PRELIMINARY REPORT ON THE FIBEX ACOUSTIC WORK TO ESTIMATE THE ABUNDANCE OF *Euphausia superba*

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Abstract: The FIBEX acoustic work to estimate the abundance of krill (*Euphausia superba*) is briefly reported. A multi-ship echo integrator survey was carried out in three separate areas of the Southern Ocean, totalling about 1.3 million square nautical miles. Communal analysis of the data at an international data workshop indicated a total abundance of about 78 million t in these areas, giving a mean density of 17.5 g per square metre. The standard deviation was estimated as 19.5 million t, taking only the survey variance into account. Of particular interest was the apparent finding of the major portion of the biomass between 60° and 80°E, rather than in the Scotia Sea/Antarctic Peninsula region. It is stressed, however, that the results of the workshop are preliminary, and must be checked against estimates made by the individual FIBEX participants in their own areas.

On the basis of the workshop results and previous knowledge on the large-scale distribution of the species, the total krill biomass at the time of the survey is tentatively estimated to have been between 200 and 600 million t.

1. Introduction

Acoustic work aimed at assessing the distribution and abundance of *Euphausia superba* was carried out by all the vessels which participated in the FIBEX (First International BIOMASS Experiment). Acoustic surveys were carried out in three separate sectors, namely the West Atlantic, Indian and Pacific Sectors (see Fig. 1), over the period January to March 1981. The localities and time periods of each ship's survey are set out in Table 1. On all the vessels echo integrators were used, to a large extent in the same way. The integrator data were jointly analysed by FIBEX participants at a data-interpretation Workshop in Hamburg towards the end of 1981. A description of the Workshop, which includes a summary of the acoustic results, is given in BIOMASS Report 20 (1982). A full report on the acoustic work in Hamburg is in preparation.

The purpose of this report is to describe briefly the acoustic methods used in FIBEX, and the analysis of the data at the Hamburg Workshop, and to outline areas where further analysis is necessary. Results obtained at the Workshop are presented, but it is emphasized that they must be taken as preliminary because of the limited time available at the Workshop for checking them. The results are the joint responsibility of those who collected and analysed the data, and not of any one individual. However, the estimation of total krill biomass from these results (Section 9), is the responsibility of the author.

Table 1. Survey dates and areas for ships participating in FIBEX acoustic survey.

Ship	Country	Area	Dates
NELLA DAN	Australia	62°S to continent 60°E to 90°E	Jan. 18–Feb. 13, 1981
E.L. HOMBERG	Argentina	58°S to 62°S 42°W to 48°W	Jan. 19–Feb. 16, 1981
ITSUMI	Chile	61°S to 64°S 54°W to 63°W	Jan. 28–Feb. 28, 1981
MARION-DUFRESNE	France	60°S to 64°S 30°E to 50°E	Feb. 12–22, 1981
WALTHER HERWIG	FRG	57°S to 64°S 48°W to 56°W	Jan. 26–Feb. 21, 1981
KAIYO MARU	Japan	63°S to 68°S 30°E to 55°E	Jan. 16–29, 1981
UMITAKA MARU	Japan	58°S to 68°S 120°E to 165°E	Dec. 29, 1980 Feb. 5, 1981
PROFESSOR SIEDLECKI	Poland	59°S to 66°S 66°W to 56°30′W	Feb. 14–Mar. 13, 1981
S.A. AGULHAS	South Africa	60°S to 70°S 15°E to 30°E	Feb. 16–Mar. 10, 1981
MELVILLE	USA	58°S to 61°S 46°W to 49°W	Jan. 24–Mar. 3, 1981
ODYSSEE	USSR	56°S to 61°S 40°W to 34°W	Feb. 7–24, 1981
		53°S to 55°S 34°W to 38°W	Feb. 25–Mar. 7, 1981

2. Survey Details

The areas surveyed during FIBEX are shown in Fig. 1. In the West Atlantic Sector, the areas surveyed by each ship were contiguous, with the exception of the small area around South Georgia. There was a small latitudinal gap, about 500 km wide, in the coverage of the Indian Sector, and a large latitudinal gap of about 3000 km in the Pacific Sector. The sub-sectors so formed were designated as Indian and Pacific Sectors A and B (Fig. 1).

