# ANALYSES OF ACOUSTIC LINE-TRANSECT DATA FROM THE WATERS AROUND SOUTH GEORGIA: ESTIMATION OF KRILL (*EUPHAUSIA SUPERBA* DANA) - BIOMASS

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## Abstract

A large-scale acoustic survey of zooplankton stocks in the waters around South Georgia was carried out during November and December 1981. The data have been analysed using various definitions of strata. The total biomass in the area of 155 786 km$^2$ was estimated to be 1.8225 x 10$^6$ tonnes (Coefficient of Variation = 9.5%). This gives an estimate of mean density throughout the region of 11.7 tonnes km$^{-2}$. Although the estimate of the mean is not sensitive to the definition of strata, the variance of the estimate is sensitive. The analyses highlight the importance of careful planning of acoustic surveys.

## Résumé

Une campagne d'évaluation acoustique à grande échelle des stocks de zooplancton s'est déroulée dans les eaux adjacentes à la Géorgie du Sud en novembre et décembre 1981. Les données ont été analysées pour diverses stratifications. La biomasse totale de l'aire de 155 786 km$^2$ a été estimée à 1,8225 x 10$^6$ tonnes (coefficient de variation = 9,5%). Ceci donne une estimation de densité moyenne pour toute la région de 11,7 tonnes km$^{-2}$. Bien que l'estimation de la moyenne ne soit pas sensible à la définition de la strate, la variance de l'estimation, elle, l'est. Les analyses soulignent l'importance de la conception minutieuse des campagnes acoustiques.

## Резюме

В течение ноября и декабря 1981 г. в водах Южной Георгии была проведена крупномасштабная акустическая съемка запасов зоопланктона. Полученные данные анализировались с использованием различных определений страт. Общая биомасса в районе площадью 155 786 км$^2$ составила 1,8225 ч 10$^6$ тонн (коэффициент изменчивости = 9,5%). Средняя плотность во всем районе составила таким образом 11,7 тонн км$^{-2}$. Хотя оценка средней величины не зависит от определения страт, изменчивость самой оценки чувствительна к ним. Этот анализ подчеркивает важность тщательного планирования акустических съемок.


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Resumen

Durante noviembre y diciembre de 1981 se realizó una prospección acústica a gran escala de las poblaciones de zooplancton que existen en las aguas alrededor de Georgia del Sur. Esta información se ha analizado empleando varias definiciones de estratos. La biomasa total de esta área que cubre 155 786 km$^2$, se estimó en 1.8225 x 10$^6$ toneladas (coeficiente de variación = 9.5%), que implica una estimación de la densidad media de la región de 11.7 toneladas•km$^{-2}$. Aunque la estimación de la media no es susceptible a la definición de los estratos, es el caso contrario con la varianza de la estimación. Los análisis demuestran la gran importancia que tiene la planificación minuciosa de las prospecciones acústicas.


## 1. INTRODUCTION

Acoustic surveys have become a standard technique in the study of the distribution and abundance of Antarctic krill *(Euphausia superba* Dana). There are, however, a number of problems in the application of these techniques for the routine surveying of krill populations in the Southern Ocean. In particular, the design of field surveys presents various logistical and analytical problems. Many of these design problems are similar to those encountered in the development of acoustic survey programs of fish populations. The ICES Acoustic Working Group has produced a draft report on current acoustic survey design practices (ICES, unpublished manuscript) which forms a good starting point for considering many of these problems. However, the highly heterogeneous nature and scale-related patchiness of krill distributions produce some particular problems which have not been adequately addressed to date.

In this paper we report on a major acoustic survey of krill abundance and distribution in the South Georgia region. The data have been analysed using a number of different approaches to illustrate the effect of the estimation technique on the final results. This emphasises the importance of careful pre-survey planning and post-survey analyses.

## 2. METHODS

### 2.1 The Survey Design

The survey was designed to investigate some of the interactions taking place in the South Georgia marine ecosystem and involved a major interdisciplinary program of data collection, various aspects of which have been discussed by Priddle *et al.* (1986) and Atkinson and Peck (1988). The survey region was a 180 by 240 n mile box centred on the island of South Georgia (Figure l). There was no information available at the planning stage to produce a stratified sampling design based on the biomass distribution. The large size of the area prohibited the execution of a suitable pilot study in the time available. The chosen design was systematic parallel transects with the direction of the transect perpendicular to the long-axis of the island. Nine major transects were traversed over the period from 24 November to 19 December 1981. The survey start was chosen at random to reduce the possibility of systematic errors. Each transect was divided into six sections approximately 30 n miles in length. Each section was further divided into 1 n mile integration intervals (ESDU). Density was estimated from the acoustic parameter mean volume backscattering strength (MVBS).

At the end of each section various 'station' activities were carried out as part of the interdisciplinary program. This included deployment of a CTD system to produce temperature and salinity profiles.

## 2.2 The Acoustic Methods

A Simrad EKS 120 echosounder connected to a Simrad QM Analogue echo-integrator was used for the study. The echosounder was calibrated on 22 November and 23 December 1981 and the following values obtained.

| Constant | Date 22 November 1981 | Date 23 December 1981 |
|---|---|---|
| Source Level [dB//1 μPa ref. 1 metre] | 218.3 | 218.9 |
| Voltage Response [dB//1 volt/μPa] | -108.9 | -107.8 |

Pulse duration was measured at 0.6 msec.

Not all of the acoustic targets will have been krill. However, krill are likely to be the major zooplankton target in this area so in this study we assume all target are krill for the purpose of the analyses of the dataset. The length distribution of all krill taken during the survey period is shown in Figure 2. Most of the krill were small, with a mean length of 29.73 mm. This mean size is similar to that of the krill used by Everson *et al.* (1990) to estimate the target strength of krill. Based on that study we have used a mean target strength of -75 dB to estimate the biomass of krill in this region. The mean weight of the sampled krill was 0.18 g.

An estimate of the mean bottom depth was available for each section. The CTD profiles collected at either end of a section allowed an estimate of the mean temperature minimum to be obtained and used to characterise water mass (Atkinson *et al.*, 1990).

