CCAMLR Science, Vol. 11 (2004): 33–58

A HYBRID APPROACH TO ACOUSTIC CLASSIFICATION AND LENGTH ESTIMATION OF KRILL

M. Azzali✉, I. Leonori and G. Lanciani
Istituto di Scienze Marine ISMAR-CNR
Sezione Pesca Marittima – Ancona
Largo Fiera della Pesca, I-60125 Ancona, Italy
Email – m.azzali@ismar.cnr.it

Abstract

The problem of acoustically identifying and estimating the sizes of two euphausiid species is considered. A euphausiid aggregation is represented by a three-dimensional probabilistic vector whose components are the mean ratios of the volume backscattering coefficients, measured at two different frequencies. The decisions on the species and the relative misclassification errors are calculated individually for each component of a vector, using classical Bayesian techniques. Classification probabilities are derived by integrating the individual decisions. The size structure of the classified aggregation is derived from a fluid-sphere model. The effectiveness of the method is demonstrated by comparing the acoustic estimates of species and sizes to net samples collected during three surveys conducted in the Ross Sea under various environmental conditions.

Résumé

Ce document examine la difficulté associée à l'identification et à l'estimation de la taille de deux espèces d'euphausiidés par acoustique. Une concentration d'euphausiidés est représentée par un vecteur de probabilité tridimensionnel dont les composantes sont les rapports moyens des coefficients de rétrodiffusion par volume, mesurés à deux fréquences différentes. Les décisions concernant les espèces et les erreurs relatives de classification sont calculées séparément pour chaque composante d'un vecteur au moyen de techniques Bayésiennes classiques. Afin de dériver les probabilités de classification, on a intégré les décisions individuelles. La structure des tailles de la concentration classifiée est dérivée d'un modèle de sphère fluide. L'efficacité de la méthode est démontrée en comparant les estimations acoustiques des espèces et des tailles aux échantillons prélevés au filet pendant trois campagnes d'évaluation menées en mer de Ross sous diverses conditions environnementales.

Резюме

В статье рассматривается проблема акустической идентификации и оценки размеров двух видов эвфаузиид. Скопление эвфаузиид представлено трехмерным вероятностным вектором, компонентами которого являются средние коэффициентов объемного обратного рассеяния, измеренных на двух различных частотах. Решения в отношении видов и относительные ошибки классификации рассчитываются отдельно для каждого компонента вектора с использованием классических байесовских методов. Вероятности классификации получены путем интегрирования индивидуальных решений. Размерная структура классифицированного скопления получена по модели жидкой сферы. Эффективность этого метода демонстрируется путем сравнения акустических оценок видов и размеров с траловыми пробами, полученными во время трех съемок, проведенных в море Росса при различных условиях окружающей среды.

Resumen

Se considera el problema de la identificación acústica y estimación de la talla de dos especies de eufáusidos. Se representa una concentración de eufáusidos mediante un vector probabilístico tridimensional cuyos componentes son las razones promedio de los coeficientes de reverberación volumétrica, medidos con dos frecuencias diferentes. Se calculó la clasificación de la especie y su error relativo individualmente para cada componente del vector, mediante técnicas Bayesianas clásicas. Se obtuvo la probabilidad de cada clasificación mediante una integración de las decisiones individuales. La composición de tallas de la concentración clasificada se obtuvo con un modelo de esferas duras. La eficacia del método fue demostrada mediante una comparación entre las estimaciones acústicas de las especies y tallas con las estimaciones de muestras de la red recolectadas durante tres prospecciones realizadas en el Mar de Ross bajo diversas condiciones ambientales.

Keywords: euphausiids, acoustic species classification, acoustic size estimation, CCAMLR

Introduction

In the Ross Sea, two similar krill species play a fundamental role in the pelagic food web: *Euphausia superba* and *E. crystallorophias*. However, only *E. superba* is used for human food and consumed by whales. Therefore it is important to estimate the abundance and geographical distribution of each population in the Ross Sea.

In principle, the abundance of the two populations can be estimated using data from a single-frequency echo sounder and the standard echo-integration method (MacLennan and Simmonds, 1992). The standard method assumes that the composition (species and size) of a population is knowable by frequent net sampling, visual analysis of echograms, and in situ target strength measurements (split-beam or dual-beam method). Unfortunately, the standard method is often insufficient for complex environmental and biological conditions, such as those found in the Ross Sea. Opportunities to carry out net sampling are severely limited by the presence of ice. Both krill species can form similarly-shaped aggregations, and visual differentiation using echograms is therefore difficult. To measure target strength in situ, an acoustic resolution volume must be based on a single animal measurement. For small schooling organisms, such as euphausiids, this criterion is seldom met. Therefore, in the Ross Sea the standard method can only be applied sporadically, in particularly favourable conditions.

To overcome these measurement obstacles, a new method has been under development since the first Italian survey to the Ross Sea (1989/90). The new method extracts information on species and size primarily from the acoustic backscatter data, using net samples largely to validate the acoustic data (Azzali et al., 2000a). This paper presents the mathematical approach to the method, which incorporates a fluid-sphere model (Johnson, 1977) and Bayesian decision theory (Devijver and Kittler, 1982). The performance of the new method is estimated by comparing the acoustic estimates of species and sizes to ground-truth samples. Specifically, the average probability of misclassification using the new method is calculated. All the acoustic data and net samples used to design and test the method were collected during three surveys in the Ross Sea (1989/90, 1997/98 and 2000).

Methods

Deterministic methods

Theoretical and empirical studies (Johnson, 1977; Greenlaw, 1977, 1979; Greenlaw and Johnson, 1983; Foote et al., 1990; Kalinowski and Azzali, 1992; Brierley and Watkins, 1996; Mitson et al., 1996; Demer et al., 1999) have demonstrated that the ratio ($\Delta_{fj/fi}$) of mean volume backscattering coefficients measured at two different frequencies (f_j, f_i) from a non-resonant marine organism can be used to estimate the radius of the backscattering cross section from a model such as that for a fluid sphere (Johnson, 1977):

$$\Delta_{fj/fi} = \frac{f_r^4 + 1.5 f_r^2 \left(k_m a_{fj/fi}\right)^4}{1 + 1.5 f_r^2 \left(k_m a_{fj/fi}\right)^4};$$

$$a_{fj/fi} = \frac{1}{k_m}\left(\frac{f_r^4 - \Delta_{fj/fi}}{1.5 f_r^2 \left(\Delta_{fj/fi} - 1\right)}\right)^{1/4} \; ; \; \left(1 < \Delta_{fj/fi} < f_r^4\right)$$

where:

- $a_{fj/fi}$ is the average radius in mm of the fluid sphere's equivalent in volume to each of the organisms in the dominating sound-scatter volume at the frequency $\sqrt{f_j f_i}$;
- $k_m = (2\pi/c)\sqrt{f_j f_i}$ is the geometric mean of the acoustic wave number (c = speed of sound in m/s; f_j, f_i = selected frequencies in kHz);
- $f_r = (f_j/f_i) > 1$ is the ratio of the selected frequencies.

The asymptotic limits of $\Delta_{fj/fi}$ are:

if $1.5 f_r^2 \left(k_m a_{fj/fi}\right)^4 << 1$;then $\Delta_{fj/fi} \approx f_r^4$

if $1.5 f_r^2 \left(k_m a_{fj/fi}\right)^4 >> f_r^4$;then $\Delta_{fj/fi} \approx 1$

if $1 < 1.5 f_r^2 \left(k_m a_{fj/fi}\right)^4 < f_r^4$;then $\Delta_{fj/fi} \approx f_r^2 / 1.5 \left(k_m a_{fj/fr}\right)^4$.

The model has the shape of a two-state low-pass filter with the two bends at approximately the input/output values:

$$a_1 \approx \left(k_m \sqrt[4]{1.5 f_r^2}\right)^{-1}, \Delta(a_1) \approx \left(f_r^4 + 1\right)/2;$$

$$a_2 \approx \left(\sqrt[4]{f_r^2/1.5}\right)/k_m, \Delta(a_2) \approx 2 f_r^4 / \left(1 + f_r^4\right).$$

The two bends are not equally sharp: in general, the first is sharper than the second. The sensitivity of $\Delta_{fj/fi}$ to $a_{fj/fi}$ is given by:

$$\frac{\partial \Delta}{\partial a} = \frac{4\left(1.5 f_r^2 k_m^4\right)\left(1 - f_r^4\right) a_{fj/fi}^3}{\left(1 + 1.5 f_r^2 k_m^4 a_{fj/fi}^4\right)^2}.$$

The largest frequency ratios are the most sensitive to changes in a. The sensitivity increases quickly as $a_{fj/fi}$ approaches the first bend and reaches its peak value at:

$$a_{\text{peak}} = 0.88\left(k_m \sqrt[4]{1.5 f_r^2}\right)^{-1}, \quad \Delta\left(a_{\text{peak}}\right) \approx \left(f_r^4 + 0.6\right)\Big/1.6 .$$

Then the sensitivity decreases gradually reaching a low value at the second bend. Thus to have a reliable value of $a_{fj/fi}$, $\Delta_{fj/fi}$ should be between: $\Delta(a_1) \leq \Delta_{fj/fi} \leq \Delta(a_2)$.

The relative error of the equivalent radius for a measurement error $d\Delta$ of $\Delta_{fj/fi}$ is given by:

$$\delta = \frac{1 - f_r^4}{4\left(\Delta_{fj/fi} - 1\right)\left(f_r^4 - \Delta_{fj/fi}\right)} d\Delta .$$

The relative error $|\delta|$ is high for $a_{fj/fi} < a_1$, decreases approaching the middle point between the two bends, where it is lowest, then increases again, reaching high values for $a_{fj/fi} > a_2$. It is assumed that euphausiids are identified for an output ranging between $1 < \Delta_{fj/fi} < f_r^4$ and their equivalent radius can be estimated confidently in the interval ($a_{\text{min}} - a_{\text{max}}$) where $100|\delta| < 20\%$, for a given $d\Delta$.

The mean length (L) of a euphausiid with equivalent radius ($a_{fj/fi}$) can be estimated by approximating its trunk with an equivalent cylinder $0.3L$ in length and $0.1L$ in diameter (Clay and Medwin, 1977) and equating the volume of the scatterer to the volume of the equivalent sphere: $L(\text{mm}) \approx 12.1 a_{fj/fi}$ (mm).

If only one frequency ratio is available (two-frequency method), its output can produce estimates only within a single size class of euphausiids, depending on the frequency ratio used. The size (the equivalent radius) within the class is not known and can vary. For example, the ratio of 120 to 38 kHz is highly 'tuned' (error < 20%) to measuring sizes within the class from $a = 1.6$ to 6.0 mm. If N frequency ratios are available, their outputs allow estimation of sizes within $C(N,2)$ classes ($C(N,2)$ = binomial coefficient). These estimates can be combined and estimation of the mean animal size that dominates the scattering, can be improved. For example, for a sound speed = 1 470 m/s and three frequencies (f_i = 200, 120, 38 kHz), there are three frequency combinations (f_r = 200/120; 120/38; 200/38), and three model outputs:

$$\Delta_{200/120} = \frac{7.716 + 0.801\left(a_{fj/fi}\right)^4}{1 + 0.801\left(a_{fj/fi}\right)^4};$$

$$\Delta_{200/38} = \frac{767.336 + 0.801\left(a_{fj/fi}\right)^4}{1 + 0.801\left(a_{fj/fi}\right)^4};$$

$$\Delta_{120/38} = \frac{99.447 + 0.104\left(a_{fj/fi}\right)^4}{1 + 0.104\left(a_{fj/fi}\right)^4} .$$

Each $\Delta_{fj/fi}$ produces independent estimates of partially overlapping size classes (Table 1). The limits of each size class can be established by a percentage error < 20% in the radius computation for a 26% (or 1 dB) measurement error of Δ (Table 1). The smallest scattering organisms (equivalent radius from 1 to 1.8 mm) are detected by $\Delta_{200/120}$; the largest organisms (equivalent radius from 1.6 to 6 mm) by $\Delta_{120/38}$ and the bulk of organisms (equivalent radius from 0.9 to 6 mm) by $\Delta_{200/38}$. The maximum errors in the estimates of equivalent radius are at the limits of each interval, the minimum error falls around the midpoint of each interval. The relative abundance of the organisms in each size class is derived from the geometric mean of the volume backscattering coefficients at the frequencies f_j and f_i: $\left(\sqrt{S_{fj} S_{fi}}\right)$.

Hybrid methods

The aforementioned methods assume a deterministic dependence of $\Delta_{fj/fi}$ on the volume of the body of a non-resonant animal up to several centimetres, irrespective of its species. Differences in $\Delta_{fj/fi}$ were observed for different euphausiid species of similar size (Madureira et al., 1993). Such differences may be generated by:

(i) Differences in the chemical and physical composition of the body:
The body compositions of *E. superba* and *E. crystallorophias* have different biochemical characteristics (Bottino, 1974), and the elastic shells (carapaces) that surround the bodies of the two species may have different thicknesses. The $\Delta_{fj/fi}$ function is sensitive to the physical characteristics of the body and very sensitive to the relative thickness of the shell (Clay and Medwin, 1977; Stanton et al., 1996). The longitudinal and transverse waves that take place in the shell cause large variations in the scatter around the value for a fluid sphere, which increase with relative shell thickness (Hickling, 1964; Zhang, 1990). A change of 1% in sound-speed contrast or in density contrast results in a change of approximately 40% or about 2 dB in target

strength (Kristensen, 1983). Therefore, the two euphausiid species may have equivalent radius classes or $\Delta_{fj/fi}$ patterns, which are separable even if their length classes are the same. Unfortunately, measurement of the physical parameters is difficult, also because of the strong seasonal components in the variability of both the environment and the species. Measurement of relative shell thickness is complicated, even within species, by the temporal effects of carapace development and moulting (Bucholz, 1982).