In the West Atlantic Sector the vessels for the most part steamed randomly-spaced meridional transects, while in the Indian Sectors the ships steamed uniformly-spaced zonal transects. Pacific Sectors A and B were surveyed on a single meridional transect. Spacing between transects was typically 15 to 30 km in the West Atlantic Sector and 80 to 160 km in the Indian Sector. With the exception of *Odyssee*, which did not conduct acoustic work at night, the ships surveyed around the clock (conditions permitting), apart from the time spent on station or in towing nets.

3. Equipment

The acoustic equipment used by each vessel and the fishing gear employed to identify the acoustic targets is listed in Table 2. Note that both analogue and digital integrators were used, and that all vessels with the exception of MARION-DUFRESNE and

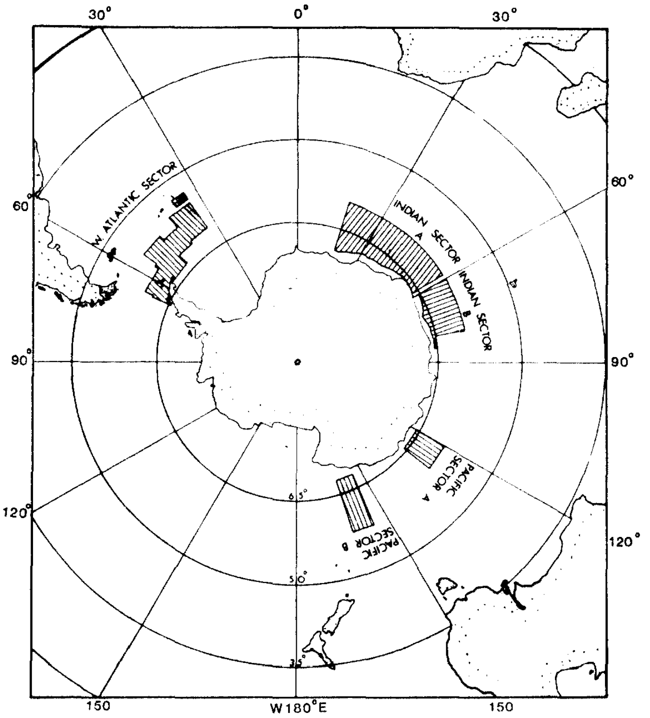

Fig. 1. FIBEX survey areas.

Table 2. Acoustic and fishing gear used during FIBEX.

Ship	Echo sounder type	Echo sounder frequency (kHz)	Integrator type	Fishing gear
NELLA DAN	Simrad EK-120	120	Digital	Opening/closing RMT-8
E.L. HOMBERG	Simrad EK-120	120	Analogue	Commercial trawl +CALCOFI net
ITSUMI	Simrad EK-120	120	Analogue	CALCOFI net
MARION-DUFRESNE	Simrad EK-120	120*	Digital	RMT-8
WALTHER HERWIG	Elac LSE 134	50	Digital	Opening/closing RMT-8 +commercial trawl
KAIYO MARU	Furuno FQ-30	200	Digital	Opening/closing KMT
UMITAKA MARU	Simrad EK-120	120	Digital	Opening/closing KMT +Bongo
PROFESSOR SIEDLECKI	Simrad EK-120	120	Analogue	Bongo+commercial trawl
S.A. AGULHAS	Simrad EK-120	120	Digital	Opening/closing RMT-8 and RMT-2
MELVILLE	Biosonics BS050	50*	Digital	MOCNESS
ODYSSEE	Simrad EK-120	120	Analogue	Bongo+commercial trawl

* Towed transducers.

MELVILLE used hull-mounted, as opposed to towed transducers. The echo sounders were calibrated with hydrophones, according to the procedures specified in NIELSON *et al.* (1980). For some of the ships, not all of the pertinent system parameters could be measured for practical reasons: in these cases the manufacturer's specifications were adopted. This applied particularly to the transducer directivity index, which was measured directly on only two of the ships.

4. Density Estimation for Each Integration Interval

Integrator readings for each integration interval were used to calculate the mean volume back-scattering strength ($\bar{S}_v$) for the interval. The volume back-scattering strength is a measure of the amount of sound reflected back from 1 m^3 of water, and is defined by;

$$S_v = 10 \log I_r / I_o,$$

where I_o is the incident sound intensity and I_r the reflected intensity, measured 1 m from the reflecting volume. Over one integration interval, $\bar{S}_v$ is the volume back-scattering strength, averaged over all sound transmissions within the interval and over the depth channel (ΔR) insonified. Since

$$\bar{S}_v = 10 \log \bar{\rho}_N + \overline{TS},$$

where $\overline{TS}$ is the mean reflecting power (target strength) of individual scatterers in the insonified volume, and $\bar{\rho}_N$ is their mean number density, the mean density of targets within an integration interval can be estimated if $\overline{TS}$ can be estimated.