# 3. RESULTS AND ANALYSIS

## 3.1 Analytical Techniques

The notation of Jolly and Hampton (1990) is followed throughout. There are j = 1, .., $n_i$ sample units and i = 1, .. ,N strata. The density of a sample unit is then given by:

$$\hat{\rho}_{ij} = \frac{b_{ij}}{L_{ij}} \qquad (1)$$

**$b_{ij}$** is the biomass recorded over the $j_{th}$ sample unit in the $i_{th}$ stratum
**$L_{ij}$** is the length of $j_{th}$ sample unit in the $i_{th}$ stratum

The mean density in the strata is given by:

$$\hat{\rho} = \frac{1}{n_i} \sum_{j=1}^{n_i} w_{ij} \hat{\rho}_{ij} \qquad (2)$$

where the weights are based on the sample unit length:

$$w_{ij} = \frac{L_{ij}}{\overline{L}_i} \tag{3}$$

and the mean sample unit length is:

$$\overline{L}_i = \frac{1}{n_i} \sum_{j=1}^{n_i} L_{ij} \tag{4}$$

The estimated mean density for the whole region is then:

$$\hat{\overline{\rho}} = \frac{\sum_{i=1}^{N} A_i \hat{\overline{\rho}}_i}{\sum_{i=1}^{N} A_i} \tag{5}$$

where $\mathbf{A_i}$ = Area of stratum **i**.

The variance is:

$$Var\left(\hat{\overline{\rho}}\right) = \frac{\sum_i A_i^2 \, Var\left(\hat{\overline{\rho}}_i\right)}{\left(\sum_i A_i\right)^2} \tag{6}$$

where

$$Var\left(\hat{\overline{\rho}}_i\right) = \frac{\sum_{j=1}^{n_i} w^2{}_{ij} \left(\hat{\overline{\rho}}_{ij} - \hat{\overline{\rho}}_i\right)^2}{n_i\left(n_i - 1\right)} \tag{7}$$

The assumption underlying such analyses is of random sampling within a stratum. In the survey reported here it was assumed that the between-transect distance is sufficiently large to remove any systematic error; that is at a scale at which the krill distribution can be considered random with respect to the transects.

The equations can be applied to the data for any size of sample unit. However, the problem of non-random sampling within a stratum can invalidate the basic assumptions of the statistical methods. The simplest case would be to consider each ESDU to be a sample. However, the inherent serial correlation in the datasets makes the estimation of variance on this basis meaningless.

For the variance of the final estimate to be a minimum the sampling units should be chosen to give low within-stratum variability. The definitions of strata are given in Table 1. The results of the analyses of the data using various sampling units and strata definitions are shown in Table 2. Those estimates in which the ESDU are taken as the basic sampling unit (Table 2, lines 1 to 6) suffer from serial correlation problems. A possible breakdown of the data (Table 2, line 7) is to produce 18 transects by splitting the transects into two transects either side of the shelf region (Figure 4), and taking a section as the basic sampling unit. This is not unreasonable as the transecting was delayed for station sampling at the end of each section. The next three estimators (8 to 10) consider the six strata shown in Figure 5. These strata split the sample region on the basis of the bathymetric contours. Each of these estimators takes a different basic sampling unit: transects, sections or ESDU.

The different estimators are presented here to highlight that the estimate of mean density and total biomass is not sensitive to the analytical breakdown used. However, the variance of the estimates can change markedly. The variance of the mean density estimate from the Jolly method (Jolly and Hampton, 1990) is a weighted sum of the within-stratum variances. Thus, the stratification at the large-scale is aimed at the removal of the largest element of the variance. The sampling units within the strata should then be chosen to produce least variance within strata. The between-stratum variance does not enter into the overall calculation of the variance. An analysis of variance (Table 3) shows that most of the variation is explained by the chosen strata and that sections within strata are more variable than the transects. This indicates that the strategy of running transects perpendicular to the shelf produced runs which crossed the steepest gradient in the krill density distribution, and consequently lower variation between transects. The best combination of sampling unit and strata in this case is six strata and transects as sample units (Table 2, line 10), producing an estimate of the mean density of 11.7 tonnes $km^{-2}$ and total biomass for the region of 1.8225 x $10^6$ tonnes (CV = 9.5%). Statistics for the 18 transect breakdown (Figure 4) and the six strata breakdown (Figure 5) are given in Tables 4 and 5 respectively. These estimates are based on the assumption of random sampling within strata which is not the case. However, the conclusion that there were generally higher densities of krill in the north east region around South Georgia is reasonable.

Further stratifications were made by water mass, characterised by contiguous regions of similar minimum temperature (Table 2, lines 11 and 12). These do not simply describe strata in the distribution of krill in the region so do not give particularly useful biomass estimates. Bathymetry and temperature are aliased in this region (correlation coefficient, r = -0.428). Analyses of the data to produce estimates of mean density classified by bathymetric region and minimum temperature range are shown in Tables 6 to 8. In all depth regions the highest krill densities were found in the colder, less than zero degree minimum temperature water mass. The highest densities were found in the shelf slope regions of 250 to 1 000 m in depth. The greatest biomass is found offshore and is associated with the colder water regions to the east.

### 3.2 Kriging Analysis

A simple Kriging analysis was performed using the UNIMAP (1990) software system. A biomass estimate was obtained for an area approximately 1.63 x $10^5$ $km^2$, which compares with the 1.56 x $10^5$ $km^2$ used in the above analyses. Blanking regions were defined to set similar boundaries to the area of interpolation to these used in the above estimates. The semivariogram was fitted by eye at an angle to the vertical of 150°; settings used were: range = 1, sill = 650, nugget = 0. No trend corrections were made. This produced the map of krill density shown in Figure 7. The volume of the integrated surface gives an estimate of the total biomass in the region. This was 2.13 x $10^6$ tonnes giving a mean krill density estimate of 13.07 tonnes $km^{-2}$. Reasonable changes in the parameter settings used in the semivariogram model produced changes in the density estimate of approximately ± 3 tonnes $km^{-2}$.

## 4. DISCUSSION

The target strength value we have used produces larger values for a given MVBS than those used in earlier studies (BIOMASS, 1984). Few data are available to cross reference to this analyses carried out in this study. The density estimated for the West Atlantic section of the Southern Ocean from the BIOMASS cruises (February, 1981) was 4.46 tonnes $km^{-2}$ which is lower than the 11.7 tonnes $km^{-2}$ obtained in the present study. The USSR vessel *Odyssey* surveyed part of the north side of the South Georgia area during February, 1981 and these results gave a density estimate of 15.63 tonnes $km^2$ (BIOMASS, 1984). In this study the same region produced some of the highest density estimates with stratum values of 13.08 and 23.59 tonnes $km^{-2}$ (Table.5). The BIOMASS analyses used a much higher target strength value so this suggests there was a higher krill biomass in the BIOMASS sampled regions during the early part of 1981 than was observed in this study in the latter part of 1981.

Other estimates of krill density in the South Georgia region are those from trawl based studies (Latogursky *et al.*, 1990). The values for the early part of 1981 are of the same order as those obtained in this study, 37.4 and 5.4 tonnes $km^{-2}$ and are consistent with the *Odyssey* data These values are low compared to other trawl estimates obtained for the region in other years.

