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

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Abstract

In this paper we consider the results of three mesoscale surveys covering a wide area of krill distribution between the Antarctic Peninsula and South Georgia Island. Surveys including from 158 to 202 stations were carried out by Soviet research vessels in the summer–autumn periods of 1983/84 and 1987/88 and in the spring–summer of 1984/85 using a grid of stations according to the standard method for Isaacs-Kidd midwater trawls operating in the layer 0 to 100 m. Overall krill biomass distribution (g/1 000 m^3) and its mean values were analysed by subarea (Subareas 48.1, 48.2 and 48.3) and for the whole study area. Survey results confirm current understanding of the general pattern of krill distribution and drift in the western part of the Atlantic sector of the Antarctic (e.g. Priddle et al., 1988; Makarov, 1996). The greatest degree of spatial–temporal stability in the krill distribution field with high biomass of aggregations was observed in the western part of the area stretching from the Antarctic Peninsula to the eastern part of the South Orkneys area. The greatest variability of krill distribution on the spatial–temporal scale of the survey, which is characterised by a change in biomass of more than two orders of magnitude in different seasons, was observed in the South Georgia region and the adjacent waters of the Scotia Sea (Subarea 48.3). The possibility of krill transportation into the South Georgia region is considered. It is shown that the absence of krill in the island region during the 1983/84 season was caused exclusively by unfavourable oceanological conditions (lack of water flow from southern areas). It is also demonstrated that the absence of krill in the eastern part of the Scotia Sea may cause it to be absent from the South Georgia region regardless of oceanological conditions (spring–summer period 1984/85). The possibility of recruitment of the krill stock to the South Georgia region from the central part of the Scotia Sea is considered. Analysis of variability of mean biomass by area and season indicates that patterns of krill abundance and biomass recently observed in Subarea 48.1 (Siegel et al., 1997, 1998) are not representative of the survey area as a whole. The total biomass index in the study area during all seasons remained at a constant level (76.5–101.7 g/1 000 m^3).

Résumé

Examen des résultats de trois campagnes d'évaluation à échelle moyenne ayant couvert un vaste secteur de répartition du krill, entre la péninsule antarctique et l'île de la Géorgie du Sud. Les évaluations, comptant de 158 à 202 stations, ont été réalisées par des navires de recherche soviétiques au cours des périodes d'été-automne 1983/84 et 1987/88 et de printemps-été 1984/85. Le quadrillage des stations suivies répondait à la méthode standard d'utilisation du chalut pélagique Isaacs-Kidd dans l'intervalle de profondeur de 0 à 100 m. La répartition générale de la biomasse de krill (g/1 000 m^3) et ses valeurs moyennes sont analysées par sous-zone (sous-zones 48.1, 48.2 et 48.3) et pour l'ensemble du secteur étudié. Les résultats des évaluations confirment notre connaissance actuelle du schéma général de la répartition et de la dérive du krill dans l'ouest du secteur atlantique de l'Antarctique (par ex. Priddle et al., 1988; Makarov, 1996). Le degré de stabilité spatio-temporelle le plus élevé dans le domaine de la répartition du krill, accompagné d'une forte biomasse des concentrations, est observé dans la partie ouest du secteur qui s'étend de la péninsule antarctique à la partie est de la zone des Orcades du Sud. La variabilité la plus importante de la répartition du krill à l'échelle spatio-temporelle de la campagne d'évaluation, qui se caractérise par un changement de biomasse de plus de deux ordres de grandeur au cours de saisons différentes, est observée dans la région de la Géorgie du Sud et des eaux adjacentes de la mer du Scotia (sous-zone 48.3). La possibilité de transport du krill dans la région de la Géorgie du Sud est envisagée. Il est démontré que l'absence de krill dans la région de l'île pendant la saison 1983/84 est la conséquence exclusive de conditions océanologiques défavorables (faible flux en provenance des zones du sud). Par ailleurs, l'absence de krill dans le secteur est de la mer du Scotia pourrait provoquer celle de la région de la Géorgie du Sud, quelles que soient les conditions océanologiques (printemps–été 1984/85). La possibilité de recrutement du stock de krill dans la région de la Géorgie du Sud en provenance de la partie centrale de la mer du Scotia est envisagée. L'analyse de la variabilité de la biomasse moyenne par zone et saison indique que les caractéristiques de l'abondance et de la biomasse de krill observées récemment dans la sous-zone 48.1 (Siegel et al., 1997, 1998) ne sont pas représentatives de l'ensemble de la zone évaluée. L'indice de la biomasse totale du secteur étudié au cours des quatre saisons garde un niveau constant (76,5–101,7 g/1 000 m^3).

