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NOTE

Biomass and population structure of a large aggregation of krill near Prydz Bay, Antarctica

I. R. Higginbottom, G. W. Hosie

Australian Antarctic Division, Channel Highway, Kingston, 7050 Tasmania, Australia

ABSTRACT: A dense aggregation of krill *Euphausia superba* in the region of Prydz Bay, Antarctica, was investigated in March 1987 using hydroacoustic and net sampling techniques. Maximum aggregation density was estimated to be 1530 g m^{-3}; total biomass 57 000 tonnes wet weight. This is the first reported observation of an aggregation of this magnitude in the Prydz Bay region. The aggregation is also unique in that it consisted mainly of very large sexually immature males, the majority 48 to 58 mm in body length.

Large aggregations of krill have been reported commonly in the region of the Antarctic Peninsula but not in the Indian or Pacific regions of the Southern Ocean. None have been reported in the region of Prydz Bay. Large aggregations are attractive targets for predators, including the commercial krill fishery, and contain a large but unknown proportion of the total biomass of krill within a given region (Mauchline 1981, Mathisen & Macauley 1983).

During the course of an acoustic and net survey to estimate the abundance of krill in the Prydz Bay region a concentration of Antarctic krill *Euphausia superba* Dana was found before dawn on 9 March 1987 in the vicinity of Cape Darnley, near Prydz Bay (echogram, Fig. 1). The concentration extended for 11 km (6 n miles) and contained within it a relatively dense aggregation, at 66° 53.5′ S, 70° 15.5′ E. Preliminary results of opportunistic net-based and hydroacoustic investigations into the size, density structure and population structure of the dense aggregation are presented.

Methods. Density structure and extent of the area of high density referred to as the 'swarm' were mapped acoustically. First contact with the swarm was made at 21:03 h GMT (8 March), and all surveying, including net sampling, was completed at 02:58 h GMT (9 March). A Simrad EKS-120 echosounder operating at 120 kHz and a Simrad QD echointegrator were used to determine the krill biomass. The echosounder was calibrated before the cruise by Simrad Subsea in Horten, Norway, and the source level plus the receiving sensitivity was 110.1 dB. Instrument settings of the echosounder were: range 0 to 250 m, pulse duration 0.6 ms, receiver bandwidth 3 kHz, gain 0 dB, time-varied gain function 20 logR, time-varied gain range 3 to 100 m, equivalent beam width −18.0 dB re. 1 steradian, echosounder constant 'c' − 40.5 dB and recorder mode 'normal'. The technique of echo-integration (Johannesson & Mitson 1983) was used to estimate krill biomass. A detailed description of the echosounding equipment on board MV 'Nella Dan' and a summary of the echo-integration technique (including a discussion of errors inherent in the technique) is given in Higginbottom et al. (1988). The acoustic parameter mean volume back-

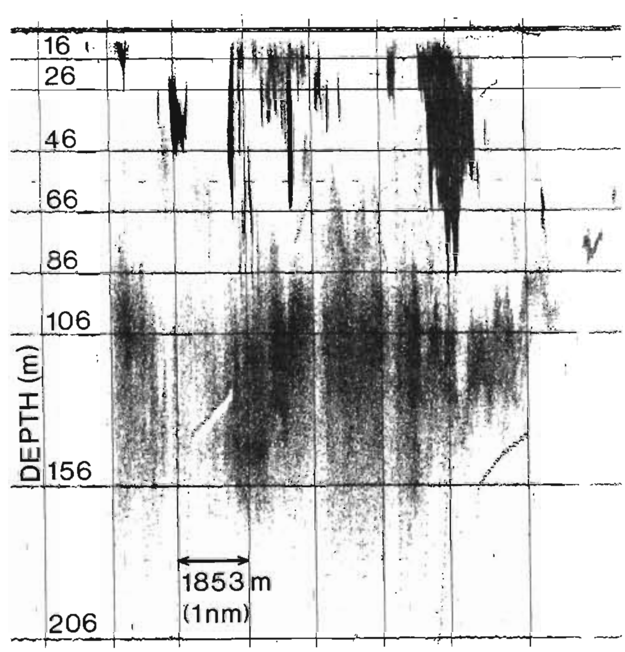

Fig. 1. *Euphausia superba*. Echogram (120 kHz) of first contact of krill 'concentration' including the dense aggregation ('swarm'). The diffuse aggregation below the swarm is clearly seen