The above analyses have highlighted that the various estimation methods based on classical statistical techniques produce little difference in the estimate of mean density but they do affect the variance. Careful design is the only way that a valid estimate of mean density can be obtained. There is little that can be done at the post-processing stage except to consider the precision of the estimate. The underlying estimate may be wrong but there is nothing that can be done about this at this stage. This highlights the importance of careful pre-planning of the survey. Assumptions of randomness at the wrong scale will give incorrect variance results for krill biomass.

The use of Kriging or other spatial statistical techniques clearly requires far more investigation but holds some promise (Foote and Stefansson, 1991). However, we can say at this stage that the simple application of bilinear interpolation techniques is incorrect and is likely to produce erroneous results. The distribution of krill is extremely patchy and the variability of the distribution must be taken into account using an approach such as Kriging. The spatial techniques must be rigorously applied and all of the interpolated estimates should be reported with details of the fits and confidence in the estimates. The development of spatial statistical analytical methods is a continually evolving field of study (Ripley, 1988).

Croxall *et al.* (1985) produced a value of 16 x $10^6$ tonnes as an estimate of the consumption of krill by seabirds and seals in Scotia Sea area. Approximately 42% were taken by South Georgia based predators (approximately 6.7 x $10^6$ tonnes). The estimate of the standing stock is low compared to the predator consumption figure for the South Georgia area. This predator consumption rate is spread throughout the year and should not be compared directly with standing stock estimates. The Antarctic Circumpolar Current is a potential source of replenishment of the krill stocks in the South Georgia area (Everson, 1984). This is likely to mean that several times the standing stock may be available in the region in any year.

For 6.7 x $10^6$ tonnes to be available in a year and assuming no local production then a crude estimate of input rate may be calculated. Assuming the standing stock remains constant and that demand is constant throughout the year, then the estimated demand is 18 356 tonnes $day^{-1}$. If the krill enter the region only through the eastern side of the box (Figure 1, this dimension is approximately 333 km in length) then 55.1 tonnes are brought in each day along each kilometre of the side of the box. If the density outside the area in the Scotia Sea is in the range 4.5 to 11.7 tonnes $km^{-2}$ then the required flow rates are 0.28 to 0.11 knots respectively. These values are well within the expected current speeds for the region (Foster, 1984).

In this study we have assumed all detected targets in this area are krill, this is unlikely to be the case and will have produced an overestimate of krill biomass. However, some of the krill were much larger than the mean length and use of a mean target strength will have caused underestimation of the biomass. The distribution of the krill within the area is consistent with the suggestion of the occurrence of the Antarctic Surface Water in the region (Everson, 1984; Atkinson and Peck, 1988). This water mass was the cooler water region to the east where the higher densities of krill were recorded during this study. The higher densities of krill in the shelf regions support suggestions that these areas are important in the development of krill aggregations (see Miller and Hampton, 1989 for a discussion).

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Table 1: Definitions of strata used in the analyses of the transect data.

| Strata | Description of Stratification |
|---|---|
| 9 transects | Each of the long transects treated as a contiguous sample region (Figure 3). |
| 18 transects | Each of the nine long transects split in the middle (Figure 4). |
| 6 strata | Each set of three half transects were grouped together on the basis of geographic region (Figure 5). |
| 6 strips | Each of the sections running west to east were considered as a single stratum (Figure 6). |
| 3 depth bands | The data were analysed according to bathymetric region. These regions are not necessarily contiguous. |
| 3 temperature bands | The data were analysed according to minimum temperature region. These regions are not necessarily contiguous. |
| 3 temperature regions | Stratum boundaries were set on the basis of contiguous regions of similar temperature. |

Table 2: Mean density and total biomass estimates produced by the application of different stratification criteria (Table 1) to the transect data.

| | Method of Estimation | Mean Density (tonnes km$^{-2}$) | Variance | Total Biomass (tonnes x $10^6$) | Variance |
|---|---|---|---|---|---|
| 1 | Stratified by 18 transects (resets as units) | 11.44 | 0.410 | 1.8225 | 0.00950 |
| 2 | Stratified by 9 transects (resets as units) | 11.48 | 0.419 | 1.8225 | 0.01017 |
| 3 | Stratified by 6 strips (resets as units) | 11.86 | 0.437 | 1.8225 | 0.01060 |
| 4 | Stratified by 54 sections (resets as units) | 11.61 | 0.373 | 1.8225 | 0.00906 |
| 5 | Stratified by 3 depths (resets as units) | 11.30 | 0.438 | 1.8225 | 0.01063 |
| 6 | Stratified by 3 temperature bands (resets as units) | 12.11 | 0.436 | 1.8225 | 0.01059 |
| 7 | Jolly 18 transects (sections as units) | 11.70 | 2.070 | 1.8225 | 0.05024 |
| 8 | Stratified by 6 strata (resets as units) | 11.59 | 0.416 | 1.8225 | 0.01011 |
| 9 | Jolly 6 strata (sections as units) | 11.70 | 1.816 | 1.8225 | 0.04408 |
| 10 | Jolly 6 strata (transects as units) | 11.70 | 1.228 | 1.8225 | 0.02980 |
| 11 | Jolly 3 temp/geographic (transects as units) | 11.70 | 2.969 | 1.8225 | 0.07205 |
| 12 | 3 temp/geographic strata (resets as units) | 11.27 | 0.437 | 1.8225 | 0.01060 |

Table 3: Accumulated analysis of variance based on the six regional strata shown in Figure 5.

| Source of Variation | Degrees of Freedom | Sum of Squares | Mean Square | Variance Ratio |
|---|---|---|---|---|
| Stratum | 5 | 58306.6 | 11661.3 | 20.62 |
| Stratum / Transect | 12 | 21686.3 | 1807.2 | 3.20 |
| Stratum / Section | 33 | 101585.0 | 3078.3 | 5.44 |
| Residual | 1463 | 827425.3 | 565.5 | |
| Total | | 1009003.2 | 666.9 | |

Table 4: Mean density and biomass estimates based on the 18 transects defined in Figure 4. Sampling units are transect sections.

