Krill of the Ross Sea: distribution, abundance and demography of *Euphausia superba* and *Euphausia crystallorophias* during the Italian Antarctic Expedition (January-February 2000)*

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SUMMARY: Net samples data from the 15th Italian Antarctic Oceanographic Cruise (Jan-Feb 2000) were analysed to obtain a general picture of the summer distribution pattern, abundance and demography of krill in the western Ross Sea (Antarctica). A midwater sampler-trawl (Hamburg Plankton Net) was used to collect zooplankton and fish larvae. Mean relative biomass of Antarctic krill *Euphausia superba*, in the area north of Continental Shelf, was 9.3 g/1000 m^3 of filtered water with a mean density of 10.9 ind./1000 m^3. Ice krill *Euphausia crystallorophias* replaced the Antarctic krill in dominance in the High Antarctic Zone (south of 74°), with a mean relative biomass of 3.0 g/1000 m^3 and a mean density of 19.1 ind./1000 m^3. The present data have demonstrated that in the Ross Sea the two species of euphausiid inhabited different areas during the summer period. Oceanographic data indicate that both euphausiid species were found in surface waters, *Euphausia crystallorophias* in proper Ross Sea water, and *Euphausia superba* in Antarctic Surface Water. The catch data of *Euphausia superba* were characterised by the complete absence of larval stages, scarce occurrence of juveniles and composed primarily of large adult stages, whereas the overall length frequency distribution of *Euphausia crystallorophias* was characterised by a first mode of juvenile individuals and a second mode consisting of sub-adults and adults.

Keywords: abundance, Antarctica, krill, demography, distribution, *Euphausia crystallorophias*, *Euphausia superba*, Ross Sea.

INTRODUCTION

The present paper analyses the catch data collected during the last survey in the Ross Sea (January–February 2000), to study the abundance, distribution and demographic parameters of the krill populations.

Relatively few studies have concerned krill populations from the Pacific sector, and in particular in the Ross Sea. In order to improve the krill knowledge in the Ross Sea, the Italian National Project of Antarctic Research (PNRA) has supported acoustic surveys and net samplings since 1989. The Antarctic expeditions have been carried out in different years and seasons and in ice-covered conditions to estimate the biomass and to describe the spatial and temporal distributions of krill populations (Azzali and Kalinowski, 1992, 1999).

The 1989-90 survey was conducted in early summer (26 December 1989 - 25 January 1990), contemporary with the melting of the ice. Krill was sampled using the EZ-NET-BIONESS plankton net,

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with nominal mouth opening of 0.25 m^2 (Guglielmo, 1992). However, the catches were insufficient for any demographic analysis because the net was not efficient in sampling adult stages of krill (<10 individuals per haul).

The 1994 survey was conducted in late spring and early summer (9 November - 27 December) when the Ross Sea was still covered with ice. The southern limit of the net stations was generally determined by the ice-covered condition –in particular the southernmost net station was at 75°S latitude. Krill was sampled using either EZ-NET-BIONESS (nominal mouth opening 0.5 m^2) or Hamburg Plankton Net (5 m^2). The latter replaced the BIONESS, because it proved to be more efficient in sampling krill, larvae and juvenile fish. The net abundance of *Euphausia superba* (Antarctic krill) was mainly concentrated on the continental slope (between 71° and 73°S) and in the central part of the continental shelf (between 73° and 75°S along 175°E). The high net catch of *Euphausia superba* (around 56000 individuals) which occurred at 74°35'S, 173°E, was remarkable. Westward (171°E along 75°S, up to Terra Nova Bay) *Euphausia crystallorophias* (ice krill) replaced the Antarctic krill in dominance and in large concentrations (Azzali and Kalinowski, 1999).

The 1997-98 survey was conducted in late spring (7 December 1997 - 5 January 1998) in partial ice-covered and relatively sea-dynamic conditions. Krill were sampled using the Hamburg Plankton Net (HPN). In this expedition the hauls were done only on the continental shelf and continental slope because the region adjacent to the Ross Ice Shelf was completely covered with ice. The Antarctic krill were caught regularly and abundantly at the stations

