FISHING INTENSITY OF THE SOVIET FLEET IN KRILL FISHERIES IN THE SOUTHERN ATLANTIC (SUBAREAS 48.2 AND 48.3)

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Abstract

This paper provides an assessment of the impact of the commercial fleet on the krill population in different months during the 1987 to 1990 fishing seasons within Subareas 48.2 and 48.3. During this period catches reported by the Soviet fleet amounted to more than 95% of the total catch. The calculations were based on haul-by-haul data from the Soviet fleet, using a probability statistical theory of fishery systems developed at AtlantNIRO. The impact of the commercial fleet on the krill population – on biomass and the density of krill aggregated in the fishing grounds – was assessed using data from 22 800 hauls.

The results of this study indicate that during periods of maximum fishing intensity, the Soviet fishing fleet had no impact on the krill stock or, consequently, on krill-dependent predators. It is concluded that although there is a spatial overlap of the dependent species and the fishery, this is not sufficient to amount to a functional overlap.

Résumé

Ce document présente une évaluation de l'impact de la flottille commerciale sur les populations de krill en différents mois des saisons de pêche de 1987 à 1990 dans les sous-zones 48.2 et 48.3. Pendant cette période, les captures déclarées par la flottille soviétique constituaient plus de 95% de la capture totale. Les calculs étaient fondés sur les données par trait de la flottille soviétique, au moyen d'une théorie de probabilité statistique des systèmes de pêche mise au point à AtlantNIRO. L'impact de la flottille commerciale sur la population de krill – sur la biomasse et la densité des concentrations de krill sur les lieux de pêche – a été évalué avec les données tirées de 22 800 chalutages.

Les résultats de cette étude indiquent que pendant les périodes d'intensité de pêche maximale, la flottille de pêche soviétique n'avait aucun impact ni sur le stock de krill ni, en conséquence, sur les prédateurs dépendants. Il est conclu que bien qu'il existe un chevauchement spatial entre les espèces dépendantes et la pêcherie, ce n'est pas suffisant pour produire à un chevauchement fonctionnel.

Резюме

В статье дается оценка воздействия коммерческого флота на популяцию криля в различные месяцы в течение промысловых сезонов 1987–1990 гг. в Подрайонах 48.2 и 48.3. В течение этого периода уловы, зарегистрированные советской флотилией, доходили до более чем 95% от общего вылова. Расчеты, использующие разработанную в АтлантНИРО вероятностно-статистическую теорию промысловых систем, основывались на данных советской флотилии за каждый отдельный улов. Воздействие коммерческого флота на популяцию криля – биомассу и плотность скоплений криля на промысловых участках – было оценено с использованием данных по 22 800 тралениям.

Результаты этого исследования говорят о том, что во время периодов максимальной интенсивности промысла советский рыболовный флот не оказывал никакого влияния на запасы криля и, следовательно, на зависящих от криля хищников. Можно сделать вывод, что хотя и имеется пространственное перекрытие зависимых видов и промысла, его недостаточно для того, чтобы считаться функциональным перекрытием.

Resumen

Este trabajo presenta una evaluación de los efectos de la flota de pesca comercial en la población de kril de las Subáreas 48.2 y 48.3 en distintos meses de las temporadas de pesca de 1987 a 1990. Las capturas declaradas por la flota soviética durante este período representaron más del 95% de la captura total. Los cálculos se basaron en los datos de lance a lance de la flota utilizando una teoría estadística de probabilidad de los sistemas de pesca desarrollada por AtlantNIRO. Se utilizaron los datos de 22 800 lances para evaluar el impacto de la flota comercial en la población de kril, específicamente en la biomasa y densidad de las concentraciones de kril en los caladeros de pesca.

Los resultados de este estudio demuestran que la flota de pesca soviética no afectó a la población de kril en los períodos de máximo esfuerzo pesquero, y por consiguiente, tampoco afectó a los depredadores dependientes de kril. Se concluye que si bien existe una superposición espacial entre las especies dependientes y la pesquería, ésta no es suficiente como para producir una superposición funcional.

Keywords: commercial fleet, krill-dependent predators, fishery intensity, CCAMLR

INTRODUCTION

Antarctic krill (*Euphausia superba*) plays an important role in the Antarctic ecosystem. Krill are dominant primary consumers and constitute an important food source for many predators such as baleen whales, numerous fish, seal, penguin and flying bird species. At the same time, krill are subject to a significant commercial fishery in the Southern Ocean.

The krill fishery has become a major component in the approach to management of Southern Ocean marine living resources adopted by CCAMLR. Studies of the effects of krill removal on their stock size and on dependent predator populations are extremely important for krill stock management within the framework of the ecosystem approach adopted by CCAMLR (SC-CAMLR, 1993 and 2001; Thomson et al., 2001; Hewitt and Low, 2000; Butterworth et al., 1994; Boyd, 2002a).

This topic was investigated for those years when there was the greatest recorded fishing intensity. During the two most recent decades, such years occurred in the 1987 to 1991 commercial fishing seasons. At that time the largest reported krill catches came from Statistical Area 48 with the Soviet fleet operating in Subareas 48.2 and 48.3 making up more than 95% of the total catch (CCAMLR, 1993; SC-CAMLR, 2000).

In this paper, using a probability statistical model of the fishery operation, we make a quantitative assessment of the intensity of krill removal based on the observed fishing effort of the Soviet fleet and investigate the impact of krill removal on their density and biomass during the months which are most critical for dependent species.

MATERIALS AND METHODS

The analytical method chosen was based on an application of the probability statistical theory of fisheries systems developed in AtlantNIRO by Kadilnikov (1985 and 2001). This theory provides a method for analysing the operation of individual fishing vessels in terms of catching and processing and the distribution and behaviour of the target species, in this case krill. A description of the model is given in Appendix 1 to this paper and further detail can be found in Ivanova et al. (1997); Kadilnikov (1993) and Kadilnikov et al. (1989).

In this model the fishery intensity in the local area is estimated from the volume of water fished by the trawlers within the period considered, and water volume occupied by those krill that are present within the operation area of the fleet.

Haul-by-haul data from the commercial fleet (i.e. coordinates at trawl start, time of trawl start, trawl duration, vessel speed during trawling and catch per trawl) were used to determine the operational statistics of the fishing fleet. Summarised data were checked against those data presented in *CCAMLR Statistical Bulletins* (CCAMLR, 1994 and 2001).

Fishing effort was standardised over the groups of vessels of different types operating in the fleet as set out in Appendix 1. The vessel type and the trawl that made up the greatest part of the total catch was chosen as the standard fishing system. The fishing area was determined as a polygon joining the outermost coordinates of all hauls. The actual area was calculated using the method of Krasovsky's reference ellipsoid (Kadilnikov, 1985). The water layer in which the fishable biomass was present was estimated from the depth ranges of all successful hauls.

The fishing strategy followed closely the traditional method of the Soviet fleets described by Sushin (1998), whereby groups of vessels coordinated their fishing on a variety of aggregations within a general locality. Within these groups the vessels continuously exchanged information on trawling results and krill distribution. This exchange of information extended to different fleets operating in different subareas making it possible to monitor very large areas.

