KRILL (*EUPHAUSIA SUPERBA*) DISTRIBUTION IN RELATION TO WATER MOVEMENT AND PHYTOPLANKTON DISTRIBUTION OFF THE NORTHERN SOUTH SHETLAND ISLANDS

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Abstract

In December/February 1990/91 a survey was conducted by RV *Kaiyo Maru* in the vicinity of the South Shetland Islands and Elephant Island. The main objective of the survey was to investigate the mechanisms responsible for the concentration of krill and to estimate krill biomass in the area surveyed. Krill biomass estimation was done by means of hydroacoustics. Phytoplankton distribution was assessed by measuring surface concentrations of chlorophyll *a*. Water circulation was studied with satellite-tracked buoys equipped with curtain drogues deployed at a level of 30 m from the surface because at this level krill concentrations are most frequently observed. Main krill concentrations were observed in shelf waters north of the islands as usual. Tracking of buoys demonstrated the existence of convergent complex eddies in shelf waters of these islands. A high concentration of chlorophyll *a* was also recorded in shelf waters. A spatial correlation between distributions of krill and chlorophyll *a* was observed. It is therefore considered that both hydrodynamic and food availability factors may be responsible for krill concentration. On a traditional krill fishing ground north of Livingston Island, krill density had increased 3.4 times over a period of 40 days from late December 1990 to early February 1991. This increased krill density in early February 1991 (157 g/m^2) was 54% lower than that observed in late January 1988. Information from studies of krill predators by US scientists also indicated that krill abundance during the first half of the 1990/91 summer was lower than that in previous seasons. Total biomass of krill in shelf waters of the area surveyed was estimated at 1.78 million tonnes (56 g/m^2) in late January 1991. The obtained estimate of krill biomass should be regarded as the lower level for this time of the season. From mid-February and onwards it was reported that krill abundance had increased to the normal level.

Résumé

En décembre/février 1990/91, les alentours des îles Shetland du Sud et Eléphant ont fait l'objet d'une campagne d'évaluation à bord du RV *Kaiyo Maru*. L'objectif principal de la campagne était l'investigation des mécanismes responsables de la concentration du krill et l'estimation de la biomasse du krill dans la région étudiée. C'est au moyen de méthodes hydroacoustiques qu'a été évaluée la biomasse du krill. La répartition du phytoplancton a été estimée en mesurant les concentrations de surface de chlorophylle *a*. Les mouvements de l'eau ont été étudiés à l'aide de bouées suivies par satellite et équipées d'ancres de cape, déployées à 30 m de profondeur, niveau auquel les concentrations de krill sont le plus fréquemment rencontrées. Comme de coutume, les principales

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concentrations de krill ont été observées dans les eaux du plateau nord des îles. La poursuite de bouées a révélé l'existence de tourbillons complexes d'eaux convergentes sur le plateau de ces îles. Une concentration élevée de chlorophylle *a* a également été relevée dans les eaux du plateau. Une corrélation spatiale a été établie entre la présence du krill et celle de chlorophylle *a*. Il est ainsi possible d'envisager que les facteurs hydrodynamiques et de disponibilité de nourriture soient responsables de la concentration du krill. Dans un lieu de pêche traditionnel de krill, au nord de l'île Livingston, la densité du krill a augmenté de 3,4 fois en une période de 40 jours de fin décembre 1990 à début février 1991. Cette densité accrue de krill (157g/m^2), début février 1991, était de 54% inférieure à celle observée fin janvier 1988. Les informations provenant des études des prédateurs de krill par les scientifiques des USA ont également indiqué que, pendant la première moitié de l'été 1990/91, l'abondance de krill était inférieure à celle des saisons précédentes. La biomasse totale de krill des eaux du plateau de la région étudiée était estimée à 1,78 millions de tonnes (56g/m^2) fin janvier 1991. Cette estimation devrait être considérée comme étant la plus faible pour cette époque de la saison. A partir de mi-février, l'abondance de krill relevée avait augmenté pour rejoindre le niveau normal.

Резюме

В декабре-феврале 1990/91 гг. в районе Южных Шетландских островов и острова Элефант была проведена съемка НИС *Kaiyo Maru*. Главными целями съемки являлись исследование действия механизмов, влияющих на концентрацию криля и оценка биомассы криля в районе съемки. Оценка биомассы криля была осуществлена методом гидроакустики. Распределение фитопланктона исследовалось путем измерения поверхностных концентраций хлорофилла *a*. Циркуляция воды изучалась при помощи спутникового слежения за буями, оснащенными плавучими якорями, которые были размещены на уровне 30 метров от поверхности, поскольку чаще всего концентрации криля наблюдаются на этом уровне. Основные концентрации криля, как обычно, наблюдались в шельфовых водах к северу от островов. Слежение за буями помогло обнаружить присутствие конвергентных сложных водоворотов в шельфовых водах этих островов. Также в шельфовых водах был зарегистрирован высокий уровень концентрации хлорофилла *a*. Наблюдалась пространственная коррелляция между распределениями криля и хлорофиллом *a*. В связи с этим считается, что как гидроакустический фактор, так и фактор присутствия пищи могут влиять на распределение криля. За 40-дневный период, длившийся с конца декабря 1990 г. до начала февраля 1991 г., плотность криля на традиционном участке промысла криля к северу от острова Ливингстон возросла в 3,4 раза. Эта, возросшая в начале февраля 1991 г., плотность, составившая 157 г/м^2, была на 54% ниже, чем наблюденная в конце января 1988 г. Данные исследований по хищникам криля, проведенных американскими учеными также показали, что численность криля в течение первой половины лета 1990/91 г. была ниже, чем в предыдущие сезоны. Общая биомасса криля в шельфовых водах района съемки в конце января 1991 г. составила 1,78 миллионов тонн (56 г/м^2). Полученная оценка биомассы криля должна считаться низкой для этого времени сезона. С середины февраля и далее начали поступать сведения о восстановлении нормального уровня численности криля.