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scatter strength (MVBS) was recorded at 370 m (0.2 n mile) intervals in 7 vertical layers (7–16, 16–26, 26–46, 46–66, 66–86, 86–106, and 106–156 m) referenced to the sea surface. Compensation for sound attenuation applied to the 106–156 m layer, which was beyond the range of the electronic time varied gain function, was calculated for the 106 m depth.

The mean target strength (TS) of krill in the swarm was estimated from the mean backscattering cross section of krill in the subsample (Higginbottom et al. 1988), where the target strength of an individual krill is given by $TS = 19.9\log(l) - 95.7$ (Anonymous 1986; l = krill length in mm). Mean weight of krill in the swarm was estimated by mean weight of krill subsampled from the net hauls (see below).

The survey was carried out along a cruise track that included 5 transects arranged in a modified 'man-overboard' search pattern (Watkins et al. 1986) (Fig. 2). The mean krill number- and weight-densities were calculated from the acoustic data for each integration interval. Average density of the swarm was then estimated using the 'ratio estimator' (Anonymous 1986), assuming that the 5 transects provided independent estimates of the swarm density. Size and shape of the swarm were estimated by contouring point densities representing the mean krill density along an integration interval in the 100 m of water column below the transducer. Data were contoured using the NCAR CONRAN plotting package (National Centre for Atmospheric Research, Boulder, Colorado), with additional smoothing done by hand. The swarm edge was defined as the 10 g m^{-3} contour.

Krill were sampled using a Rectangular Midwater Trawl RMT8 (4.5 mm mesh) (Baker et al. 1973). Towing speed was 1 m s^{-1} (2 knots), resulting in an effective mouth area of 8 m^2 (Roe et al. 1980). The net was equipped with a flowmeter, a combined electronic/mechanical net release and a depth monitor that was connected to a real-time read out on deck. Thus the net could be opened and closed at precise positions within the swarm.

Two horizontal hauls were carried out. The first haul sampled the swarm at a depth of 25 m, for 10 min, where the echosounder indicated that the swarm extended from 13 to 55 m (Fig. 2, Haul A). The second haul sampled a deeper more diffuse aggregation of krill situated under the swarm (Fig. 1). The net was opened for 10 min at 130 m (Fig. 2, Haul B). The net hauls were made between 21:55 and 23:45 h GMT and before the swarm was mapped acoustically.

On deck krill from the swarm catch were emptied into 6 bins of 40 to 60 l capacity. A randomly selected sub-sample was taken, a handful at a time, from the 6 bins and totalled 629 individual krill. All specimens were preserved in 10 % Steedman's solution (Steedman 1976) for subsequent examination at the Australian Antarctic Division in Hobart. Body length (Standard 1, measurement; Mauchline 1980) was measured to 0.1 mm accuracy, and body wet weight was measured to 0.001 g accuracy. Male and female krill were classified into maturity stages according to the system of Makarov & Denys (1981).

Results. The swarm was positioned above a submarine hill which rose 105 m relatively steeply from the west and fell away more gently to the north and east in the vicinity of the swarm (Fig. 3). A diffuse and apparently separate aggregation of much lower density was distinguishable below the main aggregation (Fig. 1). The survey cruise track, the positions of net hauls and the radial transects of the 'man overboard' search are plotted in Fig. 2. The area of the swarm within the 10 g m^{-3} isopleth was estimated to be 5.7 km^2 (1.7 n $miles^2$). Speed and direction of the apparent sea surface current were estimated by the 'drift' and 'set' from 11 satellite position fixes from a Magnavox satellite navigator. The speed of the apparent current ranged from 0.05 to 0.3 ms^{-1} (0.1 to 0.6 knots), and the direction ranged from 6 to 97° (Fig. 3). During the same period the wind came