| Transect | No. of Observations | Density (tonnes $km^{-2}$) | Variance | Area ($km^2$) | Biomass (tonnes) |
|---|---|---|---|---|---|
| 1 | 3 | 9.13 | 5.066 | 9260.7 | 84566.0 |
| 2 | 2 | 1.82 | 0.043 | 6173.8 | 11238.4 |
| 3 | 3 | 6.89 | 8.282 | 9260.7 | 63845.6 |
| 4 | 3 | 8.61 | 42.361 | 8849.2 | 79772.0 |
| 5 | 3 | 7.28 | 1.310 | 6070.9 | 67413.0 |
| 6 | 3 | 1.83 | 1.215 | 8231.8 | 16962.6 |
| 7 | 3 | 9.42 | 38.131 | 6173.8 | 83401.2 |
| 8 | 2 | 8.10 | 37.424 | 9157.8 | 49174.5 |
| 9 | 3 | 6.75 | 1.702 | 9260.7 | 55548.0 |
| 10 | 2 | 13.29 | 176.730 | 9260.7 | 82074.8 |
| 11 | 3 | 9.21 | 20.941 | 9260.7 | 84388.0 |
| 12 | 3 | 16.19 | 4.319 | 9260.7 | 149973.6 |
| 13 | 3 | 7.32 | 34.743 | 9260.7 | 67834.9 |
| 14 | 3 | 15.93 | 48.701 | 9260.7 | 147548.3 |
| 15 | 3 | 16.96 | 186.101 | 9260.7 | 157057.0 |
| 16 | 3 | 32.16 | 18.742 | 9260.7 | 297800.8 |
| 17 | 3 | 12.29 | 49.713 | 9260.7 | 113809.4 |
| 18 | 3 | 22.69 | 33.960 | 9260.7 | 210129.3 |

Table 5: Mean density and biomass estimates based on the six regional strata (Figure 5). Transects are taken as the basic sample unit.

| Stratum | No. of Observations | Density (tonnes $km^{-2}$) | Variance | Area ($km^2$) | Biomass (tonnes) |
|---|---|---|---|---|---|
| 1 | 3 | 7.77 | 0.477 | 27782.2 | 215824.2 |
| 2 | 3 | 4.37 | 5.398 | 24695.3 | 107972.9 |
| 3 | 3 | 8.51 | 8.510 | 26238.7 | 223336.9 |
| 4 | 3 | 13.08 | 13.08 | 21505.5 | 281222.9 |
| 5 | 3 | 12.19 | 12.19 | 27782.2 | 338700.6 |
| 6 | 3 | 23.59 | 23.59 | 27782.2 | 655477.0 |

Table 6: Classification of the acoustic density data by three water depth ranges.

| Depth Region | No. of Records | Min. | Mean (tonnes $km^{-2}$) | Max. | Median | Variance | Area ($km^2$) | Biomass (tonnes) |
|---|---|---|---|---|---|---|---|---|
| < 250 m | 170 | 0.0 | 6.61 | 41.63 | 0.0 | 83.156 | 17492.5 | 115627.7 |
| 250 - 1000 m | 176 | 0.0 | 15.40 | 341.98 | 10.16 | 943.473 | 18109.9 | 278926.5 |
| >1000 m | 1168 | 0.0 | 11.88 | 336.14 | 1.52 | 705.221 | 120184.9 | 1427996.6 |
| Total | 1514 | 0.0 | 11.70 | 341.98 | 1.52 | 666.879 | 155787.3 | $1.8225 \times 10^6$ |

Table 7: Classification of the acoustic density data by three classes of the mean minimum temperature of the vertical CTD profiles.

| Temp. Region (°C) | No. of Records | Min. | Mean (tonnes $km^{-2}$) | Max. | Median | Variance | Area ($km^2$) | Biomass (tonnes) |
|---|---|---|---|---|---|---|---|---|
| < 0.0 | 479 | 0.0 | 15.30 | 173.99 | 3.12 | 764.854 | 49287.9 | 754207.1 |
| 0 - 0.5 | 689 | 0.0 | 9.07 | 336.14 | 0.00 | 567.964 | 70896.5 | 643017.3 |
| > 0.5 | 346 | 0.0 | 11.95 | 341.98 | 2.24 | 700.396 | 35602.4 | 425318.4 |
| Total | 1514 | 0.0 | 11.70 | 341.98 | 1.52 | 666.879 | 155786.8 | $1.8225 \times 10^6$ |

Table 8: Classification of the acoustic density data by water depth and mean minimum temperature.

| Temperature Region | Bathymetric Region | | | | | |
|---|---|---|---|---|---|---|
| | < 250 m | | 250 - 1000 m | | > 1000 m | |
| | Mean | s.e. | Mean | s.e. | Mean | s.e. |
| < 0.0 | 11.90 | 2.53 | 20.28 | 2.58 | 15.29 | 1.17 |
| 0 - 0.5 | 5.70 | 2.14 | 14.08 | 2.27 | 9.09 | 1.05 |
| > 0.5 | 7.66 | 2.19 | 16.03 | 2.03 | 11.05 | 1.72 |

