SL+SRT), ψ and τ are determined by calibration.

The output signal from the echosounder is passed to the echointegrator, where the mean volume backscatter strength ($\overline{s_v}$) is computed by integrating s_v over a number of pulses of the echosounder and some distance (integration interval) along the cruise track. One nautical mile is a commonly used integration interval. The integration is carried out in a number of predetermined depth layers according to the return time of the backscattered signal.

*decibels referenced to wave of 1 µ Pascal pressure.

Mean volume backscatter strength ($\overline{s_v}$) is proportional to the mean energy backscattered from a given depth layer along the integration interval. It is assumed to be proportional to the density of organisms in the target volume and to the mean 'target strength' ($\overline{TS}$) of the organisms (Johannesson and Mitson 1983);

$$\overline{S_V} = 10 \log \overline{\sigma_V} + \overline{TS} \quad \text{(dB)} \tag{3}$$

where $\overline{s_v}$ is the mean number density (targets/m^3) in the insonified volume, and $\overline{TS}$ is the mean target strength of the organisms within the volume. The target strength of a single organism is defined as the ratio of backscattered to incident acoustic energy,

$$TS = 10 \log \frac{\text{reflected intensity 1 m from target}}{\text{incident intensity}} \quad \text{(dB)}. \tag{4}$$

TS can also be defined in terms of 'backscattering cross-section' (σ_b), i.e. the effective area the krill presents to the acoustic beam.

$$TS = 10 \log(\sigma_b) \tag{5}$$

The mean target strength of a sample of krill is defined in terms of the mean backscattering cross-section,

$$\overline{TS} = 10 \log(\overline{\sigma_b}). \tag{6}$$

It then follows that if the target strength of an individual krill is given by

$$TS = 19.9 \log(l_i) -95.7, \tag{7}$$

then the mean target strength of a sample of krill is given by

$$\overline{TS} = 10 \log \left(\frac{\sum_{i=1}^{n} l_i^{1.99}}{n} \right) - 95.7 \tag{8}$$

where n = number of krill in sample
l_i = reference length of individual krill in mm.

Equation 7 was used at the post FIBEX data workshop in 1984 (Anonymous 1986) and is based on *in situ* measurements of target strength reported by Protaschuk and Lukashova (1982).

If the mean target strength $\overline{TS}$ of the insonified target is determined and a calibrated echosounder is used to measure $\overline{S_v}$ then the mean number density of targets, $\overline{\varphi_v}$ (krill/m^3) in the insonified volume, (i.e. for the integration interval) can be determined. The mean weight density, $\overline{\rho_v}$ (g/m^3) is calculated by multiplying the mean number density by the mean weight $\overline{W}$ of the target organisms. $\overline{W}$ is calculated from the measured weights of individual krill (see equation 9).

Target density may also be expressed as a surface density, either as $\overline{\varphi_a}$ (krill/m^2) or $\overline{\rho_a}$ (g/m^2). The total krill biomass in the area surveyed is calculated by estimating an average surface density.

3. METHODS

3.1 STUDY AREA

The study area is in the region of Prydz Bay, Antarctica between 55°E and 95°E and between 60°S and the Antarctic coastline. The three survey cruises FIBEX (January - March 1981), ADBEX II (January - February 1984) and SIBEX II (December 1984 - February 1985) were carried out within this region. The southern part of the area is in Prydz Bay and is over the continental shelf. Kerguelen Plateau forms a subsurface boundary to the north and north-east (Figure 1). During winter the study area is ice covered. The ice reaches its maximum extent in September and starts to retreat in November (Jacka 1983, Stretten and Pike 1984). Some pack ice remains in the area during the summer months. The new season's ice forms in about April.

3.2 RESEARCH VESSEL

The research program was undertaken from MV *Nella Dan* (Figure 2), a 73 m ice strengthened research and resupply vessel. She was equipped with a number of scientific echosounders (Figures 3, 4) and able to undertake research scale trawling from the stern.

3.3 ECHOSOUNDERS

The program was conducted using a Simrad echosounding system that comprised an EK-38 echosounder operating at 38 kHz, an EK-120 echosounder operating at 120 kHz, a QD echo-integrator and grey scale chart recorders. The EK-38 was used only intermittently. The instrument settings of the 120 kHz echosounder used during SIBEX II are given in Table 1, and the layout of the echosounders and their peripheral equipment are given in Figure 4. Instrument settings were changed during the FIBEX cruise and $\overline{s_v}$ was normalised to standard settings during analysis. During ADBEX II and SIBEX II all settings were standardised throughout each cruise.

The echosounder transducers were hull mounted approximately 6 m below the surface. An additional 120 kHz transducer deployed from the stern by a towed body was used during the ADBEX II cruise when the hull mounted transducer failed. The towed transducer system was deployed at a nominal depth of 30 m. Backscatter from the sea surface could not be avoided and was present in the second integration layer (Figure 16c).

The 120 kHz echosounder was run continuously when MV *Nella Dan* was within the study area. The QD integrator was set to integrate 8 depth layers between 1 m and 200 m below the transducer. TVG compensation was not applied beyond 100 m from the transducer. During the SIBEX II cruise, for example, the layers selected were 1 m-10 m, 10 m-20 m, 20 m-40 m, 40 m-60 m, 60 m-80 m, 80 m-100 m, 100 m-150 m and 150 m-200 m. The upper layer was sometimes contaminated with noise and had to be rejected. The effective integration ranges were 7-206 m, 60-230 m and 16-206 m for FIBEX, ADBEX II and SIBEX II respectively.

The echointegrator output (Figure 5), including the mean volume backscatter strength for each of eight layers, was recorded on paper tape at the end of each 1 nautical mile integration interval. An hourly log (Figure 6) was kept of time, position, integration interval number ('log number'), hour interval number and comments. The position and time of each integrator interval were calculated from the log entries.

3.4 CALIBRATION OF HYDROACOUSTIC EQUIPMENT

For all cruises electronic calibrations were carried out to check transmitter power, carrier frequency, pulse duration, receiver band width and the time varied gain (TVG).

An acoustic calibration was not done before the FIBEX and ADBEX II cruises and the manufacturer's 'default' values of source level and transducer receiving sensitivity were applied $(SL+SRT = +122.9\ db/\mu Pa)$.

An electronic and acoustic calibration of the system was carried out by the manufacturer (Simrad) in Norway before the SIBEX II cruise. The acoustic calibration (i.e. determination of SL+SRT) was done by measuring the voltage across the transducer when a standard copper sphere of target strength -36.3 dB was suspended below the transducer.

In this case

$$(SL + SRT) = VRT + 2TL - TS \qquad (8)$$

where,

S = source level (dB re. 1μPa at 1 m)

SRT = sensitivity of transducer as a receiver (dB re.1V μPa^{-1})

VRT = voltage measured across transducer (dB re. 1V)

TL = transmission loss between transducer and sphere (dB)

TS = target strength of calibration sphere (dB).

A detailed account of calibration procedures is given in Johannesson and Mitson (1983).

The calibrated and default values of the combined parameter SL+SRT for the EK-120 echosounder prior to SIBEX II were +115.8 dB re. 1μPa and +122.9 dB re. 1μPa respectively. The calibration was carried out to a precision of better than ±1.0 dB (Stenbekk S., *personal communication*), where the sources of error were:

TS of sphere	±0.1 dB,
Reading the oscilloscope	±0.3 dB,
Accuracy of oscilloscope	±0.3 dB,
Positioning of the sphere in the centre of the beam	±0.2 dB,
Time varied gain	±0.2 dB.

An electronic fault in the integrator resulted in the integration of low level background noise during ADBEX II and SIBEX II. The level of noise was determined from the mean volume backscattering strength corresponding to areas of zero krill density. These were -79.0 dB for ADBEX II and -88.5 dB for SIBEX II. Krill density estimates for all integrator intervals were reduced appropriately. For those intervals for which the default values (see below) of target strength and weight were used the noise was equivalent to krill densities of approximately 3 g/m^2 for ADBEX II and 2 g/m^2 for SIBEX II.

3.5 KRILL TARGET STRENGTH AND WEIGHT

Samples of krill were caught by net haul at predetermined stations. The mean target strength of krill in each sample was calculated from the lengths of the individual krill using equation 8.

The average weight, $(\overline{W})$, of krill in the sample from each net haul was calculated from the measured weights of the individual krill.

The $\overline{TS}$ and $\overline{W}$ values determined for each station at which more than five krill were caught were used to calculate krill density for the 50 integrator intervals (approximately 50 nautical miles) on either side of the station. Where stations were less than 100 intervals apart the allocation was made to intervals up to the mid point between the stations. Default values calculated from pooled length and weight data for the entire study area were allocated to all other intervals (Tables 2a-2c).

3.6 SURVEY DESIGN

The sections of cruise track for which acoustic data were obtained during FIBEX, ADBEX II and SIBEX II are shown in Figures 7a and 9a. The three surveys were carried out within an area bounded by 55°E , 95°E, 60°S and the Antarctic coast. The surveys included a total of twenty-five transects along 10 000 km and covered a total distance of 22 500 km over three seasons, between 4 January and 14 March (Table 3).

The survey design for FIBEX followed the recommendation of the BIOMASS working group on hydroacoustics (Anonymous 1980). Transects ran in an east-west direction, i.e. parallel to the mean direction of the prevailing ocean currents and to the continental shelf (Figure 7b). Subsequently it was decided that north-south transects were more appropriate (Anonymous 1981) and were used on ADBEX II and SIBEX II (Figures 8b, 9b). There were eleven transects for FIBEX in an east-west direction and three in a north-south direction. For ADBEX II there were two long and one short north-south transects and for SIBEX II there were eight north-south transects. The cruise tracks were determined as a compromise between the competing demands of the hydroacoustic program and other programs including oceanography and krill biology.

The cruise tracks, including visits to Davis and Mawson, were determined before the commencement of each cruise (Figures 7a, 8a, 9a). The only variations permitted while underway were those required to avoid ice fields.

Net hauls were carried out with a rectangular midwater trawl (RMT-8) on all cruises. On FIBEX, horizontal tows to notional depths of either 62 m or 75 m were carried out twice daily close to local midday and midnight. On ADBEX II, only two hauls were 'blind' and all others were aimed at acoustic targets. On SIBEX II, oblique 0-200 m hauls were carried out at stations 1° of latitude and 5° of longitude apart. In addition to the regular 'blind' hauls, aimed hauls to identify target species were undertaken whenever a strong backscattering layer was seen on the echogram, and time permitted. An electro-mechanical net release system was used on FIBEX and ADBEX II to open and close the net at appropriate depths. On SIBEX II the depth of the net was estimated from tow-wire angle and length.

The wet weight of each zooplankton species, and the body length (standard 1 and reference measurements, Mauchline 1980) and weight of individual euphausiids were recorded. The measurements were made on fresh material during FIBEX and on material preserved in

Steedman's solution (Steedman 1976) on ADBEX II and SIBEX II (Williams *et al.* 1983, Ikeda *et al.* 1984, 1986).

3.7 ESTIMATION OF MEAN DENSITY AND BIOMASS

On return from each cruise the acoustic data were processed on a VAX 11/750 computer (Figure 10).

Mean density and the variance of the mean were estimated using the ratio estimator (Cochran 1963), a transect-based method adopted at the second post-FIBEX acoustic workshop (Anonymous 1986). This method assumes that the transect means are independent, that the expected number of animals is related to the transect length by a line passing through the origin, and that the variance of the number of animals is proportional to transect length. Figure 11 shows the distribution of density data for the FIBEX cruise.

Mean krill weight density, $\overline{\rho_A}$ (g/m^2) and the variance about the mean are given by :

$$\overline{\rho_A} = \frac{\sum_{i=1}^{K} \rho_i L_i}{\sum_{i=1}^{K} L_i} \tag{10}$$

and

$$Var(\overline{\rho_A}) = \frac{k}{k-1} \frac{\sum_{i=1}^{K} (\rho_i - \overline{\rho_A})^2 L_i^2}{(\sum_{i=1}^{K} L_i)^2}. \tag{11}$$

where

k = number of transects
ρ_i = mean weight density along transect i (g/m^2)
L_i = length of transect i.

Similarly for $\overline{\varphi_A}$ the mean number density of krill.

Biomass was estimated for an area defined by a box drawn around the transects and extended on two sides by half the mean spacing between the transects (Figures 7b, 8b, 9b).

Mean krill biomass in the surveyed area, variance of the biomass, and 95% confidence limits about the mean were calculated from the estimated mean and variance of the krill surface density using:

$$B_A = A. \overline{\rho_A} \tag{12}$$

and $\mathrm{Var}(B_A) = A^2\ \mathrm{Var}(\overline{\rho_A}),$ (13)

$$E(B_A) = \pm 1.96\sqrt{\mathrm{Var}(B_A)} \tag{14}$$

where A = area surveyed (m^2).

The mean density and resulting biomass were also calculated using the entire data set, including all off transect data ('all data' method) to check the significance of the off-transect data. The variance of the mean was not calculated using this method because of the difficulty in taking into account possible serial correlation of the data along the cruise track.

3.8 INDEX OF RELATIVE ABUNDANCE

An index of relative abundance (S_{RA}), that is independent of target strength, is the mean volume backscatter strength per nautical mile averaged over the survey area. S_{RA} was calculated using equation 3, i.e.

$$S_{RA} = 10\log(\overline{\varphi_v})_A + \overline{TS}\ ,$$

where $\overline{TS}$ is an arbitrary target strength and $\overline{\varphi_v}$ is the mean number density of krill per unit volume calculated using $\overline{TS}$. $(\overline{\varphi_v})_A$ is calculated similarly to $\overline{\rho_A}$ (equation 10) and includes corrections for background noise. The arbitrary krill target strength, $\overline{TS}$, is held constant over all intervals.

4. RESULTS

The results of aimed trawls undertaken during the three cruises to identify acoustic targets are presented in Table 7 (Hosie *et al.* 1988). Fifty-five percent of aimed haul catches contained greater than 95% krill, however 30% of aimed hauls contained less than 20% krill. The total catch varied between 10 g and 14 100 g and the catch of krill varied between 0 g and 7300 g (Figure 15). Other zooplankton caught in substantial numbers included a salp, *Salpa thompsoni,* a fish, *Pleuragramma antarcticum,* and other euphausiids, *Thysanoessa macrura* and *Euphausia crystallorophias*.

The quantitative distribution of krill is shown graphically in Figures 12a-c, where the weight densities of krill* are plotted linearly against interval number. Pseudo-3D plots show the density and geographic distribution of krill (Figure 13a-c). The two sets of plots demonstrate the considerable variation in the abundance of krill within the study area. There are small areas of high abundance and large areas that contain virtually no krill. Relatively high abundances were found along the continental margin during ADBEX II and SIBEX II. High concentrations were also found along 88°E (SIBEX II transect 7) between 61°S and 63°S. Localised dense

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* Unless stated otherwise it is assumed that all backscatter measured was due to *Euphausia superba* (which is referred to simply as krill). Specific names are used when a particular species (e.g. *Euphausia superba*) is intended or has been identified.

aggregations were found such as those at FIBEX integration intervals 11770 and 10530, ADBEX II integration interval 1389, and SIBEX II integration intervals 400 and 1427 (Figures 16a-f). Aggregations at FIBEX interval 11770 and SIBEX interval 400 were associated with features of the bottom topography. Figure 17 shows the density profile of the aggregation near SIBEX II integration interval 1427. Aimed trawls (SIBEX II stations 25/T1 and 25/T2) were carried out in this aggregation.

The mean and variance of the weight density of krill along each transect are given in Tables 4a-c. The results are presented for day-only and day-plus-night data to facilitate comparison with density estimates made by other countries. While there is little difference between the two sets of estimates, there was some evidence for diurnal variation in the density measured during ADBEX II. The densities were calculated for the depth ranges 7-206 m on FIBEX, 60-230 m on ADBEX II and 16-206 m on SIBEX II.

The mean krill density and sampling variance over the survey area are presented for the three cruises in Table 5. Higher density estimates were obtained using the 'all-data' method of calculating mean density rather than with the 'transect based' method. The large difference (48%) between the two densities estimated for ADBEX II should be noted since during ADBEX II only 25% of the data were collected along designated transects. All further results are based on densities calculated by the 'transect based' method.

