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A SIMULATION STUDY OF KRILL FISHING BY AN INDIVIDUAL JAPANESE TRAWLER*

D.S. Butterworth

Abstract

A model is set up for the operation (which includes both searching and fishing) of a Japanese krill trawler over a half-month period. It is based on an underlying krill distribution model whose parameters are determined primarily from the scientific FIBEX surveys. Output from the model of the operation is compared with (and partially tuned to) statistics for a sample of data from the commercial fishery. A major inconsistency is found: haul times are a factor of 4-5 times greater in reality than in the model. Two *ad hoc* model modifications are introduced to eliminate this inconsistency: artificially elongating krill swarms, and allowing hauls to continue through more than one swarm. Twenty four candidate abundance indices (generally of a CPUE form) for krill biomass in the 600 n mile square oceanic sector modelled are considered, and their performance in response to a variety of ways in which the overall krill biomass might decline is investigated. Generally the indices respond by dropping relatively less than the proportional biomass decrease. Catch statistics collected at present (centred primarily on catch per fishing time) are of low utility in detecting biomass decline. Combination catch rate indices incorporating within-concentration search time give improved performances, but are able to monitor changes in within-concentration krill distribution parameters only. Indices that distinguish primary searching time from secondary searching time (searching while waiting to finish processing) within concentrations perform better, but collection of the requisite data may not be practical. Other approaches (e.g. research vessel surveys) need to be considered to monitor changes in the number, distribution and size of krill concentrations, both because there are doubts about the reliability of indices based on concentration searching time (which do respond to such changes), and because such indices are relatively imprecise. Priority needs to be given to improving the krill distribution model underlying the analysis; this probably requires that scientific surveys be planned to operate in small areas concurrently with fishing vessels.

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* Revised and extended.

Résumé

Un modèle est établi pour l'opération (qui inclut la recherche ainsi que la pêche) d'un chalutier de krill japonais sur une période d'un demi-mois. Il est basé sur un modèle fondamental de répartition du krill, dont les paramètres sont déterminés essentiellement d'après les études scientifiques FIBEX. Les résultats du modèle de l'opération sont comparés aux (et en partie ajusté selon les) statistiques d'un échantillon de données de la pêcherie commerciale. L'on remarque une inconsistance majeure: les heures de trait sont un facteur 4 à 5 fois plus grand en réalité que dans le modèle. Deux modifications du modèle *ad hoc* sont introduites pour éliminer cette inconsistance: allonger artificiellement les bancs de krill et permettre aux traits de se poursuivre sur plus d'un essaim. Vingt-quatre indices d'abondance proposés (généralement sous forme de CPUE) sont considérés pour la biomasse de krill dans le secteur océanique de 600 milles carrés du modèle, et leur performance en réponse à une variété de manières dont la biomasse totale de krill peut baisser est l'objet de recherches. En général les indices répondent en baissant relativement moins que la baisse proportionelle de la biomasse. Les statistiques de capture recueillies à ce jour (concentrées principalement sur la capture par heure de pêche) sont de peu d'utilité pour détecter la baisse de la biomasse. Les indices de taux de pêche combinée, comprenant le temps de pêche dans la concentration, donnent de meilleurs performances mais peuvent uniquement contrôler les paramètres de répartition du krill dans la concentration. Les indices qui distinguent le temps de recherche primaire du temps de recherche secondaire (recherche dans l'attente de la fin du traitement) dans les concentrations donnent de meilleurs résultats mais il se peut que la collecte des données requises présente des difficultés. D'autres méthodes (par ex. des études des navires de recherche) doivent être considérées pour surveiller les changements dans le nombre, la répartition et la taille des concentrations de krill, en raison, d'une part, des doutes sur la fiabilité des indices basés sur le temps de recherche d'une concentration (qui répondent à de tels changements), et d'autre part, parce que d'autres indices sont relativement imprécis. Il faut accorder la priorité à l'amélioration du modèle de base de répartition du krill de l'analyse; ceci nécessite probablement de prévoir que les recherches scientifiques opèrent dans de petites zones concurrement avec les navies de pêche.

Резюме

Модель разработана для операции японского крилевого траулера, которая расчитана на полумесячный срок и влючает как поисковые, так и рыболовные действия. Эта модель базируется на модели распределения основного криля, параметры которой определены в основном из съемок по программе "FIBEX" Выходные данные модели операции сравнимы (и частично приведены в соответствие) со статистическим набором данных промышленного рыболовства. Главное несоответствие найдено: время траления - фактор в 4-5 раз больший в реальности, чем в модели. Для того, чтобы устранить это

несоответствие, созданы две специальные модификации модели, которые удлинняют скопления криля и позволяют продолжать траления через более чем одно скопление криля. Учитываются двадцать четыре индекса вероятной численности (обычно формы CPUE) биомассы криля, смоделированной в квадратном секторе океана площадью в 600 морских мили., и изучается изменение этих индексов, в зависимости от разнообразных путей, по которым общая биомасса криля может уменьшаться. Как правило, индексы отвечают относительно меньшим понижением на соответствующие уменьшения биомассы криля. Статистические данные по динамике уловов, собранные в настоящее время (касающиеся главным образом улова на единицу промыслового усилия) мало используются в выявлении уменьшения биомассы. Обобщенные индексы интенсивности вылова, объединяющие время поиска в пределах концентрации, дают более совершенные результаты, однако, они дают возможность контролировать изменения параметров только в пределах границ концентрации. Индексы, различающие первичное время поиска от вторичного (поиска в течение ожидания окончания обработки собранных данных), в пределах концентраций работают лучше, но сбор необходимых данных может быть практически невозможным. Другие методы (например, съемки с Научно-исследовательского судна) должны учитываться для мониторинга изменений в числе, распределении и размерах криля, так как имеются сомнения по поводу надежности индексов, основанных на времени поиска концентрации (которые в действительности реагируют на такие изменения), и в связи с тем также, что эти индексы относительно неточны. В первую очередь необходимо усовершенствовать модель распределения криля, которая лежит в основе исследования; это, возможно, потребует, чтобы научные съемки проводились в небольших районах одновременно со съемками с промысловых судов.

Resumen

Se establece un modelo para la operación (que incluye tanto la búsqueda como la pesquería) de un arrastrero de krill japonés durante una quincena. Se basa en un modelo subyacente de distribución del krill cuyos parámetros están determinados principalmente por las prospecciones científicas FIBEX. El resultado de este modelo de operación se compara con (y parcialmente se ajusta a las estadísticas de una muestra de datos de la pesquería comercial. Se encuentra una anomalía mayor: la duración del arrastre es 4-5 veces mayor en realidad que en el modelo. Se introducen dos modificaciones al modelo ad hoc para eliminar esta anomalía: alargar los cárdumenes de krill artificialmente, y permitir que los lances se realicen en más de un cardumen. Se consideran veinticuatro índices posibles de abundancia (generalmente en forma de CPUE) para la biomasa de krill en el sector oceánico modelado de 600 millas náuticas cuadradas, se investigan sus funcionamientos en respuesta a las diferentes maneras en que la biomasa total del krill podría declinar. Generalmente los índices reaccionan bajando relativamente menos que la disminución proporcional de la biomasa. Las estadísticas de captura recopiladas actualmente (centradas principalmente sobre captura por tiempo de pesca) son de poca utilidad para detectar la disminución de la biomasa. Los índices de la tasa de captura de combinación que incorporan tiempo de búsqueda dentro de la concentración dan resultados mejores, pero solamente pueden controlar cambios en los parámetros de la distribución del krill dentro de una concentración. Los índices que distinguen entre el tiempo de búsqueda primario y el tiempo de búsqueda secundario (explorando mientras se está terminando la elaboración) dentro de una concentración funcionan mejor, pero la recopilación de datos precisos puede que no sea práctica. Otros enfoques (por ej. prospecciones de buques de investigación) tienen que ser considerados para controlar cambios en el número, distribución y tamaño de las concentraciones del krill, tanto porque hay dudas sobre la exactitud de los índices basados en el tiempo de búsqueda de una concentración (los cuales responden a tales cambios), como porque tales índices son relativamente imprecisos. Se debe dar prioridad a mejorar el modelo de distribución del krill siendo la base del análisis; esto probablemente requiere que las prospecciones científicas sean planeadas para operar en zonas pequeñas al mismo tiempo que los buques de pesca.

1. INTRODUCTION

This document reports the results of a simulation study of krill distribution and the krill fishery in the Antarctic. The exercise is being undertaken on a contractual basis for CCAMLR to determine the (possible) utility of CPUE (catch-per-unit-effort) as an index of changes in krill biomass. A major objective is to provide insight regarding which particular catch statistics might most appropriately be collected to construct (CPUE-like) abundance indices with the greatest potential to reflect such changes.

This paper details an attempt to model the Japanese Antarctic krill fishing operation. This operation is strategically very different from the Soviet fishery, models of which have been presented in Mangel (1987, 1988). In the Soviet fishery, the activities of locating and of fishing krill concentrations are largely the separate responsibilities of different vessels, and a large number of vessels works in close collaboration. In contrast, in the current Japanese fishery (at least as a first approximation), the trawlers operate singly and independently of each other [see Butterworth (1988)], and have each to find the krill concentrations as well as to fish them.

The model developed has attempted to mimic the Japanese fishery in the "high season" (January-February). The reasons for this choice are discussed in Butterworth (1988); essentially, since catch rates are best in this period, it seems likely that future krill fishing will be concentrated in these months (as is already the case). A particular characteristic of the fishery over these months is that most hauls are reported to fish upon a single swarm of krill only.

The model is intended to reflect the operation of a single trawler off Wilkes Land. Butterworth (1988) sets out in some detail the reasons for choosing this area in preference to the Scotia Sea (where most Japanese krill fishing now takes place). The overriding concern was that initial modelling attempts should be aimed at an operation and area with as few complicating factors as possible.

The paper first describes the setting up of the underlying krill distribution model (section 2.1) for a 600 n mile square sector of the Southern Ocean and the basis for the choice of the distribution parameter values (section 2.2). The distribution model with these particular parameter values is designated the "base case". Chapter 2 then goes on to give a detailed description of the models used for the searching (both for concentrations, and for swarms within concentrations) and fishing operations.

A sample of the standard data collected in the commercial fishery was provided for the 1980/81 and 1981/82 seasons for a Japanese trawler that operated off Wilkes Land. Summary statistics are extracted from these data (section 3.1), and then compared to the "base case" simulation model output to check the realism of the model. This realism is improved by "tuning" some of the fishing operation model parameters to obtain better agreement between the data and the model output (section 3.2).

This exercise highlights a fundamental inconsistency between the model and the data: typical swarm sizes and densities, together with mean catches per haul, cannot be reconciled with average haul times and towing only a single swarm per haul. Compatibility is restored by modifying the model in two different ways (section 3.3):

(i) Artificially elongating swarms in the direction in which they are towed.

(ii) Allowing hauls to tow through more than one swarm.

For each of these approaches, the base case model krill distribution parameters are then adjusted in a variety of ways, each of which corresponds to reducing the overall krill biomass in the 600 n mile square sector under consideration by 50%. The change in the average value (over 100 simulations) of a number of potential abundance indices (developed in section 3.4) is determined for each of these adjustments, to examine the abilities of these indices to detect a biomass decline. Further, the behaviour of each of these indices is examined over a range of krill biomass values, where the change in the krill biomass from its original level is effected by a randomly chosen combination of changes in distribution parameters (sections 3.5 and 3.6).

Finally, shortcomings of the model are discussed (section 3.7), and conclusions are summarised and recommendations made in Chapter 4.

2. THE SIMULATION MODEL

The basic structure of the simulation model is set out in flow-diagram form in Figure 1. A trawler steams from its offloading point towards the southernmost limit ("ice-edge") of the 600 n mile square oceanic sector under consideration. Once a concentration of swarms is found, either *en route* to the ice-edge or following searching once the edge has been reached, the trawler will seek suitable swarms to fish in that concentration, and continue fishing in this way until either the catch-rate becomes too low, bad weather intervenes, or the time has come to return to offload (15 days after commencement). In the case of either of the first two of these reasons, searching will continue (after a period has elapsed in the event of bad weather) until another concentration is found, and the process above is then continued.

The sections of this Chapter that follow set out the details of each major element of the model as characterised in Figure 1, together with the rationale underlying that particular specification.

2.1 The Krill Distribution Model

In the first instance, it must be emphasised that the model developed here is a simplification of the real situation; it attempts to capture the main qualitative features of typical krill distribution patterns which would be relevant to the utility of catch statistics based indices as measures of biomass, but does not try to incorporate all the detailed knowledge about krill aggregation behaviour that is available. If certain abundances indices are indeed found not to have utility in this simplified situation, it is highly unlikely that the introduction of more detail into the distribution model would change this conclusion. On the other hand, if some promising candidate indices are revealed by this analysis, then the suitability of those indices should also be checked by simulation for more detailed krill distribution models; however, such an exercise is outside the scope of this initial investigation.

The largest scale considered in the model is a "sector" of the Southern Ocean. This sector is a square with sides of 600 n miles and approximates an area between, say, latitudes 60°S and 70°S spanning 20° of longitude. Clearly the simplest assumption to make would be that there is a uniform average density of krill in the area. However, a stratified habitat distribution as shown in Figure 2 has been used.

One of the reasons for deciding to use a stratified habitat is that scientific sighting surveys of minke whales (a major krill predator) carried out by the International Whaling Commission have shown that this species preferentially congregates close to the Antarctic ice-edge during the summer months [Butterworth *et al* (1987)]. It has therefore been presumed that the southernmost subsector S_1 (see Figure 2) is the most preferred habitat, and that preference for habitats decreases with movement northward.

This description is more representative of the south Indian and southwest Pacific Oceans (e.g. off Enderby Land and off Wilkes Land). For an initial modelling study, it is more convenient and appropriate to deal with such regions of simpler geography rather than, say, the complexities of the Scotia Sea with its island related krill distributional patterns [see Butterworth (1988)].

The South African FIBEX survey, which covered latitudes 60°S to 69°S in the Indian Ocean sector off Antarctica, did not show a correlation of krill abundance with latitude [Hampton (1985)], which argues against the habitat structure adopted for this krill distribution model. However, Hampton (pers. commn) suggests that it would be inadvisable to attach too much importance to this result. Although the survey in question commenced with its southernmost transect very close to the ice-edge, a major storm occurred within hours, changing conditions and rendering it impossible for the survey vessel to resume its original east-west trackline, so that it is questionable whether it really managed representative coverage of the near-ice-edge area. Further, discussions with the Captain of a Japanese krill trawler (Captain Fukui, pers. commn, September 1987) confirmed that his operations off Wilkes Land are generally within 100 n miles of the ice-edge, and often much closer (f 10 n miles) than that, which provides support for the form of habitat structure adopted.

The basic model for the krill within this sector is one of "patches within patches": the sector contains a number of *concentrations* of krill, and these concentrations consist in turn of collections of *swarms*, whose size is smaller than that of a typical concentration. The justification for a distributional model of this type is based on the more detailed hierarchical classification proposed by Kalinowski and Witek (1982, 1985) [see Butterworth and Miller (1987), Appendix I]. Attention has been restricted to swarms, as layers have too low a density for fishing them to be economic, and fishing on superswarms seems to be a relatively infrequent phenomenon [Butterworth (1988)].

The sector is taken to contain N_c concentrations of krill (see Figure 3). These concentrations are assumed to be circular with radius L_c, where L_c varies from one concentration to the next. Each concentration contains some number of swarms of krill. It is assumed that the number of swarms in a concentration (given a fixed total biomass in the sector) is proportional to its area. Thus, if L_c denotes the radius of the i^{th} concentration, the number of swarms in that concentration is given by:

$$N_{si} = D_{ci} \cdot \pi(L_{ci})^2 \qquad (1)$$

where D_{ci} is the density of that concentration in swarms per unit area. Although D_c may vary between concentrations, it is not (in terms of the assumption above) correlated with concentration size.

Individual swarms in the concentrations are characterised by physical location, length scale, density, and the nature ("quality") of the krill in the swarm. The centre of each swarm is assumed to be located uniformly and randomly within its concentration, i.e. any possible spatial correlation in the distribution of swarms within a concentration has been ignored. Each swarm is assumed to be circular in the horizontal plane with a radius r, and to contain krill of density δ measured as a biomass per unit area; both r and δ vary from swarm to swarm within a concentration.

Krill quality is a major concern for the Japanese fishery. Generally the larger sized krill are preferred, and "green" krill are avoided [see Butterworth (1988)]. It is not clear whether size and greenness are swarm or concentration properties, [although comments by Captain Fukui (pers. commn) suggest that they tend to be the latter] and the time scale over which greenness persists is unknown [Captain Fukui commented that this is definitely at least a few days, and that he suspects it is a few weeks]. For simplicity here, these quality factors will be ignored, though they should be an aspect for attention in subsequent studies. There is some further justification for ignoring greenness in this particular case, as the commercial data sample to which the simulation model output is to be compared was deliberately selected for a period where greenness was not a concern for the parent company of the vessel concerned [see Butterworth (1988)].

Although concentrations and swarms within concentrations undoubtedly do move, the model used for this study is quasi-static. For computational simplicity, general movement of the krill concentration field will be mimicked by keeping the position of the concentrations fixed and moving the fishing vessel (for example, during periods of bad weather - see section 2.4). Very large scale movements cannot be taken into account at this stage, because the simulation is restricted to a "sector" within which the krill biomass remains fixed (apart from the effects of fishing). Again, if a candidate abundance index proves to have no utility for monitoring biomass for this simple model, it is most unlikely that it would perform any better for a more complex model of krill movement.

However, in order to capture some effects of motion, a random search formula, rather than exhaustive search, will be used to characterise search both for concentrations, and for swarms within concentrations. This is discussed in more detail in section 2.6.

2.2 Setting the Krill Distribution Parameter Values

The following notation is used in this and following sections:

U[A,B] indicates a uniform distribution over the range [A,B] (from which a random number is drawn)

$N[0,\sigma^2]$ indicates a normal distribution of mean zero with a standard deviation σ.

2.2.1 Habitat Stratification

It is assumed that the ratio of the densities of krill in subsectors S_1: S_2: S_3: S_4: S_5 is 12:6:4:3:2. Note that the two southernmost subsectors have narrower widths than the others, so that the corresponding abundance ratios are 6:3:4:3:2. There is little specific justification for the numerical choices made here (which could of course be varied), though the International Whaling Commission Antarctic minke whale surveys do indicate minke whale densities within ~ 1° of latitude of the ice-edge (cf: stratum S_1) are typically 2-4 times the densities further north [Butterworth *et al* (1987)].

2.2.2 Number of Concentrations

The estimate of the number of concentrations in the 600 n mile square sector that has been used in this study is:

$$N_c = 36 \qquad (2)$$

This estimate is based in the first instance on diagrams in Ichii (1987) of the operations of a Japanese trawler off Wilkes Land, which suggests a typical inter-concentration distance of about 100 n miles. It was then (partially) tuned so that the simulation model output produced values for total concentration searching time (TCST) roughly equivalent to those evident from the sample of commercial fishing data available.