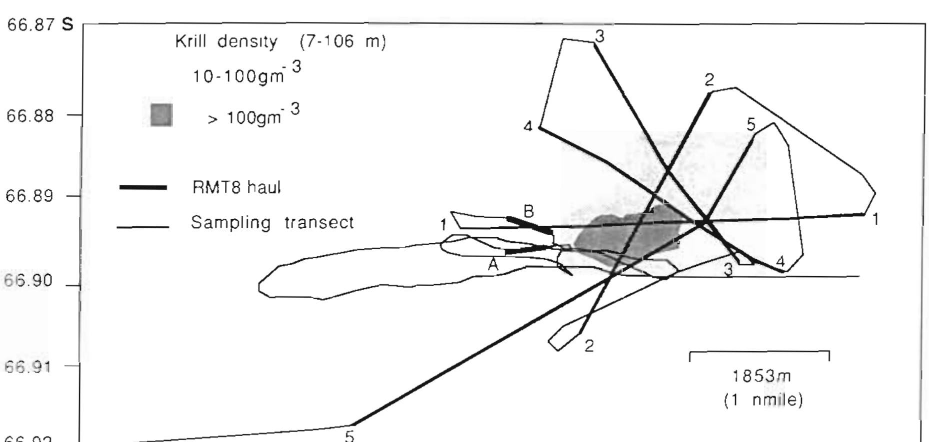

Fig. 2. *Euphausia superba*. Swarm shape indicated by 10 g m^{-3} isopleth in relation to cruise track. Sampling transects are highlighted and numbered; locations of the target trawls are labeled 'A' and 'B'

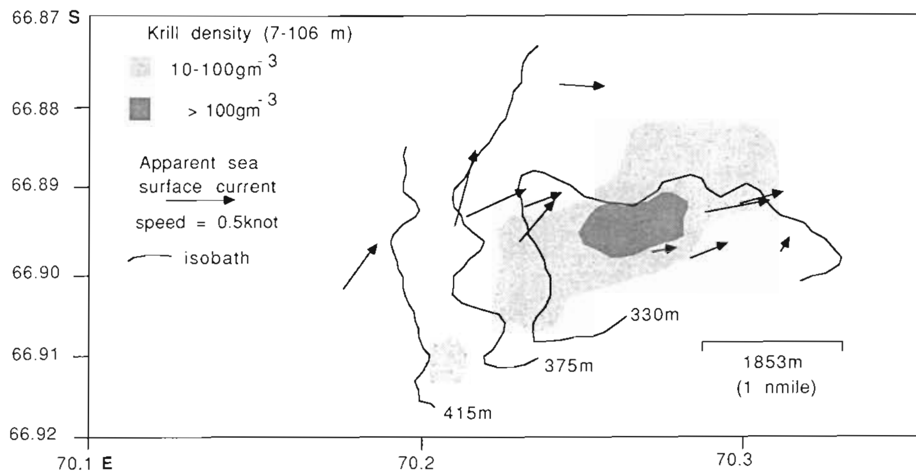

Fig. 3. *Euphausia superba*. Swarm shape in relation to local bathymetry. Apparent direction and magnitude of the sea surface current indicated by arrows at the position of each of 11 satellite fixes

from the southwest quarter and ranged in speed from 1 to 3 m s^{-1} (2 to 6 knots). It was considered unlikely that the wind was a major influence on the ship at the survey speed of 7 knots (Everson & Murphy 1987).

Vertical extent and density of the aggregation varied considerably along all transects (e.g. Figs. 4 and 5). The density structure of Transect 5 (Fig. 4) and the corresponding echogram (Fig. 5) are typical of the 5 transects. Comparison of the density structure with the echogram provides an indication of whether apparent variations in the density are caused by changes in the proportion of the sample volume occupied by the swarm, or by changes in the density of krill within the swarm per se. The swarm extended from a minimum of 7 m to a maximum of 111 m depth, and the bulk of the krill biomass, based on all transects, lay between 25 and 85 m. No krill were seen at the surface. The deeper aggregation ranged from about 80 to 170 m in depth and was some 3000 times less dense.