The estimates of mean krill density ranged from 1 to 3 g/m^2 (Table 5). These results may be compared with similar data sets obtained on other nations' cruises to the Prydz Bay region. Density estimates from day-only data for seven cruises are presented in Table 6 (Anonymous 1986, Shirakihara *et al.* 1986). Estimated densities range nearly two orders of magnitude from 0.21 g/m^2 (obtained by the *Marion Dufresne* in 1981) to 17.5 g/m^2 (obtained by the *Kaiyo Maru* in 1984). Apart from these two widely different estimates the results from all cruises, including the three MV *Nella Dan* cruises, were within the range of 1 to 4.3 g/m^2 .

Estimates of the total biomass of krill in the Prydz Bay region during the periods January to March 1981 (FIBEX), January to March 1984 (ADBEX II) and January 1985 (SIBEX II), have been made. Biomass estimates were calculated for the actual areas surveyed and then extrapolated in the case of FIBEX and ADBEX II to an area of 1.28 x 10^6 km^2, equal to that surveyed during SIBEX II (Table 5). The 95% confidence limits and coefficients of variation calculated from the between transect variances are also presented. The coefficient of variation ranged from 16% on SIBEX II to 35% on FIBEX. The biomass estimates are compared graphically in Figure 14.

Preliminary results for the FIBEX cruise were presented at both the first and second BIOMASS acoustic workshops. The estimate of 54 million tonnes (Anonymous 1981) was corrected to 1.6 million tonnes (Anonymous 1986) by the removal of a computational error. This figure should now be replaced by 1.3 million tonnes (1.6 million tonnes if extrapolated over the SIBEX II area), a figure resulting from improved analysis techniques, including the removal of noisy data and the application of measured weights of krill rather than weight derived from length. The ADBEX II estimate of 3.5 million tonnes was obtained by extrapolating over an area of 1.28 x 10^6 km^2 density estimated over an area of only 70 000 km^2.

The SIBEX II estimate is considered to be the most reliable of the biomass estimates from the three cruises because the echosounders were fully calibrated and the survey was the most extensive and systematic. The index of relative abundance, S_{RA}, for SIBEX II is estimated to be -79.8 dB and the mean density of krill was estimated to be 2.9 g/m^2, which for the surveyed area (1.28 million km^2) represents a biomass of 3.7 million tonnes.

5. DISCUSSION

The hydroacoustic program reported here was established to investigate the abundance and distribution of krill in the region of Prydz Bay. This information was required for scientific purposes and to provide data in relation to the established krill fishery. The program also formed part of Australia's contribution to the international BIOMASS program.

The results of three cruises are reported, but only one (SIBEX II) is considered to provide better than an 'order of magnitude' estimate of absolute krill abundance. In common with similar studies elsewhere, the accuracy is limited by the magnitudes of a number of sources of both random and systematic error. These are listed in Table 8 together with comments by other authors on the magnitudes of the errors. The most important sources of error were target strength estimation, backscatter from species other than *Euphausia superba,* noise from non-biological sources, echosounder calibration and statistical sampling.

The application of the appropriate target strength (TS) is considered to be the fundamental problem in the estimation of biomass. The TS values used in the present report were derived from the length distribution of krill caught in net hauls. The relationship (equation 7) used to calculate TS from length was used at the second post-FIBEX acoustic data workshop (Anonymous 1986). It is of limited accuracy, however, since it was derived from a few data points obtained in an experiment that did not directly measure the size of the krill, take account of the krill orientation in the beam or assess the physiological condition of the animals (Protaschuk and Lukashova 1982). Miller and Hampton (1987) suggest that such empirical methods of TS estimation at 120 kHz have at best accuracies of ±2 dB. Improved TS will therefore only come when methods are developed to take these factors into account.

It was assumed that the backscatter was due entirely to krill when in reality a variety of zooplankton were insonified and hence contributed to the mean volume backscatter strength. The relative contribution of *Euphausia superba* to the total zooplankton biomass varied considerably, in both time and space, within the study region (Williams *et al.* 1983; Ikeda *et a*l. 1984, 1986; Hosie *et al.* 1988). This species tended to be dominant among the zooplankton from about 62°S to just south of the continental slope. North of this region the euphausiid *Thysanoessa macrura* tended to be in greater abundance than *Euphausia superba*, while south of this region other zooplankton, particularly the euphausiid *Euphausia crystallorophias* and the fish *Pleuragramma antarcticum*, occurred in substantial numbers. Salps and copepods were found in abundance in the main krill zone and often in swarms that produced acoustic backscatter and thus led to an overestimate of the biomass of *Euphausia superba.* This source of error could have been reduced by more frequent target identification.

Bubbles, wave-slap and pitching of the ship produced noise which contaminated the upper integration layers. Such contamination was readily apparent on the echograms where the sea state was approximately 7 or above (Figure 15b). The upper integration layer(s) were removed from the records where such noise was apparent. The removal of these layers led to an underestimate of abundance where *Euphausia superba* were present in the layers.

The echosounder on MV *Nella Dan* was calibrated by the manufacturers Simrad Subsea A/S, Norway, to a precision of better than ±1.0 dB prior to the SIBEX II cruise (Stenbekk S., *personal communication*). Other authors have reported calibration precisions of between ±0.5 dB and ±2 dB (Hempel 1983, Sameoto 1983, Anonymous 1986, Do 1987).

The statistical analysis of the data essentially followed the methods used at the second post-FIBEX data workshop (Anonymous 1986). The statistical sampling unit was chosen to be the mean krill weight density per unit area and was obtained from the mean volume backscatter strengths along a survey transect, i.e. it was a transect mean. This choice permitted the use of the ratio estimator which required no assumptions about the krill distribution, either between or within transects, and no consideration of autocorrelations along transects (Anonymous 1986, Saville 1977). The transects were selected systematically rather than randomly since there was no clear trend in the distribution of krill across the areas surveyed (Shotton and Bazigos 1984). It was considered reasonable to assume that the transect means were independent because the transect spacing on all surveys was large compared to the scale of patchiness of the krill distribution.

Given the magnitudes of the errors (both random and systematic) listed in Table 9, the following errors are considered to apply to the present study; TS estimation, ±2 dB (random + systematic), instrument calibration, ±1 dB, (random), sampling variance, ±1 dB (random) and various unquantified errors. The error in target strength estimation is difficult to assess, but it is likely that target strength has been overestimated (Anonymous 1986). An error of ±2 dB was chosen as a working figure. The unquantified errors were assumed to comprise systematic and random components which each had an error of at least ±1.5 dB. The overall error, ±3.2 dB, was estimated by assuming that the contributing errors were independent and calculating the root-mean-square. Hence for SIBEX II the absolute abundance of krill, within the study area of 1.2 million km^2, is most likely to lie within the range 1.8 to 7.7 million tonnes, where the best estimate is 3.7 million tonnes.

The relative abundance index, S_{RA}, is not affected by sources of error that remain constant from survey to survey including systematic errors inherent in the estimation of target strength. Comparisons of abundance between surveys should thus be made on the basis of relative abundance rather than absolute abundance. The precision of the relative abundance index, S_{RA}, was estimated from the random sources of error above, excluding target strength, to be at best ±2.1 dB. It thus follows that any difference detected in relative abundance between surveys must be in excess of ±4.2 dB, i.e. the relative abundance would have to reduce by at least 60% or increase by at least 160%, before the change could be considered real. On this basis, no change in the abundance of krill in the region of Prydz Bay could be detected over the period of the surveys reported here.

The present series of investigations have provided estimates of the abundance and distribution of krill against which future estimates may be compared. However because there are large potential errors involved, it is particularly important before embarking on expensive surveys to determine the object of the survey and whether the precision or accuracy required can be achieved. The ecosystem monitoring program initiated by CCAMLR requires the measurement of fluctuations in krill abundance in relation to the condition of predator populations. If we assume that such a monitoring program would need to be able to detect a relative change in abundance of ±3 dB (i.e. half or double), then the surveys must be of greater precision than those reported here. Precision can be best improved by developing methods for the underway identification of target species and by better calibration and survey design. To improve the accuracy of absolute abundance estimates more accurate target strength measurements are required.

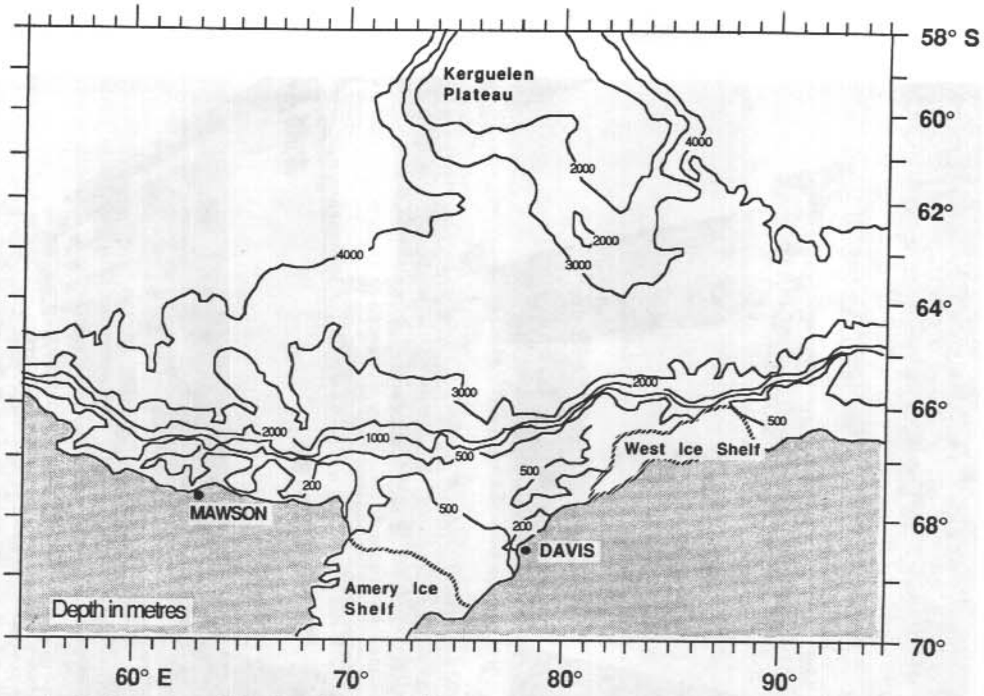


Figure 1. Bathymetry of the Prydz Bay region.

Figure 2. MV *Nella Dan*.

Figure 3. Acoustics laboratory on board *Nella Dan*.

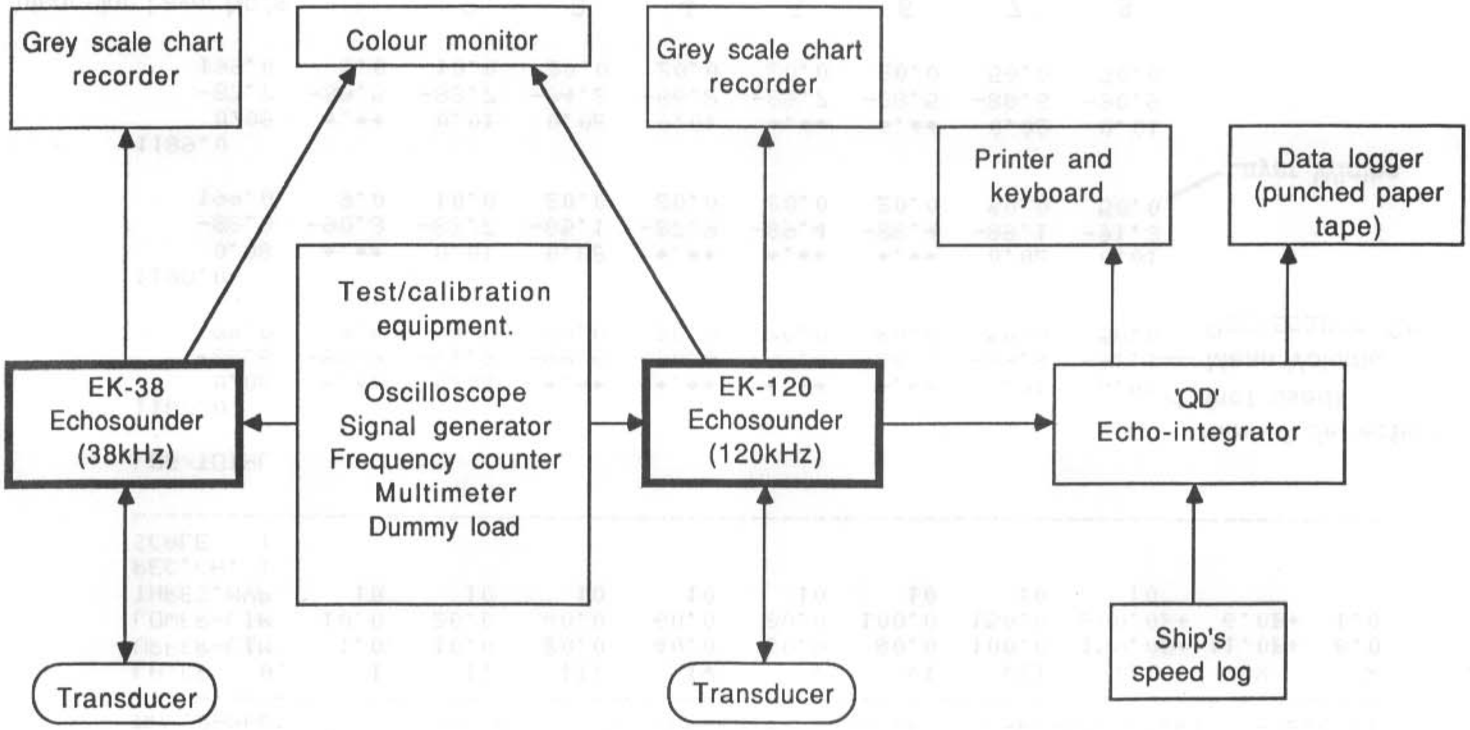
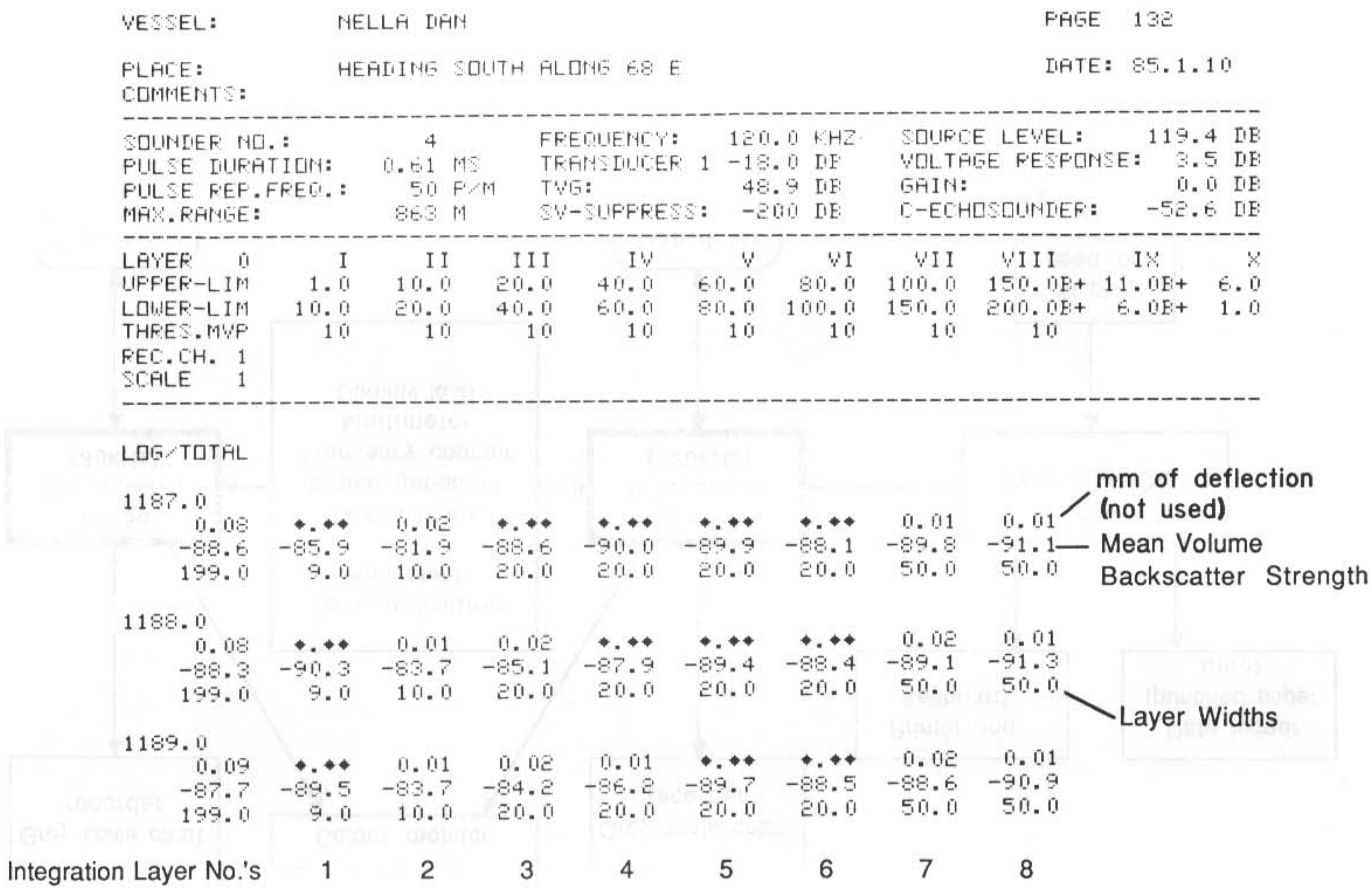
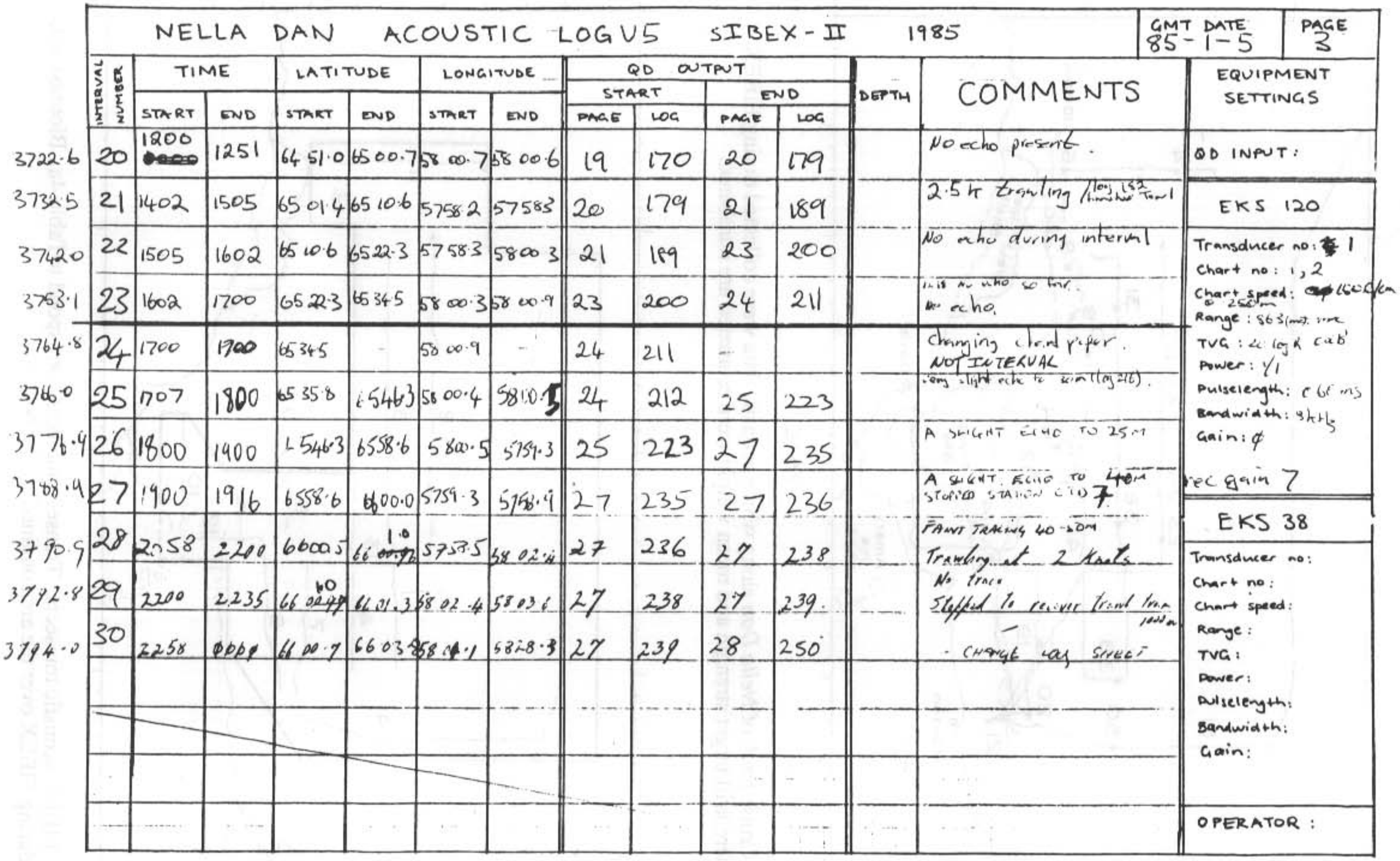


