DISTRIBUTION AND SIZE OF ANTARCTIC KRILL (*EUPHAUSIA SUPERBA* DANA) IN POLISH COMMERCIAL CATCHES TAKEN IN THE ATLANTIC SECTOR OF THE SOUTHERN OCEAN FROM 1997 TO 1999

E. Jackowski
Sea Fisheries Institute
ul. Kollataja 1
81-332 Gdynia, Poland
Email – jack@miryb.mir.gdynia.pl

Abstract

The distribution and internal structure of commercial krill concentrations were investigated in the areas of the South Shetland, Elephant, South Georgia and South Orkney Islands in the spring and summer from 1997 to 1999. The density of concentrations varied with area and season. The densest concentrations were found near the South Shetlands. Concentrations at night were several times less dense than those observed during the day. Between February and April the density of concentrations increased, while in May and June it decreased. From February to June the period of daylight becomes progressively shorter, therefore it must be assumed that there are factors other than daylight which have an impact on the density of krill concentrations. The internal structure of concentrations was very diverse, and mean density varied from 11 to 31 370 specimens per 1 000 m^3. At night, krill concentrations were scattered throughout the water column, however no clear evidence of vertical migrations was found. Between February and April concentrations occurred in much shallower waters at night than during the day, while in May and June they occurred at the same depths at night as during the day or sometimes even deeper. Between February and April concentrations during the day were found in shallower waters, while between April and June they were found in deeper waters. The size structure of the krill varied during all periods and in all areas, however krill size was observed to decrease as the season progressed.

Résumé

Étude de la distribution et la structure interne des concentrations commerciales de krill dans les secteurs des îles Shetland du Sud, Éléphant, de la Géorgie du Sud et des Orcades du Sud pendant les printemps et étés de 1997 à 1999. La densité des concentrations variait en fonction du secteur et de la saison avec les plus fortes densités près des îles Shetland du Sud. La nuit, les concentrations étaient nettement moins denses que celles qui avaient été observées pendant la journée. De février à avril la densité des concentrations a augmenté, alors qu'elle a diminué en mai et en juin. De février à juin, la durée du jour devient de plus en plus courte, ce qui laisse penser que la densité des concentrations de krill dépend de facteurs autres que la lumière du jour. La structure interne des concentrations était très diverse, la densité moyenne variant de 11 à 31 370 spécimens par 1 000 m^3. La nuit, les concentrations de krill s'éparpillaient dans la colonne d'eau, sans toutefois qu'une migration verticale n'ait été mise en évidence. De février à avril, les concentrations fréquentaient des eaux beaucoup moins profondes la nuit que le jour, alors qu'en mai et juin, les profondeurs étaient les mêmes, ou parfois plus grandes la nuit. De février à avril, elles évoluaient dans les eaux moins profondes pendant la journée, alors que d'avril à juin, on les trouvait dans des eaux plus profondes. La structure de tailles du krill variait en fonction de chaque période et de chaque secteur, mais la taille du krill observé a diminué tout au long de la saison.

Резюме

Были изучены распределение и внутренняя структура коммерческих концентраций криля в районах Южной Георгии, Южных Шетландских и Южных Оркнейских о-вов и о-ва Элефант весной и летом 1997–1999 г. Плотность концентраций изменялась в зависимости от района и сезона. Самые плотные скопления были отмечены у Южных Шетландских о-вов. Плотность концентраций ночью была в несколько раз ниже, чем днем. С февраля по апрель плотность концентраций увеличивалась, а в мае и июне она сокращалась. С февраля по июнь период дневного освещения постепенно сокращается, поэтому необходимо предположить, что на плотность скоплений криля влияют факторы, отличные от продолжительности

дня. Внутренняя структура концентраций была очень разнообразной: средняя плотность составляла от 11 до 31 370 особей на 1000 м^3. Ночью скопления криля рассредоточивались в толще воды, однако явных доказательств вертикальной миграции не было. С февраля по апрель концентрации встречались в намного более мелких водах ночью, чем днем, в то время как в мае и июне они находились ночью на тех же глубинах, что и днем, а иногда даже глубже. В дневное время скопления встречались в более мелких водах в период с февраля по апрель и в более глубоких водах в апреле и июне. Размерная структура криля варьировала во все периоды и во всех районах, однако, по наблюдениям, размер криля уменьшался с течением сезона.

Resumen

Se estudió la distribución y estructura interna de las concentraciones comerciales de kril en los archipiélagos de las islas Shetland del Sur, Elefante, Georgia del Sur y Orcadas del Sur en la primavera y verano de los años 1997 a 1999. La densidad de las concentraciones varió de acuerdo con la región y temporada. Las concentraciones más densas se encontraron cerca de las islas Shetland del Sur. La densidad de las concentraciones observada durante la noche fue mucho menor que la observada durante el día. La densidad aumentó de febrero a abril y disminuyó en mayo y junio. De febrero a junio el período de luz diurna se acorta progresivamente, por lo tanto cabe suponer que hay otros factores que afectan la densidad de las concentraciones de kril aparte de las horas de luz diurna. La estructura interna de las agregaciones varió considerablemente y la densidad promedio fluctuó entre 11 y 31 370 ejemplares por 1 000 m^3. En la noche las concentraciones de kril se encontraron dispersas a través de la columna de agua, sin embargo, no se encontraron pruebas fehacientes de migraciones verticales. Entre febrero y abril se observó que el kril se concentró en aguas menos profundas por la noche, mientras que en mayo y junio no hubo diferencia en el intervalo de profundidad entre la noche y el día, e incluso a veces, las concentraciones se encontraron en aguas más profundas. Entre febrero y abril el kril se congregó en aguas menos profundas durante el día, mientras que de abril a junio esto ocurrió en aguas más profundas. En todos los períodos y en todas las regiones la estructura de tallas del kril fue diferente, sin embargo, se observó que la talla del kril disminuye en el transcurso de la temporada.

Keywords: krill, density, vertical migration, length, CCAMLR

INTRODUCTION

In the CCAMLR Convention Area krill is mostly harvested in the Atlantic sector of the Southern Ocean (FAO Statistical Area 48).

Commercial krill concentrations in the Atlantic sector (Everson and Goss, 1991) occur mainly in the vicinity of the South Shetland, South Orkney and South Georgia Islands. Studies focused on the biology and distribution of krill concentrations have been carried out since the beginning of commercial exploitation. However, most of these studies have been short term, therefore their results do not reflect the year-round structure of krill concentrations. Additionally, the use of various investigation methods makes evaluating the structure and distribution of krill concentrations difficult. Some studies have examined the seasonal and interannual variability of krill concentrations. The use of hydroacoustic techniques has yielded basic information on the structure of krill concentrations (Kalinowski and Witek, 1982, 1985a, 1985b; Witek et al., 1981; Macaulay et al., 1984).

Antarctic krill (*Euphausia superba*) forms dense concentrations over an area of many square kilometres. The structure of these concentrations is very diverse, and they can consist of smaller or larger shoals of various densities (Kalinowski and Witek, 1982; Watkins et al., 1990). Sometimes the shoals in one concentration can be as dense as 30 000 specimens per m^{-3} of water (Hamner et al., 1983).

Hardy and Günther (1935) and Marr (1962) produced a diagram showing the distribution of krill aggregations at different times of day and night in the South Georgia area. Shevtsov and Makarov (1969) have described krill distribution in the Atlantic sector. Pavlov (1974) produced a diagram illustrating the vertical migration of *E. superba* in relation to diurnal feeding rate. Mohr (1976) described vertical distribution in the South Sandwich Islands area in relation to the daylight cycle. Kalinowski and Witek (1980) considered krill distribution relative to periods of daylight, feeding and environmental condition.

Most of the works cited above have dealt with a limited amount of material, therefore the results were frequently contradictory and it was impossible to draw general conclusions. In order to better understand how the Southern Ocean ecosystem functions, and to protect its living resources, the biology of *E. superba*, the key species in Antarctica, needs to be studied in more detail. Knowledge of krill density and the migration process is necessary to understand the trophic relationships in the Southern Ocean ecosystem and to make a proper estimation of krill biomass.

The aim of this study is to characterise commercial concentrations of krill, and their density and distribution relative to the season, depth strata and krill size in these concentrations during the 1997, 1998 and 1999 krill fishing seasons in the Atlantic sector.

MATERIALS AND METHODS

Material for the investigations was collected on board the Polish commercial vessel FV *Pollux* in the summers of 1997, 1998 and 1999 (Figure 1). This vessel fished for krill alongside other vessels in different areas of the Atlantic sector that yield the best commercial catches of krill. Each year, the periods when krill concentrations were found in various areas of the sector were determined. Entries in the ship's log were used to determine krill distribution. A WP/42+42/94 x 4 pelagic trawl with 20 mm mesh (10 mm side) in the codend was used.