Resumen

De diciembre a febrero 1990/91, el BI *Kaijo Maru* realizó una prospección alrededor de las islas Shetland del Sur y Elefante. El objetivo principal consistió en investigar los mecanismos responsables de la concentración de krill y estimar la biomasa del krill en el área estudiada que se determinó hidroacústicamente. La distribución del fitoplancton se calculó por la clorofila-*a* superficial. La circulación del agua se estudió mediante el despliegue de boyas rastreadas por satélite, equipadas con unas "pantallas para medir corrientes" a una profundidad de 30 m de la superficie ya que las concentraciones de krill se encuentran más frecuentemente a estas profundidades. Como es lo usual, las concentraciones de krill más importantes se encontraron en la plataforma, al norte de las islas. El rastreo de las boyas demostró la existencia de complicados torbellinos convergentes en las aguas de la plataforma de estas islas. Estas aguas también registraron una alta concentración de clorofila-*a*. Se observó una correspondencia espacial entre las distribuciones de krill y de clorofila-*a*, concluyéndose así que tanto la hidrodinámica como la disponibilidad de alimento son factores que afectan la concentración de krill. En un caladero tradicional de krill situado al norte de la isla Livingston, la densidad de krill ha aumentado 3.4 veces en un período de 40 días, de fines de diciembre de 1990 a principios de febrero de 1991. Este aumento de la densidad del krill a principios de febrero de 1991 (157 g/m^2) representa una reducción de un 54% en comparación con aquella observada a fines de enero de 1988. Las investigaciones de científicos estadounidenses sobre los depredadores de krill, corroboraron el descenso en la abundancia de krill durante la primera mitad de la temporada 1990/91 en comparación con temporadas anteriores. La biomasa total de krill en las aguas de la plataforma de la zona estudiada se calculó en 1.78 millones de toneladas (56 g/m^2) a fines de enero de 1991. Esta cifra de biomasa debiera ser considerada como el nivel inferior de la temporada. Desde mediados de febrero en adelante se informó que la abundancia de krill había aumentado a niveles normales.

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1. INTRODUCTION

Krill concentrations regularly observed in the waters north of the South Shetland Islands and north and west of Elephant Island. Japanese krill fishing trawlers have mainly operated in this region with the yearly catches of 10 000 to 70 000 tonnes for the past eight years. This region, because of the abundance of krill-dependent predators, is also designated as an Integrated Study Region by CCAMLR.

This krill-rich region is, however, only insufficiently known in regard to mechanisms responsible for high abundance of krill and interannual variability in its biomass. As basic information for these matters, this paper will present the distributional pattern of krill biomass in relation to water flow and chlorophyll *a* (Chl-*a*) distribution in 1990/91 austral summer.

2. MATERIALS AND METHODS

The survey conducted in December/February 1990/91 by RV *Kaiyo Maru* was comprised of two legs. The first one covered the South Shetland Islands and Elephant Island regions including waters along the western side of the Antarctic Peninsula (Leg I: 22 to 29 December, 1990, Figure 1), whereas the second one covered thoroughly the waters from north of Elephant Island to north of the South Shetland Islands (Leg II: 18 January to 4 February, 1991, Figure 2).

2.1 Physical Oceanography and Chlorophyll *a* Studies

Oceanographic data were collected using a Sea-Bird SBE-19 CTD probe. CTD stations were taken down to 1 000 m or to the sea bottom in shallow areas. Water samples were obtained from 11 depth levels (0, 10, 20, 30, 40, 50, 75, 100, 125, 150 and 200 m). Chl-*a* concentration was determined by fluorometric method with a Turner Model-III fluorometer after extraction with 90% acetone (Strickland and Parsons, 1972).

2.2 Hydroacoustic Studies

Hydroacoustic studies were carried out in order to determine (i) the overall distribution of krill biomass in the survey area; and (ii) changes in krill abundance which took place in time between Leg I and Leg II on krill fishing grounds north of Livingston Island (shown as shaded areas in Figures 1 and 2). Observations were conducted along closely-spaced transects (4-mile intervals). The fact that Leg II of the survey was carried out almost in the same area as the previous cruise of RV *Kaiyo Maru* in 1988 (Fisheries Agency, 1989), made it possible to observe interannual variability in krill biomass in this area.

The echosounder used was FQ-50 with a digital integrator (Furuno Electric, Japan). Operating frequency was 200 kHz. Operational characteristics of the acoustic system is summarised in Table 1. Throughout the whole survey, excluding time spent for station measurements and net towing, the mean volume back-scattering strength (MVBS) was measured for constant horizontal integration intervals of 1 n mile and the depth range from 10 to 200 m or to the bottom if shallower. The top level of the integration depth, 10 m, was changed sometimes to 20 m in order to avoid impact of the surface noise. The default value of the target strength of krill was -66.1 dB per kilogram wet weight of krill (Shimadzu *et al.*, 1989). This value was obtained by Shimadzu *et al.* (1989) who measured krill of about the same size as observed during the present survey. Before (29 October 1990) and after (26 March 1991) of the cruise, the echo-integrator was calibrated in the port of Tokyo with the help of a hydrophone. Two calibrations showed a little reduction in the source level and receiving sensitivity of the echo-integrator after the cruise.

2.3 Drifting Buoy Studies

For the study of flow patterns around the islands, five drifting buoys (model C-2243, TOKYOCOM, Japan) were released in each Leg (Figures 1 and 2) and tracked using the Argos system carried on TIROS-N and NOAA-A satellites. Typically, twelve locations per day were obtained for each buoy with an accuracy higher than several hundred metres. Since krill in this region tended to be most abundant within the depth range of 30 to 40 m (Fisheries

Agency, 1989; observations of the 1987/88 austral summer), each buoy was equipped with a curtain drogue (4 m x 1 m) deployed at 30 m depth in order to study flow patterns at this depth.