Figure 4. Echosounding equipment (schematic diagram).



```
VESSEL:          NELLA DAN                                                     PAGE  132

PLACE:           HEADING SOUTH ALONG 68 E                                      DATE: 85.1.10
COMMENTS:
------------------------------------------------------------------------------------------------
SOUNDER NO.:           4         FREQUENCY:     120.0 KHZ   SOURCE LEVEL:        119.4 DB
PULSE DURATION:     0.61 MS      TRANSDUCER 1  -18.0 DB     VOLTAGE RESPONSE:      3.5 DB
PULSE REP.FREQ.:      50 P/M     TVG:            48.9 DB    GAIN:                  0.0 DB
MAX.RANGE:           863 M       SV-SUPPRESS:  -200 DB      C-ECHOSOUNDER:       -52.6 DB
------------------------------------------------------------------------------------------------
LAYER    0      I      II     III     IV      V      VI     VII    VIII    IX      X
UPPER-LIM     1.0    10.0    20.0   40.0   60.0    80.0  100.0  150.0B+ 11.0B+  6.0
LOWER-LIM    10.0    20.0    40.0   60.0   80.0   100.0  150.0  200.0B+  6.0B+  1.0
THRES.MVP      10      10      10     10     10      10     10     10
REC.CH.  1
SCALE    1
------------------------------------------------------------------------------------------------

LOG/TOTAL

1187.0
       0.08   *.**    0.02   *.**   *.**   *.**   *.**   0.01   0.01
     -88.6  -85.9   -81.9  -88.6  -90.0  -89.9  -88.1  -89.8  -91.1
     199.0    9.0    10.0   20.0   20.0   20.0   20.0   50.0   50.0

1188.0
       0.08   *.**    0.01   0.02   *.**   *.**   *.**   0.02   0.01
     -88.3  -90.3   -83.7  -85.1  -87.9  -89.4  -88.4  -89.1  -91.3
     199.0    9.0    10.0   20.0   20.0   20.0   20.0   50.0   50.0

1189.0
       0.09   *.**    0.01   0.02   0.01   *.**   *.**   0.02   0.01
     -87.7  -89.5   -83.7  -84.2  -86.2  -89.7  -88.5  -88.6  -90.9
     199.0    9.0    10.0   20.0   20.0   20.0   20.0   50.0   50.0
```

Figure 5. Example of echointegrator output.



NELLA DAN ACOUSTIC LOGUS SIBEX - II 1985

GMT DATE 85 - 1 - 5

PAGE 3

	INTERVAL NUMBER	TIME		LATITUDE		LONGITUDE		QD OUTPUT				DEPTH	COMMENTS
								START		END			
		START	END	START	END	START	END	PAGE	LOG	PAGE	LOG		
3722.6	20	1200	1251	64 51.0	65 00.7	58 00.7	58 00.6	19	170	20	179		No echo present.
3732.5	21	1402	1505	65 01.4	65 10.6	5758.2	57583	20	179	21	189		2.5 h trawling / log 182 [illegible] Trawl
37420	22	1505	1602	65 10.6	6522.3	57 58.3	58 00 3	21	189	23	200		No echo during interval
3753.1	23	1602	1700	65 22.3	65 34.5	58 00.3	58 00.9	23	200	24	211		[illegible] no echo so far. no echo.
3764.8	24	1700	1700	65 34.5	-	58 00.9	-	24	211	-			Changing chart paper. NOT INTERVAL
3766.0	25	1707	1800	65 35.8	6546.3	58 00.4	5810.5	24	212	25	223		very slight echo to [illegible] (log 216).
3776.4	26	1800	1900	6546.3	6558.6	5800.5	5759.3	25	223	27	235		A SLIGHT ECHO TO 25M
3788.4	27	1900	1916	6558.6	6600.0	5759.3	5758.9	27	235	27	236		A SLIGHT ECHO TO 40M STOPPED STATION CTD 7
3790.9	28	2058	2200	6600.5	1.0 66 00.7	5758.5	58 02.4	27	236	27	238		FAINT TRACING 40-50M Trawling at 2 Knots
3792.8	29	2200	2235	60 66 02.4	66 01.3	58 02.4	58 03.6	27	238	27	239.		No trace Stopped to recover trawl from 1000 m
3794.0	30	2258	0000	66 00.7	66 03.8	58 04.1	5828.3	27	239	28	250		- - CHANGE LOG SHEET

EQUIPMENT SETTINGS

QD INPUT:

EKS 120

Transducer no: 1
Chart no: 1, 2
Chart speed: [illegible] 1600/km @ 250m
Range: 563 (m) [illegible]
TVG: 20 log R cal'
Power: 1/1
Pulselength: 0.6 ms
Bandwidth: 3kHz
Gain: 0
rec gain 7

EKS 38

Transducer no:
Chart no:
Chart speed:
Range:
TVG:
Power:
Pulselength:
Bandwidth:
Gain:

OPERATOR:

Figure 6. Sample page from acoustic log.

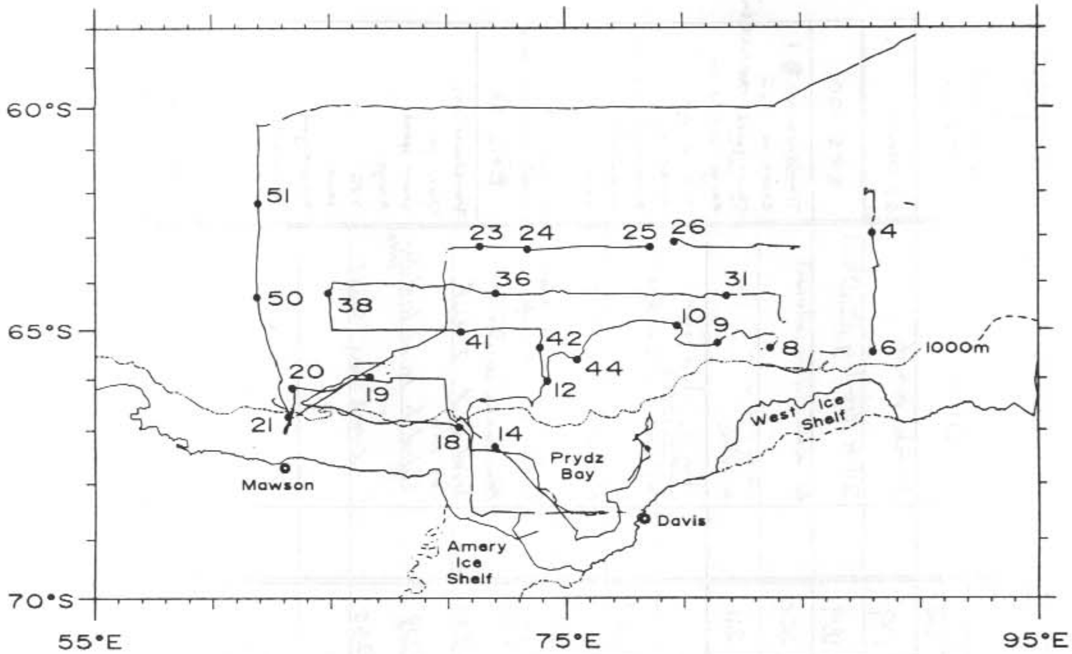


Figure 7a. Cruise track of *Nella Dan* along which acoustic data were collected during FIBEX. Stations where krill target strength and mean weight were estimated are numbered.

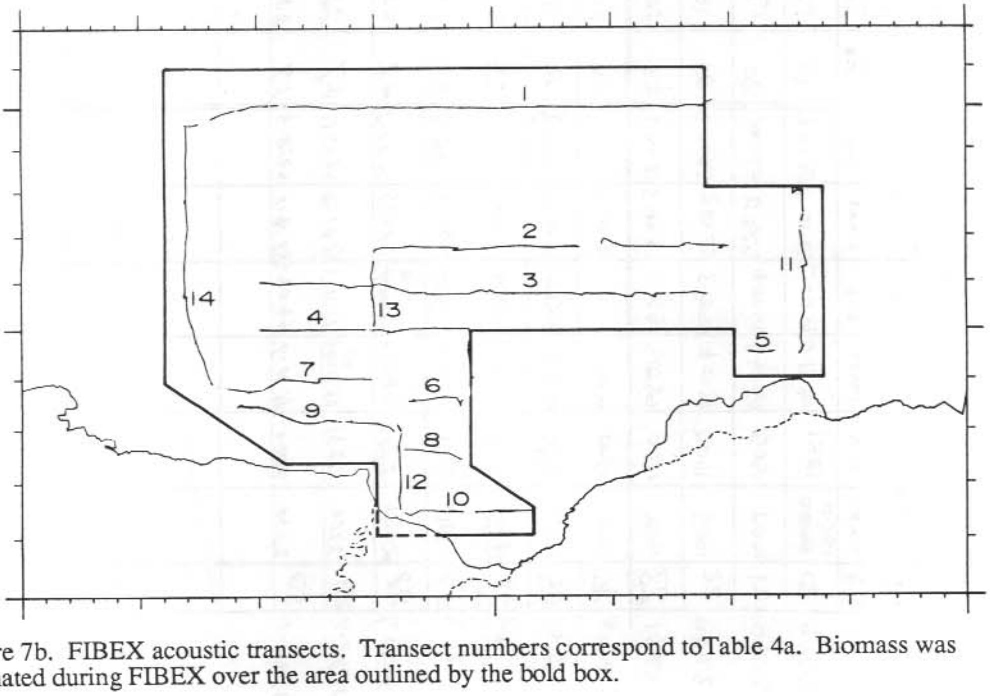


Figure 7b. FIBEX acoustic transects. Transect numbers correspond toTable 4a. Biomass was estimated during FIBEX over the area outlined by the bold box.

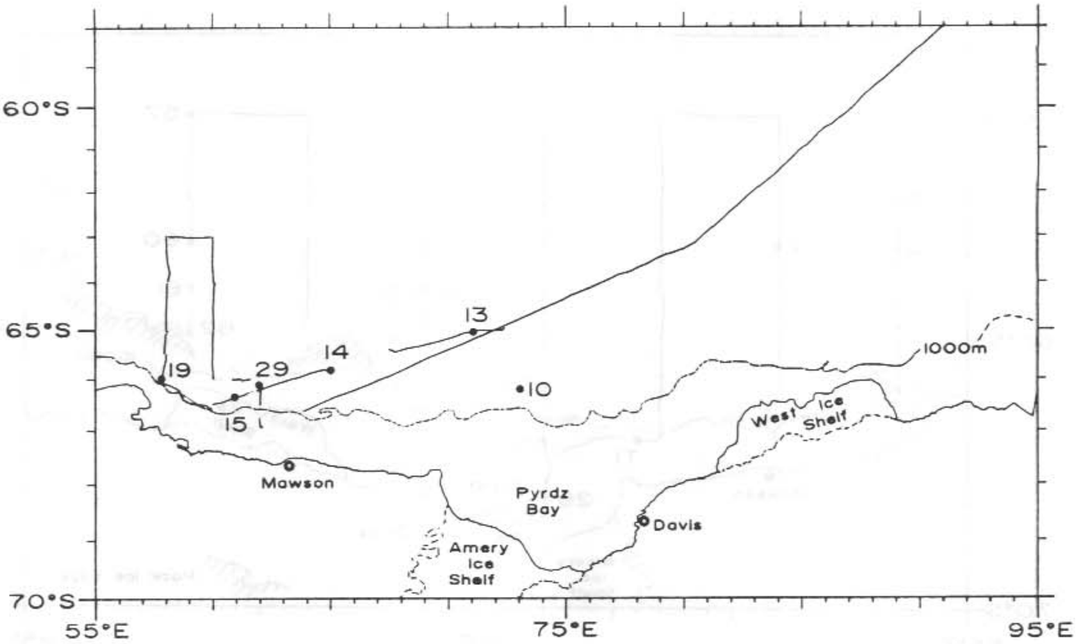


Figure 8a. Cruise track of *Nella Dan* along which acoustic data were collected during ADBEX II. Stations where krill target strength and mean weight were estimated are numbered.