Krill density in each haul was estimated as the ratio of krill weight in the catch to the volume of water filtered, and was expressed as the number of specimens per 1 000 m^3 (specimens/1 000 m^3). For calculating the volume of water filtered, the vertical trawl opening was assumed to be 35–40 m (average 37.5 m). The trawling speed varied from 2.1 to 2.8 knots and was recorded separately for each haul. Mean daytime haul duration varied from 39.8 to 74.5 min (SD: 17.2 and 25.03 respectively), while mean night-time haul duration was from 57.3 to 90.7 min (SD: 15.2 and 27.6 respectively).

Records of the beginning and the end of each trawling were used in order to determine the duration of each haul. The beginning of trawling was the time at which shooting was completed and the net began to fish. The end of trawling was the time at which hauling stopped and the net was back on deck. To determine the vertical distribution of krill concentrations, average trawling depths, derived using an echosounder, were recorded separately for each haul. The daylight period was determined according to the nautical dawn and dusk reference table (CCAMLR, 2001b).

All hauls completed before or up to 10 min after dawn or dusk were categorised as night or day hauls respectively.

To determine the density of krill concentrations, samples of krill were taken from almost every fifth haul, or 16.8% of the total. The average krill weight in samples was used to estimate krill catch weight in each haul. Krill length measurements were taken as the total length (in mm) from the front of the eye to the tip of the telson, rounded down to the nearest millimetre. Between 123 and 187 krill specimens were measured from each sampled haul.

Pairwise comparisons of krill length between year and area were conducted using ANOVA. The level of statistical significance was assumed to be 0.01.

The vertical distribution of krill concentrations was determined for each 25 m layer of the water column.

RESULTS

Distribution of Commercial Krill Concentrations in Various Fishing Areas of the Atlantic Sector

The periods of occurrence of commercial krill concentrations varied in each fishing area and year. They first started to occur in the Elephant Island area between February and April (this period varied with year), and then in the South Shetlands area (i.e. King George Island to Livingston Island) between February and June (Figure 2). The krill fishery was significantly influenced by weather conditions. In 1999, fishing for krill in the South Shetlands area stopped much earlier (April) than in 1997 and 1998 (June) due to the heavy ice cover. In 1999, no commercial krill concentrations were observed in the Elephant Island area, while they were observed in the South Orkneys area. It must be emphasised that in the years immediately preceding these studies, no large krill concentrations suitable for exploitation were observed in the South Orkneys area. However, in the 1980s and early 1990s krill concentrations in this area were found to be numerous and large catches were taken (CCAMLR, 2001a; Litvinov et al., 2001).

Table 1: Krill density in areas of the Southwest Atlantic sector of the Southern Ocean, from 1997 to 1999. Density is expressed as mean specimens per 1 000 m^3.

Area	Year	Month	No. of Samples	Mean	SD	Min.	Max.
Elephant Island	1997	February	114	378	315	22	1 768
		March	133	629	833	12	7 242
		April	182	1 565	2 175	32	19 072
	1998	February	218	972	721	11	3 339
		March	21	1 529	1 168	236	4 322
South Shetlands	1997	May	186	685	864	11	8 979
		June	43	571	509	56	2 083
	1998	March	98	1 330	1 380	11	10 541
		April	112	3 902	5 249	54	31 370
		May	190	1 428	1 874	15	22 585
		June	139	1 092	991	62	4 404
	1999	February	82	827	552	88	2 252
		March	186	876	811	18	4 692
		April	179	984	982	15	10 244
South Georgia	1997	June	82	1 215	1 765	20	15 616
South Orkneys	1999	April	20	1 598	1 232	63	4 756
		May	203	1 143	1 141	12	6 659
		June	170	1 231	1 396	15	11 282

Density of Commercial Krill Concentrations

Krill concentrations were not equally distributed throughout the Atlantic sector; they were mainly located in the South Shetland, Elephant, South Orkney and South Georgia Islands areas (Figure 1). Most frequently they occurred on shelves and only in the South Georgia area did they occur in waters beyond the shelf. This is a typical distribution of krill in this area (see catch statistics in CCAMLR, 2001a).

The mean density of krill concentrations from 1997 to 1999 varied from 663 to 1 215 specimens/ 1 000 m^3; these figures varied by area and season (Figure 3). The highest mean krill densities were found in the South Georgia area (1 215 specimens/ 1 000 m^3) and the South Orkneys area (1 204 specimens/1 000 m^3), and the lowest was in the South Shetlands area (663 specimens/1 000 m^3).

The data presented here show that the density of krill concentrations varied by month (Table 1). The density of the concentrations increased as the catch season progressed from February to April in all areas and years. However, density decreased after this period. The monthly density values increased up to two- to three-fold (Elephant Island area – 1997, South Shetlands area – 1998), while the maximum density of krill concentrations varied from 1 768 to 3 339 specimens/1 000 m^3 and from 4 756 to 31 370 specimens/1 000 m^3 in February and April respectively.

At night, krill concentrations were scattered throughout the water column and their density was several times lower than during the day (Figure 4). The most stable concentrations were observed in the Elephant Island area, while the most variable were noted in the South Shetlands area, although the distribution pattern of day and night densities was similar in all the areas. The dispersion of night concentrations differed from area to area. In February, March and April, nighttime krill concentrations in relation to daytime concentrations were less dispersed (1:1.67, 1:3.22 and 1:2.87 respectively) than in May and June (1:4.08 and 1:3.56 respectively) (Table 2).

In 1997 and 1998, krill concentrations in the Elephant Island area and the South Shetlands area were distributed in the water column from the surface to 124 m, and only in the South Georgia area were they located slightly deeper, to 149 m. In 1999, krill concentrations in the South Shetlands area were observed in much deeper waters, to 174 m, and even to 249 m in the South Orkneys area (Table 3). During the day, concentrations were usually located in deeper water layers (up

Table 2: Day and night krill abaundance (specimens/1 000 m^3) in various areas of the Southwest Atlantic sector of the Southern Ocean, from 1997 to 1999.

Area	Year	Month	Day					Night				
			No. of Samples	Mean	SD	Min.	Max.	No. of Samples	Mean	SD	Min.	Max.
Elephant Island	1997	February	96	410	320	22	1 768	17	219	226	16	758
		March	101	753	914	12	7 242	32	240	240	44	1 309
		April	115	2 171	2 530	32	19 072	66	525	433	51	1 734
	1998	February	180	1 129	695	11	3 339	38	227	142	11	589
		March	17	1 741	1 192	324	4 322	4	626	424	236	1 135
South Shetlands	1997	May	105	1 061	987	15	8 979	81	197	176	11	896
		June	22	785	433	120	1 497	21	233	96	75	449
	1998	March	66	1 663	1 460	94	10 541	32	644	879	11	3 953
		April	60	4 672	5 934	402	31 370	52	3 013	4 209	54	20 913
		May	92	2 279	2 329	28	22 585	98	628	647	15	5 646
		June	57	1 984	965	73	4 404	82	472	281	62	1 850
	1999	February	47	883	558	88	2 252	10	420	284	149	827
		March	122	1 138	843	18	4 692	59	376	438	34	2 681
		April	100	1 314	1 160	15	10 244	79	567	419	73	2 794
South Georgia	1997	June	38	1 953	2 359	20	15 616	44	577	430	20	1 757
South Orkneys	1999	April	11	2 352	1 171	63	4 756	9	676	391	204	1 189
		May	103	1 731	1 272	146	6 659	100	538	511	12	3 805
		June	76	1 972	1 777	15	11 382	93	632	425	16	2 213

Table 3: Vertical distribution of krill abundance (specimens/1 000 m^3) during the day in various areas of the Southwest Atlantic sector of the Southern Ocean, from 1997 to 1999.

Area	Year	Month	Depth (m)									
			>25	25–49	50–74	75–99	100–124	125–149	150–174	175–199	200–224	225–249
Elephant Island	1997	February		367	382	608	1 049					
		March		436	735	1 012	1 780					
		April		1 514	2 610	1 848	1 335					
	1998	February		889	1 178	1 243	1 068					
		March		1 793	908							
South Shetlands	1997	May	4 724	1 014	973	932	857					
		June		950	701	299						
	1998	March		1 638	1 804							
		April		5 344	4 367	3 501	3 165					
		May		2 087	2 946	2 369						
		June	1 660	2 269	1 188	1 475						
	1999	February		624	963	453	949	728	1 219			
		March		822	1 031	1 698	1 417	764				
		April		353	1 305	1 394	1 449	1 395	798			
South Georgia	1997	June	781	950	2 600	1 664	1 845	1 201				
South Orkneys	1999	April			1 929	3 092						
		May		875	1 734	1 827	2 095					
		June			968	1 951	2 439	2 323	1 619	2 872	1 387	1 527

to 249 m) than at night (up to 149 m) (Table 3 and Table 4). This was particularly true in February and March, while in April, May and June night-time concentrations were located in slightly deeper waters and the range of their vertical distribution sometimes overlapped with that of the daytime concentrations. During the day the density of concentrations increased with depth, while during night-time more scattered concentrations occupied the water column from 25 to 74 m. The latter pattern was observed in February, March and April, and less frequently in May and June. The night-time concentrations were found in deeper waters than the daytime concentrations only in May and June 1998 in the South Shetlands area. In 1998, in the South Shetlands area where the densest concentrations of krill were observed, density was the greatest in the 25–49 m water layer and concentrations were more dispersed in deeper waters.