Резюме

В статье рассматриваются результаты трех среднемасштабных съемок, охватывающих обширный район распространения криля между Антарктическим п-овом и Южной Георгией. Съемки, насчитывающие от 158 до 202 станций, проводились научно-исследовательскими судами СССР в летне-осенние периоды 1983/84 и 1987/88 гг. и в весенне-летний период 1984/85 г. по сетке станций, соответствующей стандартному методу для разноглубинного трала Айзекса-идда, используемому на глубине 0–100 м. Распределение общей биомассы криля (г/1000 м^3) и ее средних значений было проанализировано как по подрайонам (48.1, 48.2 и 48.3), так и по всему изучаемому району. Результаты съемок подтверждают современное представление об общем характере распределения и перемещения криля в западной части атлантического сектора Антарктики (например, Priddle et al., 1988; Makarov, 1996). Наибольшая пространственно-временная стабильность поля распределения криля с высокой биомассой скоплений наблюдалась на западе района, лежащего между Антарктическим п-овом и восточной частью акватории Южных Оркнейских о-вов. Наибольшая изменчивость распределения криля в пространственно-временном масштабе съемки, характеризующаяся изменением биомассы большим, чем на два порядка в различные сезоны, наблюдалась в районе Южной Георгии и примыкающих к ней районах моря Скотия (Подрайон 48.3). Рассматривается возможность переноса криля в район Южной Георгии. Показано, что отсутствие криля в этом районе в сезоне 1983/84 г. обусловлено только неблагоприятными океанологическими условиями (недостаточный приток вод из более южных районов). Также показано, что вне зависимости от океанологических условий такое отсутствие криля у Южной Георгии могло быть вызвано отсутствием криля в восточной части моря Скотия (весна-лето 1984/85 г.). Рассматривается возможность пополнения запасов криля в районе Южной Георгии за счет центральной части моря Скотия. Анализ изменчивости средней биомассы по районам и сезонам показывает, что недавно наблюдавшиеся в Подрайоне 48.1 биомасса и численность криля (Siegel et al., 1997, 1998) не являются типичными для всего района съемки. Индекс общей биомассы для изучаемого района оставался стабильным на протяжении всех сезонов (76,5–101,7 г/1000 м^3).

Resumen

Este estudio considera los resultados de tres prospecciones realizadas a mesoescala para estudiar la distribución de kril, que cubrieron una amplia área situada entre la Península Antártica y las islas Georgia del Sur. Las prospecciones incluyeron de 158 a 202 estaciones efectuadas por barcos de investigación soviéticos en los períodos de verano-otoño de 1983/84 y 1987/88 y primavera-verano de 1984/85. Se utilizó una cuadrícula de estaciones según el método estándar para las redes de arrastres pelágicos Isaacs-Kidd que operan entre 0 y 100 m. de profundidad La distribución general de la biomasa de kril (g/1 000 m^3) y de sus valores promedio fueron analizados por subárea (Subáreas 48.1, 48.2 y 48.3) y para el área total del estudio. Los resultados de la prospección confirman el conocimiento actual sobre las características de la distribución de kril y su transporte por las corrientes en la parte occidental del sector Atlántico de la Antártida (v.g. Priddle et al., 1988; Makarov, 1996). La mayor estabilidad espacial y temporal en la distribución del kril, con concentraciones de alta biomasa, se observó en la parte occidental del área que se extiende desde la Península Antártica hasta la parte oriental del área de las Orcadas del Sur. La variabilidad más grande de la distribución de kril en la escala espacial-temporal de la prospección, que se caracterizó por un cambio en la biomasa mayor a dos órdenes de magnitud en temporadas diferentes, fue observada en la región de Georgia del Sur y en las aguas adyacentes del mar de Escocia (Subárea 48.3). Se consideró la posibilidad de que el kril sea transportado a la región de Georgia del Sur. Se demuestra que la ausencia de kril en la región de la isla durante la temporada 1983/84 fue causada exclusivamente por condiciones oceánicas desfavorables (una falta de flujo del agua desde la zona meridional). También se demostró que la ausencia de kril en la parte oriental del Mar de Escocia puede causar su ausencia en la región de Georgia del Sur, y esta ausencia no depende de las condiciones oceánicas (período primavera-verano 1984/85). Se consideró la posibilidad del reclutamiento del stock de kril a la región de Georgia del Sur desde la parte central del Mar de Escocia. El análisis de la variabilidad de la biomasa promedio por área y temporada indica que las características de la abundancia y biomasa observadas recientemente en la Subárea 48.1 (Siegel et al., 1997, 1998) no son en general representativas para toda el área de la prospección. El índice de la biomasa total en el área de estudio durante todas las temporadas permaneció a un nivel constante (76,5–101,7 g/1 000 m^3).

