# TOWARDS AN INITIAL OPERATIONAL MANAGEMENT PROCEDURE FOR THE KRILL FISHERY IN SUBAREAS 48.1, 48.2 AND 48.3

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## Abstract

An operational management procedure for krill (*Euphausia superba*) in Subareas 48.1, 48.2 and 48.3 requires a basis for the assessment of resource status, and an algorithm for specifying the levels of regulatory mechanisms (e.g., a catch control law) that depends on the results of the assessment. The development and selection of a procedure requires a basis for the simulation testing of procedures, and an operational definition of CCAMLR Article II to provide criteria against which to assess procedure performance. Suggestions are made under each of these headings. Assessment of resource status is provided by the CPUE "Composite Index" proposed by the Workshop on the Krill CPUE Simulation Study. Annual TACs are restricted to an initial ceiling ($C_c$) for a five year period, with a reference CPUE level ($CPUE_{ref}$) calculated as the average CPUE over that time. Thereafter TACs may increase by $c_r$% per annum. However, this increase may be suspended or reversed in any year, depending on how many of the previous three years' CPUE values fall below a target level of 0.75 $CPUE_{ref}$. An operating model of krill dynamics in the region is developed for simulation testing purposes. A provisional operational interpretation of Article II is proposed: the primary objective is to prevent the expected lowest biomass of krill over a 20-year harvesting period from falling below 60% of its average unexploited level; subject to this constraint, accumulated catches should be as large as possible without substantial associated probability that TAC reductions may prove necessary during the 20-year period considered. Simulation tests, including one particular test of robustness to the assumptions of the operating model, are carried out to **illustrate** the overall process proposed; for this **illustrative** exercise, the choice of catch control law parameters would probably lie between ($C_c$=1 million tonnes; $c_r$=15%) and ($C_c$=2 million tonnes; $c_r$=10%). Suggestions for proceeding with further investigations of possible operational management procedures are made. It is proposed that possible alternative suggestions for such procedures should be made in a similar fashion to that set out in the paper. Suggestions by others for alternative forms and parameter values (or their probable ranges) for the krill dynamics operating model used for testing procedures are encouraged.



## Résumé

Une procédure de gestion opérationnelle du krill (*Euphausia superba*), dans les sous-zones 48.1, 48.2 et 48.3, nécessite une base pour l'évaluation de l'état des ressources et un algorithme pour préciser les niveaux des mécanismes régulateurs (par ex.: une loi de contrôle de capture) qui dépende des résultats de l'évaluation. La sélection et l'élaboration d'une procédure nécessitent une base pour les tests par simulation des procédures, et une définition opérationnelle de l'Article


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II de la CCAMLR pour fournir des critères selon lesquels évaluer la performance de la procédure. Des suggestions sont faites sous chacun de ces titres. Une évaluation de l'état des ressources est fournie par "l'Indice composite" de la CPUE, proposée par l'Atelier sur l'Etude par simulation de la CPUE du krill. Les TAC annuels sont limités à un plafond initial ($C_c$) pour une période de 5 ans, avec un niveau de référence CPUE ($CPUE_{ref}$), calculé comme la CPUE moyenne pour cette période. Par la suite, les TAC peuvent augmenter de $c_r$% par année. Toutefois, cette augmentation peut être suspendue ou inversée n'importe quelle année, selon le nombre de valeurs CPUE des trois années précédentes qui tombe au dessous du niveau fixé de 0.75 $CPUE_{ref}$. Un modèle opérationnel de la dynamique du krill dans la région est développé pour des raisons de tests par simulation. Une interprétation provisoire et opérationnelle de l'Article II est proposée: l'objectif premier est d'empêcher la biomasse de krill prévue comme étant la plus faible, pour une période d'exploitation de 20 ans, de tomber au dessous de 60% de son niveau moyen non exploité; sujettes à cette restriction, les captures cumulées devraient être aussi importantes que possible, sans la probabilité substantielle associée que les réductions du TAC peuvent prouver nécessaires pendant la période des 20 années considérées. Des tests de simulation, comprenant un test particulier de robustesse envers les suppositions du modèle opérationnel, sont effectués pour **illustrer** le procédé d'ensemble proposé; pour cet exercice **explicatif**, le choix des paramètres de loi de contrôle des captures se situerait probablement entre ($C_c$=1 million de tonnes; $c_r$=15%) et ($C_c$=2 millions de tonnes; $c_r$=10%). Des suggestions sont faites pour la poursuite d'autres études sur des procédures possibles de gestion opérationnelle. Il est proposé de suggérer, d'une manière similaire à celle décrite dans ce document, des alternatives possibles pour de telles procédures. Des suggestions d'une autre provenance pour d'autres formes et valeurs des paramètres (ou leurs variations probables) pour le modèle opérationnel de la dynamique du krill, utilisé pour les procédures de tests, sont encouragées.

## Резюме

Для разработки оперативной процедуры управления промыслом криля (*Euphausia superba*) в Подрайонах 48.1, 48.2 и 48.3 необходимо определить основу для оценки состояния этого запаса и зависящий от результатов этой оценки алгоритм, согласно которому устанавливается уровень регулирования (напр. - органичение вылова). Для разработки и отбора процедуры необходимо определить основу экспериментальной проверки эффективности процедур посредством моделирования. Также необходимо иметь рабочую интерпретацию Статьи II Конвенции АНТКОМ, предоставляющую критерии оценки эффективности процедур. По каждому из этих вопросов вносятся предложения. Оценка состояния запаса может быть выполнена посредством вычисления комплексного индекса CPUE, который был предложен Рабочим семинаром по исследованию CPUE криля методом математического моделирования. На протяжении первых пяти лет устанавливается порог ежегодных уровней TAC ($C_c$), при этом контрольный уровень CPUE ($CPUE_{ref}$) вычисляется как

средняя величина CPUE за этот период. После этого величины TAC могут увеличиваться на $c_r$% в год. Тем не менее, в зависимости от того, уровень скольких показателей CPUE за предыдущие три года ниже целевого уровня, равного 0,75 $CPUE_{ref}$, в течение любого года введение этого увеличения может быть временно отложено или уровень TAC может быть снижен. Рабочая модель динамики криля в этом районе была разработана в целях экспериментальной проверки посредством математи-ческого моделирования. Предлагается предварительная рабочая интерпретация Статьи II: основной задачей является предотвращение снижения предполагаемой минимальной биомассы криля на протяжении 20 лет промысла до уровня, ниже 60% ее средней величины в доэксплуатационный период. С учетом этого ограничения, аккумулированный вылов следует поддерживать на максимально возможном уровне, при котором не предполагается возникновение необходимости снижения уровня TAC на протяжении рассматриваемого 20-летнего периода. Экспериментальная проверка посредством математического моделирования, включая один конкретный тест на устойчивость по отношению к допущениям, сделанным в рабочей модели, была выполнена для того, чтобы продемонстрировать весь предлагаемый процесс; в рамках этого наглядного примера параметры ограничения вылова, вероятно, находятся в диапазоне ($C_c$=1 миллион тонн; $c_r$=15%) и ($C_c$=2 миллиона тонн; $c_r$=10%). Вносятся предложения по дальнейшему исследованию возможных вариантов оперативных процедур управления. Предлагается выдвигать возможные альтернативные процедуры, следуя приведенному в настоящей работе методу. Прочим исследователям, занимающимся этими вопросами, предлагается внести предложения по возможным альтернативным формам и параметрам (или их возможным диапазонам) рабочей модели динамики криля, служащей для экспериментальной проверки эффективности процедур управления.

## Resumen

El desarrollo de un procedimiento operativo de administración para el krill (*Euphausia superba*) en las Subáreas 48.1, 48.2 y 48.3 necesita una base para la evaluación de la condición de los recursos y de un algoritmo para determinar el alcance de los instrumentos regulatorios (por ej. una legislación pesquera), que depende de los resultados de la evaluación. El desarrollo y selección de un procedimiento necesita una base sobre la cual se pueda estudiar la factibilidad de los procedimientos y una definición operacional del artículo II de la CCRVMA, para lograr obtener un criterio que permitirá analizar el resultado de este procedimiento. Se hacen sugerencias bajo estos apartados. La evaluación de la condición del recurso se obtiene utilizando el "índice compuesto", propuesto por el Taller de Estudios de Simulación de la CPUE del Krill. Las capturas anuales totales permitidas (TAC) están restringidas a un nivel inicial ($C_c$) por un período de cinco años, con un nivel de referencia de CPUE ($CPUE_{ref}$) calculado como el CPUE medio referido a ese tiempo. Las capturas totales permisibles pueden ser aumentadas luego en un $C_r$% por año. Sin embargo, dependiendo de cuántos valores de CPUE de los tres años previos hayan sido inferiores al objetivo de 0.75 $CPUE_{ref}$, este aumento puede ser suspendido o revocado en cualquier año. Se ha desarrollado un modelo operativo de la dinámica del krill en la región con el fin de realizar estudios de simulación. Se propone una interpretación operativa provisoria del artículo II: el objetivo primario es impedir que la biomasa de krill disminuya en un período actividades pesqueras de 20 años, a menos del 60% de su nivel promedio sin explotar; sujeto a esta restricción, las pescas acumuladas deberán ser lo más voluminosas posible, sin que exista una gran probabilidad de que se necesite reducir los TAC durante el período de 20 años que se está considerando. Los estudios de simulación, incluida una prueba especial para sustentar las suposiciones del modelo operacional, se llevan a cabo para **ilustrar** el proceso general propuesto; para los fines de este ejercicio **ilustrativo**, la selección de parámetros de la ley de control de pesca oscilaría posiblemente entre ($C_c$=1 millón de toneladas; $c_r$=15%) y ($C_c$=2 millones de toneladas; $c_r$=10%). Se han hecho recomendaciones para continuar con los estudios de eventuales procedimientos operacionales de administración. Se propone que se formulen otras sugerencias en relación a formas alternativas de estudio de un modo similar a las que se exponen en el presente trabajo. Se anima que se hagan otras propuestas sobre modos y valores de parámetros alternativos (o sus rangos probables) para el modelo operativo de la dinámica del krill que es utilizado en el estudio de factibilidad de los procedimientos.