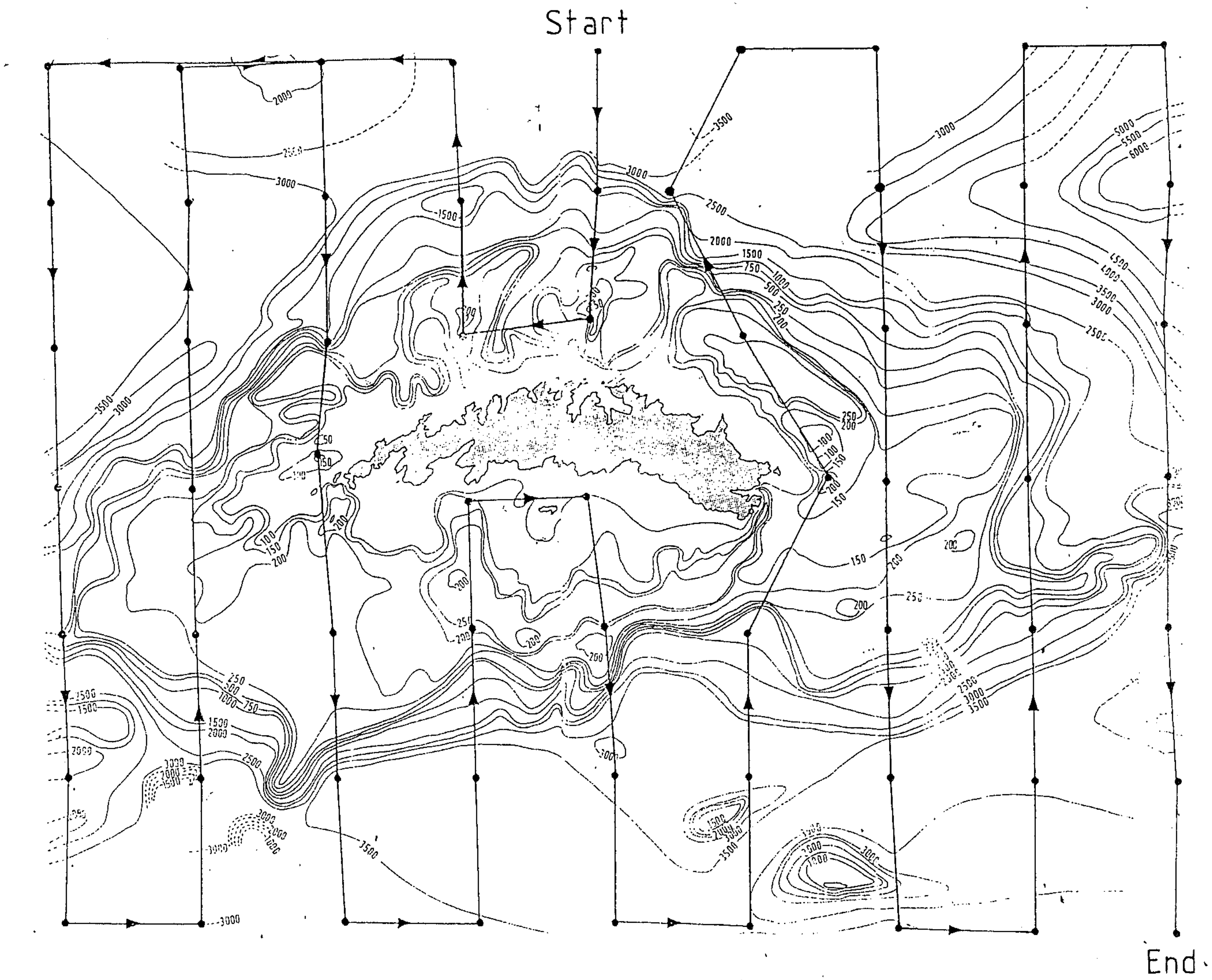


Figure 1: The realised survey track around the island of South Georgia. The survey tracks are approximately 30 n miles apart. The survey box was approximately 240 n miles x 180 n miles. The transecting started on the north side of the box and ended in the southeast corner.

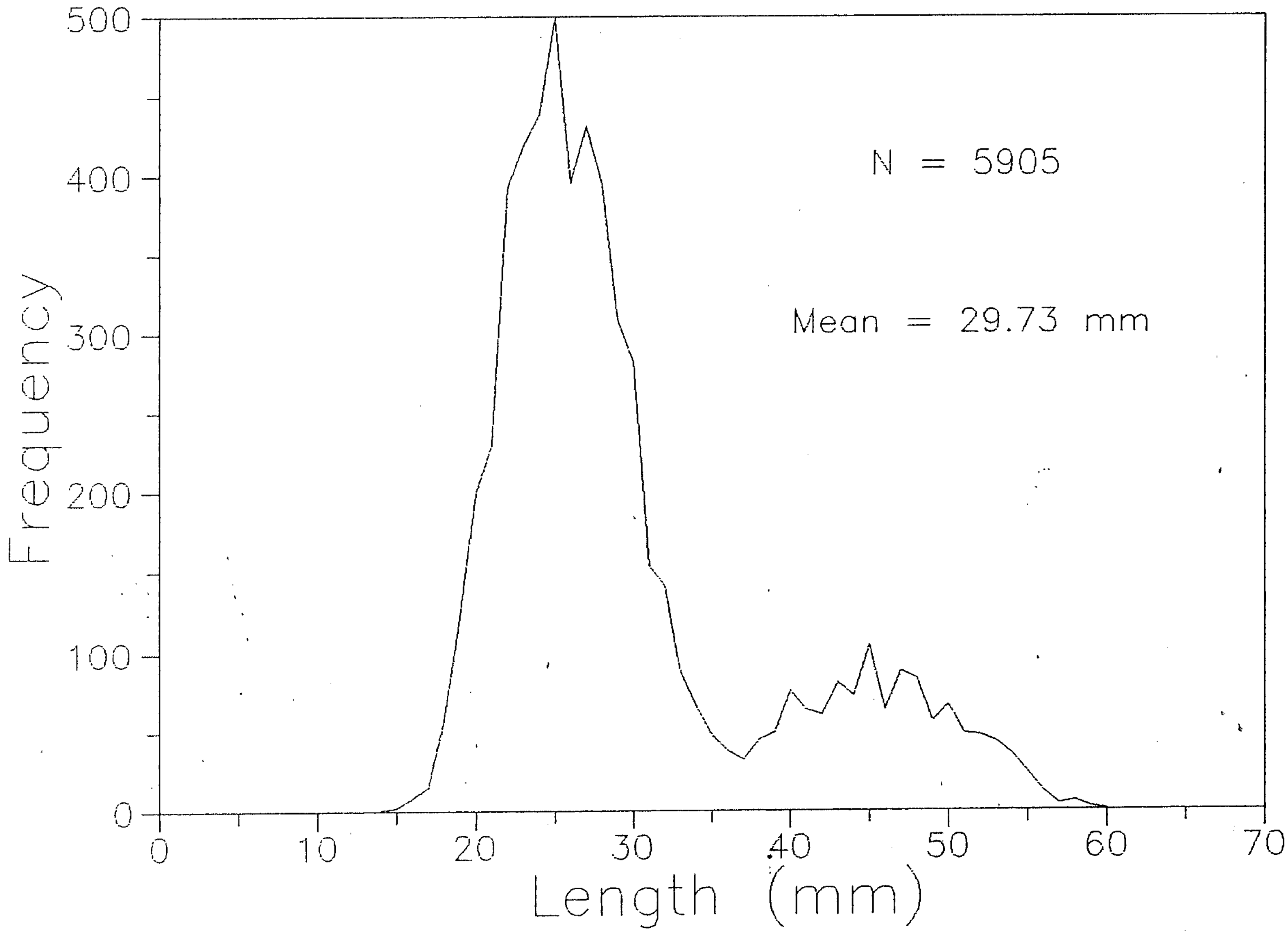


Figure 2: The length of frequency distribution of all krill measured during the survey period, 24 November 1981 to 19 December 1981.