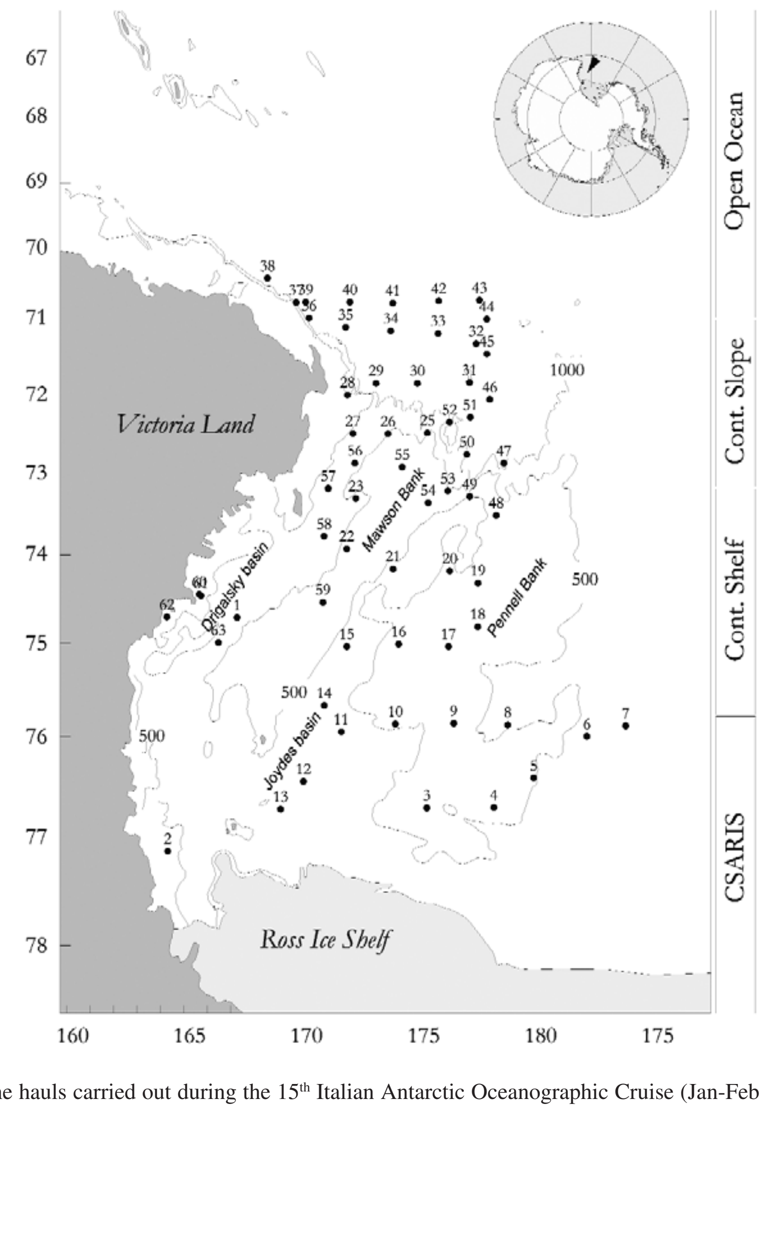

FIG. 1. – Location of the hauls carried out during the 15th Italian Antarctic Oceanographic Cruise (Jan-Feb 2000) in the western Ross Sea.

within the Mawson Bank region (73°S 173°E). In the Terranova Bay area, the only species present was *Euphausia crystallorophias,* mostly in juvenile stages (Azzali *et al.*, 2000a).

In January and February 2000 the survey was conducted in ice-free waters and in relatively stable environmental conditions. For the first time the region adjacent to the Ross Ice Shelf was sampled by net, the hauls were systematically distributed over the study area and a number of hauls almost twice that of previous surveys was carried out.

MATERIALS AND METHODS

During the Austral summer (Jan-Feb, 2000), hauls were methodically performed in ice-free waters every 6 hours with a mean tow-duration of 30 minutes (Fig. 1).

According to Lewis and Perkin (1985) the investigated area was divided into four regions:

Open ocean, covering the very deep waters of the Pacific Ocean and extending up to about 71°S;

Continental slope, where oceanic waters mix with shelf waters coming from the Ross Sea, extending between latitudes 71°S and 73°13'S;

Continental shelf, extending between latitudes 73°S and 75°48'S;

Continental shelf adjacent to the Ross Ice shelf barrier (CSARIS), include Jodes Basin, Ross Bank and extending from latitude 75°48'S up to the Ice Shelf Barrier.

Krill samples were collected using a Hamburg Plankton Net (HPN), a modification of the Isaacs-Kidd-Midwater-trawl (Hydro-Bios, Kiel, West Germany). The nominal mouth opening was 5 m^2 and the mesh size 1000 microns. The net was equipped with a mechanical flowmeter (General Oceanics, Inc., Miami, Florida) attached to the net mouth to determine the water volume filtered in each haul. Fishing experiment conditions: water volume filtered, trawl gear arrangement, estimated fishing depth, krill abundance and the mean length of krill from each haul are summarized in Table 1.

A total of 63 HPN stations were sampled from 16 January to 7 February 2000. The average towing speed during each haul was 3.0 knots, varying between 2 and 4 knots. The net was deployed in a double oblique fashion and an underwater trawl monitoring system (Simrad Integrated Trawl Instrumentation) was used to control in real-time the depth of trawling.

In order to obtain accurate data on krill composition, a subsample of at least 100 specimens was examined from each haul onboard the ship. If the total number of individuals caught was lower than 100, the whole net-sample was analysed. In addition, the samples were frozen or preserved in 4% buffered formalin for later examination. Using a dissecting microscope (Zeiss-Stemi 2000C) connected to a video analysis system (Zeiss-KS100), the following body measurements were collected both for *E. superba* and *E. crystallorophias*: total body length AT (from the anterior edge of the eye to the tip of the telson); carapace length (the oblique distance between the base of the eye-stalk and the mid-dorsal posterior edge of the carapace); and diameter of the compound eye.

In accordance with the procedures described by Makarov and Denys (1980), the condition of the sexual maturity stage was assessed only for *Euphausia superba*. In some hauls not all reproductive stages were present and for practical reasons some stages were pooled and coded as in Table 2. Each type of measurement was taken by a single observer to avoid methodologically biased differences as described by Watkins *et al.* (1985).

The spatial distribution of the krill populations was frequently patchy and samples taken from these assemblages are characterised by values of density and biomass which are typically small relative to the population mean, with a few very large exceptions. As the mean of the original (non-transformed) data may be oversensitive to extreme values and confidence intervals are large, McConnaughey and Conquest (1992) suggested that density and biomass of aggregated stocks should be indexed with an estimator such as the geometric mean. This estimator was thus computed by exponentiating the mean of the $log(x+1)$-transformed data and by subtracting one; zero catches were included in the calculation. This estimator may reduce errors associated with conventional fisheries stock-assessment practices and provide more effective management of overdispersed stocks.

In order to assess the heterogeneity structure of the Antarctic krill population, three-way variance analysis (factors: haul, sex and maturity stage) was used to test differences, in terms of their mean length, among hauls, sexes and maturity stages. The Antarctic krill sex and maturity stage compositions among haul samples were examined and compared using contingency tables.