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## 1. INTRODUCTION

The annual circumpolar Antarctic krill catch over recent seasons has been approaching 0.5 million tonnes. The first meeting of the CCAMLR Working Group on Krill held earlier this year agreed that this level of catch was unlikely to be having much impact on the circumpolar krill population (CCAMLR, 1989a). However, it also noted that about 90% of this catch has been taken from particular locations in Statistical Area 48, and was unable to say whether or not the catch was having an adverse effect on local predators. In conclusion, the Working Group recommended that the fishery should not greatly exceed the current level of catch until assessment methods are developed further and until more is known about predator requirements and local krill availability.

These deliberations of the Working Group serve to emphasise that the krill fishery has now reached a level (in Statistical Area 48, and specifically Subareas 48.1, 48.2 and 48.3) where controls may be necessary. Therefore CCAMLR needs to give urgent attention to the development of an initial operational management procedure for krill in this region. This contribution is intended as an aid and a spur to such development.

An operational management procedure for krill in this region (Subareas 48.1, 48.2 and 48.3) and its development involve four components:

(i) a basis for assessing the status of the krill resource in the region;

(ii) an algorithm for specifying appropriate levels of regulatory mechanisms (e.g., a catch control law) as a function of the results of such assessment;

(iii) a basis for simulation testing of the performance of the management procedure (i.e., components (i) and (ii) above); and

(iv) an operational definition of CCAMLR Article II to provide criteria against which performance can be assessed.

Each of these components is discussed in turn below. This discussion is in the context of a developing fishery - hence the reference to an "initial" procedure. The regulatory mechanism suggested is a TAC (Total Allowable Catch), whose size is determined by an assessment ("estimator") of the relative size of the krill resource at the time. The management procedure suggested thus consists of this combination of a control law and an estimator.

Simulation testing of the procedure requires the specification of an underlying model of the dynamics of the krill resource, which is referred to as the "operating model" (terminology suggested by Linhart and Zucchini, 1986). This model is used to generate data typical of those which would be used in practice to assess the state of the krill resource. Application of the estimator to these data provides an estimate of the relative size of the resource, and substituting this into the catch control law provides the TAC. This TAC is then fed back into the operating model, so that it affects the "actual" size of the resource and thus has an impact on the assessment data generated by the model for the next year of the simulation. In this way, the likely effect on the resource of the application of a management procedure over a certain number of years can be assessed.

The testing does not involve the use of a single operating model only. There is insufficient information available to specify an operating model of the dynamics of krill in Subareas 48.1, 48.2 and 48.3 with particular certainty at this time. Therefore it is also important to test how robust (i.e., insensitive) the performance of a management procedure is to biologically plausible variations of the structure and choices for the parameter values of the operating model.

A particular example of this process is reported in this paper, together with numerical results for the performance of a number of variants of the catch control law suggested. It is important that the context in which these results are presented is clearly understood, so this context has been set out below.

(i) The numerical results have been given as an aid in the **illustration** of the process suggested. While they are, of course, intended to bear **some** relation to the actual situation in Subareas 48.1, 48.2 and 48.3, they are **NOT** put forward at this stage as a specific basis for the choice between different management options.

(ii) The form of the management procedure, the basis for testing it, and the specification of performance objectives that are set out below, are not the only approaches possible. The important point, however, is that all have been set out in **operational** terms. If alternatives are to be suggested (as indeed it is a purpose of this paper to encourage), it is **ESSENTIAL** that they too be set out in operational terms, so that an objective process for assessment of performance remains viable.

(iii) Even if the particular approach suggested here should be preferred, it will become clear later in the paper that numerous far-reaching assumptions, for which relatively little justification can be offered at present, have had to be made in setting up the operating model used for testing the management procedure suggested. It would be surprising if other scientists with expertise concerning this resource did not consider at least some of these assumptions to be inadequate, inappropriate or incorrect. Again, it is a purpose of this paper to encourage others to voice just such reservations. But it is inadequate to offer the reservations alone. What must be provided AS WELL is alternative (and presumably better) assumptions, or indications of the quantitative extents to which it is considered that the original assumptions may be in error. It is precisely such information which is relevant to testing any management procedure that may be suggested - not only the one set out below.

The process which is being suggested is one which is already being used by other International Fishery Organisations. The Scientific Committee of the International Whaling Commission (IWC) is occupied with a very similar exercise as a primary component of the Comprehensive Assessment of Whale Stocks (IWC, 1988, 1989a and 1989b). The International Commission for the South East Atlantic Fisheries (ICSEAF) has recently designed a series of simulation tests for management procedures under its consideration (ICSEAF, 1989). The ICES Working Group on Methods of Fish Stock Assessment (ICES, 1988) has also stressed that assessment methods should be subjected to simulation tests of this type. It therefore seems appropriate for CCAMLR to give consideration to similar simulation studies in the context of the management of the krill fishery.

## 2. RESOURCE STATUS ASSESSMENT

Hydroacoustic surveys by research vessels operating independently of the fishery to assess the status of the krill resource in Subareas 48.1, 48.2 and 48.3 do not appear to be a likely immediate candidate for the routine provision of regular stock-size estimates (Miller and Hampton, 1989). As far as absolute estimates are concerned, the matter of the appropriate specification of krill target strength has yet to be settled satisfactorily. Annual surveys to provide a sufficiently precise relative biomass index seem unlikely to be viable because of their high costs and the small number of suitable vessels available world-wide.

The potential of CPUE as an index of krill abundance has been under investigation by CCAMLR, and a "Composite Index" has been suggested (CCAMLR, 1989b). Such a composite index is assumed in this analysis to provide the basis for the assessment of the status of the krill resource in Subareas 48.1, 48.2 and 48.3, and is referred to as "CPUE" hereafter. The relative size of the resource at a particular time is inferred from the ratio of CPUE at that time to a reference level. Since no historic CPUE data (in respect of the Composite Index) are available, this reference level is provided by the average value of the CPUE over the first five years of the operation of the management procedure, and will be termed $CPUE_{ref}$.

CCAMLR (1989b) drew attention to the likely non-linearity in the relationship between krill biomass and CPUE (i.e., that a drop in CPUE) would imply (on average) a greater proportional fall in krill biomass. This factor has been taken into account in the operating model which generates CPUE data as a function of the size of the krill biomass, as detailed in Appendix I* .

More sophisticated assessment methods could also be considered, for example those using catch-at-length (or, if possible, catch-at-age) data, though these would still also require data input of some index of relative abundance such as CPUE. The overall process whereby the incorporation of these methods into a management procedure should be investigated, would remain the same.

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* Details of the program are available on request to the author

## 3. THE REGULATORY MECHANISM ALGORITHM

The regulatory mechanism proposed is catch limitation (i.e., TAC). Why not effort limitation? - a mechanism which would "automatically" decrease the amount taken if the resource size falls has many attractions. The problems with effort limitation appear to be two-fold. First, the non-linearity in the CPUE-biomass relationship means that catches would be reduced by a smaller proportion than the decrease in size of the resource, and this reduction might not be adequate to prevent over-exploitation. More importantly, however, the "effort" of the composite CPUE index proposed (CCAMLR, 1989b) is a complex derived measure, and not something that could form the basis of a practical management regulation. The types of effort measure which could be used in such regulations (e.g., vessel-days) are unlikely to fulfil the needs required because of severe non-linearity effects. This is because processing time requirements are often the limiting factor in the quantity of krill that is caught (Butterworth, 1988); thus the index of catch-per-vessel day may remain almost unchanged despite a substantial drop in resource abundance.

The krill fishery is a developing fishery. During such a phase of the fishery, three considerations would seem to be appropriate.

(i) Until catches reach a certain level ($C_c$), there is no need to impose restrictions.

(ii) Once that level ($C_c$) has been reached, the rate ($c_r$) at which the fishery expands further should be limited.

(iii) The determinant of the rate of expansion permitted should be that the accumulation of data for assessment purposes during that expansion phase is adequate to allow for timeous detection of and reaction to the possibility that exploitation drives the resource below a level considered satisfactory.