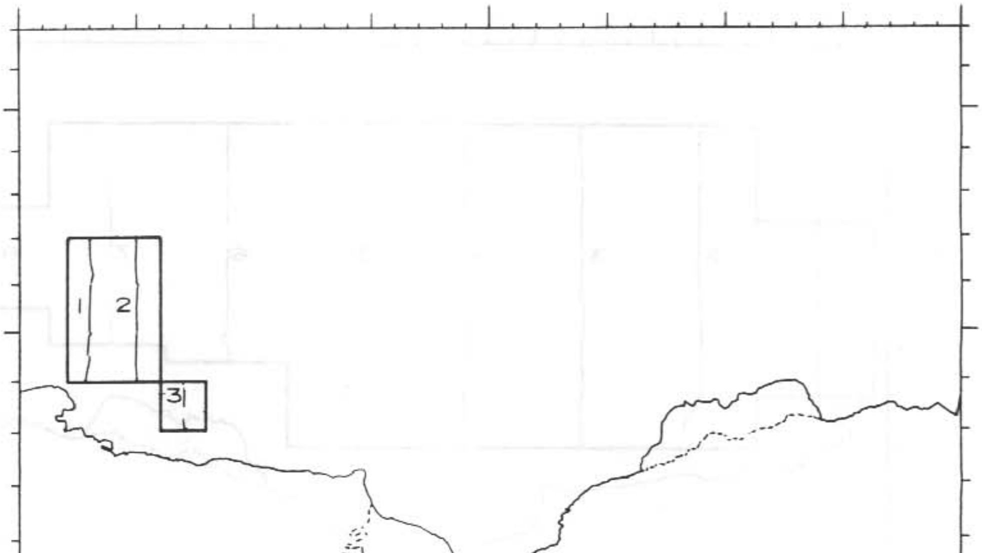


Figure 8b. ADBEX II acoustic transects. Transect numbers correspond to Table 4b. Biomass was estimated during ADBEX II over the area outlined by the bold box.

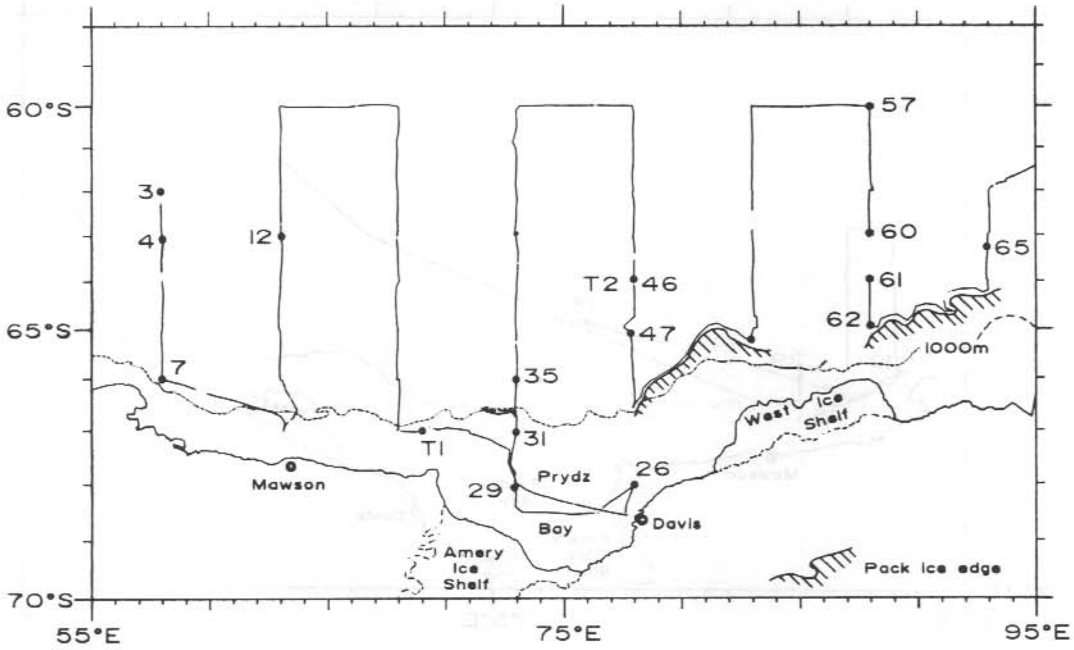


Figure 9a. Cruise track of *Nella Dan* along which acoustic data were collected during SIBEX II. Stations where krill target strength and mean weight were estimated are numbered.

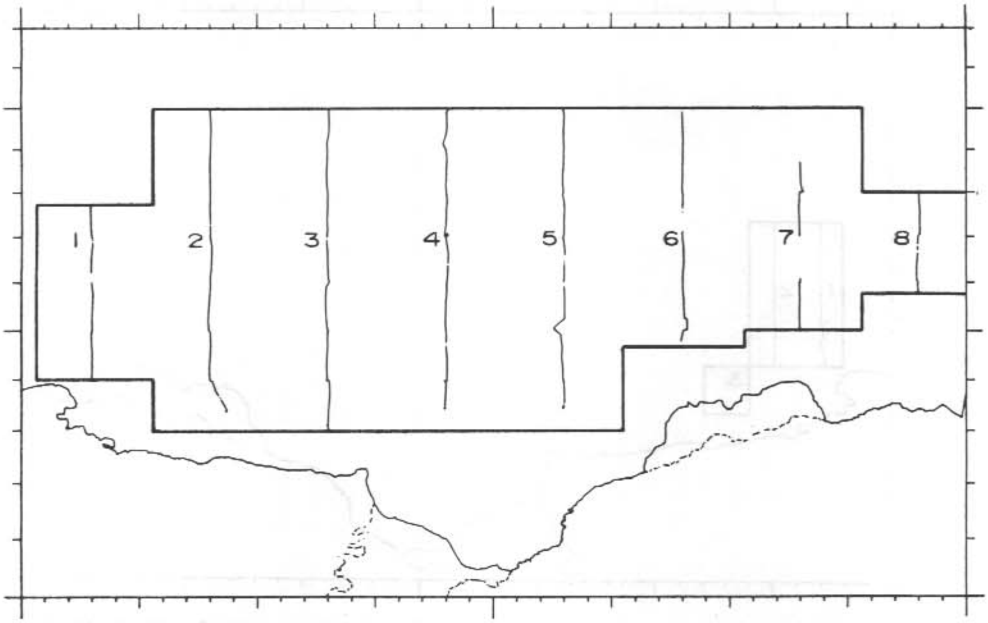


Figure 9b. SIBEX II acoustic transects. Transect numbers correspond to Table 4c. Biomass was estimated during SIBEX II over the area outlined by the bold box.

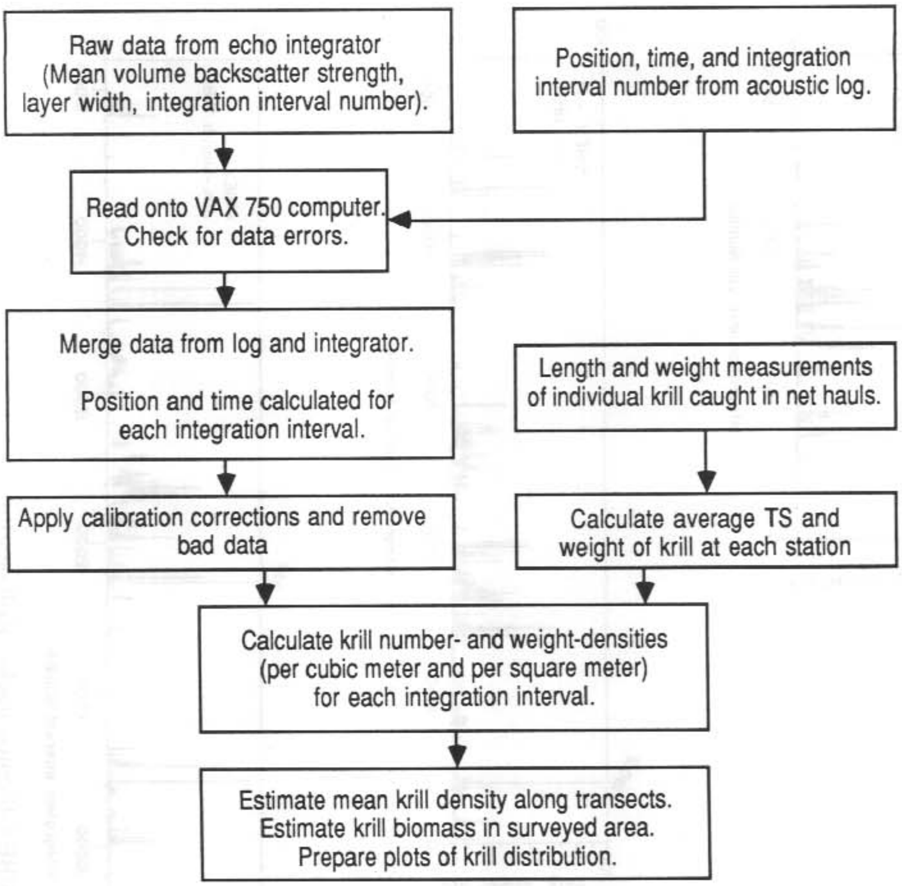


Figure 10. Procedure for data analysis.

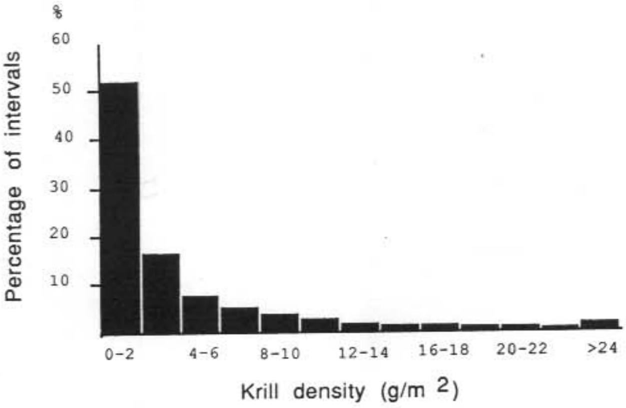


Figure 11. Distribution of FIBEX density data.

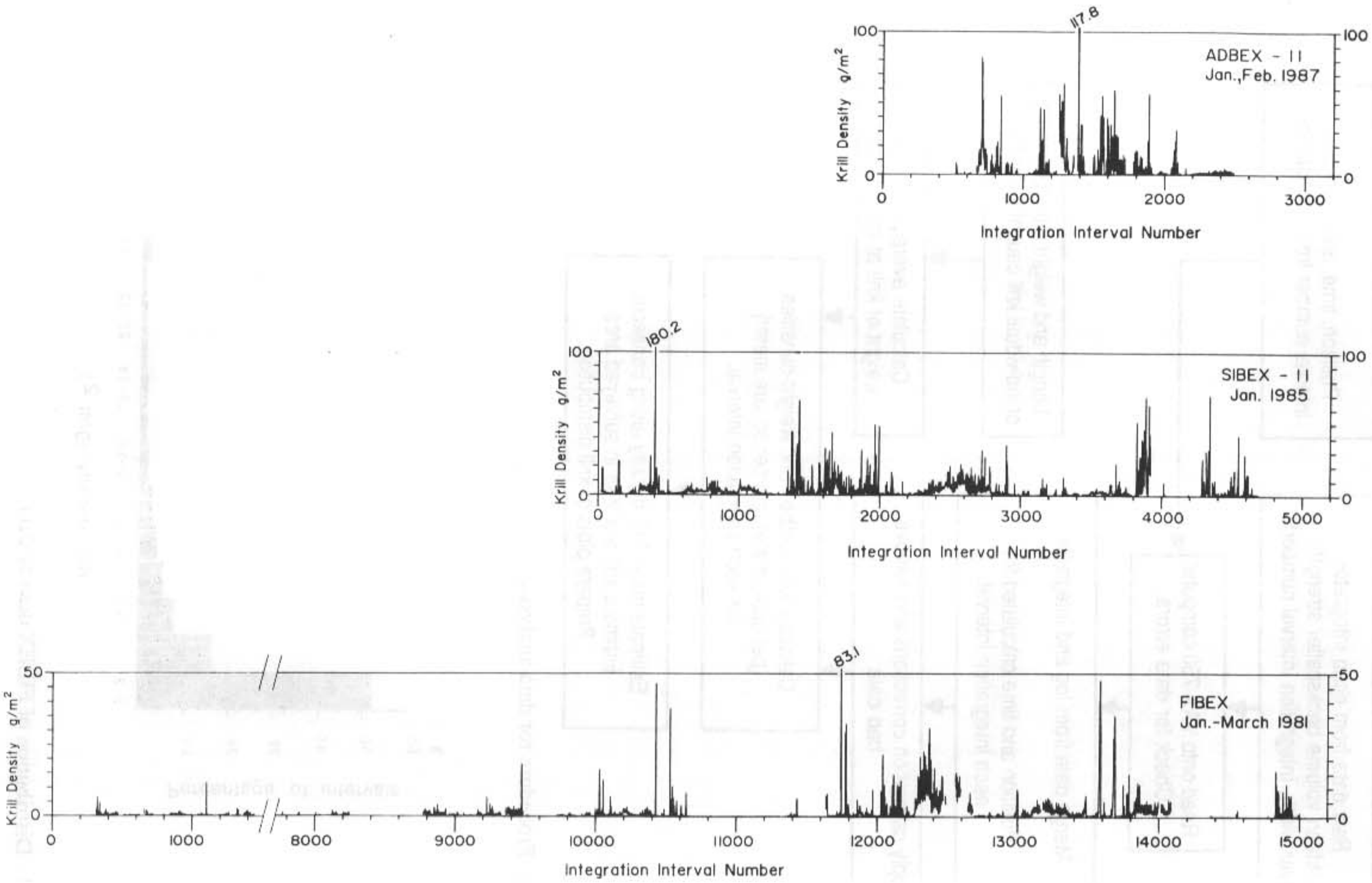


Figure 12. Krill density along FIBEX, ADBEX-II and SIBEX-II cruise tracks. Krill density (g/m^2) is plotted against integration interval number. Integration intervals are 1 mile long. During FIBEX the integration interval number was reset to 7000 at interval 1600.

