DISTRIBUTION, BIOMASS AND CHARACTERISTICS OF THE *EUPHAUSIA SUPERBA* FISHERY AROUND SOUTH GEORGIA (SUBAREA 48.3)

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Abstract

Krill distribution in the South Georgia area and many aspects of its variability have been extensively described in scientific literature. A summary of recent findings is discussed in this paper. There has been less focus on data concerning krill biomass assessments. The existing uncertainty in krill biomass assessment can be largely attributed to high variability and the wide range of biomass values obtained which in turn leads to uncertainty in interpreting krill biomass for the area. It was therefore only possible to begin to explain the reasons for the variability in the scale of krill swarms and to attempt to determine more reliable values of its biomass after a number of census surveys had been conducted. Results of the nine most representative surveys conducted by Soviet scientists in the area from 1974 to 1988 are summarized in this paper. The most important survey data and biomass assessments have been tabulated and illustrated by various survey maps. It was found that the distribution of krill swarms corresponds largely with areas where currents turn into eddies. Among these areas, aggregations of krill were observed most often to the east of the island and around 37°W. When the water circulation system is unfavourable, which means the absence of eddy formations, krill do not usually form aggregations and its density is low. When water dynamics are favourable for krill aggregations its biomass around South Georgia is approximately 400-800 thousand tonnes. Unfavourable conditions correspond to a biomass of an order of magnitude less. Short-term fluctuations of krill biomass in the South Georgia area are extremely significant. Biomass may differ by as much as eight times in a month. It also usually decreases in spring, regardless of the type of water circulation. Annual differences in krill biomass are undoubtedly associated with the volume of krill brought here by waters of the Scotia Sea Secondary Front. More extensive studies incorporating trawl and acoustic surveys of different temporal and spatial scales are recommended in order to make reliable assessments of krill biomass.

Résumé

La littérature scientifique a largement traité de la répartition du krill dans la région de la Géorgie du Sud et de nombreux aspects de sa variabilité. Un résumé de découvertes récentes est examiné dans ce document. Moins d'importance a été accordée aux données sur les évaluations de la biomasse du krill. L'incertitude actuelle touchant l'évaluation de la biomasse du krill est, dans une large mesure, imputable à la grande variabilité et à l'intervalle important des valeurs de biomasse obtenues. Ainsi, ce n'est qu'après quelques campagnes d'évaluation qu'il a été possible de commencer à expliquer les causes de la variabilité dans la

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taille des essaims de krill et de tenter de déterminer des valeurs plus fiables de sa biomasse. Cette communication résume les résultats des neuf campagnes les plus représentatives menées par des scientifiques soviétiques dans cette zone de 1974 à 1988. Les données de campagnes et les évaluations de biomasse les plus importantes sont présentées sous forme de tableau et illustrées par plusieurs cartes des campagnes d'évaluation. Il ressort que la répartition des essaims de krill correspond en grande partie aux régions où les courants créent des tourbillons. Parmi ces zones, les concentrations de krill ont, le plus souvent, été observées à l'est de l'île et autour de 37°W. Lorsque le régime de circulation des eaux est défavorable, à savoir en l'absence de formations de tourbillons, le krill ne forme pratiquement pas de concentrations et sa densité est faible. Quand la dynamique de l'eau est favorable aux concentrations de krill, sa biomasse autour de la Géorgie du Sud est d'environ 400-800 milliers de tonnes. Les conditions défavorables correspondent à une biomasse d'un ordre de grandeur moins élevé. Les fluctuations à court terme de la biomasse du krill dans la zone de la Géorgie du Sud sont extrêmement significatives. La biomasse peut varier jusqu'à huit fois en un mois. De plus, elle décroît généralement au printemps, quel que soit le type de circulation des eaux. Les variations annuelles de la biomasse de krill sont sans aucun doute liées au volume de krill amené ici par les eaux du Front secondaire de la mer de Scotia. Il est recommandé d'effectuer des études plus approfondies, comportant des campagnes d'évaluation, tant par chalutage qu'acoustiques, des diverses échelles spatio-temporelles afin d'obtenir des évaluations fiables de la biomasse du krill.

Резюме

В научной литературе широко освещались как распределение криля в районе Южной Георгии, так и ряд аспектов его изменчивости. В данном труде рассматривается сводка последних выводов. Меньшее внимание было уделено данным, имеющим отношение к оценке биомассы криля. Существующая неопределенность в оценках биомассы криля может быть в основном отнесена на счет значительной изменчивости и широкого диапазона полученных значений биомассы, что в свою очередь приводит к неопределенности в оценке биомассы криля в этом районе. Таким образом, можно было сделать только исходные попытки объяснить причины изменчивости размера скоплений криля и, по проведении ряда учетных съемок, идентифицировать наиболее достоверные значения биомассы криля. В настоящей работе приводится сводка результатов девяти наиболее представительных съемок, выполненных в этом районе советскими учеными за период с 1974 по 1988 гг. Наиболее важные данные съемок и оценки биомассы были сведены в таблицы и проиллюстрированы различными картами, отображающими районы съемок. Было установлено, что распределение скоплений криля в значительной мере совпадает с местоположением районов, в пределах которых течения образуют круговороты. Среди этих районов особо богаты скоплениями криля были те, которые располагаются к востоку от острова и приблизительно на 37° з.д. В отсутствие благоприятных условий, т.е. формирования

круговоротов, криль обычно не собирается в агрегации и характеризуется низкой плотностью. При наличии динамики вод, благоприятной для формирования агрегаций криля, его биомасса в районе Южной Георгии составляет 400-800 тысяч тонн. Неблагоприятные гидродинамические условия соответствуют биомассе на порядок ниже. Краткосрочные колебания биомассы криля в районе Южной Георгии имеют чрезвычайно большое значение. В течение месяца биомасса может измениться в восемь раз. Также, биомасса обычно понижается в течение весеннего периода независимо от типа циркуляции вод. Ежегодные изменения биомассы криля без сомнения связаны с количеством криля, приносимого в данный район водами вторичного фронта моря Скотия. Для получения достоверных оценок биомассы криля рекомендуется провести более широкие исследования, включающие выполнение траловых и акустических съемок в разных временных и пространственных масштабах.

Resumen

Son numerosos los estudios científicos que tratan con amplitud sobre la distribución del krill y otros aspectos relacionados con su variabilidad en la zona de Georgia del Sur. En este trabajo se exponen los resultados más recientes pero no se ha centrado únicamente en los datos de las evaluaciones de biomasa. La actual incertidumbre a la hora de evaluar la biomasa de krill puede atribuirse básicamente a su gran variabilidad, y los distintos valores de biomasa obtenidos crea incertidumbre cuando se intenta calcular la biomasa de krill para dicha zona. Sólo después de realizar varias prospecciones de censo, sería posible explicar las razones que causan la variabilidad en la magnitud de los cardúmenes de krill e intentar un cálculo más fiable de la biomasa. En este trabajo se presentan los resultados de las nueve prospecciones más importantes realizadas entre 1974 y 1988. Los distintos mapas y tablas presentan los datos más importantes de las prospecciones y de las evaluaciones de biomasa. Se ha visto que la distribución de los cardúmenes de krill se corresponde con las zonas en las que las corrientes forman torbellinos; en estas zonas se constata que las concentraciones se forman en gran parte al este de la isla, próximo a los 37° W. Cuando el sistema de circulación del agua es desfavorable, lo que quiere decir que no se forman torbellinos, el krill no suele agruparse y su densidad es baja. En cambio, cuando la dinámica es favorable a la formación de concentraciones, la biomasa en las aguas de Georgia del Sur oscila entre las 400-800 mil toneladas. Las condiciones desfavorables corresponden a una biomasa de menor magnitud. Las fluctuaciones a corto plazo en la zona son muy significativas. La biomasa puede variar hasta ocho veces en un mes. También suele disminuir en primavera, sea cual sea la circulación del agua. Las diferencias anuales de la biomasa están sin duda relacionadas con el volumen de krill que fluye con las aguas del Frente secundario del mar de Scotia. Se recomienda que se hagan más estudios con prospecciones de arrastre y acústicas en diferentes escalas temporales y espaciales, para poder disponer de evaluaciones de biomasa más fiables.