Before making a haul, each vessel used information from previous hauls and local acoustic survey results in order to determine the towing tack and depth. An exploratory trawl was usually set through the area where the greatest density and number of krill aggregations were observed. A number of hauls were also made along reciprocal tracks. The trawl was set so that it would be completely opened by time the vessel reached the krill aggregation. The trawl was hauled when sufficient krill had been caught according to the vessel's processing capacity and the type of product required. Most tows lasted from one to several hours depending on the distribution and size of the krill aggregations. Before catching sufficient krill, each trawl might pass through several krill aggregations as well as through areas without krill.

Krill density was estimated from the catch rate (tonnes/hour), trawl catchability (parameter p of Appendix 1, Equation 13) and volume of water filtered (parameter B of Appendix 1, Equation 5). The krill biomass available to the fishery at the start of a period was derived from the estimated fishing intensity (Appendix 1, Equation 10) and the total catch of krill as described in Appendix 1. Movement of krill aggregations within the area was incorporated into the model. However, it was assumed that the effects of advection of krill biomass into and out of the area balanced each other.

The track of each haul was used to define its activity zone and this was used to determine whether or not these activity zones intersected. This gave a maximum possible value for the fishing intensity for a given fishing effort (Appendix 1). These results were not affected by any relocation of fishing vessels during the study periods, as in all cases there were sufficient intersecting hauls.

Using this assumption, the estimated fishery intensity shifts to the right, i.e. the actual fishery intensity will be either equal to or less than, but not higher than, the estimated value. The result of this is that estimated biomass will shift to the left, i.e. the actual biomass cannot be less than, but is either equal to or higher than, the estimated value.

During trawling, krill may escape through the meshes of the trawl bag as well as from the codend. Also, some krill may be retained by becoming caught on the netting twine (Zimarev et al., 1990). It was assumed that all krill striking the trawl meshes, whether or not they passed through and escaped, were killed, thus maximising the estimated intensity of krill mortality during fishing (see Kadilnikov, 1993 and Appendix 1).

The level of krill removal during the fishery was estimated as the intensity of gross removal, P_Σ (Appendix 1, Equations 14, 15 and 16), determined as the intensities of fishing and fishing mortality as described in Appendix 1 and also in Kadilnikov (1993) and Ivanova et al. (1997).

Using these approaches, the krill removal estimates obtained represented maximum possible values, which were in line with the objective of evaluating the peak impact of the fishery on the krill population.

Data from a total of 22 800 hauls were analysed during this study.

RESULTS

Annual reported catches in the krill fishery within Statistical Area 48 are shown in Figure 1. These indicate that although the annual catch in Subarea 48.1 peaked at over 100 000 tonnes in 1990, it subsequently fluctuated at around 50 000 tonnes. Large catches were reported for Subareas 48.2 around 1990 and in Subarea 48.3 from 1986 to 1990. During that period the annual total catches reached 400 000 tonnes (CCAMLR, 1994 and 2001) from which 95 to 99% was taken by the Soviet fleet. Vessels of other national fleets operated in the South Shetland Islands area (Subarea 48.1). The largest krill catch taken from that area by Soviet vessels was during the 1988/89 season, but this amounted to only 20% of the total catch.

The analyses reported here are restricted to the Soviet fishery in Subareas 48.2 and 48.3 from 1987 to 1990. In Subarea 48.3 (South Georgia) the fishery operated during the winter months from April to September, whereas in Subarea 48.2 (South Orkney Islands), due to the presence of sea-ice, the fishery was intensive only during the summer months from December to April, sometimes extending into May. The fishing season in Subarea 48.2 includes the critical months of the breeding season for the main krill-feeding predators. The locations of fishing grounds are shown in Figures 2 and 3. In Subarea 48.3 fishing begins on the shelf and at the shelf break to the north of South Georgia. As the season progresses it extends along the shelf and at the western end around to the south of the island. In Subarea 48.2 fishing began in deep water to the northwest of Coronation Island. Depending on the prevailing conditions, it extended around the island group with an emphasis on the western end.

The Soviet fishing fleet comprised BMRT type trawlers (large freezer stern trawlers) with a main engine power of 2 000 to 5 200 hp. Most of the vessels were at the lower end of the power range, therefore the standard fishing system chosen was a trawler with an engine power of 2 000 to 2 400 hp operating with an RT 74/416 midwater trawl. Parameters of the standard RT 74/416 trawl and its catchability characteristics are given in Zimarev et al. (1990), Kasatkina and Latogursky (1990) and Kadilnikov (1993). Monthly mean values of CPUE over the four years of this analysis are shown in Figure 4 for all Soviet vessels. It demonstrates that results obtained for the standard system are in good agreement with results for the whole fleet.

During the course of each season the fleets moved around within the general area of the grounds, as indicated in Figures 2 and 3, so that they remained in localities with a minimum krill density of at least 100 g/m^2 (i.e. more than 390 tonnes/n $mile^2$). The estimated krill density and fishable biomass over the fishing ground for each month are summarised in Table 1 for Subarea 48.3 and Table 2 for Subarea 48.2.

Monthly analyses of the fleet operation and the estimated impact of the fishery on the biomass within the fishing grounds are set out in Table 3 for Subarea 48.3 and Table 4 for Subarea 48.2.

Estimates of the proportion of the biomass of krill on the fishing grounds which had been removed by the fishery in Subarea 48.2 did not exceed 19.8 ± 4.7%. This assumes that the error in estimating the size of the fishing ground from the outermost haul positions was 30%. In April 1988 the fishery took 19.7% of the available krill within the fishing area. This estimate is biased upwards because krill could be present on the same fishing ground but outside the area of fleet operation. During the other months of the three fishing seasons, the fishery intensity varied from 4.6 to 19.7%. During the fishing season the gross removal intensity in Subarea 48.2 did not exceed 19.8 ± 4.8% at the same assumption of 30% bias of the fleet operation area estimate (Table 4).

Krill removal in Subarea 48.3 was higher than in Subarea 48.2. The highest fishing intensity 36.4 ± 6.7% was observed in July 1989, when a large number of vessels (25–30 trawlers) operated within a small area and made 3 465 hauls. During the remainder of the month fishing intensity varied from 5.5 to 23.6% (Table 3).

The annual indices of the Soviet krill fishing fleet operations (summarised in Tables 5 and 6) in the areas shown in Figures 5 and 6, show that from the 1987 to the 1990 fishing seasons, the fleets, as shown by the fishing intensity index, removed no more than 15.6% of the krill biomass concentrated on the local fishing grounds of commercial interest.

Kadilnikov (1993) showed that the rope and netting parts of the RT 74/416 midwater trawl resulted in 0.5% mortality of those krill that were present within the fishing volume *B* of the trawl (Appendix 1, Equation 5). The intensity of mortality in the fishing ground was estimated by applying this value of mortality to each haul. As is evident from Tables 3 to 6, the maximum krill mortality in Subarea 48.2, as well as in Subarea 48.3, appeared to be below 1% despite interseasonal variations of fishing effort, while the gross removal intensity exceeded the fishing intensity by an average of 0.5%.

DISCUSSION

A Generalised Yield Model (GYM) has been developed by CCAMLR (Butterworth et al., 1994; Constable and de la Mare, 1996) to indicate sustainable yield levels. According to this model, krill fishing intensity is given by the fraction (γ) of the estimated pre-exploitation biomass that may be caught in a given year. The results of synoptic surveys in Statistical Areas 48 and 58 were used to indicate the estimated pre-exploitation biomass.