In the South Orkneys area, where the range of vertical krill distribution was the greatest at depths to 249 m, the density of krill concentrations during the day varied at different depths, while at night the greatest densities were noted for concentrations at a depth range of 75–124 m (Table 4).

Krill Size

The krill concentrations consisted of specimens 25 to 60 mm long (Figure 5). Using the ANOVA test for mean length, statistically significant differences ($P < 0.01$) were observed with respect to both area and season. As the season progressed, the specimens observed were increasingly smaller (Figure 6, Table 5). The length distribution had a single peak, with the exception of the multi-peaked distribution in the Elephant Island area in 1997.

The size of krill caught during the day varied at all depths (Figures 7 to 9), and no correlation was found between krill size and the depth of occurrence. An increase in mean length was sometimes observed in catches taken in deeper waters, e.g. in the South Shetlands area in April and June 1998 (Figure 8). Precisely the opposite trend was observed in the South Shetlands area in March and April 1999 (Figure 9). The size of krill varied at different depths in the Elephant Island area, and also in the South Orkneys area. The lack of data from the night-time hauls for all areas and months investigated makes it impossible to determine the relationship between krill size and depth of occurrence. Some night-time hauls were examined for the South Shetlands area in May and June and of the South Orkneys area in June. A clear relationship between krill length and depth of occurrence was observed from these data; at depths between 50 and 124 m the size of krill increased with water depth (Figure 10).

DISCUSSION

While considering the results of the studies, it must be kept in mind that they were derived from commercial catch data, which means that the hauls were carried out in areas where krill concentrations were optimal for krill fishing. This refers to both horizontal and vertical location of hauls, as well as their duration. The depth range of trawling was often broad, however sometimes catches were taken in narrow depth ranges and these hauls best reflected the real structure of krill concentrations. The trawl hauling technique also influenced the interpretation of the vertical structure of krill concentrations. While the nets were being hauled aboard the vessel, they continued to catch krill between the depth of the haul recorded and the surface. This obviously had an impact on the evaluation of both the size of specimens and the density of concentrations. Therefore, it seems that using the average haul values to determine the structure of krill concentrations is the most accurate method.

Horizontal Distribution

The results obtained confirm the general pattern of the distribution of the densest krill concentrations near the islands in the South Atlantic sector, such as the South Shetland, Elephant, South Orkney and South Georgia Islands (Mackintosh, 1973; Ichii, 1990; Everson and Goss, 1991). The catch distribution from 1997 to 1999, although different from year to year, represented a certain pattern which had been observed in previous seasons (Ichii, 1990), i.e. krill concentrations were first observed in the Elephant Island area, and then in the South Shetlands, South Orkneys and South Georgia areas.

The lack of catches reported in 1999 for the Elephant Island area, which until then had been an abundant area, and in 1997 and 1998 in the South Orkneys area, is surprising. This phenomenon had previously been observed in these areas and also around South Georgia (Siegel, 1988; Siegel et al., 1997; Sushin and Shulgovsky, 1999). Catch statistics for the Atlantic sector confirm this phenomenon (CCAMLR, 2001a), and also indicate that catches in different areas are very high in some seasons, while in others they are very low. This phenomenon is probably linked to the period

Table 4: Vertical distribution of krill abundance (specimens/1 000 m^3) at night in various areas of the Southwest Atlantic sector of the Southern Ocean, from 1997 to 1999.

Area	Year	Month	Depth (m)									
			>25	25–49	50–74	75–99	100–124	125–149	150–174	175–199	200–224	225–249
Elephant Island	1997	February	84	237								
		March		246	164							
		April		64	557	543	497					
	1998	February		210	269							
		March		977	280							
South Shetlands	1997	May		239	187	177	286					
		June			222	246						
	1998	March		1 626	393	241						
		April		3 453	854							
		May		1 108	539	484	369					
		June		495	466	451	756					
	1999	February		420								
		March		301	602	251						
		April		545	609	527	232					
South Georgia	1997	June		748	414	445						
South Orkneys	1999	April		676								
		May		537	464	1 506						
		June		237	616	643	965	356				

Table 5: Monthly and interannual values of mean krill length (mm) in various areas of the Southwest Atlantic sector of the Southern Ocean, from 1997 to 1999.

Month	Elephant Island			South Shetlands			South Georgia	South Orkneys
	1997	1998	1999	1997	1998	1999	1997	1999
February	49.51	41.56	48.31			45.39		
March	45.96	41.86			41.42	44.64		
April	42.28				41.00	44.08		48.37
May				42.24	40.42			46.02
June				41.26	39.98		38.33	45.50

of decreased ice cover in these areas. In 1983, when summer arrived quickly and the pack-ice was gone by October, the density of krill concentrations increased rapidly in the Bransfield Strait and adjacent areas (Rakusa-Suszczewski and Lipski, 1985).

Density of Concentrations

Previous studies reported that small krill concentrations were very dense and characterised by a diverse internal structure, both in terms of density and specimen size (Hamner et al., 1983; Watkins, 1986; Watkins et al., 1990). Larger concentrations consisted of small, high-density aggregations which were observed mainly during the day and which scattered at night (Kalinowski and Witek, 1982). The results presented in this work demonstrate significant diversity in concentration density, ranging from 11 to 31 370 specimens/1 000 m^3. The greatest density (31 370 specimens/1 000m^3) was observed during one five-minute haul in the South Shetlands area in April 1998. Such a dense concentration was observed only once and, as can be assumed, corresponded to an extremely small and very dense shoal. The average densities in some areas and seasons varied from 378 to 3 902 specimens/1 000 m^3. Variations in concentration density reflected a pattern that was characteristic for all areas and seasons studied: between February and April the concentration density increased and then decreased. This feature of the internal structure of concentrations is best reflected by data from the Elephant Island area (1997) and South Shetlands area (1998). During this period, night-time progressively increased from about two hours in February to about 14 hours in June (Figure 11), and since decreased densities were observed in April, it must be assumed that there are other factors besides daylight which have an impact on krill density. It may be assumed that the krill concentration pattern in February–June depends on krill biological activity related to spawning, as was observed in the Elephant Island area by Loeb and Siegel (1994), however, they recorded the maximum krill density in February, while it was recorded in April in each of the three consequent years of this study.

Vertical Migration

The results obtained indicate that commercial krill concentrations most often occurred in waters at depths to about 125 m, which concurs with the results of investigations carried out from aboard the RV *Profesor Siedlecki* in 1978 and 1979 (Kalinowski and Witek, 1980). However, it should not be assumed that this is the maximum range of occurrence: in 1999 commercial concentrations were found at a depth of 175 m in the South Shetlands area and at about 250 m around the South Orkneys. It should be noted that commercially negligent krill concentrations may be traced much deeper. According to Gutt and Siegel (1994), sampling by scientific nets shows that krill aggregations may occur at depths to 480 m.

However, the range of vertical distribution in each area is different during the day and at night. In general, during the night, krill concentrations occur in the upper water layers ranging between areas from 20 to 70 m depth (Marr, 1962; Kalinowski and Witek, 1980), while during the day they occur in significantly deeper layers. According to the same and other authors (e.g. Hardy and Günther, 1935; Shevtsov and Makarov, 1969; Pavlov, 1974; Mohr, 1976; Kalinowski, 1978), krill migrate to the upper water layers at night, and when the light intensity increases during the day they migrate to the lower layers. However, night concentrations sometimes occur at much higher depths than day concentrations; this contradicts the general scheme of krill distribution. This phenomenon was observed in the South Georgia area (Kalinowski and Witek, 1980).

The results presented in this paper confirm the general pattern of day and night krill distribution. However the observed features relate only to February–March during the studied fishing seasons. During this period, night concentrations occurred in layers closer to the surface than day ones. However, even in March this relationship was not always clear. In April, May and June krill were found in much deeper waters at night than during the day. This was especially evident in the South Shetlands area in 1998, when the longer period of studies helped to clarify the pattern observed. The pattern observed was that as nights became longer, krill scattered more widely throughout the deeper layers, and the range of its vertical distribution was sometimes greater than during the day. This may indicate that food rather than light governs diurnal krill migrations (Pavlov, 1974; Fischer, 1976; Kalinowski and Witek, 1980). All these authors confirmed that krill feed mainly at night, and environmental conditions such as dissolved oxygen and water temperature or water mass movements determine availability of phytoplankton.