The estimates of $\bar{S}_v$ were used to calculate $\bar{\sigma}$, the mean number of krill per unit area, using the expression;

$$\bar{\sigma} = 10^{0.1(\bar{S}_v + 10 \log \Delta R - \overline{TS})},$$

where ΔR is the integration (depth) channel. On some ships, multi-channel integration was performed, in which cases the integrator values were lumped together to facilitate comparison with the single-channel values. It was assumed that ΔR always encompassed the depth range of the krill within the integration interval although, as discussed later, there is reason to doubt that this assumption was always valid.

Target strength is both length- and frequency-dependent. For the three frequencies used during FIBEX, (50, 120 and 200 kHz), TS was calculated from the following expressions;

50 kHz	$TS = -100.82 + 20.0 \log l$,
120 kHz	$TS = -97.2 + 20.0 \log l$,
200 kHz	$TS = -98.1 + 23.0 \log l$,

where l is the Reference length (MAUCHLINE, 1980) of the krill in mm. The expresions at 120 and 200 kHz were obtained from experiments conducted during FIBEX; the former from *in situ* measurements of echoes from live krill, and the latter from measurements on tethered animals. The expression at 50 kHz was obtained by extrapolating the 120 kHz expression to 50 kHz, based on a comparison of the acoustic cross-sections at 50 and 120 kHz of fresh-water shrimps as reported by SAMOVOL'KIN (1980).

The target strength used for each integrator interval was calculated from the appropriate TS/length relationship, using the mean length of krill from the closest net haul. It would clearly have been preferable to have used a mean target strength weighted according to the length distribution in the sample, but time did not permit this refinement. (In Appendix D of the full report of the Acoustics Group at Hamburg it is shown that for a normal length distribution with mean 40 mm and

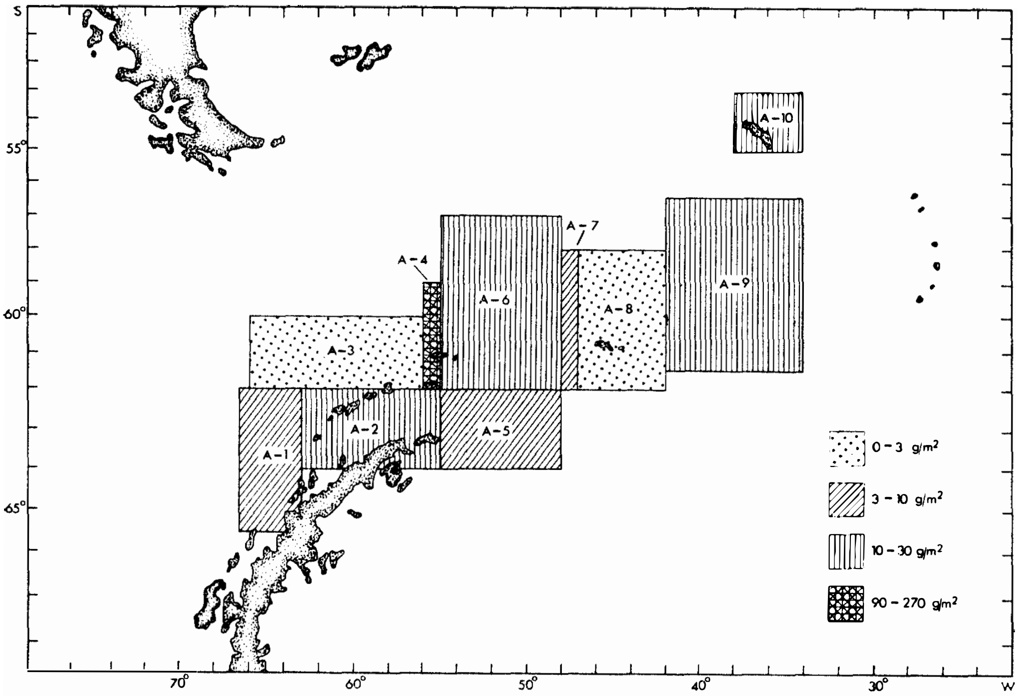

Fig. 2. Surface densities in Atlantic blocks.