Inspection of successive echograms suggested that the swarm was moving downward in the water column over the period of observation. To further investigate this trend the proportion of krill in each layer was plotted against time (Fig. 6). While this plot also suggests that the krill were moving downward, there is no evidence to suggest that the swarm was aggregating or that it had been dispersed overnight.

The average krill density observed along each of the 5 radial transects is shown in Table 1. Mean transect biomass ranged from 44.4 g m^{-3} (−59.1 dB) to 182 g m^{-3} (−40.2 dB). Maximum biomass recorded was 1534 g m^{-3} (MVBS = −30.9 dB) averaged over a 20 m depth stratum in Transect 5. Number density (krill m^{-3}) and biomass (g m^{-3}) estimates for the swarm as a whole and

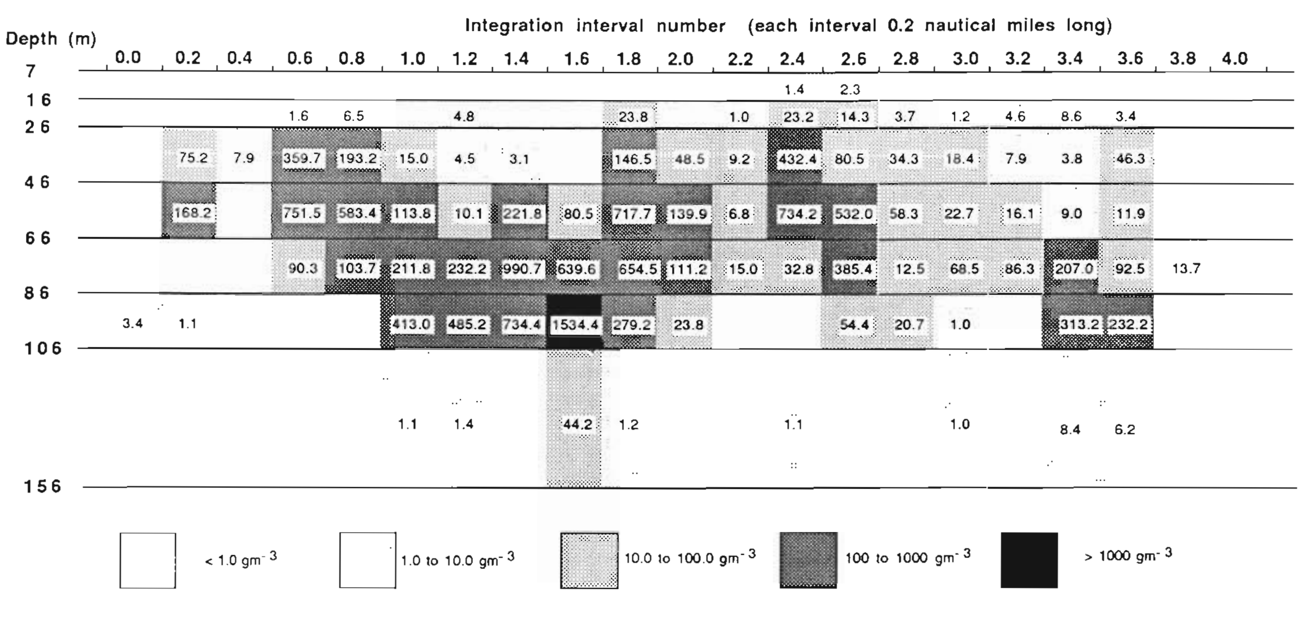

Fig. 4. *Euphausia superba*. Vertical profile of krill density along Transect 5

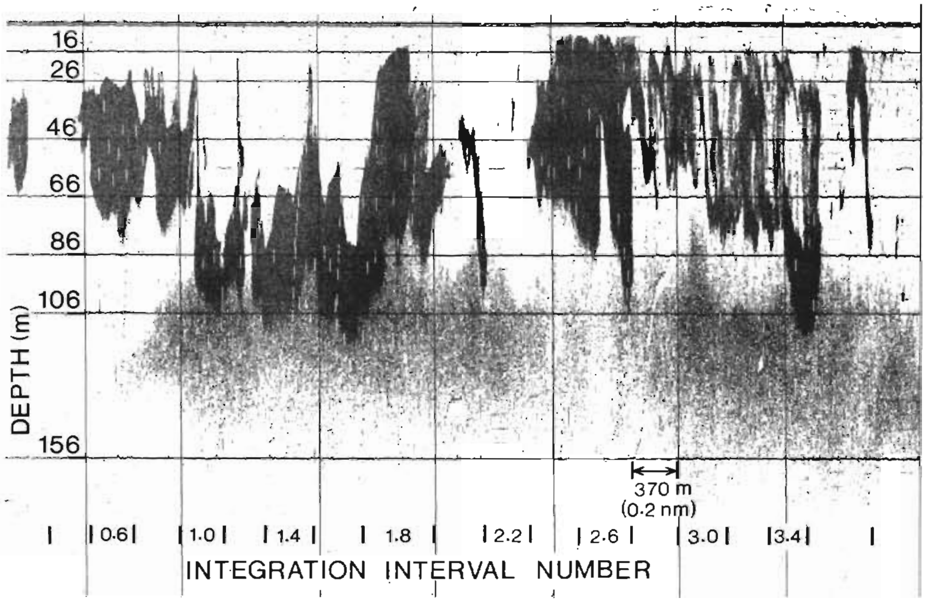

Fig. 5. *Euphausia superba*. Echogram (120 kHz) along Transect 5

for the deeper aggregation are given in Table 2. Total biomass of the swarm was estimated from the 5 transect means to be 57 000 tonnes with a standard deviation of 20 000 tonnes.

Total wet weight of krill caught during the RMT8 haul through the swarm was 294 kg. This amount of krill clogged the last 2 to 3 m of the net. No other species were observed in this haul. Prior to this haul the largest catch by Australian scientists with an RMT8 was 27.4 kg of krill caught in a 33 min haul in December 1982 (Williams et al. 1986). Only 127 individual krill were caught in the RMT8 haul through the deeper aggregation.

Males comprised 79.8 % of the krill sub-sample from the swarm catch, and of these the major component was large immature (2M) males (Figs. 7 and 8). By contrast, the deeper aggregation had a much greater component of juveniles (40.5 %) and sub-adults, and a more even distribution of body sizes. The mean target strength and mean weight of krill in the sub-sample were estimated to be −62.5 dB and 1.06 g respectively.

Discussion. The mean density of the swarm (101 g m^{-3}) is 2 orders of magnitude larger than the most dense aggregation observed either acoustically or by nets on any of 6 previous Antarctic Division cruises. Mean density is of the same order as the mean density of 80 g m^{-3} observed in a super-swarm near Elephant Is. in 1983 (Mathisen & Macaulay 1983). Maximum density recorded within the swarm was 1530 g m^{-3} averaged over a layer 20 m deep and 370 m long. Maximum densities recorded previously on Antarctic Division cruises were 1.7 g m^{-3} estimated acoustically (Higginbottom et al. 1988) and 1.7 g m^{-3} estimated by net haul (Hosie et al. 1988). The maximum density observed in the swarm is low compared to the range of swarm densities of 1 to 33 kg m^{-3} reported by Everson (1977).