(ii) Differences in swimming behaviour:
The mean swimming angle of krill depends on the centre of body gravity and the centre of force which is dislocated in the midpoint of the expodite of the third pleopod (Kils, 1982; Endo, 1993). Thus, the mean swimming angle depends on species-specific body shapes. For example, the average swimming angle of *E. superba* with a mean body length of 40 mm was estimated to be 41.9° (SD = 5.7°), which is about 12° more than that of *E. pacifica* (30.4°, SD = 19.9°) (Miyashita et al., 1996) with a body length (16.4 mm) similar to that of *E. crystallorophias* (mean body length ≈ 20 mm). The scattering cross-section and the equivalent radius become smaller as the swimming angle increases (i.e. $\Delta_{fj/fi}$ becomes larger and the largest frequency ratios are the most sensitive to the changes). Therefore, if the mean swimming angle of *E. crystallorophias* (relative to horizontal) is lower than that of *E. superba*, the equivalent radius of *E. crystallorophias* is expected to be larger than that of *E. superba* of similar size. The swimming angles of wild euphausiids are difficult to measure because they are influenced by swimming speed, animal density and by some external factors such as currents, time of day and season. The swimming angles decrease at higher swimming speeds and animal densities. Moreover, they may change frequently due to vertical migrations and feeding activities.

(iii) Differences in body volume:
Some length–weight relationships currently assumed for *E. superba* (Morris et al., 1988) and *E. crystallorophias* (Siegel, 1992) are:

$$W_{\mathrm{E.s}}(L) = 0.00385(L_{\mathrm{mm}})^{3.230}(\mathrm{mg});$$
$$W_{\mathrm{E.c}}(L) = 0.00170(L_{\mathrm{mm}})^{3.373}(\mathrm{mg}).$$

These equations, even if they neglect the variability within species, indicate that the body weight of *E. crystallorophias* is 25–35% lower than that of *E. superba* of the same length. Therefore the body volume and the equivalent radius of *E. crystallorophias* can be expected to be proportionally smaller than those of *E. superba* of similar length. The effect of differences in body volume on equivalent radius estimates seems to be quite opposite to that of swimming angle (discussed above). Moreover, *E. superba* and *E. crystallorophias* of the same body volume have different shapes and therefore cannot be expected to have the same $\Delta_{fj/fi}$.

The differences in body composition, in swimming angles, in body volume and shape between *E. superba* and *E. crystallorophias* are the bases for their acoustic recognition. However, given the number and complexity of the acoustic processes that generate these differences (Stanton and Chu, 2000), it would be extremely complicated or even impossible to include them in the fluid-sphere model which is quite effective in the classification of a single species by size. This kind of difficulty can be overcome by using both statistical and deterministic methodologies in a 'hybrid approach' to species recognition and length estimation.

Bayesian decision theory is the basis of the new method for recognising two krill species by acoustic means. This method consists of three steps: (i) design prototype probability density functions for the two krill species and each of the three frequency ratios; (ii) select decision criteria for classification of an aggregation; (iii) quantify the error probability of the Bayesian classifier. Performance of the Bayesian classifier is further quantified by estimating the size structure of the classified aggregation. This provides qualitative information about the relationship between species and size. The three equivalent radii of the dominant organisms within each size class and the average equivalent radius of the whole aggregation are derived from the fluid-sphere model. The conversion factor (from average equivalent radius to average length) is calculated for each species by linear regression.

The Bayesian method requires large quantities of data to design the classifier. The acoustic and net sample data used in this paper were collected in three surveys to the Ross Sea (1989/90; 1997/98 and 2000), using different acoustic and net systems (Table 2).

In the survey of 26 December 1989 to 25 January 1990, acoustic data were collected with a BioSonic 102 scientific echo sounder and ESP echo integrator with 38 and 120 kHz dual-beam transducers. Echo signals were recorded, each ping from 10 to 160 m, on digital audio tape. Pulses of 0.6 ms were triggered alternately every 0.6 s at 38 and 120 kHz. The noise margin was set to 0 dB and the threshold level to –85 dB for both frequencies. The euphausiid aggregations were sampled using a 0.25 m^2 EZNET-BIONESS plankton net (Azzali and Kalinowski, 2000).

In the surveys of 7 December 1997 to 5 January 1998 and 16 January to 7 February 2000, measurements were made with a Simrad EK500 echo sounder configured with 38 and 120 kHz split-beam, and 200 kHz single-beam subsystems. Echo signals were integrated from 10 to 260 m in 125 sub-layers of 2 m thickness and recorded on an HP 9000/715 Work Station. The noise margin was set to 0 and the threshold level to –85 dB. Pulses of 1.0 msec were triggered at 38 and 120 kHz and 0.6 msec at 200 kHz. The ping rate was 1 s^{-1} for each frequency. Euphausiids were sampled using a 5 m^2 Plankton Hamburg Net with one net of either 500 or 1 000 μm (mesh size).

The sampling strategy used in the three surveys is summarised in Table 2. Generally, the net was positioned according to the acoustic detection of aggregations (targeting hauls).

At each sampling site, euphausiids were identified and counted. If the catch was large, the mean length of each species being compared with acoustic estimations was determined haul by haul from a random sub-sample of 100 individuals. Otherwise, the mean lengths were determined from measurements of all individuals. In post-processing, the aggregations that could be misclassified (e.g. mixed hauls or hauls dominated by other scatterers) were discarded. The S_{fi} values recorded over each selected aggregation at depth intervals of 2 m were filtered for noise by subtracting the adjacent S_{fi} values devoid of signals. Values corrupted by high noise were discarded.

The species classifier and size estimator were based on all available acoustic and biological samples. Therefore the performance of the design was tested using the 'resubstitution method of error estimation' (Devijver and Kittler, 1982). The same sets of acoustic and biological data used to design the classifier were used to evaluate the performance of the design. This approach makes the best use of the data for designing the classifier and the bias of the resubstitution method approaches zero as the size of the design set increases without bound (i.e. it is a consistent error estimator). The alternative to the resubstitution scheme is to partition the data in two mutually exclusive subsets and to use one subset for designing the classifier and the other one to test it (the holdout method). This approach makes poor use of the data and, if the test is satisfactory, one will normally re-design the classifier with all the samples and use the resubstitution method for evaluating the performance of the final design.

The efficiencies of the standard and new methods are compared by analysing the biomass and length of *E. superba* and *E. crystallorophias* in the 1997/98 survey to the Ross Sea.

Results

In 26 60-minute hauls carried out in the 1989/90 survey, 55 swarms of *E. superba* were identified with certainty (Table 2). All hauls were located in the continental slope region. Because the net was ineffective at catching euphausiids of all sizes, samples were inadequate for any analysis of size distribution.

During the 1997/98 survey, 32 of 35 60-minute hauls contained euphausiids (Figure 1a and Table 2). Fifteen hauls were conducted in the continental slope region: *E. superba* was present in only 11 hauls (13 swarms were sampled), and four hauls contained a mixture of the two euphausiid species. Seventeen hauls were conducted in the continental shelf region: *E. superba* was present in 10 hauls (15 swarms were sampled) and *E. crystallorophias* in three hauls (six swarms were sampled).

During the 2000 survey, 56 30-minute hauls of were conducted, but only 37 were dominated by euphausiids (Figure 1b and Table 2). Twenty-one hauls were conducted in the continental slope region: *E. superba* was present in 18 hauls (46 swarms were sampled) and *E. crystallorophias* in only one haul (four aggregations were sampled), with two hauls containing a mixture of the two euphausiid species. Eight hauls were conducted in the continental shelf region: *E. superba* was present in only one haul (two aggregations were sampled) and *E. crystallorophias* in six hauls (14 aggregations were sampled), with only one haul containing a mixture of the two euphausiid species. The eight hauls conducted in the region adjacent to the ice-shelf edge contained only *E. crystallorophias*; 28 aggregations were sampled. In all hauls of the three surveys, the only euphausiids caught were *E. superba* and *E. crystallorophias*.

In total, 131 aggregations of *E. superba* sampled in 66 monospecific hauls and 52 aggregations of *E. crystallorophias* sampled in 18 monospecific hauls were analysed. Eleven hauls contained a mixture of the two euphausiid species and were discarded.

Aggregations of the two euphausiid species, henceforth classes (ω_1 = *E. superba*, ω_2 = *E. crystallorophias*) were represented by a matrix:

$$S(\omega_h) = [S_{200,m}, S_{120,m}, S_{38,m}],\ (m = 1,2,3\ldots N; h = 1,2)$$

where m is the index of the depth interval associated with each of the N intervals dividing the vertical range and covering the horizontal extent of the aggregation.

The matrix $S(\omega_h)$ was transformed into a vector. Each component of a vector is the mean output generated by an aggregation at a certain frequency ratio:

$$\Delta(\omega_h) = \left[\bar{\Delta}_{200/120}, \bar{\Delta}_{200/38}, \bar{\Delta}_{120/38}\right]$$

where

$$\bar{\Delta}_{fj/fi} = \frac{\sum_{m=1}^{N} 10\log\left(S_{fj}/S_{fi}\right)_m}{N}; 1 < \bar{\Delta}_{fj/fi} < f_r^4.$$

The components of the Δ vectors were divided into three sets on the basis of the frequency ratios. Each set is made up of two independent subsets containing the data assigned respectively to classes ω_1 and ω_2:

$$B\left(\bar{\Delta}, \omega_h\right) = \begin{Bmatrix} \left(\bar{\Delta}(\omega_1)_{n1}, \bar{\Delta}(\omega_2)_{n2}\right)_{200/120} \\ \left(\bar{\Delta}(\omega_1)_{n3}, \bar{\Delta}(\omega_2)_{n4}\right)_{200/38} \\ \left(\bar{\Delta}(\omega_1)_{n5}, \bar{\Delta}(\omega_2)_{n6}\right)_{120/38} \end{Bmatrix}.$$

The number of elements (i.e. swarms), filtered for noise, within each subset (n_i) was:

$$n_1 = 75;\ n_2 = 52;\ n_3 = 75;\ n_4 = 49;\ n_5 = 130;\ n_6 = 49.$$

$B\left(\bar{\Delta}, \omega_h\right)$ is the body of data used for species recognition and size estimation. In this study it is assumed that the acoustic data $\bar{\Delta}_{fj/fi}$ taken from each aggregation are correct and that they can be correctly assigned to one of two possible classes $\omega_{h=1,2}$ on the basis of net sampling.

Design of the prototype probability density functions

To begin with, the three sets of $B\left(\bar{\Delta}, \omega_h\right)$ were transformed into three conditional probability density functions of classes ω_h, $h = 1,2$:

$$B\left(\bar{\Delta}, \omega_h\right) \to p\left(\bar{\Delta}, \omega_h\right) = \begin{Bmatrix} \left(p\left(\bar{\Delta}_{200/120}/\omega_h\right)\right) \\ \left(p\left(\bar{\Delta}_{200/38}/\omega_h\right)\right) \\ \left(p\left(\bar{\Delta}_{120/38}/\omega_h\right)\right) \end{Bmatrix}.$$

The task of classifying the two euphausiid species gives rise to the problem of measuring the probabilistic distance of the probability density functions $p\left(\bar{\Delta}_{fj/fi}/\omega_1\right); p\left(\bar{\Delta}_{fj/fi}/\omega_2\right), \forall \bar{\Delta}_{fj/fi}$.

The class-conditional probability density functions $p\left(\bar{\Delta}_{fj/fi}/\omega_h\right), h = 1,2$ were estimated for each set of frequency ratios, resulting in the histograms of the elements $\bar{\Delta}_{fj/fi}$ of classes ω_1 and ω_2. The range of each element was divided into a fixed number (n = 40 Log f_j/f_i) of equal intervals (1 dB). The relative number of observations $\bar{\Delta}_{fj/fi} \in \omega_h$ falling in each bin defines the histogram estimate of the conditional probability density function of class ω_h (h = 1,2). The relative number of observations $\bar{\Delta}_{fj/fi}$ falling in each bin belonging to both class ω_1 and class ω_2 defines the histogram estimate of the unconditional probability density function: $p\left(\bar{\Delta}_{fj/fi}\right)$. The histograms (probability density functions) and the box plots of the estimators constructed for each frequency ratio are shown in Figure 2 and described in Table 3. They provide a realistic picture of the dependence of $\bar{\Delta}_{fj/fi}$ on class ω_h, mutual class overlap, class separability and class probabilistic structure.

To test the hypothesis that the data are from a normal distribution, the Shapiro–Wilk and the Kolmorov–Smirnov tests were applied to the conditioned probability density functions of both classes at each frequency ratio. Neither test rejects the hypothesis of normality for all histograms ($p < 0.05$), except that of ω_1 at 200/120 kHz, in which the six extreme values (outliers) at the right tail depart from that of a normal distribution. The t-test for equality of means (Table 3) indicates that the two classes in each histogram are significantly separated ($p < 0.0001$).