The precautionary krill catch limit in Area 48 was estimated at 4.1 million tonnes from the results of the 1981 survey (at $\gamma = 0.116$) (SC-CAMLR, 1994 and 1995) and at 4 million tonnes from the results of the CCAMLR-2000 Krill Synoptic Survey (at $\gamma = 0.091$) (SC-CAMLR, 2000). The analysis of international catch statistics showed that in the course of the 20-year fishing history, the precautionary catch limit had never been approached. Furthermore, the maximum total annual catch by all countries did not exceed 1% of the pre-exploitation biomass in any year (CCAMLR, 1994 and 2001). The total international krill catch during the 2000/01 season from Area 48 amounted to just 0.25% of the pre-exploitation biomass for that year or about 3% of the total allowable catch (SC-CAMLR, 2001). These results demonstrate that the fishing fleet is not in competition with krill-dependent predators on the largest spatial scale in terms of the total biomass relative to the total catch.

When considering the information on predator requirements for krill in areas of the main fishing grounds, it was noted that the total consumption of krill by predators in Subarea 48.3 was estimated at 11.8 million tonnes per year (Boyd, 2002b). In comparison with this estimate, the total krill catch in Subarea 48.3, even when in the past it had reached 256 000 tonnes (Figure 1), was equivalent to only 2% of the estimated predator requirements. It should be noted that recent catches have been lower than in the 1999/2000 season, when the krill catch in this area was less than 5 000 tonnes (SC-CAMLR, 2001).

It has been known for some time, and confirmed in Figures 2 and 3, that krill fishing is concentrated almost entirely in reasonably well-defined local grounds. Even in the 1987 to 1990 seasons under consideration in the present study, when the highest recorded fishing fleet activity occurred, vessels operated in an area that consisted of at most 8–9% of the size of Subareas 48.2 and 48.3. The biomass density in the fleet operation areas amounted to 100 ÷ 200 g/m^2 (or 390 ÷ 780 tonnes/mile^2). Except for one month when the fishing intensity was 33.4%, the upper theoretical limits of the fishing intensity were from 4.6 to 23.8%, while the intensity of gross removal ranged from 4.6 to 23.9% (Tables 3 and 4).

Our estimates of the gross removal intensity exceed the value of γ adopted for the entire Statistical Area 48, including the traditional areas of high krill abundance and adjacent grounds. On the basis of the CCAMLR-2000 Survey results, the mean density value here amounted to 21.32 g/m^2 (CV = 11.5%) (SC-CAMLR, 2000). The gross removal intensity estimated here, as calculated for Subareas 48.2 and 48.3, affects the commercial biomass, but since it is concentrated in the local grounds it forms only a small portion of the pre-exploitation biomass B_0. At the same time, the fishery is carried out only during a brief season and not throughout the year, i.e. four to five months per year. As an example, in the South Georgia area it is evident that the mean krill consumption by predators, estimated at 900 000 tonnes per month (11.2 million tonnes per year) is extremely large in comparison with the maximum monthly krill catch of 62 700 tonnes (July 1988, Table 3). The above considerations lead to the conclusion that fishing intensity estimates observed in the years of the maximum fleet intensity are not critical when compared to the γ value.

Even though on the scale of a statistical region, for example Subareas 48.2 and 48.3, there are known to be large interannual fluctuations in krill density (Sushin and Shulgovsky, 1999), on the smaller scale of a fishing ground, high krill densities have always been recorded (Tables 1 and 2). Krill retention and accumulation in these local areas is caused by hydrodynamic features (Makarov, 1996; Maslennikov and Solynkin, 1988; Sushin, 1998). For example, within the anticyclonic water circulation around the South Orkney Islands, quasi-stationary eddies occur caused by the shelf features. The most stable eddy is permanently observed near the western edge of Coronation Island, a locality favoured as a traditional fishing ground by Soviet vessels. Field experiments carried out in the area covering the traditional fishing grounds and reported by Kasatkina et al. (1997) indicated that the total krill biomass transported by water mass into the study area across its boundary exceeded the biomass flowing out. The inflow–outflow balance associated with the study area had a mean value of 2 088 tonnes/hour (CL 95% = 831.0 tonnes/hour). These calculations indicated that the annual outflow of krill into adjacent areas in which the fleet was operating may have amounted to approximately 9.2 million tonnes per year (Kasatkina et al., 1997). In comparison, the maximum krill catch there for the fishing season amounted to 132 500 tonnes. This provides further evidence that competition between the fishery and krill-dependent predators is very small. This is the same conclusion that Ichii et al. (1994) found from an analysis of haul-by-haul data from the Japanese krill fishery.

The analysis presented here assumes that there is no krill flux across the boundary of the fishing grounds. The effect of the annual outflow of krill from the area noted above would result in the reduction of actual fishing intensity even further. This makes an even stronger case for the estimated removal intensity being of minor importance with respect to competition between the fishery and krill-dependent predators.

In terms of monitoring the marine ecosystem, it is very important to understand how the interactions between upper-trophic level predators and krill biomass might be used to manage levels of krill fishing (CCAMLR, 2001). Boyd (2002a) suggested that reduced or even zero fishing might be allowed in the years when the krill biomass was below 24 g/m^2. Analyses of the Soviet fishery presented here indicate that krill availability conditions for the fleet are satisfactory when the mean catch rate exceeds 3–4 tonnes/hour and the commercial biomass density is greater than 100 g/m^2. The minimum CPUE observed during the 1987 to 1991 seasons amounted to 1.7 tonnes/hour and occurred when the krill density in the area was 70 g/m^2. In the region of Elephant Island (Subarea 48.1), Kadilnikov et al. (1989) reported acoustic estimates of krill density of 170 g/m^2 associated with a CPUE of 6.4 tonnes/hour and 210 g/m^2 with a CPUE of 7.9 tonnes/hour.

Comparing these density values, it appears that the fleet and dependent predators operate in different krill density niches. However these do not take into account the availability of krill to dependent species, a topic that requires information on the vertical and horizontal distribution of krill aggregations relative to the predators' foraging range and depth. Comparison of the results derived from analyses of data from commercial krill aggregations sampled by commercial trawls may provide further insights into understanding competition between the fishing fleets and krill-dependent predators.

The use of acoustic methods in krill stock monitoring does not negate the validity of applying analytical models. However, direct comparisons of biomass estimates derived by these two methods must be made with extreme care due to their different characteristics. The analytical methods used in this study provide for direct monitoring of the rate of removal of krill by assessment of the observed fishing intensity and estimates of the biomass on fishing grounds. The acoustic method provides a direct indication of the krill biomass available to the fishing fleet. Combining the two methods allows for the rational exploitation of krill resources by moderating the allowable fishing effort in line with predetermined allowable removal fractions (Kadilnikov et al., 1989; Kasatkina, 2000).

CONCLUSIONS

The results of this study indicate that during periods of maximum fishing intensity, the Soviet fishing fleet had no impact on the krill stock or, consequently, on krill-dependent predators. It is concluded that although there is a spatial overlap of the dependent species and the fishery, this is not sufficient to amount to a functional overlap.

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Table 1: Estimated krill density and biomass over the fishing grounds of the Soviet fleet in Subarea 48.3 (South Georgia) during the seasons 1987 to 1990.