3. RESULTS

3.1 Physical Oceanography

Figure 3 shows the horizontal distribution of salinity at 30 m depth during Leg II. Waters in the study region are divided into three categories, i.e. oceanic, frontal and shelf waters. The frontal waters, which are called CWB (Continental Water Boundary), are characterised by a relatively intense southward increase in salinity (from 33.7 to 34.1 ppt) and are restricted to a narrow band near the continental slope.

3.2 Chlorophyll *a*

High concentration of surface Chl-*a* was observed in the shelf waters with the richest area (higher than 1.0 mg/m^3) located to the north of Livingston Island (Figure 4). High gradients of Chl-*a* concentration were observed over the frontal waters with concentration values decreasing northward. Chl-*a* concentration was very low (0.2 to 0.3 mg/m^3) in the oceanic waters.

3.3 Hydroacoustic Surveys

Mean krill density was calculated for each distance between stations along the cruise track (Figures 5 and 6). In Leg I krill tended to form small or dispersed swarms with the biomass of 22 to 76 g/m^2 along the Antarctic Peninsula and 16 to 123 g/m^2 near Livingston Island. The highest value (123 g/m^2) was observed in the shelf waters north of Livingston Island. Krill were absent from a large part of the survey region. The fact that one krill fishing trawler operated at that time not only to the north of Livingston Island but also to the north of King George Island implies that the acoustic survey failed to detect krill to the north of King George Island, probably because krill occurred in widely spaced small swarms. On the traditional fishing ground on the northern shelf of Livingston Island, where the intensive acoustic survey was undertaken, the average biomass of krill was 46 g/m^2 on 25 December, 1990.

During Leg II the acoustic survey revealed a distinct tendency of high krill abundance observed in shelf waters, low abundance in oceanic waters and intermediate abundance in frontal waters. Higher values of biomass (> 100 g/m^2) were most frequently observed to the north of the South Shetland Islands with the highest biomass of 397 g/m^2. In oceanic waters, where krill were almost absent during Leg I, biomass of approximately 10 g/m^2 was observed during Leg II. On the traditional fishing ground the average biomass was 157 g/m^2 on 3 February, 1991.

To obtain the total biomass throughout the Leg II survey area (defined by broken lines in Figure 6), the area was divided into five subareas according to the regularity in krill density distribution. Krill biomass was calculated for each subarea. The total biomass, the sum of the biomass calculated for each subarea, was 2.11 million tonnes, of which 1.78 million tonnes (157 g/m^2) was concentrated in shelf waters (subareas C, D and E).

3.4 Drifting Buoy Studies

Seven buoys continued to operate for more than 50 days, while the other three failed shortly after deployment. Figure 7 shows tracks of four buoys.

Buoy 1 deployed in oceanic waters moved northeast with meandering and eddying current and arrived at South Georgia region five and a half months after deployment. The buoy appeared to drift in the Weddell-Scotia Confluence from west of Elephant Island onward. It was retrieved west of South Georgia, where Russian and Japanese trawlers were conducting winter krill fishing. Another buoy released in oceanic waters in Leg I (not shown in Figure 7) drifted eastward between Elephant Island and King George Island, and was trapped by erratic oceanic eddies to the east of Elephant Island. This buoy, in the end, became entrained in waters adjacent to Elephant Island.

Buoys 2 and 3 drifted eastward in the northern and southern portions of frontal waters, respectively. The latter one, however, recurved landward, then became entrained within the eddy north of Livingston Island and for a duration of one and half circulations before exiting it. The buoy left the eddy on the day when a furious storm occurred (wind scale was 10 by Beaufort scale). The buoy further travelled round the South Shetland Islands anticlockwise (with smooth current on the southern side of the islands and erratically rotating current on the northern side) and, surprisingly, executed more than one and a half circulations around the islands before ceasing to transmit. The track of this buoy elucidated the occurrence of complex eddies in the waters north of the South Shetland Islands. As for Buoy 2, it continued to drift eastward, then became entrained in the waters adjacent to Elephant Island, and went round the island anticlockwise while moving in loops along both the northern and western sides of the island.

Buoy 4 deployed in the shelf area moved east, then reversed and was trapped in Barclay Bay on the northern side of Livingston Island. It stalled there for more than seven months.

Thus, the buoys exhibited a distinct tendency to be trapped in complex topographical eddies generated in shelf waters.

4. DISCUSSION

Major concentrations of krill were observed in shelf waters north of the South Shetland Islands and Elephant Island, which mainly corresponds with the general pattern of krill distributions expected for the summer season. This study suggests two factors responsible for krill concentration. One is a convergent accumulation of krill by complex topographic eddies. Because of its rather stationary nature, the topographic eddies may provide some spatially-stable sites for retention of krill swarms, leading to the formation of persistent concentrations. Another factor is a behavioural response of krill. High concentration of Chl-*a* was observed in shelf waters. Krill arriving to near the islands would detect and respond to concentration gradient of phytoplankton (Price, 1989) and as the result would congregate actively in shelf waters. It is reasonable to assume that these two factors worked together, and resulted in a marked increase of krill abundance over the period from Leg I to Leg II (Figures 5 and 6).

Buoy 1 travelled all the way to South Georgia and has been trapped on krill winter fishing grounds. This implies that krill can reach their favourable habitats (e.g., island regions) even by passive drifting only. Considering the observed strong current-borne movement of krill (Everson and Murphy, 1987), krill may make much use of these currents for migration.

Krill abundance increased 3.4 times on the traditional fishing ground north of Livingston Island over the 40-day period during 25 December 1990 to 3 February 1991. This increase rate is quite comparable with 5-fold increase observed around Elephant Island over the two-month period from January to February in 1990 (Amos *et al.*, 1990).