It is assumed that when the number of observations becomes large, each class can be adequately represented by the three Gaussians. The characteristics of each Gaussian are those suggested by the test, excluding the six outliers. That is:

$$p\left(\bar{\Delta}_{fj/fi}/\omega_1\right) \approx G(2.83, 1.21)_{200/120};$$
$$G(12.97, 3.26)_{200/38}; G(10.16, 2.44)_{120/38}$$

$$p\left(\bar{\Delta}_{fj/fi}/\omega_2\right) \approx G(6.04, 1.44)_{200/120};$$
$$G(22.35, 1.90)_{200/38}; G(16.33, 1.35)_{120/38}$$

where $G(\mu, \sigma)$ is a normal distribution with mean value μ and standard deviation σ in dB.

The pair of Gaussian-distributed pattern classes $\{G(\mu_1,\sigma_1),G(\mu_2,\sigma_2)\}_{fj/fi}$ represent the prototype probability density functions used for classifying an unknown aggregation (Figure 3a, b, c). The divergence between classes ω_1 and ω_2 in the pattern $\bar{\Delta}_{fj/fi}$ is given by:

$$J_{fj/fi} = \int\left(p\left(\bar{\Delta}_{fj/fi}/\omega_1\right) - p\left(\bar{\Delta}_{fj/fi}/\omega_2\right)\right) \mathrm{Log}\left(\frac{p\left(\bar{\Delta}_{fj/fi}/\omega_1\right)}{p\left(\bar{\Delta}_{fj/fi}/\omega_2\right)}\right) d\bar{\Delta}_{fj/fi}$$

where $p\left(\bar{\Delta}_{fj/fi}/\omega_h\right), h = 1,2$ are the Gaussian density functions of the patterns in classes ω_h, $h = 1,2$. The divergence is greatest when the classes are disjointed and equals zero when probability density functions are identical. Using the values of the prototype density functions, the following is obtained:

$$J_{200/38} = 7.22 \text{ dB}; J_{120/38} = 6.26 \text{ dB}; J_{200/120} = 3.82 \text{ dB}.$$

These results confirm the ‘separability’ of the Gaussian probability density functions, given above for constructing histograms using a *t*-test, and indicate that the ‘distance’ between size classes in the pattern $\bar{\Delta}_{200/38}$ is almost twice as much than in the pattern $\bar{\Delta}_{200/120}$.

Decision criterion to classify an unknown aggregation

The problem of classifying an aggregation represented by a probabilistic vector with three components $\bar{\Delta}_{fj/fi}$ of unknown class is considered:

$$\Delta(\omega_x) = \left[\bar{\Delta}_{200/120}, \bar{\Delta}_{200/38}, \bar{\Delta}_{120/38}\right].$$

The probability of a component $\bar{\Delta}_{fj/fi}$ belonging to class ω_h is the class *a posteriori* probability $P\left(\omega_h/\bar{\Delta}_{fj/fi}\right)$. This probability can be computed by the Bayesian rule:

$$P\left(\omega_h/\bar{\Delta}_{fj/fi}\right) = \frac{p\left(\bar{\Delta}_{fj/fi}/\omega_h\right)P_h}{p\left(\bar{\Delta}_{fj/fi}\right)}; h = 1,2$$

where:

- $p\left(\bar{\Delta}_{fj/fi}\right) = \sum_{h=1,2} p\left(\bar{\Delta}_{fj/fi}/\omega_h\right)P_h$ is the unconditional probability density function governing the distribution $p\left(\bar{\Delta}_{fj/fi}\right)$ for each frequency ratio;
- P_h is the *a priori* probability of the class ω_h. Because it is scarcely known which target class (*E. superba* or *E. crystallorophias*) may occur, changing their spatial distributions continually as a result of, say, geographical location and environmental conditions, it is assumed that the two classes are equally probable: $P_1 = P_2$.

It is assumed that the classifier employs the Bayesian decision criterion. That is:

- decide $\bar{\Delta}_{fj/fi} \in \omega_1$ if $P\left(\omega_1/\bar{\Delta}_{fj/fi}\right) > P\left(\omega_2/\bar{\Delta}_{fj/fi}\right)$
- decide $\bar{\Delta}_{fj/fi} \in \omega_2$ if $P\left(\omega_2/\bar{\Delta}_{fj/fi}\right) > P\left(\omega_1/\bar{\Delta}_{fj/fi}\right)$.

Since $P\left(\omega_h/\bar{\Delta}_{fj/fi}\right)$ are the *a posteriori* probabilities of the classes ω_h, $h = 1,2$ they satisfy the relation:

$$P\left(\omega_2/\bar{\Delta}_{fj/fi}\right) + P\left(\omega_1/\bar{\Delta}_{fj/fi}\right) = 1.$$

The Bayesian decision rule can be reformulated as a function of the rejection thresholds $T_{fj/fi}$ (Figure 3d):

$$\bar{\Delta}_{fj/fi} \in \omega_1 \text{ if } < T_{fj/fi}$$
$$\bar{\Delta}_{fj/fi} \in \omega_2 \text{ if } > T_{fj/fi}.$$

The threshold of the pattern $\bar{\Delta}_{200/120}$ is 4.3 dB. In this case a random value belongs to ω_1 if the threshold is <4.3 dB and belongs to ω_2 if it is >4.3 dB. The probability that a random value belonging to ω_1 falls above 4.3 dB is 0.067. The probability that a random value belonging to ω_2 falls below 4.3 dB is 0.073. The threshold of the pattern $\bar{\Delta}_{200/38}$ is 18.5 dB. In this case a random value belongs to ω_1 if the threshold is <18.5 dB and to ω_2 if it is >18.5 dB. The probability that a random value belonging to ω_1 falls above 18.5 dB is 0.045. The probability that a random value belonging to ω_2 falls below 18.5 dB is 0.022. The threshold of the pattern $\bar{\Delta}_{120/38}$ is 13.8 dB. In this case a random value belongs to ω_1 if the threshold is <13.8 dB and to ω_2 if it is > 13.8 dB. The probability that a random value belonging to ω_1 falls above 13.8 dB is 0.067. The probability that a random value belonging to ω_2 falls below 13.8 dB is 0.030.

The values given above (i.e. 0.067; 0.045; 0.067) are the probabilities at frequencies 200/120, 200/38 and 120/38 kHz respectively, that class one (ω_1) is actually present but the authors estimate that it is class two (ω_2). The values (0.073; 0.022; 0.030) are the probabilities for the same frequency combinations that the class two (ω_2) is actually present but the authors estimate that it is class one (ω_1).

Majority rule

The Bayesian decision criterion classifies the individual components of a vector $\Delta(\omega_x)$ independently. The final decision rule is to assign one class to the vector $\Delta(\omega_x)$, given the decisions on each of its components $\left[\bar{\Delta}_{200/120}, \bar{\Delta}_{200/38}, \bar{\Delta}_{120/38}\right]$. Three situations can occur:

(i) the classifier assigns the three components to the same class ω_h;

(ii) the classifier assigns two components to the class ω_i and one component to the class ω_j;

(iii) the identification of one component is 'weak' ($\bar{\Delta}_{fj/fi}(\omega_x)$close to the threshold) and the identifications of the other two components are in conflict.

The 'majority vote rule' is used: the class assigned at least to two components out of three is assumed to be the correct class of the vector $\Delta(\omega_x)$. If there is no majority (situation (iii)), no decision is taken.

Error probability of the Bayesian classifier

The error incurred in classifying a pattern $\bar{\Delta}_{fj/fi}$ using the Bayesian decision rule is:

$$\begin{aligned} e\left(\bar{\Delta}_{fj/fi}\right) &= \min\left(P\left(\omega_1/\bar{\Delta}_{fj/fi}\right), P\left(\omega_2/\bar{\Delta}_{fj/fi}\right)\right) \\ &\leq \sqrt{P\left(\omega_1/\bar{\Delta}_{fj/fi}\right) P\left(\omega_2/\bar{\Delta}_{fj/fi}\right)} \quad . \end{aligned}$$

The probability of misrecognition $E_{fj/fi}$ is given by:

$$\begin{aligned} E_{fj/fi} &= \int e\left(\bar{\Delta}_{fj/fi}\right) p\left(\bar{\Delta}_{fj/fi}\right) d\bar{\Delta}_{fj/fi} \\ &\leq \int \sqrt{P\left(\omega_1/\bar{\Delta}_{fj/fi}\right) P\left(\omega_2/\bar{\Delta}_{fj/fi}\right)}\, p\left(\bar{\Delta}_{fj/fi}\right) d\bar{\Delta}_{fj/fi} . \end{aligned}$$

The misrecognition probability $E_{fj/fi}$ (or alternatively the probability of correct classification $C_{fj/fi} = 1 - E_{fj/fi}$) of $\bar{\Delta}_{fj/fi}$ obtained from each frequency ratio is:

- $E_{200/120} \leq 0.167$ $C_{200/120} \geq 0.833$
- $E_{120/38} \leq 0.135$ $C_{120/38} \geq 0.865$
- $E_{200/38} \leq 0.095$ $C_{200/38} \geq 0.905$.

Correct classification improvement (majority rule)

Combining the information obtained on the same subject from three frequency ratios, the probability of correct classification of $\Delta(\omega_x)$ increases. It becomes equal to or better than that of its best component $\bar{\Delta}_{200/38}$. Suppose, for simplicity, that the probability of correct classification for each pattern is $C = 0.833$, the majority vote rule will correctly identify an aggregation with probability:

$$C_3 = 3C^2(1 - C) + C^3 = 3(0.833)^2(0.167) + (0.833)^3 = 0.926.$$

This expression assumes that the individual decisions at each frequency ratio are independent. The actual change of classification performance, increasing the frequency ratios from 1 to 3, is:

$$\Delta C_1 = C_3 - C_1 = (C(1 - C))(2C - 1) = 0.093.$$

The conclusion that can be drawn from these results is that an unknown class ω_x is assigned to the class ω_h, $h = 1{,}2$ with a probability of correct classification >0.90.

Estimation of the euphausiid equivalent radius

The same aggregations, which were used for species recognition, and represented by the matrix:

$$S(\omega_h) = [S_{200,m}, S_{120,m}, S_{38,m}];\ (m = 1{,}2{,}3\ldots.N; h = 1{,}2)$$

were used for estimating the euphausiid mean length. They were transformed into vectors:

$$a\left(\omega_h\right) = \left[\bar{a}_{200/120}, \bar{a}_{200/38}, \bar{a}_{120/38}\right]$$

where:

$$\bar{a}_{fj/fi} = \frac{\sum_{m=1}^{N} \left(a_{fj/fi}\right)_m}{N} ; a_{\min} \leq \left(a_{fj/fi}\right)_m \leq a_{\max}.$$

Three size classes are assumed to dominate the scattering. The smallest organisms are represented by the component $\bar{a}_{200/120}$, the medium-sized organisms by the component $\bar{a}_{200/38}$ and the largest organisms by the component $\bar{a}_{120/38}$. The weighted mean $\bar{a}_w(\omega_h)$ (weight = relative abundance = $\sqrt{S_{fj} S_{fi}}$) of the three equivalent radii $\bar{a}_{fj/fi}$ is assumed to be the acoustic estimate corresponding to the euphausiid mean length $\bar{L}(\omega_h)$ in the catch, called biological length. From Table 1 it is obtained that: 0.9 mm $\leq \bar{a}_w(\omega_h) \leq$ 6 mm.

Calculation of the conversion factor

The regression-line method was used to estimate the value of the length associated with the calculated mean equivalent radius.

The conversion factor (10.83) from the equivalent radius $\bar{a}_w(\omega_1)$ to the biological length L for *E. superba* was estimated by the following regression line (Figure 4a):

$\bar{L}(\omega_1) = (10.83)\bar{a}_w(\omega_1) + 14.99$ mm
$R^2 = 0.60$; Pearson correlation $r = 0.64$; $p < 0.002$;
haul number = 38.

The correlation differs very significantly from 0 (no correlation).

The conversion factor (15.73) for *E. crystallorophias* was estimated by (Figure 5a):

$\bar{L}(\omega_2) = (15.73)\bar{a}_w(\omega_2) + 0.76$ mm
$R^2 = 0.67$; Pearson correlation $r = 0.57$; $p < 0.05$;
haul number = 18.

The correlation differs significantly from 0.

The two regression lines indicate that the equivalent radius of *E. crystallorophias* of up to 2.9 mm (i.e. up to $\bar{L}(\omega_2)$ = 46.40 mm) is larger than that of *E. superba* of the same length. These results may be explained by differences in swimming angle and perhaps in body composition and shape between the two species, but are opposite to those expected given the differences in body volume.

Validation of the method

The performance of the method was tested using all available acoustic and biological data, including the values discarded as outliers during the analysis.

Species recognition

Using the discrimination thresholds shown above, 91.3% of the 76 *E. superba* and 96.6% of the 52 *E. crystallorophias* aggregations sampled by net during the 1997/98 and 2000 surveys were correctly classified. In particular, during the survey in January–February 2000, the misclassification error was less than 4% for both euphausiid species. These results agree with the probability of correct classification calculated theoretically ($C > 90\%$).

Size estimation

The correlation between 'acoustic length' $\bar{L}_a$, calculated from each net sample from the equivalent radius, and mean catch length $\bar{L}_b$, measured from each net sample, is shown in Figure 4(b) for *E. superba*, and in Figure 5(b) for *E. crystallorophias*. The correlation for *E. superba* was significant during the 2000 survey and highly significant in both the 1997/98 survey and in the 1997/98 and 2000 surveys combined. On the contrary, the correlation for *E. crystallorophias* was not significant during the 2000 survey and slightly less than significant in the 1997/98 and 2000 surveys combined. This is probably because several equivalent radii of *E. crystallorophias* fall within a range of around 1 mm (Figure 5a), where the errors in radius computation may be large (Table 1).