Length of Krill

The results of our study revealed that the size of krill in concentrations varies depending on the season and area of fishing; this concurs with observations of other authors (Jazdzewski et al., 1978; Kawaguchi et al., 1997; Makarov et al., 1970; Siegel, 1989; Siegel et al., 1990; Siegel et al., 1997; Watkins, 1986; Watkins, 1999). Observations made by Watkins (1986) regarding the lack of correlation between krill size and depth of occurrence were also confirmed ($0.01 < R^2 < 0.14$; $0.18 < P < 0.24$).

The largest individual krill were observed in the Elephant Island and South Shetlands areas, and the smallest in the South Georgia area, confirming the results of earlier studies (Jazdzewski et al., 1978; Wolnomiejski et al., 1980; Siegel et al., 1997). Analysis of krill size structure in the South Shetlands area (Subarea 48.1) revealed statistically significant differences between krill sizes (two-sample test: $P < 0.01$) in the Elephant Island and South Shetlands areas. In the three years analysed (1997–1999), larger krill specimens were observed in the Elephant Island area than in the South Shetlands area.

For all periods and areas the length distribution curve was unimodal, indicating the homogenous structure of krill concentrations. The only exception were data from the Elephant Island area in 1997, which indicated the existence of three size groups, with peaks at 39, 45 and 51 mm. During the same season, a bimodal distribution of krill sizes was observed for the South Georgia area (37 and 40.5 mm) and a unimodal distribution (peak at 42 mm) for the South Shetlands area. This distribution (in accordance with criteria for age estimation by Martin et al. (1997) and Watkins (1999)) indicates a multi-generation structure of the stocks (2+, 3+ and 4+ age groups) in the Elephant Island area. In the South Georgia area there were two age groups (2+ and 3+), and in the South Shetlands area only the 3+ age group predominated. The significant number of krill from the 2+ age group reflects good recruitment from the 1994/95 generation, which has been regarded as very abundant (Watkins, 1999).

Results of studies published to date report an increase of krill size over fishing season (Martin et al., 1997; Siegel and Kalinowski, 1994). These authors suggest that 'these changes are related to the drift of swarms, not to changes in krill behaviour thought to occur during the winter post-spawning non-feeding season. It is hard to explain these changes by the impact of the fishery on larger krill specimens'. The results presented here appear to be the opposite to those expected: the average krill sizes in each area decreased as the season progressed and the differences were statistically significant ($P < 0.01$). Similar observations were made in the South Orkneys area from March to June (Vagin et al., 1992).

Since the fishing season partially overlapped with the spawning season (Siegel et al., 1997), the conclusion can be drawn that larger specimens spawn first and are followed by smaller ones.

CONCLUSIONS

(i) Commercially important krill concentrations occur at the depth range to 125–250 m. The variations in depth relate to the location of krill occurrence: in the Elephant Island area the depth is up to 125 m, South Georgia area – 150 m, South Shetlands area – 175 m and the South Orkneys area – 250 m.

(ii) Daily krill migrations may vary according to area, however they mainly depend on the length of day and night. In February (short night), night concentrations come close to the surface and as the season progresses and nights lengthen they move in deeper waters. In April, May and June, they do not migrate to the upper layers, but remain scattered at the same depths, or even deeper, than the day concentrations.

(iii) The density of night concentrations of krill is several times lower than the density of day concentrations.

(iv) The average density of krill concentrations increases between February and April–May and then decreases, which is probably related to krill reproductive activity.

(v) The krill sizes varied depending on area and season. The largest krill specimens were found in the Elephant Island area and the smallest in the South Georgia area.

(vi) No relationship was found between krill size and its vertical distribution.

REFERENCES

CCAMLR. 2001a. *Statistical Bulletin,* Vol. 13 (1991–2000). CCAMLR, Hobart, Australia: 153 pp.

CCAMLR. 2001b. Nautical dawn and dusk reference table. In: *CCAMLR Scheme of International Scientific Observation: Scientific Observers Manual*, Part IV, Section 4. CCAMLR, Hobart, Australia.

Everson, I. and C. Goss. 1991. Krill fishing activity in the southwest Atlantic. *Ant. Sci.*, 3 (4): 351–358.

Fischer, W. 1976. Tagesperiodische Wanderungen des Antarktischen Krill. *Inf. Fischwirtsch., Hamburg*, 3: 90–92.

Gutt, J. and V. Siegel. 1994. Benthopelagic aggregations of krill (*Euphausia superba*) on the deeper shelf of the Weddell Sea (Antarctica). *Deep-Sea Res.*, 41: 169–178.

Hamner, W.M., P.P. Hamner, S.W. Strand and R.W. Gilmer. 1983. Behaviour of Antarctic krill, *Euphausia superba*: chemoreception, feeding, schooling and moulting. *Science*, 220: 433–435.

Hardy, A.C. and E.R. Günther. 1935. The plankton of the South Georgia whaling grounds and adjacent waters, 1926–1927. *Discovery Rep.*, 11: 1–456.

Ichii, T. 1990. Distribution of Antarctic krill concentrations exploited by Japanese krill trawlers and minke whales. *NIPR Symposium on Polar Biology*, 3: 36–56.

Jazdzewski, K., J. Dzik, J. Porebski, S. Rakusa-Suszczewski, Z. Witek and N. Wolnomiejski. 1978. Biological and populational studies on krill near South Shetlands, Scotia Sea and South Georgia in the summer 1976. *Pol. Arch. Hydrobiol.*, 25 (3): 607–631.

Kalinowski, J. 1978. Vertical migration of krill in the region of South Georgia, February–March 1976. *Pol. Arch. Hydrobiol*., 25 (3): 573–583.

Kalinowski, J. and Z. Witek. 1980. Diurnal vertical distribution of krill aggregations in the Western Atlantic. *Pol. Polar Res*., 1 (4): 127–146.

Kalinowski, J. and Z. Witek. 1982. Forms of Antarctic krill aggregations. *ICES Biological Oceanography Committee.* Mimeo CM L:60: 8 pp.

Kalinowski, J. and Z. Witek. 1985a. Elementy biologii i formy grupowego wystepowania kryli. *Studia i Materialy*, Seria B, 52: 162 pp. (in Polish).

Kalinowski, J. and Z. Witek. 1985b. Scheme for classifying aggregations of Antarctic krill. *BIOMASS Handbook*, 27: 9 pp.

Kawaguchi, S., T. Ichii and M. Naganobu. 1997. Catch per unit effort and proportional recruitment indices from Japanese krill fishery data in Subarea 48.1. *CCAMLR Science*, 4: 47–63.

Litvinov, F.F., V.A. Sushin, G.A. Chernega and O.A. Berezhinskiy. 2001. Soviet krill fishery in 1977–1992, Part 1. Distribution, fishing effort interannual situation patterns. Document *WG-EMM-01/57*. CCAMLR, Hobart, Australia.

Loeb, V. and V. Siegel. 1994. Status of the krill stock around Elephant Island in 1991/92 and 1992/93. *CCAMLR Science*, 1: 7–33.

Macaulay, M.C., T.S. English and O.A. Mathisen. 1984. Acoustic characterisation of Antarctic krill (*Euphausia superba*) from Elephant Island and Bransfield Strait. *J. Crust. Biol*., 4 (Spec. No. 1): 16–44.

Mackintosh, N.A. 1973. Distribution of post-larvae krill in the Antarctic. *Discovery Rep.*, 36: 1–94.

Makarov, R.R., A.G. Naumov and V.V. Shevtsov. 1970. The biology and distribution of the Antarctic krill. In: Holdgate, M.W. (Ed.). *Antarctic Ecology*, Vol. 1. Academic Press, London and New York: 173–176.

Marr, J.W.S. 1962. The natural history and geography of the Antarctic krill (*Euphausia superba* Dana). *Discovery Rep*., 32: 33–464.

Martin, J., R. Hewitt and R. Holt. 1997. The US Antarctic Marine Living Resources (AMLR) program: 1996–1997 field season activities. *US Antarctic Journ.*, 32 (5).

Mohr, M. 1976. Tageszeitlich bedingte rhytmik im verhalten von halbwuchsigen krill (*Euphausia superba*). *Inf. Fischwirtsch. Hamburg*, 4/5: 132–134.

Pavlov, V. 1974. O kharaktere svyazi mezhdu pitaniem i niekotorymi osobennostyami povedeniya *Euphausia superba* Dana. *Trudy VNIRO*, 99: 104–116.

Rakusa-Suszczewski, S. and M. Lipski. 1985. Report on the RV *Profesor Siedlecki* expedition during the BIOMASS-SIBEX in 1983/1984. *Pol. Polar Res.*, 6 (1/2): 7–19.

Shevtsov, V.V. and R.R. Makarov. 1969. K biologii antarkticheskogo krilya. *Trudy VNIRO*, 66: 177–206.

Siegel, V. 1988. A concept of seasonal variation of krill (*Euphausia superba*) distribution and abundance west of the Antarctic Peninsula. In: Sahrhage, D. (Ed.). *Antarctic Ocean and Resources Variability.* Springer-Verlag, Berlin Heidelberg: 219–230.