1. INTRODUCTION

The South Georgia area holds a special place among those areas of the Southern Ocean where *Euphausia superba* forms aggregations. Soviet research vessels have been studying this area since 1965 although it was not until 1972 that commercial fishing began.

So far research has been of an integrated nature and has examined questions not only of euphausiid biology and its population resources but also matters concerning the physical environment and its biotic components, primarily plankton. This integrated approach has led to an increase in knowledge about various aspects of *E. superba* biology, especially krill distribution in relation to environmental conditions. Together with biomass assessments this has paved the way for the development of a rationally managed krill fishery in this area. Waters from the Weddell Sea transport krill to the South Georgia area which is located at the northern edge of its habitat (Marr, 1962; MacIntosh, 1973; Maslennikov and Solyankin 1980; Fedulov *et al.*, 1984). Investigations into size composition relative to water structure showed that krill may also be brought here by the waters of the southern periphery of the Antarctic Circumpolar Current (ACC) (Makarov *et al.*, 1980; Maslennikov *et al.*, 1983). This is supported by the fact that the same types of water correspond to the species composition of phytoplankton (Makarov *et al.*, 1984) and size composition of copepods (Vladimirskaya, 1978; Makarov *et al.*, 1986). Strictly speaking, krill aggregations which form off the island are augmented by the Secondary Frontal Zone of the Scotia Sea which is characterized by a constantly high density of *E. superba* (Maslennikov, 1978; Makarov *et al.*, 1980; Fedulov *et al.*, 1984).

After being carried along by the drift into the island's waters krill is retained here for a time (the "shade effect"; Shevtsov and Makarov, 1969) before continuing to flow with the currents in an easterly direction (Everson, 1976; Maslennikov and Solyankin, 1980). This retention of krill off the island will result in the formation of concentrations only when eddies and meanders develop around the island shelf and slope. Moreover, aggregations may be quite large in off-shore island waters (Maslennikov, 1979; Makarov *et al.*, 1980). When straight currents are prevailing krill is dispersed, abundance is low and aggregations in general are not formed. These types of conditions were observed in 1969 (Makarov *et al.*; 1980) and 1987. The nature of dynamic forces which facilitate the formation of krill concentrations is one of the most important factors determining the level of euphausiid abundance in the South Georgia area.

Experiments carried out in the South Georgia area showed that the largest aggregations of *E. superba* are formed around the northern edge of the island and it was here that later studies were conducted, a fundamental part of which included census surveys.

Although *E. superba* aggregations were encountered over the whole area, in certain areas they tended to form more regularly (Makarov *et al*, 1980; Sysoeva, Shevtsov, 1980). The type of bottom relief determines this regularity because this is where eddies and whirlpools are most often formed as a result of the interaction of the bottom relief with currents travelling by the island (Maslennikov, 1979).

Therefore the formation of *E. superba* aggregations depends primarily upon the direction of transportation by currents and factors influencing its retention in the shelf and slope waters of the island (Marr, 1962; MacIntosh, 1972; Makarov *et al.*, 1980). As opposed to aggregations in the southern part of the Scotia Sea, aggregations here, for example, are non-spawning (Makarov, 1978 and 1980). Processes occurring in this area, especially in relation to krill distribution and swarming, are entirely dependent upon physical environmental factors. The low status of the area in the functional structure of the *E. superba* habitat, especially in relation to its reproduction in the Atlantic sector, is a result of South Georgia being located at the edge of the habitat area in unusually low latitudes for this species and the dependence of the formation of krill aggregations upon drift transport both on the macro and meso-scales. The appearance of *E. superba* larvae in plankton is synchronous (by dates and size composition) with reproduction of the species in the southern part of the Scotia Sea (with allowance for drift periods), but not with the reproduction of krill near the island (Menshenina, 1988). Larvae and adult specimens are brought to the area by currents from the south or south-east. Larvae spawned in the island waters are eventually carried away from the region as indeed are adults.

Drift transportation of krill in the area and factors influencing swarming around the island are characterized by a high level of variability.

The most noticeable type of variability is seasonal. Aggregations occur here in almost all months of the year although spring research did not uncover any particularly large abundance. At this time the very profuse spring blooming takes place which, by analogy with spring in the Scotia Sea (see Makarov *et al.*, 1980), causes aggregations to break up. It is probable that as a result of dispersion krill is carried beyond the island waters. In other words *E. superba* abundance around South Georgia always drops with the onset of spring. This assertion is backed up by data from the fishery which always ceases operations in spring (Table 1).

Aggregations build up again with the onset of summer and are maintained until winter, i.e. the probability of encountering *E. superba* aggregations in the island waters increases during the other seasons although they may also be absent in winter (Latogursky, 1975; Heywood *et al.*, 1985). It is typical that if during summer *E. superba* aggregations occur most often toward the east of the region then in autumn and especially winter they are more prolific in the west (Latogursky, 1973).

Therefore the notable fluctuations in krill numbers over the whole year depend upon the variability of water dynamics in the mesoscale. Variability associated with the effects of meteorological conditions is especially short-lived. As cyclones pass, krill disperse and sink to deeper layers. After a time, however, the situation returns to its initial condition.

Interannual changes in krill distribution and particularly abundance are also possible. Apart from the situation in 1969 and 1978 as described earlier, a low level of abundance prevailed in the seasons 1982/83 and 1983/84. It should be noted that it has always been very difficult to identify and separate seasonal and interannual fluctuations in this area. Even surveys carried out more than once a year do not create a foundation for identifying the type of change taking place. During the above years the low abundance of *E. superba* can be attributed to the effects of the fishery. Interannual variations are caused by water advection from the Scotia Sea secondary front into the island area. This advection depends on the interaction of the large circulation systems of the Atlantic sector, i.e. the ACC and the Weddell Circulation (Maslennikov and Solyankin, 1979). It is difficult to evaluate these interactions using survey data from South Georgia alone. Nevertheless some indirect assessments have been made (Bogdanov, Solyankin, 1970), in particular in terms of analysing the variability of the latitudinal gradient of atmospheric pressure (Fedulov *et al.*, 1984). The data obtained correlate well with krill swarm density off the island.

Distribution trends and many aspects of its variability have been extensively described in scientific literature (see Lubimova *et al.*, 1980) (SC-CAMLR-I/BG/1). There has been less focus on data concerning specific biomass assessments of krill. In the work of Lubimova and Shevtsov (1980) the range of variability for krill biomass is given for the initial study period in the area (1965 to 1976) with values from 0.9 to 3.6 million tonnes. The uncertainty in krill biomass assessment can be largely attributed to high variability and the wide range of biomass values obtained which in turn leads to uncertainty in interpreting krill biomass for the area. It was therefore only possible to begin to explain the reasons for the variability in the scale of *E. superba* swarms and to attempt to determine the more reliable values of its biomass after a large number of census surveys had been conducted. Results of these studies are summarized in this paper.

2. SURVEY RESULTS

It is not possible to examine here all surveys conducted off the island, especially since some of them covered only limited area and were not representative. Therefore we have chosen only those surveys which are comparable according to area covered, fishing gear used, the number of stations made and availability of necessary background data and which were carried out using accepted methods (data from earlier studies were used only as a guide).

The study of *E. superba* distribution, swarm density and biomass assessment were carried out using standard methods (as in other areas of the Southern Ocean) based on census trawl surveys regularly conducted in the South Georgia area.

The general approach to conducting biomass assessments of krill in the area under investigation can be described by taking one of the most detailed surveys, which was made from 4 to 13 February 1975, as an example (see below - Survey 2).

The survey was conducted towards the north of the island between 34° and 41°W. Thirty-two hauls (generally lasting half an hour each) were carried out over this area of 54 450 square miles. Stations were made along five lines radiating out from the island with six to seven stations along each line.