In the analysis presented in this paper, management (and the availability of CPUE data) is assumed to commence after 10 years of annual catches of 0.4 million tonnes, a scenario which corresponds roughly to the present situation in Subareas 48.1, 48.2 and 48.3. Catches are assumed to increase immediately to the initial ceiling ($C_c$), where they are maintained for five years to obtain $CPUE_{ref}$. In reality, catches would not necessarily reach $C_c$ so rapidly. The consequences of this would be that the results of this analysis reflect a greater degree of resource depletion than would occur in practice under the procedure described here.

After this initial five year period, catches increase by a certain percentage ($c_r$) each year over the balance of the 20-year period that is considered. However, provision is necessary to suspend or even reverse this increase if assessment indicates that the size of the resource has fallen too low. To this end a target CPUE level ($CPUE_{tar}$) is chosen; because of the non-linearity of the CPUE-biomass relationship, this target level is set quite high relative to the reference level:

$$CPUE_{tar} = 0.75\ CPUE_{ref} \qquad (1)$$

The simplest catch control algorithm might be one that requires catch reductions immediately CPUE drops below $CPUE_{tar}$. However, this could lead to unnecessarily and undesirably large inter-annual TAC fluctuations due to the fact that CPUE itself would be expected to fluctuate considerably from year to year. This is because natural fluctuations in recruitment produce fluctuations in krill biomass which are likely to be quite substantial even in the absence of exploitation (see Figure 1). Further, the CPUE-biomass relationship will have a stochastic component. To offset these problems, the catch control law for the TAC in year y is based on the CPUE values for the previous three years (y-1, y-2 and y-3):

$$C(y) = \begin{cases} C(y-1)[1-2c_r/100] & \text{if all of CPUE(y-1), CPUE(y-2), CPUE(y-3)} < CPUE_{tar} \\ C(y-1) & \text{if any two of CPUE(y-1), CPUE(y-2), CPUE(y-3)} < CPUE_{tar} \\ C(y-1)[1+c_r/100] & \text{otherwise} \end{cases} \quad (2)$$

(i.e., if two of the last three CPUE values are less than the target level, the catch increment is suspended; and if all three are less, the TAC is reduced by twice the increment percentage).

This paper intends no implication that the control law of equation (2) is the best possible. Clearly other laws could be conceived, and almost certainly some of these will lead to better performance by the associated management procedure - further investigations along these lines should be carried out in due course. Equation (2) has been used here because it is simple to comprehend, simple to implement in the simulation analyses, and happens to perform adequately for the illustrative purposes for which it has been introduced.

## 4. THE BASIS FOR TESTING THE PROCEDURE'S PERFORMANCE

The operating model of the dynamics of the krill resource in Subareas 48.1, 48.2 and 48.3 which is used to generate CPUE data for the simulation testing of the management procedure described above, is detailed in the Appendix. This Appendix also provides information on the assumptions made, and the basis for choosing particular values for the various model parameters.

Only one test of robustness is carried out in this paper. This test is designed to ascertain to what extent the performance of the procedure deteriorates if the size (and consequently the productivity) of the krill resource is only half that assumed in the operating model.

In a full analysis, many other tests of the robustness of the management procedure to biologically plausible variations of the operating model structure and parameter values should also be carried out. This paper does not, of course, pretend to offer such a complete analysis. The single test has been included to serve as an illustration of the sort of analysis which is required.

## 5. ARTICLE II: OPERATIONAL DEFINITIONS OF PERFORMANCE CRITERIA

The operating model suggested in the Appendix is unashamedly a simple single-species model. How can this be reconciled with CCAMLR's Article II, which specifically requires that considerations wider than those of single-species harvesting be taken into account in management? In particular, the Article states that the indirect effect of harvesting must be considered, and it is precisely this concern that is evident in the extract of the Report of the Working Group on Krill (CCAMLR, 1989a) which was referenced earlier ("whether or not the catch was having an adverse effect on local predators").

Taking such indirect effects into account explicitly requires a credible multi-species model of the dynamics of krill and krill predators in the region under consideration, where the parameters of this model can be estimated with reasonable precision from pertinent data. Those data requirements include long time series of abundance estimates of the populations in question; such requirements cannot be met now, nor in the short or medium term in the future.

Since an explicit approach thus seems impossible, the only alternative would appear to be one which attempts to take account of the requirements of Article II in an implicit manner. The interpretation suggested here (for the interim, not all time) is thus:

(i) aim to keep the krill biomass at a level higher than would be the case if only single-species harvesting considerations were of concern; and

(ii) focus on the lowest biomass that occurs over the projection period considered, rather than the average biomass at the end of the period as might be the case in a single-species context.

The underlying intent of Article II in the context of krill harvesting is surely that such exploitation should not unduly affect the predators which depend on krill for their food. The interpretation above seeks to achieve this by ensuring that krill biomass is maintained at a reasonably high level, and so remains an adequate food source for predators.

The interpretation suggested still requires translation into operational terms. In a single-species context, an objective might typically be to maintain the resource biomass (on average) at 50% of its average unexploited level, corresponding to a size assumed to provide MSY (maximum sustainable yield). Bearing in mind the interpretation of Article II suggested above, this transforms, for the purpose of the illustrative exercise of this paper, to the following.

I. Attempt to prevent the expected lowest biomass of krill over a 20-year harvesting period from falling below 60% of its average unexploited level.

The 60% figure given may be criticised as being somewhat arbitrary. But this "arbitrariness" needs to be viewed in the context of the equally near-arbitrary level of some of the targets conventionally adopted for fisheries management elsewhere in the world. For example, data are seldom adequate to allow estimation of the fraction of the mean unexploited biomass level at which MSY (in an average sense) is achieved; use of the 50% figure that corresponds to the Schaefer model is little more than a convenient and conventional assumption in most situations. The important point to note about the 60% figure put forward is that it is LARGER than the MSY level usually assumed for assessments of relatively short-lived prey species.

This objective is naturally not the only one appropriate for a developing krill fishery. Two other considerations that should sensibly also be addressed (within the constraint of I. above) are as follows.

II. Aim to obtain as large a total catch as possible over a 20-year harvesting period.

III. Minimise the chance that a TAC reduction becomes necessary during a 20-year harvesting period.

Naturally objectives II. and III. cannot be satisfied simultaneously, and the choice of an appropriate trade-off between them by the management authority would be necessary.

In order to assess the performance of the management procedure in terms of objectives I. to III., quantitative measures need to be specified. The simulation analysis has been used to calculate five statistics which relate to these objectives. Since the analysis is stochastic, the statistics change from one 20-year simulation to the next, so that both the mean and the standard deviation are given for each distribution that has been obtained from the results of a large number of simulations. The five statistics are listed below.

(i) Average annual catch over 20 years: $C_{av}$ (objective II.).

(ii) Catch in twentieth year: $C_{20}$.

(iii) Biomass after 20 years relative to average unexploited biomass: $B_{21}/K$.

(iv) Lowest biomass during 20 years, relative to average unexploited biomass: $(B/K)_{min}$ (objective I.).

(v) Average annual probability that a TAC reduction will be made between projection year 6 and year 20 (i.e., number of reductions over this period divided by 15): $P_{redn}$ (objective III.).

(Statistics (ii) and (iii) are not directly relevant to the objectives suggested, but are helpful in interpreting the other results).

## 6. RESULTS AND DISCUSSION

Calculations were carried out for a variety of combinations of the catch control law parameters $C_c$ (initial ceiling) and $c_r$ (subsequent increase rate). In each case, 1 000 simulations of the 20-year projection period under management were computed, and the means and standard deviations of the resultant distributions were calculated.

Figure 1 shows the distributions of $B_{21}/K$ and $(B/K)_{min}$ for the case of no exploitation at all after the commencement of management ($C_c$=$c_r$=0). Note that even in the absence of exploitation, biomass values substantially below the average unexploited level K can occur because recruitment fluctuates from year to year.

Table 1 lists the means and standard deviations of the distributions of the five statistics of interest, for various $C_c$ and $c_r$ values. Certain trends that would be expected are evident in the Table: as either $C_c$ or $c_r$ is increased, $C_{av}$ and $C_{20}$ become larger, $P_{redn}$ increases, but $B_{21}/K$ and $(B/K)_{min}$ decrease. The increase in $P_{redn}$ values is only marked for the largest catch increase rate ($c_r$) options listed; this in turn leads to corresponding substantial increases in the standard deviations of $C_{av}$ and $C_{20}$ for the largest $c_r$ values. Increases in the standard deviations of $B_{21}/K$ and $(B/K)_{min}$ are scarcely evident as the extent of exploitation is increased, with changes apparent only for the largest $c_r$ values listed.

Figures 2a and 2b compare the distributions of $B_{21}/K$ and $(B/K)_{min}$ in the absence of further exploitation ($C_c$=$c_r$= 0) with those for the control law option $C_c$=2 million tonnes and $c_r$=15% per annum. Note that the latter option corresponds to objective I) in that the expected $(B/K)_{min}$ value is 60%.