Siegel, V. 1989. Winter and spring distribution and status of the krill stock in Antarctic Peninsula waters. *Arch. FischWiss.*, 39: 45–72

Siegel, V. and J. Kalinowski. 1994. Krill demography and small-scale processes: a review. In: El-Sayed, S.Z. (Ed.). *Southern Ocean Ecology: the BIOMASS Perspective*. Cambridge University Press: 145–163.

Siegel, V., B. Bergström, J.O. Strömberg and P.H. Schalk. 1990. Distribution, size frequencies and maturity stages of krill, *Euphausia superba*, in relation to sea-ice in the northern Weddell Sea. *Polar Biol.*, 15: 161–174.

Siegel, V., W. de la Mare and V. Loeb. 1997. Long-term monitoring of krill recruitment and abundance indices in the Elephant Island area (Antarctic Peninsula). *CCAMLR Science*, 4: 19–35.

Sushin, V.A. and K.E. Shulgovsky. 1999. Krill distribution in the western Atlantic sector of the Southern Ocean during 1983/84, 1984/85 and 1987/88 based on the results of Soviet mesoscale surveys conducted using an Isaacs-Kidd midwater trawl. *CCAMLR Science*, 6: 59–70.

Vagin, A.V., R.R. Makarov and L.L. Meshenina. 1992. Diurnal variations in biological characteristics of krill, *Euphausia superba* Dana, to the west of the South Orkney Islands, 24 March to 18 June 1990 – based on data reported by a bioligist–observer. In: *Selected Scientific Papers, 1992 (SC-CAMLR-SSP/9)*. CCAMLR, Hobart, Australia: 201–222.

Watkins, J.L. 1986. Variations in the size of Antarctic krill *Euphausia superba* Dana, in small swarms. *Mar. Ecol. Prog. Ser.*, 31: 67–73.

Watkins, J.L. 1999. A composite recruitment index to describe interannual changes in the population structure of Antarctic krill at South Georgia. *CCAMLR Science*, 6: 71–84.

Watkins, J.L., D.J. Morris, C. Ricketts and A.W.A. Murray. 1990. Sampling biological characteristics of krill: effect of heterogeneous nature of swarms. *Mar. Biol.*, 107 (3): 409–415.

Witek, Z., J. Kalinowski, A. Grelowski and N. Wolnomiejski. 1981. Studies of aggregations of krill (*Euphausia superba*). *Meeresforschung*, 28: 228–243.

Wolnomiejski, N., Z.Witek and H. Czykieta. 1980. Metody i kryteria biologicznej oceny przemyslowych skupien kryla antarktycznego. (Methods and biological criteria for commercial krill aggregation assessment). In: Rozmieszczenie i charakterystyka skupien kryla w rejonie Polwyspu Antarktycznego w sezonie letnim 1997 r. *Studia i Materialy*, Seria A, 25. Sea Fisheries Institute, Gdynia: 27–63 (in Polish).

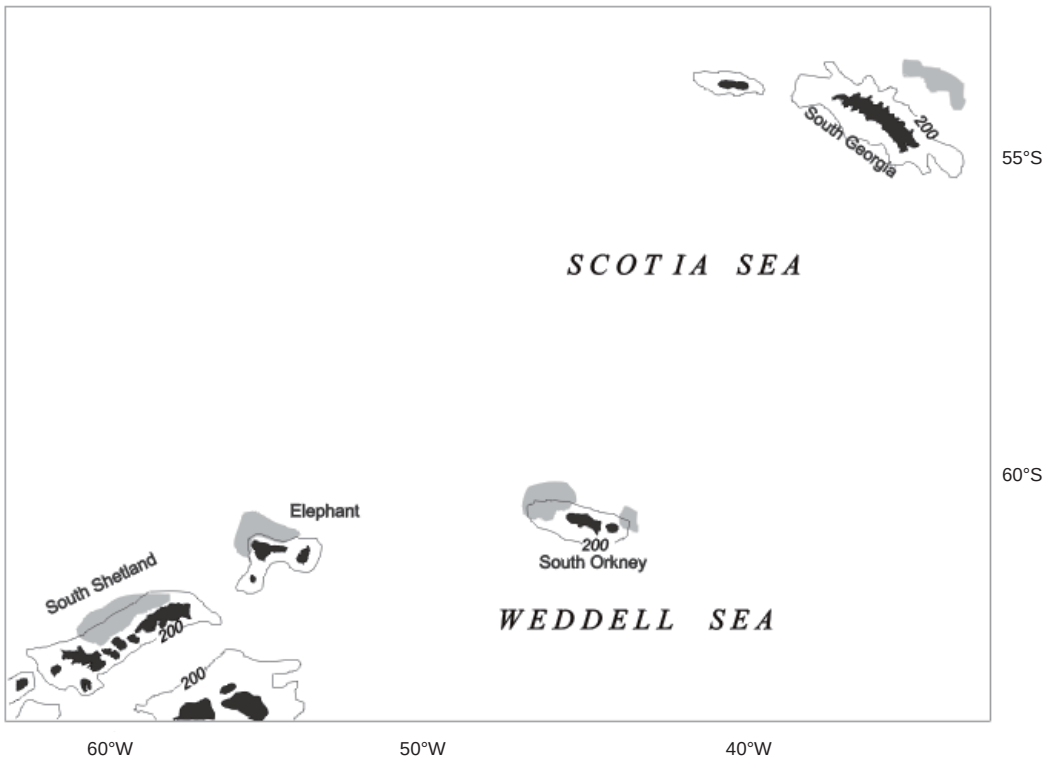

Figure 1: Areas of the Polish krill fishery where data were collected from 1997 to 1999.

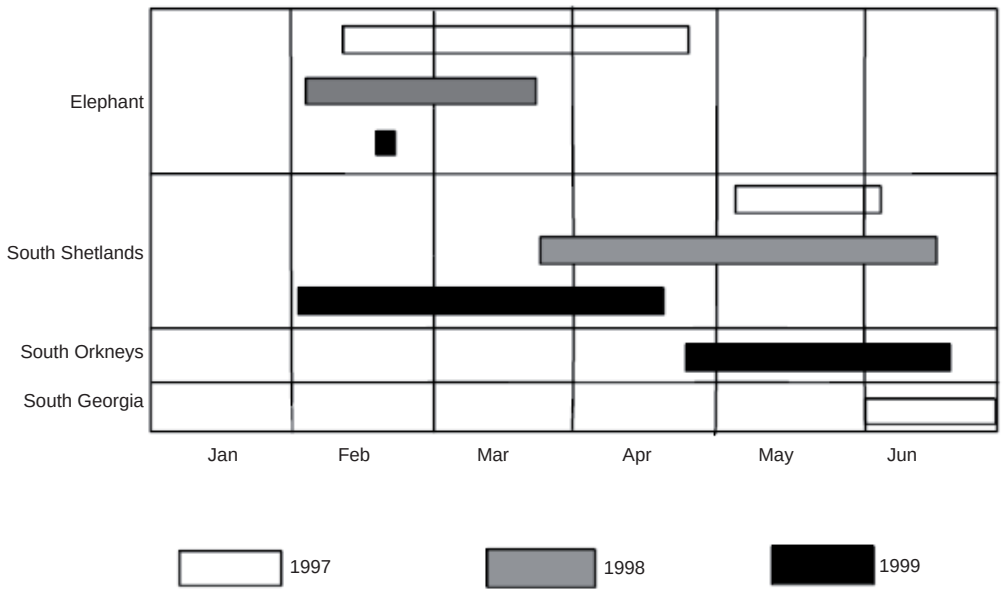

Figure 2: Periods of Polish commercial krill fishing in various areas of the Southwest Atlantic sector of the Southern Ocean, from 1997 to 1999.

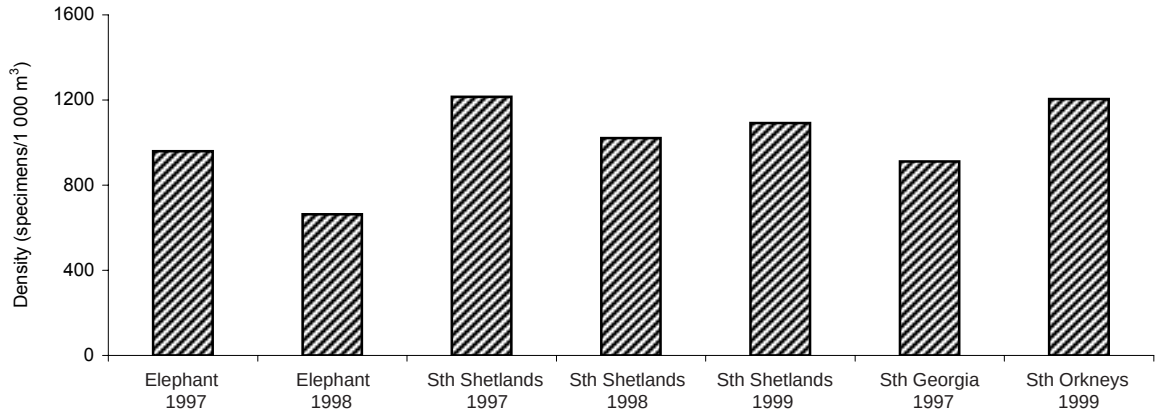

Figure 3: Mean krill density in various areas of the Southwest Atlantic sector of the Southern Ocean, from 1997 to 1999.