Year and Month	Estimated Krill Density (g/m^2)	Estimated Krill Biomass (thousand tonnes)
1987/88		
July	163.0 ± 51.1	205.3 ± 50.2
August	148.6 ± 37.1	194.6 ± 52.3
April	158.0 ± 31.7	159.5 ± 40.3
May	153.3 ± 38.3	341.9 ± 91.2
June	143.8 ± 32.1	206.5 ± 47.2
Mean for season	154 ± 41.2	221.0 ± 62.1
1988/89		
July	121.3 ± 30.9	404.5 ± 26.3
August	102.4 ± 27.3	315.0 ± 84.0
September	51.8 ± 20.6	63.5 ± 17.4
April	145.3 ± 25.9	216.9 ± 55.7
May	140.3 ± 33.9	255.6 ± 67.3
June	163.8 ± 42..3	188.8 ± 48.1
Mean for season	120.6 ± 39.9	240.3 ± 115.9
1989/90		
July	106.5 ± 21.2	93.3 ± 17.7
August	102.8 ± 23.1	106.7 ± 27.0
September	90.4 ± 28.1	56.2 ± 16.7
May	153.2 ± 40.2	18.3 ± 5.3
June	207.5 ± 50.3	170.1 ± 44.1
July	138.9 ± 32.1	209.5 ± 51.0
August	127.9 ± 30.1	152.6 ± 37.9
September	237.5 ± 67.3	79.1 ± 17.9
Mean for season	130.3 ± 36.1	110.4 ± 63.0

Table 2: Estimated krill density and biomass over the fishing grounds of the Soviet fleet in Subarea 48.2 (South Orkney Islands) during the seasons 1987 to 1990.

Year and Month	Estimated Krill Density (g/m^2)	Estimated Krill Biomass (thousand tonnes)
1987/88		
December	*	0
January	112.3 ± 25.4	96.3 ± 24.2
February	135.5 ± 22.6	101.3 ± 26.2
March	158.7 ± 39.8	165.1 ± 43.2
April	184.7 ± 54.1	206.5 ± 49.3
Mean for season	147.1 ± 37.2	142.3 ± 53.1
1988/89		
December	*	0
January	178.6 ± 33.7	214.8 ± 58.6
February	164.1 ± 47.3	234.1 ± 64.9
March	186.3 ± 42.1	76.0 ± 19.1
Mean for season	175.4 ± 33.9	174.7 ± 86.1
1989/90		
December	138.4 ± 25.7	239.4 ± 64.0
January	144.8 ± 31.9	404.2 ± 114.2
February	267.9 ± 56.3	181.8 ± 49.9
March	326.3 ± 99.1	282.4 ± 76.7
April	312.3 ± 72.3	303.9 ± 78.1
Mean for season	237.5 ± 62.3	281.0 ± 78.3

* Insufficient number of hauls

Table 3: Analysis by month of fishing by the Soviet fleet in Subarea 48.3 (South Georgia) during the seasons 1987 to 1990. CPUE – mean catch per hour of trawling using the standard fishing system. Fishing intensity calculated from Annex 1, Equation 1; fishing mortality intensity from Annex 1, Equation 14; gross removal intensity from Annex 1, Equations 15 and 16.

Year and Month	Mean CPUE (tonnes/hour)	Total Catch (all vessels) (tonnes)	Fishing Effort (hours trawling)	Fishing Intensity (*i*)	Fishing Mortality Intensity	Gross Removal Intensity	Proportion of Available Krill Removed by Fishery (%)
1987							
July	5.4	38 604	7 149	0.188 ± 0.046	0.00107 ± 0.00049	0.190 ± 0.046	18.8
August	5.2	25 101	4 827	0.129 ± 0.034	0.00071 ± 0.00033	0.130 ± 0.034	12.9
1988							
April	5.2	16 428	3 159	0.103 ± 0.028	0.00056 ± 0.00026	0.104 ± 0.053	10.3
May	5.0	41 025	8 205	0.120 ± 0.032	0.00073 ± 0.00031	0.121 ± 0.039	12.0
June	4.7	47 901	10 192	0.232 ± 0.53	0.00140 ± 0.0063	0.233 ± 0.032	23.2
July	4.0	62 694	15 674	0.155 ± 0.039	0.00094 ± 0.00042	0.156 ± 0.039	15.5
August	3.4	37 799	11 117	0.120 ± 0.032	0.00070 ± 0.00031	0.121 ± 0.032	12.0
September	1.7	5 779	3 399	0.091 ± 0.025	0.00051 ± 0.00023	0.092 ± 0.026	9.1
1989							
April	4.8	29 442	6 134	0.136 ± 0.035	0.0009 ± 0.00036	0.137 ± 0.036	13.6
May	4.6	34 001	7 392	0.133 ± 0.035	0.00077 ± 0.00035	0.134 ± 0.036	13.3
June	5.4	29 645	5 490	0.157 ± 0.040	0.00092 ± 0.00041	0.158 ± 0.040	15.7
July	3.5	33 960	9 703	0.334 ± 0.067	0.00220 ± 0.00099	0.235 ± 0.067	36.4
August	3.4	16 006	4 708	0.150 ± 0.038	0.00087 ± 0.00039	0.151 ± 0.036	15.0
September	3.0	7 755	2 585	0.138 ± 0.041	0.00080 ± 0.00036	0.139 ± 0.041	13.8
1990							
May	5.0	1 009	202	0.055 ± 0.016	0.00031 ± 0.00014	0.055 ± 0.016	5.5
June	6.8	19 565	2 877	0.115 ± 0.030	0.00066 ± 0.00030	0.116 ± 0.030	11.5
July	4.6	39 600	8 609	0.189 ± 0.046	0.00113 ± 0.00051	0.190 ± 0.046	18.9
August	4.0	25 787	6 447	0.169 ± 0.042	0.00100 ± 0.00045	0.170 ± 0.042	16.9
September	4.2	18 670	4 445	0.238 ± 0.054	0.00150 ± 0.00067	0.239 ± 0.054	23.6

Table 4: Analysis by month of fishing by the Soviet fleet in Subarea 48.2 (South Orkney Islands) during the seasons 1987 to 1990.