A midwater trawl was employed at each station. The cross-section of the trawl opening at the level where fine mesh (10 to 14 mm) begins was 140 square metres and was taken as the working area of the trawl opening. Since the catchability coefficient was difficult to calculate it was taken to be equal to 1.

The density of *E. superba* in fished swarms (g/m^3) was worked out according to the size of the catch taken at each point of the survey and the amount of filtered water (this was calculated based on vessel speed (usually 2.8 knots), trawl opening and duration of haul).

At the same time the layer of water where krill swarms were distributed was recorded using hydroacoustic equipment. Values obtained for density were taken to be typical for the whole layer. Over the period of the survey in question, *E. superba* swarms were distributed in the upper 50 m layer in particular. More calculations were made to determine krill biomass bearing in mind the vertical distribution characteristic of euphausiids. Mean biomass was also estimated per square kilometre and square mile.

The density values obtained at each station were interpolated, biomass was calculated by strata (areas between adjacent isolines) and the results were summarized for the entire area of the survey.

This paper presents the results of seven surveys carried out using a commercial midwater trawl during various seasons from 1974 to 1988. Naturally the areas covered by the surveys and the number of hauls made were not identical. Most of the surveys were carried out in areas to the east, north and west of the island (between 40° and 34 °W and from 54°S to the shore (the boundary of territorial waters). The southern part of the island's waters was studied less frequently. Therefore the biomass values contained refer mainly to the north-west, north and north-eastern inshore waters of South Georgia.

Table 2 contains important details of the surveys and data obtained from observations on the quantitative parameters of *E. superba* concentrations. Each survey has a map (Figures 1 to 7) showing where it took place and areas where abundance of krill was found to be greatest.

It should also be noted that although trawls of identical area were not always used, their design and main parameters were similar (for details of each survey see below). As with the above example, the size of the trawl opening was calculated according to where the fine mesh section of the trawl began (data on trawl openings are shown in Table 2).

Each survey conducted with echosounders recorded vertical distribution and, consequently, biomass estimates were made based on the length of the layer where krill were distributed.

Therefore in calculating *E. superba* biomass for each survey all natural variables and parameters were taken into consideration which necessitated the introduction of changes into the above procedure of estimation.

In recent years the Isaacs-Kidd trawl has been used in a number of census surveys to make oblique hauls in the 0 to 100 m layer. Preliminary data indicate that this trawl has a catchability rate inferior to commercial trawls. Therefore it appears that *E. superba* biomass assessments made using the Isaacs-Kidd trawl are underestimates. In view of this, biomass assessments from Surveys 8 and 9 can only be used for rough comparison with assessments obtained from commercial trawl data.

We shall briefly examine the results of each survey individually. For ease of comparison each surveys has an identifying number.

The most important survey data and assessments of quantitative indices for the *E. superba* population are given in Table 1. Figures 1 to 4 show survey areas and also where large concentrations of krill were detected. Figures 5 to 7 give data on the system of surface currents for most of the surveys (a reading of 1 000 dB relative to the conditional surface).

Survey 1 (9 to 23 March 1974, *RV Salekhard*; Figure 1A)

Fifty-nine trawls were carried out to the north and east of the island. The survey itself together with additional searching operations made it possible to characterize in detail the distribution of *E. superba* in the area. The largest concentrations were discovered over the island slope (29 g/m^3) and at an oceanic depth (3.5 g/m^3) to the north-east of the island. Apart from these two areas in Figure 1A, the area to the far south-east should also be noted. Over the remainder of the survey area there were either very few euphausiids or none at all (especially in the western part of the region). Most often krill was distributed in the 0 to 100 m layer and deeper (up to 200 m). However in the area of massive swarming near the island, krill swarms were distributed in the upper layer from 12 to 35 m. These differences were taken into consideration when calculating biomass. The high values for density gave a high biomass assessment which was over 560 000 tonnes for the study area over the period of the survey (Table 2).

Comparison of *E. superba* distribution (Figure 1A) and water dynamics in the area (Figure 5A) showed that the largest concentrations of krill were encountered either in areas of strong eddies in the system of currents or on the edge of streams flowing together from opposite directions.

Survey 2 (4 to 13 February 1975, *RV Akademik Knipovich*; Figure 1B)

One of the most extensive by area, this survey covered 54 450 square miles and was carried out to the west, north and east of the island and consisted of 41 hauls. The average density of krill was 1.4 g/m^3. The largest concentrations were encountered to the east of the island. The survey was begun after two micro-surveys. The first was from 28 January to 3 February and consisted of 40 hauls and the second took place from 25 to 27 March and consisted of 23 hauls. Mean density in the micro-survey areas was 2.4 and 5.3 g/m³ respectively. *E. superba* biomass in aggregations in the east (see Table 2) made up more than half of the total biomass in the eastern part of the survey (511 000 tonnes). Overall biomass in the western and central parts of the survey was less (395 000 tonnes) than for aggregations in the west in March alone.

The nature of water dynamics is fully consistent with the location of sites with high abundance of krill (Figure 5B).

Survey 3 (12 to 18 June 1981, *RV Argus*, Figure 2A)

This survey was relatively small in area (18 hauls) and was carried out to the north-east of the island. Aggregations were encountered over all island slopes where krill density was almost 6 g/m³. With the exception of a handful of specimens, it is interesting that *E. superba* was practically absent in the open part of the area. It is typical that in such a situation localized swarming will only occur in waters near the shallows. Krill density in the area 37° and 38°W reached maximum levels - 5.64 and 5.15 g/m³ respectively. These values for krill swarm density and those approaching them were responsible for a fairly high total biomass for the survey period (476 000 tonnes, see Table 2).

Survey 4 (18 to 29 June 1981, *RV Argus*, Figure 2B)

Despite the increase in the size of the study area, this survey (23 hauls), which was carried out almost one month after Survey 3, showed a sharp drop in *E. superba* abundance. Areas of increased density were now towards the west. One of the areas (maximum density - 0.88 g/m³) was located at 37°W while the other was near the western extremity of the island (0.75 g/m³). Calculations showed that by comparison with June of the same year biomass decreased by six times (79 000 tonnes, see Table 2).

Survey 5 (1 to 4 June 1983, *RV Argus*, Figure 2C)

A census on krill abundance was carried out in the beginning of winter 1983 (17 hauls) in approximately the same location as Survey 4. The overall location of areas with increased abundance were also similar. Extremely localized and small aggregations of *E. superba* were noted in the area 36 °W (maximum density 5.6 g/m³) and to the west of the island (4.6 g/m³). This accounted for only 3% of the survey area. Over the rest of the territory no large swarms of euphausiids were encountered and many hauls were unsuccessful. On the whole this was responsible for the extremely low overall biomass assessment (54 000 tonnes, see Table 2).

The dynamic relief on the surface was homogeneous and lacked any clearly discernible eddies in the current field (Figure 6A). The lack of eddies which usually facilitate the formation of aggregations undoubtedly played a role in the low level of krill density and biomass. It was only in the very western part where the current began to flow south that somewhat larger levels of abundance were noted.

Survey 6 (22 November to 9 December 1986, *RV Gizhiga*, Figure 3A)

Although this was a fairly extensive survey (41 hauls), it did not cover territory further south than 54°S. It was carried out in the very beginning of the summer season and showed areas of high density in the western part of the region. Krill were dispersed over the remainder of the study area. As opposed to a number of other surveys (1, 3 and 5), aggregations of krill were also discovered a long way out to sea (maximum density here was 1.2 g/m^3.) although at the same time they were encountered in larger numbers in the area of the island shelf (maximum density 2.5 g/m^3). In the north-east part of the area there were practically no krill at all. They began to appear in small numbers only as the survey neared 54 °S. On the whole, areas of high krill abundance were characterized by their large size which was reflected by the values of the biomass assessments made over the survey area (607 000 tonnes, see Table 2).

Mesoscale eddies were noted in a number of areas which quite clearly coincided with areas of high krill abundance. As usual they appear to be the reason for the concentration of krill both around the continental shelf and further away from shore towards the oceanic zone. Although the survey did not cover the area east of the island, judging by the water dynamics it may be assumed that *E. superba* aggregations were present there.