2.2.3 Radius of (Circular) Concentrations of Swarms

The radii of concentrations are drawn at random from the following distribution:

$L_c = U[10/\sqrt{\pi},\ 20/\sqrt{\pi}]$ n miles

The basis for this choice is to be found in Butterworth and Miller (1987), Appendix I [which is essentially extracted from information in Kalinowski and Witek (1982, 1985)], which describes concentrations as extending over distances of 1 to 100 km. The $\sqrt{\pi}$ factor is an historical anomaly; it originated from maintaining equal concentration areas in two earlier analyses, one of which had modelled concentrations as square in shape. It has been maintained here to preserve some consistency with earlier work.

2.2.4 Surface (Areal) Density of Krill Within a Swarm

The surface densities (i.e. integrated over the vertical dimension) of krill swarms within concentrations are drawn at random as follows:

$$\delta = 150e^{\varepsilon}\ \text{g/m}^2 \qquad \varepsilon \text{ from } N[0,(1.4)^2] \tag{4}$$

Butterworth and Miller (1987) quote a range of 10 to several hundred g/m^3 for the volume density of krill in a swarm. The combined results from FIBEX [BIOMASS (1986), Table XI] give a mean krill volume density ρ = 59 g/m^3 and a mean swarm thickness of 5 m; this corresponds to a mean surface density $\delta \cong 300$ g/m^2. Kalinowski and Witek (1983) fit the ρ distribution with a log-normal distribution corresponding to $N[4.28,(1.40)^2]$, for which the median ρ is 72 g/m^3.

BIOMASS (1986), Table XI also indicates that:

c.v.(swarm thickness) ~ 0.25 c.v.(horizontal dimension)

so that the variability of swarm thickness is relatively negligible for the purposes of these calculations.

Accordingly, this suggests:

$$\delta = 300e^{\varepsilon}\ \text{g/m}^2 \qquad \text{where } \varepsilon \text{ from } N[0,(1.4)^2]$$

However, it should be noted that most of the data that contributed to the estimates above were collected in the Antarctic Peninsula area. Butterworth (1988) quotes Japanese Captains' statements that krill catch rates (which seem to relate primarily to within-swarm density) are higher in the Scotia Sea compared to the area off Wilkes Land. Further, Shimadzu (pers. commn) advises that swept-area experiments off Wilkes Land yielded density estimates of 5-10 g/m^3 over a 20 m deep net mouth, which correspond to surface densities δ = 100-200 g/m^2.

Since the sample of commercial data with which the results of this simulation are to be compared was taken from an operation off Wilkes Land, the median density value suggested above was halved to the 150 g/m^2 used.

2.2.5 Radius of (Circular) Swarms Within a Concentration

The radii of swarms within concentrations are drawn at random from the distribution:

$$r = 50\ e^{\varepsilon} \qquad \varepsilon \text{ from } N[0,(1.1)^2] \qquad (5)$$

Butterworth and Miller (1987) [extracted from Kalinowski and Witek (1982, 1985)] state "swarms are several tens of metres long". The FIBEX data [BIOMASS (1986), Table XI] give the mean intersected swarm length $\lambda = 73$ m. Kalinowski and Witek (1983) fit intersected swarm length by a log-normal distribution corresponding to $N[3.69,(1.09)^2]$, for which the median $\lambda \sim 40$ m.

If swarms are assumed to be circular, the radius r is related to λ by:

$$r = (2/\pi)\lambda \qquad (6)$$

so that the FIBEX data correspond to a mean $r \sim 47$ m, and Kalinowski and Witek's (1983) results to a mean $r \sim 25$ m.

This would seem to suggest that the median value for r of 50 m adopted for this analysis may be rather too high, particularly as the estimates extracted from the data should be modified further by the $e^{-\sigma^2/2}$ factor for mean-to-median conversion for a log-normal distribution. Further, intercept survey [on which the BIOMASS (1986) results were based] is size biased, and will give a positively biassed estimate of the average radius of circular swarms. On the other hand, the non-circularity of swarms that occurs in practice will introduce a bias in the other direction [Hampton (1985)]. A further fact which suggests this median value choice may be too large is that Kalinowski and Witek (1983) fit the distribution of swarm biomasses by a log-normal corresponding to $N[6.03,(2.54)^2]$, for which the median swarm biomass $B_s = 0.42$ tonnes. This corresponds to a mean $\bar{B}_s = 10.5$ tonnes, which is somewhat less than the $\bar{B}_s = 35$ tonnes to which the chosen distribution model parameters correspond (see summary subsection following). These aspects have not been pursued further at this stage, but merit more investigation in due course.

2.2.6 Density of Swarms Per Unit Area in a Concentration

Swarm densities within concentrations have been generated from:

$$D_c = 20e^{\varepsilon}\ (\text{n miles})^{-2} \qquad \varepsilon \text{ from } N[0,(0.1)^2] \qquad (7)$$

The rationale which follows for estimating the median value, was drawn to the author's attention by I. Hampton.

Consider an area A containing N_s circular swarms each of radius r. If F is the fraction of the area A that is covered by the swarms, then:

$$F = N_s \cdot \pi\ r^2/A \qquad (8)$$

For an echosounder based line intercept survey of krill swarms, the echosounder beam width is much less than the typical swarm diameter (~100 metres), so that if s is the average distance between swarms detected on the echosounder, and given that these swarms have been assumed to be circular, an estimate of fractional cover F is provided by:

$$F = [2r \cdot \pi/4]/s \qquad \text{(for } s >> r) \qquad (9)$$

so that:

$$D_c = N_s/A = 1/(2rs) \qquad (10)$$

Inspection of the sample of data provided from the Japanese krill fishery suggests that s ~ 3 n miles [see distance between successive hauls (DBH) in Table 1)]. However, application of equation (10) is inappropriate in this case, as it seems from comments made to the author by Mr Ichii and Captain Fukui that sonars (of much wider effective search width than echosounders) do play a major role in swarm detection by the fishing vessels [in contrast to the impression given in Butterworth (1988)], and also because it seems that there is considerable selection taking place in the choice of swarms for fishing (see section 2.7). Nevertheless, equation (10) can be applied to the FIBEX results which report an average inter-swarm spacing of 2.2 km [BIOMASS (1986)]. Taking $r = 50$ m then, gives $D_c = 15.6$ swarms per (n mile)^2.

The $s = 2.2$ km FIBEX figure includes some effective between-concentration as well as the within-concentration spacings, and hence is positively biased for the purpose used here. Accordingly, the median value in (7) was rounded upwards from the estimate obtained using equation (10). The choice of a value for the variance is semi-arbitrary; some variation seems appropriate to allow for differences in D_c from concentration to concentration, which must exist in practice.

2.2.7 Summary and Relation to Circumpolar Krill Biomass

The krill distribution model parameters chosen (for what will subsequently be referred to as the "base case") are therefore:

Relative densities of strata: $S_1{:}S_2{:}S_3{:}S_4{:}S_5 = 12{:}6{:}4{:}3{:}2$
Number of concentrations: $N_c = 36$ (11)
Concentration radius: $L_c = U[10/\sqrt{\pi},\ 20/\sqrt{\pi}]$ n miles
Swarm density: $D_c = 20e^{\varepsilon}\ (s)^{-2}$ ε from $N[0,(0.1)^2]$
Swarm radius: $r = 50e^{\varepsilon}$ metres ε from $N[0,(1.1)^2]$
Swarm (areal) density: $\sigma = 150e^{\varepsilon}$ g/m^2 ε from $N[0,(1.4)^2]$

These parameter values can be used to compute the overall abundance of krill to which the distribution model then corresponds. Using the median values for the parameter distributions yields:

Swarm biomass: $B_s = \sigma \pi r^2 = 1.18$ tonnes
Number swarms in concentration: $N_s = D_c \pi L_c^2 = 4\ 500$
Concentration biomass: $B_c = N_s B_s = 5\ 300$ tonnes
Sector biomass: $B_{sec} = N_c B_c = 0.19$ million tonnes
Biomass around Antarctica: $B_{Ant} = 18\ B_{sec} = 3.4$ million tonnes.

This last figure seems at least an order of magnitude too small. Estimates of (historic) krill consumption by predators have been in the 100-200 million tonne range. Growth rate and longevity estimates for krill [see Rosenberg *et al* (1986)] suggest a production:biomass ratio for krill certainly rather less than unity, so that 500 million tonnes might be an appropriate order of magnitude estimate for the circumpolar krill biomass.

However, the calculations above need to be amended to take into account the bias factors that arise when distributions rather than single values are used for the parameters. For example, the mean of a log-normal distribution (used above for D_c, r and δ) is not equal to its median as utilised in the preceding calculation, but is a factor $e^{\sigma^2/2}$ larger. Revised multiplications along these lines yield mean values:

$\overline{B}_s$ = 35.3 tonnes

$\overline{N}_s$ = 4 690

$\overline{B}_c$ = 166 000 tonnes
B_{sec} = 6 million tonnes
B_{Ant} = 108 million tonnes

which appear to be far more realistic figures.

The basic distribution model, and the rationale for the choice of parameter sp16 values, were presented to participants at a BIOMASS SIBEX Workshop in Cambridge in July 1988. While the obvious shortcomings of the model were recognised, it was generally agreed that existing data were neither adequate to allow substantial improvements to the model at this time, nor radically in conflict with any aspect of the model.

2.3 Generation of the Krill Concentration Field

The total of N_c = 36 concentrations is located in the basic 600 n mile square sector with its stratified habitat, where the southernmost strata are the more preferred regions for krill concentrations. The east-west coordinate of each concentration centre is selected on a uniform random basis from [0,600] n miles; the north-south coordinate is also selected at random from [0,600] n miles, but from a step-wise uniform distribution corresponding to the relative densities chosen for the stratified habitats. A particular realisation of the procedure is shown in Figure 3.

For computational convenience in simulating the fishing operation, two constraints are applied in generating this distribution: potential concentrations whose position and radius (selected from $L_c = U[10/\sqrt{\pi}, 20/\sqrt{\pi}]$ n miles) are such that they overlap the sector boundaries are disallowed, and potential concentrations which overlap those already placed in the sector are similarly excluded.

The chosen parameters are such that a considerable fraction of the potential concentrations (typically some 15% of the desired total number) can be excluded by these constraints. Accordingly, in scenarios (see section 3.5) where the L_c range is reduced for comparative abundance index studies, the original $[10/\sqrt{\pi}, 20/\sqrt{\pi}]$ n miles range is used in applying the constraints when setting up the concentration field, and only then are the concentration radii all diminished by the desired fraction.

2.4 Bad Weather Periods

Ichii (*in litt.*, 30 May 1988) has provided information on the frequency with which bad weather led to suspension of Japanese krill fishing operations. In his compilation, drawn from the 1973/74 to 1985/86 seasons, a total of 37 out of 1472 days, or 2.5%, were affected. The frequencies of the durations of these bad weather periods were:

one day : 68%
two days : 28%
three days : 4%

In the simulation, the probability that bad weather commences (as distinct from occurs) on a particular day within the 15 day (half-month) period under consideration is accordingly taken to be 0.02. The duration of that period is chosen at random to be 24, 48, or 72 hours according to probabilities of 0.68, 0.28 and 0.04 respectively. The time of onset of a particular period of bad weather during the day concerned is selected at random. Bad weather will not, however, recommence on the same day that a previous period of bad weather abated. [Note that this is a slightly more complex prescription than in the study by Mangel (1987), where the bad weather periods all commence and end at midnight.]

Once bad weather commences, the vessel can neither search for concentrations nor seek and fish swarms within a concentration (though a trawl in progress at the time of commencement will be completed); however, transit both to and from offloading remains possible. One minor exception to this (for computational convenience) is that if bad weather occurs while the vessel is *en route* to its chosen spot on the ice-edge, and its track intersects a concentration during that bad weather period, it waits at that position and commences fishing once good weather returns. If bad weather occurs on the way back to the offloading point, this is counted as transit time rather than loss to bad weather; this is because the vessel continues searching/fishing until the last possible moment that will allow it to get back (travelling at 10 knots) to the offloading point within the 15-day deadline, and so would be unable to fish on any concentrations that might be detected on the return trip - hence bad weather at such a time does not result in the loss of any opportunity to fish.

A vessel affected by a 24/48/72 hour period of bad weather is moved 50 n miles in a random direction (reselected if it would move the vessel outside the sector boundaries), and has to recommence searching for a concentration at the end of that period. To a limited extent, this mimics movement of the krill concentration field. (This movement does not occur in the case of the minor exception discussed in the preceeding paragraph.)

The model feature of "losing" concentrations during bad weather is not entirely realistic, as echo sounders do enable vessels to search and keep track of swarms during such periods. However, no allowance has been made in the model for temporal variability in the parameters describing a concentration and the distribution of krill within it, because of the absence of pertinent data to parameterise such effects. Dispersion of a concentration would lead to a vessel leaving to search for another concentration because of a drop in catch rate, so that the manner in which bad weather consequences are modelled can be considered in part as a surrogate for the effect of such temporal variability.

2.5 Initial Searching Strategy for Concentrations

Ichii (pers. commn) advises that a Japanese krill trawler needs to offload at a cargo vessel typically twice a month; accordingly, a 15 day period (a "half-month") was chosen for this simulation study. The trawler commences operations for the half-month from the offloading position, which is assumed to be on the western boundary of the sector at a distance 100 miles from the ice-edge [i.e. the point (0,100)]. This choice may be rather larger than is realistic, as Ichii (*in litt.*, 30 May 1988) advises that his experience is that the cargo transfer is carried out close to the ice-edge to take advantage of the calmer conditions there.

Butterworth (1988) reports that "the opening strategy is often to move to an area where good catches were made the previous season". This "area" is assumed in the simulation model to be close to the ice-edge and near the east-west midpoint of the sector, so that the vessel sets an initial course for the point (300,0), steaming at the searching speed of 10 knots.

If no krill concentration is encountered, the vessel commences its general search strategy once the ice-edge is reached. However, if an encounter takes place - determined in the simulation model by checking whether the transit line intersects the circular boundary of any of the concentrations placed in the sector - fishing commences on the first concentration found in this manner. Once fishing on this concentration has concluded, the vessel commences its general search strategy from the position of that concentration, i.e. the original strategy of heading for the ice-edge is "forgotten"; having found krill in that vicinity, the vessel would regard it as a "good area" and so consider it worthwhile to seek further concentrations in that region.

The period steaming to the ice-edge (except insofar as bad weather intervenes) is regarded as "concentration searching time" (CST) commensurate with that incurred during the exercise of the general search strategy described in the next section.

2.6 General Search Strategy for Concentrations

In order to capture some of the effects of concentration movement, a random search formula rather than an exhaustive search process is used to characterise the search for concentrations. Suppose that an area A contains a krill concentration and that this area is searched at rate W_s units of area per unit time, so that after t units of time the area searched is W_st. In exhaustive search, if W_st is greater than A, the concentration is detected with probability 1. In circumstances where the concentration moves relative to the searcher, it could move back into a region which has already been searched. Such a situation can be regarded as a random search, and under very general conditions random search is characterised by the formula (see Figure 4):

$$\text{Prob \{detecting the object after t time units\}} = 1 - \exp(-W_st/A) \qquad (12)$$

For this analysis, this formula becomes:

$$\text{Prob \{detecting a concentration after t hours\}} = p(t) = 1 - e^{-wdvt} \qquad (13)$$

where:
w is the effective search width (n miles)
d is the density of concentrations (per n mile^2)
v is the searching speed (knots).

Since echosounder and sonar beam widths are much less than the modal concentration radius used ($15/\sqrt{\pi} \cong 8.5$ n miles), the effective search width is taken to be the modal concentration diameter:

$w = 17$ n miles

(i.e. a concentration is detected if the vessel crosses its boundary).

For the searching speed:

$v = 10$ knots

and for the southernmost stratum in the base case:

$$d = 12/(75 \times 600) = 1/3750 \text{ (n miles)}^{-2}$$

so that the random search formula becomes:

$$p(t) = 1 - e^{-0.045t} \tag{14}$$

which corresponds to a mean search time to find a new concentration of 22 hours.

This formula must be adjusted for strata with different concentration densities, or simulations where the modal L_c value is changed; in general, it becomes:

$$p(t) = 1 - \exp\{-0.045\ (3750d)\ (L_c/8.5)\ t\} \tag{15}$$

The search for concentrations is considered in blocks of time which are each of 8 hours duration. The reason for this limitation is to allow the value of d in equation (15) to be changed if the vessel's search moves it into a stratum with a different concentration density. Thus, a random number u from U[0,1], coupled with a value for d corresponding to the vessel's position at the start of that search time block, is used together with equation (15) to determine the time t until a concentration was found as follows:

$$t = -\ [ln(1 - u)]/[0.045(3750d)(L_c/8.5)] \tag{16}$$

If equation (16) provides a value $t > 8$ hours, the vessel is moved to a new position, and the process repeated until a value of $t < 8$ hours is obtained.

As the vessel would not necessarily steam along a single straight line over such an 8 hour period, 80 n miles is the maximum distance the vessel could have moved from its position at the start of the search time block. For simplicity, it is assumed that the actual distances in n miles moved by the vessel from its various starting points are drawn at random from the uniform distribution U[0,80]. The vessel is then moved the selected distance in a randomly chosen direction, and the calculations are repeated for the next search time block. (The direction is reselected if it is such as would move the vessel outside the sector boundaries.)

Once equation (16) yields a value of $t < 8$ hours, the simulation model program determines which concentrations (i) have their centres a distance s_i from the vessel's starting point for that search time block, where $s_i < 10t$. Note that 10t n miles is the maximum radial distance that the vessel could have steamed from the starting point in t hours. If there are no such concentrations, the vessel is moved some distance within a circle of radius 10t n miles. This distance is calculated on the same basis as described in the preceding paragraph, and another 8 hour search time block then commences at a time t hours later.

Alternatively, one or more concentrations are found within this 10t n mile radius. If only one is found, this is the concentration taken to be discovered. If more than one possibility exists, a choice (using random number generation) is made between those concentrations based on the relative weightings:

$$w_i = L_{ci}/(s_i + 10) \tag{17}$$

The rationale for the L_{ci} term is that larger concentrations are more likely to be discovered, as the effective search width is proportional to concentration radius. In the absence of any concentration within a 10t n mile radius, the vessel would move a distance drawn from U[0,10t], so that the distribution of distances to concentrations actually found should have a similar form. However, because of the expanding area effect, the number of concentrations possibly discovered will increase linearly with s (on average), so that larger values of s from the [0,10t] range would be favoured. The denominator term involving s in equation (17) was introduced to compensate for this effect; the added 10 n miles is an *ad hoc* adjustment to deaccentuate what would otherwise be very high weights accorded to concentrations very close by.

In cases where the previous concentration has been left because of a poor catch rate, the simulation model program precludes the vessel from rediscovering this same concentration during this search process (though it could be rediscovered later after another concentration has been fished). This restriction does not apply to cases where bad weather has interrupted the fishing, however.