Keywords: krill distribution, biomass, variability, geostrophic currents, CCAMLR

INTRODUCTION

Knowledge of krill horizontal distribution is important in developing stock assessments and fishery regulations according to CCAMLR's ecosystem approach. This phenomenon is very important in the area from the Antarctic Peninsula to South Georgia (Subareas 48.1 to 48.3), where, according to the data available (CCAMLR, 1994), the entire krill fishery is concentrated and for which krill stock management measures have been implemented on the basis of a precautionary catch limit, allocated by subareas (CCAMLR, 1992). In particular, the CCAMLR Working Group for Ecosystem Monitoring and Management (WG-EMM) considered the links between Subareas 48.1, 48.2 and 48.3 (SC-CAMLR, 1996, 1997), and the necessity to submit and analyse data on krill distribution over the entire area, including all of the subareas mentioned. Further mesoscale surveys are needed to obtain such material. Previous surveys carried out annually over nearly 20 years covered only part of Subarea 48.1 adjacent to the north of the Antarctic Peninsula and did not give a complete picture of krill distribution in other subareas (Siegel, 1992; Siegel et al., 1997).

In this article we present an analysis of krill distribution using data obtained during three mesoscale surveys (1983/84, 1984/85 and 1987/88) which covered most krill fishing grounds in Subareas 48.1, 48.2 and 48.3. The data on krill distribution were collected simultaneously with complex oceanographic data which provided an indication of geostrophic currents in the area. Combining data in this way provides an assessment of krill distribution in relation to water circulation. Detailed analyses of such combined data have not been presented before, and are only mentioned briefly in some publications as examples to confirm conclusions made on the basis of other materials (Latogursky et al., 1990; Sushin et al., 1990; Makarov, 1996).

MATERIAL AND METHODS

Krill assessment surveys were carried out by the Soviet research vessels *Argus* and *Evrika* during 1983/84, 1984/85 and 1987/88 (Table 1).

The surveys covered only the summer–autumn periods of the 1983/84 and 1987/88 seasons and the spring–summer period of the 1984/85 season (Table 1).

Table 1: Krill assessment surveys.

Survey No.	Vessel	Period	No. of Stations	Survey Area (sq. miles)
1	RV *Argus*	27 January–16 March 1984	177	210 781
2	RV *Evrika*	11 October–14 December 1984	202	173 569
3	RV *Evrika*	20 January–9 March 1988	158	202 370