Survey 7 (2 May to 5 June 1988, *Gr. Kovtun*, Figure 3B)

This survey was for the most part conducted in May. In fact it was a series of micro-surveys made in the north-east and northern sectors of the area of the shelf and the island slope. Observations were made from a fishing vessel which carried out several dozens of hauls in each area which in turn ensured a detailed assessment of *E. superba* aggregations in the area. The vessel's regime also included elements of a search close to where the fishing fleet operates. The data obtained can therefore be examined in conjunction with the results of other surveys.

Krill was encountered in the 0 to 50 (70) m layer and calculations of density and biomass were made in relation to that layer. The density of aggregations from the south-east to the north-west of the areas under investigation was 12.5 g/m^3, 14.1 g/m^3 and 8.6 g/m^3. Total biomass was estimated to be 1 402 000 tonnes (see Table 2).

Survey 8 (11 to 23 October 1984, *RV Evrika*, Figure 4A)

This was the first time that a survey was conducted around the whole island. An Isaacs-Kidd trawl was employed to make 66 hauls. On the whole the distribution tendencies of *E. superba* turned out to be the same as were previously observed. The main areas of high krill concentration were towards the east, north (this is usually rare) and western sectors of the study area. The largest concentrations were encountered in the north (in the area 37°W, maximum density 2.5 g/m^3), but in general, lower values prevailed. In essence it was only in those places marked on the map that krill density was high while in other areas covered by this extensive and detailed survey they were absent altogether. Despite the extent of the survey (its area was four-times that of Surveys 3, 4, 5 and 6) a low biomass figure was obtained over the period of investigations (3 800 tonnes, see Table 2).

It is very interesting to note that the water dynamics on the surface were conducive to the formation of krill aggregations (Figure 7A). Small local increases in density in each instance (place) coincided with more complex forms of dynamic relief. However, in keeping with the general seasonal variability of *E. superba* abundance in the region, there were very few observations in the area over the survey period.

It should be pointed out that repeated observations made here over the brief period 15 to 18 January 1985 in the south-east of the island showed dense swarms (density up to 5.9 g/m^3).

Survey 9 (20 January to 9 February 1988, *RV Evrika,* Figure 4B)

As in October 1984, this survey covered the area around South Georgia where 65 hauls were made with the Isaacs-Kidd trawl. The general distribution patterns were somewhat similar to those from Survey 8, although dense aggregations were encountered in the area around 37°W. An extensive area stretching from the south-east to the edge of the survey's range was noteworthy for its high abundance of krill. Two areas, located on the shelf and the outer part of the island slope to the east of the island and around 37°W, stood out due to their density which exceeded 10 g/m^3. Aggregations were extremely long, leading to a biomass estimate of 868 000 tonnes (see Table 2). It is worth repeating that census surveys made with the Isaacs-Kidd trawl give underestimates in regard to density and biomass of *E. superba.* It is therefore not impossible that over the period of the survey krill biomass could actually have been much greater.

3. DISCUSSION

Comparison of data on *E. superba* distribution with the pattern of currents (Figure 7B) showed generally favourable and regular conditions for swarming.

This brief description demonstrates that most surveys in the South Georgia area adequately covered those areas where krill forms concentrations. Despite slight differences in the number of hauls, the data obtained from each survey are entirely comparable.

A comparison of maps depicting the location of areas with high density of *E. superba* and patterns of water circulation around South Georgia during each survey shows an overlap of swarming areas and areas where currents turn into eddies. Even in those instances where biomass was quite low (e.g., Survey 8), abundance increased in places where dynamic activity was greater (cf. Figures 4B and 7A). Among these places, aggregations of *E. superba* were encountered most often in waters to the east of the island and around 37°W.

When the circulation system presents unfavourable conditions (such as the straight currents off the northern shore of the island, which means the absence of eddy formations leading to euphausiid concentration) aggregations do not form at the usual time and density is insignificant. This was the case for Survey 5 (cf. Figures 2A and 6A). This in turn was reflected by the biomass assessment for *E. superba.*

Territory was covered fairly evenly during the surveys and vessels did not specifically remain in areas of aggregations. Especially high values for density obtained after fishing a particular aggregation did not significantly effect the biomass estimate for any of the surveys. Therefore biomass estimates from each of the surveys only indicate the general picture of *E. superba* abundance for the relevant periods.

From the above we can see that krill swarming also occurs in other coastal areas of South Georgia. Although swarming in these areas occurs less regularly and on a smaller scale their very existence is invariably associated with irregular currents. Eddies around the island contribute to a general increase in krill abundance over the whole area and determine levels of density which vary from one survey to another. The biomass estimate for euphausiids changed in accordance with values for density in the study area. By comparing the estimates in Table 2 it is clear that they correspond to two levels of values which differ by an order of magnitude (tens of thousand and hundreds of thousands of tonnes). It is obvious that such large differences depend upon swarming conditions.

When conditions for water dynamics are favourable *E. superba* biomass is around 400-800 thousand tonnes. It is precisely when these kinds of conditions prevail and krill biomass reaches several hundred thousand tonnes that the fishing fleet is able to operate. The values of overall density estimated during the relevant survey are accepted as correct for the operation of fishing vessels. Summary data from early research in the area (1972 to 1981) shows that fishing was only conducted when density was 6 to 12 g/m^3 (Fedulov *et al.*, 1984). In certain months there was a marked decrease in density and fishing did not take place (Fedulov *et al.*, 1984). During the periods when those surveys being reviewed in this paper (1 to 3, 6, 7 and 9) were carried out, commercial vessels did operate when density and biomass were high.

Thus the circumstances prevailing at the time of Surveys 1 to 3, 6, 7 and 9 are entirely usual for the area when there are favourable hydrological conditions. The values for biomass obtained from these surveys correspond to the normal level of accumulation of *E. superba* in the waters off South Georgia.

It will be recalled, however, that we are examining overall krill density in the survey area. As we have seen with individual cases, the extent to which *E. superba* forms aggregations in certain areas affects specific biomass values. In this regard it is extremely important to assess the extent of swarm formation within the confines of areas of aggregation.

There was no specific focus on areas where krill form aggregations proper during most of the surveys which were aimed at making integrated studies of off-shore waters. This would have made the research more expensive and time consuming and reduced the value of any results obtained. Surveys were carried out over brief periods, usually one or two weeks. The design used for Survey 2 (a survey plus and separate research into aggregations) was to some extent a compromise. Only rarely can such a survey design be used by research vessels which usually work to tight and varied schedules. However, this survey design turned out to be the most acceptable for expressing quantitative values graphically.

In order to characterize areas where krill aggregations are distributed, micro-surveys are needed to contour these areas and to carry out within their boundaries a series of hauls aimed at determining krill biomass. This was done in two instances only (Surveys 2 and 7). Calculations made using these data showed that more than half the total biomass may be in these aggregations and sometimes this value even approaches the total biomass (see data from Survey 2). Data from Survey 7 are indicative here and point to an especially high biomass of krill accumulated around the island in summer 1988. Considering the above, biomass could have reached 1.5 million tonnes. Therefore it may be assumed that *E. superba* summary biomass (i.e., total biomass and biomass concentrated in aggregations) regularly reaches a figure in the order of one million tonnes (Surveys 2 and 9) and sometimes greater (7). It should be recalled that a catchability coefficient of 1 was used when in reality it should have been lower.

Therefore standard surveys which do not focus on aggregations underestimate the value of *E. superba* biomass in the South Georgia area. It is also clear that in certain areas the high total biomass indicates the presence of fairly large aggregations of krill. Although the above only deals with variability in relation to total density it may nevertheless be assumed that the higher total density, the more likely the increase in the number and scale of aggregations.