Throughout these calculations, checks are made regarding the onset of bad weather and the need to return to the offloading point [identical to the (0,100) commencement point] before the end of the 15 day period. In circumstances where either of these deadlines occur at a time t^* after commencement of a search time block, and $t^* \leq \min\,[t,8]$ where t is determined from equation (16), only t^* hours is added to the "concentration searching time" (CST) and this period of search is regarded as unsuccessful.

2.7 Generation of the Krill Swarm Field Within a Concentration - Fishing Selectivity

To save on computer time requirements, the swarm field within a concentration is only set up if that particular concentration is discovered in the searching activities during a specific simulation run. Values of the parameters of the distributions of δ , r and D_c are needed for this process and are generated using equations (11).

The question arises of whether swarm radius and density are correlated, i.e. do larger swarms tend to be more (or less) dense than average? From the Kalinowski and Witek (1983) log-normal fits to ρ and λ, it follows that:

$$\sigma_\rho^2 + (2\sigma_\lambda)^2 = (2.59)^2 \qquad (18)$$

This is very close to the variance of their log normal fit to swarm biomass [$(2.54)^2$], suggesting little covariance between swarm size and density. This provides some justification for the simulation model procedure of generating the r and δ parameters for a particular swarm from independent distributions.

What would be the average catch per swarm taken from a swarm distribution with the parameter values of equation (11), by a typical fishing net of size 20 m by 20 m? The vertical range of most swarms would be completely encompassed by such a net, so that a well directed tow on a circular swarm would yield on average:

$$\begin{aligned} C &= 20 \cdot 2\,\bar{r} \cdot \bar{\delta} \\ &= 20 \cdot 2 \cdot 50 \exp\{(1.1)^2/2\} \cdot 150 \exp\{(1.4)^2/2\}\ \text{g} \qquad (19) \\ &= 1.46 \text{ tonnes} \end{aligned}$$

This cannot be reconciled with data in Shimadzu (1984) that the average number of swarms trawled per haul is 1.5, and in Shimadzu (1985) that the average catch per haul of the Japanese independent trawlers is about 6 tonnes (8 tonnes for the specific commercial data set examined in this study - see Table 1), unless (as indeed might be expected) considerable selection is taking place.

The simulation model program assumes that only those swarms whose biomass exceeded a certain limit (B_{min}) are selected by the fishery. In reality, the Captain does not, of course, make a quantitative estimate of the actual swarm biomass, but rather exercises his judgement based on the indications of swarm size and density evident from his echosounder and sonar. Swarm biomass is a simple and convenient way of combining the measures that will contribute to the Captain's decision into a single quantity. The limit is chosen to provide an average catch per swarm in the vicinity of 8 tonnes (as in Table 1 - see section 3.2), and further incorporates a stochastic component to allow for the fact that there will be imprecision involved in a Captain's estimate of whether a swarm is sufficiently large to warrant its being fished. Thus, the biomass of each swarm generated in the swarm field creation procedure is compared with:

$$B_{min}\, e^{\varepsilon} \text{ tonnes} \qquad \varepsilon \text{ from } N[0,(0.2)^2] \qquad (20)$$

and only those swarms of greater biomass are regarded as "fishable".

The value chosen for the variance in equation (20) is the same as used in modelling the precision with which the Captain estimates the amount of krill caught while the haul is taking place, the basis for which is discussed in section 2.8 [immediately preceding equation (22)].

The limitation of equation (20) means that only a smallish proportion of the total number of krill swarms are fishable (about 7% and about 30% for two modified models eventually considered - see sections 3.2 and 3.3). The simulation model program only needs to retain the parameter values of this subset of all the swarms in the concentration, which saves considerably on storage needs and calculation time.

The positions of the centres of each fishable swarm within the concentration are selected at random (i.e. possible spatial correlation is ignored). This is the only constraint applied; the swarms are not precluded from overlapping each other or the perimeter of the concentration. A particular realisation of this process is shown in Figure 5.

For reasons discussed earlier, the simulation model does not take into account any krill quality aspects - neither "greenness" nor size.

2.8 Searching and Fishing for Swarms Within a Concentration

The initial swarm fished in the concentration discovered is selected at random from all the swarms, irrespective of its position in the concentration. [Note: for terminological convenience, "swarm" is used in this section in the sense of a "fishable swarm", as defined in section 2.7, unless specifically indicated otherwise]. Fishing on this swarm is assumed to commence immediately upon discovery of the concentration, without expenditure of any further search time.

The catch made during a tow is given by:

$$C = \min[40r\delta,\ B_s] \qquad (21)$$

This assumes that swarms are towed along their diameter using a net with 20m x 20m mouth opening, that this net encompasses the complete vertical range of the swarm, and that there is no substantial net avoidance behaviour by the krill. In earlier work the inclusion of an adjustment factor to allow for larger swarms being more easily towed close to their diameter was considered. However, the typical size of those swarms which are ultimately selected as fishable swarms is >> 20m, so that this aspect (whose quantitative parametrisation is problematic anyway) has been disregarded because such large swarms are probably easily targeted. Note that as swarms are assumed to be circular, no allowance "needs" to be made for the Japanese trawlers having to carry out their tows with the wind behind them [Butterworth (1988)].

The simulation model program does also allow for tows being curtailed before the net has passed through the whole swarm. This occurs on occasions because the vessels have limited processing capacity, and the complete catch from a haul has to be processed within a certain period before the krill deteriorates. Because the turnaround time from one haul to the next is roughly two hours, the Captain will aim to make a catch that is about twice the vessel's hourly processing capability. Data on vessels' exact processing capabilities are not available (the information is classified for commercial reasons), but Ichii (pers. commn) advises that for the vessel for which the data sample was provided, the processing capability was in the vicinity of 5 tonnes/hour.

It is therefore assumed in the simulation model that the Captain aims for a catch of a maximum of 10 tonnes, and curtails his fishing time accordingly. The Captain's estimate of the curtailment time will, however, be subject to error, and Captain Fukui (pers. commn) suggested that the catch made could typically differ from that intended by some 20%. Thus, the maximum catch permitted in a haul by the model is:

$$C_{max} = 10\ e^{\varepsilon}\ \text{tonnes} \qquad \varepsilon \text{ from } N\ [0,(0.2)^2] \tag{22}$$

The hauling time that is recorded in the standard data reported for the krill fishery corresponds to the period from the net reaching the desired towing depth to the moment when the net starts to be raised; this will be referred to as the "fishing time" (FISHT). Captain Fukui (pers. commn) advised that the net generally reaches the intended depth about 300 m before entering the krill swarm itself. If b metres is the length of the swarm towed through [calculated from equations (21) and (22)], then as the trawlers tow at 2 knots, the fishing time is calculated as:

$$\text{FISHT} = b/(2 \times 1852) + 0.08 \text{ hours} \tag{23}$$

Allowance must also be made for the time required to lower the net to the desired depth, and later to recover it back on deck with the catch. Rough estimation using a small sample of some very detailed data collected by one particular Japanese trawler during the 1986/87 season (and kindly provided by Dr Shimadzu) suggested:

$$\begin{aligned} t_{lower} &= 0.33\ e^{\varepsilon_1} \quad \text{hours} \qquad \varepsilon_1 \text{ from } N[0,(0.35)^2] \\ t_{raise} &= 0.33\ e^{\varepsilon_2} \quad \text{hours} \qquad \varepsilon_2 \text{ from } N[0,(0.12)^2] \end{aligned} \tag{24}$$

where the lowering time is measured from the moment the swarm is first detected to the instant the net reaches the desired depth (and FISHT begins). Ichii (*in litt.*, 30 May 1988) advises that both these times are correlated with the depth of the haul. The model has therefore, pending further analysis of available data, assumed the extreme of exact correlation [i.e. generate ε_1, then $\varepsilon_2 = 0.12\ \varepsilon_1/0.35$].

The effect of fishing on a swarm is assumed to be only a reduction in that swarm's radius. The position and surface density δ are taken to be unchanged, and the revised radius is calculated to correspond to the original biomass of the swarm less the catch made.

The initial version of the simulation model restricts hauls to towing through a single swarm. For reasons discussed in section 3.2, this restriction has been relaxed in a subsequent modification. In this modification, once a concentration is found, the parameters of the fishable swarms only are stored as before, but if after towing through one of these fishable swarms, the "Captain" estimates that he has yet to obtain the desired total catch of 10 tonnes, he continues the haul. He then fishes on further swarms which he finds in his path until either a maximum towing distance TOW_{max} (taken here to be 4 n miles) is reached, or he estimates that the additional krill taken from these further swarms has resulted in his catch now having reached 10 tonnes.

To effect this in the modified simulation model for cases where towing continues beyond the initial swarm, further swarms (of any size, not only fishable swarms) are generated in the manner described in section 2.7 in a rectangular area. This area is of length TOW_{max} less the distance already towed at the point of exiting the initial swarm, and width 0.5 n miles either side of the vessel's trackline. Only the parameters of those swarms which intersect the trackline, or whose perimeters come to within 17.5 metres of the trackline (corresponding to an assumed sonar detection width), are stored. For the computational convenience of avoiding having to deal with overlapping swarms, the distances between swarms intersecting this "sonar band" around the trackline are increased so that swarms which did intersect in this band consequently only touch at their boundaries; any swarms overlapping the TOW_{max} distance as a result are excluded. The vessel then fishes each swarm in turn along its longest chord within the sonar band (i.e. deviation by the vessel up to 17.5 metres either side of the trackline to effect this is allowed), until TOW_{max} is reached or the estimated catch exceeds 10 tonnes (this may involve ending the haul midway through one of the subsequent swarms). A particular realisation of this process is shown in Figure 6.

Once the net has been raised, searching commences for another swarm on which to tow. [Strictly, this searching starts at some stage during the raising of the net (Ichii, pers. commn), but this factor is ignored in the model for simplicity.] If a good catch rate has been obtained from the swarm just fished, attempts will be made to relocate and refish that swarm. [A further criterion in practice is whether the catch contained the larger sizes of krill, though this is beyond the scope of this model which ignores krill quality aspects.] Ichii (pers. commn), in the light of observations made on a Japanese krill trawler, estimates that such attempts are made after some 40% of the hauls, but that only about half of these are successful in relocating the swarm just fished. In the program, therefore, whenever:

$$C/FISHT > (C/FISHT)_{rpt} \tag{25}$$

the swarm just fished is refished with a probability of 0.5. When refishing occurs, a fixed period of 0.2 hours was added to the "total primary searching time" for swarms (TPST).

The value of $(C/FISHT)_{rpt}$ in constraint (25) is chosen to have the program produce a refishing attempt probability in the vicinity of Ichii's 40% estimate (see section 3.2). The 0.2 hours is slightly less than the average interswarm searching time recorded for a Japanese trawler in the 1986/87 season [see discussion following equation (27)]. More than one sequential retowing of a swarm is possible; the model program repeats the above procedure until constraint (25) is not satisfied, or the swarm is not relocated (as determined by random number generation and the 0.5 relocation probability).

If refishing of a swarm does not occur, search has to be conducted for a new swarm to fish. The computational procedure used is basically identical to that described for concentrations in section 2.6. The random search formula used [analogous to equation (15), with t again in hours] is:

$$p(t) = 1 - \exp\{-4\ (D_c/20)\ (S/S_b)\ t\} \tag{26}$$

where: D_c is the density of swarms per (n mile)^2

S is the selectivity, which is the ratio of the number of fishable swarms [from equation (20)] to the total number of swarms in the concentration

S_b is the selectivity for the base case krill distribution parameters.

Mangel (1988) considers a more detailed model for searching for swarms within a concentration, and reports that it results in distributions of search times that are well fitted by exponential distributions of the form of equation (26).

For the base case, $D_c = 20$ and $S = S_b$ so that:

$$p(t) = 1 - e^{-4t} \tag{27}$$

which corresponds to an average search time of 0.25 hours. The value of 4 was in fact chosen on the basis that a sample from the time-budget data collected on a Japanese trawler during the 1986/87 season, and provided to the author by Dr Shimadzu, indicated a mean interswarm searching time of about 15 minutes. Ichii (*in litt.*, 30 May 1988) advises that he observed interswarm searching times of about 10-15 minutes off Wilkes Land in the 1985/86 season, and that the time to rediscover the same swarm was comparable. Note that this implies less efficiency than the random search formula [equation (13)] indicates, the equivalent parameter values for model modifications to be considered (see sections 3.2 and 3.3) being:

$$\left.\begin{array}{l} w = 1 \text{ n mile (see following paragraph)} \\ v = 10 \text{ knots} \\ d = D_cS = 20 \times (0.07 - 0.30) \text{ (n. mile)}^{-2} \end{array}\right\} wdv = 14 - 60 \text{ hrs}^{-1} \tag{28}$$

However, the value of an appropriate estimate for w is uncertain, and use of the empirical data seems a more secure approach.

The exponent in equation (26) is taken to be proportional to the density of fishable swarms in the concentration (D_cS); note that S will change in those of the scenarios to be considered (section 3.5) where the parameters of the r or δ distributions are altered. An argument could be made that the exponent should also contain a term proportional to the median of the swarm radius (r) distribution. However, comments to the author by Ichii and Captain Fukui (pers. commn, Sept. 1987) indicate that sonar is quite important in finding swarms. Sonar can have an effective search width of up to 2 n miles, which is rather larger than typical swarm radii (even for the fishable swarms only). It is therefore assumed that the effective search width for swarms is invariant, and the effects of changes in r on search times are manifest only through the selectivity term S.

The "primary search time" (PST, measured in hours) to the next swarm is thus determined by use of a random number u from U[0,1] and equation (20):

$$PST = -[ln(1-u)]/[4(D_c/20)(S/S_b)] + 0.01 \tag{29}$$

The additional 0.01 hours is added to avoid unrealistically small divisions occurring for certain CPUE indices. Unlike the situation with concentrations, no search time block approach needs to be applied, because there is no swarm density gradient within any of the simulated concentrations.

A search is then made by the program for all swarms whose centres are within a distance of 10*PST n miles of the swarm previously fished (excluding that last swarm).

[Strictly the centre point of the swarm previously fished is not always used; this occurs particularly in the model modification which allows for a tow through more than one swarm. Provided the tow proceeds further than half way through the initial swarm, the point from which searching commences for a new swarm upon which to set the net allows for the distance moved by the vessel beyond the centre of the initial swarm, including the time needed to raise the net. The tow direction is taken to be random, but the movement is precluded from taking the vessel beyond the concentration boundary.] If there are no swarms within this distance, fishing is assumed to take place on the nearest swarm in the concentration (for simplicity of programming; this happens only very rarely, and is not unfeasible because of the possibility of swarm movement). If one or more swarms are present, the selection procedure to determine which swarm is actually discovered is as for concentrations (see section 2.6); the relative weighting factors for each swarm (j) [analogous to equation (17)] are:

$$w_j = r_j/(s_j + 0.1) \qquad (30)$$

where s_j is the distance in n miles to the jth swarm, 0.1 is an *ad hoc* adjustment to deaccentuate weights accorded to swarms very close by.

However, a further complication can arise with the discovery of this next swarm, as fishing may need to be delayed to allow processing of the previous catch to progress sufficiently. Processing can continue while a new haul is in progress, but to avoid problems with deterioration of the new catch, processing of the previous catch should be complete by the time the new catch arrives on deck.

This creates a non-trivial problem, as it is not clear beforehand how long the next haul will take, though there is the option of leaving the net in the water longer to slow deterioration of the krill while processing of the catch from the previous haul is completed. However, to simplify matters in constructing the simulation, it is assumed that, given the typical interhaul turnaround time of about 2 hours, the Captain allows for a fixed maximum 1.5 hours of processing during the forthcoming tow.

Even so, by the time the next swarm is discovered, the amount of the previous catch left to process may still exceed 7.5 tonnes (corresponding to 1.5 hours processing at 5 tonnes/hour), so that commencement of the next haul has to be delayed. [The processing rate depends on the particular krill product being produced, but this complication is ignored here for simplicity.] The period from discovery of the swarm until the haul can commence is termed "secondary searching time" (SST). In practice, it is spent keeping track of the swarm found, deciding the best strategy for fishing it, and possibly also examining other swarms seen nearby which may be chosen for towing instead. For simplicity, however, the simulation model assumes that the haul is always carried out on the swarm first found.

The initial version of the simulation model assumes that all hauls are made on a single swarm only. Data (see section 3.1 and Table 1) and comments received from vessel Captains [Butterworth (1988)] indicate that this is the predominant pattern in the Japanese krill fishery during the "high season" (January-February). While the placement of the swarms in the concentration does not preclude overlapping, the simulated tows in the initial implementation ignore this possibility, taking krill from only the single swarm "discovered".

Figure 5 shows a particular realisation of a vessel moving within a concentration while both towing and searching (note that the tow lengths shown correspond to the model modification with f = 8 - see section 3.3).

Fishing on a concentration may end for one of three possible reasons in the simulation model: the need to return to offload, the onset of bad weather, or a poor catch rate. A check on elapsed time is maintained throughout the model program, so that the vessel breaks off fishing with enough time remaining to return to the offloading point (steaming in transit at 10 knots) before the end of the 15 day period. If bad weather occurs, the vessel is moved 50 n miles in a random direction, and has to start searching again for a concentration when the bad weather ends.

Ichii (pers. commn) advises that the catch rate (per overall time) is regarded as too poor if it falls below about half the vessel's processing rate capability. This is usually assessed on a daily basis, as not all fishing occurs at times and places where there is 24 hour daylight (as assumed in the simulation model), and there is a diurnal pattern in krill availability. In the simulation, a continuous check is kept of the ratio of total catch per time elapsed for the previous 10 hauls (close to a 24 hour period for normal operations); fishing on the concentration is ended if this ratio falls below CR_{min}. The value of CR_{min} has been tuned to obtain improved agreement between the simulation model output and the commercial vessel data sample provided (see section 3.2), with this exercise commencing with CR_{min} = 2.5 tonnes/hour (i.e. half the 5 tonnes/hour processing rate assumed).

It is possible that future searching (for concentrations) may return the vessel to a concentration that has been fished earlier during that same half-month (the only exclusion by the simulation model is immediate return to a concentration just left because of poor catch rate). In such a case, that concentration's biomass has been reduced by the previous fishing activity. The swarm distribution within that concentration is then set up anew, as swarms would have intermingled during the intervening period, by repeating the process described in section 2.7. However, to adjust for the catch already taken, all swarm radii are reduced by the square root of the proportion of the original biomass of the concentration still remaining. In practice though, for the chosen parameter values, this adjustment is negligible.

2.9 Moving the Vessel

At certain times during the simulation, it is necessary to adjust the vessel's position in a random direction - this arises either because of a bad weather period, or during the general search for concentrations.

In these cases, the distance to be moved is specified as described in sections 2.4 and 2.6. The compass direction of the movement is chosen using a random number generator. Only one constraint is imposed: the movement may not take the vessel outside the 600 n mile square sector. If a compass direction is selected which has this result, it is disregarded and a further selection is made until the direction obtained will keep the vessel within the sector.