Figures 4(b) and 5(b) show large variations in the acoustic length estimates for close biological length estimates. This indicates that haul-by-haul comparison of acoustic and biological mean lengths has some shortcomings. One shortcoming is that hauls have most often fished multiple aggregations (Table 2). However, acoustic data are related to single aggregations, generally targeted one by one, while biological data are related to all aggregations sampled along transects positioned differently within fished aggregations. Another shortcoming is that the acoustic mean length of krill in the aggregations is estimated from the relative abundance of three dominant size classes, while net estimates are derived from the absolute abundance of all size classes. A third shortcoming is that no reliable acoustic information is provided on classes with an equivalent radius of <1 mm. These shortcomings make the haul-by-haul comparison of acoustic and biological length estimation difficult. However, acoustic and biological mean lengths in several hauls converge, averaging acoustic and biological data. Table 4 compares biological and acoustic estimates calculated from *E. superba* and *E. crystallorophias* aggregations sampled during each survey and in all surveys combined. For *E. superba* the acoustic estimates of mean length were 8.5% lower than net estimates during the 2000 survey, and 2.6% higher during the 1997/98 survey. During the 1989/90 survey, although the BIONESS net was ineffective at capturing *E. superba* and only the frequencies 120 and 38 kHz were used, the relatively crude acoustic and biological means were close. The acoustic and net estimates of mean length derived from all aggregations sampled in all surveys combined were very close (Table 4). For the 2000 survey, the *E. superba* length probability density function estimated from all catches had three peaks at lengths of approximately 37, 43 and 48 mm (Sala et al., 2002). The three dominant size classes calculated at 200/120, 200/38 and 120/38 frequency ratios were 36.40 ± 5.32, 46.86 ± 6.82 and 50.88 ± 9.66 mm. The distances of biological peaks from the corresponding acoustic means are lower than the standard deviations from the means. From the *E. superba* length probability density function of all the 1997/98 catches, four peaks were identified (Azzali et al., 2000b). The peaks were interpreted as juveniles and sub-adults (around 12 and 20 mm) and two adult size classes (around 35 and 45 mm). However, the three frequency ratios do not highlight the juvenile and sub-adult size classes (Table 4). This is probably because the lengths of the two smallest classes fall below the lower limit for which the model is considered valid (lower limit for *E. superba* = 24.7 mm for an equivalent radius of 0.9 mm).

For *E. crystallorophias* the acoustic estimates of mean length were 7% lower than net estimates in the 2000 survey, but consistently 20.5% higher in the 1997/98 survey when the catches were dominated by small sizes (<14 mm). The acoustic and net estimates of mean length derived from all aggregations sampled during both surveys combined were close (Table 4). In the 2000 survey the length probability density function estimated from all *E. crystallorophias* catches was characterised by three modes (Sala et al., 2002): juveniles (mean length ≈13 mm), sub-adults (mean length ≈22 mm) and adults (mean length ≈26 mm). The dominant size classes calculated at the 200/120 frequency ratio were 28% higher than the juvenile size class, but the other two frequency ratios gave estimates which were only 4 and 14% higher than the related biological size (Table 4). In the three monospecific hauls carried out around Drygalsky Basin during the 1997/98 survey, the acoustic mean lengths (17.59, 16.64 and 19.79 mm) were respectively 27, 27 and 17% higher than the biological mean lengths (13.88, 13.07 and 16.80 mm). Note that the percentage error between acoustic and biological estimates of *E. crystallorophias* mean lengths is >20% only when the mean lengths of net estimates fall below the lower confidence limit (lower limit for *E. crystallorophias* = 14.9 mm for an equivalent radius of 0.9 mm). These results seem to agree with the model.

Biomass estimation

The three-frequency method was compared with the standard method in the estimation of biomass of *E. superba* and *E. crystallorophias* found in the Ross Sea during the 1997/98 survey. The results, expressed in relative density S_a (m^2/nm^2) at 120 kHz, are summarised in Table 5. The discrimination of the two euphausiid species obtained by the three-frequency method is close (<6%) to that obtained by the standard method in the regions where results using this method were supported by the catch results. However, in the region adjacent to the Ross Ice Shelf, where no hauls were possible and the standard method had to rely only on visual estimation of proportions of each species by using echograms, the difference between the two methods is consistently large (≈70%).

Discussion and conclusion

A lack of net samples and the necessity to base species identification and size estimation of *E. superba* and *E. crystallorophias* only on acoustic methods is the major shortcoming in estimation of their abundance in the Ross Sea. In this study a euphausiid aggregation was represented by a three-dimension probabilistic vector whose components are the ratios $\bar{\Delta}_{fj/fi}$, $\left(1 \le \bar{\Delta}_{fj/fi} \le (f_r)^4\right)$. It was assumed that a decision rule for the size class estimation of *E. superba* or *E. crystallorophias* can be formulated for each group of size classes from which an equivalent radius of the dominant size class at the two frequencies (f_j,f_i) can be estimated. Each decision and estimate as to the identity of the class and radius is based on the classical Bayesian rule and fluid-sphere model. Bayesian decision criteria require *a priori* knowledge of the class-conditional probability density functions $p(\Delta_{fj/fi}/\omega_h)$,$h = 1{,}2$ and *a priori* estimation of which class may occur. The two classes were considered equally probable ($P_1 = P_2$). The bodies of acoustic and biological data collected during three different surveys allowed the authors to assume that the classes are normally distributed (six prototype probability density functions) and that the probabilistic distance or divergence between two classes in each pattern $\bar{\Delta}_{fj/fi}$ is > 0 (i.e. the classes in the three patterns $\bar{\Delta}_{fj/fi}$ are separable). The decisions on the class of each component of a vector produced by an unknown aggregation were expressed in terms of rejection/acceptance thresholds $T_{fj/fi}$. The probabilities of making the correct decision were calculated for each threshold. By integrating the individual decisions (majority rule), an improvement of correct classification probability is obtained. The final probability of correct classification of an unknown aggregation (i.e. of an unknown vector) is estimated to be >0.90. The same sets of acoustic and biological data used to design the method were used to validate it (resubstitution method of error estimation). About 91% of the 76 *E. superba* aggregations and 97% of the 52 *E. crystallorophias* aggregations found during the 1997/98 and 2000 surveys were identified correctly by the method. Then, the problem of estimating the size class of a classified aggregation was considered. The same set of acoustic and biological data used to design the Bayesian decision criteria was used to estimate the conversion factors from equivalent radius to length for *E. superba* (10.83 mm) and *E. crystallorophias* (15.73 mm). It is assumed in this study that three size classes dominated each aggregation and the equivalent radius for the dominant organism of each class can be calculated independently from the three ratios $\Delta_{fj/fi}$, using the fluid-sphere model. The smallest organisms were detected by the two frequencies 200 and 120 kHz, the medium-sized organisms by the frequencies 200 and 38 kHz, and the largest organisms by the frequencies 120 and 38 kHz. The weighted mean (weight = relative abundance of each dominant class) of the three equivalent radii was assumed by comparing the acoustic quantity with the mean length obtained from the biological samples. The conversion factors, estimated using the regression method, were highly significant for *E. superba* and significant for *E. crystallorophias.* They indicated that the equivalent radius of *E. crystallorophias* is larger than that of *E. superba* of the same length. The correlation between the length estimated acoustically and the biological length estimated by the net sampling carried out during the 1997/98 and 2000 surveys was significant for *E. superba* but not significant for *E. crystallorophias*. The percentage error between acoustic and biological estimates of mean lengths of both species was less than 20% only if the mean lengths of net estimates fell within the limits for which the model is considered valid. The estimates of the biomasses of the two euphausiid species, obtained using the three-frequency method, may differ by up to 70% in some areas from those obtained using the standard method, but these differences seem to decrease consistently when the number of hauls is increased.

The three-frequency method requires further studies in order to answer the following questions:

(i) What are the physical differences between *E. superba* and *E. crystallorophias* that allow an acoustic misclassification error of less than 10% and size estimation errors of less than 20%? Is misclassification due to intrinsic differences in the species' body composition and shape, differences in their behaviour (swimming/orientation), or certain oceanographic conditions that may affect each class differently? Surprisingly, the differences in body volume between the two species under the same length seem to be insignificant.

(ii) Is it correct to assume that the acoustic data have zero uncertainty and that they can be correctly assigned to one of two possible species on the basis of net sampling?

(iii) Should the processes of species recognition and size estimation be absolutely objective or allow for a subjective rejection threshold?

(iv) How important is the assumption that the three parameters $\Delta_{fj/fi}$ of an aggregation (and consequently the three equivalent radii generated by them) are statistically independent? While this is clearly not so, there is great difficulty in establishing exact correlations between these parameters.

(v) Is it acceptable to use relative abundances, instead of absolute abundances, as parameters for estimating the average equivalent radius of an aggregation? This was used in this study as assumption because reliable scattering models for the two euphausiid species at the three frequencies are not yet available (Demer, in press).

Despite these unanswered questions and the uncertainties in the model parameters, the three-frequency acoustic method seems to provide important information on species and size composition of euphausiid aggregations. The effectiveness of the method is demonstrated by comparing the acoustic estimates to ground-truth samples, collected in various environmental conditions. However the results should be considered tentative because at present the design is based and tested only on a moderate sample size.

Acknowledgements

This research was supported by ENEA-Progetto Antartide. The authors thank the anonymous referees who revised the paper and gave many useful and valuable comments and suggestions. The authors are grateful to the captain, crew and the colleagues on board the RV *Italica* for their assistance with field work.

References

Azzali, M. and J. Kalinowski. 2000. Spatial and temporal distribution of krill *Euphausia superba* biomass in the Ross Sea (1989/90 and 1994). Faranda, F.M., L. Guglielmo and A. Ionora (Eds). *Ross Sea Ecology.* Springer-Verlag, Berlin Heidelberg: 433–455.

Azzali, M., J. Kalinowski and G. Lanciani. 2000a. A multiple-frequency method for identifying and assessing the Antarctic krill stock in the

Ross Sea (1989/90, 1997/98 and 1999/2000). Document *WG-EMM-00/37*. CCAMLR, Hobart, Australia.

Azzali, M., J. Kalinowski, G. Lanciani and I. Leonori. 2000b. Comparative studies on the biological and acoustical properties of krill aggregations (*Euphausia superba*, Dana) sampled during the XIII Italian Expedition to the Ross Sea (December 1997–January 1998). Document *WG-EMM-00/39*. CCAMLR, Hobart, Australia.

Bottino, N.R. 1974. The fatty acids of Antarctic phytoplankton and euphausiids. Fatty acid exchange among trophic levels of the Ross Sea. *Mar. Biol.*, 27: 197–204.

Brierley, A.S. and J.L. Watkins. 1996. Acoustic targets at South Georgia and the South Orkney Islands during a season of krill scarcity. *Mar. Ecol. Prog. Ser*., 138 (1–3): 51–61.

Bucholz, F. 1982. Drach's molt staging system adapted for euphausiids. *Mar. Biol.*, 66: 301–305.

Clay, C.S. and H. Medwin. 1977. *Acoustical Oceanography: Principals and Applications.* John Wiley and Sons, New York: 544 pp.

Demer, D.A. In press. An estimate of error for CCAMLR 2000 estimate of krill biomass. *Deep-Sea Res.*, II, Special Issue on the CCAMLR 2000 Synoptic Survey.

Demer, D.A., M.A. Soule and R.P. Hewitt. 1999. A multiple-frequency method for potentially improving the accuracy and precision of in situ target strength measurements. *J. Acoust. Soc. Am*., 105 (4): 2359–2376.

Devijver, P.A. and J. Kittler. 1982. *Pattern Recognition: a Statistical Approach*. Prentice-Hall International, Inc., London: 448 pp.

Endo, Y. 1993. Orientation of Antarctic krill in an aquarium. *Nippon Suisan Gakkaishi*, 59: 465–468.

Foote, K.G., I. Everson, J.L. Watkins and D.G. Bone. 1990. Target strengths of Antarctic krill (*Euphausia superba*) at 38 and 120 kHz. *J. Acoust. Soc. Am*., 87 (1): 16–24.

Greenlaw, C.F. 1977. Backscattering spectra of preserved zooplankton. *J. Acoust. Soc. Am*., 62 (1): 44–52.

Greenlaw, C.F. 1979. Acoustical estimation of zooplankton populations. *Limnol. Oceanogr.*, 24: 226–242.

Greenlaw, C.F. and R.K. Johnson. 1983. Multiple-frequency acoustical estimation. *Biol. Oceanogr.*, 2: 227–252.

Hickling, R. 1964. Analysis of echoes from a hollow metallic sphere in water. *J. Acoust. Soc. Am.*, 36: 1124–1137.

Johnson, R.K. 1977. Sound scattering from a fluid sphere revisited. *J. Acoust. Soc. Am.*, 61 (2): 375–377.

Kalinowski, J. and M. Azzali. 1992. Possibility of discrimination of various groups of species using dual-frequency hydroacoustic system. In: *Underwater Acoustics, Proceedings of the IXth Symposium on Hydroacoustics*. Hydroacoustics Department of Naval Academy, Hydroacoustics Division of the Technical University of Gdansk, Gdynia (Poland): 219–229.