The estimate of krill abundance (157 g/m^2) obtained for this traditional fishing ground on 3 February 1991 was approximately half of the estimate (342 g/m^2) obtained there on 20 January 1988 (Fisheries Agency, 1989). The distributional pattern of krill was also different between these seasons: in 1991 'layers' (a form of krill swarm with horizontal length exceeding 1 000 km) were observed only occasionally, whereas in 1988 'layers' were the main feature (Endo and Shimadzu, 1989). Brinton (1987) reported similar differences between March 1981 and March 1984 in biomass (229 g/m^2 vs 134-201 g/m^2) and distributional pattern (large, thick swarms vs smaller, dispersed swarms) of krill near Elephant Island.

The US AMLR report (1991) described the 1990/91 season as characterised by the following features: krill abundance was low (compared with other seasons) during the first half of summer (December to early February), whereas it approximated to the normal level towards the end of summer (mid-February to mid-April). On Seal Island, low krill abundance in the beginning of this summer caused approximately 20% decline (as compared to last year) in numbers of penguins occupying nests, and made feeding trips of fur seals rather long (5 to 9 days compared to 1 to 3 days later in the season) (AMLR, 1991). Krill fishery data from the 1990/91 season have also indicated that density index of krill (catch-per-hour of fishing) remained low in January. Therefore, the estimate of total krill biomass throughout shelf waters in late January 1991, i.e., 1.78 million tonnes (157 g/m^2), should be regarded as the lower level of krill biomass for this region at this time of the season.

ACKNOWLEDGMENTS

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Table 1: Operational characteristics of the echosounder Furuno FQ-50.

Frequency	200 kHz
Equivalent beam width	0.007 sr
Pulse duration	1.8 ms
Depth range	0 to 200 m
Depth channel	10* to 200 m (9 channels)
Integration interval	1 nautical mile
Attenuator	20 dB
Threshold	15 dB
TVG	20 log R
Gain constant	78.9 dB

* The level of the top depth integration range was changed to 20 m in order to avoid impact of the surface noise when the sea was rough.

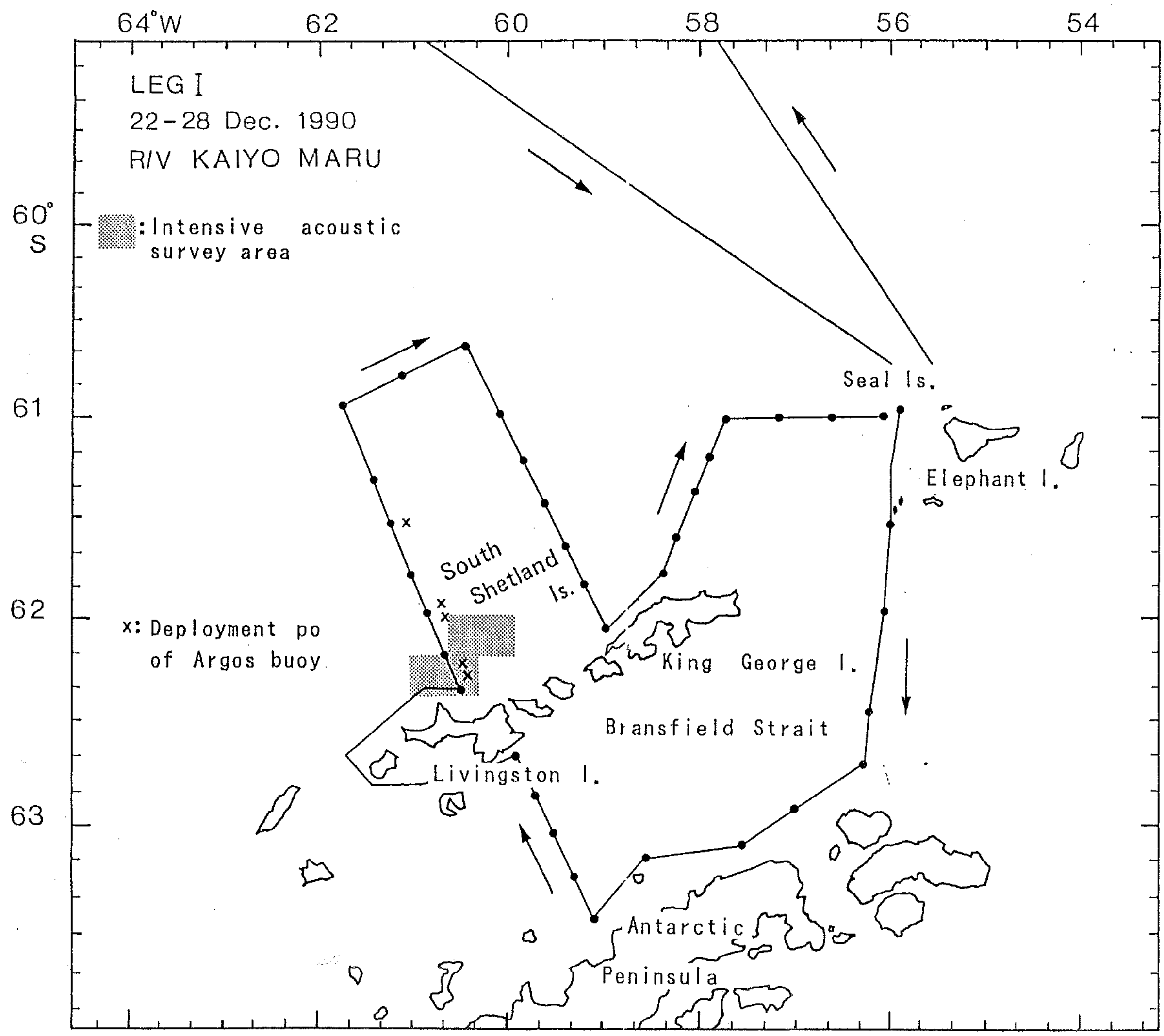

Figure 1: Cruise track and stations in Leg I.