For the species *Euphausia crystallorophias*, one-way analysis of variance was used to test whether

TABLE 1. – Fishing experiment conditions: water volume filtered, trawl gear arrangement, estimated fishing depth, total weight and number of krill caught from each haul. The mean length of each euphausiid species caught is included (♦ estimated data).

Haul	Water volume filtered (m^3)	Max warp length (m)	Max fishing depth (m)	Total weight of krill caught (g)		Total number of krill caught (num)		Density (ind./1000 m^3)		Biomass (g/1000 m^3)		Overall mean length (mm)	
				E. cry	*E. sup*	*E. cry*	*E. sup*	*E. cry*	*E. sup*	*E. cry*	*E. sup*	*E. cry*	*E. sup*
01	18988	-	-	1400	-	19642	-	1034.4	-	73.73	-	21.56	-
02	20714	250	-	-	-	-	-	-	-	-	-	-	-
03	11654	350	109	1500	-	16272	-	1396.3	-	128.71	-	23.36	-
04	13298	300	95	50	-	405	-	30.4	-	3.76	-	25.60	-
05	14303	350	105	400	-	9673	-	676.2	-	27.97	-	18.18	-
06	16371	800	240	260	-	3032	-	185.2	-	15.88	-	22.84	-
07	17968	100	34	1.4♦	-	15	-	0.8	-	0.08	-	23.47	-
08	12668	200	63	6000	-	59604	-	4705.1	-	473.64	-	24.01	-
09	12186	150	50	-	-	-	-	-	-	-	-	-	-
10	12139	100	35	-	-	-	-	-	-	-	-	-	-
11	10921	100	35	-	-	-	-	-	-	-	-	-	-
12	12945	200	65	120	-	3329	-	257.2	-	9.27	-	17.42	-
13	14995	200	64	70	-	2592	-	172.9	-	4.67	-	15.92	-
14	21660	300	91	380	-	5883	-	271.6	-	17.54	-	20.90	-
15	20060	350	107	620	-	5113	-	254.9	-	30.91	-	25.45	-
16	20554	300	93	2500	-	29038	-	1412.8	-	121.63	-	22.87	-
17	12323	-	-	-	-	-	-	-	-	-	-	-	-
18	13474	200	63	-	-	-	-	-	-	-	-	-	-
19	21056	500	150	1.4♦	-	102	-	3.9	-	0.38	-	23.69	-
20	17016	200	62	-	-	-	-	-	-	-	-	-	-
21	20961	250	77	-	-	-	-	-	-	-	-	-	-
22	17952	150	49	11♦	-	662	-	36.9	-	0.61	-	13.67	-
23	19372	200	62	-	-	-	-	-	-	-	-	-	-
24	-	100	33	-	-	-	-	-	-	-	-	-	-
25	16100	250	78	-	10900	-	13291	-	825.5	-	677.02	-	46.25
26	20806	200	61	-	14800	-	17209	-	827.2	-	711.35	-	46.94
27	13836	200	64	-	12000	-	15481	-	1118.9	-	867.29	-	45.44
28	13471	100	34	-	-	-	-	-	-	-	-	-	-
29	16909	200	62	-	-	-	-	-	-	-	-	-	-
30	17502	150	48	-	2300	-	3261	-	186.3	-	131.42	-	44.12
31	12667	100	35	-	10♦	-	14	-	1.1	-	0.79	-	44.06
32	14155	100	34	-	2300	-	3162	-	223.4	-	162.49	-	44.55
33	9902	150	50	-	-	-	-	-	-	-	-	-	-
34	13757	100	34	-	1800	-	2397	-	174.2	-	130.84	-	45.00
35	20762	300	91	-	10♦	-	13	-	0.6	-	0.48	-	45.20
36	16327	300	93	-	9400	-	12250	-	750.3	-	575.72	-	45.30
37	16717	550	165	-	700	-	1035	-	61.9	-	41.87	-	43.55
38	15106	150	48	120	380	869	519	57.5	34.4	7.94	25.16	26.50	44.63
39	18844	400	121	-	7♦	-	9	-	0.5	-	0.37	-	45.45
40	14303	300	93	-	30	-	32	-	2.2	-	2.10	-	48.33
41	13282	150	48	-	15♦	-	18	-	1.4	-	1.13	-	46.29
42	13565	100	35	-	-	-	-	-	-	-	-	-	-
43	24100	400	120	-	-	-	-	-	-	-	-	-	-
44	14120	100	34	-	4300	-	6106	-	432.4	-	304.53	-	44.10
45	22191	400	119	0.5♦	800	12	1114	0.5	50.2	0.02	36.05	18.42	44.37
46	17986	100	33	-	6600	-	9899	-	550.3	-	366.94	-	43.35
47	15877	100	34	-	3♦	-	5	-	0.3	-	0.19	-	41.81
48	12771	100	34	-	-	-	-	-	-	-	-	-	-
49	10920	100	33	-	16500	-	20713	-	1896.8	-	1510.95	-	45.83
50	30913	1000	299	-	10♦	-	15	-	0.4	-	0.32	-	46.20
51	12361	100	35	-	-	-	-	-	-	-	-	-	-
52	13239	100	35	-	10	-	15	-	1.2	-	0.76	-	42.96
53	24205	50	17	-	-	-	-	-	-	-	-	-	-
54	22284	800	241	6	1♦	101	1	4.5	0.0	0.27	0.04	20.39	53.51
55	26328	650	197	-	-	-	-	-	-	-	-	-	-
56	13780	200	65	2♦	-	137	-	9.9	-	0.15	-	13.13	-
57	25576	200	62	-	-	-	-	-	-	-	-	-	-
58	15885	150	48	300	-	13701	-	862.5	-	18.89	-	14.91	-
59	21404	150	47	-	-	-	-	-	-	-	-	-	-
60	15611	250	78	100	-	1747	-	111.9	-	6.41	-	20.13	-
61	19164	250	78	80	-	2501	-	130.5	-	4.17	-	16.78	-
62	11649	250	77	40	-	1487	-	127.7	-	3.43	-	15.90	-
63	14243	-	-	70	-	924	-	64.9	-	4.91	-	21.97	-

Table 2. – *Euphausia superba*. Reproductive Stage defined according to Makarov and Denys (1980).