Kils, U. 1982. Swimming behavior, swimming performance and energy balance of Antarctic krill *Euphausia superba*. *BIOMASS Sci. Ser.*, 3: 122 pp.

Kristensen, A. 1983. Acoustic classification of zooplankton. Thesis at Universitet I Trodheim – Norges Tekniske Hogskole. ELAB report STF44 A83187: 107 pp.

MacLennan, D.N. and E.J. Simmonds. 1992. *Fisheries Acoustics*. Chapman and Hall, London.

Madureira, L.S.P., I. Everson and E.J. Murphy. 1993. Interpretation of acoustic data at two frequencies to discriminate between Antarctic krill and other scatterers. *J. Plankton. Res*., 15 (7): 787–802.

Mitson, R.B., Y. Simarad and C. Goss. 1996. Use of a two-frequency algorithm to determine size and abundance of plankton in three widely spaced locations. *ICES J. Mar. Sci.*, 53 (2): 209–215.

Miyashita, K., I. Aoki and T. Inagaki. 1996. Swimming behaviour and target strength of isada krill (*Euphausia pacifica*). *ICES J. Mar. Sci.*, 53 (2): 303–308.

Morris, D.J., J.L. Watkins, C. Ricketts, F. Bucholz and J. Priddle. 1988. An assessment of the merits of length and weight measurements of Antarctic krill *Euphausia superba*. *Brit. Ant. Surv. Bull.*, 79: 37–50.

Sala, A., M. Azzali and A. Russo. 2002. Krill of the Ross Sea: distribution, abundance and demography of *Euphausia superba* and *Euphausia crystallorophias* during the Italian Antarctic Expedition (January–February 2000). *Sci. Mar.*, 66 (2): 123–133.

Siegel, V. 1992. Review of length–weight relationships for Antarctic krill. In: *Selected Scientific Papers, 1992 (SC-CAMLR-SSP/9)*. CCAMLR, Hobart, Australia: 145–155.

Stanton, T.K., D. Chu and P.H. Wiebe. 1996. Acoustic scattering characteristics of several zooplankton groups. *ICES J. Mar. Sci.*, 53 (2): 289–295.

Stanton, T.K. and D. Chu. 2000. Review and recommendations for the modelling of acoustic scattering by fluid-like elongated zooplankton: euphausiids and copepods. *ICES J. Mar. Sci.*, 57 (4): 793–807.

Zhang, J. 1990. Numerical prediction for vibration and sound radiation from submerged revolutional shell excited by sound source. *Proceedings of International Workshop on Marine Acoustics*. Beijing, China: 369–372.

Table 1: Upper and lower limits of the intervals over which the variations of the equivalent radius for Δ error = 1 dB are less than 20%. The minimum variation of the equivalent radius occurs for a = 1.35 mm, Δ = 4.25 dB at 200/120 (variation = 13.80%); for a = 2.40 mm, Δ = 14.59 dB at 200/38 (variation = 7%); for a = 3.10 mm, Δ = 10.12 dB at 120/38 (variation = 8%).

Frequency Ratio	Lower Limits			Upper Limits		
	a_{min} (mm)	$\Delta(a_{min})$ (dB)	Variation of a for Δ error = 1 dB (%)	a_{max} (mm)	$\Delta(a_{max})$ (dB)	Variation of a for Δ error = 1 dB (%)
200/120	1	6.74	18.54	1.8	2.34	17.50
200/38	0.9	27.02	18.91	6.0	2.4	15.33
120/38	1.6	17.74	16.30	6.0	2.36	15.60

Table 2: Hauls (bold) and aggregations (in parentheses), sampled by net and acoustically in three surveys in the Ross Sea. In total, 66 hauls contained *Euphausia superba* only and sampled 131 aggregations. Eighteen hauls contained *E. crystallorophias* only and sampled 52 aggregations. Eleven hauls contained both euphausiid species. The hauls in which euphausiids were absent or were not the dominant species are not reported. Environmental conditions, acoustic and net systems, and sampling strategies used in each survey are summarised.

Environmental Conditions	Acoustic System	Net System	Sampling Strategy	Sampled Region	Ground-truth Samples		
(a) 26 December 1989 to 25 January 1990 (26 hauls of *Euphausia superba*)							
					E. superba		
Sea-ice retreating	Biosonics with 38 and 120 kHz dual-beam towed transducers.	0.25 m^2 EZNET BIONESS with 10 nets of 240–500 µm.	26 60-minute hauls. targeting *E. superba* swarms. Towing speed: 2–3 knots	Continental slope region	**26** (55)		
(b) 7 December 1997 to 5 January 1998 (32 hauls: 21 *E. superba*; 3 *E. crystallorophias*; 8 *E. superba* and *E. crystallorophias*)							
					E. superba	*E. crystallorophias*	Mixed
Partial ice-cover	Simrad EK 500 with 38 and 120 kHz split-beam and 200 kHz single-beam transducers mounted on hull of vessel and on towed body.	5 m^2 HPN with 1 net of 1000 or 500 µm. Net depth controlled by Simrad 'ITI'. Net equipped with a flowmeter.	32 60-minute hauls (with euphausiids) every 6 hours. Net is lowered to 250 m depth and then positioned according to acoustic detection of aggregations. Towing speed: 3–4 knots	Continental slope region	**11** (13)	**0**	**4**
				Continental shelf region	**10** (15)	**3** (6)	**4**
				Region adjacent to ice-shelf edge	-	-	-
(c) 16 January to 7 February 2000 (37 hauls: 19 *E. superba*; 15 *E. crystallorophias*; 3 *E. superba* and *E. crystallorophias*)							
					E. superba	*E. crystallorophias*	Mixed
Ice-free water	see 1997/98 survey	see 1997/98 survey	37 30-minute hauls (with euphausiids) every 6 hours. The same strategy as in 1997/98 survey.	Continental slope region	**18** (46)	**1** (4)	**2**
				Continental shelf region	**1** (2)	**6** (14)	**1**
				Region adjacent to ice-shelf edge	**0**	**8** (28)	**0**

Table 3: The main statistical descriptors of *Euphausia superba* (ω_1) and *E. crystallorophias* (ω_2) histograms at each frequency ratio. For all six histograms there is little variation between the mean, 5% trimmed mean and median. The ratios of each skewness and kurtosis to its respective standard error are well within the range (–2, 2), where the hypothesis of normality is not rejected. Not surprisingly, both Kolgomonov–Smirnov and Shapiro–Wilk tests do not reject normality. All three *t*-tests for equality of means strongly agree that the two classes in each histogram are separated.

		Frequency Ratio					
		200/120		200/38		120/38	
Classes		ω_1	ω_2	ω_1	ω_2	ω_1	ω_2
Aggregations		*N* = 69	*N* = 52	*N* = 75	*N* = 49	*N* = 130	*N* = 49
Mean (dB)	Stat.	2.56	6.04	12.97	22.35	10.16	16.33
	Std. error	0.14	0.17	0.38	0.27	0.19	0.19
95% confidence interval for mean (dB)	Lower bound	2.28	5.70	12.22	21.80	9.73	15.95
	Upper bound	2.83	6.38	13.72	22.90	10.58	16.72
5% trimmed mean (dB)		2.52	6.02	12.98	22.38	10.20	16.38
Median (dB)		2.33	5.74	15.15	22.32	10.13	16.57
Std. deviation (dB)		1.15	1.21	3.26	1.90	2.44	1.35
Minimum (dB)		0.43	3.39	5.77	17.78	2.69	12.32
Maximum (dB)		5.10	8.73	21.27	27.03	16.87	18.84
Range (dB)		4.67	5.34	15.50	9.25	14.18	6.52
Interquartile range (dB)		1.59	1.80	4.34	2.59	2.93	1.95
Skewness	Stat.	0.49	0.38	0.21	–0.11	–0.28	–0.58
	Std. error	0.29	0.33	0.28	0.34	0.21	0.34
Kurtosis	Stat.	–0.46	–0.54	–0.33	0.03	0.59	0.43
	Std. error	0.57	0.65	0.55	0.67	0.42	0.67
Shapiro–Wilk test	Stat.	0.962	0.963	0.974	0.986	0.989	0.974
	Sig.	0.030	0.105	0.131	0.817	0.375	0.355
Kolmogorov–Smirnov test	Stat.	0.105	0.130	0.098	0.078	0.048	0.094
	Sig.	0.059	0.030	0.070	0.200	0.200	0.200
t-test equality of means	*t*	–16.410		–20.215		–21.420	
	Sig.	<0.000		<0.000		<0.000	

Table 4: A comparison of biological and acoustic estimates from all the aggregations sampled during each survey and during all the surveys combined.

	Euphausia superba				*Euphausia crystallorophias*					
	2000	1997/98	1989/90	Combined	2000	1997/98	1997/98 haul by haul			Combined
Biological estimates:										
No. monospecific hauls	19	21	26	66	15	3	Haul no. 1	Haul no. 2	Haul no. 3	18
No. individuals caught	105 964	475 179	144	581 287	192 940	3 532	1 000	2 200	332	196 472
No. individuals measured	1 217	2 007	144	3 368	1 424	300	100	100	100	1 724
Mean length ± SD (mm)	44.84 ± 3.64	36.90 ± 9.51	40.80 ± 3.6	39.93 ± 9.42	20.20 ± 6.11	14.57 ± 4.16	13.88 ± 1.58	13.02 ± 1.61	16.8 ± 6.28	19.22 ± 6.20
Minimum length (mm)	32	8		8	7	7				7
Maximum length (mm)	55	55		55	41	36				41
Range (mm)	22	47		47	34	29				29
Lengths at peaks of the length probability density function (mm)	37; 43; 48	12; 20; 37; 47			13; 22; 26					
Acoustic estimates:										
No. aggregations	48	28	55	131	46	6	2	2	2	52
Weighted mean length ± SD (mm)	41.01 ± 6.40	37.87 ± 5.37		39.36 ± 6.02	18.77 ± 3.03	17.56 ± 4.64	17.59 ± 5.37	16.64 ± 5.76	19.79 ± 2.00	18.64 ± 3.13
Dominant size class at:										
200/120 ± SD (mm)	36.40 ± 5.32	33.70 ± 5.50		34.98 ± 5.52	17.22 ± 3.30	16.49 ± 2.95	16.64 ± 4.58	15.86 ± 2.34	17.75 ± 2.42	17.41 ± 3.08
200/38 ± SD (mm)	46.86 ± 6.82	43.24 ± 5.77		44.91 ± 6.50	22.30 ± 3.39	20.81 ± 3.91	20.58 ± 4.07	19.32 ± 4.22	24.98 ± 1.17	22.17 ± 3.31
120/38 ± SD (mm)	50.88 ± 9.66	48.49 ± 5.91	40.20 ± 4.87	49.59 ± 7.68	29.08 ± 3.45	26.36 ± 8.48	26.24 ± 7.46	23.41 ± 10.71	33.95 ± 2.42	28.83 ± 6.92

Table 5: A comparison of the standard and three-frequency methods for estimating relative abundances from four regions of the Ross Sea, sampled during the 1997/98 survey. In regions (a), (b), (c), where the standard method was corroborated by net samples, the estimates of the two methods are close. However, in region (d), where no hauls were possible and the standard method relied only on visual interpretation of the echograms, the two estimates differ considerably.

	Units	Method		Difference (A–B)
		Standard (A)	Three-frequency (B)	
(a) Continental slope: 659 n miles^2; 14 hauls				
E. superba	S_a (m^2/n mile^2)	128 855	125 599	3 256.0
	% ref. both species	90.7	88.4	2.3
E. crystallorophias	S_a(m^2/n mile^2)	13 226	16 422	–3 196.0
	% ref. both species	9.3	11.6	–2.3
Both euphausiid species	S_a(m^2/n mile^2)	142 081	142 081	0.0
	%	100	100	0.0
(b) Continental shelf: 722 n miles^2; 15 hauls				
E. superba	S_a(m^2/n mile^2)	12 112	11 530	581.9
	% ref. both species	80.0	76.2	3.8
E. crystallorophias	S_a(m^2/n mile^2)	3 022	3 604	–581.9
	% ref. both species	20.0	23.8	–3.8
Both euphausiid species	S_a(m^2/n mile^2)	15 134	15 134	0.0
	%	100	100	0.0
(c) Drygalski Basin: 238 n miles^2; 3 hauls				
E. superba	S_a(m^2/n mile^2)	0	136	–136.0
	% ref. both species	0	5.2	–5.2
E. crystallorophias	S_a(m^2/n mile^2)	2 593	2 457	136.0
	% ref. both species	100	94.8	5.2
Both euphausiid species	S_a(m^2/n mile^2)	2 593	2 593	0.0
	%	100	100	0.0
(d) Region adjacent to ice-shelf edge (CSARIS): 250 n miles^2; 0 hauls				
E. superba	S_a(m^2/n mile^2)	3 789	930	2 858.5
	% ref. both species	93.4	22.9	70.5
E. crystallorophias	S_a(m^2/n mile^2)	267	3 126	–2 858.5
	% ref. both species	6.6	77.1	–70.5
Both euphausiid species	S_a(m^2/n mile^2)	4 056	4 056	0.0
	%	100	100	0.0