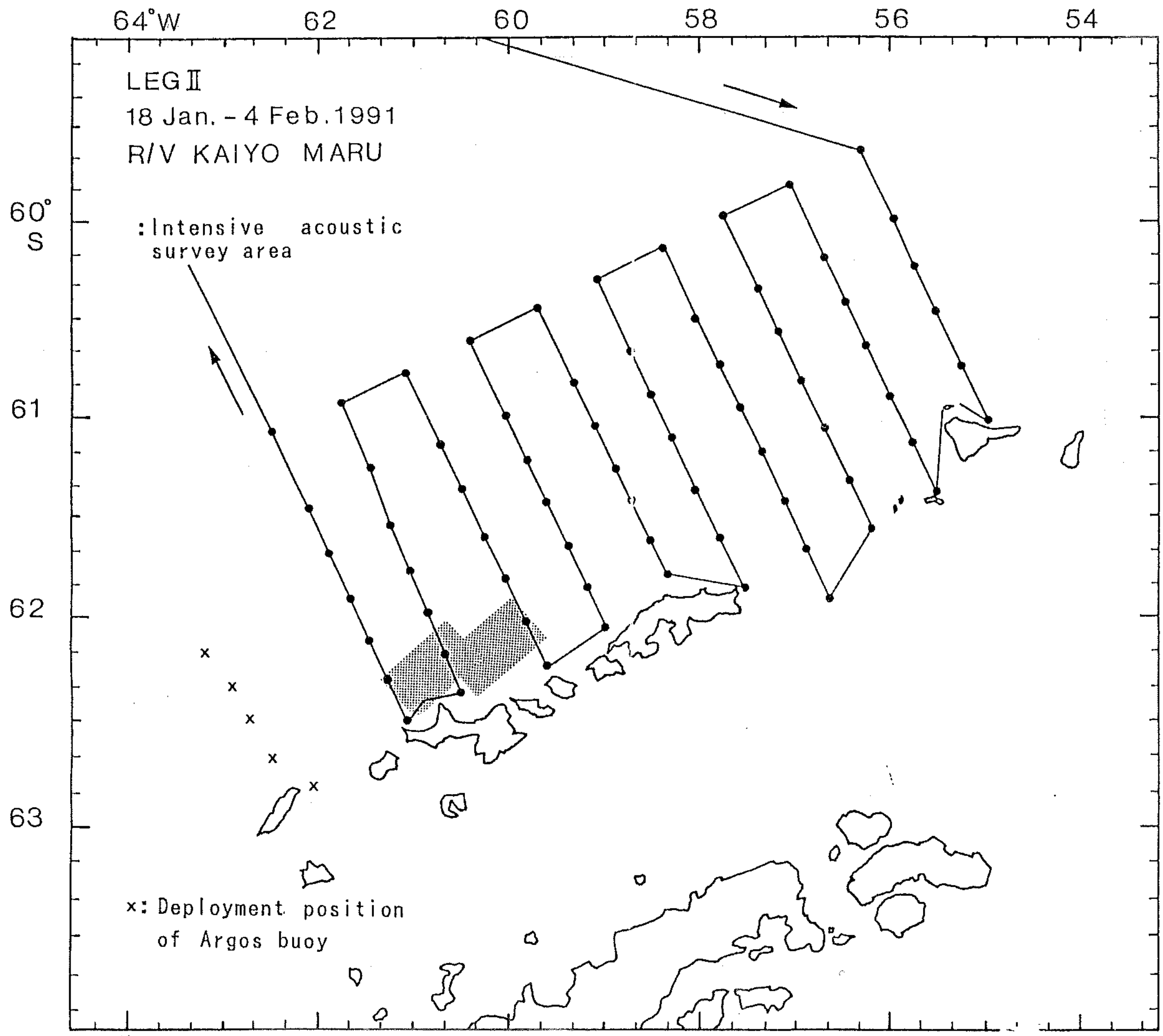

Figure 2: Cruise track and stations in Leg II.