As we have already emphasized, the fluctuations in *E. superba* biomass in the South Georgia waters are extremely significant. Moreover, the situation here is subject to rapid change. For example, the biomass figure may vary by as much as eight times in a month (cf. Surveys 3 and 4). During the 1982/83 and 1983/84 seasons unfavourable conditions predominated for an extended period (Survey 5) and due to low biomass and small catches the fishing fleet found it impossible to operate in the area (see catch statistics in Subarea 48.3, CCAMLR).

Annual differences (long-term trends) in *E. superba* biomass in the South Georgia area are undoubtedly associated with the volume of krill brought here by waters of the Scotia Sea Secondary Front. Short-term fluctuations in biomass may occur when there is an abrupt, although impermanent, change in the system of currents off the island. It should be recalled once again that the more regular changes in krill abundance in the area are of a seasonal nature. Krill biomass usually decreases in spring regardless of the type of circulation determining water dynamics. Although the type of circulation may be extremely favourable aggregations do not form and density is very low (see, e.g. data from Survey 8).

Variability of krill abundance is quite significant in the other seasons even when swarming conditions are favourable. Nevertheless the biomass figures for Surveys 1 to 3, 6, 7 and 9 are on the whole consistently high and it is only when this level of krill swarming has been reached that fishing operations can take place.

4. CONCLUSION

Individual observations made during the surveys indicate wide differences in *E. superba* biomass in the South Georgia area. This complicates research and leads to uncertainty in relation to many questions associated with assessing krill abundance. For the present we are restricted to speaking alternately about favourable and non-favourable conditions for swarming in the study area. These types of conditions also govern the regime of the fishing fleet. The above two biomass estimates which vary by an order of magnitude reflect the true differences in the notion of favourable and unfavourable conditions.

In reality the situation is more complex since transitions between the two levels of biomass are possible and it is as yet unclear how long these transitions take. In one example the transition interval was less than one month (cf. Surveys 3 and 4) but there are obviously other possibilities. This question should actually include an assessment of the combination of interannual and short-term variability. Interannual variability is associated with changes in the scale of krill transport towards the island whereas short-term variability is related to the conditions for the formation of aggregations in the area. The subsequent drift of krill beyond the island should also be borne in mind, although this question is especially complex and has so far been poorly studied. Indeed, with the breaking up of aggregations associated with changes in water circulation krill may remain in the island area in a dispersed form. As eddies build up again swarms reappear, however, due to the extended nature of this change, they may be carried away from the island. In other words, this transport is a constant phenomenon but its magnitude is the decisive factor.

Carrying out surveys in the island area alone is insufficient to research properly interannual variability. In order to assess the interaction of the ACC and the Weddell Circulation investigations should be made into the system of large-scale circulation. Together with large-scale surveys, it would appear worthwhile to continue the analysis of trends on the basis of indirect indices (Bogdanov and Solyankin, 1980; Fedulov *et al.*, 1984; Yakovlev and Altman, 198).

These factors should also reflect krill swarming conditions in waters adjacent to South Georgia. It is clear from the preceding discussion that more frequent and detailed surveys, including micro-surveys on aggregations, are necessary for further investigations into the variability of krill biomass in the area. International cooperation under the auspices of CCAMLR would be one way of addressing these tasks by way of a program of successive surveys conducted by various vessels over the period of a year. It should be noted that the discovery of the most common places of krill swarming in the eastern waters off the island and around 37°W is particularly important for conducting census surveys in relation to the CEMP monitoring program, for example.

The above is based on data from trawl catches. The use of hydroacoustic equipment in combination with controlled hauls undoubtedly ensures the speeding up of investigations and gives a more detailed impression of *E. superba* distribution and biomass. An assessment of the biotic background as well as biological characteristics of krill is also very important. These factors, which are not discussed in this paper, unquestionably influence swarming dynamics of *E. superba* in the area under investigation.

It should be stressed once more that data obtained from any survey correspond to single observations. This holds true for *E. superba* biomass assessments based on materials from each survey. It is important to have a realistic notion of an integral value for biomass which might be obtained as a result of further systematic research.

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Table 1: Seasonal fluctuations in krill abundance around South Georgia with the onset of spring (based on fishing catch statistics, 000' tonnes).

Year	July	August	September	October	November
1985	36.3	14.4	0.5	4.9	4.4
1986	16.5	4.5	6.4	1.7	0.03
1987	37.7	25.1	16.9	4.5	-
1988	62.4	34.7	5.8	-	-

Table 2: Main results of surveys in the South Georgia area (1974 to 1988).

Survey Number	Dates	Vessel	Gear	Trawl Opening (sq. m)	Survey Area (sq. m)	Biomass	
						Total (000' tonnes)	Per sq. km (tonnes)
1	9-23 Mar 1974	*Salekhard*	CT	135	51690	560	108.4
2	4-13 Mar 1975	*Akademik Knipovich*	CT	80	33370	906	28.6
					E (2100)	(220)	(104.8)
					W (2800)	(450)	(160.7)
3	Jun 1981	*Argus*	CT	190	12700	476	37.9
4	Jul 1981	*Argus*	CT	190	14700	79	5.4
5	1-4 Jun 1983	*Argus*	CT	190	11700	54	4.6
6	22 Nov-9 Dec 1986	*Gizhiga*	CT	190	12600	607	48.2
7	2 May to 5 Jun 1988	*Kovtun*	CT	200	(2820)	(1402)	(310)
8	11-23 Oct 1984	*Evrica*	IK	8	48113	3.8	0.1
9	20 Jan-9 Feb 1988	*Evrica*	IK	8	79120	868	10.9

CT - commercial trawl, IK - Issacs-Kidd trawl
Data from micro-scale surveys are in brackets