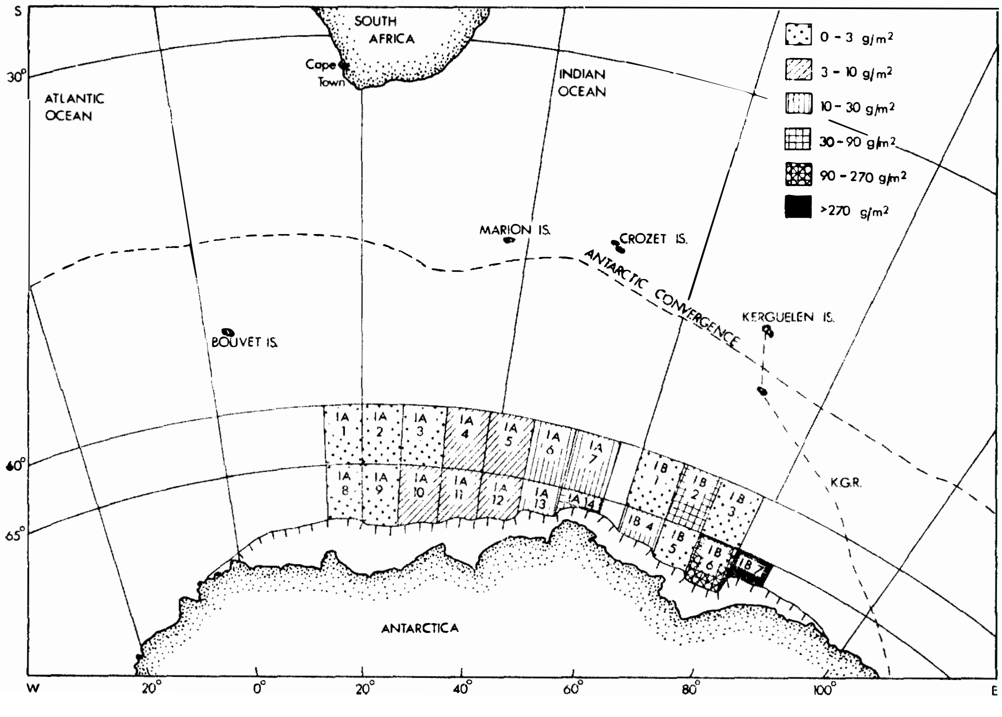

Fig. 3. Surface densities in Indian blocks.

standard deviation 10 mm, the error is 6% at 50 and 120 kHz and about 9% at 200 kHz.) If no krill sample was taken within 24 hours and 180 km on either side of the integration interval, a specified default length was taken in the $\overline{TS}$ calculation. The default values were either the mean or the median lengths of krill in the surrounding block (see Figs. 2 and 3).

For each interval, the mean weight of krill per unit area was calculated from;

$$\bar{\rho}=\bar{\sigma}\bar{w},$$

where $\bar{w}$ is the mean weight of krill in the appropriate sample, obtained as a weighted mean from the length distribution using the length/weight relationship given by RAKUSA-SUSZCZEWSKI (1981), *viz*;

$$w_i=0.0018\, l_i^{3.383},$$

where w_i is the wet weight in mg and l_i the reference length (in mm) of animals in length class i. If no appropriate sample could be found, $\bar{w}$ was obtained by using the default length in the above equation.

5. Biomass Estimation

For the estimation of biomass, the West Atlantic and Indian Sectors were subdivided into the blocks shown in Figs. 2 and 3, and B_j, the biomass in block j, estimated from;

$$\hat{B}_j=\hat{A}_j\hat{\bar{P}}_j=\hat{A}_j\sum_{i=1}^{N_j}\frac{(\bar{\rho}_j)_i(D_j)_i}{(D_T)_j}, \qquad (1)$$

where $\hat{A}_j$: estimated area of block j,

$(\bar{\rho}_j)_i$: mean weight of krill/unit area estimated from the ith interval in block j,

N_j: number of intervals in block j,

$(D_j)_i$: integration distance for the ith interval in block j,

$(D_T)_j$: total integration distance in block j,

$\hat{\bar{P}}_j$: estimated mean weight of krill/unit area in block j,

Note that $\hat{\bar{P}}_j$ is a weighted mean, obtained by weighting the individual density estimates by the corresponding integration distance. This was necessary since integration distances used on different ships ranged from 0.06 km to greater than 15 km.