The robustness test of a 50% reduction in the size of the krill resource assumed in the operating model has been carried out for a few of the control law parameter combinations of Table 1 which yielded an expected $(B/K)_{min}$ value close to 60%. The results are shown in Table 2. Where results for two different $c_r$ values are given for a particular $C_c$ value, it is evident that $(B/K)_{min}$ shows greater sensitivity when the larger of the two $c_r$ values is used.

If the choice of a specific management procedure were to be made on the basis of the results in Table 2 (in reality, of course, a considerable number of robustness tests would need to be carried out), such a choice would probably lie between the two control law options ($C_c$=1 million tonnes; $c_r$=15%) and ($C_c$=2 million tonnes; $c_r$=10%). The latter provides a larger total catch over the period considered, but at the expense of a greater likelihood that the TAC will fail to show steady growth, as a result of TAC decreases being implemented in some years.

## 7. CONCLUDING REMARKS

Obviously there is scope for further analyses along the lines illustrated above, if the approach suggested is considered to have potential in respect of the development of an operational management procedure for krill in Subareas 48.1, 48.2 and 48.3. It is, however, important to consider the relative priority for attention to be given to each of the four components of the process:

(i) the assessment method (the "estimator");

(ii) the catch control law;

(ii) the operating model and robustness tests for performance evaluation; and

(iv) the interpretation of Article II to provide operational definitions of management objectives.

Further developments with respect to (i) and (ii) might be carried out most effectively by individual researchers, for reporting at future CCAMLR meetings. However, if their efforts are to be focussed effectively, progress first needs to be made on components (iii) and (iv). Component (iv) falls within the purview of CCAMLR's Working Group for the Development of Approaches to Conservation of Antarctic Marine Living Resources, and the pertinent sections of this paper are offered as a contribution to their further deliberations. Component (iii) would seem to be most appropriately addressed by the Working Group on krill. It is most desirable that there should be some general agreement on the operating model and robustness tests to be used to evaluate the performance of candidate operational management procedures **BEFORE** further attempts are made to develop and investigate such procedures.

The management procedure discussed in this paper is very simple and uses a minimum of data (only CPUE). Does this mean that other information ("ancillary data") regarding krill and its predators in the region concerned is of no consequence in the formulation of management decisions, and that these decisions would become effectively automated? Exactly the same question has arisen in the IWC's Scientific Committee in the context of its investigation of alternative management procedures. The remarks of that Committee's Sub-Committee on Management Procedures (IWC, 1989b) seem (in a broad sense) to be equally appropriate to krill as to whale management:

> "In terms of the development of alternative management procedures, the Sub-Committee recognised that it is possible in principle to augment a management procedure to allow for the planned collection and analysis of at least some types of ancillary data. However, it strongly believed that it would never be possible to develop a grand all-encompassing procedure that could handle internally all relevant possible types of ancillary data. Indeed, it rejected the concept of a management procedure that accepted data in one end and produced a single unassailable and unalterable assessment out the other end (42?).
>
> Rather, the Sub-Committee believed that it would always be necessary for the Scientific Committee to exercise its scientific judgement in providing stock assessment advice to the Commission. Even after a management procedure has been adopted by the Commission as a result of this current development process, the Scientific Committee and the Commission should weigh the import of other data available for a stock, which have not been used explicitly in the management procedure, against the assessment generated by that procedure. However, that being said, the Sub-Committee emphasised that the primary purpose of developing an alternative management procedure

that was as robust as possible to uncertainties in data and violations in assumptions, was to minimise the chances of it producing inappropriate assessment advice. The Sub-Committee believed that in the normal course of events, the catch limit produced by the management procedure should be accepted unchanged by the Committee, and that the catch limit should only be varied in the face of very strong contrary evidence from ancillary data."

ACKNOWLEDGEMENTS

Helpful discussions with Denzil Miller (Sea Fisheries Research Institute, South Africa), and particularly his suggestions on sources for estimates of various parameters used in the operating model, are gratefully acknowledged. Jane De Decker (University of Cape Town) kindly prepared the Figures.

GLOSSARY

This glossary provides a list of the symbols used in the main text of the paper, together with their definitions, for the convenience of readers. It does not include symbols which occur in the Appendix only; the definitions of such symbols may be found in the Appendix itself.

| | |
|---|---|
| y | "Year" (i.e., fishing season index). |
| CPUE | "Composite Index" of krill abundance suggested by CCAMLR (1989b). |
| CPUE(y) | CPUE in year y. |
| $CPUE_{ref}$ | Average value of CPUE over the first five years of operation of the management procedure. |
| $CPUE_{tar}$ | Target CPUE which is set as a fraction (0.75) of $CPUE_{ref}$; the decision to increase, maintain or decrease the TAC depends on how many of the CPUE values for the previous three years fell below $CPUE_{tar}$ (see equation (2)). |
| $C_c$ | Initial TAC ceiling imposed during the first five years of operation of the management procedure. |
| $c_r$ | Annual percentage increase of the TAC which may be permitted after the first five years of operation of the management procedure. |
| $C_y$ [or C(y)] | TAC in year y. |
| $C_{av}$ | Average annual catch over the first 20 years of operation of the management procedure $$\left( \sum_{y=1}^{20} C_y/20 \right)$$ |
| $C_{20}$ | TAC in twentieth year of operation of the management procedure. |
| B | Exploitable krill biomass at the start of year y (subsequently termed "biomass"). |

| | |
|---|---|
| K | Average biomass in the absence of any harvesting. |
| $B_{21}/K$ | Biomass after 20 years of operation of the management procedure, as a proportion of K. |
| $(B/K)_{min}$ | Minimum biomass during 20 years of operation of the management procedure (i.e., $\min(B_1, B_2, \ldots, B_{20})$), as a proportion of K. |
| $P_{redn}$ | Number of occasions between years y=6 and y=20 that the TAC is reduced, divided by 15. |

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Table 1: Results from a 20-year projection of the krill operating model. The means and standard deviations (in parenthesis) over 1 000 stochastic simulations are given for a variety of catch control law parameter values. All biomass units are million tonnes.

| Ceiling on catch for first five years | Subsequent annual catch increase | Average annual catch over 20 years | | Catch in 20th year | | Final/Average unexploited biomass | | Lowest/Average unexploited biomass | | Average annual prob. quota reduction made | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $C_c$ | $C_r(\%)$ | $C_{av}$ | | $C_{20}$ | | $B_{21}/K$ | | $(B/K)_{min}$ | | $P_{redn}$ | |
| 0 | 0 | Unexploited | | | | 0.99 | (0.21) | 0.70 | (0.09) | [0.015 | (0.052)] |
| 0.5 | 5 | 0.67 | (0.04) | 0.96 | (0.14) | 0.98 | (0.21) | 0.69 | (0.09) | 0.016 | (0.053) |
| | 10 | 0.94 | (0.11) | 1.86 | (0.39) | 0.97 | (0.23) | 0.69 | (0.09) | 0.012 | (0.047) |
| | 15 | 1.37 | (0.23) | 3.49 | (0.96) | 0.94 | (0.21) | 0.68 | (0.09) | 0.013 | (0.048) |
| | 20 | 1.97 | (0.48) | 6.14 | (2.21) | 0.89 | (0.21) | 0.67 | (0.09) | 0.016 | (0.048) |
| | 25 | 2.92 | (0.88) | 10.46 | (4.62) | 0.80 | (0.21) | 0.65 | (0.09) | 0.019 | (0.053) |
| | 30 | 4.31 | (1.53) | 16.84 | (8.93) | 0.68 | (0.26) | 0.59 | (0.12) | 0.024 | (0.056) |
| 1.0 | 5 | 1.34 | (0.09) | 1.93 | (0.26) | 0.96 | (0.22) | 0.69 | (0.09) | 0.015 | (0.048) |
| | 10 | 1.86 | (0.24) | 3.62 | (0.87) | 0.93 | (0.21) | 0.68 | (0.09) | 0.017 | (0.055) |
| | 15 | 2.66 | (0.50) | 6.59 | (2.11) | 0.89 | (0.23) | 0.66 | (0.09) | 0.017 | (0.055) |
| | 20 | 3.88 | (0.97) | 11.62 | (4.62) | 0.79 | (0.23) | 0.62 | (0.10) | 0.021 | (0.059) |
| | 25 | 5.44 | (1.80) | 17.32 | (9.41) | 0.67 | (0.28) | 0.56 | (0.12) | 0.031 | (0.065) |
| 2.0 | 5 | 2.67 | (0.17) | 3.84 | (0.54) | 0.92 | (0.20) | 0.66 | (0.09) | 0.016 | (0.052) |
| | 10 | 3.69 | (0.49) | 7.11 | (1.78) | 0.86 | (0.21) | 0.64 | (0.09) | 0.019 | (0.053) |
| | 15 | 5.15 | (1.06) | 12.24 | (4.49) | 0.76 | (0.22) | 0.60 | (0.10) | 0.024 | (0.057) |
| | 20 | 7.05 | (1.92) | 16.93 | (8.99) | 0.64 | (0.26) | 0.50 | (0.13) | 0.041 | (0.072) |
| 4.0 | 5 | 5.31 | (0.38) | 7.54 | (1.19) | 0.86 | (0.20) | 0.61 | (0.09) | 0.021 | (0.064) |
| | 10 | 7.16 | (1.10) | 13.03 | (4.14) | 0.74 | (0.22) | 0.56 | (0.10) | 0.033 | (0.070) |
| | 15 | 9.25 | (2.08) | 16.42 | (8.16) | 0.62 | (0.26) | 0.46 | (0.13) | 0.057 | (0.080) |