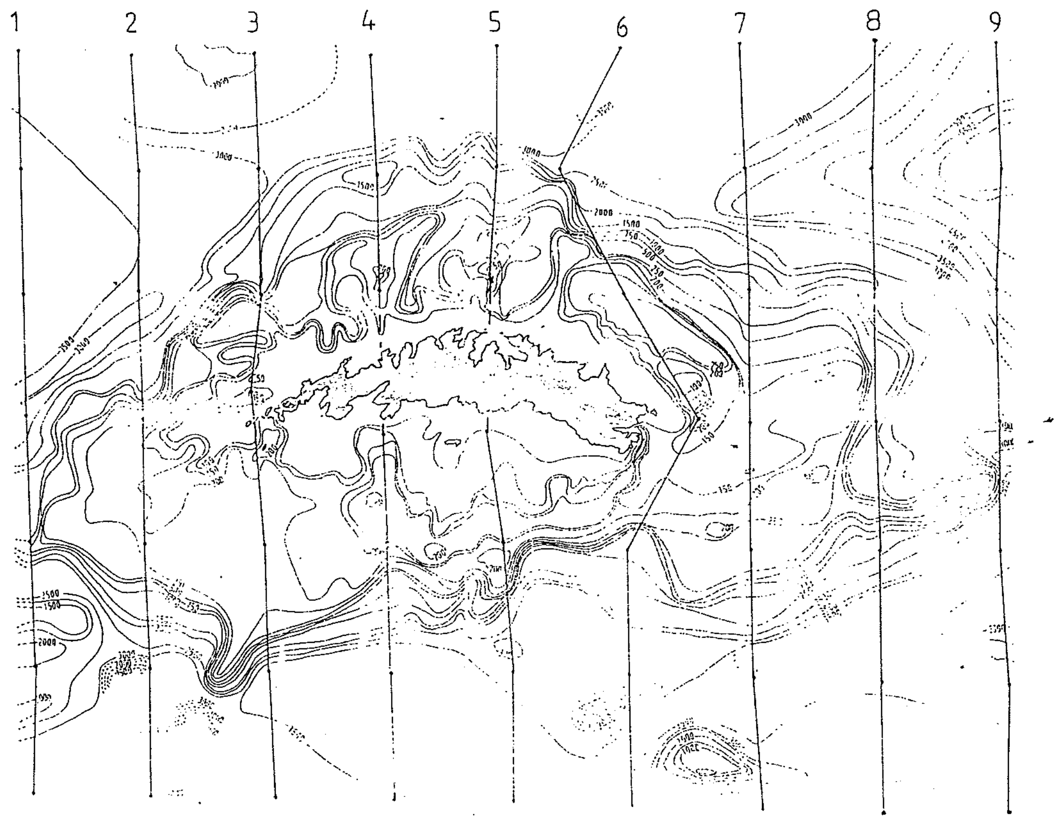


Figure 3: Nine parallel transects.

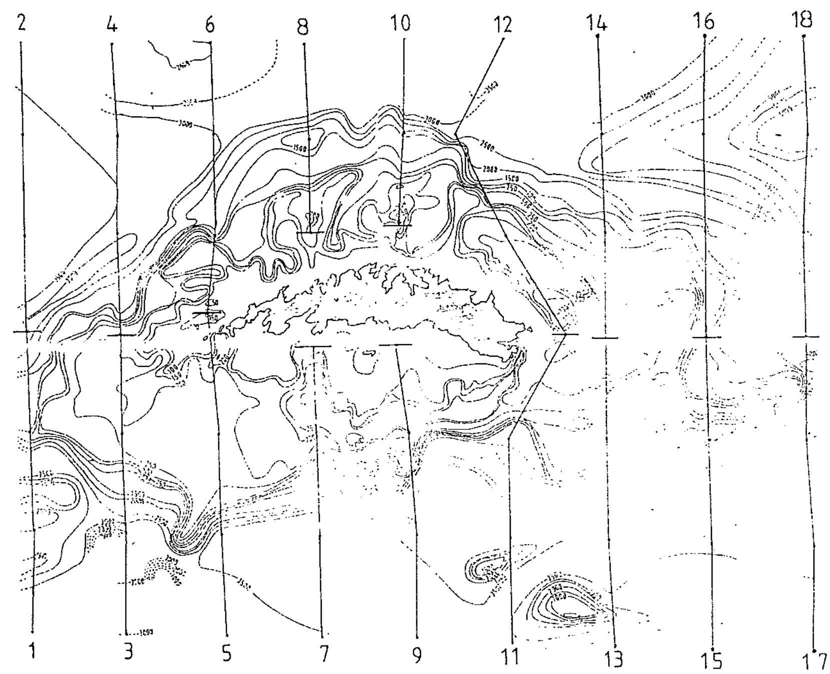


Figure 4: Eighteen transects obtained by splitting the nine transects along the long axis of the island.

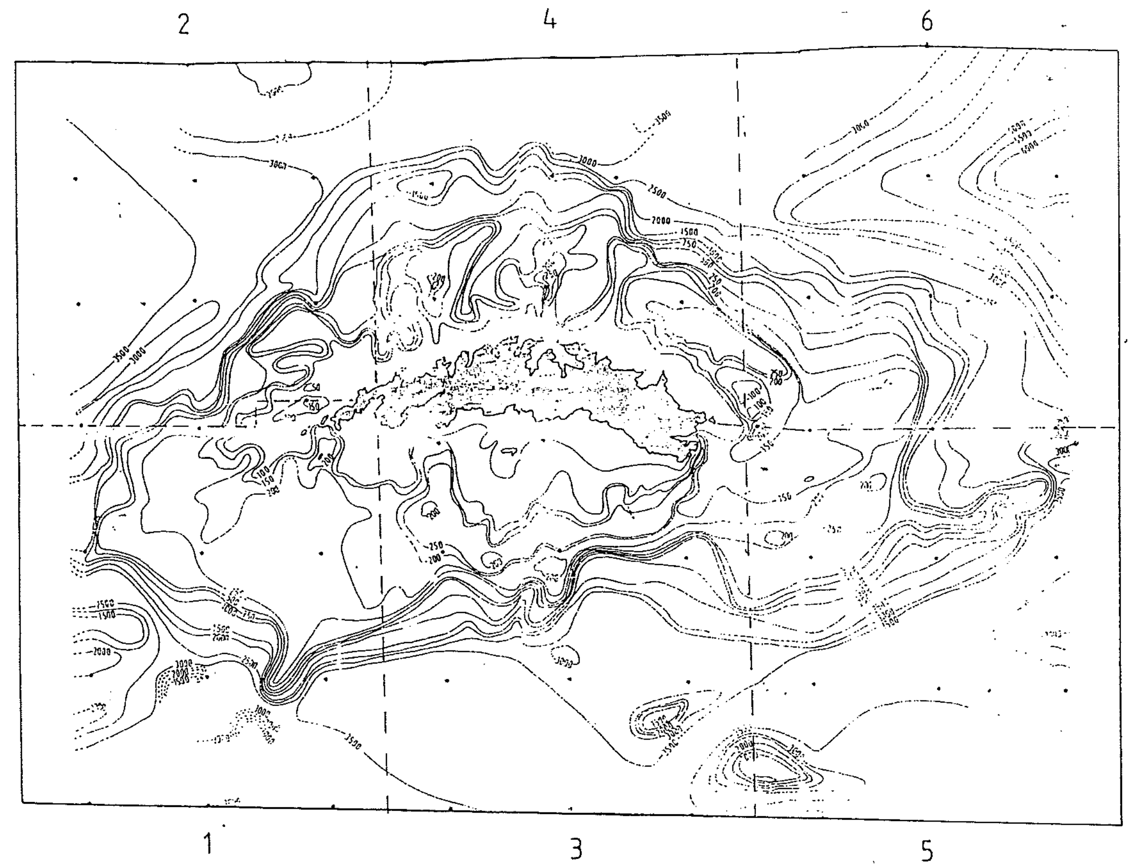


Figure 5: Six regional strata covering on-shelf regions around South Georgia.