Biomass estimates were made for each of the blocks using all the integrator intervals within them. Consideration was also given to discarding data collected at night because of the possible negative bias arising from krill rising to the surface at night and

Table 3. Biomass, variance and density data for all sectors.

Sector	Area (km × 10^6)	Biomass (t × 10^6)	Variance ($t^2 \times 10^{12}$)	Standard deviation (t × 10^6)	Coefficient of variation	Mean density (g/m^2)*
Atlantic	1.03	11.33	1.34	1.15	0.10	11.0
Indian A	1.89	11.77	5.11	2.26	0.19	6.2
Indian B	0.89	54.12	374.35	19.35	0.35	60.8
Pacific A	0.34	0.12	0.0025	0.05	0.42	0.4
Pacific B	0.41	0.25	0.0025	0.05	0.20	0.6
All sectors	4.56	77.59	380.8	19.51	0.25	17.0

* 1 $g/m^2 \simeq 3.3$ t/n. mile^2

Table 4. Biomass, variance and density data for all blocks.

Block	$\hat{B}$ ($t\times10^6$)	var ($\hat{B}$) ($t^2\times10^{12}$)	Density (g/m^2)	Block	$\hat{B}$ ($t\times10^6$)	var ($\hat{B}$) ($t^2\times10^{12}$)	Density (g/m^2)
A-1	0.19	0.011	3.2	IA-8	0.12	0.002	0.9
A-2	1.32	0.233	15.2	IA-9	0.07	0.001	0.5
A-3	0.06	0.003	0.5	IA-10	0.96	1.996	7.6
A-4	3.26	not calculated	92.3	IA-11	0.88	0.053	8.5
A-5	0.53	0.021	6.9	IA-12	0.94	0.022	9.7
A-6	2.18	0.429	11.9	IA-13	1.08	0.029	16.9
A-7	0.24	0.020	5.0	IA-14	1.37	0.024	41.6
A-8	0.08	0.004	0.8				
A-9	2.88	0.561	11.6	IB-1	0.11	0.003	0.7
A-10	0.59	0.043	10.5	IB-2	7.10	29.02	42.7
				IB-3	0.44	0.042	2.7
IA-1	0.31	0.003	1.9	IB-4	0.85	0.410	11.0
IA-2	0.16	0.001	1.0	IB-5	0.10	0.003	1.1
IA-3	0.39	0.557	2.4	IB-6	25.29	238.98	216.5
IA-4	0.50	0.186	3.0	IB-7	20.23	105.99	279.2
IA-5	1.38	1.734	8.3				
IA-6	0.58	0.089	11.6	PA	0.12	0.002	0.4
IA-7	3.03	0.408	18.2	PB	0.25	0.003	0.62

becoming undetectable acoustically. A Student's-t test showed that in the West Atlantic Sector in particular, the integrator values recorded by day were significantly higher than those recorded at night, but there was evidence that some of these differences might have been due to spatial rather than diurnal effects. In view of this ambiguity, it was decided not to discard any data, although the possibility of thereby underestimating the biomass, particularly in the West Atlantic Sector, was recognized.

The estimates of biomass and mean density for each of the sub-sectors are shown in Table 3. The estimates for each of the blocks within these sub-sectors are shown in Table 4.

6. Estimation of Variance

The variance in B_j was first estimated from the following expression, which assumes that the individual integrator values are independent of each other;

$$\text{var}\,[\hat{B}_j]_o = A_j^2\ \text{var}\,[\hat{\bar{P}}_j]_o.$$

Since $\hat{\bar{P}}_j$ is a weighted mean (see eq. 1), var $[\hat{\bar{P}}_j]_o$ was calculated from;

$$\text{var}\,[\hat{\bar{P}}_j]_o = \sum_{i=1}^{N_j} \frac{[(\bar{\rho}_j)_i - \bar{P}_j]^2 (D_j)_i^2}{(D_T)_j^2}.$$

This estimate is a lower bound on the variance, as it excludes the effects of, among others, auto-correlation between the integrator values, which because of the serial nature of the sampling, was significant. An attempt was made to correct for this by including an appropriate covariance term. A model was constructed in which the integrator intervals within each block were grouped according to "transects"; a "transect" being defined as a sequence of consecutive intervals. The covariance for each "transect" was then computed and added to var $[\hat{P}_j]_o$. The transects were assummed to be independent of each other, *i.e.* the corrections accounted for intra-transect, but not inter-transect correlation.