Stage code	Definition	Characteristics	Sub-group
J	Juvenile	Sexual characteristics are not visible	Juvenile
M2	Beginning of maturation	Small single lobed petasma	Sub-adult
M3	Completion of maturation	Petasma has one wing but is not fully developed	“
M(4+5)	Fully matured	Fully developed petasma	Adult
M6	Resting stage (diapause)	Petasma is reduced to the size as in stage M2. This stage can be distinguished from M2 only by its larger size	“
F2	Beginning of maturation	Thelycum is not fully developed or coloured. Thorax is not swollen. Ovary is small	Sub-adult
F(3+4)	Fully matured	Red fully developed thelycum. Ovary fill thoracic cavity	Adult
F5	Spawn	Red fully developed thelycum. Thorax is swollen. Ovary is small and subsided	“
F6	Resting stage (diapause)	Thelycum is reduced and not coloured. Ovary is shrunk as in stage F2, but the size is larger than newly matured females	“

any differences existed among hauls in terms of their mean lengths. The normality (Kolmogorov-Smirnov test) and homogeneity of variances (Levene's test) of the length data were verified before applying ANOVA tests. In many cases these assumptions were not verified and a common transformation was applied. The statistical procedures were performed using the SPSS Rel. 9.01 software package.

The length frequency data of the two euphausiid species were investigated using the statistical distribution mixture analysis (Macdonald and Pitcher, 1979) to examine the ages of the distinct size-groups of the euphausiids. Variables of the age class components were calculated by stepwise optimisation (i.e. proportion, mean length and sigma, standard errors).

During the survey, 34 oceanographic stations were performed with a Sea Bird Electronics SBE 911plus CTD (Conductivity Temperature Depth) probe, measuring pressure, temperature, conductivity (from which salinity and density were derived) and fluorescence from the sea surface to the bottom (or at least 400 m depth), and 72 Sippican T7 XBT (eXpandable BatiThermograph) probes were launched, allowing for measurement of temperature from the sea surface until the bottom (or a maximum depth of 760 m, whichever was less). CTD sensors were calibrated before and after the cruise, and the manufacturer's claimed accuracy of around 0.15 bar (1 bar = 10^5 pascal) for pressure, 0.002°C for temperature and 0.003 S m^{-1} for conductivity was verified. XBT probes were built and shipped to New Zealand just before the start of the cruise, so we can rely on the manufacturer's claimed accuracy of 0.15°C. Moreover, sea surface temperature values were continuously acquired with a sampling period of 30 seconds.

Immediately before or after every haul, a CTD station was performed or a XBT probe was launched, and a XBT probe was launched about half way between two successive hauls. This strategy made it possible to obtain detailed (especially for sea temperature) information of the oceanographic conditions of the survey area, while consuming little ship time.

RESULTS

Species distribution, density and biomass

Zooplankton and fish larvae were analysed onboard the RV “Italica”. *Euphausia superba* and *Euphausia crystallorophias* were the only species of

TABLE 3. – Mean length of *E. crystallorophias* for each haul.

Haul	Mean length of all krill (mm)
01	21.56
03	23.63
04	25.60
05	18.18
06	22.84
08	24.01
12	17.42
13	15.92
14	20.90
15	25.45
16	22.87
19	23.69
22	13.67
38	26.50
54	20.39
56	13.13
58	14.91
60	20.13
61	16.78
62	15.90
63	21.97

TABLE 4. – Mean length, sex and maturity stage composition of *Euphausia superba* for each haul.

	Mean length (mm)				Percentage of krill (%)									
Haul	all sample	male	female	Juv.	% M	% J	M2	M3	M4+M5	M6	F2	F3+F4	F5	F6
25	46.25	47.14	45.33	-	51	-	7	3	22	19	-	3	45	1
26	46.52	48.96	44.40	-	56	-	-	3	14	39	-	1	43	-
27	45.42	46.02	45.22	-	28	-	-	5	18	5	2	9	58	3
30	43.90	46.15	43.44	-	25	-	-	7	4	14	11	17	46	-
32	44.35	44.81	44.43	-	32	-	16	-	1	15	6	17	44	1
34	44.60	45.66	44.55	-	40	-	9	6	18	7	8	27	25	-
36	45.25	46.49	44.54	-	39	-	4	3	19	13	2	17	42	-
37	43.63	45.59	42.92	33.73	27	1	9	2	7	9	11	5	56	-
38	44.63	46.57	43.89	40.05	29	1	7	-	13	10	10	1	59	-
40	48.33	48.33	-	-	100	-	-	-	100	-	-	-	-	-
44	43.71	44.88	43.89	36.63	43	3	18	-	12	13	7	10	37	-
45	44.59	46.81	43.39	33.84	34	2	7	-	21	6	7	14	40	2
46	43.49	45.01	42.82	36.91	30	2	6	6	3	15	13	2	53	-
49	45.68	47.80	45.15	39.47	28	1	2	1	11	14	-	-	71	-

euphausiid caught in the western Ross Sea waters during this cruise. The hauls that sampled krill are listed in Tables 3 and 4.

For comparative purposes and prior to computing abundance values for several hauls, krill catch frequencies (number and weight) were adjusted to a standard filtered water volume of 1000 m^3. The distribution of *E. superba* and *E. crystallorophias* did not overlap in any hauls, with the exception of three, and a distinct geographical separation can be seen in the plots of the spatial distribution of the two species (Fig. 2).