3. RESULTS AND DISCUSSION

3.1 Fishing Operation Statistics Extracted from the Commercial Data Sample

A sample of the data collected routinely during the Japanese krill fishing operations was kindly supplied to the author by Dr Shimadzu. The basis for the vessel and the period chosen is described in detail in Butterworth (1988). Briefly, the vessel is a fairly typical independent trawler, and the data pertains to operations off Wilkes Land in the 1980/81 and 1981/82 seasons.

Summary parameters of these fishing operations extracted from the data are shown in Table 1. The object of the extraction is to provide values to compare with the simulation model output, as a test of the realism of the model developed. As the intention has been to model a "high season" operation, the Table shows data extracts for the months of January and February only.

An explanation for the basis of the entries in Table 1 is necessary. Some of the statistics constitute a single value: thus, the ratio of the total catch during the month (TC) divided by the total time spent "fishing" (note the definition in section 2.8) (T/FISHT), provides one number for each month. However, the ratio catch-per-fishing-time (C/FISHT) can also be evaluated for each haul, and provides a large set of numbers for a particular month; in such cases, Table 1 shows the mean and standard deviation for this set.

An average column has been presented for ease of comparison of these statistics to the simulation model output, and gives the mean of the four monthly values shown. Where only a single statistic was provided each month, the standard deviation shown is that of the four values concerned. However, in cases where a mean and standard deviation are given for each month, the "standard deviation" figure shown with the average was calculated by taking the average of the four monthly coefficient of variation values, and then multiplying this by the average of the four monthly means. (This procedure may give a better impression of the degree of variation than some other averaging methods which are more influenced by mean-variance correlations.)

The distances between successive hauls (DBH) were calculated from the latitude and longitude given for the position of each haul. The shorter of such estimated distances may be rather imprecise, as position is only recorded to the nearest minute of latitude and longitude. The values may also be inflated compared to the actual situation in the concentration, as no allowance can be made for both the swarm and the fishing vessel moving with the current (insofar as the two may be similarly influenced thereby).

A movement from one concentration to another was inferred when both the time between successive hauls (TBH) and DBH showed much larger values than normal. "Bad weather" was assumed when only the TBH (and not the DBH) value was much greater than usual (this could, of course, reflect other aspects such as repairs to machinery). It is difficult to distinguish transiting to offload from inter-concentration movement by inspection of the data; only one clear case of transiting was evident, and added to the bad weather time.

Overall, this exercise involved some guesswork and the results from it should be regarded with caution, particularly in relation to the "independent searching for concentrations" process assumed in the simulation model (section 2.6). There were 7 instances during the 4 months examined of movement (generally in an east-west direction) of over 200 n miles; these hardly seem likely to reflect true searching, but rather probably correspond to movement on the basis of external information received of good fishing in another area. Sometimes a few (typically < 5) hauls were made at an intermediate position between two areas which were both intensively fished. Presumably these constitute some trial tows made in transit, where the locality was left almost immediately because of poor krill quality or catch rate. Also, there were occasions where the vessel clearly moved to another concentration nearby, but returned to the concentration previously fished after only a few tows. In Table 1, the figure shown for number of concentrations fished reflects inclusion of the former but not the latter of these last two instances in the total count; the minimum excludes, while the maximum includes both.

The overall average of 8 concentrations fished per month seems high when compared to a statement by Ichii to the author that typically only 2-3 concentrations would be fished during such a period. Ichii (*in litt.,* 30 May 1988) has also investigated five Japanese mothership type operations over the high season, and found that typically 1-3 concentrations were fished per month on these occasions. It is also clear from the data that, if "bad weather" periods have been correctly interpreted, they do not necessarily result in the vessel losing contact with the concentration as is assumed in the simulation model structure (though note also the comments made in section 2.4 about this feature of the simulation model mimicking the effect of temporal changes in krill distribution parameters).

The position of the ice-edge during these operations was not known, so that distances therefrom could not be calculated. The values shown for the north-south fishing extent are probably a positively biased measure of the range of vessel distance from the ice, as the latitude values from which they were deduced showed a southerly trend with time, presumably related to the ice-edge's summer retreat.

The overall time budget deduced from these data is:

TCST : 23%
TFISHT : 32%
BW + TRANS : 13%
TPST + TSST + (TTOWT - TFISHT) : 32% (by subtraction)

where

CST	is the time searching for a concentration (the prefix "T" indicates total, i.e. summation over the period of interest)
FISHT	is fishing time (with the net at the desired depth)
BW	is time lost to bad weather
TRANS	is transit time
PST	is primary search time for a swarm within a concentration
SST	is secondary search time (time needed to complete processing). [Note that (TPST + TSST) measures total search time within concentrations; the two constituents cannot be distinguished from the data available.]
TOWT	is the total period the net is in the water (including FISHT) during a haul
(TOWT-FISHT)	is thus the net lowering and raising time.

The above may be compared to the detailed records kept by another Captain and listed in Butterworth (1988), which in this terminology correspond to:

TCST + TPST + TSST = TAST : 45%
TFISHT : 18%
TTOWT - TFISHT : 24%
BW + TRANS : 13%

where TAST is the total of all searching time, both for concentrations and for primary and secondary searching for swarms within concentrations.

A further comparison may be made to the time budget data collected during the 1986/87 season throughout the Japanese fleet. Dr Shimadzu has advised the author that this corresponds approximately to:

TCST + TPST + TSST = TAST : 25%
TTOWT : 50%
BW + TRANS : 25%

Certainly these schedules indicate considerable variation, though in a very general sense it is probably true to say that the fractions of time devoted to searching (TCST + TPST + TSST= TAST) and to fishing plus net handling (TTOWT) are roughly the same.

3.2 Tuning the Model Parameters Using the Commercial Data Statistics
- the FISHT Problem

Table 2 lists the parameters of the fishing operation model. A number of these have already been fixed, as discussed in Chapter 2. A few remain for adjustment (or "tuning") to have the simulation model output show better agreement with the commercial data sample (Table 1) and other information available on the Japanese krill fishery, as set out in the first column of Table 3 (though now amended where relevant to reflect the half-month period pertinent to the simulation model). These few, which include one (N_c) which is strictly a distribution model rather than a fishing operation model parameter, are:

$(C/FISHT)_{rpt}$: the minimum catch rate to attempt to refish a swarm

B_{min} : the minimum estimated biomass for a swarm to be selected for fishing

CR_{min} : the minimum catch rate per total elapsed time for the vessel not to stop fishing and search for another concentration

N_c : the number of concentrations in the sector.

The statistics in the first column of Table 3 are not all independent; for example, parameter values that give a reasonable fit to the figures for mean catch per haul ($\overline{C/H}$) and mean fishing time per haul ($\overline{FISHT}$) are also going to fit the catch rate expressed as TC/TFISHT. While the effects of changing the values of the parameters available for tuning are not totally independent, for practical purposes the tuning amounts to adjusting:

$(C/FISHT)_{rpt}$	to fit the fraction of attempted repeated hauls
B_{min}	to fit mean catch per haul (C/H)
N_c and CR_{min}	to fit total concentration searching time (TCST) and the number of concentrations fished (TNC).

The first column under the heading "Simulation Model Output" in Table 3 corresponds to a fit of the fishing/distribution model as presented in Chapter 2. As pointed out in section 2.6, a non-zero value of B_{min} (i.e. some selectivity) is essential to raise the $\overline{C/H}$ value to the 6-10 tonnes range compatible with the data sample used here and statistics quoted in Shimadzu (1985).

Immediately, one major discrepancy between the simulation model output and the actual data stands out. This is the five-fold difference between the average fishing time per haul ($\overline{\text{FISHT}}$) for the data sample of 1.23 hours, compared to 0.23 hours in the simulation output. [Note also from equation (23) that 0.08 of those 0.23 hours is made up by a fixed contribution comprising the time between the net reaching the desired depth and its entering the swarm.]

This reflects the problem of reconciling the typical length of Japanese trawlers' tows (~ 2 n miles at 2 knots) with typical dimensions of krill swarms reported from scientific surveys (~ 100 metres), together with the fact that the Japanese report most of their tows to be through a single swarm. Introducing the selectivity criterion of equation (20) does reduce this discrepancy to a limited extent by extending the average length of swarm towed per haul to some 550 metres, but by no means removes it. Increasing B_{min} would not solve this problem because even though a smaller fraction still of the swarms with a yet larger average radius would then be selected, the desired catch limit of 10 tonnes per haul would mean suspension of tows before the complete extent of the larger swarms had been traversed, so that FISHT would not increase markedly.

Obviously a fundamental inconsistency exists somewhere in the distribution-operation model which was developed in Chapter 2 with the intention of its being representative of the krill fishery, and this casts some doubt on using any results emanating from that model as a basis to judge the potential utility of alternative abundance indices as measures of krill biomass. In the following section, some possible resolutions of the inconsistency are discussed, and two different model modifications are introduced to achieve reasonable agreement between the simulation model output and the commercial data.

[Strictly, it is not entirely correct to describe the first column under simulation model output in Table 3 as corresponding to a fit of the model precisely as it has been presented in Chapter 2. First, because the mean tow time ($\overline{\text{TOWT}}$ - which includes time for lowering and raising the net) is 0.91 hours, it would be unrealistic for the model to have the "Captain" allow for 1.5 hours of processing during the forthcoming tow (see section 2.8). Thus this period was shortened to 0.75 hours. Secondly, because it is the model modifications developed in the next section that are ultimately used for investigating the response of abundance indices to krill biomass decline, it is actually these modified versions which were tuned. For ease of comparison purposes, the B_{min} and N_c values adopted above for the original (Chapter 2) model are as for the elongated ($f = 8$ - see next section) modification; only $(C/\text{FISHT})_{rpt}$ and CR_{min} were further adjusted.]

3.3 Two Model Modifications

There are a number of possible explanations for the inconsistency revealed in the previous section:

(i) The commercial data (see Table 1) do not reflect a single swarm only towed for <u>every</u> haul. It could be, therefore, that tows in the fishery through more than one swarm are much longer than those through a single swarm. Further inspection of the data, however, does not support this hypothesis. Table 1 shows that the differences in such average FISHT values are small and of variable sign; none of the four cases examined corresponds to a difference that is statistically significant at the 5% level.

(ii) The swarms observed during FIBEX (the results from which contributed substantially to the distribution parameter values chosen for the model developed here) are not typical of those upon which the fishery operates. Ichii (*in litt.*, 30 May 1980) comments that the latter "are much bigger", and are also presumably less dense. It should be borne in mind as well that quoting single summary statistics for the FIBEX data can be misleading. For example, Table XI of BIOMASS (1986) shows that different vessels in the FIBEX exercise recorded very different values for mean intersected swarm length λ . The smallish mean $\lambda = 73$ m quoted in section 2.2 is a reflection of the total FIBEX sample being dominated in number terms by the typically small swarms recorded in the surveys by the *S.A. Agulhas*, *Professor Siedlecki* and *Walther Herwig*. In contrast, the surveys by the *Dr Eduardo L. Holmberg* and *Itzumi* reported mean λ values ~ 500 m, which correspond to much larger swarms [though I Hampton (pers. commn) considers that this might rather reflect differing criteria used to distinguish swarms from layers].

(iii) The definition of a "swarm" used by the fishermen in recording commercial data differs substantially from that used in scientific publications [such as BIOMASS (1986)], and typically rather more than one "scientific" swarm is towed in a haul. Ichii (*in litt.*, 30 May 1988) comments that he often observed fishermen record a haul as fishing a single swarm only even though several swarms were towed, and suggests that their data are less reliable in this respect because their interest centres on the catch-per-haul rather than the number of swarms towed. Ichii has also shown the author an echo chart of a krill aggregation fished by a commercial vessel and recorded thereby as a single swarm, which could readily be interpreted as up to six separate swarms. Failure to discriminate "scientific" swarms may also reflect spatial correlation effects (absent from the model of Chapter 2), with individual swarms clustered together being regarded as one swarm only.

(iv) Non-circularity of swarms. Although an exercise in section 2.2 showed that the krill distribution parameters used were consistent with a circumpolar krill biomass of about one hundred million tonnes, the results from FIBEX [BIOMASS (1986)] give a much lower value. This is "surprising", since those same FIBEX results were used to choose a number of the krill distribution parameter values used for this model. A possible reason for this discrepancy is that swarms are distinctly non-circular, contrary to the assumptions of the model in Chapter 2.

(v) Net avoidance. If the effective net width is less than the 20 m assumed, hauls would need to be longer to achieve the same catch. However, this effect would need to be very large to rectify the inconsistency found in the previous section.

Unfortunately little information is available, or has yet been analysed, that would allow either a choice between the hypotheses above, or their independent quantification to allow, say, fixed revised krill distribution parameter values to be set. Instead two somewhat *ad hoc* model modifications have been introduced drawing on the suggested explanations in (ii) - (iv) above.

(a) Elongated swarms

This modification combines the ideas of (ii) and (iv). The restriction to one swarm per haul is maintained. However, the (fishable) swarms are artificially elongated in the direction in which they are towed by a "fudge factor", f:

$$\begin{array}{lll} r \text{ (perpendicular to tow direction)} & \rightarrow & r \\ r \text{ (along tow direction)} & \rightarrow & r f \\ \delta & \rightarrow & \delta / f \end{array} \qquad (31)$$

This form of transformation means that B_{min} can be kept fixed in a tuning exercise [having being used be fix a realistic average catch per haul ($\overline{C/H}$) simulation model output figure], while f provides the extra degree of freedom needed to increase the average time required to make such a catch ($\overline{FISHT}$) in the simulation model. In practice a value of $f = 8$ was found to be appropriate (see Table 3). It could be argued that introduction of this factor necessitates adaptions to other elements of the model; for example, the derivation of equation (26) for the swarm search operation might be modified, but since the factor of 4 in that equation was empirically motivated, the net result might not reflect any eventual change to equation (26).

(b) More than one swarm towed per haul

The rationale for this modification is provided by (iii) above. As described in section 2.8, tows do not necessarily end after traversing the swarm (here assumed again to be circular) initially selected for fishing; instead they continue up to a maximum total distance (TOW_{max}) chosen here to be 4 n miles. Other swarms (any swarms, not only "fishable" ones) intersecting a 17.5 m "sonar band" either side of the trackline are also then fished in that haul. A feature of note in tuning the fishing operation parameters for this modification is that it proves necessary to reduce B_{min} to 5 tonnes [one tenth of its value for (a)] to secure a realistic simulation model output value for the catch rate TC/TFISHT, which is otherwise much too large. Given more than one swarm per haul, an average catch per haul ($\overline{C/H}$) of 6-10 tonnes is much less difficult to achieve, and swarm selectivity increases from 8% in (a) to 29% here. It seems unrealistic to assume that the simulated vessels would "forego" a potentially much higher catch rate by being prepared to start towing on smaller swarms, but in terms of the simulation model this may be a means of compensating for the limitations of the model's two-dimensional nature - not all swarms intersecting the "sonar band" around the trackline may be fished readily because of depth variation. The modified simulation model suggests an average of about 5 swarms fished per haul (see Table 3).

The fishing operation parameter values eventually chosen and listed in the second and third columns of Table 2 reflect only a partial tuning of the model output to the commercial statistics available. Tuning is carried out using the average of the output for a number of simulation runs; as many as 100 runs have been used in this analysis, but this nevertheless gives rise to not insubstantial standard errors for the estimated means, which range up to 7%. This precision could be improved by using a larger number of runs, but this would be unrealistic in computer time terms. Typically 100 half-month runs of the one-swarm-per-haul model require 20 minutes on a mainframe computer (a Sperry UNIVAC 1108 was used), or some 20 times that period on a microcomputer. The more-than-one-swarm-per-haul modification requires about 40 minutes on the mainframe for 100 runs. The aspect of the simulation model that consumes most of the computer time is the generation of the swarm field within a concentration; when tows are continued beyond the initial swarm, the additional swarm field generation procedure then needed adds further to the computer time requirements. Because of this, the computer time requirements for a set of runs depend critically on the average number of concentrations fished per half-month. Thus, although still better agreement could be achieved between model output and commercial statistics than is reflected in Table 3 by further tuning of parameters, this was not considered warranted because of the additional computer time requirements and because, given the simplified model being used (ignoring krill quality considerations, for example), the levels of differences reflected in the comparisons in Table 3 were not considered a serious impediment to use of the model to draw conclusions about the potential utility of alternative abundance indices as measures of krill biomass.

The more-than-one-swarm-per-haul model modification developed in section 2.8 restricts vessel deviation to the "sonar band" 17.5 m either side of its trackline when towing swarms encountered after the initial swarm, so that these swarms are towed offcentre. The results of a complete relaxation of this condition, whereby deviation is unrestricted so that all such subsequent swarms are also towed along their diameters, are shown in the final column of Table 3. The principal features of these results are increases in the total catch (TC) and catch rate (TC/TFISHT) to values yet further above the commercial data statistics. While better agreement could be restored by reducing B_{min} and increasing CR_{min}, it was considered more realistic to retain the feature of offcentre towing of the subsequent swarms for further analysis.

The major remaining discrepancy between the commercial data sample and the output from the two modifications of the simulation model is the average number of concentrations fished per half-month (TNC): 4 and about 2 respectively (see Table 3). Higher TNC values could be achieved in the simulation model outputs by increasing the number of concentrations in the sector (N_c), or improving the concentration searching efficiency of the vessels. The latter could be rationalised as a reflection of "external" information received from other vessels or based on experience of persistent concentrations in certain areas in previous seasons. [This may be the reason for the longer inter-concentration distances indicated by the commercial statistics compared to the model outputs (see Table 3).] However, the identification of the number of concentrations fished from the commercial data sample was problematic (see section 3.1). Further, the values provided by Ichii (section 3.1) of TNC ~ 1-2 compare well with the simulation model outputs. Accordingly, possible further adjustments to the models in this respect were not pursued.

Some other aspects of the comparisons of Table 3 merit mention. The simulation model outputs show greater variability in the total catch (TC) and number of hauls (TH) than do the commercial data statistics. This is a reflection of the greater variability of the number of concentrations fished (TNC) for the former. On the other hand the catch rate TC/TFISHT is more variable in reality than for the model - perhaps a reflection of temporal variability in the krill distribution parameters in the real world. The total times spent searching (TAST) and fishing plus net handling (TTOWT) are very similar as seems appropriate for a fit to commercial data (see final paragraph of section 3.1). The mean of the simulated distances between successive hauls of about 2.6 n miles is slightly less than the 3 n miles indicated by the commercial data, but this may reflect the effect of currents as alluded to in section 3.1.

3.4 Potential Indices of Abundance

The simulation model output provides values for a number of indices (mainly of the CPUE type) which may reflect a change in the sector biomass. These fall under a number of headings, and are listed below together with the direction of response to decreases in the values of some (or all) of the krill distribution parameters which might be expected *a priori*. (Recall that the prefix "T" used in the following implies summation over the half-month period under consideration.)

(A) Total measures related to catching:

(1) TC^{+++}: Total catch: decrease for N_c, L_c, D_c, r or δ decrease.

(2) TH^{+++}: Total number of hauls: decrease in response either to more time being required for searching, or to longer FISHT being needed on a haul to obtain the desired catch, i.e. for N_c, L_c, D_c, r or δ decrease.