Note that the "transects" were not transects as normally defined, in that they were defined by breaks in sequence rather than by changes of course. Although this method of grouping the data was probably not optimum (time did not permit experimentation with other models), it did divide the data into groups within which the auto-correlation was likely to be significant, which is the type of model necessary for improving variance estimates in the presence of correlation.

This model gave the following estimator for the variance in the biomass estimate for each block;

$$\text{var}\,[\hat{B}] = \text{var}\,[\hat{B}]_o + 4A^2 \sum_{k=1}^{K} \frac{(\text{cov})_k}{(n_k-1)(n_k-2)}, \qquad (2)$$

where k is the "transect" index, K is the number of "transects" in the block, n_k is the number of intervals in the kth transect and

$$(\text{cov})_k = \sum_{i=1}^{n_k-1} \sum_{l=i+1}^{n_k} (\bar{\rho}_i - \bar{P})_k (\bar{\rho}_l - \bar{P})_k .$$

For simplicity the "block" index, j, has been dropped.

The variances, standard deviations and coefficients of variation for the sub-sectors, all calculated from eq. 2, are shown in Table 3.

7. Other Sources of Error

The variances given in Table 3 only reflect the statistical sampling errors. There were other types of error whose magnitudes could not be estimated adequately, if at all, in Hamburg.

a) *Non-detection of krill*

Krill closer to the surface than about 10 m would not have been detected by any of the vessels, as all used downward-sounding transducers situated at or near the depth of the keel. Any tendency for the krill to rise at night would aggravate this effect at night. The comparison of the day/night biomass estimates indicated that the bias at night could have been severe at times, particularly in the West Atlantic Sector. There is also the possibility of some krill having been too dispersed or too deep to be detected acoustically (K.I. YUDANOV, pers. commun.). These situations would cause the biomass to be underestimated.

b) *Errors in TS/length/weight relationships*

Inaccuracies in the length/weight relationship or any of the $\overline{TS}$/length relationships used would introduce biases into the abundance estimates. No data were available on possible errors in these relationships, but it seems likely that the errors could be large particularly in the case of the $\overline{TS}$/length relationships.

c) *Biased net samples*

Another error, whose severity could not be estimated, was that arising from taking the incorrect mean length of krill in computing $\overline{TS}$. Such errors could occur because the swarm sampled was unrepresentative of the swarms in the area, or because the net took a biased sample of the swarm. The possibility of bias in the net sample seems particularly real. The bias could be positive in the case of a commercial net, or negative in the case of small research nets.

d) *Calibration errors*

In Hamburg, no data were available on the calibration accuracy of the acoustic systems used on each of the ships, but it seems unlikely, considering the calibration methods and equipment used, that any of the systems could have been calibrated to better than about ± 1 dB. In some cases, as previously explained, certain key parameters were not measured, but were taken from the manufacturer's specifications. Although the effect of these errors on the overall estimate would be reduced by their random nature, there is still a possibility of a significant resultant calibration error. In the absence of general inter-calibration data, the possible magnitude of this error can only be assessed once data is available on the calibration accuracy of each system.

8. Distribution

As it was not possible to contour the density estimates in the time available, density maps were compiled from the computed densities in each block (Figs. 2 and 3). These maps reveal a number of features, *viz.*:

1) The highest densities in the West Atlantic Sector occurred in the vicinity of Elephant Island and the Bransfield Strait, and the lowest in the Drake Passage and the Southern Scotia Sea. Densities were generally highest around islands and over shelf areas, and lowest in deep water.

2) In the Indian Sector there was a general trend towards increasing abundance and density from west to east, both north and south of the Antarctic Divergence ($\pm$ 65°S). The highest densities recorded were in Indian Sector B, particularly close to the continent. The distribution in this sector appeared to be markedly more patchy than in the adjacent Indian Sector A.