Year and Month	Mean CPUE (tonnes/hour)	Total Catch (all vessels) (tonnes)	Fishing Effort (hours trawling)	Fishing Intensity (*i*)	Fishing Mortality Intensity	Gross Removal Intensity	Proportion of Available Krill Removed by Fishery (%)
1987/88							
December	0	0	0	0	0	0	0
January	3.5	16 074	4 592.6	0.167 ± 0.042	0.00098 ± 0.00044	0.1678 ± 0.042	16.7
February	3.7	14 579	3 940.3	0.144 ± 0.037	0.00084 ± 0.00038	0.1447 ± 0.037	14.4
March	4.5	21 459	4 768.7	0.130 ± 0.034	0.00075 ± 0.00034	0.1306 ± 0.038	13.0
April	5.3	40 681	7 675.7	0.197 ± 0.047	0.00120 ± 0.00054	0.1980 ± 0.046	19.7
1988/89							
December	0	0	0	0	0	0	0
January	5.9	21 268	3 604.7	0.099 ± 0.027	0.00056 ± 0.00021	0.0995 ± 0.027	9.9
February	5.4	19 427	3 597.6	0.083 ± 0.023	0.00047 ± 0.00021	0.0834 ± 0.022	8.3
March	5.6	10 034	1 791.8	0.132 ± 0.034	0.00076 ± 0.00034	0.1327 ± 0.033	13.2
1989/90							
December	4.6	27 776	6 038.3	0.116 ± 0.031	0.00067 ± 0.00030	0.1166 ± 0.033	11.6
January	4.8	18 591	3 873.1	0.046 ± 0.013	0.00026 ± 0.00012	0.0462 ± 0.013	4.6
February	8.9	16 542	1 858.6	0.091 ± 0.025	0.00051 ± 0.00023	0.0915 ± 0.015	9.1
March	10.8	25 981	2 405.6	0.092 ± 0.025	0.00052 ± 0.00023	0.0925 ± 0.025	9.2
April	10.4	43 763	4 208.0	0.144 ± 0.037	0.00084 ± 0.00038	0.1450 ± 0.034	14.4

Table 5: Results of fishing by the Soviet fleet in Subarea 48.2 (South Orkney Islands) by fishing season.

Season	Mean CPUE (tonnes/hour)	Total Catch (all vessels) (tonnes)	Fishing Effort (hours trawling)	Krill Biomass (thousand tonnes)	Fishing Intensity (*i*)	Fishing Mortality Intensity	Gross Removal Intensity
1987/88	4.3	92 793	21 580	468.7 ± 114.2	0.156 ± 0.038	0.00120 ± 0.00054	0.1990 ± 0.0380
1988/89	5.6	50 729	9 059	539.7 ± 149.3	0.094 ± 0.026	0.00053 ± 0.00024	0.0945 ± 0.0260
1989/90	7.4	132 653	17 926	908.8 ± 230.3	0.146 ± 0.037	0.00085 ± 0.00628	0.1467 ± 0.0370

Table 6: Results of fishing by the Soviet fleet in Subarea 48.3 (South Georgia) by fishing season.

Season	Mean CPUE (tonnes/hour)	Total Catch (all vessels) (tonnes)	Fishing Effort (hours trawling)	Krill Biomass (thousand tonnes)	Fishing Intensity (*i*)	Fishing Mortality Intensity	Gross Removal Intensity
1987/88	4.3	211 626	49 215	1640.5 ± 432.4	0.129 ± 0.034	0.00075 ± 0.00034	0.130 ± 0.034
1988/89	4.3	150 809	35 072	1032.9 ± 261.8	0.146 ± 0.037	0.00085 ± 0.00036	0.147 ± 0.037
1989/90	4.8	104 631	21 798	792.6 ± 204.2	0.132 ± 0.034	0.00076 ± 0.00034	0.133 ± 0.034

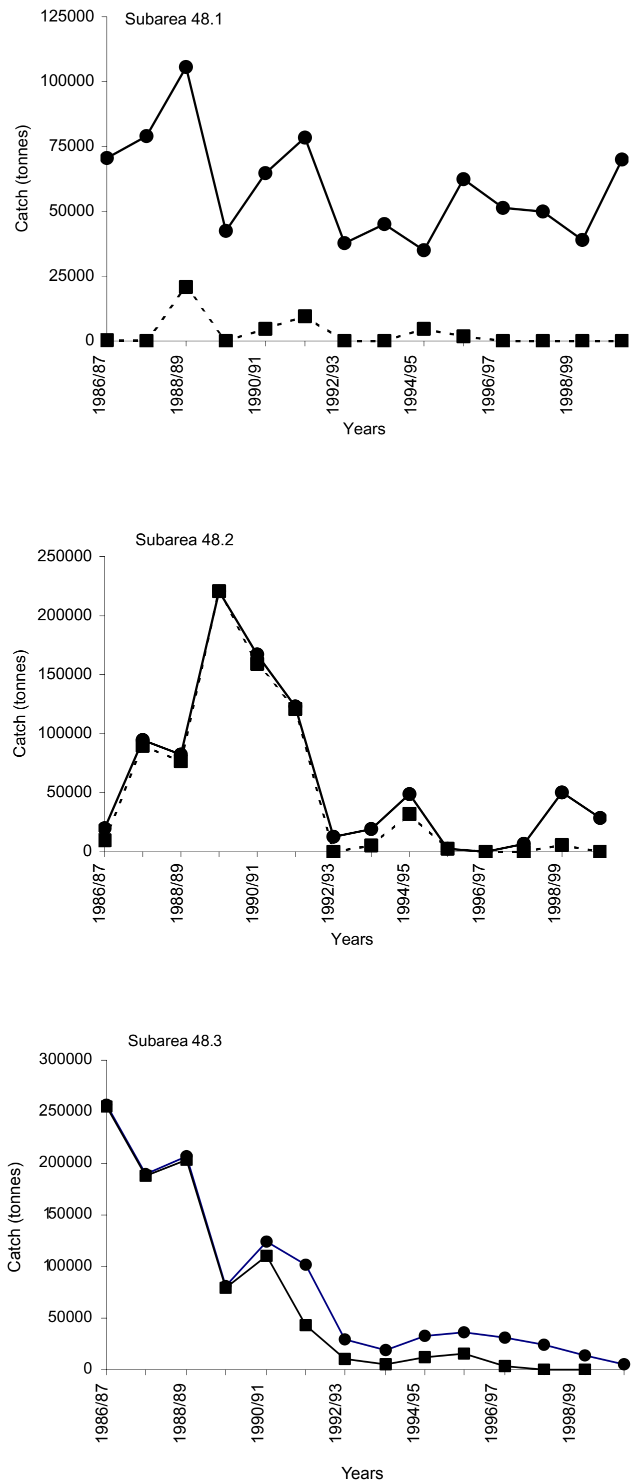


Figure 1: Distribution of annual reported krill catches. ■ – catches of Soviet fleet; • – total catches.