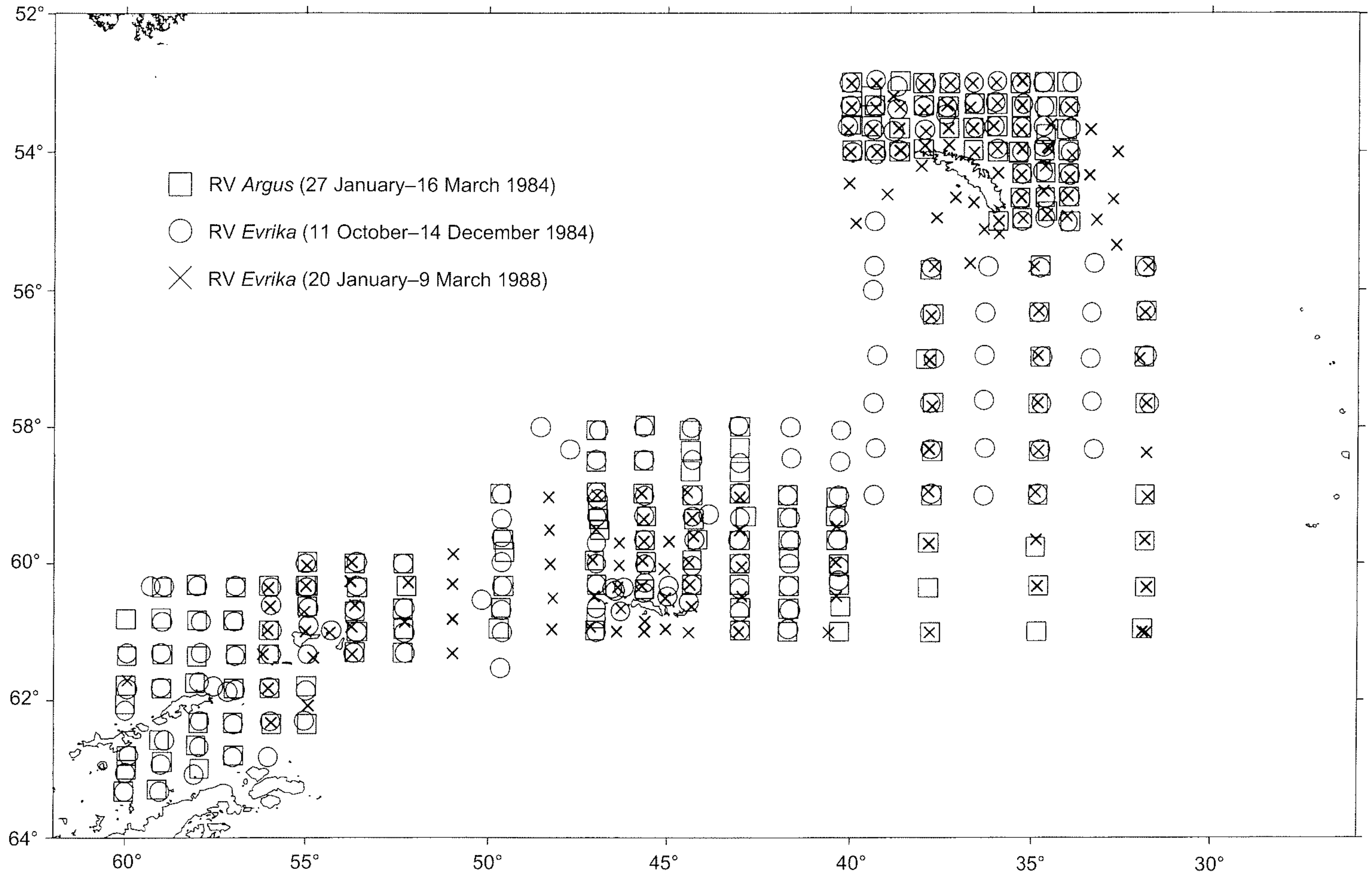

Figure 1: Station grid for krill sampling surveys.

Generally, the grid of stations covered the entire area from the Antarctic Peninsula to South Georgia, including Bransfield Strait, South Orkney Islands and the eastern Scotia Sea (Figure 1). All surveys were started from South Georgia. The vessels first moved along meridional sections, located to the north of the island, then sailed to the eastern part of the Scotia Sea, and then westwards along meridional sections until the end of the survey near the Antarctic Peninsula. Therefore, the survey first covered Subarea 48.3, followed by Subarea 48.2, and finally Subarea 48.1. In general, the vessels moved in the opposite direction of the general water drift (see e.g. Murphy et al., 1997).

Surveys were carried out using an Isaacs-Kidd midwater trawl (IKMT) as modified by Samyshev–Aseev. In the modified trawl the length of the trawl netting is increased to 26 m, while the netting has a similar mesh size (6 mm) along the entire length.

Krill assessment was carried out for the layer between 0 and 100 m using the following sampling regime. Once shot, the trawl was deployed at a depth of 100 m. This took about 8 minutes at vessel speed 3 knots. The trawl remained at a depth of 100 m for about 3 minutes, after which the trawl warp was slowly pulled up and the trawl towed for 5-minute periods at intermediate depths of 75, 50 and 25 m. In the absence of a heavy swell, the trawl was then towed at the surface for 2 to 3 minutes. The total period of trawling from the time the trawl reached the 100 m depth until it was hauled aboard ranged from 26 to 35 minutes (30 minutes on average). The vessel speed during trawling was 3 to 3.5 knots. The depth of the trawl and its operational parameters (including the trawl mouth opening) were monitored using an FNR-400 transducer which was attached to the upper beam of the trawl. The volume of water passed through the trawl was measured by a special instrument fixed at the trawl mouth. The average volume of water per tow was 23 000 m^3.

After the trawl was hauled aboard and the catch sorted (mainly by species), the total catch of krill was weighed and samples of krill were taken to conduct various measurements and biological analyses.

Krill biomass at each station was estimated by dividing krill weight in the catch by the volume of water passed through the trawl, and is expressed in grams per 1 000 m^3.

In addition to net sampling, water temperature and salinity were measured at each station at standard depths up to 1 200 m using 'Nansen' bottles. The data thus obtained were used to estimate geostrophic current fields during the study period.

Data from other Soviet vessels surveying within the Antarctic Atlantic Ocean during the same period have also been used to obtain a more comprehensive picture of current fields. Those data were taken from AtlantNIRO's oceanological database on the southern Atlantic.

Currents were described using Somov's method (Somov, 1937). This method allowed us to calculate currents for the shallow-water station by taking into account data for the nearby deep-water station. The calculation was made relative to the 1 000 dbar.

RESULTS

Krill distribution is shown in Figures 2 to 4. One feature observed was the permanent existence of extensive zones of high biomass in the western half of the survey area (westward of 40°W), including areas adjacent to the South Orkney and South Shetland Islands and the Antarctic Peninsula. The shape and location of these zones are fairly stable from survey to survey, which seems to be due to relatively stable hydrodynamic areas and bottom topography.

Unlike the western part of the survey area, the pattern of krill distribution in the eastern part varies significantly. In the spring period (Figure 3) krill was virtually absent in the eastern Scotia Sea and off South Georgia.

In the summer–autumn period of the 1983/84 season (Figure 2) an extensive zone of high krill biomass was observed in the southeastern Scotia Sea. Moreover, a small patch of krill was also observed in the northwestern part of the South Georgia shelf.