Table 2: Sensitivity of the results of 20-year projections of the krill operating model to the size assumed for the krill resource. A duplicate set of results is shown for each choice of catch control law parameter values: the first is for the original model as reported in Table 1; the second corresponds to halving the assumed average unexploited biomass (and hence productivity) of the krill resource.

| Ceiling on catch for first five years $C_c$ | Subsequent annual catch increase $C_r(\%)$ | Average annual catch over 20 years $C_{av}$ | Catch in 20th year $C_{20}$ | Final/Average unexploited biomass $B_{21}/K$ | Lowest/Average unexploited biomass $(B/K)_{min}$ | Average annual prob. quota reduction made $P_{redn}$ |
|---|---|---|---|---|---|---|
| 0.5 | 20 | 1.97 (0.48) | 6.14 (2.21) | 0.89 (0.21) | 0.67 (0.09) | 0.016 (0.048) |
| | | 1.92 (0.50) | 5.71 (2.37) | 0.79 (0.22) | 0.62 (0.10) | 0.021 (0.059) |
| | 25 | 2.92 (0.88) | 10.46 (4.62) | 0.80 (0.21) | 0.65 (0.09) | 0.019 (0.053) |
| | | 2.78 (0.86) | 9.05 (4.61) | 0.65 (0.27) | 0.56 (0.12) | (0.025 (0.042) |
| 1.0 | 15 | 2.66 (0.50) | 6.59 (2.11) | 0.89 (0.23) | 0.66 (0.09) | 0.017 (0.055) |
| | | 2.61 (0.52) | 6.22 (2.26) | 0.76 (0.23) | 0.60 (0.10) | 0.025 (0.060) |
| | 20 | 3.88 (0.97) | 11.62 (4.62) | 0.79 (0.23) | 0.62 (0.10) | 0.021 (0.059) |
| | | 3.54 (1.00) | 8.74 (4.68) | 0.63 (0.25) | 0.51 (0.13) | 0.039 (0.068) |
| 2.0 | 10 | 3.69 (0.49) | 7.11 (1.78) | 0.86 (0.21) | 0.64 (0.09) | 0.019 (0.053) |
| | | 3.57 (0.53) | 6.43 (2.05) | 0.73 (0.21) | 0.56 (0.10) | 0.035 (0.071) |
| | 15 | 5.15 (1.06) | 12.24 (4.49) | 0.76 (0.22) | 0.60 (0.10) | 0.024 (0.057) |
| | | 4.60 (1.08) | 8.09 (4.09) | 0.62 (0.26) | 0.46 (0.13) | 0.060 (0.080) |
| 4.0 | 5 | 5.31 (0.38) | 7.54 (1.19) | 0.86 (0.20) | 0.61 (0.09) | 0.021 (0.064) |
| | | 5.16 (0.46) | 6.91 (1.46) | 0.70 (0.21) | 0.50 (0.09) | 0.047 (0.087) |

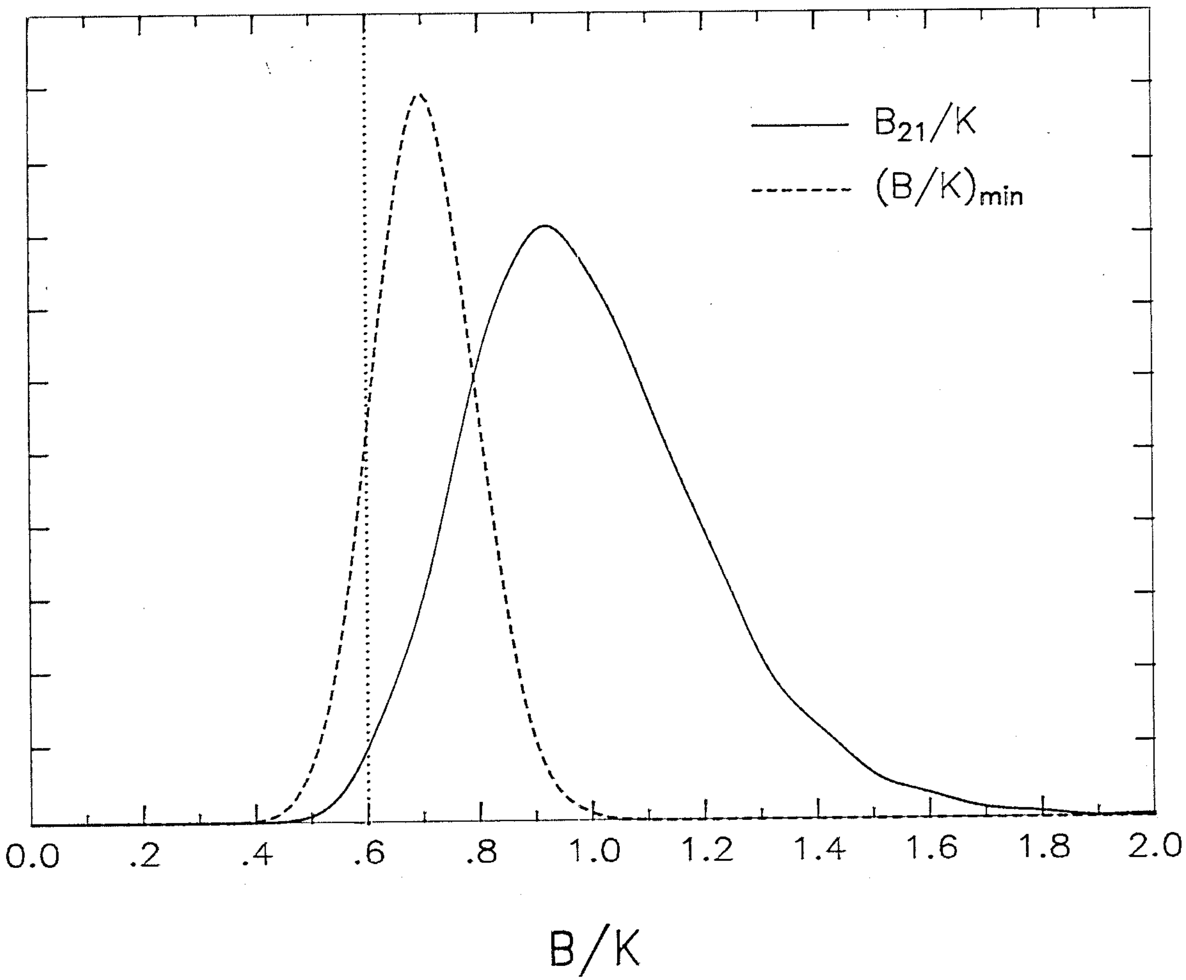


Figure 1: Biomass distributions relative to the average unexploited population size (K) are shown for the case of no exploitation after the management procedure comes into operation ($C_c = c_r = 0$). The solid curve shows the distribution of the biomass after the 20 year period considered: $B_{21}/K$. The dashed curve shows the distribution of the lowest biomass over this period: $(B/K)_{min}$.