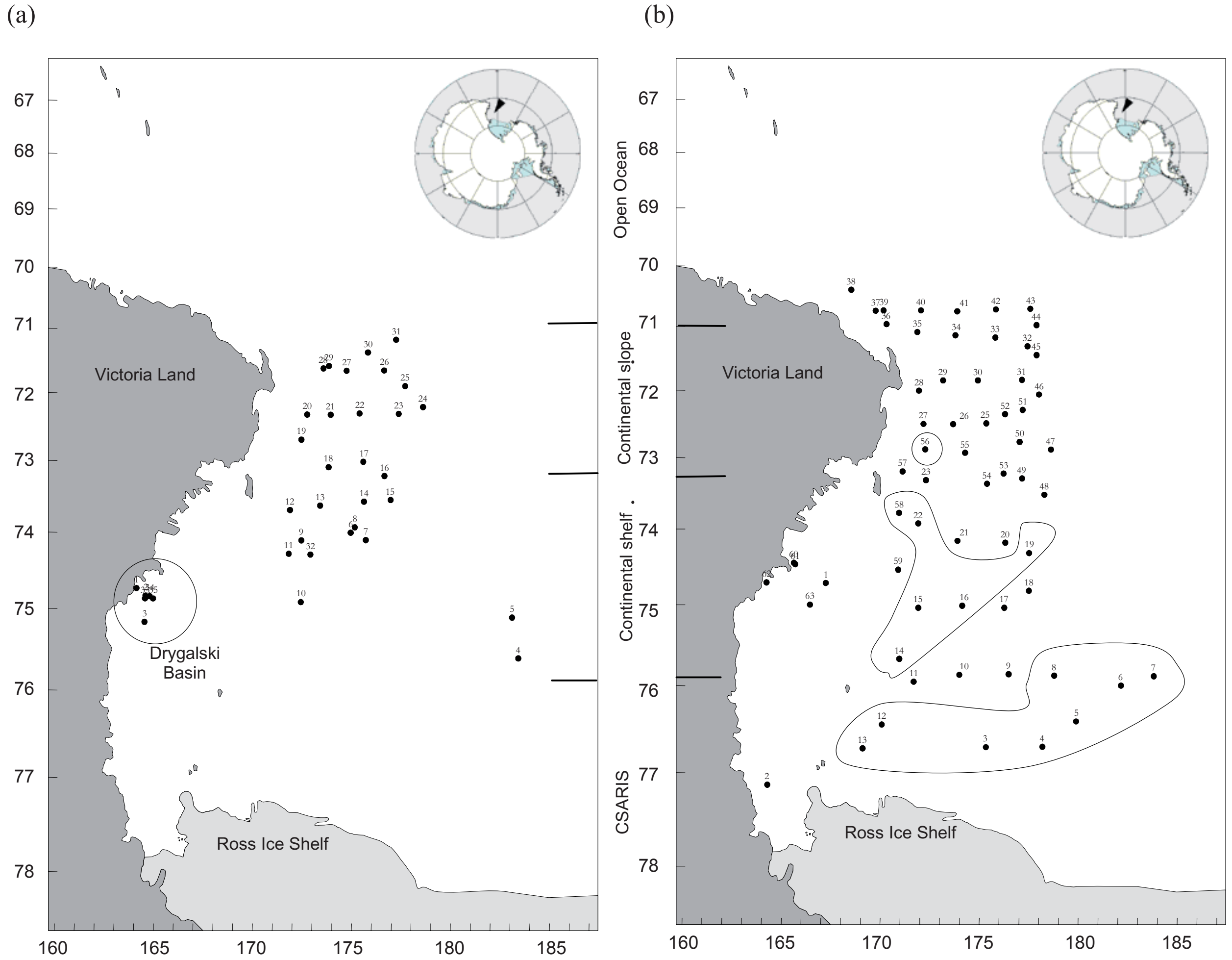


Figure 1: (a) Location of hauls carried out during the XIIIth Italian Antarctic Expedition (December 1997 to January 1998) in the Ross Sea. In 10 hauls (5, 7, 8, 9, 10, 11, 13, 14, 15, 16) carried out on the continental shelf, only *Euphausia superba* was present. Three hauls (33, 34, 35) carried out in the Drygalski Basin caught only *E. crystallorophias*. On the continental slope, *E. superba* was caught in 11 monospecific hauls (17, 18, 20, 21, 22, 23, 24, 26, 27, 28, 29). In hauls 9, 10, 11, 13 (continental shelf) and 26 (continental slope) juvenile *E. superba* constituted the dominant age class (Azzali et al., 2000b). In four hauls (4, 6, 12, 32) conducted on the continental shelf and in four hauls (19, 25, 30, 31) conducted on the continental slope, the two species were mixed.

(b) Location of hauls carried out during the XVth Italian Antarctic Expedition (January to February 2000) in the Ross Sea. Eight hauls (3, 4, 5, 6, 7, 8, 12, 13) located in the region adjacent to the ice-shelf barrier contained only *E. crystallorophias*. Six hauls (14, 15, 16, 19, 22, 58) carried out on the continental shelf contained only *E. crystallorophias*, while in this region *E. superba* was caught only in haul 49. On the continental slope, 19 of the hauls were monospecific. Hauls 25, 26, 27, 30, 31, 32, 34, 35, 36, 37, 39, 40, 41, 44, 46, 47, 50, 52 contained only *E. superba*, and haul 56 only *E. crystallorophias.* In three hauls (38, 45 on the continental slope and 54 on the continental shelf) the two species were mixed.

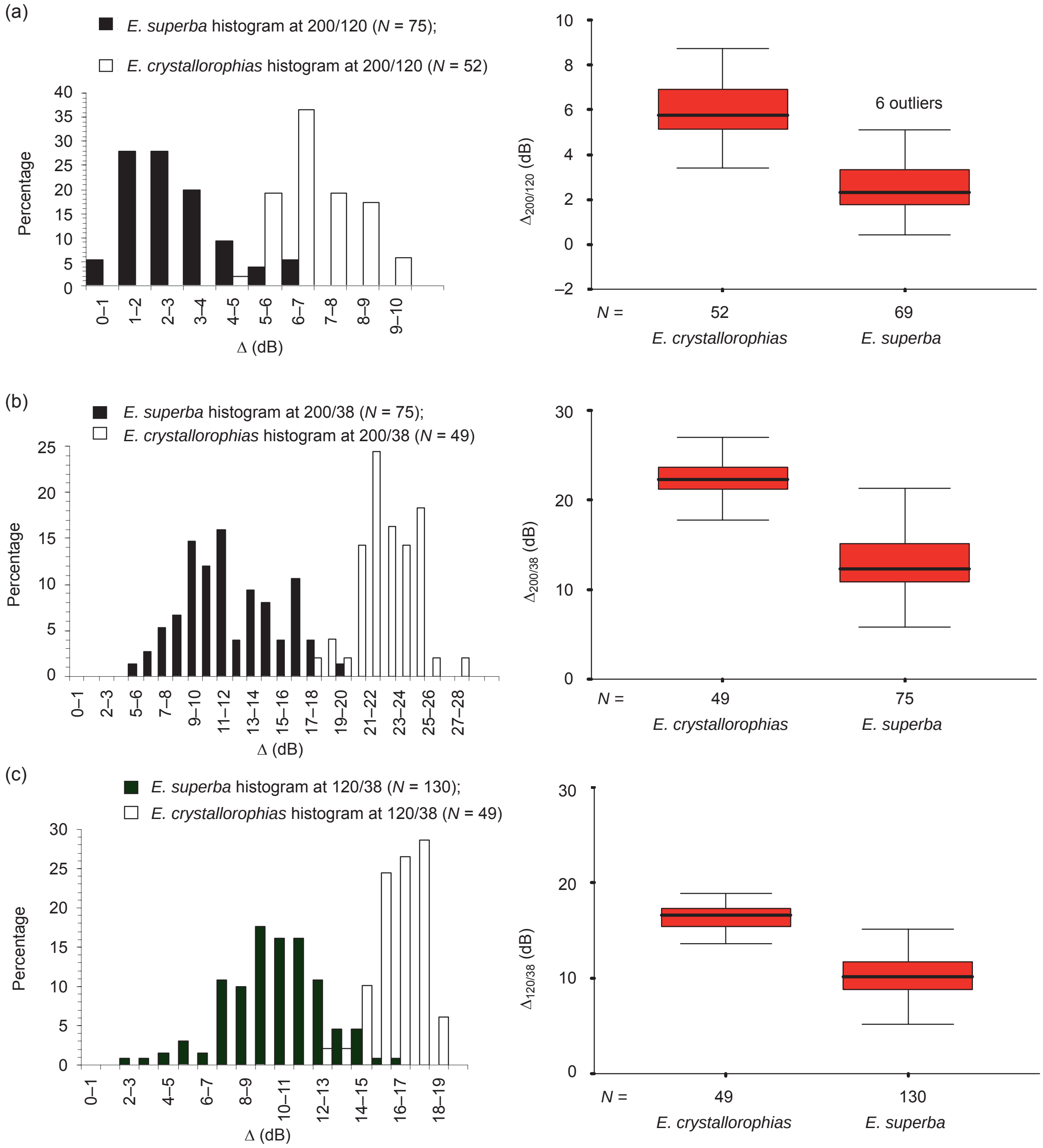
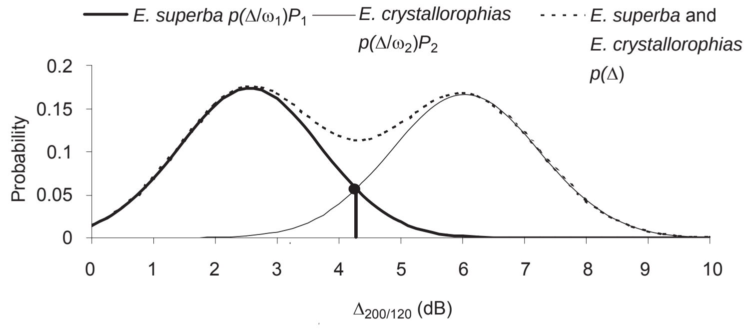


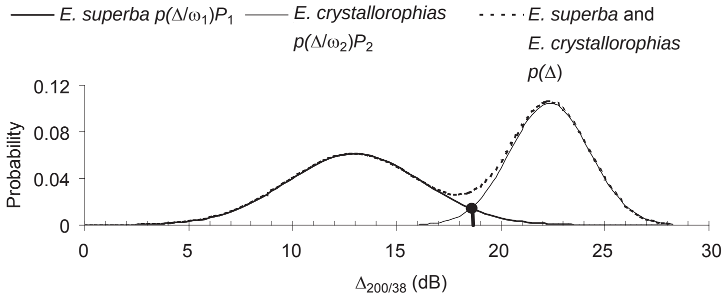
Figure 2: (a) The two distributions are right-skewed with tails shorter than those of a normal distribution. (b) The distribution of *Euphausia superba* is right-skewed with tails longer than those of a normal distribution, while the distribution of *Euphausia crystallorophias* is left-skewed with tails slightly longer than those of a normal distribution. (c) The two distributions are left-skewed with tails longer than those of a normal distribution.



(a) Frequency ratio 200/120

E. superba
$\mu = 2.56$ dB; $\sigma = 1.15$ dB
$P(\Delta_{200/120} < 4.3) = 93.3\%$

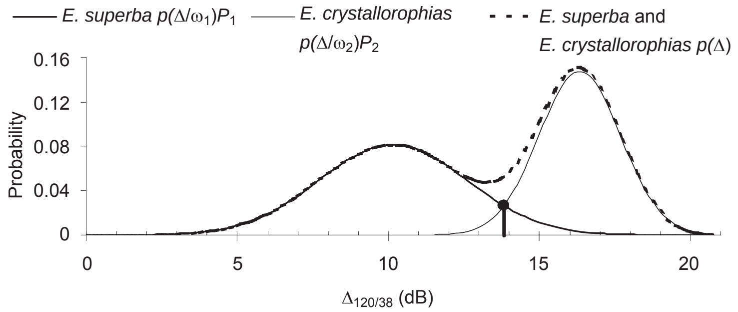
E. crystallorophias
$\mu = 6.04$ dB; $\sigma = 1.2$ dB
$P(\Delta_{200/120} > 4.3) = 92.7\%$



(b) Frequency ratio 200/38

E. superba
$\mu = 12.97$ dB; $\sigma = 3.26$ dB
$P(\Delta_{200/38} < 18.5) = 95.5\%$

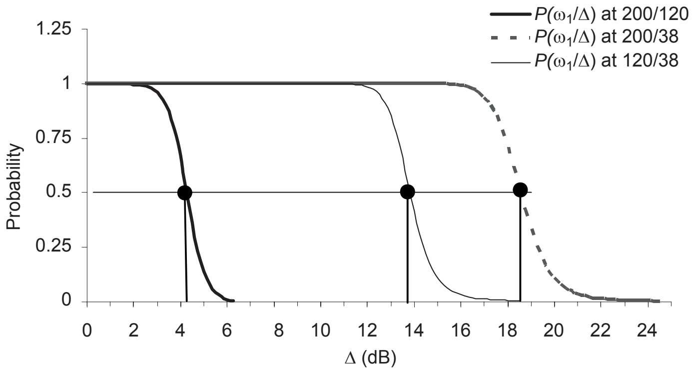
E. crystallorophias
$\mu = 22.35$ dB; $\sigma = 1.9$ dB
$P(\Delta_{200/38} > 18.5) = 97.8\%$



(c) Frequency ratio 120/38

E. superba
$\mu = 10.16$ dB; $\sigma = 2.44$ dB
$P(\Delta_{120/38} < 13.8) = 93.3\%$

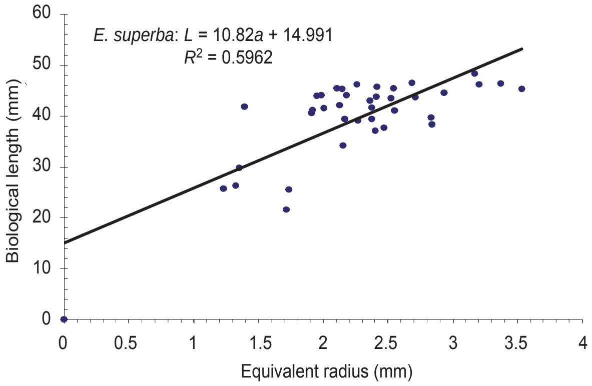
E. crystallorophias
$\mu = 16.33$ dB; $\sigma = 1.35$ dB
$P(\Delta_{120/38} > 13.8) = 97.8\%$



(d) Decision thresholds

$T_{200/120} = 4.3$ dB
$T_{200/38} = 18.5$ dB
$T_{120/38} = 13.8$ dB

Figure 3: The conditional and unconditional probability density functions governing the distributions of the two classes ω_1 (*Euphausia superba*) and ω_2 (*Euphausia crystallorophias*) for each frequency combination are shown in (a), (b) and (c). The decision thresholds for each frequency combination for class ω_1 are represented in (d).