Finally, during the summer–autumn period of 1987/88 (Figure 4) high krill biomass was observed in the most of the eastern Scotia Sea and around South Georgia. In addition, a zone with krill biomass of 100–1 000 g/1 000 m^3 extended from the eastern Scotia Sea, enveloped South Georgia from the east and continued along the northeastern shelf to its northwestern edge. It is worth noting that the direction of this zone's

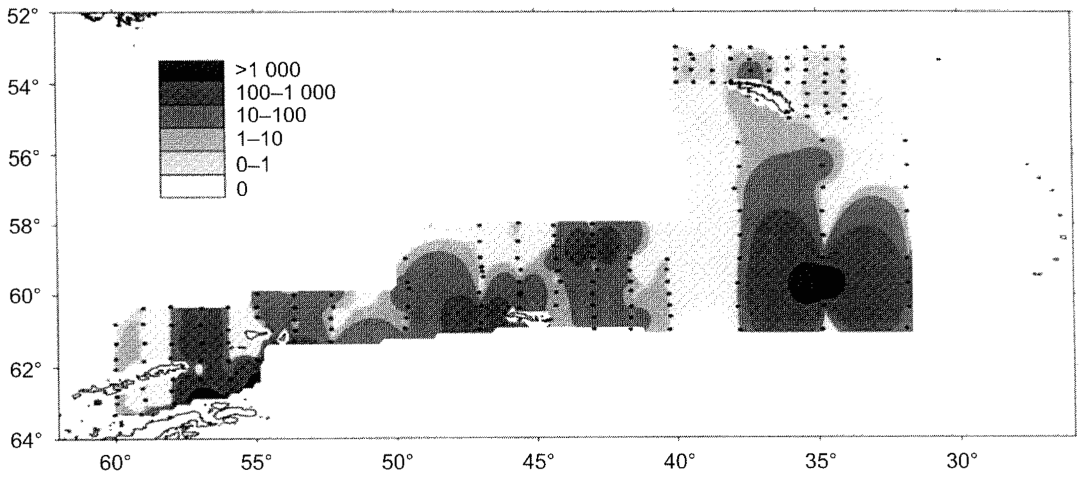

Figure 2: Krill distribution (g/1 000 m³) in strata 0 to 100 m, 27 January to 16 March 1984.

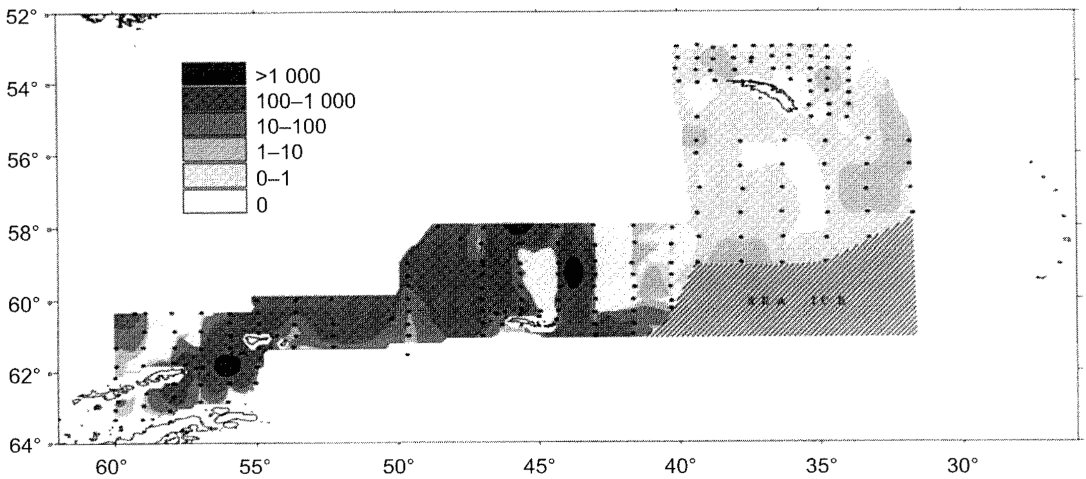

Figure 3: Krill distribution (g/1 000 m³) in strata 0 to 100 m, 11 October to 14 December 1984.