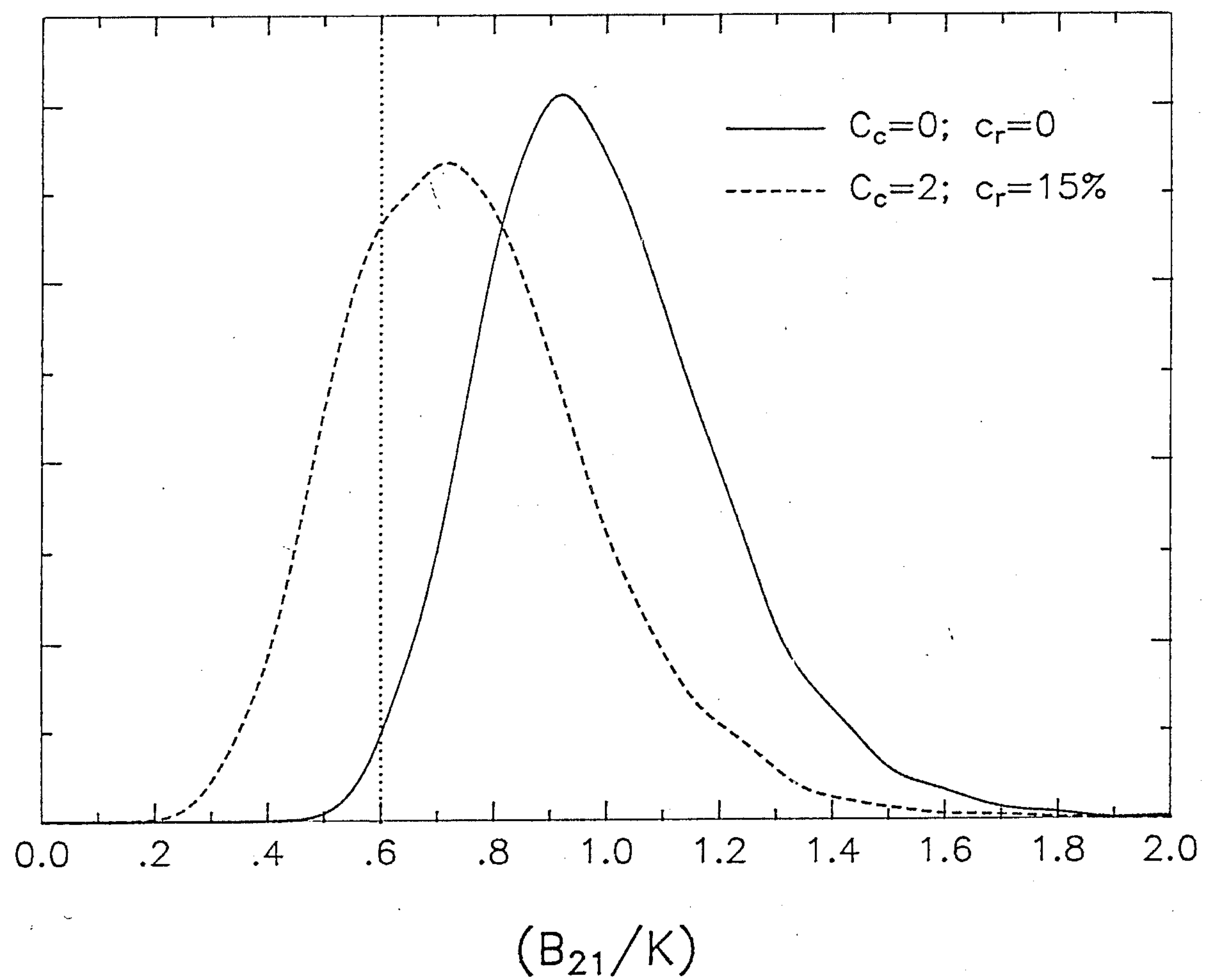


Figure 2a: The distribution of $B_{21}/K$ for the case of no exploitation after the management procedure comes into operation ($C_c$=$c_r$=0) (solid curve) is compared with that for the catch control law with $C_c$=2 million tonnes and $c_r$=15% per annum (dashed curve).

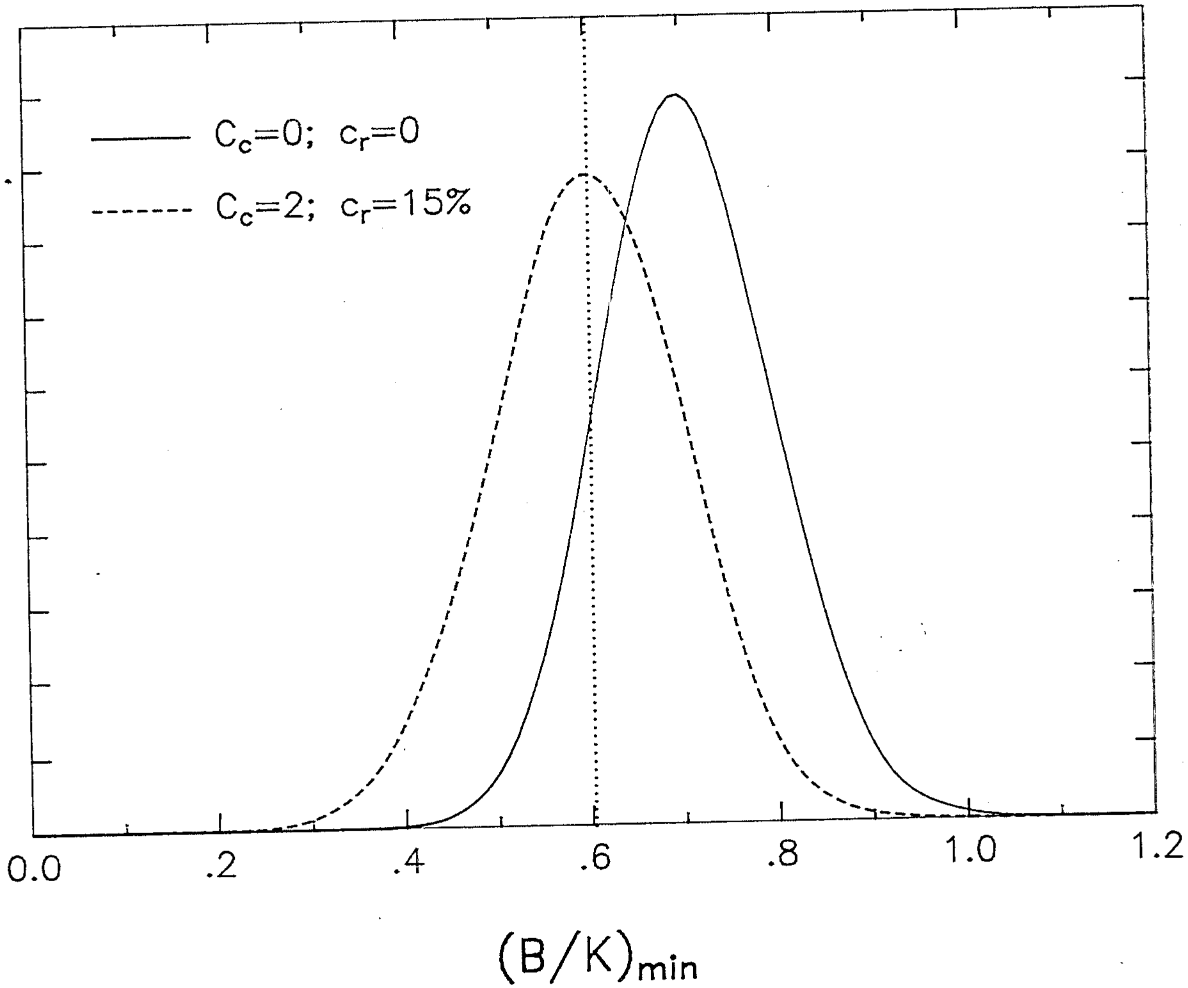


Figure 2b: As for Figure 2a, except that distributions of $(B/K)_{min}$ are shown for the two sets of catch control law parameter values in question.

[Note: The distribution curves were produced by smearing the results of 8 000 simulation runs using a normal kernel. The standard deviation of the kernel was set at 0.04 throughout, which was found necessary to produce reasonably smooth results for the $B_{21}/K$ distribution. This choice means that the standard deviations of the $(B/K)_{min}$ distributions are inflated by about 10% in the Figures; the corresponding inflation of the $B_{21}/K$ distributions is negligible.]

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первая величина была получена при прогоне исходной модели, описанной в Таблице 1; вторая величина соответствует половинному значению предполагаемой доэксплуатационной биомассы (и следовательно продуктивности).

## Список рисунков



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[Nota: Las curvas de distribución se obtuvieron uniformando los resultados de 8 000 simulaciones usando una distribución normal. La desviación estándar de la distribución normal se fijó en 0.04 para toda la operación, la cual se encontró necesaria para producir resultados más o menos uniformes para la distribución $B_{21}/K$. Esto significa que en las figuras, las desviaciones estándar de las distribuciones $(B/K)_{min}$ están abultadas en un 10% aproximadamente; el abultamiento correspondiente a la distribución $B_{21}/K$ es insignificante.]

# AN OPERATING MODEL FOR KRILL DYNAMICS IN SUBAREAS 48.1, 48.2 AND 48.3

## 1. FORMULATION

Basic Dynamics:

$$N_{y+1,a+1} = \begin{cases} N_{y,a}e^{-M} & 0 \le a < 3 \\ N_{y,a}(1-F_y)e^{-M} & 3 \le a \le 7 \end{cases} \qquad (A1)$$

where $N_{y,a}$ is the number of krill of age a at the start of year (fishing season) y,
$F_y$ is the fishing mortality in year y, and
$M$ is the natural mortality.

Stock-Recruit Relationship:

$$N_{y,0} = \begin{cases} R\exp(\varepsilon_y) & B_y \ge 0.2K \\ (B_y/K)\,R\exp(\varepsilon_y) & B_y \le 0.2K \end{cases} \qquad (A2)$$

where $B_y = \sum_{a=3}^{7} w\, N_{y,a}$ (A3)

$K = R\exp(\sigma_r^2/2) \sum_{a=3}^{7} w_a\, e^{-Ma}$ (A4)

$\varepsilon_y$ from $N(0; \sigma_r^2)$

$N(0; \sigma^2)$ is a normal distribution of zero mean and variance $\sigma^2$, and

$w_a$ is the mass of krill of age a,

(i.e., B is the spawning biomass, here taken to be the same as the exploitable biomass, and K is the average value of the spawning biomass in the absence of exploitation.)