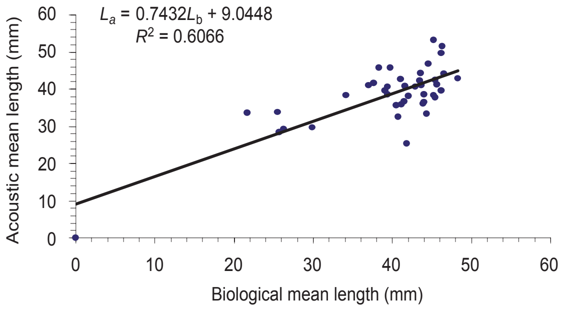


(a) Biol. length vs. equiv. radius

Sample size $N = 38$
Pearson corr. coeff. $r = 0.638$
Pearson *t*-test = 5.04 ($t_{0.2\%} = 3.31$)
$p < 0.002$ (highly significant)

(b) Acous. length vs. biol. length

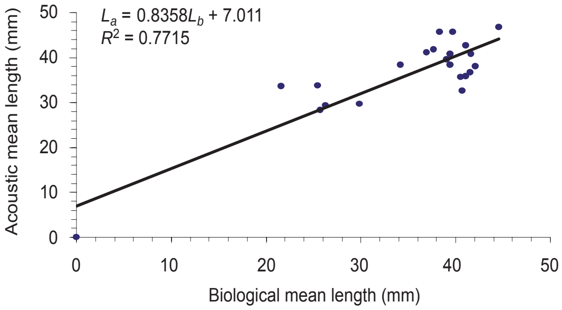
1997/98 and 2000



1997/98 and 2000 surveys:

Sample size $N = 40$
Pearson corr. coeff. $r = 0.551$
Pearson *t*-test = 4.07 ($t_{0.2\%} = 3.35$)
$p < 0.002$ (highly significant)

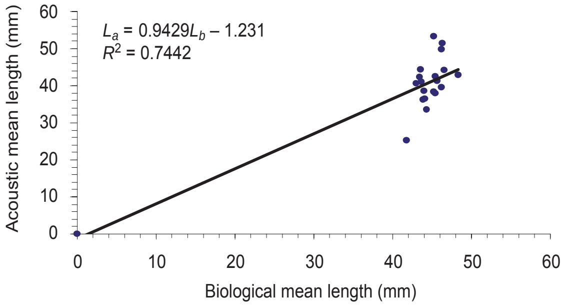
1997/98



1997/98 survey:

Sample size $N = 21$
Pearson corr. coeff. $r = 0.878$
Pearson *t*-test = 8.01 ($t_{0.2\%} = 3.61$)
$p < 0.002$ (highly significant)

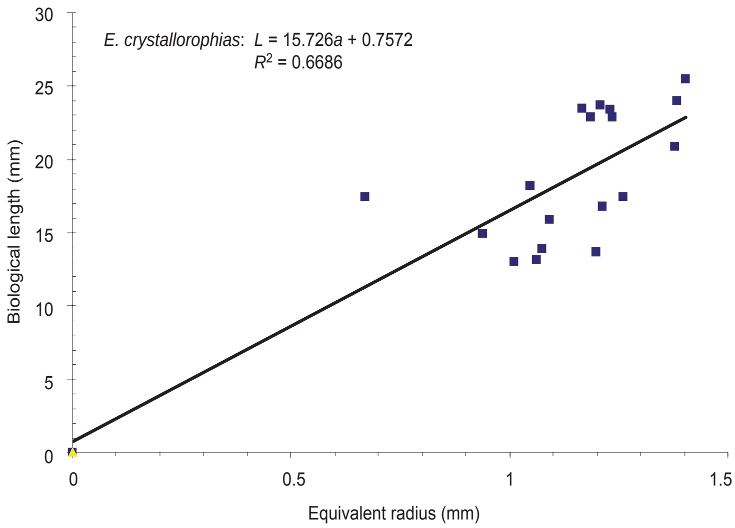
2000



2000 survey:

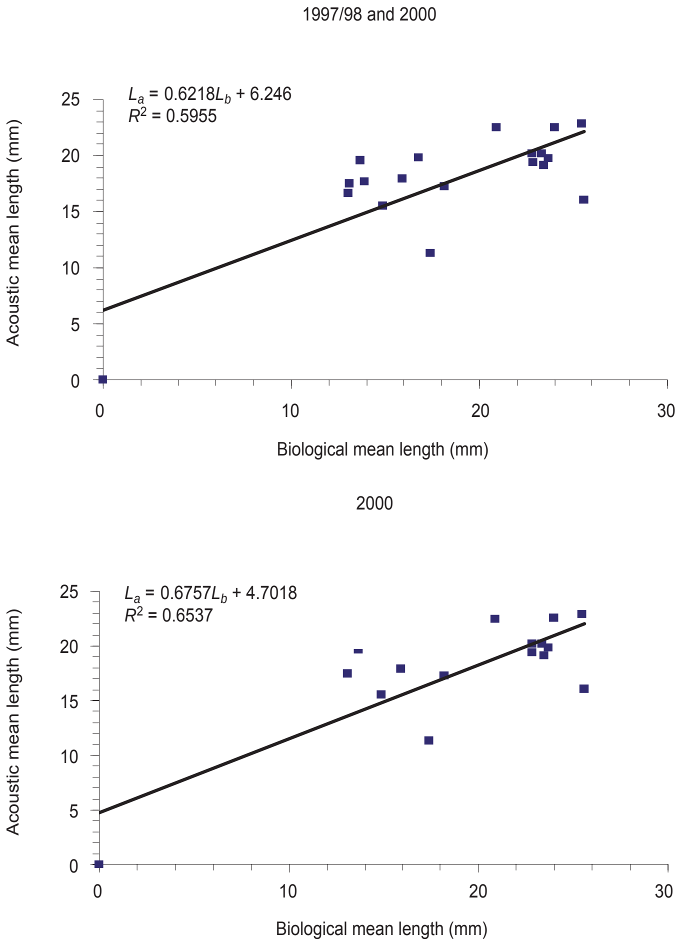
Sample size $N = 19$
Pearson corr. coeff. $r = 0.538$
Pearson *t*-test = 2.63 ($t_{5\%} = 2.12$)
$p < 0.05$ (significant)

Figure 4: (a) Linear regression to predict *Euphausia superba* mean length from equivalent radius measurements. (b) Relationships between acoustic estimates and mean catch length for *E. superba* sampled during the 1997/98 and 2000 surveys combined, and during each survey separately. The results of the significance tests are shown.



(a) Biol. length vs. equiv. radius

Sample size $N = 18$
Pearson corr. coeff. $r = 0.571$
Pearson t-test = 2.78 ($t_{5\%} = 2.13$)
$p < 0.05$ (significant)



(b) Acous. length vs. biol. length

1997/98 and 2000 surveys:

Sample size $N = 18$
Pearson corr. coeff. $r = 0.465$
Pearson t-test = 2.10 ($t_{5\%} = 2.13$)
$P < 0.10$ (not significant)

2000 survey:

Sample size $N = 15$
Pearson corr. coeff. $r = 0.462$
Pearson t-test = 1.88 ($t_{5\%} = 2.18$)
$p < 0.10$ (not significant)

Figure 5: (a) Linear regression to predict *Euphausia crystallorophias* mean length from equivalent radius. (b) Relationships between acoustic estimates and mean catch length for *E. crystallorophias* sampled during the 2000 and 1997/98 surveys combined, and during the 2000 survey. The results of the significance tests are shown.

Liste des tableaux

Tableau 1: Limites supérieure et inférieure des intervalles au-delà desquels les variations du rayon équivalent de l'erreur $\Delta = 1$ dB sont inférieures à 20%. La variation minimale du rayon équivalent se produit, pour a = 1,35 mm, $\Delta = 4,25$ dB à 200/120 (variation = 13,80%); pour a = 2,40 mm, $\Delta = 14,59$ dB à 200/38 (variation = 7%); for a = 3,10 mm, $\Delta = 10,12$ dB à 120/38 (variation = 8%).

Tableau 2: Chalutages (en gras) et concentrations (entre parenthèses) échantillonnés au chalut et par acoustique pendant trois campagnes d'évaluation de la mer de Ross. En tout, 66 chalutages qui ne contenaient qu'*Euphausia superba* ont échantillonné 131 concentrations. Dix-huit chalutages qui ne contenaient qu'*E. crystallorophias* ont échantillonné 52 concentrations. Onze chalutages contenaient les deux espèces d'euphausiidés. Les chalutages n'ayant pas capturé d'euphausiidés où dans lesquels ces espèces ne constituaient pas l'espèce dominante ne sont pas déclarés. Les conditions environnementales, les systèmes acoustiques et de filets et les stratégies d'échantillonnage suivies dans chaque campagne d'évaluation sont récapitulés.

Tableau 3: Principaux indicateurs statistiques des histogrammes *Euphausia superba* (ω_1) et *E. crystallorophias* (ω_2) à chaque rapport de fréquence. Pour les six histogrammes, il y a peu de variation entre la moyenne, la moyenne élaguée (élagage de 5%) et la médiane. Le rapport de chaque asymétrie et chaque aplatissement par rapport à son erreur standard respective se situe largement dans l'intervalle (–2, 2), où l'hypothèse de normalité n'est pas rejetée. Comme on pouvait le prévoir, ni le test de Kolgomonov–Smirnov ni celui de Shapiro–Wilk ne rejettent la normalité. Ces trois tests-*t* d'égalité des moyennes convergent pour affirmer que les deux classes de chaque histogramme sont séparées.

Tableau 4: Comparaison des estimations biologiques et acoustiques de toutes les concentrations échantillonnées pendant chaque campagne d'évaluation individuellement et pour toutes les campagnes combinées.

Tableau 5: Comparaison des méthodes standard et à trois fréquences pour l'estimation de l'abondance relative de quatre régions de la mer de Ross, dérivée de la campagne d'évaluation 1997/98. Dans les régions (a), (b), (c), dans lesquelles la méthode standard était corroborée par des échantillons pris au filet, les estimations résultant des deux méthodes sont très proches l'une de l'autre. Toutefois, dans la région (d), dans laquelle il n'a pas été possible de réaliser de chalutage et où la méthode standard reposait uniquement sur l'interprétation visuelle des échogrammes, les deux estimations diffèrent considérablement.

Liste des figures

Figure 1: (a) Emplacement des chalutages effectués pendant la XIII^{e} Expédition antarctique italienne (décembre 1997 à janvier 1998) dans la mer de Ross. Sur les chalutages effectués sur le plateau continental, 10 (5, 7, 8, 9, 10, 11, 13, 14, 15, 16) n'ont capturé qu'*Euphausia superba*. Trois chalutages (33, 34, 35) menés dans le bassin de Drygalski n'ont capturé qu'*E. crystallorophias*. Sur le talus continental, *E. superba* a été capturé dans 11 chalutages monospécifiques (17, 18, 20, 21, 22, 23, 24, 26, 27, 28, 29). Dans les chalutages 9, 10, 11, 13 (plateau continental) et 26 (talus continental) les juvéniles d'*E. superba* constituaient la classe d'âges dominante (Azzali et al., 2000b). Dans quatre chalutages (4, 6, 12, 32) effectués sur le plateau continental et dans quatre autres (19, 25, 30, 31) menés sur le talus continental, les deux espèces étaient présentes.

(b) Emplacement des chalutages effectués pendant la XV^{e} Expédition antarctique italienne (janvier à février 2000) dans la mer de Ross. Huit chalutages (3, 4, 5, 6, 7, 8, 12, 13) effectués dans la région adjacente à la barrière de la plate-forme glaciaire n'ont capturé qu'*E. crystallorophias*. Six autres (14, 15, 16, 19, 22, 58) sur le plateau continental n'ont capturé qu'*E. crystallorophias*, alors que dans cette région *E. superba* n'a été capturé que lors du chalutage 49. Sur les chalutages réalisés sur le talus continental, 19 se sont révélés monospécifiques. Les chalutages 25, 26, 27, 30, 31, 32, 34, 35, 36, 37, 39, 40, 41, 44, 46, 47, 50, 52 n'ont capturé qu'*E. superba,* alors que le chalutage 56 n'a capturé qu'*E. crystallorophias.* Dans trois chalutages, (38, 45 sur le talus continental et 54 sur le plateau continental), les deux espèces étaient présentes.