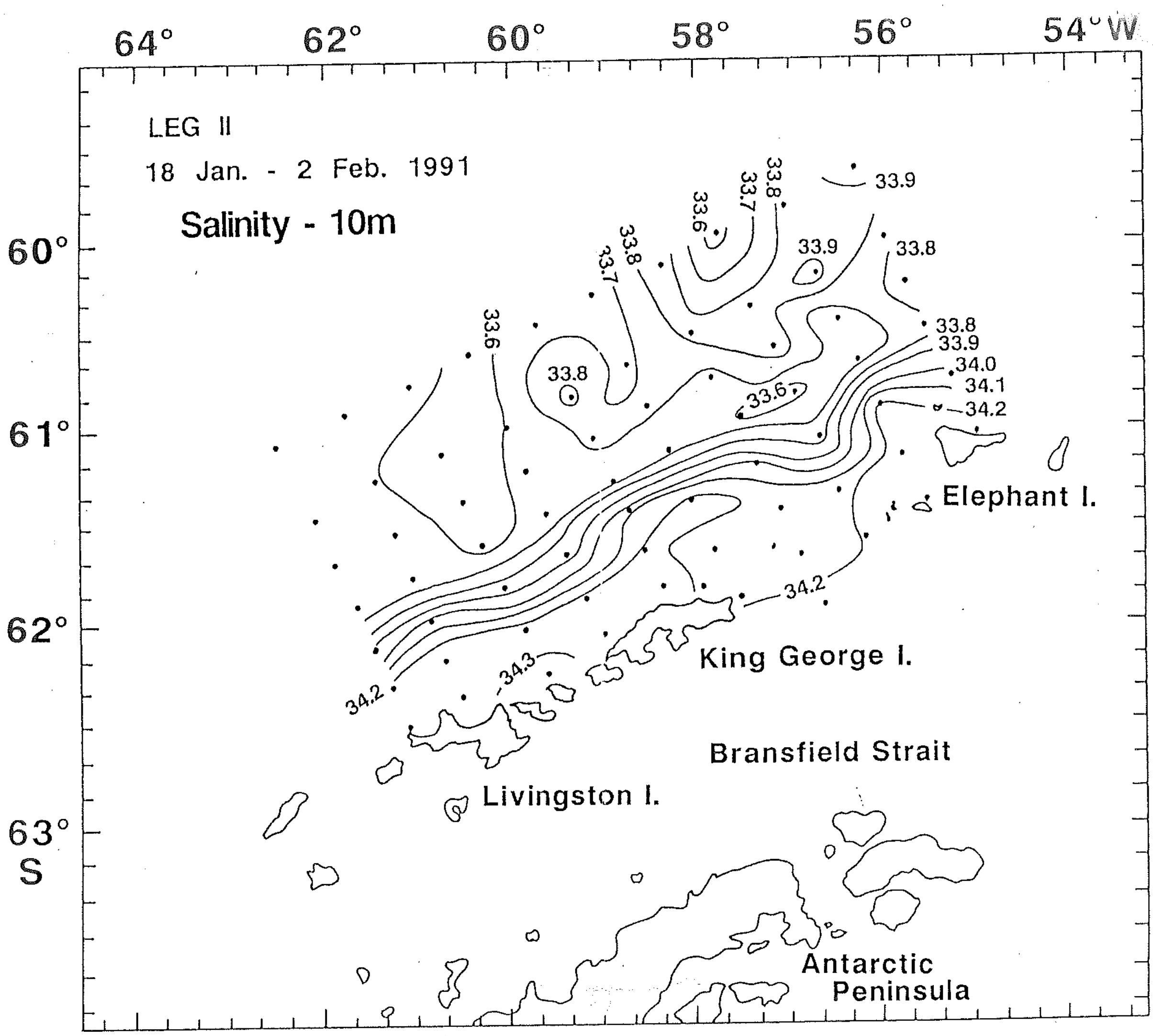

Figure 3: Distribution of salinity at 10 m depth in Leg II.

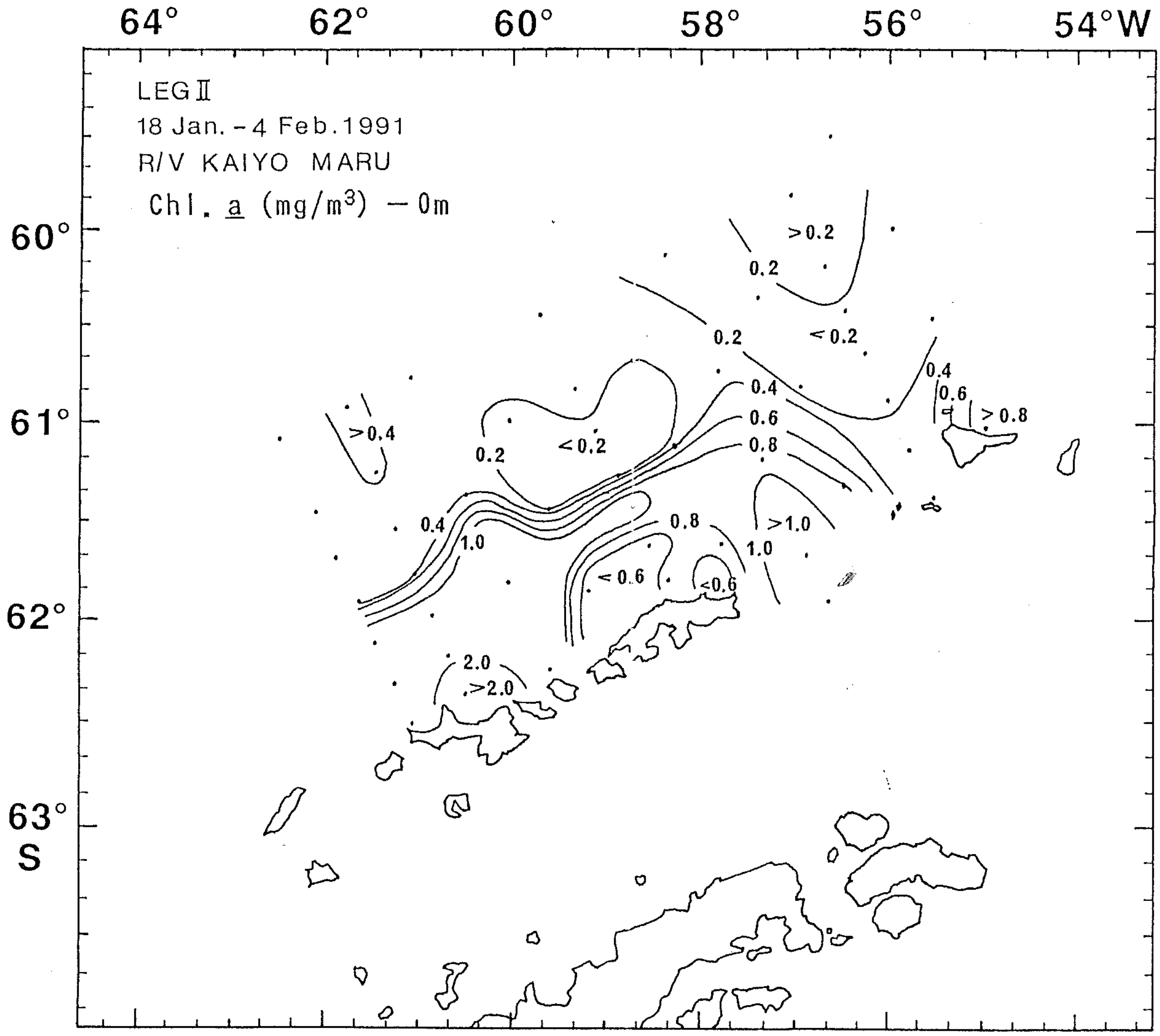

Figure 4: Distribution of chlorophyll *a* (mg/m^3) at the surface in Leg II.