(B) Total time related measures:

(Here only the anticipated direction of primary response is indicated; since the total time in the half-month is fixed, the resultant negative correlations will cause secondary responses to other measures in the reverse direction.)

(1) TFISHT^{+++}: Total time spent fishing swarms: increase for δ decrease.

(2) TPST: Total primary searching time for swarms within concentrations: increase for D_c decrease [note: not for r in a primary sense, insofar as the motivation for equation (26) is justified, though there would be secondary effects through the selectivity S of an increase for an r or δ decrease].

(3) $\mathrm{TPST} + \mathrm{TSST}^{+}$: Total primary and secondary searching time (the latter for processing needs, in terms of the model) within concentrations: increase for D_c decrease.

(4) TCST^{+}: Total searching time for concentrations: increase for N_c or L_c decrease.

(5) TAST^{++}: Total of all searching time (= TPST + TSST + TCST): increase for N_c, D_c, and L_c decrease: unclear for r as FISHT would also be affected.

(C) Catch per time CPUE measures:

(1) $\mathrm{TC/TFISHT}^{+++}$: Total catch for all hauls divided by total fishing time for all hauls: decrease for δ decrease.

(2) $\overline{\mathrm{C/FISHT}}^{+++}$: Catch per fishing time for each haul, averaged over the half-month: decrease for δ decrease.

(3) TC/TPST: Total catch for all hauls divided by total primary searching time for all hauls: decrease for D_c decrease.

(4) $\overline{\mathrm{C/PST}}$: Catch per primary searching time for each haul, averaged over the half-month: decrease for D_c decrease.

(5) $\mathrm{TC/(TPST{+}TSST)}^{+}$: Total catch divided by sum of total primary and secondary searching time within concentrations: decrease for D_c decrease.

(6) $TC/TCST^{+}$: Total catch divided by total searching time for concentrations: decrease for N_c or L_c decrease.

(D) Combination catch-time indices:

Note that each index in (C) is anticipated to respond to changes in only one or two of the five krill distribution parameters, a decrease in any one of which could reflect a biomass decline. The motivation for combination indices is to have a measure that will respond to changes in a greater number of these parameters.

(1) $TC/TFISHT/\overline{PST}$: Catch per fishing time, divided by the average primary searching time for each swarm fished: decrease for D_c, r or δ decrease.

(2) $TC/TFISHT/(\overline{PST+SST})^{+}$: Catch per fishing time, divided by average primary plus secondary searching time for each swarm fished: decrease for D_c, r or δ decrease.

(3) $TC/TFISHT/\overline{PST}/\overline{CST}$: D.1 divided by the mean concentration searching time (i.e. total concentration searching time TCST divided by number of concentrations found and fished TNC): decrease for N_c, L_c, D_c, r or δ decrease.

(4) $TC/TFISHT/(\overline{PST+SST})/(\overline{CST})^{+}$: D.2 divided by the mean concentration searching time: decrease for N_c, L_c, D_c, r or δ decrease.

(5) $TC/TFISHT/TAST^{++}$: Catch per fishing time, divided by the total of search times of all types (TAST = total of all search time = TPST + TSST + TCST): decrease for N_c, L_c, D_c, r or δ decrease.

(E) Indices related to the number of concentrations fished:

(1) TNC^{+}: Total number of concentrations fished: increase for D_c, r or δ decrease, but decrease for N_c or L_c decrease.

(2) TH/TNC^{+}: Number of hauls per concentration: decrease for D_c, r or δ decrease.

(F) Per haul measures:

(1) $\overline{C/H}^{+++}$: Average catch per haul: decrease for r or δ decrease, but this could be offset by saturation effects arising from curtailment of hauls due to processing rate limitations.

(2) $\overline{FISHT}^{+++}$: Average fishing time per haul: increase for r or δ decrease.

(3) $\overline{\text{TOWT}}^{++}$: Average fishing plus net raising and lowering time per haul: increase for r or δ decrease.

(4) $\overline{\text{TBH}}^{++}$: Average inter-haul time: increase for D_c, r or δ decrease.

For each index above, an indication has been made regarding the possibility of collecting such data in practice as follows:

+ + + : Data are already collected.

+ + : Data could be collected (and have been for some experimental periods), but such collection is onerous.

+ : Data could be collected, but there would be difficulties of definition, and considerable difficulties with collection.

Blank : Extreme difficulties of definition and collection.

These indications are based on impressions gathered by the author during discussions in Japan with krill fishery scientists and vessel Captains and Commanders [see Butterworth (1988)]. Generally the problems centre on the practicalities of collecting searching time information. Total searching time (TAST) can be obtained essentially by subtraction of the total time spent on other activities, which is more readily recorded. Separating out concentration searching from swarm searching time would run into a field definition problem. Distinguishing primary and secondary searching time while operating within a concentration would be almost impossible in practice. This is the reason why a number of indices listed above combine primary and secondary searching time (TPST + TSST); use of primary searching time alone is preferable in principle, but including secondary searching time may be a practical necessity. In general, there is a trade-off between collection practicality, and the anticipated magnitude of the reaction of the index to overall biomass changes, which one would expect to be damped by the inclusion of extraneous contributions (such as secondary searching time). (Note: TBH data are already collected, but would need censoring for bad weather, inter-concentration movement, and so forth - hence the ++ designation.)

3.5 Biomass Reduction Scenarios Examined

In the first instance, six variations of the base case distribution model parameter values, and the resultant influence on various potential abundance indices, have been considered. Each of these scenarios corresponds to a reduction of 50% in the total biomass of krill in the 600 n mile square sector. The variations are:

(i) Number of concentrations drops by 50% (by the same proportion in each stratum):

$$N_c = 36 \rightarrow 18$$

(ii) Number of concentrations drops by 50% with a "Pelagic Shift" (P.S.) (number of concentrations in the southernmost two strata unaltered; no concentrations in three northernmost strata:

$$N_c = 36 \rightarrow 18$$

(iii) Concentration radius drops by 30% (i.e. to $1/\sqrt{2}$ of original value):

$$L_c = U[5.6,11.3] \rightarrow U[4.0,8.0] \text{ n miles}$$

(iv) Density of swarms per unit area in a concentration drops by 50%:

$$D_c = 20e^{\varepsilon} \rightarrow 10e^{\varepsilon} \qquad \varepsilon \text{ still from } N[0,(0.1)^2]$$

(v) Swarm radius drops by 30% (i.e. to $1/\sqrt{2}$ of original value):

$$r = 50e^{\varepsilon} \rightarrow 35.4e^{\varepsilon} \qquad \varepsilon \text{ still from } N[0,(1.1)^2]$$

(vi) Surface density of krill within a swarm drops by 50%:

$$\delta = 150e^{\varepsilon} \rightarrow 75e^{\varepsilon} \qquad \varepsilon \text{ still from } N[0,(1.4)^2].$$

The "Pelagic Shift" change envisaged in scenario (ii) is by analogy with pelagic fish populations, whose response to biomass reduction is to decrease their geographical extent while local density in the most favoured habitat (where catch rates would be best) may scarcely be affected [e.g. the northern anchovy off California, MacCall (1983)].

In each of the scenarios, all parameters except the one indicated are unchanged from their base case values. The selection criterion for a fishable swarm [B_{min}: equation (20)], the condition for attempting to refish a swarm [$(C/FISHT)_{rpt}$: constraint (25)], the criterion for leaving a concentration because of poor catch rate (per total time elapsed) [< CR_{min} tonnes per hour averaged over the last ten hauls], and (where appropriate) the swarm elongation "fudge factor" [f: equation (31)] remain unchanged from the pertinent values listed in Table 2.

Comparisons of the output from the base case model and these six alternative scenarios corresponding to different ways in which the overall krill biomass could fall by 50%, are given for the two model modifications under consideration in Tables 4, 6, and 7. Table 5 is a rerepresentation of the information in Table 4.

Table 4 compares the performance of the 24 candidate abundance indices suggested in section 3.4. It is important to be clear as to the meaning of the standard errors given in this Table. For each scenario, the simulation model was run 100 times. Thus, in the base case instance for example, 100 values of half-month catch (TC) were generated. These 100 values have a mean and a standard deviation. This mean will, however, differ from the expected value [i.e. the average which would be obtained if model runs were repeated a very large (infinite) number of times], because the mean of the 100 values will be subject to sampling variation. The size of this variation must be known so that true differences from scenario to scenario are not confused with sampling variability. A measure of this variation is the standard error of the mean (1/10 of the standard deviation of the 100 values that contribute to the mean TC in this case). It is this standard error of the mean which is shown with the mean values of the base case indices.

Such standard errors of the mean can be used to estimate the precision of the estimated change in mean value of an index from one scenario to another. This precision has been expressed as the standard error of the percentage change in an index from the base case to an alternative scenario, which is calculated by:

$$\text{s.e.} = 100\ a/b\sqrt{[\text{s.e.m.}(a)/a]^2 + [\text{s.e.m.}(b)/b]^2}\ \% \qquad (32)$$

where b is the mean value of the index for the base case over 100 simulation runs, and s.e.m.(b) is the associated standard error of the mean

a is similarly the mean, and s.e.m. (a) the standard error of the mean, for the same index for the alternative scenario.

[Note: Strictly, equation (32) is an approximation which could be corrected for bias, but this adjustment is likely to be small for most of the indices considered. Later, the assumption of normality is made in relating ± 1.96 of these standard errors to a 95% confidence interval. Again, this is approximate because the distributions of the indices (and also their ratios) are skew. However, making detailed corrections for these effects does not seem critical for what is only an initial investigation of this problem at this stage.]

These precision levels could be improved by increasing the number of simulation runs from 100 used, though that would be expensive in terms of computer time as discussed in section 3.3. Table 4 shows that for most indices, value changes between scenarios have been determined up to a standard error of 10% or better, which seems adequate for this analysis for which interest centres on biomass changes as large as 50%. All the exceptions involve concentration searching time (CST), with associated standard errors up to 28%. The reason is that far fewer concentrations (~ 200) are fished than hauls (~ 10 000) are made over 100 simulations, so that the precision with which concentration-linked indices can be assessed is necessarily relatively poorer.

Some runs of the simulation model result in no concentrations at all being discovered in the half-month period, and so no catch being made. This is a very infrequent occurrence for the base case, but can occur up to 20% of the time for scenario I) above where the number of concentrations (N_c) is decreased by 50%. Such instances remain included in the statistics quoted in Table 4 for summation-type indices A.1-2, B.1-5 and E.1, and also for the ratio index TC/TCST (C.6); however, since they provide no pertinent data, they are excluded from other ratio indices such as C.1-5 and D.1-5.

Table 5 summarises the information in Table 4 in a less quantitative manner (which is described in detail in the Table caption) to provide a clearer overall comparative perspective. Note that "significant" is used in Table 5 in its statistical sense, and does not necessarily imply "substantial", In fact some differences, although detected to be statistically significant at the 5% level, are no more than 2% in magnitude.

If krill biomass was to drop, it is more likely that this would be manifest by some combination of changes in the various krill distribution parameters, rather than a change in one only as examined thus far. However, there is no basis at present to determine whether some parameters would be more likely to change than others. Thus a further scenario is examined where a random combination of changes in N_c, L_c, D_c, r and δ is chosen to effect a fixed net reduction in the overall krill biomass in the sector [a possible change in the relative distribution of concentrations with habitat - such as the Pelagic Shift of (ii) above - is ignored here for simplicity]. Accordingly, a reduction factor α (the krill sector biomass as a fraction of the base case level) is chosen, and simulations are run for 100 different combinations of changes in N_c, L_c, D_c, r and δ that effect this same reduction. The proportion of change attributed to each parameter is specified by choosing four numbers from U[0,1] and then ordering them, with the resultant five intervals on [0,1] providing the proportions (except that these proportions are adjusted to allow for rounding the changed value of N_c to the nearest integer).

Table 8 shows the results of simulation model outputs for such scenarios. The values of potential abundance indices are expressed as fractions of their estimated base case levels. (The inverse of such fractions has been taken wherever this was necessary to have the statistics listed show a generally increasing trend with α). The results are given for $\alpha = 0.1(0.1)0.9$, i.e. for biomass reductions down to 10% of the base case level. The standard errors shown for the estimated relative levels of the abundance indices reflect both the sampling error pertinent to 100 runs of the simulation model for fixed parameters, and also the variation associated with the random allocation of the biomass reduction amongst the five krill distribution parameters.

Figure 7 plots the results of Table 8 for a selected subset of the potential abundance indices examined. In these plots, mean abundance index estimates have been normalised to the estimates of their respective mean base case levels. The error bars shown are estimates of the central 68% interval of the index distributions (i.e. distributions of the indices for vessel-half-months); the ranges of ± one standard error of the mean will be about one-tenth of the sizes of these intervals. Note that while the error bars for the base case ($\alpha = 1$) estimate reflect sampling error only, the error bars for other values of *a* also incorporate variation arising from the differing contributions of changes in the various krill distribution model parameters to the overall krill biomass reduction, and so are typically larger.

Curves of the form:

$$\text{index} = a + (1-a)\alpha^b \tag{33}$$

have been fitted to the normalised mean abundance index estimates. Such curves are constrained to pass through the point (1,1), so that only the estimates for $\alpha = 0.1$ to $\alpha = 0.9$ were used in the fitting process. The curve parameters a and b were estimated using weighted least squares and a non-linear optimisation program, where the weights were chosen to be the squared inverses of the standard errors of the mean of the mean abundance index estimates.

Note that equation (33) provides a convex or concave curve depending on whether the parameter b is less than or greater than 1 respectively. As $\alpha \to 0$, all the indices must also $\to 0$. However, fits of equation (33) were not constrained in this way (i.e. the fits did not force $a = 0$) so as to achieve a better representation of the relationship over the α range of [0.1, 1.0]. The equations shown on Figure 7 cannot be extrapolated reliably beyond this range, particularly for $\alpha < 0.1$.

Figure 9 shows similar plots to Figure 7, but for the case where α (the relative level to which the biomass is reduced) is occasioned by a decrease in within-swarm krill surface density δ only. The index vs α equations shown for those fits have been determined in exactly the same manner as described above.

3.6 The Performance of Alternative Abundance Indices in Detecting Biomass Decline

In view of the somewhat *ad hoc* nature of the model modifications introduced in section 3.3 to reconcile the simulation model outputs with the commercial data, the question must immediately arise: how much reliance can be placed on conclusions that are drawn from the outputs of these modified models, particularly as regards the utility of alternative abundance indices as measures of krill biomass? Even given reservations about these modifications, the model nonetheless still hopefully incorporates the major factors that need to be taken into account in a Japanese krill fishing vessel's strategy. Thus, the effects of changing the krill distribution parameters on various candidate abundance indices, together with these indices' likely variability, may still be reasonably reflected in a qualitative and relative sense, although quantitative results such as the assessed magnitudes of non-linearities in index-biomass relationships should be regarded as much less reliable.

Tables 4 and 5 show essentially only two counter-intuitive sets of results in relation to the directions of change of indices under various biomass reduction scenarios, which were hypothesised *a priori* in section 3.4. The first set all relate to FISHT when the swarm radius r is reduced; contrary to expectation TC/TFISHT, $\overline{C/FISHT}$ and $\overline{C/H}$ increase, while FISHT and $\overline{TOWT}$ decrease. The reason, presumably, is the inter-relation with the selectivity criterion of equation (20), which means that fishing remains restricted to the larger swarms. This anomaly occurs only for the one swarm-per-haul situation; the direction of change is as expected when more than one swarm can be towed.

The second set of counter-intuitive results relate to situations where a decrease in the number of concentrations (N_C) is accompanied by a "Pelagic Shift". It might have been anticipated that the increase in TCST, and decreases in TC, TH, TC/TCST and indices involving $\overline{(CST)^{-1}}$, would be less marked than when all strata are similarly affected by the N_c decrease, as is evident for the one swarm-per-haul case. However, when more than one swarm may be towed, the directions of change are the reverse of those expected, with catch rates per concentration searching time (CST) increasing despite the N_c decrease. This is presumably an artefact of the concentration searching procedure (section 2.6) implemented in the simulation model. Once equation (16) has provided the time until the next concentration is found, movement may occur to any concentration within a 10 knot steaming range for that period. In the absence of a "Pelagic Shift", such movement may be selected to be to a concentration north of the highest density strata S_1 and S_2 (see Figure 2); once the vessel has moved to a more northern stratum where the concentration density (d) is lower, more time becomes required for possible further concentration searching in terms of equation (16).

However, for the "Pelagic Shift" example considered, there are no concentrations north of strata S_1 and S_2, so that the simulated vessel remains in the high densities of the southernmost strata and needs, on average, to expend less of the available time on searching for concentrations, thus enhancing many catch-rate indices. Why the quantitative effect of this should be larger for the case of towing more than one swarm-per-haul is not immediately clear. Future model modifications might perhaps build a positive bias towards southward movement into the concentration selection weighting factors of equation (17) to compensate for this effect. This would produce a more realistic representation of the actual fishing strategy, which would be to move preferentially towards areas known from previous seasons to provide higher densities of concentrations (i.e. to move southward in the context of the krill distribution pattern assumed for the model).

There are what might seem to be some other counter-intuitive results if the point estimates only of Table 4 are considered, but such apparent anomalies are attributable either to sampling variation (note the high standard errors associated with such estimates) or, where total-time-related measures are concerned, to secondary responses as described in section 3.4, part B].

The primary concern of this study is the ability of candidate abundance indices to detect biomass declines. A number of important features that emerge from Tables 4, 5 and 8 are discussed under the seven subheadings that follow.

3.6.1 Non-Proportional Response

It is immediately clear from Tables 4 and 5 that the number of instances where an index responds to a 50% biomass drop by a change approaching that same magnitude is relatively rare. For certain indices, the response never reaches 20% for any of the biomass reduction scenarios examined. Thus, from a resource monitoring perspective, there is the undesirable situation that the indices generally respond to biomass drops by proportionately smaller changes. The effects of saturation and compensation on the indices, which arise from the complexity of the overall operation, are evidently of more than a little importance.

It does seem, however, from these Tables that most indices do detect significant and substantial change when the krill surface density δ drops by 50% for either model modification considered. Further, when more than one swarm-per-haul may be towed, changes in swarm radius (r) and areal density (D_c) are similarly well detected. The last result is not surprising, as the rate of finding subsequent swarms in the "sonar band" in such extended tows will be proportional to both r and D_c.

The positive impression given by such results may, however, be misleading. The essential reason for the changes in many of these indices is that the vessel finds considerably greater difficulty in meeting the catch rate per overall elapsed time criterion (CR_{min} - see section 2.8) in these situations, and consequently leaves concentrations much more frequently to search for others. (Table 7 shows that approaching 90% of concentration departures are because of poor catch rate in these instances, compared to the values of typically 60-70% otherwise. Note also the associated large changes in TNC and TH/TNC in Table 4.) However, it may well be that by lowering CR_{min}, the vessel could achieve a larger total catch over the half-month than by spending more time steaming between concentrations in search of better catch rates (see Figure 8 and discussion in section 3.7). This would have the effect of reducing the magnitude of the differences indicated in Table 4 for these scenarios.