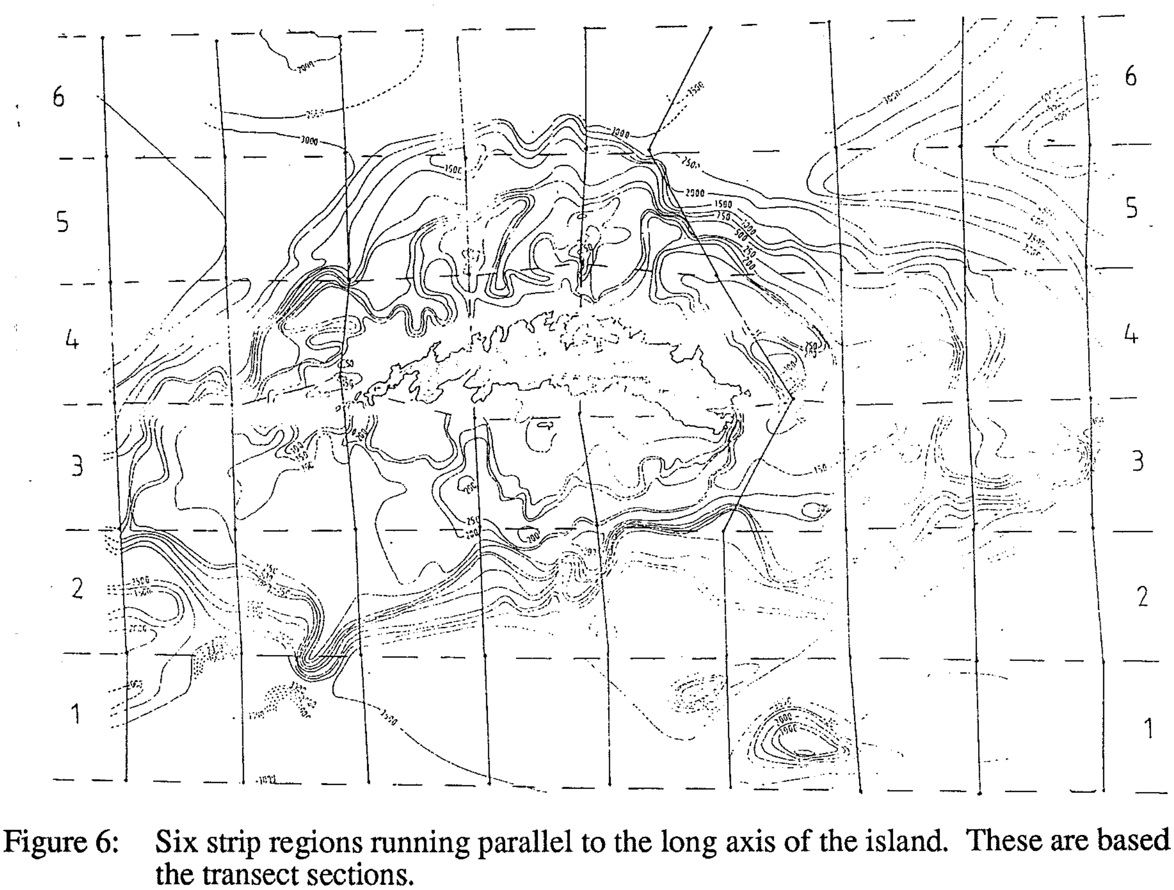


Figure 6: Six strip regions running parallel to the long axis of the island. These are based on the transect sections.

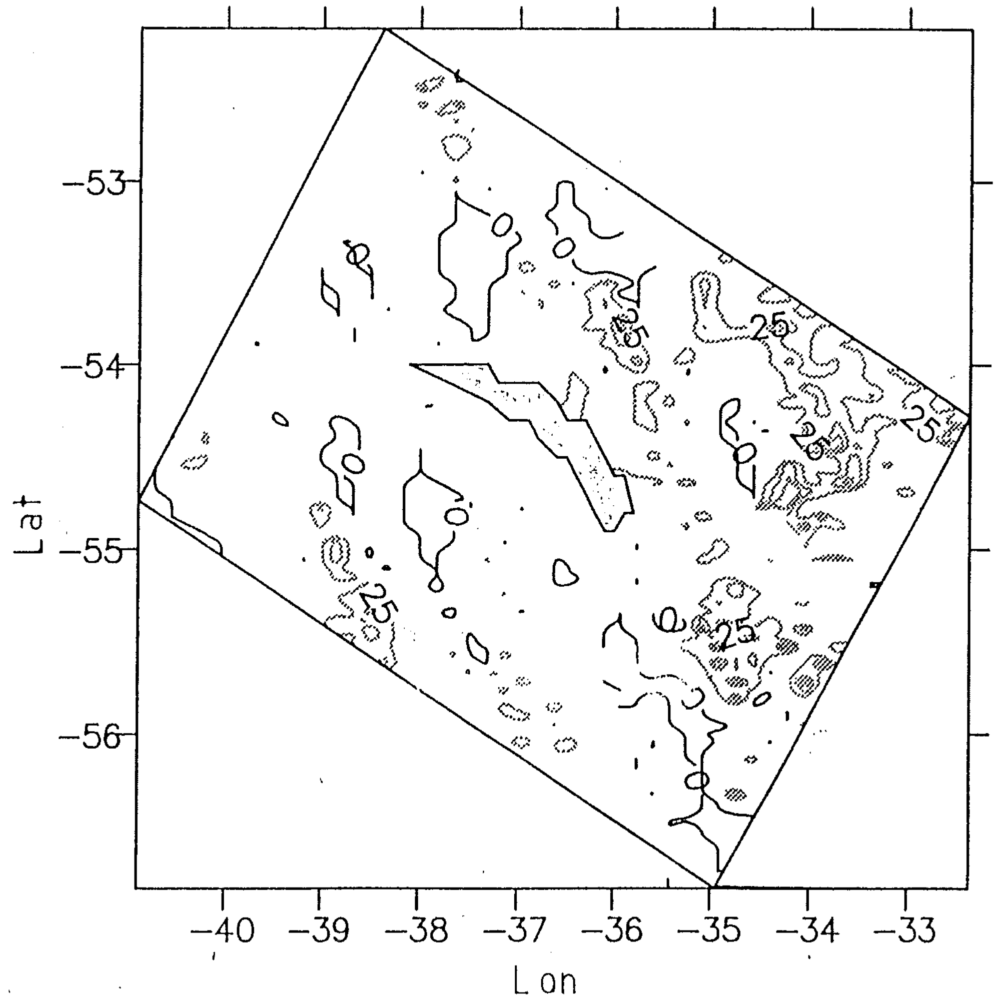


Figure 7: Map of krill density (tonnes km$^{-2}$) produced by universal Kriging techniques using UNIMAP (UNIMAP, 1990).