Figure 2: (a) Les deux distributions sont décalées vers la droite et leurs queues sont plus courtes que celles d'une distribution lognormale. (b) La distribution d'*Euphausia superba* est décalée vers la droite avec des queues plus longues que celles d'une distribution lognormale, alors que la distribution d'*Euphausia crystallorophias* est décalée vers la gauche avec des queues légèrement plus longues que celles d'une distribution lognormale. (c) Les deux distributions sont décalées vers la gauche avec des queues plus longues que celles d'une distribution lognormale.

Figure 3: Les fonctions de densité de probabilité conditionnelles et inconditionnelles régissant la distribution des deux classes ω_1 (*Euphausia superba*) et ω_2 (*Euphausia crystallorophias*) pour chaque combinaison de fréquences sont illustrées en (a), (b) et (c). Les seuils de décision pour chaque combinaison de fréquences de la classe ω_1 sont représentés en (d).

Figure 4: (a) Régression linéaire pour prévoir la longueur moyenne d'*Euphausia superba* à partir de mesures équivalentes du rayon. (b) Rapports entre les estimations acoustiques et la longueur moyenne d'*E. superba* dans les captures échantillonnées pour les deux campagnes d'évaluation 1997/98 et 2000 combinées et pour chacune d'elle séparément. Les résultats des tests d'importance sont indiqués.

Figure 5: (a) Régression linéaire pour prévoir la longueur moyenne d'*Euphausia crystallorophias* à partir de mesures équivalentes du rayon. (b) Rapports entre les estimations acoustiques et la longueur moyenne d'*E. crystallorophias* dans les captures échantillonnées pour les deux campagnes d'évaluation 2000 et 1997/98 combinées et pour celle de 2000 séparément. Les résultats des tests d'importance sont indiqués.

Список таблиц

Табл. 1: Верхний и нижний пределы интервалов, в которых изменения приведенного радиуса при Δ ошибке = 1 дБ составляют менее 20%. Минимальная вариация приведенного радиуса наблюдается для a = 1.35 мм, Δ = 4.25 дБ на 200/120 (вариация = 13.80%); для a = 2.40 мм, Δ = 14.59 дБ на 200/38 (вариация = 7%); для a = 3.10 мм, Δ = 10.12 дБ на 120/38 (вариация = 8%).

Табл. 2: Выборки (жирный шрифт) и скопления (в скобках), по которым были собраны траловые и акустические данные в ходе трех съемок в море Росса. В итоге, 66 уловов содержали только *Euphausia superba* из 131 скопления. Восемнадцать уловов содержали только *E. crystallorophias* из 52 скоплений. Одиннадцать уловов содержали оба вида эвфаузиид. Уловы, в которых эвфаузииды отсутствовали или не являлись преобладающим видом, не приводятся. Дается сводная информация по условиям окружающей среды, акустическим и траловым системам и стратегиям сбора данных, применявшимся в каждой съемке.

Табл. 3: Основные статистические характеристики гистограмм для *Euphausia superba* (ω_1) и *E. crystallorophias* (ω_2) по каждой частоте. Для всех шести гистограмм наблюдается небольшой разброс между средним, 5%-ным усеченным средним и медианой. Отношения асимметрии и эксцесса к соответствующим им стандартным ошибкам лежат внутри диапазона (–2, 2), в котором не отвергается гипотеза о нормальности. Как можно ожидать, критерии Колмогорова–Смирнова и Шапиро–Уилка также не отвергают нормальность. Все три *t*-критерия равенства средних убедительно подтверждают, что эти два класса на каждой гистограмме являются раздельными.

Табл. 4: Сравнение биологических и акустических оценок для всех обследованных скоплений по каждой съемке и по всем съемкам вместе.

Табл. 5: Сравнение стандартного и трехчастотного методов оценки относительной численности для четырех регионов моря Росса, обследованных во время съемки 1997/98 г. В регионах (a), (b) и (c), где для подтверждения стандартного метода использовались траловые выборки, оценки этих двух методов близки. Однако в регионе (d), где траления были невозможны и стандартный метод основывался только на визуальной интерпретации эхограмм, эти две оценки существенно различаются.

Список рисунков

Рис. 1: (a) Местоположение тралений, выполненных во время XIII Итальянской антарктической экспедиции (декабрь 1997 г. – январь 1998 г.) в море Росса. В уловах 10 тралений (5, 7, 8, 9, 10, 11, 13, 14, 15, 16), проведенных на континентальном шельфе, присутствовал только вид *Euphausia superba*. При трех тралениях (33, 34, 35), проведенных в бухте Дригальского, был пойман только *E. crystallorophias*. На континентальном склоне *E. superba* был пойман в результате 11 моноспецифических тралений (17, 18, 20, 21, 22, 23, 24, 26, 27, 28, 29). В тралениях 9, 10, 11 и 13 (континентальный шельф) и 26 (континентальный склон) молодь *E. superba* являлась доминирующим возрастным классом (Azzali et al., 2000b). В четырех тралениях (4, 6, 12, 32), проведенных на континентальном шельфе, и четырех тралениях (19, 25, 30, 31), проведенных на континентальном склоне, присутствовали оба этих вида.

(b) Местоположение тралений, выполненных во время XV Итальянской антарктической экспедиции (январь–февраль 2000 г.) в море Росса. В уловах восьми тралений (3, 4, 5, 6, 7, 8, 12, 13), проведенных в регионе, примыкающем к шельфовому леднику, содержался только вид *E. crystallorophias*. Шесть тралений (14, 15, 16, 19, 22, 58), выполненных на континентальном шельфе, содержали только вид *E. crystallorophias*; в этом регионе *E. superba* был пойман только в тралении 49. На континентальном склоне 19 тралений были моноспецифическими тралениями. Траления 25, 26, 27, 30, 31, 32, 34, 35, 36, 37, 39, 40, 41, 44, 46, 47, 50 и 52 содержали только *E. superba*, а траление 56 – только *E. crystallorophias*. В трех тралениях (38 и 45 на континентальном склоне и 54 на континентальном шельфе) присутствовали оба этих вида.

Рис. 2: (a) Два распределения имеют положительную асимметрию и более короткие хвосты, чем при нормальном распределении. (b) Распределение *Euphausia superba* положительно асимметрично, его хвост длиннее, чем при нормальном распределении, в то время как распределение *Euphausia crystallorophias* отрицательно асимметрично и его хвост немного длиннее, чем при нормальном распределении. (c) Два распределения отрицательно асимметричны и имеют более длинные хвосты, чем при нормальном распределении.

Рис. 3: Условная и безусловная плотности распределения вероятностей, определяющие распределение двух классов ω_1 (*Euphausia superba*) и ω_2 (*Euphausia crystallorophias*) для каждой комбинации частот, показаны в (a), (b) и (c). Пороги принятия решения по каждой комбинации частот для класса ω_1 показаны в (d).

Рис. 4: (a) Линейная регрессия для определения средней длины *Euphausia superba* по измерениям приведенного радиуса. (b) Зависимость между акустическими оценками и средней длиной улова *E. superba*, полученной по съемкам 1997/98 и 2000 гг. вместе и по каждой съемке отдельно. Показаны результаты расчета критериев значимости.

Рис. 5: (a) Линейная регрессия для определения средней длины *Euphausia crystallorophias* по приведенному радиусу. (b) Зависимость между акустическими оценками и средней длиной улова *E. crystallorophias*, полученной по съемкам 1997/98 и 2000 гг. вместе и съемке 2000 г. Показаны результаты расчета критериев значимости.

Lista de las tablas

Tabla 1: Límites superior e inferior de los intervalos para los cuales la variación del radio equivalente correspondiente a un error Δ = 1 dB es menos de 20%. La variación mínima del radio equivalente correspondió a un valor de a = 1,35 mm, Δ = 4,25 dB a 200/120 (variación = 13,80%); para a = 2,40 mm, Δ = 14,59 dB a 200/38 (variación = 7%); para a = 3,10 mm, Δ = 10,12 dB a 120/38 (variación = 8%).

Tabla 2: Lances (en negrita) y concentraciones (entre paréntesis), muestreados mediante redes y técnicas acústicas en tres prospecciones realizadas en el Mar de Ross. Un total de 66 lances contenían solamente *Euphausia superba* y tomaron muestras de 131 concentraciones. Dieciocho lances contenían solamente *E. crystallorophias* y tomaron muestras de 52 concentraciones. Once lances contenían ambas especies de eufáusidos. No se mencionan los lances que no capturaron eufáusidos o en los cuales estas especies no predominaron. Se resumen las condiciones del medio ambiente, las técnicas acústicas, las redes y las estrategias de muestreo utilizadas en cada prospección.

Tabla 3: Histogramas de los índices estadísticos principales de *Euphausia superba* (ω_1) y de *E. crystallorophias* (ω_2) para cada razón de frecuencias. En los seis histogramas se observa escasa variación entre el promedio, la media recortada en 5% y la mediana. Las razones entre cada una de las asimetrías y curtosis y su error estándar bien caben dentro del margen (–2, 2), y no se rechaza la hipótesis de normalidad. Como es lógico, las pruebas de Kolgomonov–Smirnov y de Shapiro–Wilk no rechazan la normalidad. La alta concordancia entre todas las pruebas-*t* de igualdad de las medias comprueba la separación de las dos clases en cada histograma.

Tabla 4: Comparación de las estimaciones biológicas y acústicas de todas las concentraciones muestreadas durante cada prospección y en todas las prospecciones combinadas.

Tabla 5: Comparación del método estándar y el método de tres frecuencias para estimar la abundancia relativa en cuatro regiones del Mar de Ross, de muestras tomadas en la prospección de 1997/98. En las regiones (a), (b), (c), donde el método estándar fue corroborado mediante muestras de la red, las estimaciones de los dos métodos son similares. Sin embargo, en la región (d), donde no fue posible realizar lances y el método estándar solamente pudo evaluar visualmente los ecogramas, las dos estimaciones fueron bastante diferentes.

Lista de las figuras

Figura 1: (a) Ubicación de los lances efectuados durante la Decimotercera Expedición Antártica Italiana (diciembre de 1997 a enero de 1998) en el Mar de Ross. Diez de los lances efectuados en la plataforma continental (5, 7, 8, 9, 10, 11, 13, 14, 15, 16) solamente extrajeron *Euphausia superba*. Tres lances realizados en la cuenca Drygalski (33, 34, 35) extrajeron *E. crystallorophias* solamente. En el talud continental, 11 lances (17, 18, 20, 21, 22, 23, 24, 26, 27, 28, 29) capturaron exclusivamente *E. superba*. En los lances 9, 10, 11, 13 (plataforma continental) y 26 (talud continental) los ejemplares juveniles de *E. superba* fueron la clase de edad dominante (Azzali et al., 2000b). Cuatro de los lances (4, 6, 12, 32) realizados en la plataforma continental y cuatro (19, 25, 30, 31) realizados en el talud continental contenían una mezcla de las dos especies.

(b) Ubicación de los lances realizados durante la Decimoquinta Expedición Antártica Italiana (enero a febrero de 2000) en el Mar de Ross. Ocho de los lances (3, 4, 5, 6, 7, 8, 12, 13) realizados en la región adyacente a la banquisa de hielo solamente contenían *E. crystallorophias*. Seis de los lances (14, 15, 16, 19, 22, 58) efectuados en la plataforma continental contenían solamente *E. crystallorophias*, y en esta región se capturó *E. superba* solamente en el lance 49. En el talud continental, 19 de los lances extrajeron una sola especie. Los lances 25, 26, 27, 30, 31, 32, 34, 35, 36, 37, 39, 40, 41, 44, 46, 47, 50, 52 contenían solamente *E. superba*, y el lance 56 contenía solamente *E. crystallorophias.* Tres lances (38, 45 en el talud continental y el lance 54 en la plataforma continental) contenían una mezcla de las dos especies.

Figura 2: (a) Las dos distribuciones son asimétricas hacia la derecha y con colas más cortas que las de la distribución normal. (b) La distribución de *Euphausia superba* es asimétrica hacia la derecha con colas son más largas que las de la distribución normal, mientras que la distribución de *Euphausia crystallorophias* es asimétrica hacia la izquierda con colas un poco más largas que las de la distribución normal. (c) Las dos distribuciones son asimétricas hacia la izquierda con colas más largas que las de la distribución normal.

Figura 3: Las funciones de densidad de probabilidad condicional e incondicional que gobiernan las distribuciones de las dos clases ω_1 (*Euphausia superba*) y ω_2 (*Euphausia crystallorophias*) para cada combinación de frecuencias se muestran en (a), (b) y (c). En (d) se representan los umbrales de decisión para cada combinación de frecuencias para la clase $\omega_{1.}$

Figura 4: (a) Regresión lineal para predecir la talla promedio de *Euphausia superba* a partir de mediciones del radio equivalente. (b) Relaciones entre las estimaciones acústicas y la talla promedio de la captura de *E. superba* muestreada durante las prospecciones de 1997/98 y 2000 combinadas, y durante cada prospección por separado. Se muestran los resultados de las pruebas de significación.

Figura 5: (a) Regresión lineal para predecir la talla promedio de *Euphausia crystallorophias* a partir de mediciones del radio equivalente. (b) Relaciones entre las estimaciones acústicas y la talla promedio de la captura de *E. crystallorophias* muestreada durante las prospecciones de 2000 y 1997/98 combinadas, y durante la prospección de 2000. Se muestran los resultados de las pruebas de significación.