3.6.2 Indices Based on Data Currently Being Collected

The indices available from data currently being collected are TC, TH, TFISHT, TC/TFISHT, $\overline{\text{C/FISHT}}$, $\overline{\text{C/H}}$ and $\overline{\text{FISHT}}$. Of these, the crudest indices TC and TH give generally the best responses over the range of biomass reduction scenarios considered (see Tables 4 and 5, and Figure 7 (i). Their responses are nearly identical, which is essentially a reflection of the very poor performance of $\overline{\text{C/H}}$ as an index of biomass; $\overline{\text{C/H}}$ reacts only to a few of the reduction scenarios (and then weakly), because it is determined primarily by processing rate limitations (see section 2.8). A disadvantage of TC and TH is that they show typically 2-3 times the variability of some other indices [the (C) and (D) catch rate indices that do not involve $\overline{\text{CST}}$], so that they would not be able to determine biomass declines as precisely. Much of this additional variability, and the apparent good performance of these indices in detecting changes in the number of concentrations (N_c), is related to concentration searching time (CST), and so they need to be considered in the context of the reservations in this regard expressed under the next subheading. Similarly the performance of TFISHT, changes in which are essentially reflections of an inevitable negative correlation with TCST, must be considered reservedly.

The performances of ratio indices related to FISHT are very poor. Only a decrease in δ is detected consistently, and even then there is some doubt about the realism of those particular results for the reasons discussed under the previous subheading. This is a matter for some concern, as these particular ratio indices are the primary CPUE-type measures presently collected for the Japanese krill fishery.

3.6.3 Detecting Changes in the Number of Concentrations N_c

Tables 4 and 5 show that effective detection is achieved only by indices incorporating concentration searching time (CST). (This incorporation may be indirect in the sense of TC, TH, TNC and total-time-related indices.)

However, there are two problems in regard to such indices. First, their variance is relatively larger (particularly for indices using CST directly), because of the small number of concentrations (compared to swarms) fished per half-month. Secondly, as discussed in section 3.1, the author suspects that, in reality, a substantial fraction of inter-concentration movements of a vessel reflect receipt of external information, rather than the vessel's own searching activities.

To obtain some idea of how serious this second source of concern might be, calculations were repeated for the "One elongated ($f = 8$) swarm per haul" case with concentration searching efficiency increased 7.5 times [by appropriate multiplication of the exponent in equation (15)], to mimic availability of external information on concentration positions. The results are shown in Table 9, which is to be compared to Table 5a. Such a comparison shows that abundance indices change by much lesser amounts in response to a reduction in N_c given greater efficiency in searching for concentrations.

The TC/TCST index appears to have the potential to detect changes in N_c as well as many of the other distribution parameters, even it if is relatively imprecise. There is though a further problem with this index, at least in the context of the model developed. Cases do arise of a concentration being found almost immediately after the vessel leaves its starting point, and fishing continuing for the rest of the half-month in this same concentration (until the time comes to return to offload) because the catch rate never drops below CR_{min}. Such instances provide very high TC/TCST values, so that this statistic has a very long tailed distribution. "Outlier" values from this tail have considerable influence on mean and variance estimates, and it may be necessary to consider trimmed means or harmonic means to obtain estimates with greater precision, if an index of this type is to be considered further.

Detection of changes in N_c by various indices may be confounded by simultaneous changes in the relative density of concentrations between strata, such as the "Pelagic Shift" examined here. However, for reasons discussed at the beginning of this section, the quantitative results for the "Pelagic Shift" shown in Tables 4 and 5 are probably an artefact of an over-simplistic concentration search model, and so should not be considered as reliable.

3.6.4 Detecting Changes in the Concentration Radius L_c

Again it is only indices involving CST which change by non-minimal amounts in response to changes in L_c, but the magnitudes of the changes in such indices are considerably less than for changes in N_c (see Tables 4 and 5).

This confirms the concern expressed in Butterworth (1988) about the likely inability of catch-statistics-based indices to monitor average concentration size. (Note that the typical catch by a vessel from a concentration over the half-month period considered makes no substantial impact on the concentration's total biomass.)

3.6.5 Precision of Indices of Krill Biomass in Practice

Even given estimates of the proportional change in various abundance indices under certain biomass depletion scenarios, a pertinent question is: what is the ability of the "Japanese krill fleet" to detect such changes from one year to the next, given the sampling variability associated with any single abundance measure? The standard errors of the differences shown in Table 4 would also apply to the case of detecting differences between two successive years in each of which 100 vessel-half-months of krill fishing effort was expended. This would correspond to, say, 20 vessels working 2.5 months each year and catching an annual total approaching 100 000 tonnes of krill. This is perhaps twice the size of the current Japanese krill fishery, so that estimates of inter-annual sampling variability would be about $\sqrt{2}$, or approximately 1.5 times as large as the figures in parenthesis in Table 4.

These, however, would be minimum estimates. In practice greater variability would arise because of inter-month and inter-vessel cooperation correlations, catchability fluctuations and so forth. This means that detection of any significant change in an index, and hence in the krill biomass, would be more difficult.

In practice, therefore, the inter-annual variance of abundance indices will not be negligible for the present level of catching. This means that it is important to compare alternative abundance indices in the context of the precision with which they can estimate biomass decline, as well as considering the extent of non-proportionality in the index-biomass relationship.

3.6.6 Choice of the "Best" Index

To simplify the comparison of the large number (24) of potential abundance indices listed in section 3.4, these have been reduced to six for further consideration:

(i) A.1: TC
(ii) C.1: TC/TFISHT
(iii) C.3: TC/TPST
(iv) D.1: TC/TFISHT/$\overline{\mathrm{PST}}$
(v) D.2: TC/TFISHT/($\overline{\mathrm{PST+SST}}$)
(vi) D.3: TC/TFISHT/$\overline{\mathrm{PST/CST}}$

"Per haul" measures (F.1-4) have been rejected because they detect very few distribution parameter changes, and even for those they change by only small amounts. The direction of change for total time measures (B.1-5) is not always clear, and these indices are also influenced by the uncertainty surrounding CST, so that they have not been included. Most indices involving CST directly (e.g. TC/TCST) or indirectly (e.g. TNC) have been omitted because of their imprecision, while "total/total" ratio indices are preferred because they are more precise than the corresponding "average individual ratios" indices (e.g. TC/TFISHT is preferred to $\overline{\mathrm{C/FISHT}}$). The performances of TC and TH are very similar, but where they differ the magnitude of the TC change is greater, so that TC has been chosen.

Comparisons between these six choices enable most of the pertinent considerations to be addressed as adequately as might be possible using alternative or additional choices. Important considerations amongst these are:

(a) Do combination catch-time indices detect biomass decline more effectively by being sensitive to more possible sources of such falls?

(b) How seriously does failure to differentiate PST and SST compromise indices using within-concentration search time?

(c) What is the bias-variance trade-off in incorporating CST into an abundance index?

For ease of comparison of these indices, the corresponding point estimates of proportional changes from Tables 4a and 4b have been set out in a consolidated form in Table 10. Further, Figure 7 provides graphical representations of the results in Table 8 (which presents results for random combinations of changes in the krill distribution parameters) for both model modifications considered.

Consideration (a) is addressed by comparing D.1 with C.1 and C.3 in Table 10, and also Figure 7 (iv) with Figures. 7 (ii) and (iii). The combination index TC/TFISHT/$\overline{\text{PST}}$ performs better than either TC/TFISHT or TC/TPST separately in terms of general magnitude of response, though at the expense of a slight variance increase. TC/TPST performs better than TC/TFISHT, which does not reflect changes in D_c and r as effectively. This result is, however, certainly in part a consequence of the (invariant) criterion used for fishable swarm selectivity [equation (20)] TC/TPST responds to a δ decrease because this reduces the proportion of fishable swarms), and consequently is subject to the reservations discussed in section 3.7. All these indices, however, respond only to changes in within-concentration krill distribution parameters, and are insensitive to N_c and L_c.

Regarding consideration (b), the results for D.1 and D.2 in both Table 10 and in Figures 7 (iv) and (v) suggest that failure to distinguish primary and secondary searching time degrades the effectiveness of the combination index by about one third, where "effectiveness" is measured by the slope of the curve of index against biomass. [Compare also Figs 9 (iii) and (iv) in this regard.] One compensating advantage, however, is that the variance of TC/TFISHT/($\overline{\text{PST+SST}}$) is slightly less than that of TC/TFISHT/$\overline{\text{PST}}$.

Finally, regarding consideration (c), the TC index has a large variance, and fails to reflect D_c or r changes for the one elongated swarm-per-haul model modification. Incorporation of $\overline{\text{CST}}$ into the combination catch-time index D.3 does provide a measure which responds to changes in N_c and L_c, but at the expense of a 3-5 fold standard deviation increase. While D.3 could, of course, be used in conjunction with, say, D.1 in assessing trends in krill biomass, this high variance together with uncertainties in the reliability of $\overline{\text{CST}}$ statistics as representative of a truly random search strategy suggest that indices incorporating CST would have limited utility.

Thus, the analysis suggests that the choice of a "best" index lies between TC/TFISHT/$\overline{\text{PST}}$ and TC/TFISHT/($\overline{\text{PST+SST}}$). Data other than those likely to arise from the Japanese krill fishery as it operates at present would be needed to detect changes in extra-concentration krill distribution parameters such as N_c and L_c.

3.6.7 The Trade-Off Between Effectiveness and Practicality of Collection

Tables 4 and 5 in general, as well as the specific indices extracted for Table 10, reflect the supposition in section 3.4 that there is a trade-off between the effectiveness of an index in detecting biomass decline and the practicality of collection of the requisite data. In particular, indices based on primary searching time (PST) alone reflect the magnitude of biomass changes better than when they are combined (as may be practically necessary) with secondary searching time (SST).

Care must be taken not to over-interpret this result, as the model simplifies what is a very complex searching process within a concentration; PST and SST are idealisations, and given field definition problems, statistics collected during commercial operations might not perform nearly as effectively as the model indicates.

As an initial test of the effect of difficulties of definition, the model runs were repeated allowing for a random error chosen with uniform probability over the range (-30%, +30%) in the allocation of time to PST from the total (PST+SST) period between each successive pair of hauls in a concentration. The results are shown in Table 10, and suggest that introduction of this misallocation effect has virtually no influence on the extent of the greater effectiveness of indices using PST compared to those not needing to differentiate between the two types of within-concentration searching. (The variance increase in the PST indices arising from the misallocation effect is marginal only.)

While the result of this initial test is promising, it is certainly not conclusive. It does, nevertheless, suggest that it may be premature to consider abandoning the use of PST based indices at this stage because of potential data collection problems.

3.7 Reservations About the Model

Obviously, numerous parameter value variations and further model modifications are possible and may merit investigation. However four particularly important problem areas stand out.

3.7.1 Krill Distribution Model

The model modifications adopted in section 3.3 to solve the "FISHT problem" were of an *ad hoc* nature, and so are not particularly satisfactory. If one is to be confident about the magnitudes predicted for the extent of the non-proportionality between abundance indices and overall krill biomass, rather than have to be satisfied with qualitative predictions only, equal confidence is needed in the krill distribution model adopted. Such confidence is impossible given comments (see section 3.3) to the effect that the distribution statistics from FIBEX (upon the results of which many of the choices for distribution parameter values for this exercise were based) are atypical of the swarms on which the Japanese krill fishery operates. While there is scope for further analysis of krill distribution data from previous scientific surveys, the greatest need would seem to be for additional intensive hydroacoustic surveys by research vessels over small areas in which fishing vessels are operating concurrently. Such surveys should be planned and the results analysed with a view to developing more realistic "within-concentration" krill distribution models. In particular they might provide information on the important aspect of temporal variability of the distribution parameters, which is pertinent to more realistic modelling of the process of diminishing catch rates which causes a vessel to leave a concentration, as discussed further below.

The concentration-swarm distinction is also a simplification of a more complex spatially aggregated distribution pattern. Here further analysis of existing data may provide the basis for a more realistic distribution model (on a larger length scale than was the concern of the previous paragraph), and an investigation of whether this would affect the conclusions on the performance of various potential abundance indices should then be carried out.

3.7.2 Swarm Selectivity

The considerable difference between the tuned values of B_{min} for the two model modifications (see Table 2) suggests that at least one of these modifications is not a realistic representation of the actual situation. Empirical data from actual fishing operations on the proportion of swarms considered fishable would provide a valuable constraint for further model development.

Of more concern is whether the swarm selectivity criterion (the B_{min} value) would change if krill biomass declined, rather than remain invariant as assumed in the calculations reported. The sensitivity of the TC/TPST index to a decline in δ for the one swarm-per-haul model, for example, is essentially just a reflection of this assumption. It is arguably logically more consistent (internal to the model) to choose B_{min} and other selectivity related parameters [$(C/FISHT)_{rpt}$ and CR_{min}] for each scenario that maximise the total catch per half-month under those distributional conditions. This would, however, be a very lengthy exercise in computer time terms.

If the selectivity arguments in this paper are reasonably close to reality, the fishery operates on only the upper 7% (or 30%, if more than one swarm may be towed in a haul) of the swarm biomass distribution, which is very long-tailed. How will the shape of this distribution change in response to biomass depletion? One would be rather more confident about model robustness to the assumption in this analysis of relative shape invariance and a change only in the modal value of a distribution, if the fishery covered the centre rather than only the tail of the krill swarm biomass distribution.

3.7.3 The Criterion to Leave a Concentration

Figure 8 shows how sensitive the base case model output is to the choice of a value for the parameter CR_{min}. Over a narrow range of about [1.5, 2.5] for CR_{min}, the behaviour of the simulated vessel changes from the one extreme of remaining in the concentration first found for the balance of the half-month period, to fishing as many concentrations as possible and waiting only long enough in each to conduct sufficient hauls to establish that the CR_{min} criterion has not been met. Though Figure 8 is for the "One elongated ($f = 8$) swarm per haul" model modification, similar results follow if more than one swarm may be towed in a haul.

Figure 8 also points to a weakness of the model, viz. TC is maximal for the extreme of remaining in the concentration first found, rather than for moving between concentrations as does occur in the real world. This points to the need to take one or both of temporal variability of distribution parameters and krill quality considerations into account. (In the latter respect, "greenness" also would vary with time.) The argument in section 2.4 that the manner in which the model deals with the occurrence of bad weather mimics temporal variation of within-concentration distribution parameter values is neither strong nor satisfactory.

The ogive-like nature of the plot shown in Figure 8 (ii) has an important bearing on the shapes of the relationships between abundance indices and biomass, because the effect of changing within-concentration distribution parameter values is similar to changing CR_{min}, and so has a large influence on the proportion of total available time spent in searching for concentrations (CST). Figure 9 shows similar plots of abundance index vs biomass to

Figure 7, but for the case where only the swarm density parameter δ changes. Note that these relationships, although generally closer to proportionality than in Figure 7 because most indices are able to reflect changes in δ well, range from convex to near-linear to concave, rather than showing only the convexity expected from saturation effects. These complicated shapes are a reflection of the manner in which swarm-selectivity and concentration-leaving have been modelled, and may well prove not to be robust to variations in the models of such processes.

3.7.4 Concentration Searching

There is considerable doubt that searching for concentrations resembles random search in reality; rather, some information is passed (directly or indirectly) between vessels, and some concentrations are associated with oceanographic features whose positions have become known as vessel Captains have gained experience. Model modifications to reflect such features might be considered to examine their effect on CST-related abundance indices.

4. CONCLUSIONS AND RECOMMENDATIONS

(a) The simulation indicates that the catch statistics data routinely collected at present would be of low utility in detecting biomass decline. Catch per vessel-day (cf: TC) responds to the widest variety of biomass reduction scenarios, but is an imprecise index. Catch per fishing time indices (e.g. TC/TFISHT) perform very poorly.

(b) This utility might be improved by the collection of search time data to allow calculation of the index TC/TFISHT/($\overline{\text{PST+SST}}$), for example. This could be achieved by keeping records of the times spent on various other vessel activities, so that searching time could be deduced by subtraction. It would be desirable also to have an indication of the periods spent steaming between or searching for concentrations, so that within-concentration search time could be distinguished.

(c) Indices distinguishing primary searching time (PST) for swarms within concentrations, such as TC/TFISHT/$\overline{\text{PST}}$, perform better than those which do not. However, collection of such data would be much more onerous than would be the case for what is proposed in (b) above, and practical field definitions to distinguish PST and SST (secondary searching time) may not be achievable. Before considering routine implementation of such data collection:

  (i) small scale experiments to test collection viability should be performed, and

  (ii) further model tests of the robustness of PST based indices to errors in recording should be carried out.

(d) The priority for further research is improving the krill distribution model underlying the calculations presented here, as there are sound reasons for considerable misgivings about this model. Existing scientific data bases may not be adequate for this purpose, and intensive hydroacoustic surveys by research vessels in areas in which fishing vessels are operating concurrently merit consideration.

(e) Only indices including concentration searching time (CST) seem capable of responding to changes in the number of krill concentrations, and even these remain rather insensitive to concentration size. There are, however, important reservations about the utility of any CST data that might be extracted from the Japanese krill fishing operations. Thus, while these operations may be able to provide information on changes in krill abundance per unit area within concentrations, monitoring of changes in the number, distribution and size of the krill concentrations themselves will probably need to be effected by other means, such as research vessel surveys.

(f) While the model developed has ignored considerations of krill quality and product targeting thus far, nevertheless immediate consideration should be given to possibly requiring the routine recording of a vessel's product targeting and sensitivity to "greenness". Discussion in Butterworth (1988) indicates that is it quite likely that these factors may influence the values of CPUE-like abundance indices, and data should be collected to allow for empirical analysis of this possibility.

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REFERENCES

BIOMASS. 1986. Report on the post-FIBEX acoustic workshop, Frankfurt, Federal Republic of Germany, 3-14 September 1984. BIOMASS Report Series No. 40: 106 pp.

D.S. BUTTERWORTH. 1988. Some aspects of the relation between Antarctic krill abundance and CPUE measures in the Japanese krill fishery (Report of discussions with Japanese industry and fishing agency members and scientists: 11-16 October, 1986). This volume.

BUTTERWORTH, D.S.,S.T. BUCKLAND, H. KISHINO, and M.J. SILBERBAUER. 1987. Revised sighting estimates of Antarctic minke whale abundance from the 1978/79 to 1984/85 IWC/IDCR assessment cruises. IWC Document SC/39/Mi18: 37 pp.

BUTTERWORTH, D.S. and D.G.M. MILLER 1987. A note on relating Antarctic krill catch-per-unit-effort measures to abundance trends. S. Afr. J. Antarct. Res. 17(2): 112-116. (Earlier version circulated as CCAMLR Document KRILL WG/1985/Doc.3, 15 pp.)

HAMPTON, I. 1985. Abundance, distribution and behaviour of *Euphausia superba* in the Southern Ocean between 15° and 30°E during FIBEX. Antarctic Nutrient Cycles and

Food Webs (ed. by W. R. Siegfried, P. R. Condy, and R. M. Laws), Springer-Verlag, Berlin Heidelberg: 294-303.