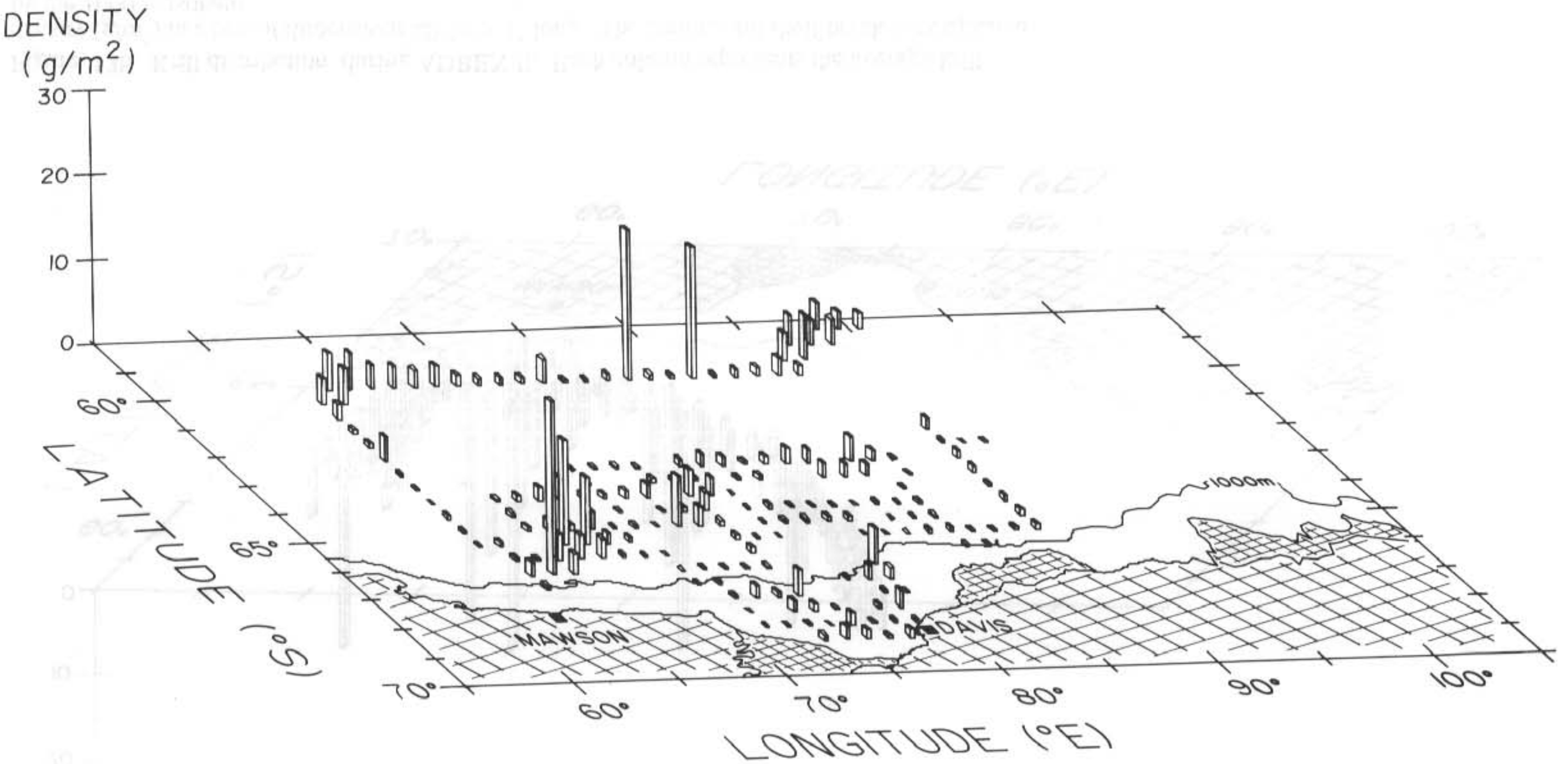


Figure 13a. Krill distribution during FIBEX. Each column represents the average krill density (g/m^2) in a box of dimensions 20' lat x 1° long. The continental shelf break is designated by the 1000 m isobath.

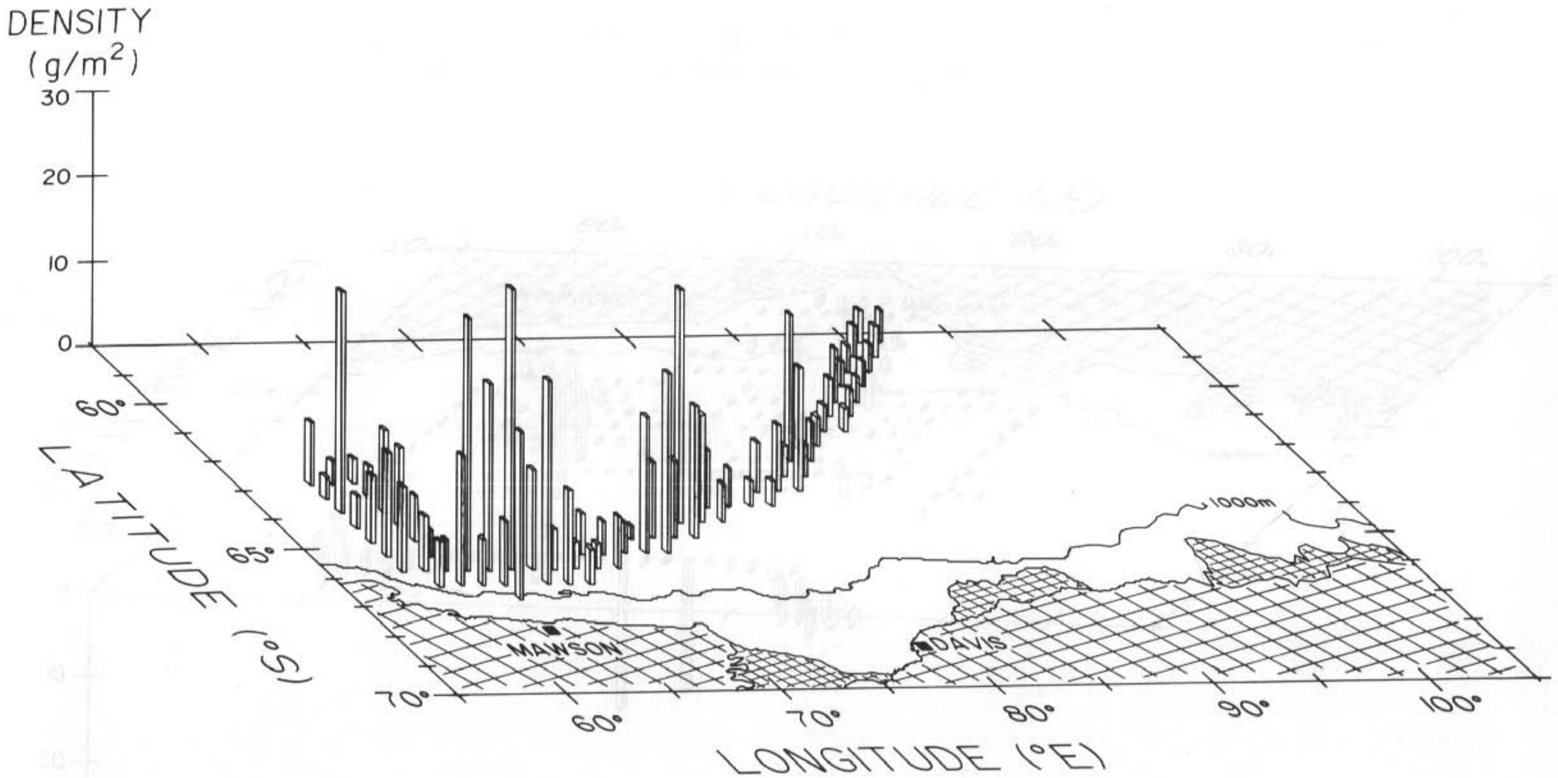


Figure 13b. Krill distribution during ADBEX II. Each column represents the average krill density (g/m^2) in a box of dimensions 20' lat x 1° long. The continental shelf break is designated by the 1000 m isobath.

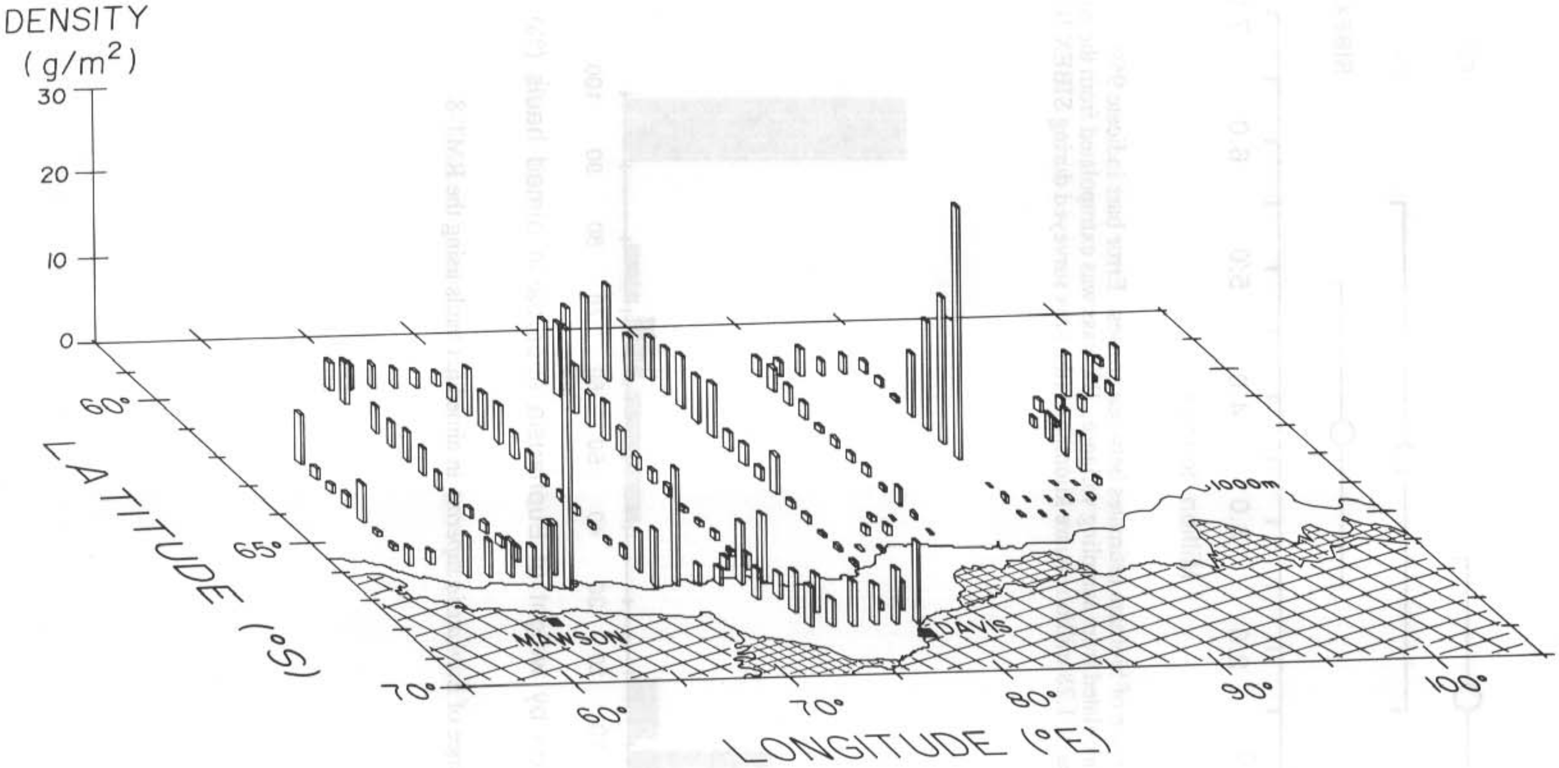


Figure 13c. Krill distribution during SIBEX 11. Each column represents the average krill density (g/m^2) in a box of dimensions 20' lat x 1° long. The continental shelf break is designated by the 1000 m isobath.

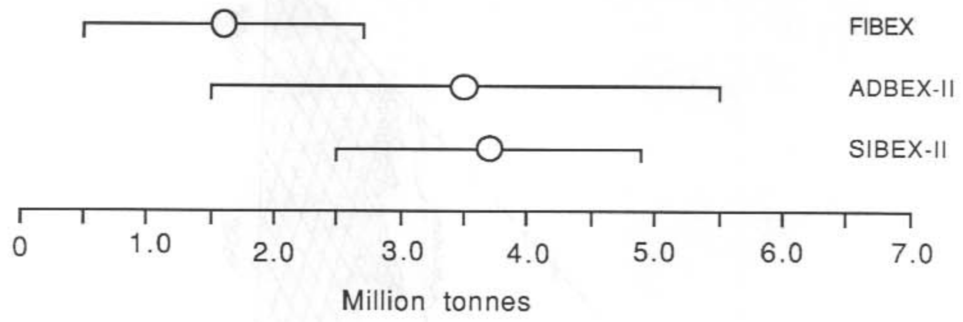


Figure 14. Comparison of biomass estimates between cruises. Error bars indicate 95% confidence limits calculated from sampling variance. Biomass was extrapolated from the area surveyed to an area of 1.28 million square kilometres (the area surveyed during SIBEX II) to aid comparison.

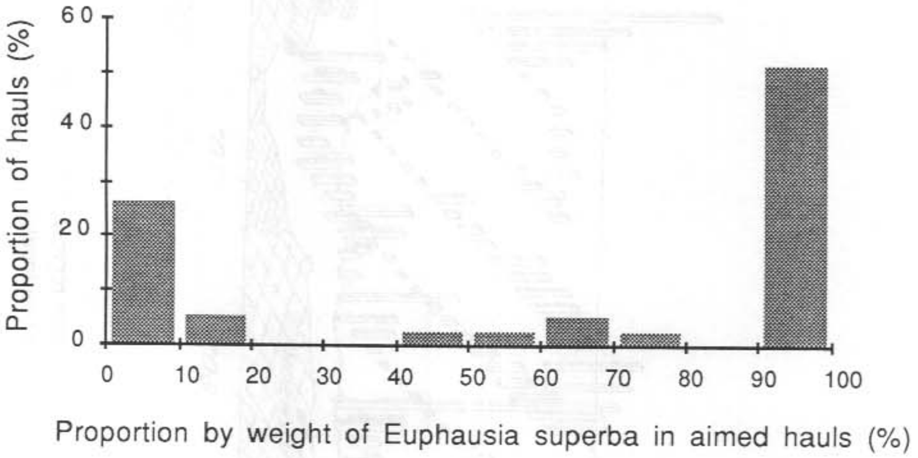


Figure 15. Occurrence of *Euphausia superba* in aimed net hauls using the RMT-8.

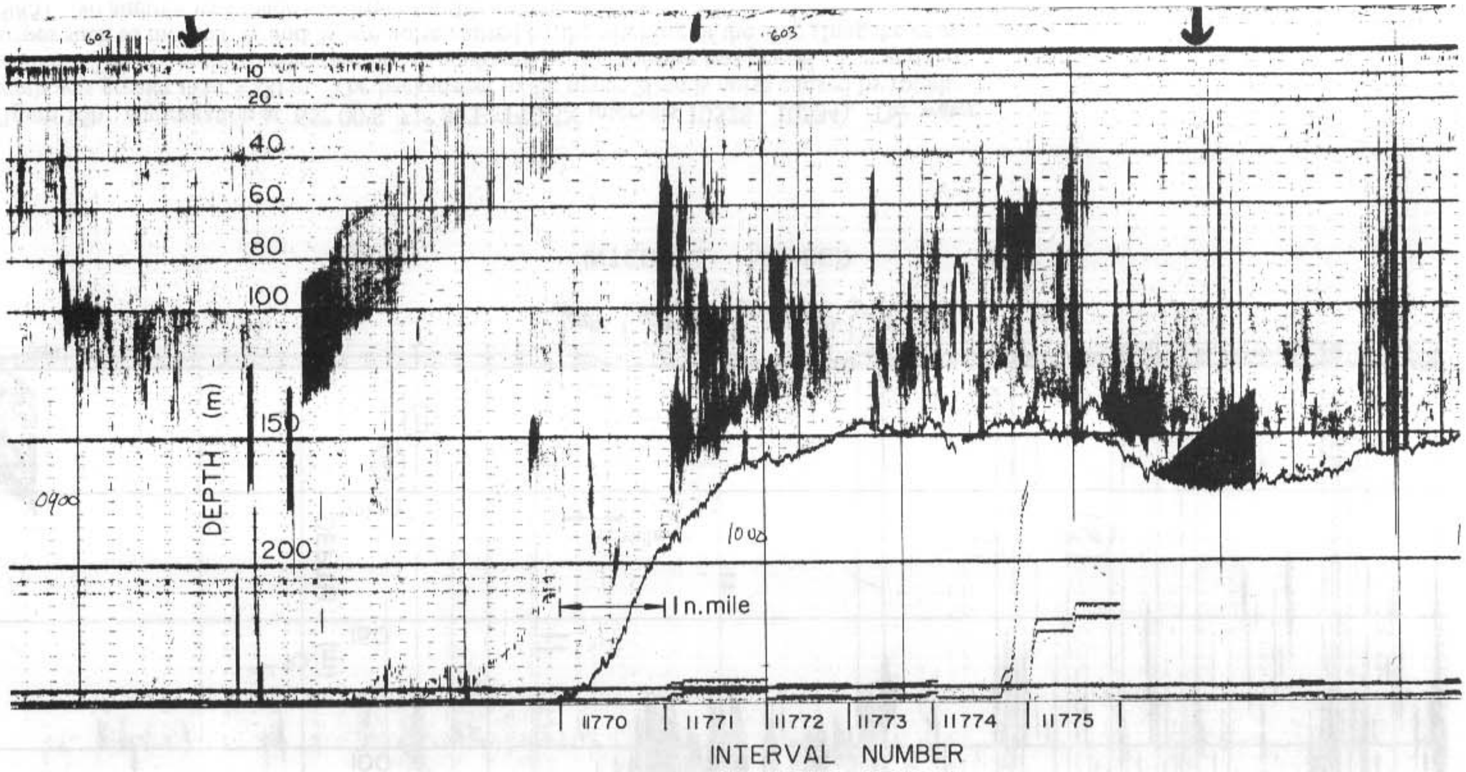


Figure 16a. Aggregations of krill at 66° 52'S, 78° 37'E (FIBEX intervals 11 770 - 11 778). The sea floor rises from greater than 250 m to about 190 m in the vicinity of the aggregations. A proportion of the biomass in this swarm was not assessed because the bottom echo was within the two deepest integration layers.