Liste des tableaux

Tableau 1: Définitions des strates utilisées dans les analyses des données de transect.

Tableau 2: Estimations de densité moyenne et de biomasse totale produites en appliquant différents critères de stratification (tableau 1) aux données de transect.

Tableau 3: Analyse cumulée de variance fondée sur les six strates régionales illustrées à la figure 5.

Tableau 4: Estimations de densité moyenne et de biomasse fondées sur les 18 transects définis à la figure 4. Les unités d'échantillonnage sont les sections de transect.

Tableau 5: Estimations de densité moyenne et de biomasse fondées sur les six strates régionales (figure 5). Les transects servent d'unité de base à l'échantillonnage.

Tableau 6: Classification des données de densité acoustique pour trois intervalles de profondeur d'eau.

Tableau 7: Classification des données de densité acoustique pour trois intervalles de température minimale moyenne des profils verticaux de CTD.

Tableau 8: Classification des données de densité acoustique par profondeur d'eau et température minimale moyenne.

Liste des figures

Figure 1: Trajet parcouru autour de l'île de Géorgie du Sud. Les trajets de la campagne sont espacés d'environ 30 milles n. Le cadre de la campagne était d'environ 240 milles n x 180 milles n. Le tracé des transects, débuté sur le coté nord du cadre, se termine dans le coin sud-est.

Figure 2: Longueur de la distribution de fréquences de tous les individus de krill mesurés pendant la campagne, du 24 novembre 1981 au 19 décembre 1981.

Figure 3: Neuf transects parallèles.

Figure 4: Dix-huit transects obtenus en divisant en deux les neuf transects le long de l'axe le plus long de l'île.

Figure 5: Six strates régionales couvrant les régions du plateau de Géorgie du Sud.

Figure 6: Six régions allongées parallèles à l'axe le plus long de l'île. Elles sont basées sur les sections de transect.

Figure 7: Carte de densité du krill (tonnes $km^{-2}$) produite par les techniques universelles de Kriging à l'aide de UNIMAP (UNIMAP, 1990).

Список таблиц

Таблица 1: Определения страт, использованных в анализе данных по разрезам.

Таблица 2: Оценки средней плотности и общей биомассы, вычисленные при помощи применения к данным по разрезам различных критериев стратификации (Таблица 1).

Таблица 3: Совокупный анализ изменчивости, основанный на шести региональных стратах, изображенных на Рисунке 5.

Таблица 4: Оценки средней плотности и биомассы, основанные на 18 разрезах, изображенных на Рисунке 4. Единицы сбора проб являются участками разреза.

Таблица 5: Оценки средней плотности и биомассы, основанные на шести региональных стратах (Рисунок 5). Разрезы взяты как стандартная единица сбора проб.

Таблица 6: Классификация акустических данных по плотности по трем диапазонам глубины.

Таблица 7: Классификация акустических данных по плотности по трем классам средней минимальной температуры вертикальных профилей CTD.

Таблица 8: Классификация акустических данных по плотности по глубине и средней минимальной температуре.

Список рисунков

Рисунок 1: Маршрут съемки, выполненный вокруг острова Южная Георгия. Маршруты съемки проходят на расстоянии приблизительно в 30 морских миль друг от друга. Площадь съемки сотавляла приблизительно 240 морских миль x 180 морских миль. Разрез был начат на северной стороне и завершен в юго-восточном углу сетки.

Рисунок 2: Частотное распределение длины криля, измеренное в ходе съемки с 24 ноября 1981 г. по 19 декабря 1981 г.

Рисунок 3: Девять параллельных разрезов.

Рисунок 4: Восемнадцать разрезов, полученные путем разбивки девяти разрезов вдоль длинной оси острова.

Рисунок 5: Шесть региональных страт над шельфами вокруг Южной Георгии.

Рисунок 6: Шесть полосообразных участков, пролегающих параллельно длинной оси острова. Участки основаны на разрезах.

Рисунок 7: Карта плотности криля (тонны км$^{-2}$), составленная при помощи универсального метода Кригинга с использованием UNIMAP (UNIMAP, 1990).

Lista de las tablas

Tabla 1: Definiciones de los estratos utilizados en los análisis de los datos de transectos.

Tabla 2: Cálculos de densidad media y biomasa total obtenidos al aplicar diversos criterios de estratificación a los datos de transecto (tabla 1).

Tabla 3: Análisis de varianza acumulados, basados en los seis estratos regionales presentados en la figura 5.

Tabla 4: Cálculos de densidad media y de biomasa basados en los 18 transectos definidos en la figura 4. Las unidades de muestreo son secciones de transectos.

Tabla 5: Cálculos de densidad media y de biomasa basados en los seis estratos regionales (figura 5). Los transectos se consideran como las unidades básicas de muestreo.

Tabla 6: Clasificación de los datos de densidad acústica, según los tres rangos de profundidad.

Tabla 7: Clasificación de los datos de densidad acústica según las tres clases de temperatura mínima media de los perfiles verticales CTD.

Tabla 8: Clasificación de los datos de densidad acústica según la profundidad del agua y la temperatura mínima media.

## Lista de las figuras

Figura 1: Derrota de prospección llevada a cabo alrededor de la isla de Georgia del Sur. Las derrotas de prospección están separadas por 30 millas naúticas, aproximadamente. El rectángulo de prospección fue aproximadamente de 240 x 180 millas naúticas. Se comenzaron los transectos en el sector norte del rectángulo, terminando en la esquina sudoriental.

Figura 2: La distribución de la frecuencia de tallas del krill medido durante el período de prospección, 24 de noviembre de 1981 al 19 de diciembre de 1981.

Figura 3: Nueve transectos paralelos.

Figura 4: Dieciocho transectos obtenidos al dividir los nueve transectos paralelos al eje longitudinal de la isla.

Figura 5: Seis estratos regionales que cubren las zonas de la plataforma alrededor de Georgia del Sur.

Figura 6: Seis bandas, paralelas al eje longitudinal de la isla. Estas se basan en las secciones de transectos.

Figura 7: Mapa de la densidad del krill (toneladas•$km^{-2}$) producido utilizando técnicas universales Kriging empleando UNIMAP (UNIMAP, 1990).