ICHII, T. 1987. Observations of fishing operations on a krill trawler and distributional behaviour of krill off Wilkes Land during the 1985/86 season. Selected papers presented to the Scientific Committee of CCAMLR 1987: 337-368.

KALINOWSKI, J. and Z. WITEK. 1982. Forms of Antarctic krill aggregations. ICES Biological Oceanography Committee C.M. 1982/L: 60 (mimeo), 8 pp.

KALINOWSKI, J. and Z. WITEK. 1983. Elementy biologii, formy grupowego wystepowania i zasoby antarktycznego kryla *Euphausia superba* /Dana/Crustacea/. Sea Fisheries Institute, Gdynia, 207 pp.

KALINOWSKI, J. and Z. WITEK. 1985. Scheme for classifying aggregations of Antarctic krill. BIOMASS Handbook No 27: 9 pp.

MANGEL, M. 1987. Simulation of Southern Ocean krill fisheries. CCAMLR Document SC-CAMLR/VI/BG/22, 86 pp.

MANGEL, M. 1988. Analysis and modelling of the Soviet Southern Ocean krill fleet. This volume.

MACCALL, A.D. 1983. Population models of habitat selection, with application to the northern anchovy. Ph.D. Dissertation, University of California at San Diego, 170 pp.

ROSENBERG A.A., J.R. BEDDINGTON and M. BASSON. 1986. Growth and longevity of krill during the first decade of pelagic whaling. Nature 324 (6093): 152-154.

SHIMADZU, Y. 1984. A brief summary of Japanese fishing activity relating to Antarctic krill, 1972/73-1982/83. Selected papers presented to the Scientific Committee of CCAMLR 1982-1984 Part 1: 439-452.

SHIMADZU, Y. 1985. An updated information of the Japanese krill fishery in the Antarctic. CCAMLR Document KRILL WG/1985/Doc.5: 7 pp.

GLOSSARY OF ACRONYMS AND SYMBOLS

Note: (i) A prefix "T" indicates summation over the period considered (a half-month in the simulation).

(ii) A bar (—) over a symbol indicates an average.

(I) Krill distribution related

N_c : Number of concentrations in 600 n mile square sector

L_c : Radius of (circular) concentration

D_c : Density of swarms within a concentration (number per unit area)

r : Radius of (circular) swarm

δ : Surface (areal) density of krill within a swarm (biomass per unit area)

ρ : Volume density of krill within a swarm (biomass per unit volume)

B_s : Biomass of krill in a swarm

λ : Intersected swarm length in a survey

s : Distance to a swarm (or concentration)

f : Swarm elongation factor in modified model - see equations (31)

α : Fraction of base case level to which sector biomass is reduced

P.S. : Pelagic Shift in krill concentration distribution - see section 3.5

U[A,B] : Uniform distribution between A and B

$N[0,\sigma^2]$: Normal distribution with mean zero and standard deviation σ.

(II) Fishing operation related

S : Selectivity - fraction of swarms in a concentration considered to be fishable

B_{min} : Minimum biomass for swarm to be considered fishable

$(C/FISHT)_{rpt}$: Minimum catch rate per fishing time for repeat tow on a swarm to be attempted

CR_{min} : Minimum catch rate per total elapsed time (average over last 10 hauls) to continue fishing in a concentration

v : Vessel speed (10 knots searching: 2 knots towing)

w : Effective search width (also used to indicate relative weight)

(III) Fishery statistics

C : Catch (by mass)

H : Haul

DBH : Distance between successive hauls (within the same concentration)

TBH : Time between successive hauls (within the same concentration)

TNC : Total number of concentrations fished in period under consideration

PST : Primary search time for a swarm in a concentration

SST : Secondary search time for a swarm (while waiting to complete processing)

CST : Search time for a concentration

TAST : Total of all search time (TPST + TSST + TCST)

FISHT : Fishing time with net at desired depth (as recorded routinely at present)

TOWT : Total period net is in the water during a haul

TOWT-FISHT : Sum of net lowering and raising times

BW : Time lost to bad weather

TRANS : Time in transit to offload.

Table 1: Summary statistics from a sample of data from a Japanese commercial krill trawler. A number followed by another in parenthesis corresponds to mean (standard deviation), except where indicated otherwise or where only a single statistic is involved.

	JAN 1981	FEB 1981	JAN 1982	FEB 1982	AVERAGE
Number of hauls (TH)	227	163	185	174	187 (28)
Swarms fished per haul	1.34 (0.67)	1.36 (0.69)	1.05 (0.23)	1.09 (0.34)	1.21 (0.46)
Total catch (TC) (tons)	1502	1085	1485	1935	1502 (347)
Catch per haul (C/H) (t)	6.62 (4.70)	6.66 (5.14)	8.03 (4.76)	11.12 (5.43)	8.11 (5.20)
Total fishing time (TFISHT) (hours)	236.5	226.2	162.1	278.5	225.8 (48.1)
TC/TFISHT (t/h)	6.35	4.80	9.16	6.95	6.82 (1.81)
C/FISHT (t/h)	9.08 (10.71)	5.88 (5.29)	15.06 (17.48)	9.01 (9.48)	9.76 (10.46)
FISHT per haul (h)	1.042 (.578)	1.388 (.672)	0.876 (.573)	1.601 (.742)	1.227 (.661)
FISHT per haul (Swarms = 1) (h)	1.034 (.591)	1.416 (.695)	0.874 (.583)	1.604 (.754)	1.232 (.678)
FISHT per haul (Swarms > 1) (h)	1.066 (.543)	1.317 (.593)	0.908 (.372)	1.556 (.566)	1.212 (.526)
Time between hauls (TBH) (h)	2.14 (0.95)	2.68 (1.02)	2.39 (1.13)	2.95 (1.40)	2.54 (1.13)
C/TBH (t/h)	3.66 (2.81)	3.00 (2.50)	4.51 (3.66)	4.30 (2.30)	3.87 (2.85)
Average C/TBH (over 10 successive hauls) (t/h)	3.61 (1.38)	2.84 (0.92)	3.82 (1.00)	3.77 (0.81)	3.51 (1.04)
Distance between hauls (DBH) (n.m.)	2.35 (2.37)	3.39 (3.51)	2.51 (2.08)	3.62 (2.76)	2.97 (2.70)
Speed of haul (knots)	2.01 (0.03)	2.00 (0.02)	2.01 (0.03)	2.00 (0.02)	2.01 (0.02)
No. concentrations fished (TNC) [min, max]	7 [7,10]	7 [4, 8]	11 [10,11]	7 [5, 7]	8 [6.5, 9]
Total concn search time (TCST) (h)	195.7	117.5	276.1	75.3	166.2 (88.7)
Search time per concn (CST) (h)	21.7 (13.1)	16.8 (15.2)	25.1 (37.8)	12.6 (8.1)	19.1 (17.5)
Inter-concentration distance (n.m.)	115 (106)	138 (122)	100 (87)	70 (68)	106 (96)
North-South fishing extent (n.m.)	100	71	108	119	100 (21)
Bad weather and transit time (h)	57.2	113.2	91.0	107.8	92.3 (25.2)
Balance time (net raising, lowering; searching for swarms; processing) (h)	254.6	215.1	214.8	210.4	223.7 (20.7)

Table 2: Values of fishing operation parameters for various modifications. Where a value of a “partially tuned” parameter is shown in square brackets, the value was not tuned for that modification, but set equal to the tuned value for a related modification.

PARAMETER	MODEL			
	One Swarm per Haul		More than One Swarm per Haul	
	No elongation**	Elongation++	Off-Centre++	Through Centre
Fixed				
Start search position (n.m.)	(0,100)	(0,100)	(0,100)	(0,100)
Initial search aim point (n.m.)	(300,0)	(300,0)	(300,0)	(300,0)
Dist moved bad weather (n.m.)	50	50	50	50
Process rate (t/h)	2.5	2.5	2.5	2.5
Process time estimated available during next haul (h)	0.75	1.5	1.5	1.5
Target catch per haul (t)	10	10	10	10
No swarms per haul	1	1	(free)	(free)
Max length haul TOW_{max} (n.m.)	(free)	(free)	4	4
Sonar detection width (m)	N.A.	N.A.	35	35
Partially Tuned				
Swarm elongation factor, f	(1)	8[1]	(1)	(1)
Swarm Selectivity, B_{min} (t)	[50]	50[2]	5[3]	[5]
Repeat haul criterion $(C/FISHT)_{rpt}$ (t/h)	50[4]	10[4]	10	[10]
Leave concentration criterion CR_{min} (t/h)	3.2[5]	2.0[5]	3.2[5]	[3.2]
(No concentrations N_c)	[36]	36[5]	[36]	[36]

Principal fishing operation statistic to which tuned:

1) Mean fish time per haul ($\overline{FISHT}$)
2) Mean catch per haul ($\overline{C/H}$)
3) Catch per fishing time (TC/TFISHT)
4) Fraction attempted repeated hauls
5) Concentration searching time (TCST) and number of concentrations fished (TNC)

++ Modifications used for further analysis

** Corresponds to original model developed in Chapter 2.

Table 3: Comparison of statistics for the Japanese commercial krill fishery from the data sample provided and other sources with the simulation model outputs for the base case. The simulation model results reflect the mean over 100 runs. (NB: All statistics apply to a half-month period.) The numbers in parenthesis are c.v.'s, except for time budget percentages where they are standard deviations.

CATCH STATISTICS	COMMERCIAL DATA			SIMULATION MODEL OUTPUT							
				One Swarm per Haul				More than One Swarm per Haul			
	80/81 + 81/82 Data Sample (Table 1)		Other Sources	No elongation** (f=1)		Elongated swarms++ (f=8)		Non-Initial Off-Centre++		Swarms towed Through Centre	
Number of hauls (TH)	94	(0.15)		121*	(0.42)	93*	(0.38)	86	(0.40)	100	(0.39)
Swarms fished per haul	1.21	(0.38)		1*		1*		4.97	(0.55)	4.63	(0.55)
Total catch (TC) (t)	751	(0.23)		856	(0.43)	666	(0.40)	784	(0.41)	944	(0.40)
Catch per haul (C/H) (t/h)	8.11	(0.64)		7.08$^{(+)}$	(0.46)	7.17^{+}	(0.45)	9.14	(0.28)	9.43	(0.27)
Total fishing time (TFISHT) (h)	113	(0.21)		27	(0.41)	112	(0.35)	98	(0.38)	107	(0.36)
TC/TFISHT (t/h)	6.82	(0.27)		31.54	(0.14)	5.87	(0.17)	7.92^{+}	(0.10)	8.66	(0.11)
C/FISHT (t/h)	9.76	(1.07)		43.75	(0.12)	11.85	(0.21)	17.82	(0.22)	18.31	(0.21)
FISHT per haul (h)	1.23	(0.54)		0.22	(0.65)	1.20^{+}	(0.90)	1.14	(0.60)	1.07	(0.61)
Fraction attempted repeated hauls			0.4^{1}	0.40^{+}	(0.20)	0.44^{+}	(0.21)	0.44^{+}	(0.16)	0.48	(0.16)
Time between hauls (TBH) (h)	2.54	(0.44)		1.70	(0.32)	2.28	(0.49)	2.34	(0.34)	2.29	(0.34)
Distance between hauls (DBH) (n.m.)	2.97	(0.91)		1.27	(1.09)	2.61	(0.89)	2.57	(0.79)	2.40	(0.82)
Number concentrations fished (TNC)	4	(0.25)	1-2^{1}	2.09^{+}	(0.45)	2.13^{+}	(0.36)	2.37^{+}	(0.41)	1.83	(0.44)
Total concn search time (TCST) (h)	83	(0.53)		125$^{(+)}$	(0.63)	116^{+}	(0.57)	132$^{(+)}$	(0.54)	102	(0.77)
Search time per concn (CST) (h)	19.1	(0.92)		73.4	(0.94)	64.0	(0.83)	62.0	(0.91)	58.7	(1.01)
Inter-concentration distance (n.m.)	106	(0.91)		85	(0.74)	75	(0.62)	76	(0.72)	78	(0.62)
North-south fishing extent (n.m.)	100	(0.21)	< 100^{2}	52	(1.01)	40	(0.93)	57	(0.85)	55	(0.96)
Distance from ice-edge (n.m.)				66	(0.72)	67	(0.65)	64	(0.67)	65	(0.74)
<u>TIME BUDGET (%)</u>											
TPST+TSST+(TTOWT-TFISHT)	32	(3)		49	(21)	28	(15)	28	(11)	34	(13)
TCST	23	(12)		35	(22)	32	(18)	37	(20)	28	(22)
TAST=TPST+TSST+TCST			45^{3} 25^{4}	61	(11)	42	(15)	48	(15)	43	(16)
TFISHT	32	(7)	18	8	(3)	31	(11)	27	(10)	30	(11)
TTOWT (includes TFISHT)			42 50	30	(13)	49	(17)	44	(17)	49	(18)
BW+TRANS	13	(4)	13 25	9	(5)	9	(6)	8	(6)	8	(6)

* Fixed by design
\+ Partially tuned
(+) Partially tuned for related modification

1) T Ichii (pers. commn, Sept 1987)
2) Captain Fukui (pers. commn, Sept 1987)
3) Butterworth (1987)
4) Y Shimadzu (pers. commn, Sept. 1987)

** Corresponds to original model developed in Chapter 2

++ Modifications used for further analysis

Table 4: Comparison of abundance indices for the base case simulation model run with those from six alternative krill distribution scenarios, each corresponding to a 50% overall biomass drop. For the base case, the mean over the 100 simulations is shown, together with the standard error of this mean in parenthesis. For the alternative scenarios, the percentage difference from the base case mean is given, together with the standard of error that difference in parenthesis. (Units, where appropriate, are tonne-hour combinations.)

(a) One elongated (f=8) swarm per haul

INDEX	Base case	N_c × 0.5	N_c × 0.5 + P.S.	L_c × $1/\sqrt{2}$	D_c × 0.5	r × $1/\sqrt{2}$	δ × 0.5
A.1: TC^{+++}	666 (27)	-40 (9)	+ 1 (6)	-16 (7)	-17 (6)	+ 9 (6)	-60 (7)
2: TH^{+++}	93 (4)	-39 (9)	+ 2 (6)	-16 (7)	-17 (6)	+ 8 (5)	-52 (6)
B.1: TFISHT^{+++}	111.8 (3.9)	-38 (8)	+ 3 (5)	-15 (6)	-17 (5)	- 4 (5)	-32 (5)
2: TPST	22.8 (0.9)	-39 (8)	- 1 (6)	-17 (7)	+44 (6)	+63 (5)	-27 (6)
3: TPST + TSST^{+}	36.0 (1.4)	-40 (9)	+ 1 (6)	-17 (7)	+18 (6)	+39 (6)	-44 (6)
4: TCST^{+}	116.2 (6.6)	+68 (7)	- 2 (9)	+29 (8)	+20 (8)	- 8 (9)	+73 (6)
5: TAST^{++}	152.2 (5.3)	+42 (5)	- 1 (5)	+18 (5)	+19 (5)	+ 3 (5)	+45 (4)
C.1: TC/TFISHT^{+++}	5.87 (0.10)	- 8 (3)	- 2 (3)	- 4 (3)	- 0 (3)	+15 (2)	-42 (3)
2: $\overline{C/FISHT}^{+++}$	11.85 (0.24)	- 6 (4)	+ 1 (3)	- 1 (3)	+ 5 (3)	+13 (3)	-39 (4)
3: TC/TPST	28.99 (0.39)	- 1 (3)	+ 5 (2)	+ 1 (2)	-43 (2)	-33 (2)	-45 (3)
4: $\overline{C/PST}$	64.59 (1.02)	- 2 (3)	+ 2 (2)	+ 2 (3)	-31 (3)	-25 (3)	-34 (3)
5: TC/(TPST+TSST)$^{+}$	18.56 (0.18)	+ 3 (3)	+ 1 (1)	+ 0 (1)	-31 (2)	-22 (2)	-29 (2)
6: TC/TCST^{+}	13.07 (2.15)	-64 (23)	+12 (23)	-22 (24)	-37 (22)	+57 (24)	-87 (19)
D.1: TC/TFISHT/$\overline{PST}$	23.31 (0.52)	- 6 (4)	+ 4 (4)	- 1 (4)	-42 (4)	-24 (3)	-62 (4)
2: TC/TFISHT/($\overline{PST+SST}$)$^{+}$	14.84 (0.25)	- 3 (3)	+ 1 (3)	- 2 (3)	-30 (3)	-11 (3)	-52 (3)
3: TC/TFISHT/$\overline{PST}$/$\overline{CST}$	0.724 (0.085)	-57 (16)	+ 3 (15)	-17 (16)	-49 (15)	- 8 (16)	-77 (14)
4: TC/TFISHT/($\overline{PST+SST}$)/$\overline{CST}^{+}$	0.459 (0.056)	-57 (16)	+ 1 (15)	-20 (16)	-39 (15)	+ 5 (16)	-71 (14)
5: TC/TFISHT/TAST^{++}	0.045 (0.002)	-27 (7)	+ 4 (6)	-11 (7)	-18 (6)	+ 9 (6)	-62 (6)
E.1: TNC^{+}	2.13 (0.07)	-38 (8)	- 7 (6)	- 9 (6)	+ 7 (5)	0 (6)	+41 (5)
2: TH/TNC^{+}	43.6 (2.4)	- 1 (9)	+ 9 (8)	- 7 (8)	-22 (8)	+ 8 (8)	-66 (6)
F.1: $\overline{C/H}^{+++}$	7.17 (0.03)	- 2 (1)	- 1 (1)	- 1 (1)	+ 0 (1)	+ 2 (1)	-17 (1)
2: $\overline{FISHT}^{+++}$	1.20 (0.01)	+ 2 (1)	+ 1 (1)	+ 1 (1)	- 0 (1)	-11 (1)	+41 (2)
3: $\overline{TOWT}^{++}$	1.89 (0.01)	+ 1 (1)	+ 1 (1)	+ 1 (1)	- 0 (1)	- 7 (1)	+26 (1)
4: $\overline{TBH}^{++}$	2.28 (0.01)	+ 0 (1)	+ 0 (1)	+ 0 (1)	+ 7 (1)	- 1 (1)	+25 (1)

+++	Data currently collected
++	Data collectable, but onerous
+	Data collectable with difficulty
blank	Extreme difficulties data collection

Table 4: Comparison of abundance indices for the base case simulation model run with those from six alternative krill distribution scenarios, each corresponding to a 50% overall biomass drop. For the base case, the mean over the 100 simulations is shown, together with the standard error of this mean in parenthesis. For the alternative scenarios, the percentage difference from the base case mean is given, together with the standard of error that difference in parenthesis. (Units, where appropriate, are tonne-hour combinations.)