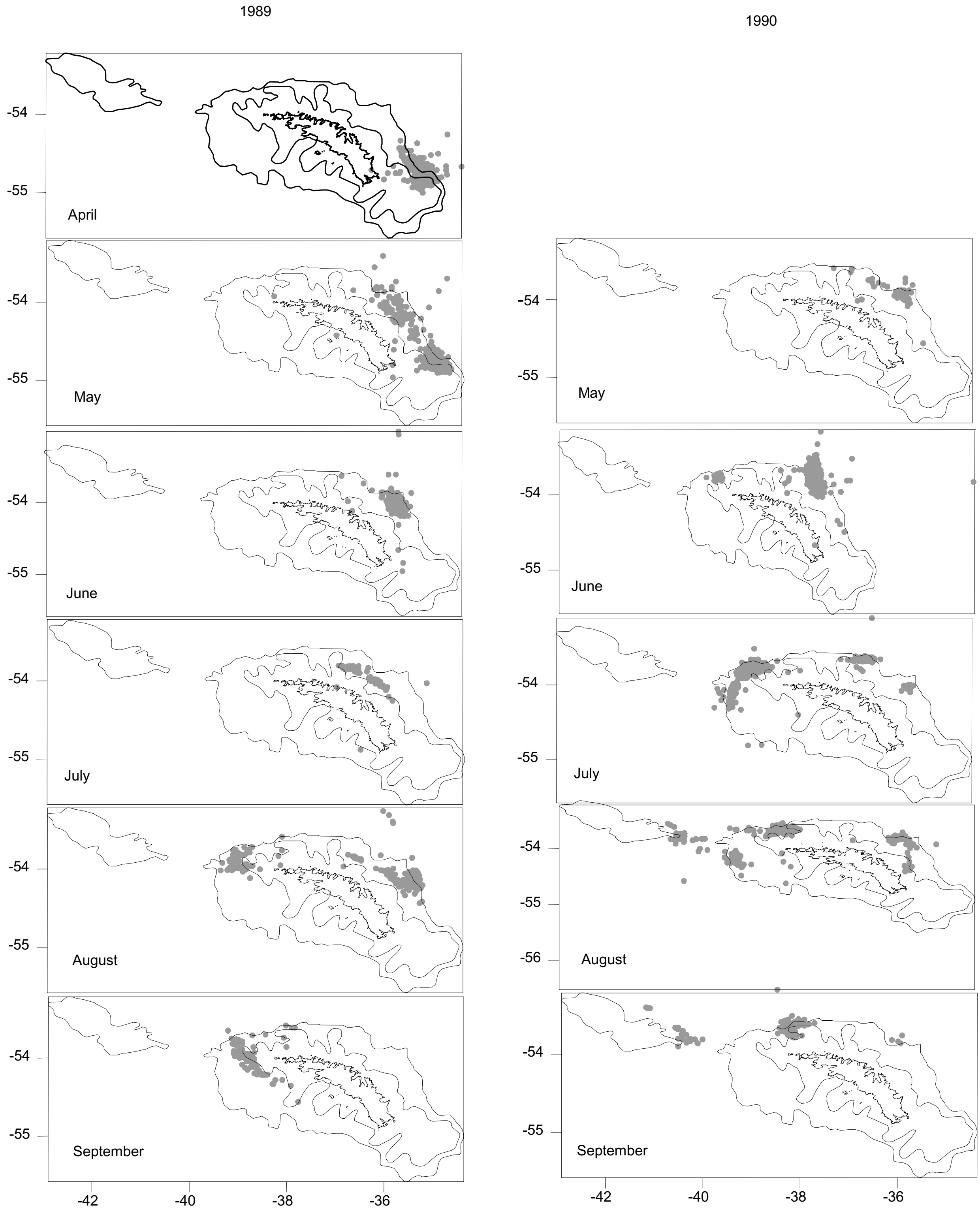


Figure 2: Location of the Soviet fleet in Subarea 48.3 during the 1989 and 1990 seasons (from April to September) by month.

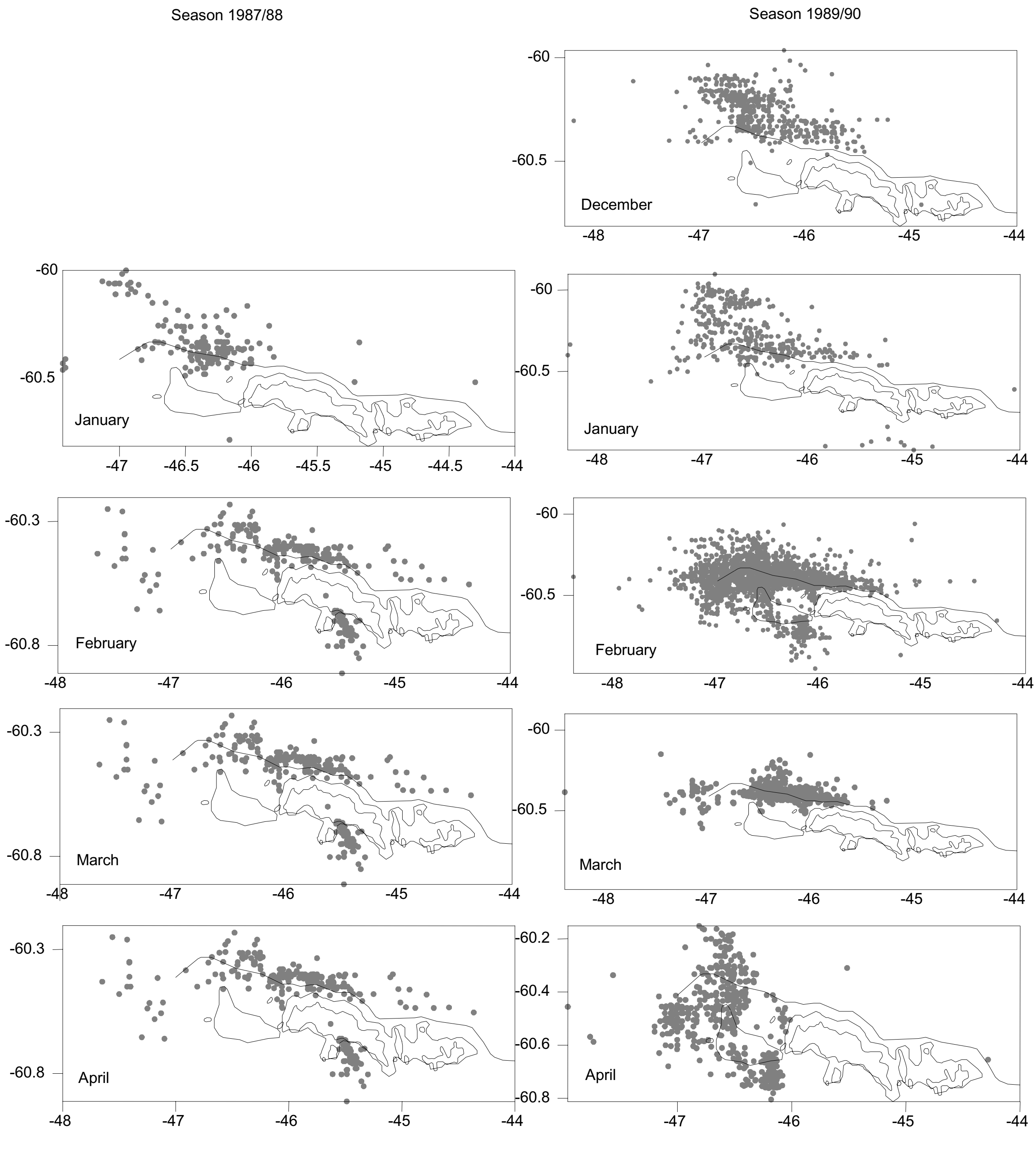
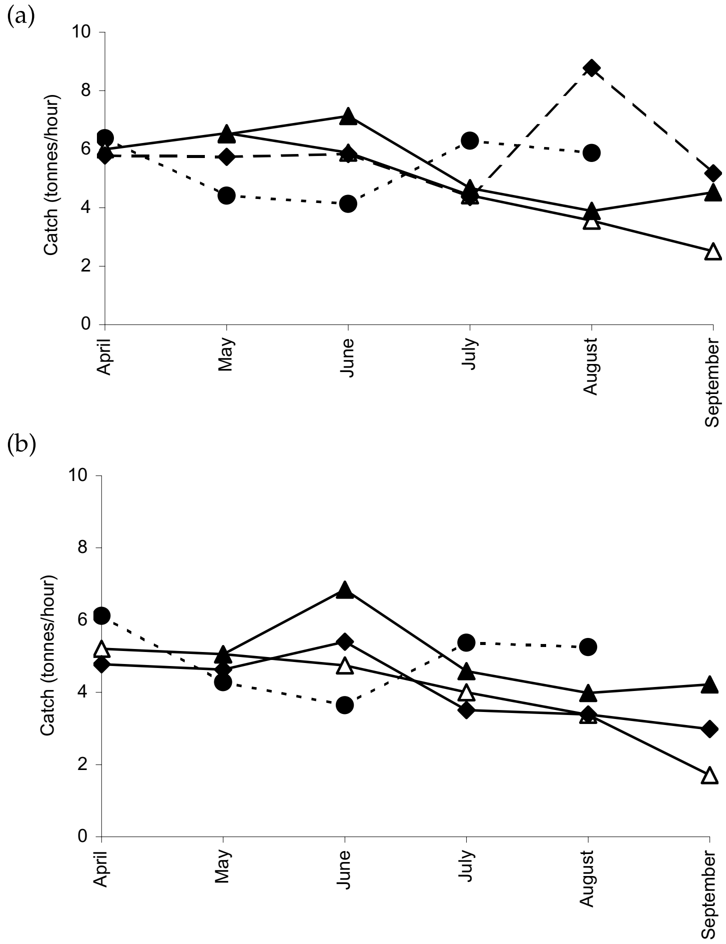