Catch in Mass:

$$C_y = \sum_{a=3}^{7} w_a F_y N_{y,a}$$

$$= F_y B_y \qquad (A5)$$

CPUE-Biomass Relationship:

$$CPUE(y) = q\sqrt{\tilde{B}_y}\,\exp(n_y) \qquad (A6)$$

where $\tilde{B}_y = \sum_{a=3}^{7} w_a N_{y,a}(1-F_y/2) = (1 - F_y/2)\, B_y \qquad (A7)$

$q$ is the catchability coefficient, and

$n_y$ from $N(O; \sigma_q^2)$.

## 2. PARAMETER VALUES AND ASSUMPTIONS

(1) Single Stock

It is assumed that the krill resource in sub-Areas 48.1 + 48.2 + 48.3 can be treated as a single stock for management purposes, and that there is no substantial immigration of krill to or emigration of krill from the region.

(2) Natural Mortality

It is assumed that the natural mortality rate M is independent of both year and age. (Actually, although equations A1 and A4 above make this assumption, the results would be unchanged if M were age-dependent for $a < 3$.)

A value of $M = 0.6\ yr^{-1}$ [calculated from data in Brinton and Townsend, 1984, on the survivorship of animals from age 2 (30 to 43 mm in length) to age 3 and 3+ (44 to 60 mm in length)] was used in the calculations. Appropriate values for M may depend on the particular growth equation used - see (9) below.

(3) Age at Maturity

Knife-edge maturity is assumed, with the age at maturity taken to be 3 years (Siegel, 1987). Equations A2 and A3 could be regarded as making an implicit assumption that the reproductive output of an individual mature krill is proportional to its mass.

(4) Nature of the Fishery

Equations A1 and A5 model the fishery as a pulse fishery at the beginning of the "year". This would seem defensible because krill fishing in Subareas 48.1, 48.2 and 48.3 takes place over a short period each year.

(5) Age-Specific Selectivity

Fishing selectivity is assumed to be knife-edged with a constant value from age 3 upwards. The choice of age 3, which is the same value as assumed for the age at maturity, is partly for calculational convenience. However, it does correspond to a krill length of 47 mm - see (9) below - which does not seem an unreasonable estimate for a "length-at-first-capture". Probably selectivity is not constant with age, but increases somewhat for the older (larger) krill which are preferred by the fishery for most of the krill products.

representation of the North Sea herring spawning biomass - recruitment data. This formulation is also used for management procedure investigations for the South African anchovy resource (e.g., Bergh and Butterworth, 1987).

(7) A Value for Median Recruitment R in Equation A2

The assumptions required here are certainly the most wide-ranging and tenuous of all those made, which is the particular reason why the robustness test carried out in the main text involved the value chosen for this parameter.

One starts with the estimate by Laws (1977) of an annual consumption of 147 million tonnes of krill in the Antarctic by baleen whales since removed, which (to be conservative) is scaled down to 100 million tonnes. Since Subareas 48.1, 48.2 and 48.3 comprise only a part of krill's circumpolar habitat, an appropriate fraction of this figure has to be taken as an estimate of the potential krill surplus production in this region. This fraction is assumed to be given by the ratio of the krill biomass in the region to the circumpolar biomass; Miller (see Appendix 2) gives four different estimates of this ratio, and his central figure of (about) 20% has been used.

Thus whales subsequently removed from the region are assumed to have consumed 20 million tonnes per annum in the past. It is further assumed that those whales "harvested" the krill at close to its MSY level, and this level is taken to be 50% of the average unexploited krill biomass (K). Finally, for computational convenience, it is assumed that the whales exhibited the same age-specific selectivity pattern when feeding on krill as has been assumed in (5) above for the fishery. (There is an apparent inconsistency here, in that the stock-recruitment relationship of equation A2 will result in an MSY level somewhat less than 0.5K. However, equation A2 may be considered to be an approximation to a more dome-shaped function, for which the MSY level is somewhat higher than would be deduced using equation A2.)

The parameter R is then obtained by solving the simultaneous equations:

$$\begin{cases} 0.5K = R \exp(\sigma_r^2/2) \sum_{a=3}^{7} w_a e^{-Ma} (1-F)^{a-3} \\ C = F\,(0.5K) \end{cases} \qquad \text{(A8)}$$

where C = 20 million tonnes. Given values for the other parameters as specified above and below, the results are:

$$\begin{cases} R \exp(\sigma_r^2) e^{-3M} = 2.7 \times 10^{12} \text{ recruits to the fishery} \\ C = 63 \text{ million tonnes} \end{cases} \qquad \text{(A9)}$$

(8) A Value for $\sigma_R$

Recruitment has been assumed to fluctuate log-normally about its median value from one year to the next. These deviations from the median are assumed to be independent (i.e.,auto-correlation is assumed to be zero). The extent of these fluctuations is given by the value of $\sigma_R$. The analysis has assumed $\sigma_R = 0.4$. This value is reasonably central over the wide range of values estimated for a large number of populations of marine species world-wide (Beddington and Cooke, 1983).

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(9) Values for Mass-at-Age $w_a$

The growth curve fitted by Rosenberg, Beddington and Basson (1986):

$$l_a = 60[(1 - \exp(- .45a)] \text{ mm} \qquad \text{(A10)}$$

was used to provide length-at-age values. Since this curve was fitted assuming that growth takes place over a short summer season only, the average length ($\bar{l}_a$) of krill of age a at the start of the season was taken to be:

$$\bar{l}_a = 0.5\,(l_a + l_{a+1}) \qquad \text{(A11)}$$

It should be noted that use of different growth curves may imply different values for M, with faster growth corresponding to larger M - see 2) above.

These lengths were converted into masses by use of a relationship from Morris, Watkins, Ricketts, Buchholz and Priddle (1988):

$$w = 3.39 \times 10^{-6}\, l^{3.23} \quad \text{(w: gm; } l\text{: mm)} \qquad \text{(A12)}$$

The resultant masses-at-age (in gm) used were: $w_3 = 8.7$; $w_4 = 11.7$; $w_5 = 14.0$; $w_6 = 15.6$; $w_7 = 16.7$.

Contributions of krill of age 8 or more were ignored in the analysis.

(10) Catch Series

The time series of catches used is as follows:

(i) Years y = -9 to 0: Fixed historic catch: $C_y = 0.4$ million tonnes.
(ii) Years y = 1 to 5: Fixed catch at initial ceiling level: $C_y = C_c$.
(iii) Years y = 6 to 20: $C_y$ given by control law of equation (2) in main text.

The simulations assume that the TAC set by the control law is always caught. Given the TAC and $B_y$, equation A5 can be used to calculate the fishing mortality $F_y$, and then equation A1 applied to provide the dynamic response of the resource. Care must be taken that $F_y < 1$ (i.e., that the TAC set is in fact available for capture); however, no instances of $F_y \geq 1$ occurred in the computations carried out for this paper.

(11) CPUE - Biomass Relationship

The definition of $\tilde{B}_y$ in equation A7 allows for the fact that the krill biomass will be reduced by the fishery during the course of the season, since CPUE would be related to some average level of the biomass over the season.

The exponent of $\tilde{B}_y$ in equation (A6) must be less than 1 if CPUE is to drop by proportionally less if biomass decreases. Little basis is available for the specific numerical choice of 0.5 (i.e., a square root relationship); an improved basis for the choice will require more data and research regarding the "Composite Index" (Anon,

(12) A Value for $\sigma_q$

The form of equation A6 implies that the variance about the CPUE-biomass relationship is dominated by catchability fluctuations. These are assumed to be independent from one year to the next, and log-normally distributed.

Simulation studies (e.g., Butterworth, 1988) have provided some indication of the size of the sampling variance contribution to equation A6, but such an analysis is not yet available for the "Composite Index" (Anon., 1989b). However, the size of the sampling variance will decrease as the catch taken grows, so that it seems likely that catchability fluctuations will be the dominant contributor to the overall variance.

The value of $\sigma_q = 0.2$ chosen is a "typical" figure. For example, de la Mare (1984) found that the coefficients of variation (approximately equal to $\sigma_q$) for 42 whale CPUE series were typically in the range 0.2 to 0.5. Fits of population models to CPUE data for four hake stocks off Southern Africa yield values of $\sigma_q$ from 0.12 to 0.16 (A.E. Punt, pers. commn).

# THE RELATIONSHIP BETWEEN KRILL (*EUPHAUSIA SUPERBA*) FISHING AREAS IN THE WEST ATLANTIC AND ITS CIRCUMPOLAR DISTRIBUTION

D.G.M. Miller*

## 1. INTRODUCTION

At its recent meeting in La Jolla, the CCAMLR Working Group on Krill recognized a number of difficulties inherent in the assessment of krill abundance and distribution throughout the Convention Area (SC-CAMLR-VIII/4). Historically, however, as more than 90% of the commercial krill catch has been taken from within Statistical Area 48, the Working Group agreed that the task of assessing krill distribution and abundance can be reduced to manageable proportions by initially focusing on the areas (particularly Subareas 48.1, 48.2 and 48.3) being fished.