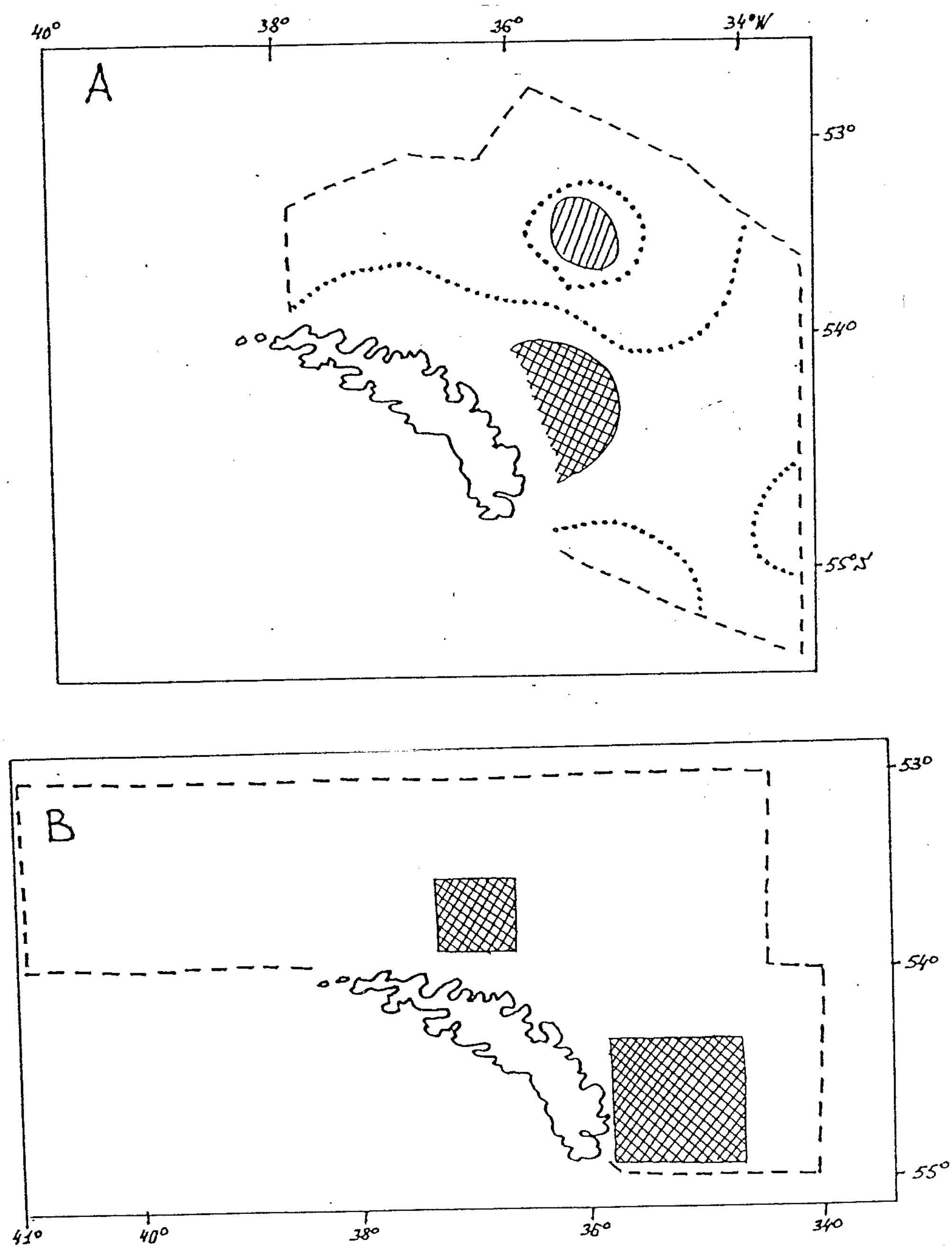


Figure 1: Krill distribution and areas of high krill abundance. A - Survey 1, 9 to 23 March 1974; B - Survey 2, 4 to 13 February 1975.

—— areas of high krill abundance, krill density, where indicated, is in g/m³;

- - - survey boundaries;

..... boundary of areas where hauls yielded no catches.

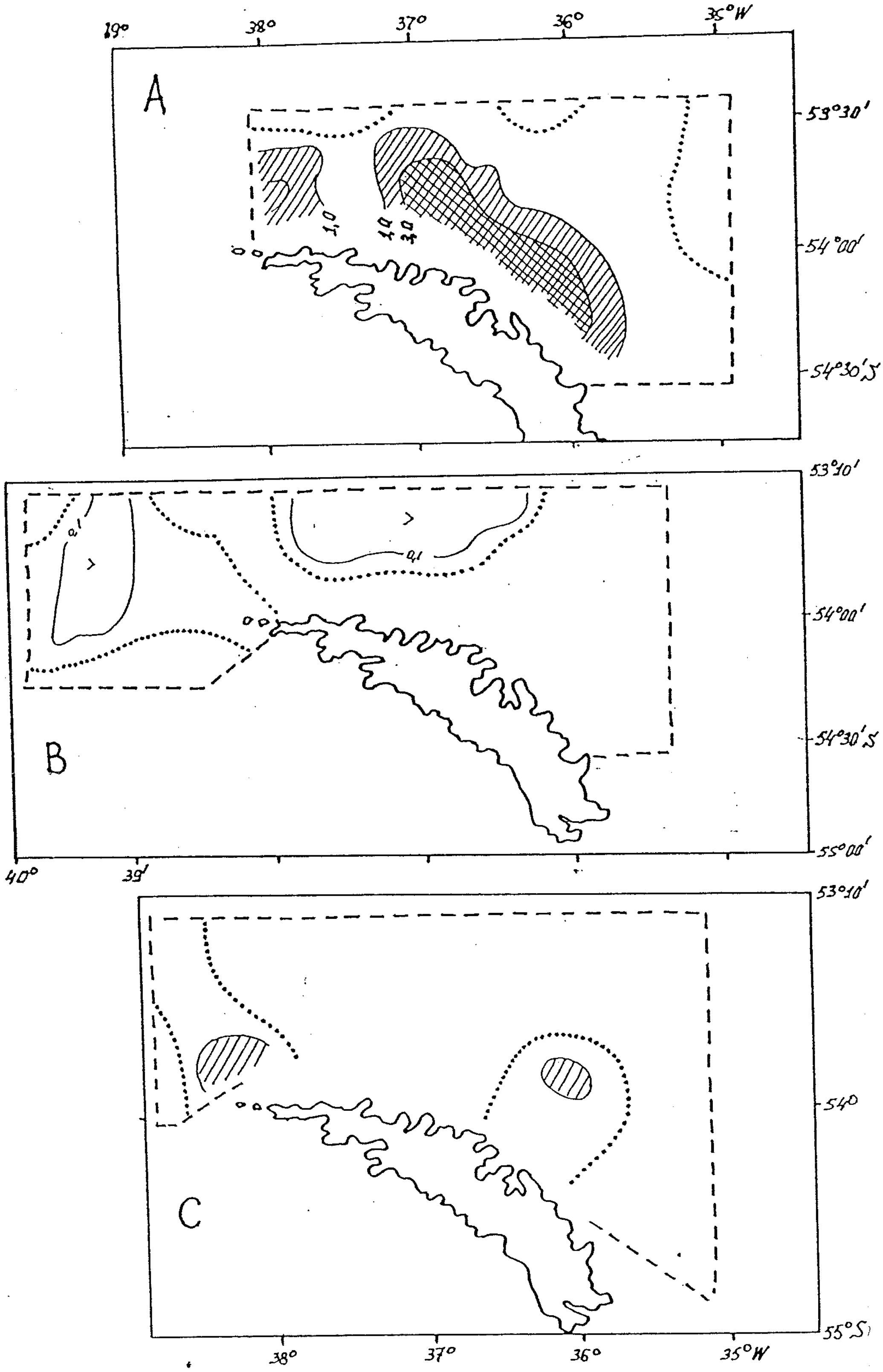


Figure 2: Krill distribution and areas of high krill abundance. A - Survey 3, 12 to 18 June 1981; B - Survey 4, 18 to 29 June 1981; C - Survey 5, 1 to 4 June 1983. (See Figure 1 for explanation of keys).

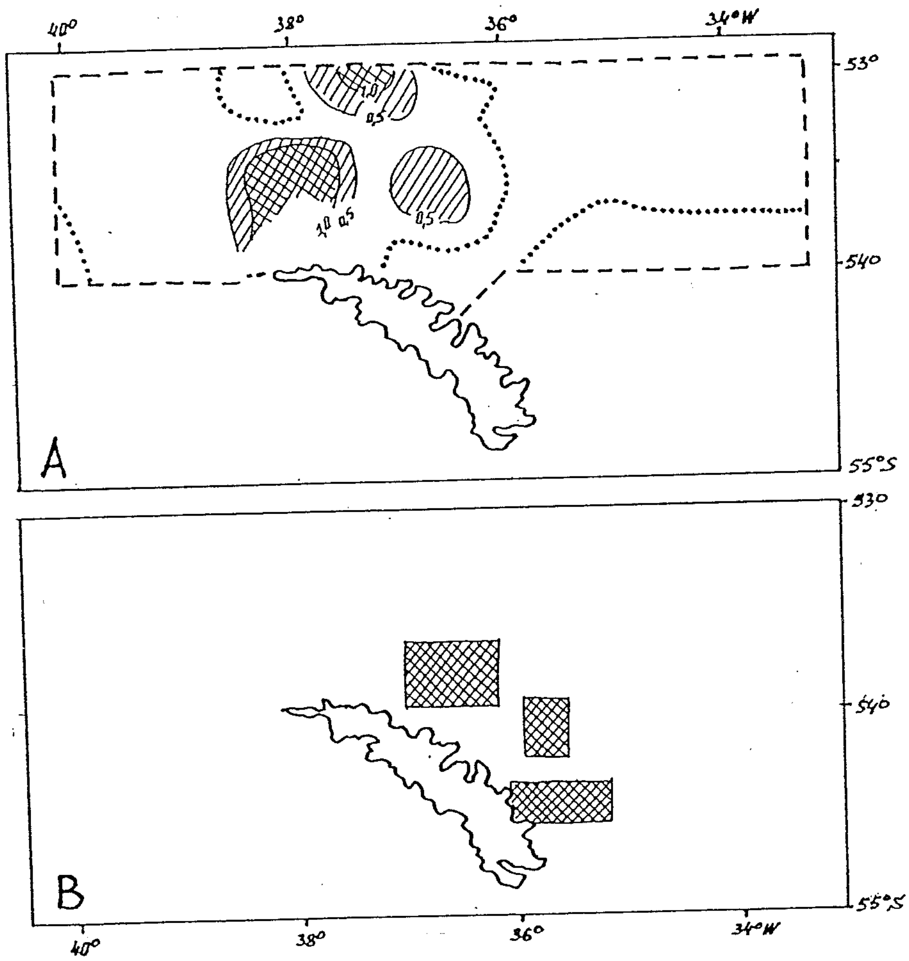


Figure 3: Krill distribution and areas of high krill abundance. A - Survey 6, 22 November to 9 December 1986; B - Survey 7, 2 May to 5 June 1988. (See Figure 1 for explanation of keys).