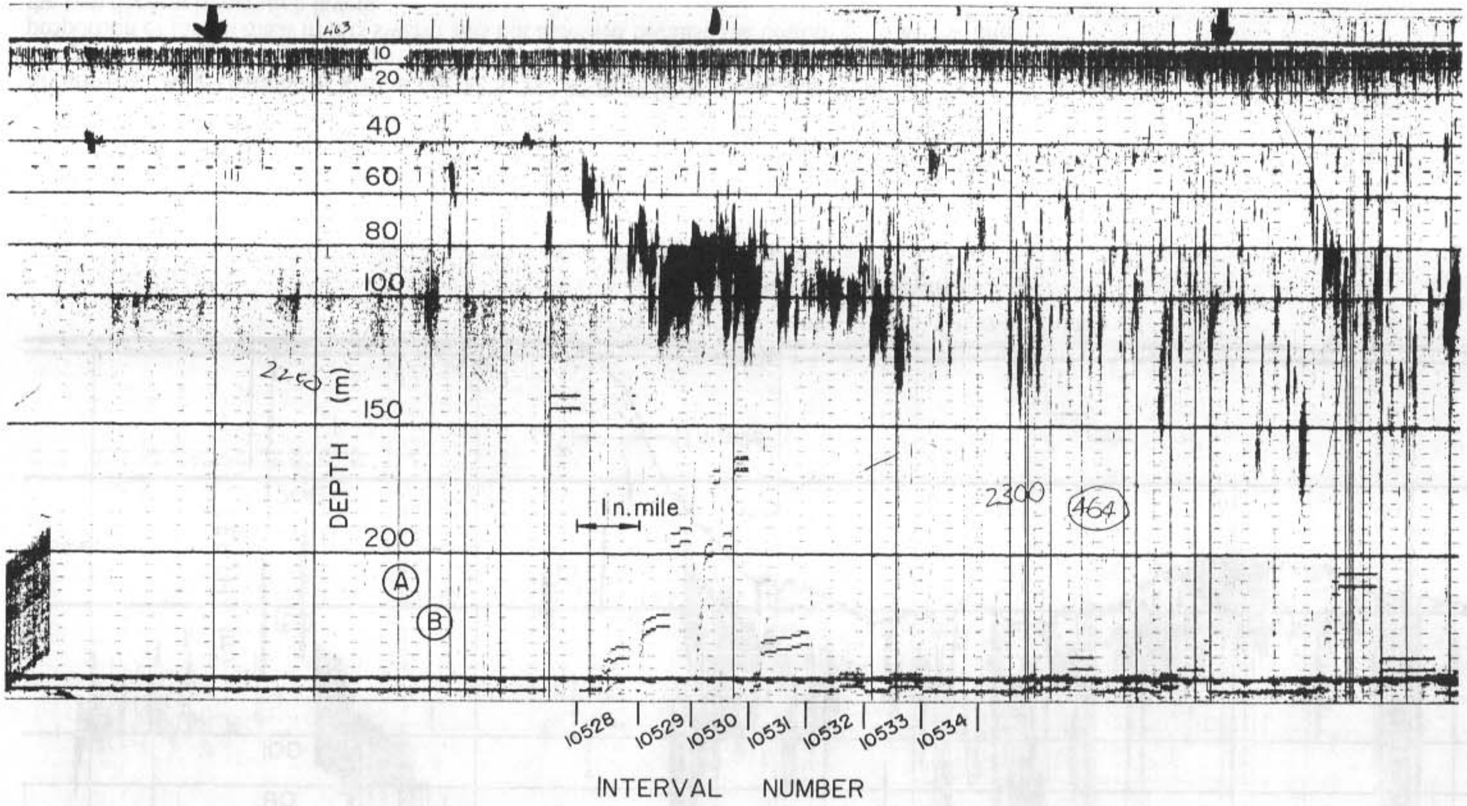


Figure 16b. Aggregation at 65° 00'S, 71° 47'E (FIBEX intervals 10528 - 10534). The water depth was greater than 3000 m. The backscatter in the upper 20 m is noise caused by rough weather. The upper two integration layers could not be used during this period. The vertical stripes such as those at 'A' and 'B' are noise caused by the pitching of the ship (Inagake *et al.* 1985). No attempt was made to correct for this source of noise.

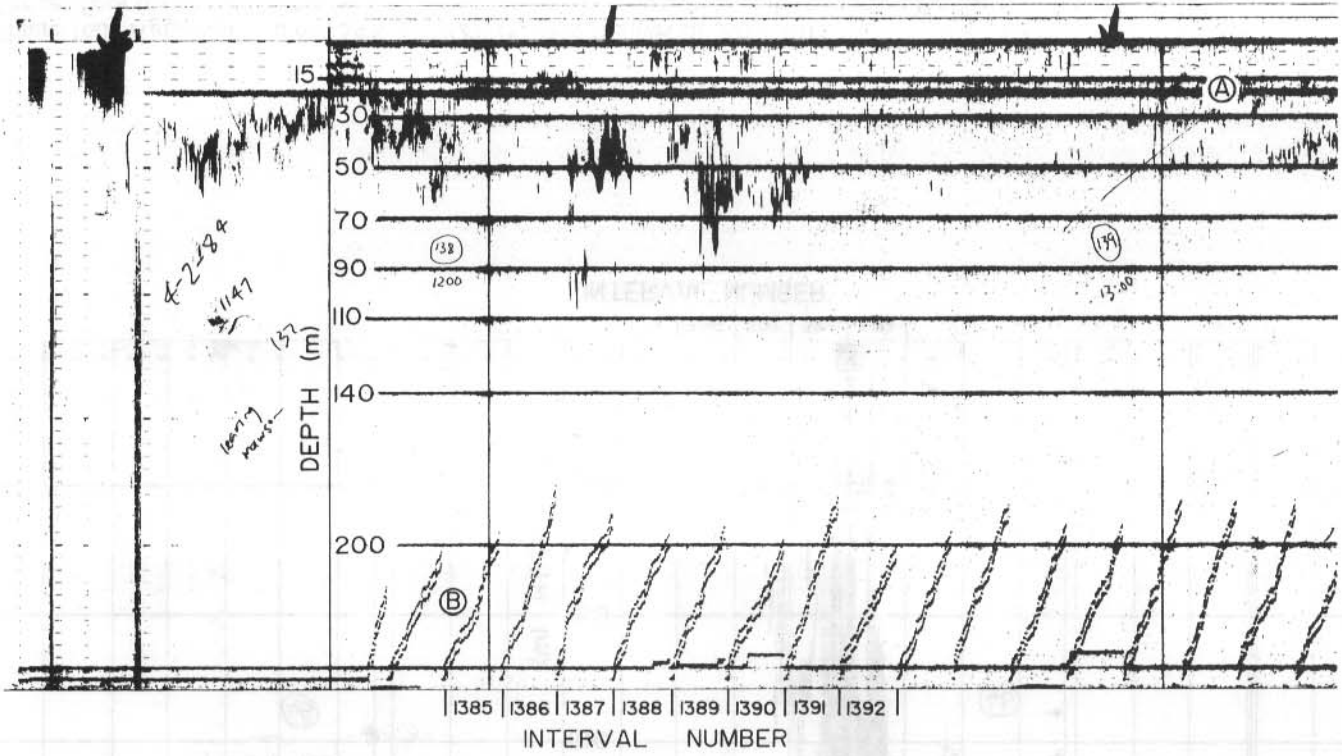


Figure 16c. Aggregation at 66° 37'S, 63° 50'E (ADBEX II intervals 1385 - 1392). During ADBEX II the echo-sounder transducer was deployed by a towed body. Reflections from the surface ('A') meant that the upper two integration layers could no be used. The stepped lines ('B') near the bottom of the chart are an analog display of the integration sum i.e. a relative measure of krill density in the water column.

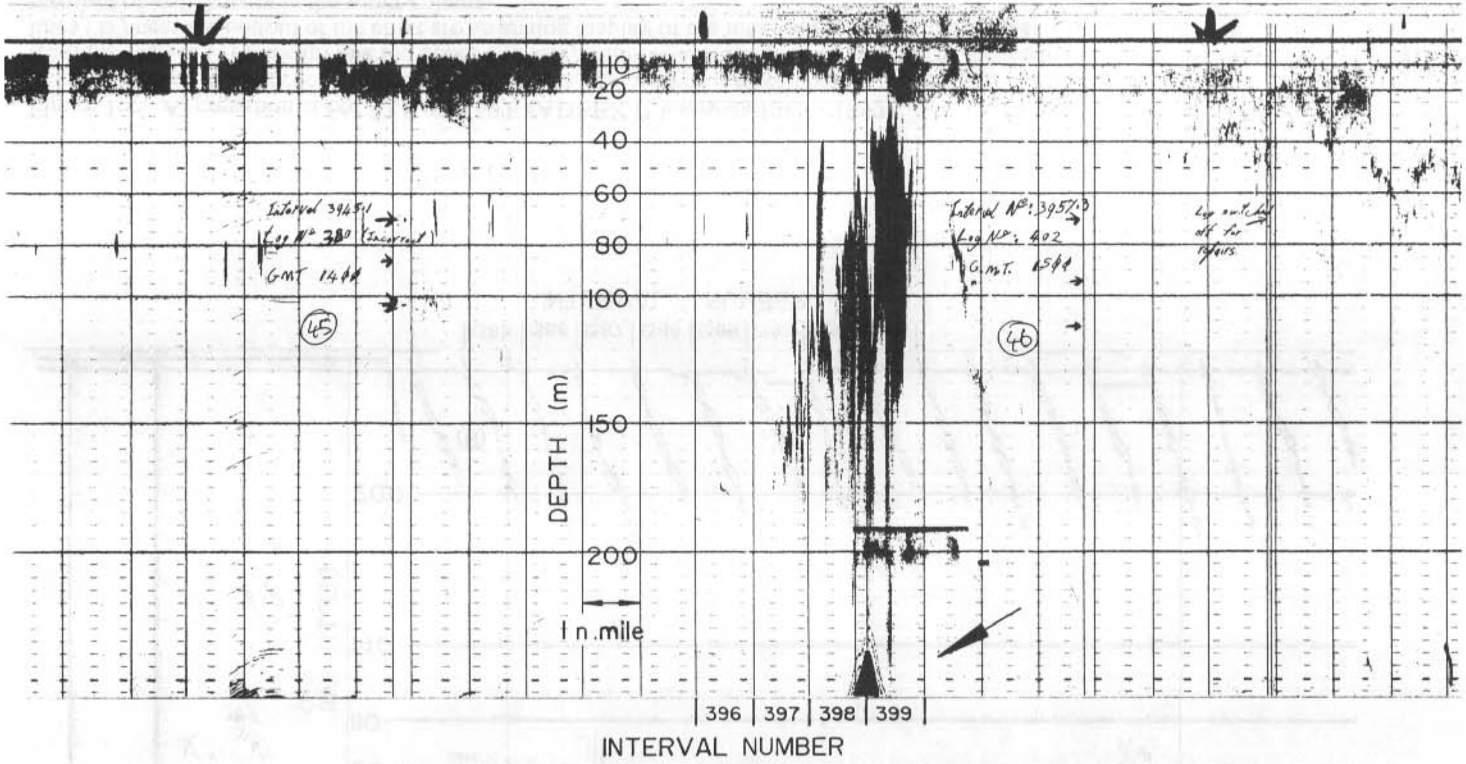


Figure 16d. Aggregation at 66° 54'S, 63° 32'E (SIBEX II intervals 397 - 401).
The sea floor (depth 240 m) can be seen (arrow) below the aggregation at the bottom of the chart.

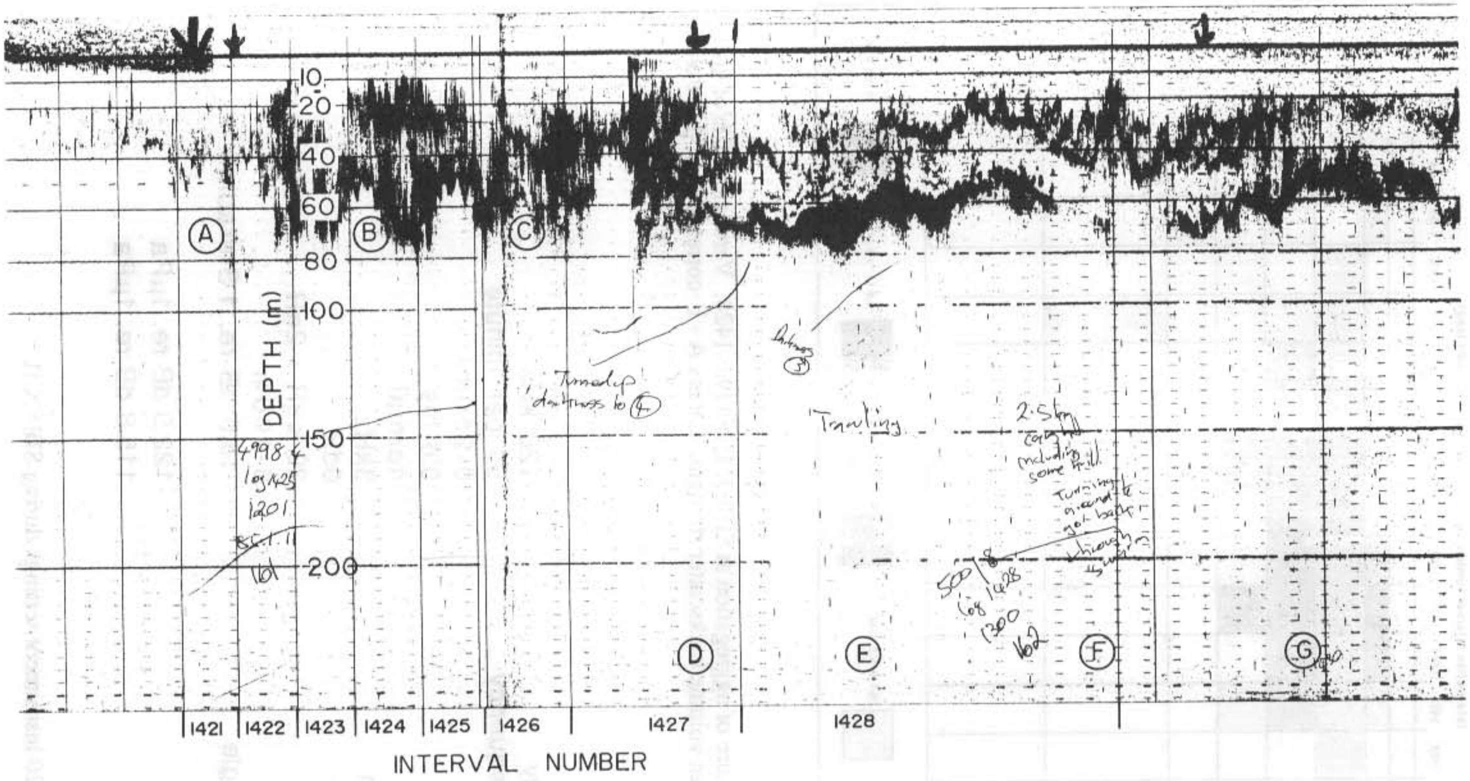


Figure 16e. Aggregation at 70° 00'S, 69° 03'E (SIBEX II intervals 1420-1428).
Strong echo continued for 6 miles (A, B, C) at depths of between 10 m and 80 m. At D the ship slowed to carry out an aimed trawl. The net was trawled at a depth of 50-70 m (E) for a period of 20 minutes (trawl station 25/T1). 2.8 kg of krill were caught. The ship turned 180° (F) to go back through the aggregation; a second aimed trawl was carried out and 900 g of krill were caught.