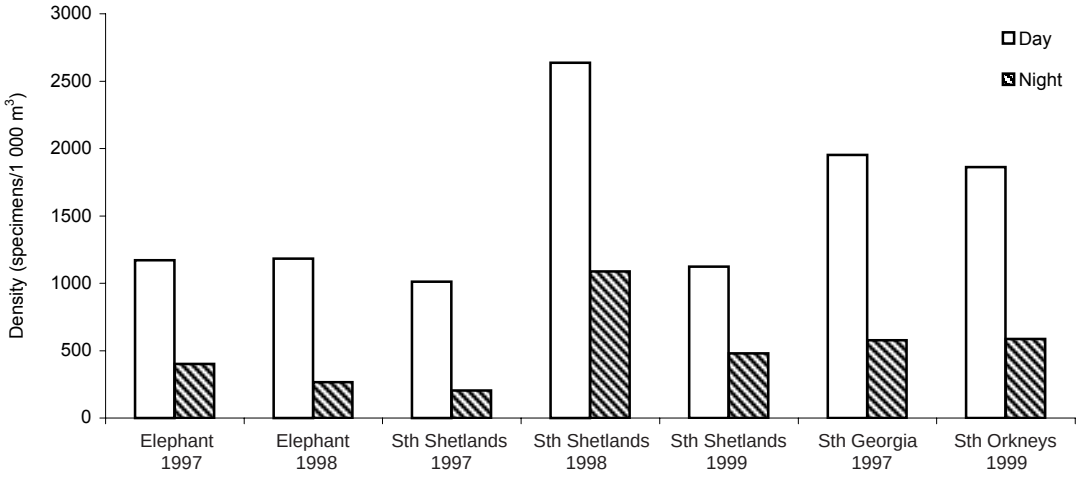

Figure 4: Mean krill density during the day and night in various areas of the Southwest Atlantic sector of the Southern Ocean, from 1997 to 1999.

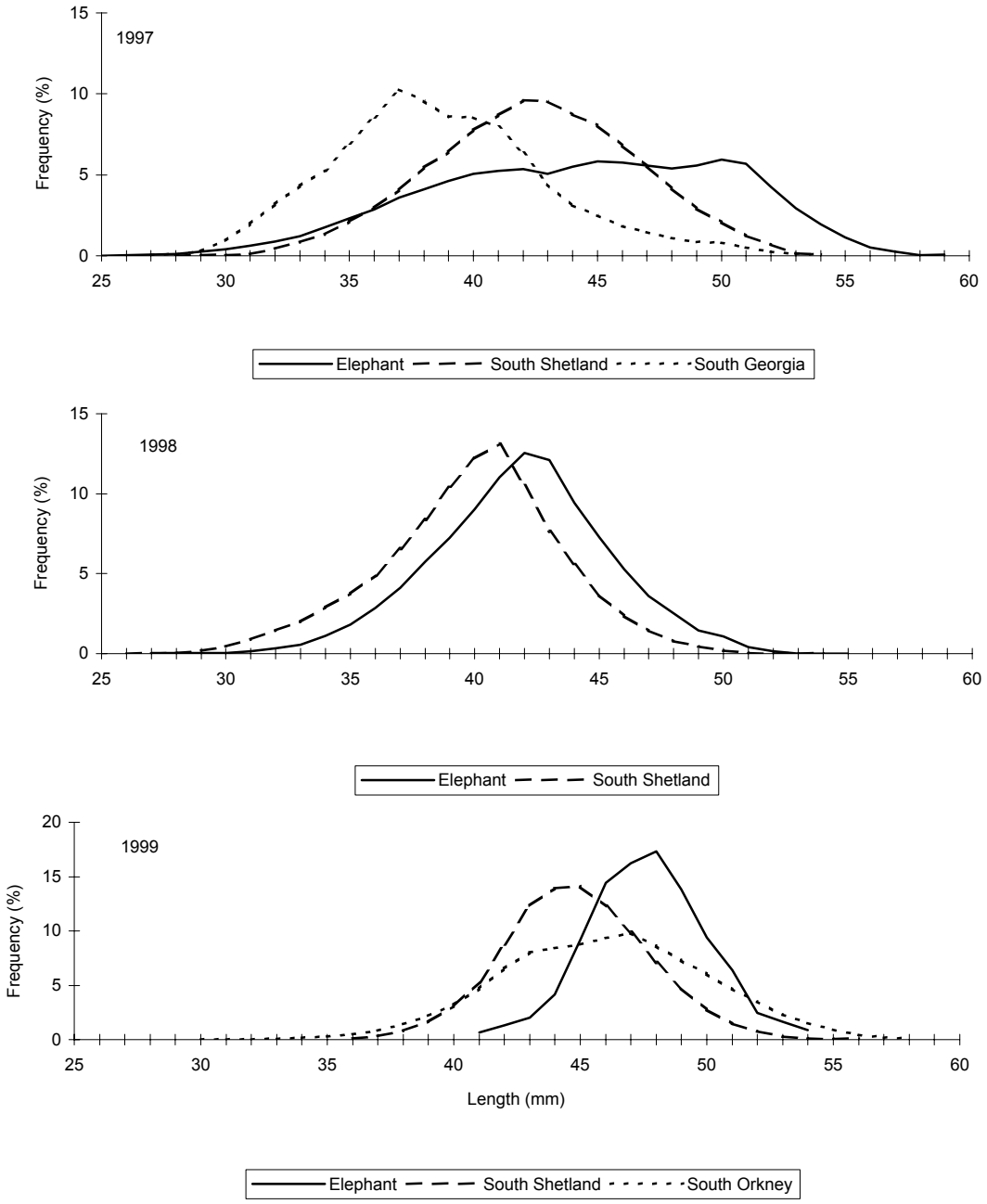

Figure 5: Krill length-frequency distributions in Polish commercial catches taken in the areas of Elephant, South Shetland, South Georgia and South Orkney Islands, from 1997 to 1999.