The overall Antarctic krill distribution corroborated the earlier findings of Azzali and Kalinowski (1999); in particular no records of Antarctic krill were obtained South of 74°S. Moreover, *E. superba*

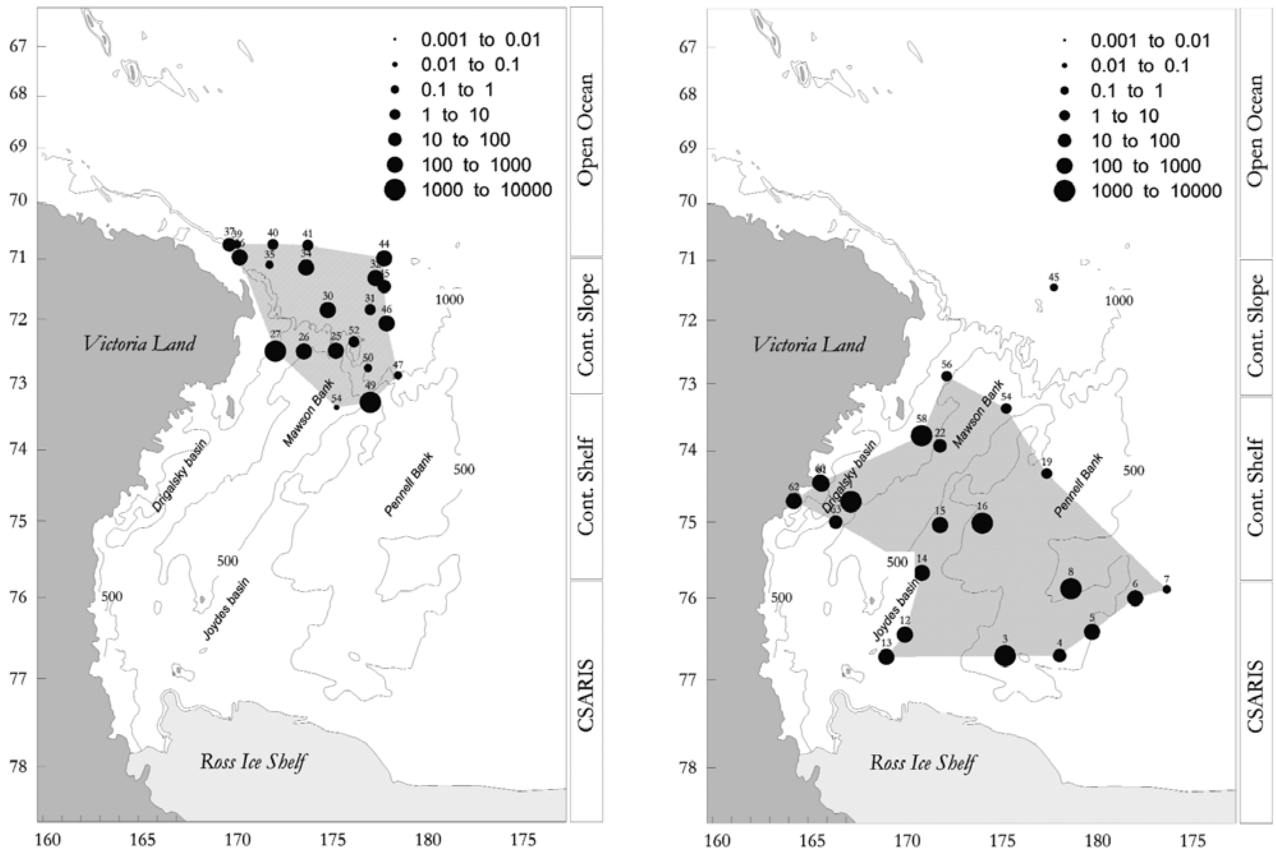

FIG. 2. – Horizontal distribution of krill abundance (*E.superba* and *E.crystallorophias*). Values are standardised at a individuals of krill caught per 1000 m^3 of filtered water.