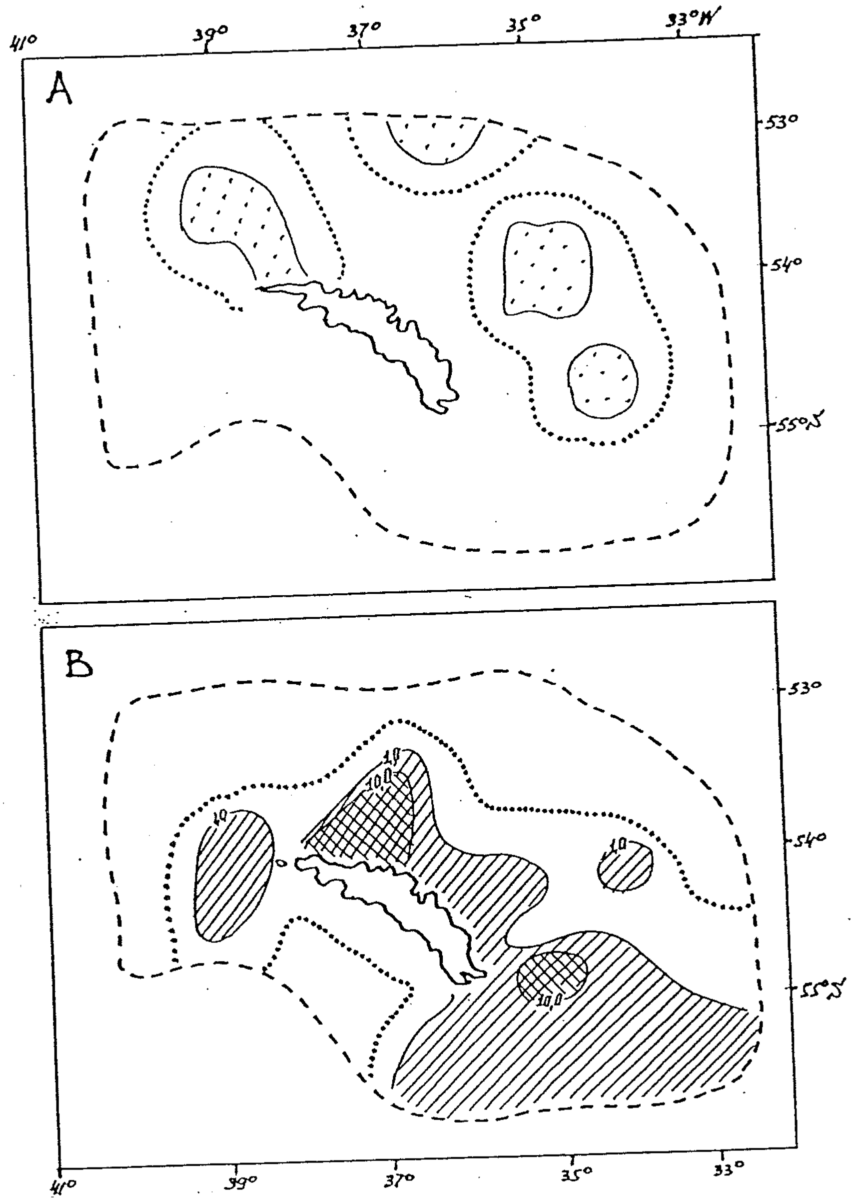
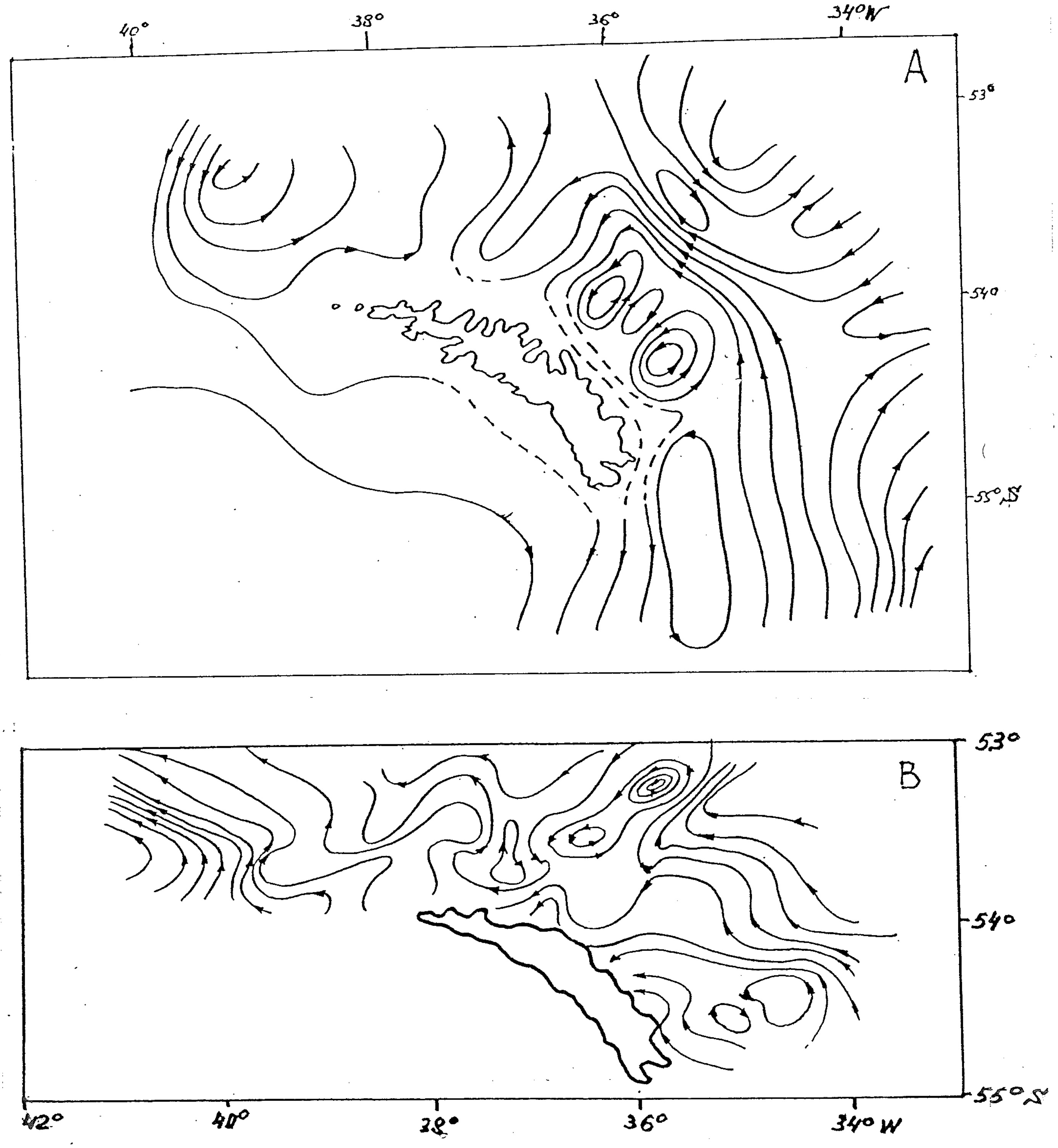


Figure 4: Krill distribution and areas of high krill abundance. A - Survey 8, 11 October to 23 October 1984; B - Survey 9, 2 January to 9 February 1988. (See Figure 1 for explanation of keys).