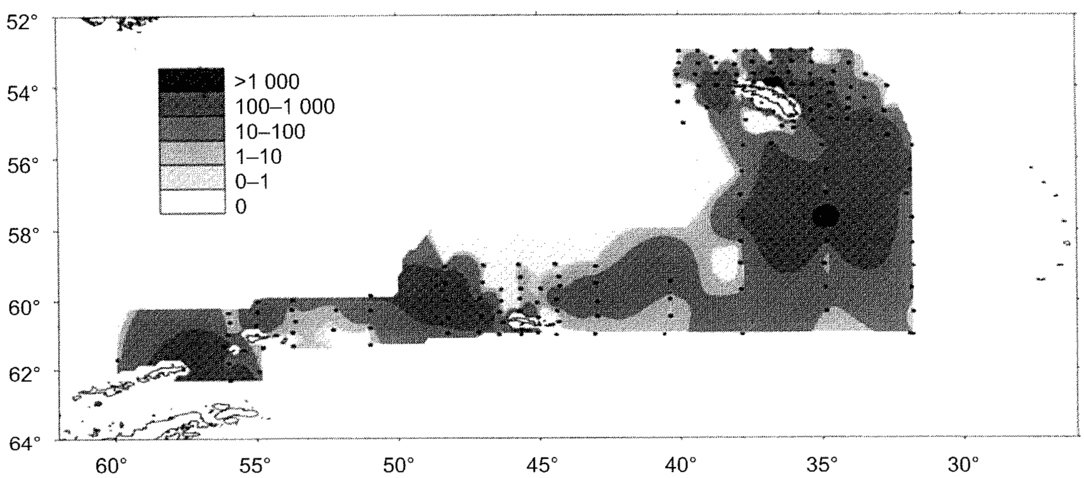

Figure 4: Krill distribution (g/1 000 m³) in strata 0 to 100 m, 20 January to 9 March 1988.

Table 2: Krill biomass estimates and their statistical characteristics. B – mean biomass (g/1 000 m^3); SE – standard error; lower (Lower CI) and upper (Upper CI) boundary of the 95% confidence interval.

Subarea	27 January–16 March 1984				11 October–14 December 1984				20 January–9 March 1988			
	B	SE	Lower CI	Upper CI	B	SE	Lower CI	Upper CI	B	SE	Lower CI	Upper CI
48.1	118.6	59.13	37.58	230.73	176.0	55.83	95.20	276.40	47.6	23.30	14.80	90.60
48.2	104.6	54.71	26.49	204.67	130.5	43.46	65.40	207.80	70.8	33.14	25.50	131.90
48.3	1.5	0.88	0.15	3.14	0.6	0.18	0.29	0.88	147.5	49.13	77.90	237.80
48.1–48.3	76.5	27.73	35.33	125.77	101.7	26.18	62.84	148.22	101.4	24.05	64.83	143.47

extension corresponds to a contemporary theory of water penetration from the Scotia Sea to the South Georgia area (Mackintosh, 1973). This theory was considered by certain authors to be valid (Fedoulov et al., 1996).

Comparison of the three surveys shows that significant krill input into the South Georgia area may have occurred in the 1987/88 season, while in the summer–autumn season of 1983/84 and the spring–summer season of 1984/85 it was insignificant.

Analysis of geostrophic current fields shows that favourable conditions for krill transport from the eastern Scotia Sea to the South Georgia area prevailed in the 1984/85 and 1987/88 seasons (Figures 5 and 6), since, during both seasons, a geostrophic current was recorded which flowed from the Scotia Sea into the eastern shelf of the island and continued quite far westwards. Moreover, a strong meander of the main current was observed which extended around the island, also from the western side, and was able to transport krill to its western edge. Apparently, the absence of krill in the South Georgia area in the 1984/85 season (during the survey) was due to a lack of krill aggregations in the Scotia Sea.

By contrast, oceanographic conditions in the 1983/84 season were unfavourable for krill transport from the eastern Scotia Sea to the South Georgia area (Figure 7). Water flow from the Scotia Sea towards the eastern shelf of the island was very weak, while the southeastern part of the sea containing krill aggregations (see Figure 2) was 'isolated' from the more northern areas of rather intensive eastward currents. It is interesting to note that during the 1983/84 season, as in other seasons considered, the meander of the main current flowed around the island from the west, which does not exclude the possibility of krill transport directly to the western edge of the island.

In addition to analysing krill distribution maps, we estimated mean krill biomass for the period of the survey for the entire study area and by subarea (Subareas 48.1, 48.2 and 48.3). A preliminary attempt was made to estimate mean biomass, as well as its statistical characteristics using delta-distribution (Pennington, 1983; de la Mare, 1994). However, the data analysis confirmed no log-normality of non-zero biomass values. Therefore, the estimate of a mean value and confidence intervals (5.95%) were obtained using a 'bootstrap' procedure (Efron, 1982; Smith, 1996).

The results are presented in Table 2. It should be noted that mean estimates are of low reliability due to the nature of the data used.

Nevertheless, taking into account the existing errors, those data did reveal some trends in krill biomass spatial–temporal variability during the study period.

Mean biomass, estimated for the entire area, was characterised by significant stability from survey to survey and fell within range 76.5–101.7 g/1 000 m^3, while the lowest values were observed in the 1983/84 season (Table 2). Mean biomass estimated for Subareas 48.1 and 48.2 showed significant fluctuation from survey to survey, while in both areas the highest values were observed in the 1984/85 season, and the lowest values in 1987/88 (Table 2). These dynamics do not correspond to the mean biomass dynamics shown above for the entire survey area.

Interannual variability of biomass in Subarea 48.3 was rather significant and reached two orders of magnitude, with a minimum (0.6 g/1 000 m^3) in the 1984/85 season and a maximum (147.5 g/1 000 m^3) in 1987/88 (Table 2). The maps of krill distribution also show significant variability of krill biomass in Subarea 48.3.