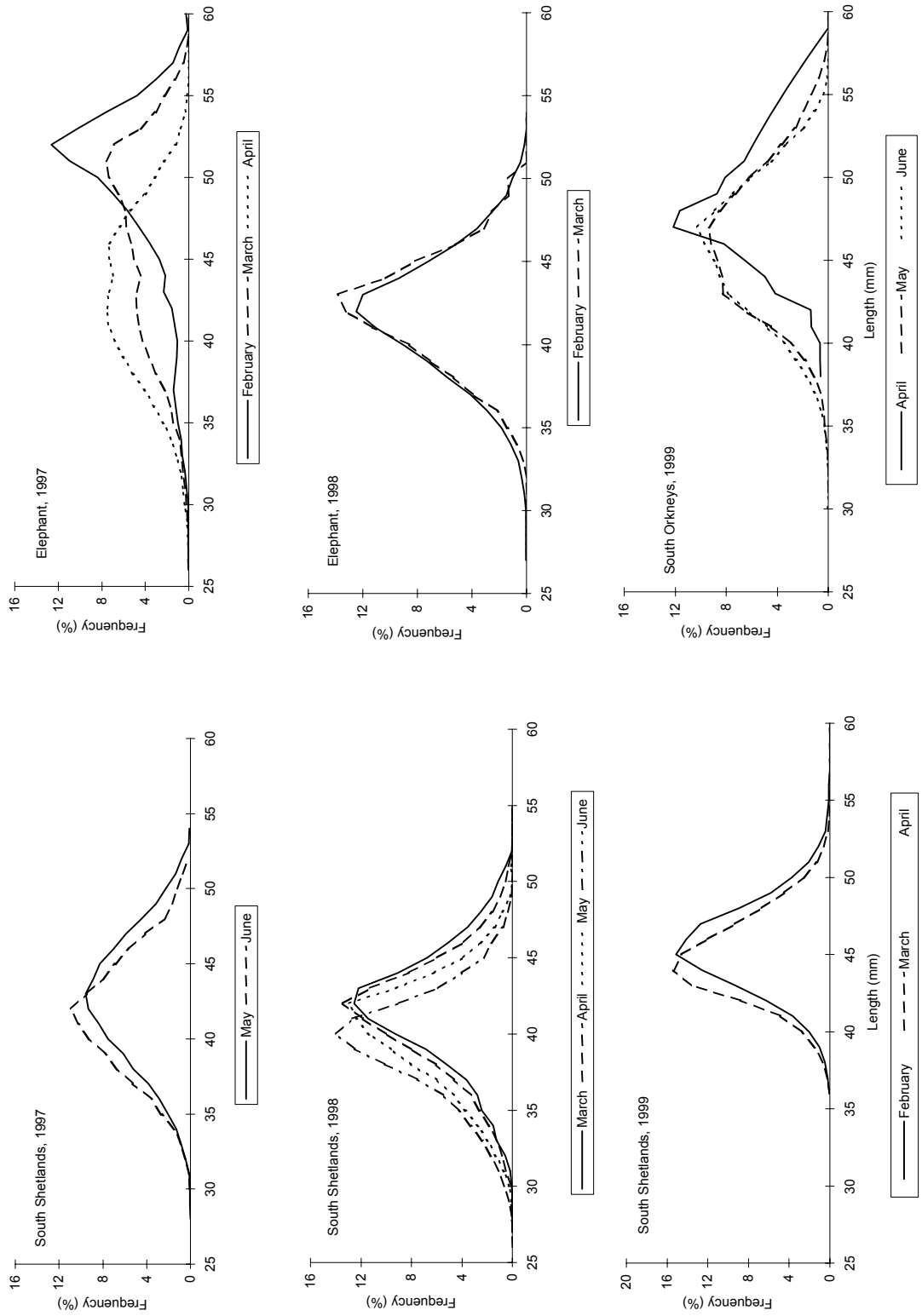

Figure 6: Monthly krill length-frequency distributions from Polish commercial catches taken in the various areas of the Southwest Atlantic sector of the Southern Ocean, from 1997 to 1999.

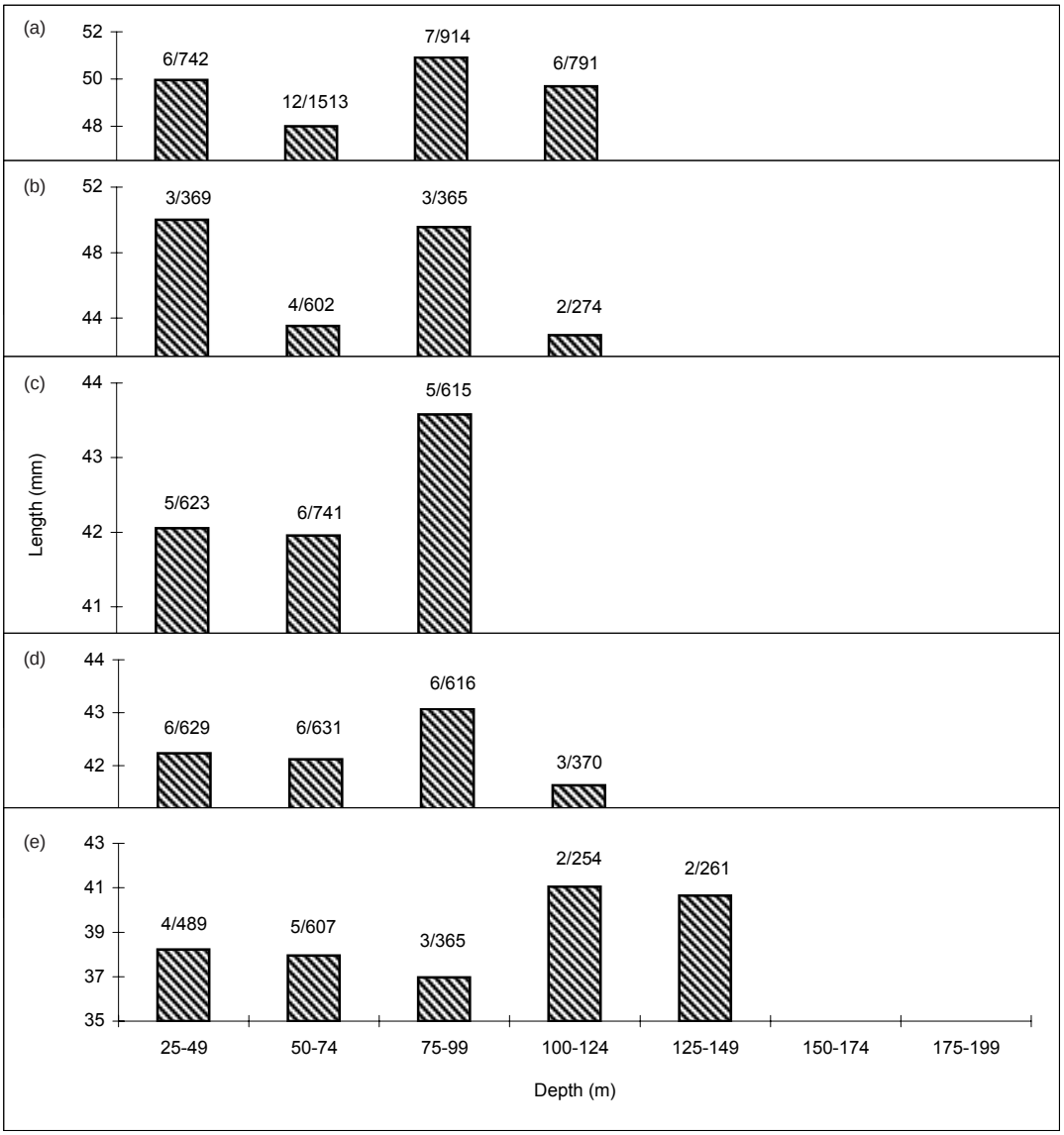

Figure 7: Mean length of krill caught in 1997 during the day by depth strata in: the Elephant Island area in (a) February, (b) March, and (c) April; (d) the South Shetlands area in May; and (e) the South Georgia area in June.

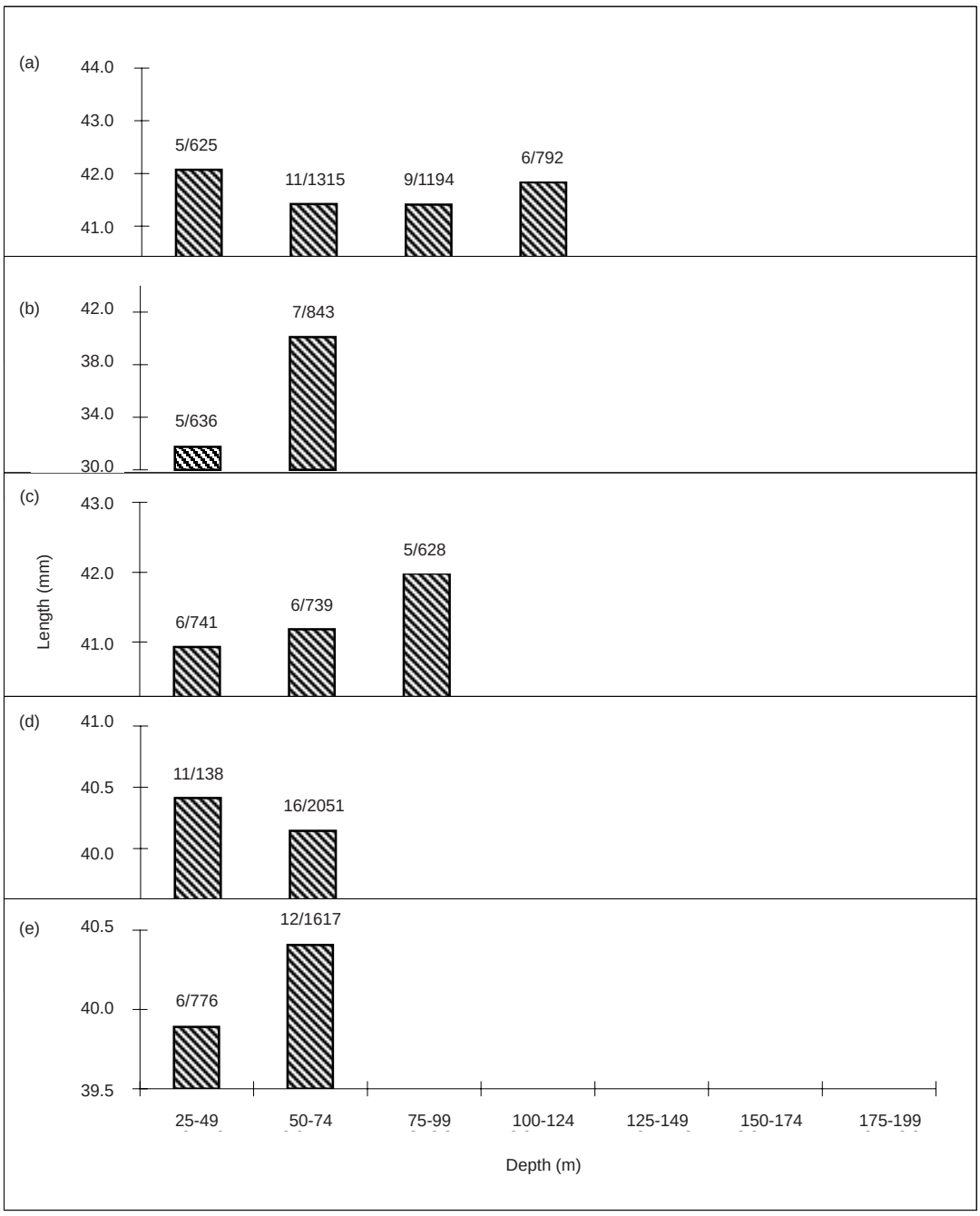

Figure 8: Mean length of krill caught in 1998 during the day by depth strata in: (a) the Elephant Island area in February; and the South Shetlands area in (b) March, (c) April, (d) May and (e) June.