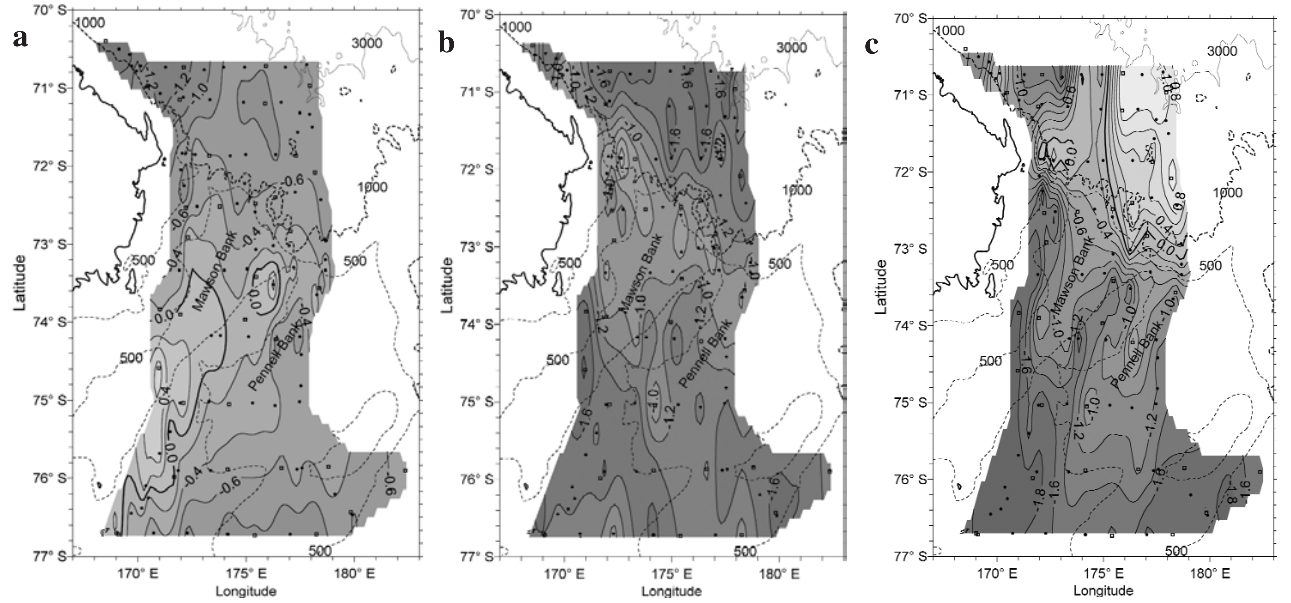

FIG. 3. – Temperature (°C) distribution at: **a**) 30 m depth, **b**) 100 m depth, **c**) 200 m depth (contour interval: 0.2); squares indicate CTD positions, circles XBT positions.

is almost completely absent in neritic waters, but commonly represents the dominant species throughout the survey area of the continental slope, whilst *E. crystallorophias* is mainly confined in large concentrations to the shelf waters and some coastal stations. In particular, in the shelf-break waters, the estimated Antarctic krill biomass was around 700 g/1000 m^3 and the maximum was 1511 g/1000 m^3 in a single haul.

The same pattern was found for density, where the highest recorded values were 1918 individuals/1000 m^3 and around 1000 ind./1000 m^3 in the other hauls. In the study area north of the Continental Shelf, the geometric mean of the biomass of the Antarctic krill sampled was 9.3 g/1000 m^3, with a 90% Confidence Interval equal to 3.5-22.5 g/1000 m^3. The mean density was 10.9 ind./1000 m^3, within a range of 4.1-27.2 ind./1000 m^3.

E. crystallorophias has a wide spread distribution, occurring in high densities on the Continental Shelf and close to the Ross Ice Shelf. In these areas, the mean density was 19.1 individuals per 1000 m^3, within a range of 7.7-45.3 ind./1000 m^3 –almost twice the density of *E. superba*. The highest density of *E. crystallorophias* was revealed at the far eastern part of the survey area close to Ross Ice Shelf, where the maximum for a single station was 6148 ind./1000 m^3. Other areas of high density of Ice krill were in the shoal waters to the south of Coulman Island (1224 ind./1000 m^3) and in offshore water close to Campbell Glacier Tongue (1862 ind./1000 m^3). In the survey area south of 74° (High Antarctic Zone), the Ice krill biomass was around 3.0 g/1000 m^3 with a 90% Confidence Interval of 1.5-5.5 g/1000 m^3. North of 74°, *E. crystallorophias* occurred in small numbers and only in neritic shallow waters. As in the previous Italian oceanographic cruise (1997-98), Antarctic krill were caught regularly and in abundance around the Mawson Bank (73°S 173°E), while on the Mawson Bank proper few catches were obtained. On the northern flank of the Mawson Bank, relatively warm Modified Circumpolar Deep Water (MCDW, or Warm Core) intrudes on the shelf and propagates toward the southwest remaining on the bank, while the two surrounding depressions are occupied by shelf waters only (Russo, 2000). Data collected during this cruise confirm this pattern (e.g. temperature distribution at 200 m, Fig. 3c), and krill is abundant in the transitional area between MCDW and shelf waters, while it is scarce on the bank in correspondence of the MCDW. More generally, both *Euphausia crystallorophias* and *Euphausia superba* were scarcely fished on the investigated Ross Sea banks (Mawson and Pennel), same areas being affected by MCDW intrusion, while both euphausiid species were abundant in the deep basins (Drygalski and Joides) occupied by shelf waters.

As shown in Table 1, the haul depths were between 17 and 299 m. Inspection of oceanographic data showed that such depths were located inside the surface water layer, formed by Antarctic Surface Water (AASW). Inside AASW, a distinction can be made between the saltier and denser surface waters produced by evolution of winter Ross Sea shelf water (Jacobs and Giulivi, 1999), here indicated for easy distinction as RSSW (Ross Sea Surface Water; Russo, 2000), and proper AASW, located outside the Ross Sea continental shelf. Figure 3a shows temperature at 30 m depth. By comparison with Figure 2, it can be seen that *Euphausia superba* is mainly located in the cold northern water (AASW), while *Euphausia crystallorophias* is found in the saltier RSSW. The temperature field at 100 m depth is shown in Figure 3d; here northernmost and southernmost areas have the same values, but water masses, identified by salinity values (not mapped because of the limited number of CTD stations), are different: in the northern area they are still AASW, while at the same depth in the southern area there is the transition between RSSW and underlying HSSW (High Salinity Shelf Water) or MCDW (Modified Circumpolar Deep Water). The highest temperatures, located along the shelf break, are the signature of the slope front, the V-shaped front typical of this area (Jacobs, 1991). At the slope front surface waters converge, while CDW eventually enters the shelf at intermediate depths and shelf waters eventually leave the shelf in the bottom layer. According to thermohaline characteristics at 100 m, surface waters coming from the open ocean appear to penetrate the shelf area until about 73-74°S. The area affected by this penetration is almost coincident with the *Euphausia superba* haul catches.

Size composition

Euphausia superba

The mean length from all samples was 44.83 mm (ranging from 32.17 to 54.49 mm, SD 3.64). The descriptive statistics for the total Antarctic krill sampled and for each sex are summarized in Table 5.