DISCUSSION AND CONCLUSION

Data analysis confirmed current theories about krill distribution in the western Antarctic sector of the Southern Ocean (Priddle, 1988; Makarov,

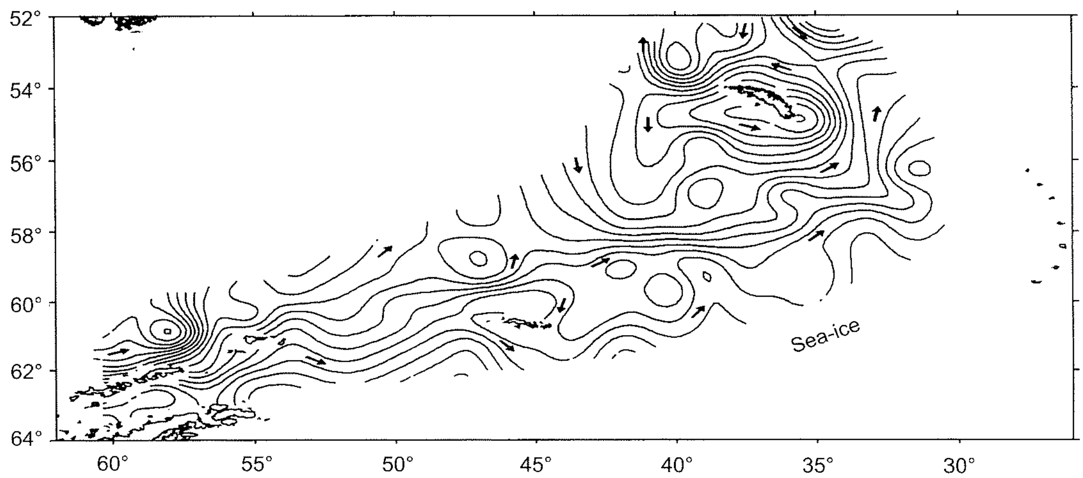

Figure 5: Surface geostrophic currents (relative to the 1 000 dbar), 11 October to 14 December 1984.

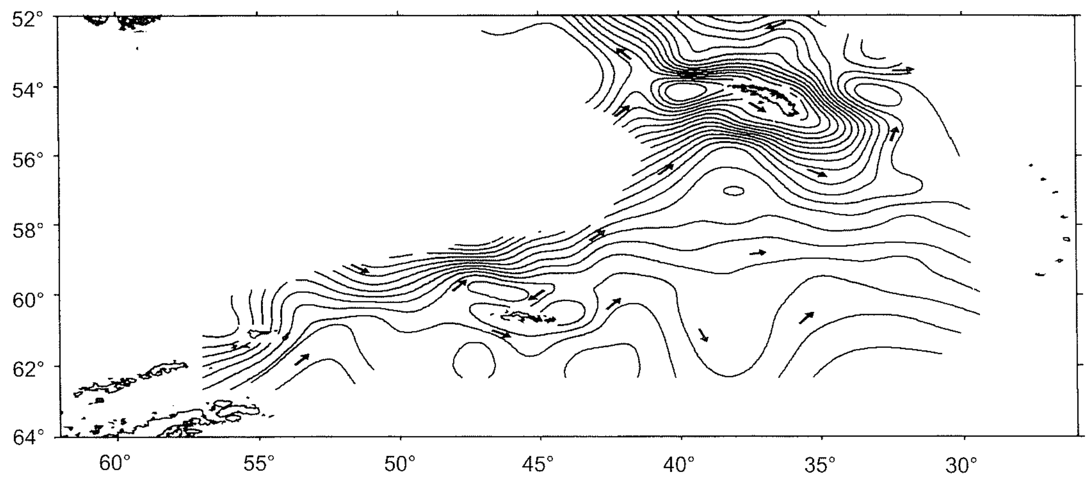

Figure 6: Surface geostrophic currents (relative to the 1 000 dbar), 20 January to 9 March 1988.