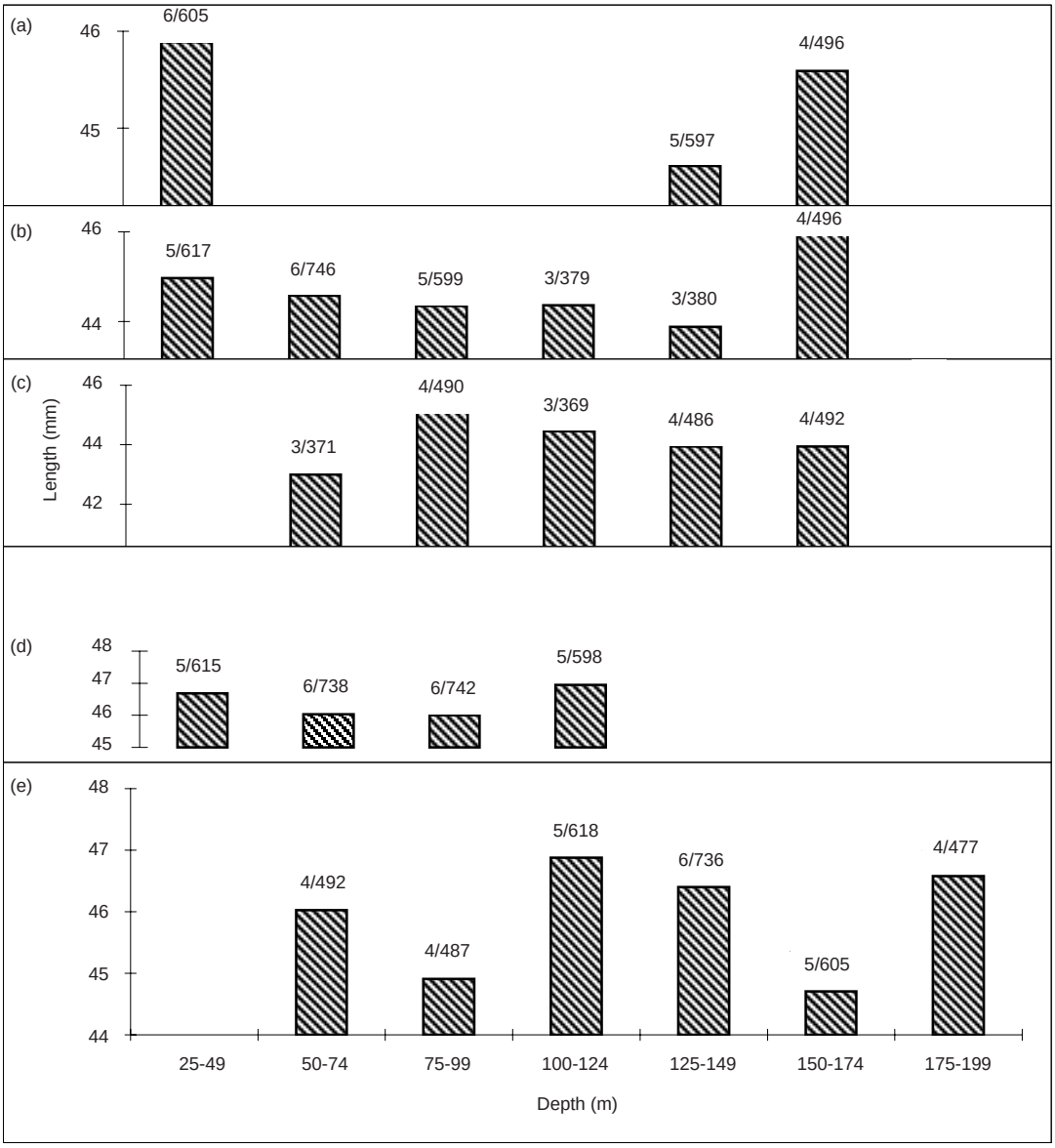

Figure 9: Mean length of krill caught in 1999 during the day by depth strata in: the South Shetlands area in (a) February, (b) March, (c) April; and the South Orkneys area in (d) May and (e) June.

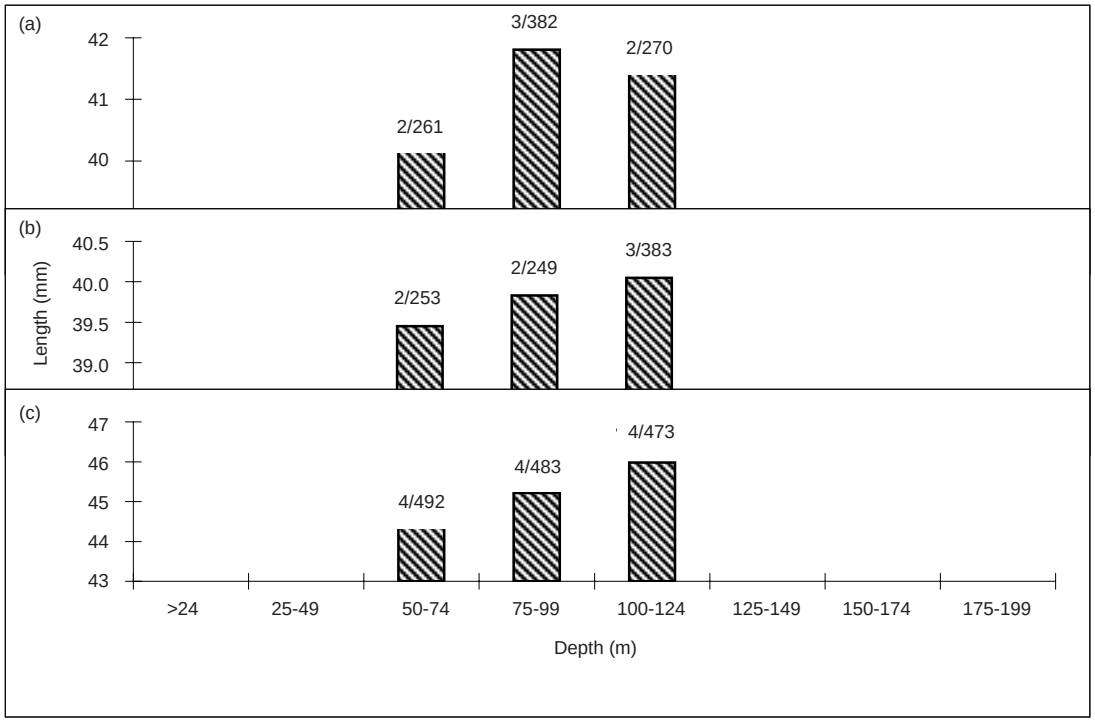

Figure 10: Mean length of krill caught in 1999 at night by depth strata in: the South Shetlands area in (a) May and (b) June; and (c) the South Orkneys area in June.

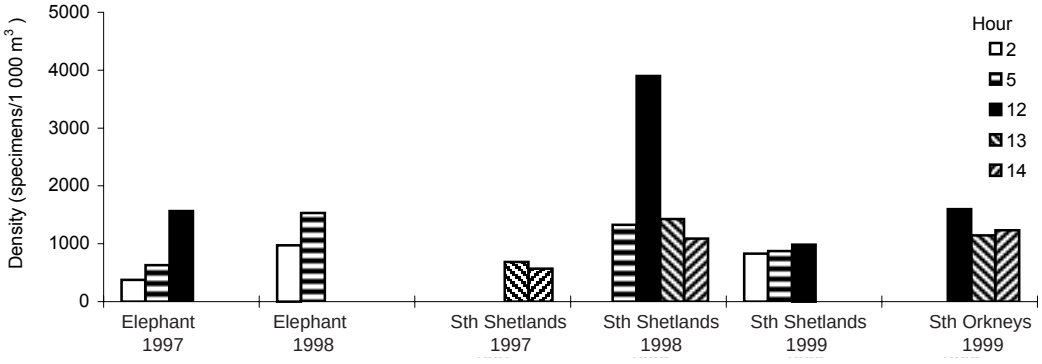

Figure 11: Mean krill density relative to the duration of daylight.

Liste des tableaux

Liste des figures

Список таблиц

Список рисунков

Lista de las tablas

Lista de las figuras