The observation that the swarm was above a submarine hill is consistent with the observations of Witek et al. (1981) who observed that large krill concentrations are often found where currents were modified by bottom elevations. There was little evidence,

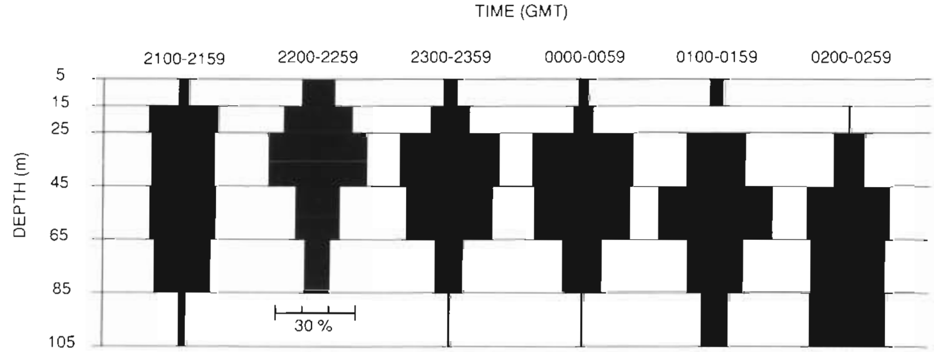

Fig. 6. *Euphausia superba*. Vertical distribution of krill biomass for each hour of the survey

Table 1. *Euphausia superba*. Mean and maximum krill densities (g m^{-3}), and mean volume backscattering strength [dB], observed along the 5 survey transects. Densities were calculated for each integration interval prior to estimating the transect mean

Transect number	Length km (nm)	Maximum density g m^{-3} [dB]	Mean density g m^{-3} [dB]
1	3.7 (2.0)	544 [−35.4]	44.4 [−59.1]
2	4.1 (2.2)	306 [−37.9]	32.2 [−60.5]
3	4.4 (2.4)	351 [−37.3]	57.6 [−45.1]
4	4.4 (2.4)	1013 [−32.7]	133.1 [−41.5]
5	7.8 (4.2)	1534 [−30.9]	181.8 [−40.2]

Table 2. *Euphausia superba*. Estimates of density within the swarm, including a comparison of acoustic estimates during the haul with simultaneous net haul estimates

Estimate	Density (no. m^{-3})	Density (g m^{-3})
Mean of acoustic intervals on 5 transects	94.7	100.8
Net haul in swarm (25 m)	48.1	51.2
Net haul in deeper aggregation (130 m)	0.023	0.0157
Acoustic intervals during and around net haul in swarm (16–46 m)	213.3	227.0

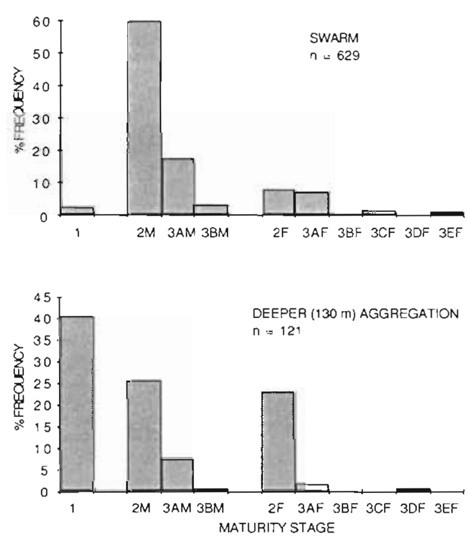

Fig. 7. *Euphausia superba*. Percentage-frequency distribution of maturity stages for the swarm and deeper (130 m) aggregation. 1 = juveniles; 2M = sub-adult (immature) male; 3AM = mature male, no spermatophore in ampullae; 3BM = mature male with spermatophore, ready to mate; 2F = sub-adult (immature) female; 3AF = mature female not mated; 3BF = mated mature female, ovaries small; 3CF = mated mature female, ovaries fill thoracic space; 3DF = mated mature female, carapace swollen with enlarged ovaries, i.e. spawning female; 3EF = spent female

though, in the present study, to indicate that the swarm was static over the hill. Neither was there clear evidence that the swarm, in its entirety, was moving with the current. The derived shape of the swarm was elongated along the line of flow (Fig. 2), possibly a result of the time difference between the acoustic transects, suggesting west-east movement. Equally, however, a current up to 0.6 knots (3 m s^{-1}) could be expected to have carried the swarm out the study area during the 6 h of this study.