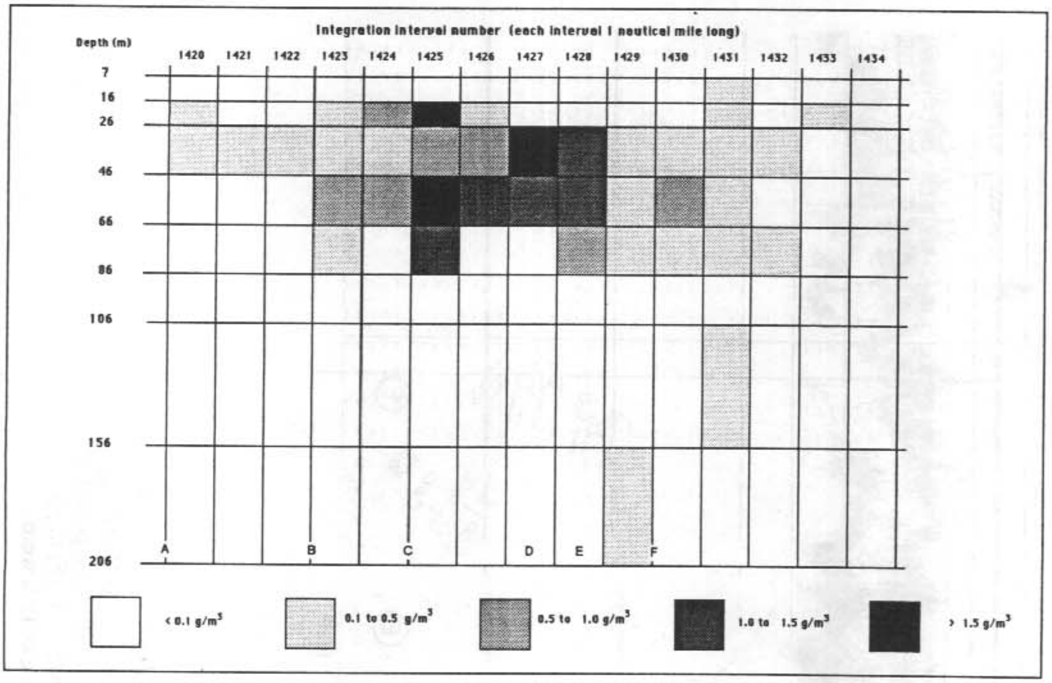


Figure 17. Density structure of aggregation at SIBEX II interval 1424. Vertical profile of krill density derived from mean volume backscatter strength. Letters A - F correspond to those on the echogram in Figure 16e.

Operating frequency	120 kHz
Pulse repetition frequency	50 per minute
Range	0-250m
Pulse duration	0.6 ms
Recording mode	normal
Receiver bandwidth	3kHz
Gain	0dB
TVG function	20 logR + 2αR
TVG range	3-100m
Equivalent beam angle	-18.0 dB re. 1 Steradian
Default SL+SRT	122.9 dB re. 1µPa
Calibrated SL+SRT	115.8 dB re. 1µPa

Table 1. Simrad EKS-120 instrument settings during SIBEX II.

Station No.	Date	Time (UST)	Trawl Depth (m)	Integration Interval No's.	Number of krill	Target Strength (dB)	Mean Weight (g)
4	20-01-81	0413	60-65	285 - 385	242	-63.1	0.69
6	21-01-81	0447	60-65	410 - 510	201	-62.6	0.85
8	22-01-81	0443	60-65	620 - 720	204	-66.1	0.26
9	22-01-81	2109	60-65	747 - 836	225	-65.8	0.25
10	23-01-81	0530	60-65	837 - 930	195	-62.6	0.90
12	24-01-81	0426	60-65	1047 - 1147	49	-63.2	0.86
14	25-01-81	0330	60-65	1238 - 1338	192	-62.7	0.94
18	29-01-81	1726	60-65	7838 - 7938	17	-65.9	0.33
19	30-01-81	0440	60-65	956 - 1056	164	-63.9	0.58
20	30-01-81	1845	60-65	8078 - 8166	180	-63.2	0.81
21	31-01-81	0700	23-27	8167 - 8255	205	-62.8	0.86
23	14-02-81	0558	60-65	9048 - 9135	130	-62.2	1.15
24	14-02-81	1804	60-65	9126 - 9226	182	-62.2	1.07
25	15-02-81	1210	50-80	9276 - 9344	28	-62.5	1.01
26	15-02-81	1715	58-62	9345 - 9411	177	-62.5	0.94
31*	18-02-81	0551	73-77	9671 - 9771	92	-61.9	
36*	19-02-81	1752	73-77	10040 -10140	91	-62.1	
38	20-02-81	1716	73-77	10238 -10338	10	-62.9	0.93
41	21-02-81	1700	73-77	10435 -10535	21	-63.0	0.82
42	22-02-81	0540	73-77	10558 -10654	79	-63.0	0.86
44	22-02-81	1744	73-77	10655 -10750	37	-67.9	0.13
50	09-03-81	1042	98-102	12835 -12935	7	-64.7	0.36
51	10-03-81	0436	33-37	12972 -13072	13	-61.8	1.18
default					2741	-63.1	0.77

Table 2a. Allocation of mean target strength ($\overline{TS}$) and mean weight ($\overline{W}$) of krill at FIBEX stations where more than five specimens of *E. superba* were caught (Figure 7a). At stations 31 and 36 krill weight was estimated from krill length.

Station No.	Date	Time (UST)	Trawl Depth (m)	Integration Interval No's.	Number of krill	Target Strength (dB)	Mean Weight (g)
10	16-01-84	2005	0-15	-	426	-70.8	0.05
13	17-01-84	1625	0-125	516 - 583	10	-69.7	0.06
14	18-01-84	0710	0-50	600 - 685	435	-64.0	0.55
15	18-01-84	1520	42-55	686 - 770	213	-62.9	0.86
19	19-01-84	1336	45-50	771 - 871	323	-64.4	0.43
29	23-01-84	1436	30-25	1250 - 1350	335	-64.8	0.41
default					1742	-65.0	0.41

Table 2b. Allocation of mean target strength ($\overline{TS}$) and mean weight ($\overline{W}$) of krill at ADBEX-II stations where more than five specimens of *E. superba* were caught (Figure 8a).

Station No.	Date (UTC)	Time (UTC)	Trawl Depth (m)	Integration Interval No's.	Number of krill	Target Strength (dB)	Mean Weight (g)
3	04-01-85	1535	0 - 280	0 - 25	7	-67.1	0.19
4	04-01-85	2214	0 - 250	26 - 112	412	-63.0	0.83
7	05-01-85	2108	0 - 240	208 - 300	23	-62.9	0.91
12	07-01-85	1801	0 - 173	580 - 684	17	-68.3	0.14
26	13-01-85	1003	0 - 242	1680 -1782	18	-64.6	0.39
29	14-01-85	0502	0 - 257	1837 -1926	79	-63.1	0.95
31	14-01-85	1245	0 - 236	1927 - 2004	267	-64.3	0.57
35	15-01-85	1022	0 - 206	2080 - 2169	6	-62.8	0.90
46	19-01-85	1233	0 - 228	2847 - 2933	51	-63.1	0.87
47	19-01-85	2124	0 - 219	2934 - 3018	78	-62.5	0.96
50	21-01-85	1412	0 - 268	3213 - 3319	145	-70.0	0.05
57	23-01-85	1706	0 - 236	3713 - 3791	24	-63.9	0.64
60	24-01-85	1213	0 - 231	3870 - 3951	74	-65.7	0.31
61	24-01-85	2044	0 - 257	3952 - 4114	73	-69.8	0.06
62	25-01-85	0212	0 - 255	4115 - 4099	8	-70.3	0.05
65	26-01-85	0820	0 - 252	4335 - 4449	294	-67.6	0.14
Default					1620	-64.6	0.52

Table 2c. Allocation of mean target strength ($\overline{TS}$) and mean weight ($\overline{W}$) of krill at SIBEX-II stations where more than five specimens of *E. superba* were caught (Figure 9a).

Cruise	Survey Period	Lat/Long box	Area surveyed* (Km^2)	No. Integration Intervals°	Surveyed Depth (m)	Number of Transects
FIBEX	20 Jan 81 to 14 March 81	61E - 95E 60S - coast	$1.09x10^6$	8070	7 - 206	14
ADBEX-II	10 Jan 84 to 7 March 84	58E - 70E 60S - coast	70,000	1587	60 - 230	3
SIBEX-II	4 Jan 85 to 27 Jan 85	55E - 95E 60S - coast	$1.28x10^6$	4680	16 - 206	8

° The number of integration intervals is equal to the number of miles of cruise track surveyed.
* 'Area surveyed' is the area over which transect based density estimates are applied.

Table 3. Survey details for FIBEX, ADBEX II and SIBEX II.

Transect No.	**Range of Integration Intervals**		**DAY + NIGHT DATA**			**DAY TIME DATA ONLY**		
	(first)	(last)	Number of Intervals	**Density** (g/m^2)	**Variance** (g^4/m^4)	Number of Intervals	**Density** (g/m^2)	**Variance** (g^4/m^4)
1	13145	13790	618	3.03	51.83	393	2.98	53.76
2	9063	9519	407	0.88	1.858	301	0.86	2.158
3	9761	10278	512	0.84	3.309	401	0.93	3.822
4	10348	10584	233	1.35	22.22	171	1.11	7.231
5	465	547	32	0.27	0.045	28	0.30	0.047
6	1149	1222	73	0.14	0.010	41	0.12	0.007
7	7946	8141	195	0.15	0.071	163	0.11	0.028
8	12132	12204	73	1.23	8.254	17	1.03	11.37
9	12222	12386	164	9.46	65.03	163	9.51	65.06
10	2029	7770	116	0.03	0.001	54	0.04	0.002
11	340	464	117	0.62	0.139	90	0.66	0.155
12	7771	7866	95	0.04	0.011	95	0.04	0.011
13	8958	9050	93	0.30	0.107	30	0.21	0.053
14	12779	13143	364	0.92	2.897	286	0.74	1.136
All data (excluding transect 9)	0	15000	5956	1.20		4132	1.24	

Table 4a. Average krill density along FIBEX transects. Average density was calculated over 24 hours (day + night) and over the daylight hours only. The high apparent krill density along transect 9 was caused by wind and wave generated noise during a storm that reached wind force 11. The transect was excluded from further analysis.

Transect No.	Range of Integration Intervals		DAY + NIGHT DATA			DAY TIME DATA ONLY		
	(first)	(last)	Number of Intervals	Density (g/m^2)	Variance (g^4/m^4)	Number of Intervals	Density (g/m^2)	Variance (g^4/m^4)
1	822	998	169	4.79	22.93	142	1.48	26.71
2	1053	1234	181	7.21	51.91	155	3.78	59.49
3	1299	1353	45	6.13	37.61	30	7.29	47.71
All data	0	3000	1852	4.12		1442	5.01	

Table 4b. Average krill density along ADBEX II transects. The average density was calculated over 24 hours (day + night) and over the daylight hours only.

Transect No.	Range of Integration Intervals		DAY + NIGHT DATA			DAY TIME DATA ONLY		
	(first)	(last)	Number of Intervals	Density (g/m^2)	Variance (g^4/m^4)	Number of Intervals	Density (g/m^2)	Variance (g^4/m^4)
1	12	236	206	1.64	12.05	145	1.09	6.057
2	380	814	430	2.18	48.12	360	2.29	57.06
3	960	1326	364	1.52	3.158	252	1.43	3.147
4	1853	2501	641	2.55	20.30	497	2.34	18.46
5	2665	3060	388	2.39	11.49	267	2.15	9.345
6	3269	3588	292	3.47	8.094	174	3.23	7.236
7	3741	4043	242	6.42	118.4	208	7.31	131.9
8	4278	4399	116	6.21	111.9	108	6.60	118.0
All data	0	5000	4491	2.99		3395	3.22	

Table 4c. Average krill density along SIBEX II transects. The average density was calculated over 24 hours (day + night) and over the daylight hours only.

Cruise		Transect based estimates					All data estimates	
	Area (million km^2)	Density (g/m^2)	Variance (g^2/m^2)	Biomass (Mtonnes)	95% limits Mtonnes	C.V. (%)	Density (g/m^2)	Difference in estimates (%)
Day + Night Data								
FIBEX	1.09	1.2	0.18	1.3	0.91	35	1.2	+0
	1.28	1.2	0.18	1.6	1.1	35		
ADBEX-II	0.07	2.7	0.64	0.18	0.11	29	4.1	+48
	1.28	2.7	0.64	3.5	2.0	29		
SIBEX-II	1.28	2.9	0.22	3.7	1.2	16	3.0	+4
Day-time Data								
FIBEX	1.09	1.1	0.15	1.2	0.83	35	1.2	+8
	1.28	1.1	0.15	1.4*	0.98	35		
ADBEX-II	0.07	3.1	0.81	0.21	0.12	29	5.0	+38
	1.28	3.1	0.81	4.0*	2.3	29		
SIBEX-II	1.28	2.9	0.39	3.7	1.6	21	3.2	+11

* Designates biomass calculated by extrapolating surface density over the larger 'SIBEX II' area.

Table 5. Density was estimated using transect based and all data methods. The 'difference in estimates' column gives the difference (expressed as a percentage of the transect based estimate) between the densities estimated using the two techniques. The large difference between the methods for ADBEX II reflects the fact that only 25% of the ADBEX II data were on transects and suggests that the area surveyed by the transects may not be representative of the region as a whole.

Cruise	Date	Survey Area	Ship	Echosounder (kHz)	Depth range (m)	Density g/m^2	CV in density (%)	Reference
FIBEX	Feb - March 1981	15°E - 30°E 60°S - 70°S	S.A. Agulhas	Simrad EK-120 (120)	? - 100	1.46	-	Hampton 1985
FIBEX	Jan 1981	30°E - 55°E 63°S - 68°S	Kaiyo Maru	Furuno FQ-30 (200)		4.3	28	Anon. 1986
FIBEX	Feb 1981	30°E - 50°E 60°S - 64°S	Marion Dufresne	Simrad EK-120 (120)		0.21	57	Anon. 1986
FIBEX	Jan - March 1981	58°E - 70°E 60°S - 70°S	Nella Dan	Simrad EK-120 (120)	7 - 206	1.1	35	This report
SIBEX-I	Jan - Feb 1984	65°E - 75°E 62°S - 70°S	Kaiyo Maru	Furuno FQ-50 (200)	10 - 120	17.5	4	Shirakihara et al. 1986
ADBEX-II	Jan - Feb 1984	58°E - 70°E 60°S - 70°S	Nella Dan	Simrad EK-120 (120)	60 - 230	3.1	29	This report
SIBEX-II	Jan 1985	55°E - 95°E 60°S - 70°S	Nella Dan	Simrad Ek-120 (120)	16-206	2.9	15	This report

Table 6. Surface densities of krill in the Indian sector of the Southern Ocean.