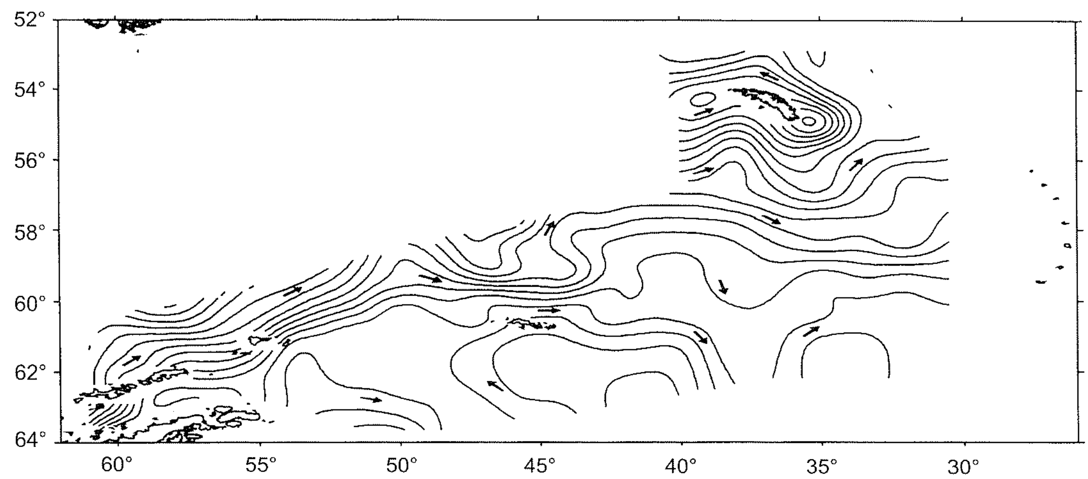

Figure 7: Surface geostrophic currents (relative to the 1 000 dbar), 27 January to 16 March 1984.

1996), as well as the absence of krill from the area off South Georgia observed during the 1983/84 season, a phenomenon which could seriously affect krill predators and the krill fishery (Priddle et al., 1988; Croxall et al., 1988; Fedoulov et al., 1996). It also confirmed the existence of an oceanological mechanism that regulates krill inflow to the eastern shelf of South Georgia (Priddle et al., 1988; Fedoulov et al., 1996).

At the same time, our data showing the absence of krill from the South Georgia area and the existence of favourable oceanological conditions from October to December 1984 confirm that krill aggregations in the adjacent areas of the Scotia Sea, along with other factors, are of great importance. In this regard, it would be interesting to determine whether such a situation (absence of krill from the eastern Scotia Sea) was an anomaly or whether it was normal for a certain time of the year.

The absence of krill aggregations from the South Georgia area, as well as from the adjacent areas of the eastern Scotia Sea from October to December 1984 (Figure 3), should have had the greatest impact on the predator populations that feed on krill, especially if one considers a previous anomaly which was unfavourable for their reproduction in the 1983/84 season (Croxall et al., 1988). This was not the case, however, and population indices were, on the contrary, out of the critical range for most species (Croxall et al., 1988). Krill stock recruitment probably took place this season, at any rate by the beginning of the critical period for animal reproduction which started in January (Priddle et al., 1988).

Initial calculations showed that with a mean drift velocity of 8.7 cm/sec (Sushin, 1998) krill from the southern Scotia Sea could reach the western edge of South Georgia (where the most numerous colonies of seabirds and animals are situated) in approximately 110 days, i.e. from early November to the middle of February. In this regard, krill stock recruitment off South Georgia had, in our opinion, most probably taken place via the 'western' route, i.e. through the central Scotia Sea (Murphy et al., 1997). Krill aggregations from the area located between 58°S and 46°W in November 1984 could be considered as a recruitment source (Figure 4). Japanese investigations (Ichii and Naganobu, 1996) show that, following this route, krill can reach South Georgia in about 35 or 40 days, i.e. by the end of December. Thus, the 'western' krill transport route is not excluded as a possibility and may play an important role in maintaining the South Georgia ecosystem. The relationship between both of these routes could be a subject for further studies.

A pattern of interannual variability in krill abundance and biomass in the Antarctic Peninsula area over recent years has been established. Based on the results of multiannual standard surveys, values were found to have decreased after the 1983/84 season before reaching their former levels at the beginning of the 1990s (Siegel et al., 1997, 1998). At the same time, a difference between maximum and minimum values of biomass was approximately two orders of values for the period under consideration (1977/78 to 1996/97), while biomass observed in the 1984/85 season differed by almost five times from that of 1987/88 season (Siegel et al., 1998).

Our data confirm the abovementioned trend for the locations surveyed within Subareas 48.1 and 48.2, i.e. the biomass decrease in Subarea 48.1 was more marked (almost three times greater) than in Subarea 48.2 (see above). However, interannual variability of biomass was not observed for the whole study area (Table 2).

Such a comparison suggests that the observed decadal cycle of variability in krill abundance and biomass (Siegel et al., 1997, 1998) is mainly related to the Antarctic Peninsula area (Subarea 48.1), and, to a lesser extent, to Subarea 48.2, which is uncharacteristic of the total krill stock within Subareas 48.1 to 48.3.

Allowing that one of the sources of krill stock recruitment in the area we considered is krill drift from the Antarctic Pacific sector through the Antarctic Peninsula (e.g. Maslennikov and Solyankin, 1988), it may be suggested that the multiannual trend observed in biomass is rather more attributable to the dynamics of the process than the state of stock within the whole area. In our opinion, this should be taken into account when extrapolating the results obtained for krill recruitment and abundance in Subarea 48.1 to all three subareas.

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