Figure 3: Location of the Soviet fleet in Subarea 48.2 during the 1987/88 and 1989/90 seasons (from December to April) by month.



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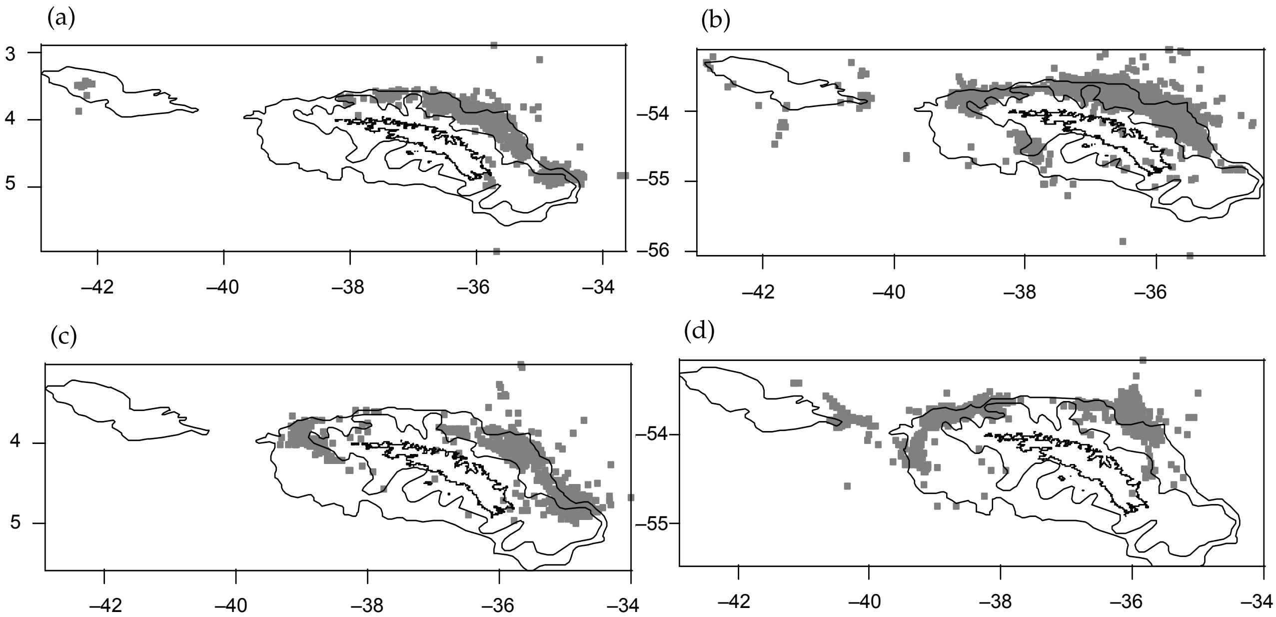
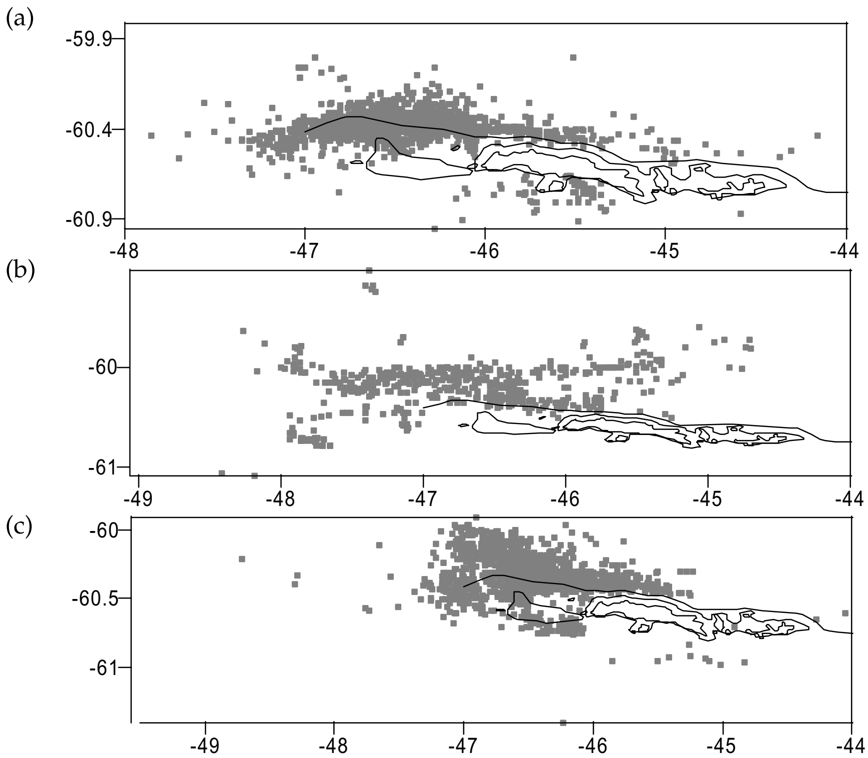


Figure 5: Distribution of Soviet krill fishing vessels in the South Georgia area from 1987 to 1990: (a) April–September 1987, (b) April–September 1988, (c) April–September 1989, (d) April–September 1990.



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APPENDIX 1

BASIC PRINCIPLES OF THE PROBABILITY STATISTICAL THEORY OF FISHERY SYSTEMS AND THE MODEL FOR FISHING INTENSITY EVALUATION

The statistical model to describe the fishing capabilities of trawl nets, developed by Kadilnikov (2001) at AtlantNIRO was used in this study. The applicability of this model to the Southern Ocean krill fishery has been tested experimentally by Kasatkina (1988); Kadilnikov et al. (1989) and Zimarev et al. (1990). The key components of the model are summarised below.

Fishing intensity (i) is assessed using the ratio of the number of the target species that are caught (n_1) to the original number n that were present in the area at the commencement of a particular period of fishing.

$$i = \frac{n_1}{n} \tag{1}$$

where the value of n might, for example, be derived from fishery-independent acoustic surveys over the fishing grounds, the value of i can be estimated from the known removals in the fishery (n_1) using Equation (1) (Kadilnikov et al., 1989; Kasatkina, 2000).