Despite agreement that current catch levels are unlikely to be having much impact on the circumpolar krill population, the Working Group was unable to give any indication whether or not the present krill catch is having an adverse impact on local predators. For this reason, the Working Group recommended that krill catches should not greatly exceed current levels, at least until assessment methods are developed to provide reliable estimates and more is known about requirements of predators in relation to local krill availability. Consequently, the need to develop more suitable procedures for assessing krill distribution/abundance was recognized as important and was encouraged by the Working Group.

## 2. MATERIALS AND METHODS

The geographical extent of Subareas 48.1, 48.2 and 48.3 (from which more than 90% of historical krill catch has been taken (Miller, 1989b) was originally calculated by Everson (1984). In this study, the size of the following four regions was calculated (Figure 1):

(a) CCAMLR Convention Area;

(b) area south of 55°S;

(c) area containing krill concentrations (as defined by Lubimova *et al.*, 1982); and

(d) area south of the mean summer position of the 0°C isotherm (as defined by Naganobu and Hirano, 1982).

These regions were considered to represent four possible limits for the global distribution of krill (Naganobu, 1986; Miller and Hampton, 1989) and their size was calculated using a specially developed computer program based on a Lambert Geographical Projection.

The FIBEX (First International BIOMASS Experiment) mean krill density estimate for the west Atlantic sector of the Southern Ocean (Anon., 1986) was extrapolated to give a global biomass of krill within each of these four regions. Similarly, the FIBEX maximum krill density estimate for the West Atlantic was used to obtain an upper limit for the biomass of krill in the three subareas of Statistical Area 48.

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## 3. RESULTS

The size of different subareas of Statistical Area 48 and corresponding estimates of krill biomass are given in Table 1. The rest of the table presents calculated areas and corresponding estimates of krill biomass in the regions of possible global limits of krill distribution described above.

By comparing krill biomass in different subareas of Statistical Area 48, where historically more than 90% of krill catches is taken, it has become evident that some evaluation of the impact of present catch levels on krill resources in these subareas is required.

A possible surplus of krill circumpolar productivity resulting from a reduction in stocks of large baleen whales, could be estimated conservatively at around 100 million tonnes (based on a figure of 147 million tonnes given by Laws, 1977). Since Subareas 48.1, 48.2 and 48.3 comprise only a part of the circumpolar krill resource, an appropriate fraction of this surplus productivity has to be taken into account in the calculation of the availablekrill biomass in Statistical Area 48. This fraction is given by the ratio of the krill biomass in Statistical Area 48 to the circumpolar biomass and was estimated at about 20% based on the figures presented in Table 1. The value 20% has been used in the Operational Model of Krill Dynamics in Subareas 48.1, 48.2 and 48.3 developed by Butterworth (see main paper).

It is clear that the implication of the range of evaluations presented in Table 1 merits further discussion, particularly within the type of analysis undertaken by Butterworth (this volume). At this stage we did not draw any other conclusions in order to avoid pre-empting such discussions.

Table 1: Size of various regions of the Southern Ocean and their estimated krill biomass.

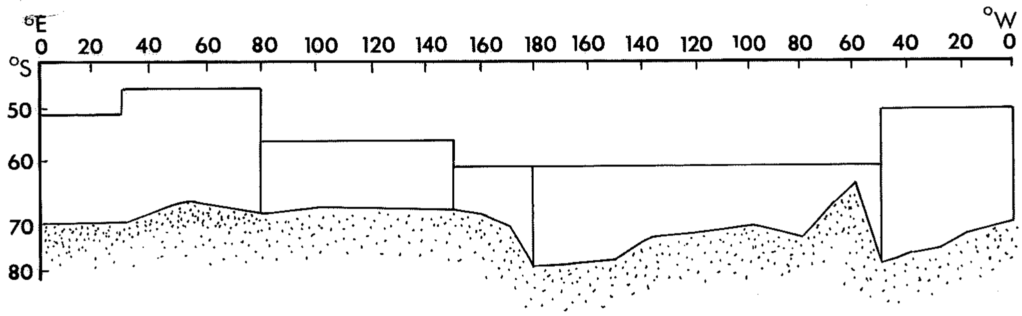
| Region | Area km² x $10^3$ | Krill Density g/m² | Ratio Areas Fished to Circumpolar Range (%) | Krill Biomass tonnes x $10^6$ |
|---|---|---|---|---|
| Subareas fished | | | | |
| 48.1 | 922.987 | *4.46 | - | 4.12 |
| 48.1 W | 592.156 | *4.46 | - | 2.64 |
| 48.1 E | 330.831 | *4.46 | - | 1.48 |
| 48.2 | 850.997 | *4.46 | - | 3.79 |
| 48.3 | 1341.672 | *4.46 | - | 5.98 |
| Total size of areas fished | | | | |
| | 3115.656 | *4.46 | - | 13.89 |
| | | **31.65 | - | 98.61 |
| Circumpolar ranges of krill distribution | | | | |
| CCAMLR Convention Area | | | | |
| | 33419.845 | *4.46 | 9.32 | 149.05 |
| Area south of 50°S | | | | |
| | 31697.702 | *4.46 | 9.83 | 141.37 |
| +Area of krill concentrations | | | | |
| | 4126.749 | *4.46 | 75.50 | 18.40 |
| +Area south of 0° C isotherm | | | | |
| | 16123.469 | *4.46 | 19.32 | 71.91 |

* FIBEX mean density estimate (from Table X in Anon., 1986)

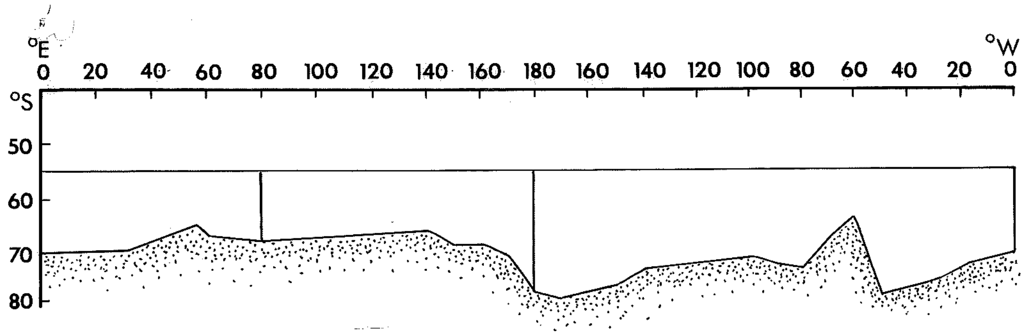
** FIBEX maximum density estimate (from Table VII in Anon., 1986)

+ For practical purposes these areas can be considered to circumscribe Subareas 48.1, 48.2 and 48.3 completely.

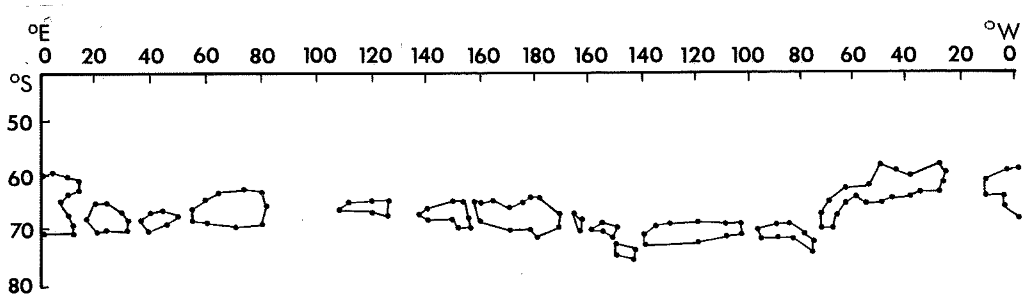
(a) CCAMLR Convention Area




(b) Area south of 55°S




(c) Area of krill concentration (after Lubimova *et al.*,1982)




(d) Area south of the 0°C isotherm (after Naganobu and Hirano, 1982)

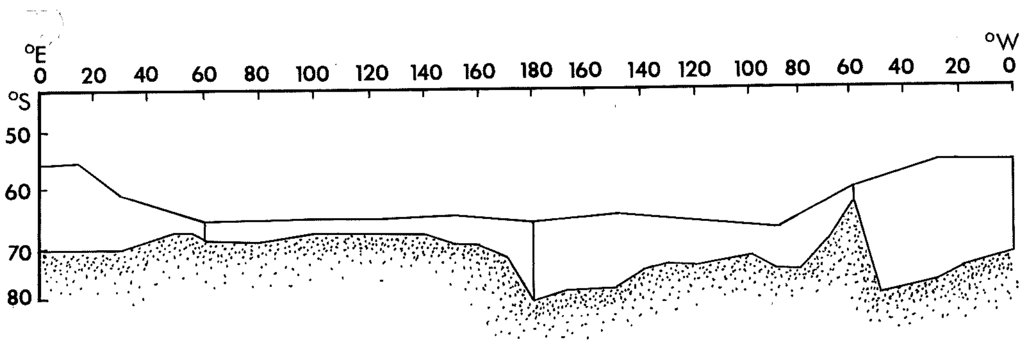



Figure 1: Various regions of ocean considered in the estimation of the global distributional range of krill.