The length frequency distribution (1 mm length groups) is shown in Figure 4. Length frequency data were characterised by three distinct size-groups (χ^2 = 24.55; df = 20). The mean sizes of age classes presented in this study do not differ significantly from those already published by other authors and reported in Table 6. In harmony with these sources the pre-

TABLE 5. – Descriptive statistics for all the krill sampled. Statistics for males, females and juveniles of Antarctic krill are included separately.

	Total Sampling	Males	Females	Juveniles
E. superba				
Mean length	44.83	46.45	44.09	36.09
Std. Deviation	3.64	3.47	3.26	2.42
SE	0.09	0.16	0.11	0.70
Minimum	32.17	35.01	32.17	32.23
Maximum	54.49	54.49	53.07	40.05
Range	22.32	19.48	20.90	7.82
Skewness[a]	-0.200	-0.301	-0.154	-0.015
Kurtosis[b]	0.148	0.161	0.197	-0.575
E. crystallorophias				
Mean length	20.39			
Std. Deviation	5.81			
SE	0.13			
Minimum	7.84			
Maximum	40.41			
Range	32.57			
Skewness[a]	0.068			
Kurtosis[b]	-0.811			

[a] Measure of asymmetry of the distribution
[b] Measure of 'peakedness' of the distribution

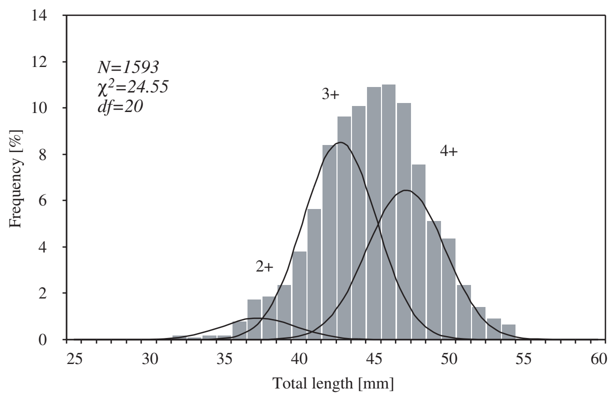

FIG. 4. – *Euphausia superba*. Length frequency distribution of specimens from all the samples and relative fitted components determined by distribution mixture analysis.

TABLE 6. – Mean length and standard deviation for various age groups of *Euphausia superba* from the Southern Ocean areas determined by distribution mixture analysis (Macdonald and Pitcher, 1979).

Age group	Cooperation Sea (Aseev, 1983)	Cooperation Sea (Pakhomov, 1995)	Weddell Sea (Siegel, 1987)	Ross Sea (This study)	
0	-	-	-	-	
1+	30.90 ± 1.30	27.20 ± 3.10	21.90 ± 2.80	-	
2+	38.35 ± 0.95	35.10 ± 4.10	39.20 ± 3.50	37.39 ± 2.47	6%
3+	44.00 ± 0.60	43.45 ± 2.95	44.50 ± 1.50	42.77 ± 2.44	52%
4+	49.25 ± 1.45	49.95 ± 1.05	50.10 ± 1.80	47.17 ± 2.60	42%
5+	54.05 ± 1.65	-	-	-	

TABLE 7. – Descriptive statistics for each maturity stage of *Euphausia superba*.

	Males				Females			
	M2	M3	M4+5	M6	F2	F3+4	F5	F6
Mean length	41.77	43.30	47.45	48.38	38.32	46.09	44.38	48.11
Std. Deviation	2.44	1.60	2.61	2.35	1.89	2.92	2.61	3.00
Minimum	35.01	37.67	41.45	45.05	32.17	37.12	39.12	44.50
Maximum	45.09	45.49	54.38	54.49	43.67	52.55	53.07	52.62
Range	10.08	7.82	12.93	9.44	11.50	15.43	13.95	8.12

sent first fitted-component identifies the age group 2+. Afterwards no differences emerged when the length measurements of age groups 3+ and 4+ of the current study were compared with those detected in the other areas of the Southern Ocean. The number of large and juvenile krill caught was too low to identify other age groups. Krakatitsa *et al.* (1993) suggested that krill recruits (1+) are scattered in surface layers (0 to 10 m), so young krill usually remain dispersed and only older individuals, which can withstand current transport, are able to swarm and dominate catches (Pakhomov, 1995). According to the literature (Hosie *et al.*, 1988; Hosie and Stolp, 1989), krill recruits (1+) were well represented in the catches of spring and early summer (November to January).

The differences among hauls in terms of the mean length of Antarctic krill (Table 4) resulted not significant at level 0.05 leading us to not reject the null hypothesis that the mean krill lengths are equal across hauls. The main-effect of both sex and maturity stage was highly significant ($p<0.001$). However, the p-value for the sex*maturity-stage combined effect term (interaction) was significant at the conventional level $\alpha = 0.05$, so the maturity stage effect was not assumed to be consistent across levels of the sex factor. Thus, in further analysis, the maturity stage effect was compared at each sex level (male

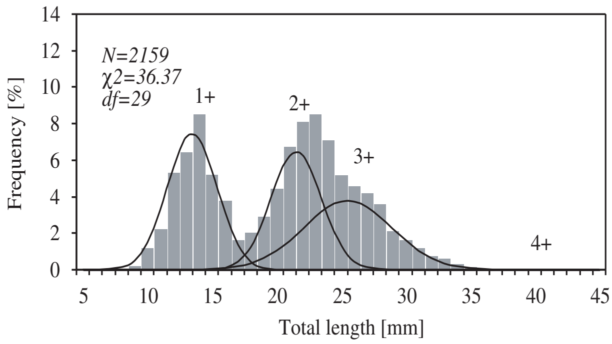

FIG. 5. – *Euphausia crystallorophias*. Length frequency distribution of the total sampling and relative fitted components determined by distribution mixture analysis.

and female separately). Table 7 shows the mean length of each reproductive stage for males and females. In both males and females, the one-way analysis of variance test confirmed a significant difference among the maturity stages in terms of the mean length ($p<0.001$).