From an analysis of the distribution of the fishing intensity (i) in Equation 1, the probability (P_Σ) that an individual krill is caught when several vessels are fishing together can be estimated.

The appropriate equation for this calculation will be dependent on the relationship between the fishing activities of the individual vessels. Two possibilities are considered.

In the situation when the tracks of individual hauls do not cross the probability $P_{\Sigma(1)}$ equivalent to the fishing intensity is estimated using Equation 1:

$$P_{\Sigma(1)} = 1 - \exp\left(-p\frac{BN}{B_0}\right) \tag{2}$$

where

B – the volume of water within which krill might be vulnerable to capture by the net (see Equation 5)
N – number of hauls;
B_0 – volume of water within the area circumscribed by all active vessels in the fleet;
p – trawl catchability.

In the situation where the tracks of the individual hauls cross, the probability $P_{\Sigma(2)}$ is given by Equation 3:

$$P_{\Sigma(2)} = 1 - \exp\left\{-\frac{BN}{B_0}\left[1-(1-p)^N\right]\right\} \tag{3}$$

Values of $P_{\Sigma(1)}$ and $P_{\Sigma(2)}$ are the estimates of fishing intensity for the two alternative fishing patterns. The actual fishing intensity will be within the following interval:

$$P_{\Sigma(1)} < i < P_{\Sigma(2)} \tag{4}$$

The value of $P_{\Sigma(2)}$ will be the maximum estimate and the actual value cannot exceed it. The greater the number of vessels operating in the fishery, the greater the chance that the tracks along which they haul will cross. This moves further to the right the smaller the area and the greater the number of vessels fishing. For the fishing activities considered in this study, the value is close to the right-hand limit.

The volume of water within which krill might be vulnerable to capture by the net calculated from Equation 5:

$$B = l_t h_t v_t \tau_t \tag{5}$$

where

l_t – horizontal distance between the trawl boards
v_t – trawling velocity;
τ_t – trawling duration;
h_1 – vertical activity zone ;
h_1 = h_t for $h_t \leq H$
h_1 = H for $h_t > H$
where:
h_t – vertical opening of the trawl net;
H – vertical extent of the water layer within which krill are present.

At high values of N the term $(1\text{-}P)^N$ in Equation 3 quickly approaches zero. Therefore at high N, the estimate of fishing intensity $P_{\Sigma(2)}$ is not dependent on catchability (p) and may be estimated using the following equation:

$$P_{\Sigma(2)} = 1 - \exp\left(-\frac{BN}{B_0}\right) \tag{6}$$

The fishing effort (in trawling hours, hauls or number of vessels) required to obtain this value can be calculated by taking the logarithms of the values in Equations 2 and 5.

When different fishing systems are present in the fishery, the fishing effort is standardised around the most commonly used gear and vessel type. The overall fishing effort is estimated as the sum of the different systems. The catch by weight per hour trawling within the standard fishing system is taken as a measure of fishing efficiency.

A coefficient of relative fishing efficiency (k_i) can be estimated for the i-th fishing system as follows:

$$k_i = \frac{q_i}{q_s} \tag{7}$$

where q_i is catch per hour of trawling with i-th fishing system and q_s is catch per hour of trawling with the standard fishing system.

Fishing effort for the standard number of trawling hours is defined as follows:

$$T_s = \sum_{i=1}^{m} k_i T_i \tag{8}$$

where T_i is the number of trawling hours for i-th fishing system and m is the number of fishing system.

The respective number of standard hauls will be

$$N_s = \frac{T_s}{\tau_s} \tag{9}$$

where T_s is mean duration of trawling with a standard fishing system.

At the relatively low catchability of the krill trawl of $0.02 < p < 0.2$ when the catch per trawling hour varies almost linearly with vessel power and trawl size (Kadilnikov, 1993; Zimarev et al., 1990; Kasatkina, 1991), the standard number of trawling hours may be obtained as a quotient of the total catch divided by the catch per trawling hour for the standard fishing system.

The initial biomass prior to the commencement of fishing, i.e. the biomass available to the fishery, is estimated as follows:

$$Q = \frac{C}{P_{\Sigma}} \tag{10}$$

where C is total catch and P_{Σ} is fishing intensity.

The estimated initial biomass value will be minimum at a fishing intensity of $P_{\Sigma(2)}$. The actual biomass will most likely be higher and within the range:

$$Q_2 \leq Q_i < Q_1 \tag{11}$$

where Q_2 is the abundance before the start of the fishery based on the fishing intensity estimate when the tracks of the individual hauls cross; Q_1 is the abundance before fishing commenced based on the fishing intensity estimate when the tracks of the individual hauls N_T do not cross; and Q_i is the actual initial abundance.

If the total catch and fishing ground are estimated with reasonable accuracy, the relative error of fishing intensity $P_{\Sigma(2)}$, estimated as the upper theoretically probable limit for the applied fishing effort, will depend only on the relative error of the volume of water in which krill are present.

$$\Sigma(P_{\Sigma(2)}) = \Sigma(Q_2) = \Sigma(B_0)\exp\left(-\frac{BN_T}{B_0}\right) \tag{12}$$

The estimation of the catchability p of the commercial trawl designated as the standard fishing gear is made applying the theoretical model to the individual types of commercial trawl. The trawl catchability p is designated by the following multiplicative scheme:

$$p = p_1 p_2 p_3 p_4 p_5 p_6 p_7 p_8 p_9 p_{10} \tag{13}$$

where p_1 to p_{10} are elements of catchability that are used to describe the process of krill being taken from the fishing zone B (the volume of water which might be fished by the net) into the codend of the trawl bag taking account of selectivity. The algorithms of these elements of the catchability used in this assessment, are based on the knowledge of the trawl design components and the distribution pattern of krill aggregations that are being fished.

The intensity of krill removal during the fishery has been estimated as the intensity of gross removal, P, determined as fishing intensities P_Σ and fishing mortality $P_{\Sigma(q)}$.

The fishing mortality intensity during a series of N hauls can be estimated as follows:

$$P_{\Sigma(q)} = 1 - \exp\left(-\frac{BN}{B_0} p_q\right) \tag{14}$$

Gross removal intensity when trawling tracks intersect is estimated as follows:

$$P_{\Sigma(2)} = P_{\Sigma(2)} + P_{\Sigma(q)} - P_{\Sigma(2)} P_{\Sigma(q)} \tag{15}$$

and when the trawling tracks do not cross it is estimated as:

$$P_{\Sigma(1)} = P_{\Sigma(1)} + P_{\Sigma(q)} - P_{\Sigma(1)} P_{\Sigma(q)} \tag{16}$$

The assessment of the intensity of krill mortality during fishing was made assuming that all krill coming into contact with the meshes of the trawl would perish, i.e. the probability of mortality of krill that are present in the vicinity of the net in a particular haul is maximised.

Haul-by-haul data from each vessel active in the fishery are used. These include the following data fields:

vessel type
coordinates of start and finish of each haul
start and end times of each haul
depth of the trawl when fishing
catch per haul
catch per hour trawling
length and species composition of the catch.