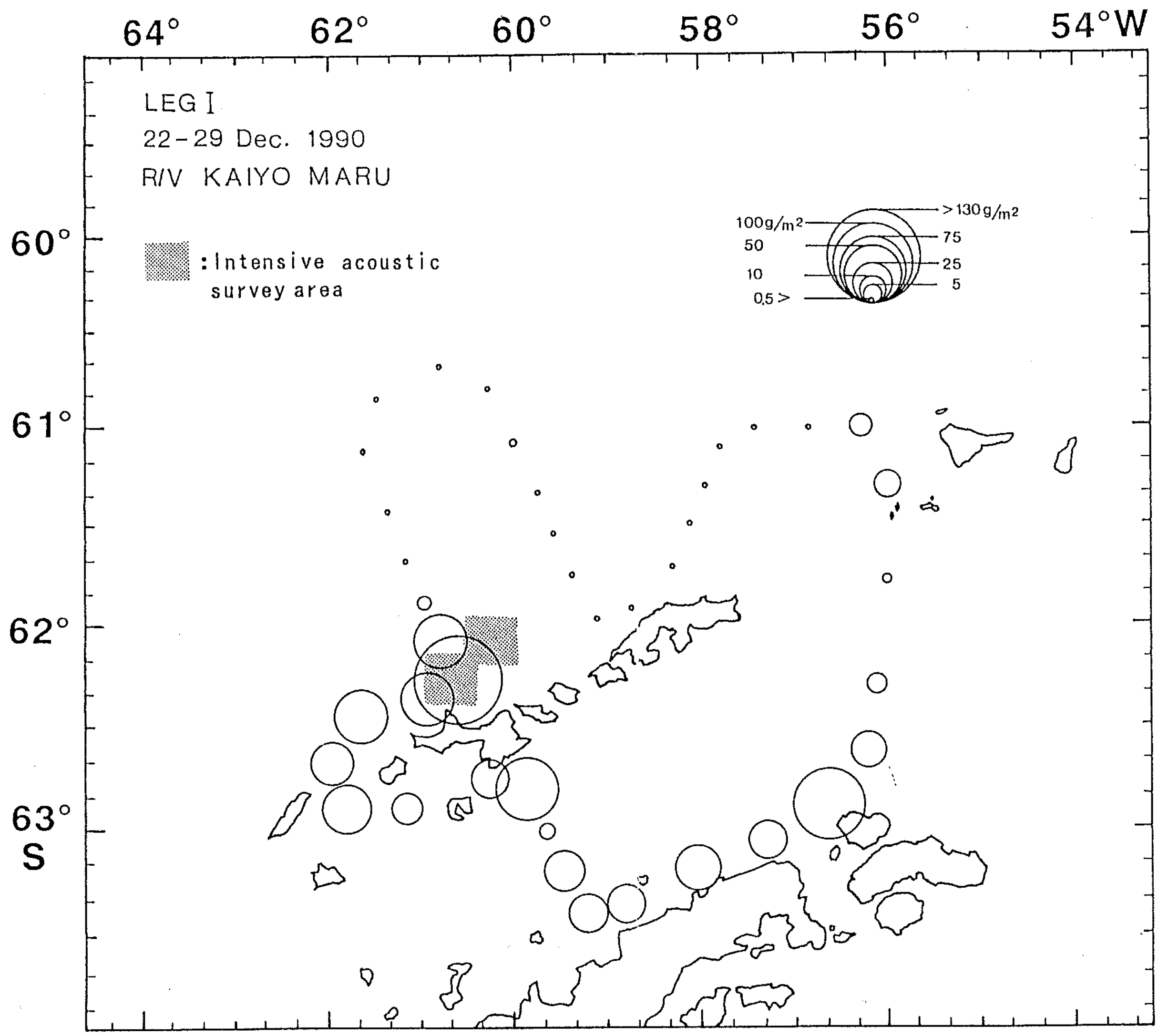

Figure 5: Hydroacoustically detected krill distribution in Leg I.