Euphausia crystallorophias

Figure 5 shows the length frequency distribution (1 mm length groups). The mean length of Ice krill was 20.39 mm (ranging from 7.84 to 40.41 mm, SD 5.81; Table 5). The overall length frequency distribution was characterised by the juvenile stage (mean length 13.47 mm, SD 1.92), which made up 35.9% of the stock. A second mode consisted of sub-adults and adults, 31.5% (21.53±1.94 mm) and 32.4% (25.51±3.44 mm) respectively. A fourth component was identified at 39.43±4.62 mm and represented only 0.2% of the stock ($\chi^2=36.37$; df=29).

These results are similar to those found by Siegel (1987), who found that the smallest juveniles were 11 mm in length and the largest measured 20 mm, whilst the smallest sub-adults were 17 mm. The sub-adults of *Euphausia crystallorophias* were less than 24 mm during the spawning season, while the smallest adults were at least 21 mm at that time. Tattersall (1908) found 13 mm specimens of *Euphausia crystallorophias* in January, presumably larvae of the preceding season, and concluded that it takes at least one year to reach the final adult size of 32 mm. The present results stated that two years (age group 3+) would be necessary to reach this size and confirm that the species takes one year to reach maturity at age class 2+, as suggested by Siegel (1987). The largest size of *E. crystallorophias* recorded from this study was 40 mm, whereas Siegel (1987) found specimens having a maximum length of 41.5 mm. In harmony with Pakhomov and Perissinotto (1996), it was possible to assume that there are not so many differences among populations of *Euphausia crystallorophias* in the Southern Ocean.

TABLE 8. – Sex and maturity stage composition of *Euphausia superba* sampled.

				Sub-adults	Adults	Juv
Males	36%	M2	17%	25%	75%	
		M3	7%			
		M(4+5)	42%			
		M6	34%			
Females	63%	F2	10%	10%	90%	
		F(3+4)	15%			
		F5	74%			
		F6	1%			
Total				15%	84%	1%

The one-way analysis of variance result was highly significant ($p<0.001$) for detecting that some differences exist among the hauls. In particular in some hauls, the overall mean length of krill was reduced by the occurrence of a large proportion of juvenile specimens.

Sex and reproductive stage composition

The catch data of *Euphausia superba* were composed primarily of large adults, characterised by the complete absence of larval stages and scarce occurrence of juveniles. Table 8 shows the sex and maturity stage compositions for *Euphausia superba* from all the hauls. 84% of the krill caught were adults, with females comprising 63%, males 36% and juveniles less than 1%. 74% of the females had reached the maturity stage F5 (recent spawning of eggs) and this comprised 47% of the total krill caught.

In adults and sub-adults (the juvenile cases are not taken into account), the sex-proportion in the hauls was compared (Table 4). The contingency table and the Pearson Chi-square test clearly showed a significant heterogeneity among the hauls (*Pearson* $\chi^2 = 94.347$, $p<0.001$).

DISCUSSION AND CONCLUSIONS

On the basis of the catch data of the summer Italian expedition to the Ross Sea and the results of the previous expeditions carried out in different seasons, the following conclusions can be drawn.

A geographical separation between the two species of euphausiids was detected, which appears consistent with the shelf-break waters. *Euphausia superba* was dominant in the hauls conducted North of 74°S (Continental Slope). In the surveys carried out in November 1994 and in December 1997, abundant catches of *Euphausia superba* were obtained north of 75°30'S (Azzali *et al.*, 1999, 2000a). The geographical separation is consistent with oceanographic characteristics: both euphausiid species were sampled in surface waters, *Euphausia superba* being mainly located in open ocean Antarctic Surface Water (AASW) and *Euphausia crystallorophias* in the saltier southern surface waters of the Ross Sea.

Catches were abundant around the Mawson Bank, especially on the northern flank where the slope front is located, while on the Mawson Bank proper, occupied by the intruding warm and "old" Modified Circumpolar Deep Water (MCDW), catches were scarce. A similar situation was noted for *Euphausia crystallorophias* in correspondence of the Pennel Bank. Dynamics around banks appear to significantly influence euphausiid distribution.

A significant homogeneity, in terms of mean length, was identified in the Antarctic krill assemblages sampled, probably due to the occurrence of a scarce proportion of juvenile specimens. On the other hand, in the survey of December 1997, large catches of juveniles of *Euphausia superba* occurred south of 74°, so a highly significant heterogeneity of mean lengths among the hauls was observed.

The analysis of the population structure of *Euphausia crystallorophias* revealed a highly significant heterogeneity among the hauls in terms of the mean length. The juveniles were an important portion of the sampled population. Similar results were obtained from the hauls of December 1997 (Azzali *et al.*, 2000b).

A difference in the mean length between sexes and among the maturity stages of the *Euphausia superba* hauls was observed, as in the previous survey in the Ross Sea (Azzali *et al.*, 2000b) and in other sectors of Southern Ocean (Witek *et al.*, 1981; Siegel, 1986; Watkins *et al.*, 1986).

The heterogeneity of krill assemblages has important implications in the assessment of the local population structures. Sampling programmes must take into account when a spatial heterogeneity occurred and a characterisation of local populations will be achieved only by increasing the number of hauls performed. Finally, we point out that this study used the geometric mean to estimate the abundance of krill in the Ross Sea. The geometric mean reduces the influence of the occasional extreme values and produces much lower confidence intervals than the arithmetic mean. This procedure, together with the sampling procedure and the type of net used, must be taken into account to compare the euphausiid abundances presented in this paper and the ones found by other authors.

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