The high proportion (80 %) of males within the swarm is not unusual. Wide variations in the sex ratio have been observed in aggregations of a number of euphausiid species (see review by Nicol 1984). For example, Nemoto et al. (1981) observed swarms of *Euphausia superba* with sex ratios in the range 0 to 100 % female. Females, however, predominated in most swarms by 60 to 70 % (Nemoto et al. 1981). Watkins et al. (1986) observed a number of swarms of *E. superba* comprising more than 70 % males in the Atlantic sector. A unique feature of the large Prydz Bay aggregation was the very high proportion of large immature males, i.e. males with undeveloped petasmae. These males are comparable in body size with the

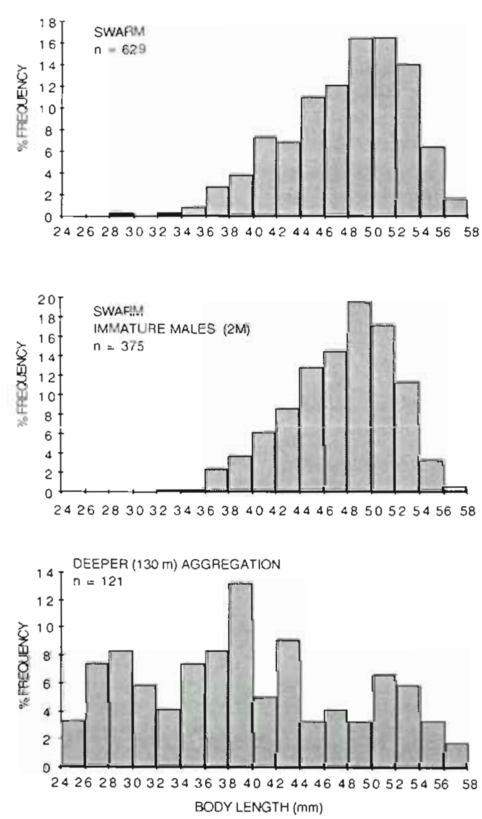

Fig. 8. *Euphausia superba*. Percentage size-frequency distribution, all maturity stages combined, for the swarm and deeper (130 m) aggregation, as well as for immature males (2M) collected from the swarm

specimens identified as Year 3+, 4+ and 5+ age-groups by Siegel (1986) and Hosie et al. (1988) which were considered to be sexually mature after 3 yr. Laboratory-based observations (Ikeda 1987) have confirmed that krill reach full sexual maturity after 3 yr and have shown that females are capable of regressing in external sexual characteristics at the end of the spawning period (Thomas & Ikeda 1987). The presence of a large number of large sexually immature males in March, close to the end of the spawning period in Prydz Bay (Hosie et al. 1988), suggests that males are also capable of post-reproductive sexual regression. The 80 % bias of males also supports the suggestion of Nemoto et al. (1981) that there may be a separation of sexes after mating and spawning occur.

The problems of determining the biomass of a species that aggregates are highlighted by the fact that this is the first description of an aggregation of such large magnitude in the region of Prydz Bay. A 20 km long aggregation was detected acoustically during the Australian FIBEX (Kerry & Higginbottom unpubl.) cruise but its biomass and composition were not determined. Large areas of low or no abundance and small areas of high abundance (Higginbottom et al. 1988, Hosie et al. 1988), lead to problems in the statistical analysis of the data, e.g. variances that exceed the mean by a large extent (Nast 1982, Siegel 1985, Miller 1986, Hosie et al. 1988). Sample sizes which are small in comparison to the area being surveyed also contribute to high variances and hence to wide confidence limits on biomass estimates.

The biomass (57 000 tonnes) of this single dense aggregation represents 1.3 % of the total biomass estimated for the region of Prydz Bay during January 1985 (Higginbottom et al. 1988), yet the aggregation occupied an area of only 7 km^2 out of 1.3 million km^2 of ocean in the region. This suggests that large aggregations may contain a substantial proportion of the biomass of krill in the region. These findings also reinforce the suggestions of Mackintosh (1966), Mauchline (1981) and Macaulay et al. (1984) that large dense aggregations must be considered separately from routine transect data when estimating biomass.

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