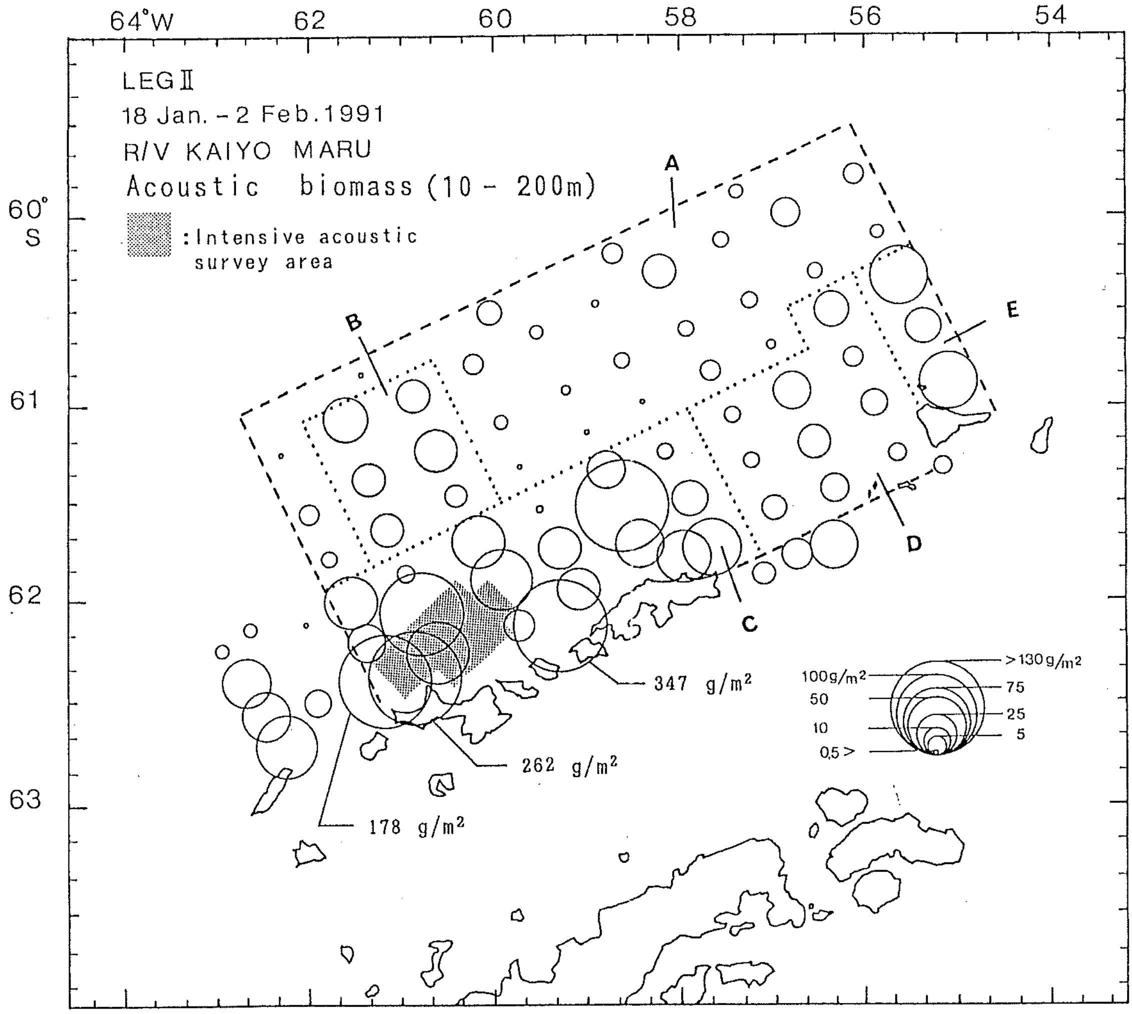

Figure 6: Hydroacoustically detected krill distribution in Leg II.

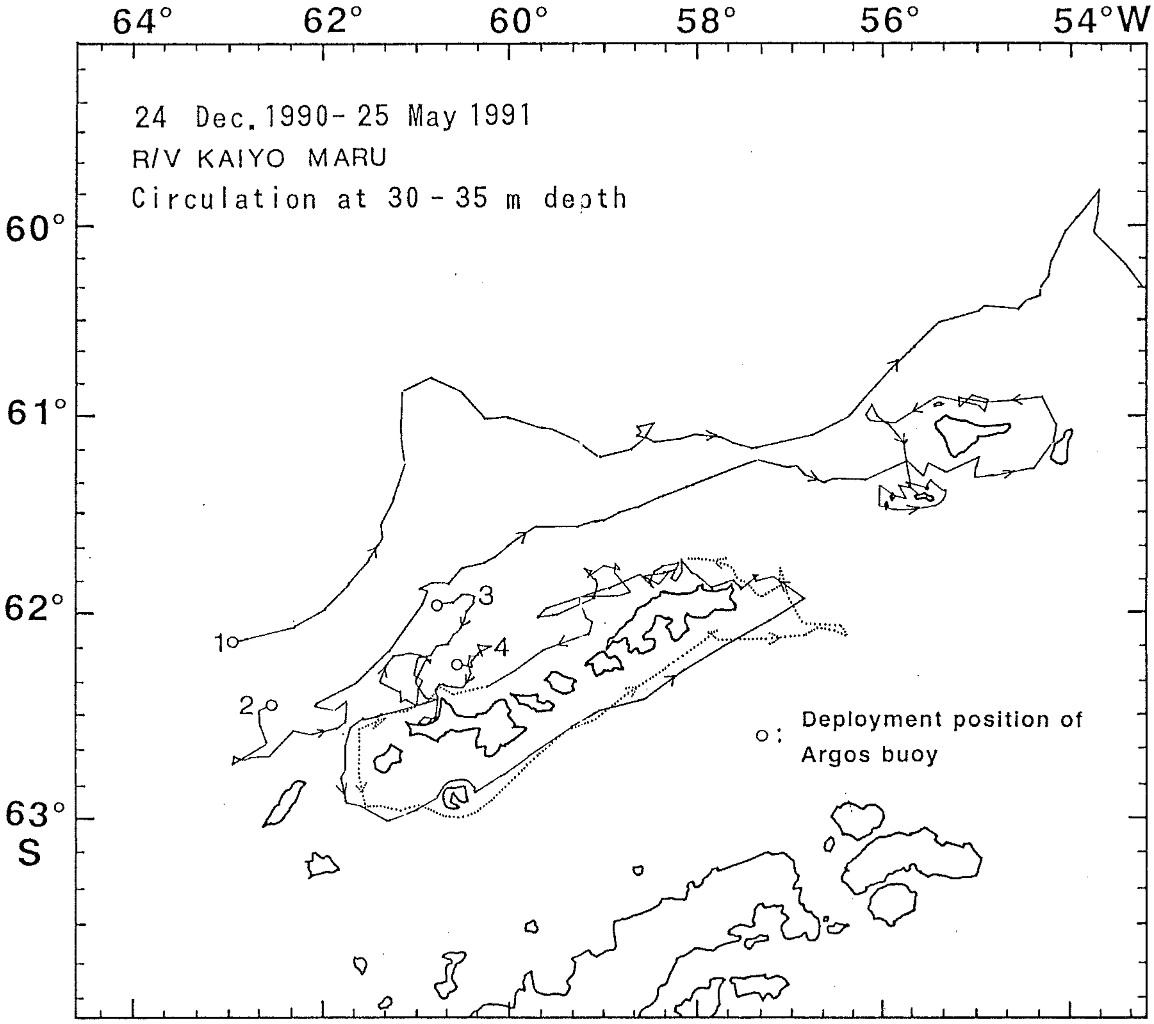

Figure 7: Water circulation at 30 to 35 m depth derived from the paths of four satellite-tracked buoys. Since Buoy 3 drifted more than one and a half circulations around the South Shetland Islands, its second circulation is shown by dotted line.

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