Cruise	Station No. /Haul No.	Total Catch (g)	*E. superba* (g)	*E. superba* (%)	Other Species (%) (where > 1% of catch)
FIBEX	29 / 72	6621	6620	100	
FIBEX	30 / 74	560	342	61	
"	32 / 77	18		-	VA (20), CP (34), TM (23)
"	32 / 78	11		-	CP (38), TM (9), RG (13), TL (10)
"	32 / 79	10		-	CP (21), SN (29)
"	35 / 83	120	109	91	TC (4), PG (4), TM (1)
"	35 / 84	1057	1017	96	PG (3), TM (1)
"	35/ 85	8381	8375	100	
"	35 / 86	1295	1272	98	TM (1)
"	39 / 94	567	369	65	CP (28), TC (3), TM (2)
"	40 / 95	886	878	99	
"	40 / 96	2404	2401	100	
"	40 / 97	336	191	57	TM (33), TC (9)
"	43 / 102	1349	1282	95	
"	44 / 105	1682	21	1	Attola wyvillei (86) [one only]
"	46 / 108	526	214	41	EA (48)
"	47 / 110	382	10	3	ST (59), IR (14), PA (14), SN (4), EC (3)
"	47 / 111	955	156	16	PA (67), EC (4)
"	47 / 112	4120	4	0	PA (99)
"	49 / 115	1548	1132	73	EA (12), ST (11)
"	49 / 116	1664	1636	98	PG (1)
ADBEX II	10 / 6	161.5	21	13	PM (55)
"	14 / 10	5514	5459	99	
"	14 / 11	1495	1465	98	
"	15 / 12	1096	1030	94	
"	15 / 13		-	0	
"	19 / 17	14100	141	1	ST (72), PM (2)
"	24 / 24		-	0	
"	29 / 30	7293	7293	100	
SIBEX	25 / T1	2890	2779	92	
"	25 / T2	922	861	96	
"	46 / T1	3659	3470	98	
"	46 / T2	2038	1966	96	

Species List

VA	Vanadia antarctica
CP	Clio pytramidata
TM	Thysanoessa macrura
RG	Rhyncalanus giga
TC	Tomopteris carpenteri
EA	Electrona antarctica
NC	Notolepis coatsi
SN	Siphonophore nectophore
PG	Parathemisto gaudichaudi
ST	Salpa thompsoni
IR	Ihlea racoviteai
PA	Pleuragramma antarcticum
EC	Euphausia crystallorophias
PM	Primno macropa

Table 7. Proportion (% by weight of total catch) of krill in aimed trawls. Data were taken from Williams *et al.* (1983), Ikeda *et al.* (1984,1986), Hosie *et al.* (1987).

Potential Error Source	Reference	Comments
Target strength of krill	Anon. 1986	Method of Protaschuk and Lukashova (1982) tended to overestimate krill TS "perhaps by a large amount".
	Shirakihara *et al.* 1986	Probably most serious error.
	Hempel 1983	TS/l, TS/W systematic errors significant and a major source of variance.
	Miller and Hampton, Pers. Com.	Accuracy of TS as used during FIBEX (and on many subsequent surveys) is limited - TS depends on physiology and orientation.
	Everson 1982a	Orientation changes may alter TS significantly.
	Greenlaw 1977	30 dB difference between vertical and horizontal TS in Euphausiids.
Echosounder calibration	Hempel 1983	±0.5 dB potential accuracy using suspended sphere.
	Anon. 1986	Worse than ±1.5 dB accuracy @ 95% CL for FIBEX participants.
	Anon. 1986	Kaiyo Maru ±2 dB.
	Sameoto 1983	±0.5 dB.
	Stenbekk, S. Pers. Com.	Simrad calibrate sounder on *Nella Dan* to better than ±1.0 dB.
	Do 1987	Difference between theoretical and measured transducer beam width can be large and must be considered. Receiver bandwidth must be considered. Compensation may be required for variation of α with depth.
	Shirakihara *et al.* 1986	Temperature dependence observed in sound absorption coefficient α at 200 kHz, but can be corrected for.
Integration of other organisms	Anon.1986	Indeterminate amount.
	Mathisen and Macaulay 1983	Potentially avoidable if several frequencies are used to differentiate between species.
Biased sampling of krill with nets	Watkins 1986	Single net hauls may not give representative sample of krill in their vicinity.
Integration of background noise	Hempel 1983	Largely avoidable.
Attenuation of signal by bubbles	Miller and Hampton, Pers. Com.	Largely avoidable but "may entail temporary suspension of survey".
Near surface krill undetectable	Anon.1986	No quantifiable information.
	Shirakihara *et al.* 1986	Assume "unknown density from 0 m to top depth is equal to measurable density from top depth to 120 m" [i.e. about 8% of biomass if top depth is 10 m.].
	Everson and Bone 1986	Upward looking transducer can detect but not quantify near surface swarms.
	Yudanov 1986	Combined with non-detection of dispersed krill could cause "considerable underestimate of krill abundance".
Dispersed krill undetectable	Anon.1986	"Some but probably not significant".
	Yudanov 1986	Krill disperse at night and become undetectable.
Multiple/coherent scattering	Sameoto 1979	A small percentage of coherent scatters could cause large density errors.
	Everson 1982	A possible cause of observed 8.5 dB diurnal variation of Sv.
	Yudanov 1986	Expect only in very high krill densities of the order of 1000's of krill/m^3.
	Macaulay *et al.* 1984	Multiple scattering detected when sounding a swarm near Elephant Island.
Krill under pack ice	Shirakihara 1986	Cannot sample acoustically.
	Miller and Hampton, Pers. Com.	Cannot sample acoustically.
Inclusion/exclusion of superswarms	Anon. 1986	Biomass underestimated because swarms infrequent and most likely missed.
	Macaulay *et al.* 1984	Should be treated separately from usual transect data because rare and often associated with geographic features.

Table 8. Some potential sources of error in hydroacoustic surveys. References are to authors who have discussed or quantified the error. Comments are quoted or paraphrased from referenced papers.

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REFERENCES

Anonymous (1977). Biological investigations of marine Antarctic systems and stocks. El-Sayed, S.Z. (convenor). *BIOMASS 1*. 79 pp.

Anonymous (1980). FIBEX acoustic survey design, Dammarie-les-Lys, France 4-6 June 1980. *BIOMASS Report Series 14*. 14 pp.

Anonymous (1981). Report of ad hoc acoustics working group, Post-FIBEX Data Interpretation Workshop 1981. *BIOMASS Report Series Number 20*. 47 pp.

Anonymous (1986). Post-FIBEX Data Interpretation Workshop. Frankfurt, Federal Republic of Germany, September 1984. *BIOMASS Report Series Number 40*. 106 pp.

Cochran, W.G. (1963). *Sampling techniques*. J Wiley and Sons, New York. 413 pp.

Do, M.A. (1987). Minimising errors in estimating fish populations and biomass densities using the 'acoustic volume backscattering strength' method. *New Zealand Journal of Marine and Freshwater Research* 21:99-108.

Everson, I. (1982a). Diurnal variations in mean volume backscattering strength of an Antarctic krill (*Euphausia superba*) patch. *Journal of Plankton Research 4*:155-162.

Everson, I. (1982b). Variations in vertical distribution and density of krill swarms in the vicinity of South Georgia. *Proceedings of BIOMASS Colloquium 1983*. Pp. 84-92.

Everson, I. *and* Bone, D.G. (1986). Detection of krill (*Euphausia superba*) near the sea surface: preliminary results using a towed upward-looking echo-sounder. *British Antarctic Survey Bulletin* 72:61-70.

Food and Agriculture Organisation of the United Nations (1984). Yearbook of fishery statistics. *FAO Fisheries Series* 23(56).

Greenlaw, C.F. (1977). Backscattering spectra of preserved zooplankton. *Journal of the Acoustical Society of America 62*(1):44-52.

Hampton, I. (1983). Preliminary report on the FIBEX acoustic work to estimate the abundance of *Euphausia superba*. *Memoirs of National Institute of Polar Research* 27:165-175.

Hampton, I. (1985). Abundance, distribution and behaviour of *Euphausia superba* in the Southern Ocean between 15° and 30° during FIBEX. In: W.R. Siegfried, P.R. Condy, R.M. Laws (Eds). *Antarctic Nutrient Cycles and Food Webs* Pp. 294-303.

Hempel, G. (1983). FIBEX- An international survey in the Southern Ocean: review and outlook. *Memoirs of National Institute Polar Research, Special Issue 27*:1-15.

Hosie, G.W., Ikeda, T. *and* Stolp, M. (1988). Distribution, abundance, and population structure of the Antarctic krill (*Euphausia superba* Dana) in the Prydz Bay region, Antarctica. *Polar Biology 8*:213-224.

Inagake, D., Matsuura, N. *and* Kurita, Y. (1985). Stock and quantitative distribution of the Antarctic krill (*Euphausia superba* Dana) in the Antarctic Ocean south of Australia in January and February 1984. *Transactions of the Tokyo University of Fishies 6*:139-147.

Ikeda, T., Hosie, G. *and* Kirkwood J. (1984). ADBEX II cruise krill/zooplankton sampling data. *ANARE Research Notes Number 23*. 32 pp.

Ikeda, T., Hosie, G. *and* Stolp, M. (1986). SIBEX II cruise krill/zooplankton data. *ANARE Research Notes Number 32*. 70 pp.

Jacka, J. (1983). A computer data base for Antarctic sea ice extent. *ANARE Research Notes Number 13*. 54 pp.

Johannesson, K.A. *and* Mitson, R.B. (1983). Fisheries acoustics. A practical manual for aquatic biomass estimation. *FAO Fishery Technical Paper 240*:249

Mauchline, J. (1980). Measurement of body length of *Euphausia superba* Dana. *BIOMASS Handbook 4*:1-9.

Protaschuk, V.A. *and* Lukashova, T.A. (1982). Determination of Antarctic krill acoustic backscattering cross section. *ICES Symposium on fisheries acoustics, Bergen 1982. Contract No. 66*.

Sameoto, D.D. (1979). In situ orientation of euphausiids and its effect on acoustic measurements. *Contribution to Joint USA-USSR Meeting on Hydroacoustical Methods for the Estimation of Marine Fish Populations, Cambridge, MA, USA, 25-29 June 1979.*

Sameoto, D.D. (1983). Euphausiid distribution in acoustic scattering layers and its significance to surface swarms. *Journal of Plankton Research 5*(2):129-143.

Saville, E. (Editor) (1977). Survey methods of appraising fishery resources. *FAO Fisheries Technical Paper 171*.

Scientific Committee for the Conservation of Antarctic Marine Living Resources (1986). *Report of the fifth meeting of the Scientific Committee*. P. 209.

Shirakihara, K., Nakayama, K. *and* Komaki, Y. (1986). Acoustic estimates of krill biomass in R. V. *Kaiyo Maru* SIBEX I survey area (Indian sector of the Southern Ocean). *Memoirs of the National Institute for Polar Research Special Issue 40*:140-152.

Shotton, R. *and* Bazigos, G. P. (1984). Techniques and considerations in the design of acoustic surveys. *Rapports et Proces-Verbaux des Reunions Conseil International pour l'Exploration de la Mer 184*:34-57.

Steedman, H.F. (1976). Zooplankton fixation and preservation. *Monographs on Oceanographic Methodology 4*:1-359.

Stretten, N.A. *and* Pike, D.J. (1984). Some observations of the sea-ice in the southwest Indian Ocean. *Australian Meteorology Magazine 32*:195-206.

Watkins, J.L., Morris, D.J., Ricketts, C. *and* Priddle, J. (1986). Differences between swarms of Antarctic krill and some implications for sampling krill populations. *Marine Biology 93*:137-146.

Williams, R., Kirkwood, J.M. *and* O'Sullivan, D. (1983). FIBEX cruise zooplankton data. *ANARE Research Notes Number 7*. 163 pp.

Yudanov, K.I. (1986). Detection and quantitative estimation of krill concentrations by hydroacoustic instruments. Selected Scientific Papers 1986. *Scientific Committee for the Conservation of Antarctic Marine Living Resources*. P. 373.

Appendix I. Data archival

Raw mean volume backscatter strengths and the calculated krill number and weight densities presented in this report have been archived at the Antarctic Division. Krill lengths and weights for the calculation of target strength and FORTRAN programs for data processing have also been archived. The VAX 'BACKUP' utility was used to store the data and programs on a magnetic tape labeled 'HA_ARCHIVE'. The procedure for data processing is presented as a flow chart (Figure 18) and a brief description of the data files and FORTRAN programs is given below.

DATA FILES

file.DAT	Files containing data from paper tapes.
file.RAW	file.DATs have been edited to remove blank lines, bells etc.
cruise.EDI	Appended .RAW files.
cruise.RRT	Reformatted data for easy computer manipulation.
cruise .DMP	Contains unrecognisable commands or data.
cruise.ERR	Identifies integration intervals where echosounder parameters or data values are outside reasonable bounds.
cruise.LAY	Contains interval numbers where integration layer settings changed.
cruise.PAR	Records any parameter changes made during a cruise.
cruise.COM	Records comments field (see Figure 5).
cruise.LOG	Data file containing acoustic log (see Figure 4).
cruise.INT	Ship's position and time, obtained by interpolating between hourly positions, for each integration interval.
cruise.MRG	Data from cruise.INT is incorporated in cruise.RRT to generate cruise.MRG.
cruise.MSG	Records any inconsistencies between data in cruise.INT and cruise.RRT files.
cruiseN.SUM	Summary file containing mean volume backscatter strength for water column, summed over selected layers (e.g. layers 2-8). N= summary number. Several summary files may be generated for the one cruise.
cruise.WTS	Mean krill target strengths and weights and integration intervals to which they apply.
cruiseNX.DEN	Contains surface densities (weight and number) for each integration interval. Threshold and calibration corrections have been applied. N = summary number, X = density file identifier (A-Z).

FORTRAN programs

RERITE.FOR	Reformats data files.

CHECK.FOR	Checks that parameters and data values are within reasonable bounds.
EXAMINE.FOR	Detects changes in parameter values, integration layer settings or comments.
MERGE.FOR	Merges data from the files cruise.RRT and cruise.INT.
SUMMARY.FOR	Produces file containing mean volume backscatter strength for water column between two integration layers MINLAY to MAXLAY. MINLAY and MAXLAY are in the range 1 to 8 (e.g. layers 2-8).
CALCWTS.FOR	Calculates mean krill weight and target strength from length and weight distribution of krill caught at each station. Output file also contains integration intervals over which they are applied.
DENSITY.FOR	Calculates number and weight densities of krill for each integration interval from mean volume backscatter strength, mean TS and mean weight.
PLTBOX.FOR	Plots coastline and ships cruise track in the region of Prydz Bay. Uses CALCOMP plotter.
TRANSECT.FOR	Calculates mean and variance of krill density along transects defined as the interval between two integration interval numbers. Plots frequency distribution of density data.
TRANTIME.FOR	As for TRANSECT.FOR, except that a time interval can be specified in addition to transects.
PLT3D.FOR	Uses NCAR package to plot pseudo 3-D diagrams of krill distribution. Mean krill density is first calculated for 1° latitude by 20' longitude boxes.

ANARE Research Notes Number 62

ERRATA

Page 4, line 1:

replace 'stock assessment' with 'biomass estimation'

Page 7, equation 8:

the first term should read 'SL = source level'

Page 8, second last line:

replace 'euphausiids' with *'E. superba'*

Page 10, section 4, line 2:

delete the reference (Hosie et al. 1988) - the full reference is given in Table 7

Page 45, paragraph 1:

the last sentence should read 'A brief description of the data files and FORTRAN programs is given below.'

Page 40, last column of Table 7:

change *'Attola wyvillei'* to *'Atolla wyvillei'*

Page 40, species list:

replace with

VA	*Vanadis antarctica*
CP	*Clio pyramidata*
TM	*Thysanoessa macrura*
RG	*Rhincalanus gigas*
TC	*Tomopteris carpenteri*
EA	*Electrona antarctica*
NC	*Notolepis coatsi*

SN	*Siphonophore nectophore*
PG	*Themisto gaudichaudi*
ST	*Salpa thompsoni*
IR	*Ihlea racovitzai*
PA	*Pleuragramma antarcticum*
EC	*Euphausia crystallorophias*
PM	*Primno macropa*