From Table 3 it can be seen that about 67% of the total biomass was located in three blocks within Indian Sector B (Blocks IB-2, IB-6 and IB-7, see Table 4) which together comprised only 8% of the total area surveyed. Similarly, 27% of the biomass in the West Atlantic Sector was found in Block A-4 (Table 4) whose area was only 9% of the sector area. In each of these blocks there were reports of at least one ultra-large swarm ("superswarm") having been detected, which suggests that such swarms could contain a substantial proportion of the krill biomass. Unfortunately, there was insufficient time for further analysis to estimate what proportion of the biomass detected was concentrated in "superswarms". The observations do however confirm earlier speculation that the large-scale distribution of krill is extremely patchy.

9. Estimation of Total Biomass

The survey design was by its nature unsuitable for estimating the total (*i.e.* circumpolar) krill biomass, in that the survey effort was concentrated in areas of high abundance, *i.e.* the sample was biased. Nonetheless, as the survey was the largest, most systematic direct survey of krill yet attempted, an attempt should be made to estimate the total biomass from the results.

Taking the overall mean density from Table 3 and applying it over the known geographic range of the krill (*i.e.* the whole Southern Ocean south of the Antarctic Convergence; an area of 35.8×10^6 km^2 according to MACKINTOSH, 1973), gives an estimate of about 600 million t. This estimate is probably too high, as more than half the area falls within the West Wind Drift–a sparsely populated region (except in the Atlantic Sector) which was under-sampled during FIBEX. A more conservative estimate is obtained by expanding the density measured in the West Atlantic Sector over the area of the Weddell Drift, and the densities in the other sectors over the area of the East Wind Drift. Taking these areas as 5.8 and 7.8×10^6 km^2 respectively (MACKINTOSH, 1973) gives estimates of 64 and 146 million t for the Weddell and East Wind Drifts respectively, the regions which are generally regarded as being the richest in krill. It is estimated therefore that the total krill population at the time of the survey lay somewhere between 200 and 600 million t. There is clearly a high degree of speculation in this type of extrapolation, but the estimates are more likely to reflect the true situation than estimates based on net hauls (which sample a much smaller volume of water than the echo sounders), predation rates or primary production. It is interesting to note that the mean overall density in Table 3 lies within the range estimated by MARR (1962) for the surface density of krill in the Weddell and East Wind Zones (2.5 to 29 g/m^2).

10. Discussion

The results obtained in Hamburg must be treated with caution. Apart from the errors inherent in the acoustic techniques used, which were briefly described earlier, there could be further errors due to the fact that the analysis in Hamburg was carried out in the space of only a few days with little opportunity for checking the results. This was particularly so in the case of Indian Sector B where the data was only available for analysis on the penultimate day, and could therefore not be analysed as thoroughly as the data from the other sectors. The present estimates of biomass and variance can probably be improved by some, or all, of the following measures;

1) Refining the concept of the default value for integrator intervals for which there are no nearby krill samples. (For example, the default value could be calculated from all samples within a large block around the position, rather than from the mean value within a previously-selected block within which the interval happens to fall),

2) Incorporating more accurate $\overline{TS}$/length relationships as these become available,

3) Post-stratification of the areas into regions of different density, and the estimation of biomass and variance for each stratum separately,

4) Correction for serial correlation by cluster models based on the real transects,

5) Estimation of error in the $\overline{TS}$/length and length/weight regressions used, and

in the calibration constants of the equipment,

6) Exclusion of some of the data collected at night.

As a first step towards checking the Hamburg acoustic results, each national group should make an independent estimate of the biomass in their own areas, using the $\overline{TS}$/length and length/weight relationships adopted in Hamburg. Allowing for some degree of overlap in the West Atlantic Sector, the sum of these estimates should agree with the total biomass in Table 3.

Accepting the reservations expressed above, it can still be said that perhaps the most significant finding of the FIBEX acoustic survey is the exceptionally high abundance in Indian Sector B, which indicates that this area, which has been comparatively little studied to date, may be very important in influencing the distribution and dynamics of the krill population. The highest concentrations were found a little to the west of the western boundary of the Kerguelen Gaussberg "stock" postulated by MACKINTOSH (1973). Whether the krill were concentrated there because of some process associated with the Kerguelen-Gaussberg Ridge, or some other local feature, is a challenging question for further study.

Acknowledgements

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At the Workshop the acoustic and associated biological data were managed and analysed through a data base system developed for this specific purpose at the University of Hamburg by D. CRAM, J-C. FREYTAG, M. MALL and T. SCHWINGHAMMER.

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