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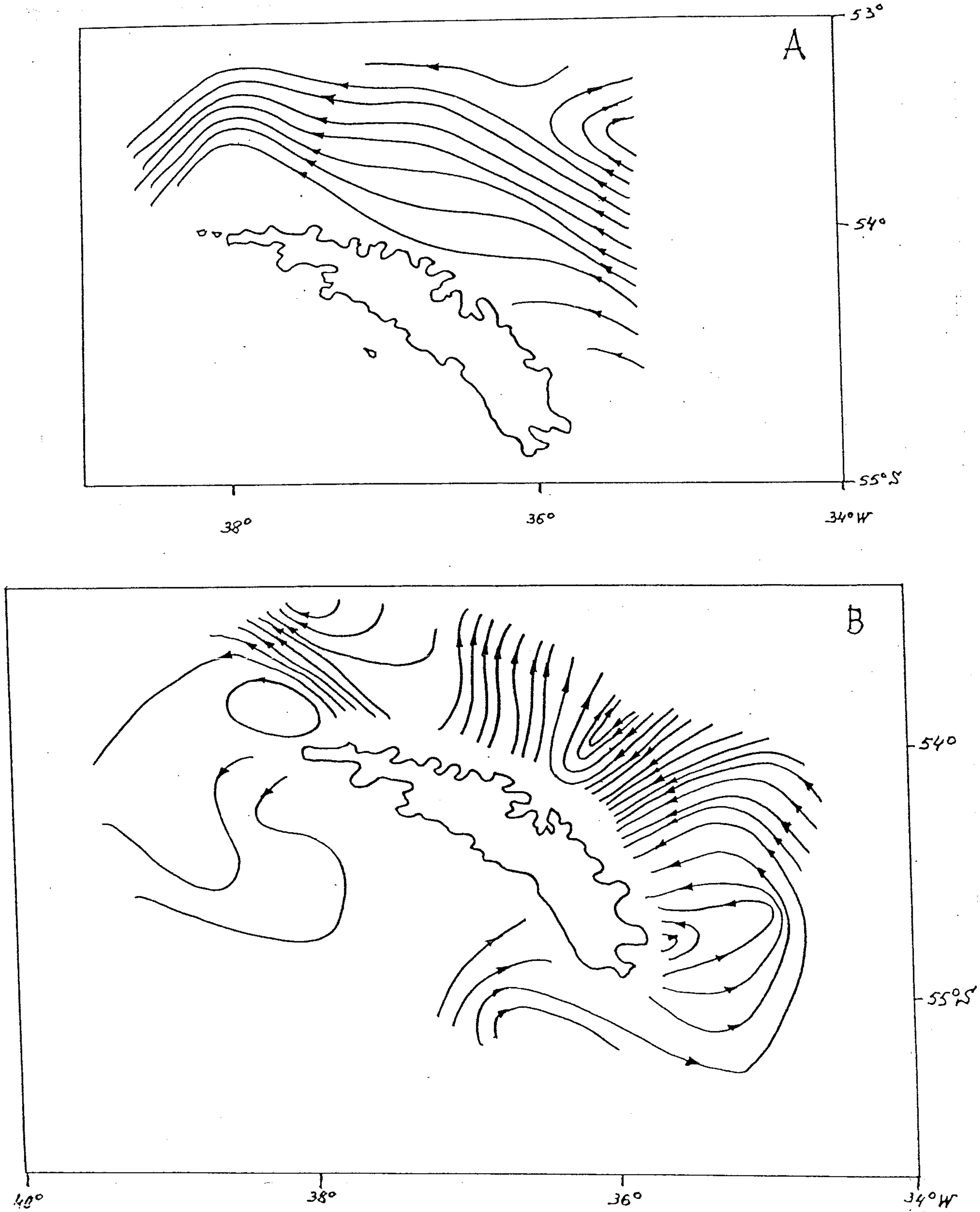
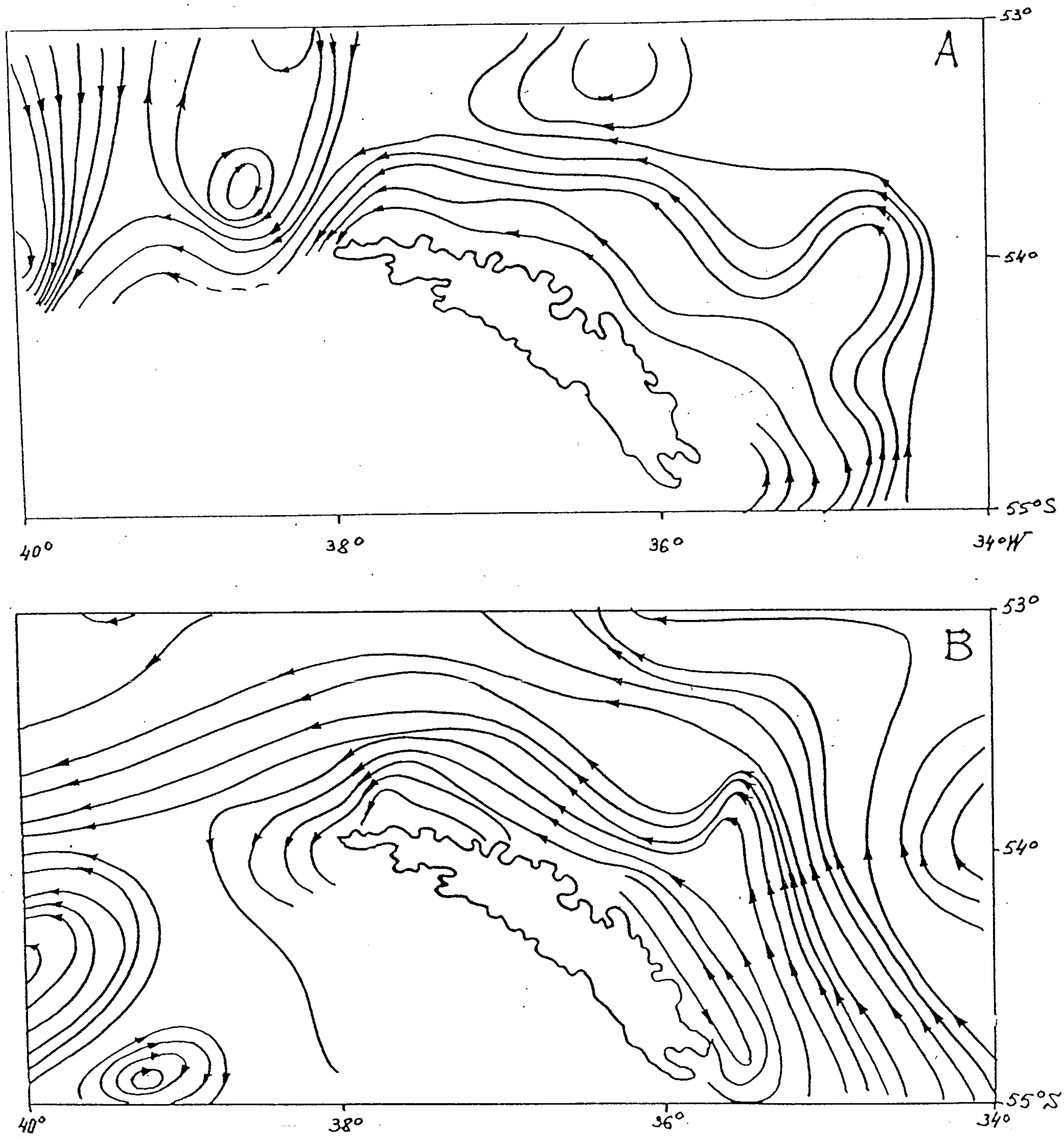


Figure 6: System of currents on the surface. A - Survey 5, 1 to 4 June 1983; B - Survey 6, 22 November to 9 December 1986.



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