(b) More than one swarm per haul

INDEX	Base case		$N_c \times 0.5$		$N_c \times 0.5$ + P.S.		$L_c \times 1/\sqrt{2}$		$D_c \times 0.5$		$r \times 1/\sqrt{2}$		$\delta \times 0.5$	
A.1: TC^{+++}	784	(32)	-41	(9)	+25	(5)	-10	(6)	-62	(6)	-51	(6)	-64	(6)
2: TH^{+++}	86	(3)	-42	(4)	+24	(5)	-11	(6)	-53	(6)	-46	(6)	-57	(6)
B.1: TFISHT^{+++}	98.0	(3.8)	-42	(8)	+26	(4)	-10	(6)	-41	(6)	-34	(6)	-42	(6)
2: TPST	20.7	(0.8)	-42	(9)	+22	(5)	-14	(6)	-18	(6)	-30	(6)	-43	(6)
3: TPST + TSST^{+}	42.9	(1.8)	-40	(9)	+26	(5)	-10	(6)	-49	(6)	-48	(6)	-61	(6)
4: TCST^{+}	131.5	(7.1)	+55	(7)	-36	(8)	+12	(7)	+64	(6)	+59	(6)	+70	(6)
5: TAST^{++}	174.4	(5.5)	+32	(4)	-21	(4)	+ 6	(4)	+37	(4)	+33	(4)	+38	(4)
C.1: $\mathrm{TC/TFISHT}^{+++}$	7.92	(0.08)	+ 0	(2)	- 0	(1)	+ 0	(2)	-35	(2)	-26	(2)	-38	(2)
2: $\overline{\mathrm{C/FISHT}}^{+++}$	17.82	(0.40)	- 4	(4)	- 5	(3)	- 2	(3)	-26	(4)	-19	(4)	-46	(5)
3: TC/TPST	37.96	(0.51)	+ 3	(2)	+ 3	(2)	+ 5	(2)	-51	(3)	-30	(2)	-36	(3)
4: $\overline{\mathrm{C/PST}}$	86.52	(1.67)	- 1	(4)	+ 7	(2)	+ 4	(3)	-43	(4)	-22	(3)	-29	(4)
5: $\mathrm{TC/(TPST+TSST)}^{+}$	18.39	(0.14)	+ 0	(1)	- 1	(1)	- 1	(1)	-23	(2)	- 7	(1)	- 7	(2)
6: $\mathrm{TC/TCST}^{+}$	10.18	(1.04)	-37	(27)	+98	(16)	+17	(28)	-84	(13)	-79	(13)	-86	(12)
D.1: $\mathrm{TC/TFISHT/}\overline{\mathrm{PST}}$	32.08	(0.57)	+ 3	(3)	+ 2	(2)	+ 4	(3)	-63	(4)	-44	(3)	-55	(3)
2: $\mathrm{TC/TFISHT/(}\overline{\mathrm{PST+SST}}\mathrm{)}^{+}$	15.50	(0.18)	- 0	(2)	- 2	(1)	- 2	(2)	-42	(3)	-26	(2)	-34	(2)
3: $\mathrm{TC/TFISHT/}\overline{\mathrm{PST}}\mathrm{/}\overline{\mathrm{CST}}$	0.883	(.071)	-45	(17)	+85	(11)	-11	(16)	-76	(11)	-62	(10)	-72	(11)
4: $\mathrm{TC/TFISHT/(}\overline{\mathrm{PST+SST}}\mathrm{)/}\overline{\mathrm{CST}}^{+}$	0.421	(.032)	-48	(15)	+79	(10)	-18	(14)	-62	(11)	-49	(10)	-59	(11)
5: $\mathrm{TC/TFISHT/TAST}^{++}$	0.051	(.002)	-18	(6)	+20	(4)	- 6	(5)	-55	(4)	-49	(4)	-59	(4)
E.1: TNC^{+}	2.37	(0.10)	-43	(8)	+27	(5)	-15	(6)	+42	(6)	+45	(6)	+38	(6)
2: $\mathrm{TH/TNC}^{+}$	36.2	(1.8)	+ 3	(9)	- 2	(7)	+ 5	(7)	-67	(5)	-62	(6)	-69	(5)
F.1: $\overline{\mathrm{C/H}}^{+++}$	9.14	(0.03)	+ 1	(1)	+ 1	(0)	+ 1	(0)	-17	(1)	-11	(1)	-17	(1)
2: $\overline{\mathrm{FISHT}}^{+++}$	1.14	(0.01)	- 1	(1)	+ 2	(1)	+ 2	(1)	+27	(1)	+21	(1)	+35	(1)
3: $\overline{\mathrm{TOWT}}^{++}$	1.83	(0.01)	- 0	(1)	+ 1	(1)	+ 1	(1)	+17	(1)	+13	(1)	+22	(1)
4: $\overline{\mathrm{TBH}}^{++}$	2.34	(0.01)	+ 0	(1)	+ 1	(1)	+ 1	(1)	+17	(1)	+11	(1)	+16	(1)

+++	Data currently collected
++	Data collectable, but onerous
+	Data collectable with difficulty
blank	Extreme difficulties data collection

Table 5: Efficiency of abundance indices in detecting changes in krill biomass :

blank : 100 simulations detect no change significant at 5%
+ / - : direction of change if difference significant at 5% level detected
* : Index (or its inverse) drops by > 20%
* * : index (or its inverse) drops by > 45% (within 95% limits)

(a) One elongated (f=8) swarm per haul

INDEX	$N_c \times 0.5$	$N_c \times 0.5$ + P.S.	$L_c \times 1/\sqrt{2}$	$D_c \times 0.5$	$r \times 1/\sqrt{2}$	$\delta \times 0.5$
A.1: TC^{+++}	-**		-	-		-**
2: TH^{+++}	-**		-	-		-**
B.1: TFISHT^{+++}	-**		-	-		-*
2: TPST	-**		-	+*	+**	-*
3: TPST + TSST^{+}	-**		-	+	+*	-*
4: TCST^{+}	+**		+*	+		+**
5: TAST^{++}	+*		+	+		+*
C.1: TC/TFISHT^{+++}	-				+	-**
2: $\overline{\text{C/FISHT}}^{+++}$					+	-**
3: TC/TPST		+		-**	-*	-**
4: $\overline{\text{C/PST}}$				-*	-*	-*
5: TC/(TPST+TSST)$^{+}$				-*	-*	-*
6: TC/TCST^{+}	**	**	**	**	+**	-**
D.1: TC/TFISHT/$\overline{\text{PST}}$				-**	-*	-**
2: TC/TFISHT/($\overline{\text{PST+SST}}$)$^{+}$				-*	-	-**
3: TC/TFISHT/$\overline{\text{PST}}$/$\overline{\text{CST}}$	-**		**	-**		-**
4: TC/TFISHT/($\overline{\text{PST+SST}}$)/$\overline{\text{CST}}^{+}$	-**		**	-**		-**
5: TC/TFISHT/TAST^{++}	-*			-		-**
E.1: TNC^{+}	-**					+*
2: TH/TNC^{+}				-*		-**
F.1: $\overline{\text{C/H}}^{+++}$	-				+	-
2: $\overline{\text{FISHT}}^{+++}$			+		-	+*
3: $\overline{\text{TOWT}}^{++}$			+		-	+*
4: $\overline{\text{TBH}}^{++}$			+	+		+

Table 5: Efficiency of abundance indices in detecting changes in krill biomass :

blank	:	100 simulations detect no change significant at 5%
+ / -	:	direction of change if difference significant at 5% level detected
*	:	Index (or its inverse) drops by > 20%
* *	:	index (or its inverse) drops by > 45% (within 95% limits)

(b) More than one swarm per haul

INDEX	$N_c \times 0.5$	$N_c \times 0.5$ + P.S.	$L_c \times 1/\sqrt{2}$	$D_c \times 0.5$	$r \times 1/\sqrt{2}$	$\delta \times 0.5$
A.1: TC^{+++}	-**	+*		-**	-**	-**
2: TH^{+++}	-**	+		-**	-**	-**
B.1: $TFISHT^{+++}$	-**	+*		-**	-**	-**
2: TPST	-**	+	-	-	-*	-**
3: $TPST + TSST^{+}$	-**	+*		-**	-**	-**
4: $TCST^{+}$	+**	-**		+**	+**	+**
5: $TAST^{++}$	+*	-*		+*	+*	+*
C.1: $TC/TFISHT^{+++}$				-*	-*	-*
2: $\overline{C/FISHT}^{+++}$				-*	-	-**
3: TC/TPST			+	-**	-*	-*
4: $\overline{C/PST}$		+		-**	-*	-*
5: $TC/(TPST+TSST)^{+}$				-*	-	-
6: $TC/TCST^{+}$	**	+**	**	-**	-**	-**
D.1: $TC/TFISHT/\overline{PST}$				-**	-**	-**
2: $TC/TFISHT/(\overline{PST+SST})^{+}$				-**	-*	-*
3: $TC/TFISHT/\overline{PST}/\overline{CST}$	-**	+**		-**	-**	-**
4: $TC/TFISHT/(\overline{PST+SST})/\overline{CST}^{+}$	-**	+**	**	-**	-**	-**
5: $TC/TFISHT/TAST^{++}$	-	+		-**	-**	-**
E.1: TNC^{+}	-**	+*		+*	+*	+*
2: TH/TNC^{+}				-**	-**	-**
F.1: $\overline{C/H}^{+++}$	+	+	+	-	-	-
2: $\overline{FISHT}^{+++}$		+		+*	+	+*
3: $\overline{TOWT}^{++}$		+		+	+	+
4: $\overline{TBH}^{++}$		+	+	+	+	+

Table 6: Further comparative statistics from 100 model runs for the base case and for six alternative scenarios each corresponding to a 50% overall biomass drop. The format is as for Table 4 except that values in parenthesis for the base case are standard deviations (<u>not</u> standard errors of the mean).

(a) One elongated (f-=8) swarm per haul

	Base case		$N_c \times 0.5$		$N_c \times 0.5$ + P.S.		$L_c \times 1/\sqrt{2}$		$D_c \times 0.5$		$r \times 1/\sqrt{2}$		$\delta \times 0.5$	
Proportion of fishable swarms per concentration	0.075	(0.004)	+ 1	(0.6)	+ 1	(0.5)	0	(0.7)	+ 1	(0.6)	-40	(0.6)	-41	(0.5)
Mean biomass of fishable swarms (t)	439	(4920)	- 1	(5)	+ 1	(5)	+ 1	(6)	+ 1	(6)	-19	(5)	-21	(5)
Mean radius of fishable swarms (m) (before elongation)	370	(331)	- 0	(0.5)	- 0	(0.4)	- 0	(0.6)	+ 0	(0.5)	-14	(0.5)	+21	(0.4)
Mean length of swarm towed through (m)	4160	(4003)	+ 2	(2)	+ 1	(1)	+ 1	(1)	- 0	(1)	-12	(1)	+44	(2)
Proportion of attempted refishing of swarm*	0.44	(0.09)	-10	(4)	- 2	(3)	- 4	(4)	+ 0	(3)	+11	(3)	-43	(5)
Mean distance between swarms fished (n.m.) ($\overline{DBH}$)	2.61	(2.34)	+ 2	(2)	+ 1	(1)	- 5	(1)	+13	(1)	+ 1	(1)	+41	(2)
Mean distance between concentrations fished (n.m.)	75	(47)	+20	(11)	-18	(9)	- 3	(10)	- 4	(10)	- 4	(10)	- 4	(9)
Proportion of concentrations found that had previously been fished that half-month	0.09	(0.29)	-65	(54)	-49	(39)	-47	(39)	-31	(34)	-31	(35)	+30	(27)
Mean distance to ice-edge of concentrations fished (n.m.)	67	(44)	+ 1	(7)	-13	(6)	- 8	(6)	+ 0	(7)	- 4	(7)	+ 8	(6)
Mean distance excluding case where no concentration was found during initial transit to ice	85	(56)	-14	(14)	-41	(13)	-22	(12)	-17	(13)	-33	(13)	-10	(13)

*Standard deviation is of set of 100 estimated proportions.

Table 6: Further comparative statistics from 100 model runs for the base case and for six alternative scenarios each corresponding to a 50% overall biomass drop. The format is as for Table 4 except that values in parenthesis for the base case are standard deviations (<u>not</u> standard errors of the mean).

(b) More than one swarm per haul

	Base case	$N_c \times 0.5$	$N_c \times 0.5$ + P.S.	$L_c \times 1/\sqrt{2}$	$D_c \times 0.5$	$r \times 1/\sqrt{2}$	$\delta \times 0.5$
Proportion of fishable swarms per concentration	0.290 (0.007)	+ 0 (0.3)	0 (0.3)	- 0 (0.3)	+ 0 (0.3)	-29 (0.3)	-29 (0.3)
Mean biomass of fishable swarms (t)	127 (1972)	+ 2 (5)	+ 2 (5)	- 7 (4)	+ 8 (8)	-29 (5)	-28 (4)
Mean radius of fishable swarms (m)	204 (213)	- 0 (0.4)	- 0 (0.3)	- 0 (0.4)	+ 0 (0.3)	-16 (0.3)	+18 (0.3)
Mean length of tow from entering first swarm (m)	3935 (2531)	- 1 (1)	+ 2 (1)	+ 2 (1)	+29 (1)	+23 (1)	+38 (1)
Number of swarms fished per haul	4.97 (2.76)	+ 0 (1)	+ 4 (1)	+ 3 (1)	-24 (1)	+ 3 (1)	+27 (1)
Proportion of attempted refishing of swarm*	0.44 (0.07)	- 3 (3)	- 3 (2)	- 2 (2)	-41 (4)	-33 (3)	-55 (5)
Mean distance between swarms fished (n.m.) (DBH)	2.57 (2.03)	- 2 (1)	+ 2 (1)	- 2 (1)	+40 (1)	+26 (1)	+41 (1)
Mean distance between concentrations fished (n.m.)	76 (55)	+14 (12)	-32 (8)	+13 (10)	-4 (8)	+ 7 (8)	+ 8 (8)
Proportion of concentrations found that had previously been fished that half-month	0.06 (0.23)	-33 (52)	+95 (32)	- 0 (40)	+196 (30)	+160 (30)	+156 (30)
Mean distance to ice-edge of concentrations fished (n.m.)	64 (43)	+ 1 (8)	- 1 (5)	+ 9 (7)	+13 (6)	+20 (6)	+20 (6)
Mean distance excluding case where no concentration was found during initial transit to ice	50 (29)	+48 (12)	+28 (16)	+52 (10)	+53 (11)	+67 (13)	+57 (12)

*Standard deviation is of set of 100 estimated proportions.

Table 7: Additional comparative statistics from simulation model runs for the base case and six alternative scenarios each corresponding to a 50% overall biomass drop. The values given are means over 100 runs, with the standard errors of those means given in parenthesis.

(a) One elongated (f=8) swarm per haul

	Base case		$N_c \times 0.5$		$N_c \times 0.5$ & P.S.		$L_c \times 1/\sqrt{2}$		$D_c \times 0.5$		$r \times 1/\sqrt{2}$		$\delta \times 0.5$	
Proportion occasions fishing concentration terminated due to: bad weather	0.10	(.02)	0.07	(.02)	0.07	(.02)	0.05	(.02)	0.08	(.02)	0.07	(.02)	0.03	(.01)
poor catch rate	0.55	(.03)	0.68	(.04)	0.62	(.04)	0.60	(.03)	0.73	(.03)	0.53	(.04)	0.86	(.02)
Proportion of runs where concentration found prior to initial transit reaching ice-edge	0.74	(.04)	0.47	(.05)	0.72	(.05)	0.54	(.05)	0.66	(.05)	0.73	(.05)	0.67	(.05)
TIME BUDGET (%)														
BW + TRANS	9	(1)	10	(1)	8	(1)	9	(1)	9	(1)	8	(1)	9	(1)
TAST	42	(1)	60	(2)	42	(2)	50	(2)	50	(2)	43	(1)	61	(1)
TTOWT	49	(2)	30	(2)	50	(2)	41	(2)	40	(2)	48	(2)	30	(1)

(b) More than one swarm per haul

	Base case		$N_c \times 0.5$		$N_c \times 0.5$ & P.S.		$L_c \times 1/\sqrt{2}$		$D_c \times 0.5$		$r \times 1/\sqrt{2}$		$\delta \times 0.5$	
Proportion occasions fishing concentration terminated due to: bad weather	0.06	(.02)	0.09	(.03)	0.09	(.02)	0.06	(.02)	0.03	(.01)	0.03	(.01)	0.01	(.01)
poor catch rate	0.70	(.03)	0.66	(.04)	0.64	(.02)	0.69	(.03)	0.91	(.01)	0.86	(.02)	0.89	(.02)
Proportion of runs where concentration found prior to initial transit reaching ice-edge	0.66	(.05)	0.40	(.05)	0.93	(.03)	0.58	(.05)	0.70	(.05)	0.79	(.04)	0.63	(.05)
TIME BUDGET (%)														
BW + TRANS	8	(1)	11	(1)	7	(1)	9	(1)	10	(1)	9	(1)	10	(1)
TAST	48	(2)	64	(2)	38	(1)	52	(2)	66	(1)	64	(1)	67	(1)
TTOWT	44	(2)	25	(2)	55	(1)	39	(2)	24	(1)	27	(1)	23	(1)

Table 8: Abundance indices as a proportion of their values for the base case simulation model run. When the overall krill biomass is decreased to a fraction α of its base case level through a random combination of changes in N_c, L_c, D_c, r and δ. Results relate to the means over 100 simulations in every case. The figures in parenthesis are standard errors of the proportions estimated. Note that some of the indices listed are the inverses of those shown in Tables 4 and 5; the inverse has been taken whenever necessary to make the index an increasing function of α - such cases are indicated by *.

(a) One elongated (f=8) swarm per haul

INDEX	α	0.1		0.2		0.3		0.4		0.5		0.6		0.7		0.8		0.9	
A.1: TC^{+++}		0.55	(.08)	0.63	(.07)	0.70	(.07)	0.70	(.07)	0.79	(.07)	0.83	(.06)	0.86	(.06)	1.00	(.05)	0.95	(.06)
2: TH^{+++}		0.59	(.07)	0.67	(.07)	0.73	(.06)	0.72	(.07)	0.81	(.07)	0.84	(.06)	0.88	(.06)	1.00	(.05)	0.95	(.06)
B.1: $TFISHT^{+++}$		0.63	(.06)	0.71	(.06)	0.76	(.06)	0.76	(.06)	0.82	(.06)	0.86	(.06)	0.89	(.06)	1.03	(.05)	0.97	(.05)
2: TPST		0.94	(.07)	1.01	(.07)	1.02	(.06)	0.92	(.07)	0.98	(.07)	0.96	(.06)	0.97	(.06)	1.09	(.05)	0.96	(.06)
3: $TPST + TSST^{+}$		0.77	(.07)	0.83	(.07)	0.87	(.06)	0.82	(.07)	0.90	(.07)	0.91	(.06)	0.92	(.06)	1.04	(.05)	0.96	(.06)
4: $[TCST^{+}]^{-1}$	*	0.62	(.07)	0.66	(.07)	0.71	(.07)	0.70	(.08)	0.77	(.08)	0.79	(.08)	0.85	(.08)	1.01	(.08)	0.92	(.09)
5: $[TAST^{++}]^{-1}$	*	0.71	(.04)	0.74	(.05)	0.78	(.04)	0.78	(.05)	0.83	(.05)	0.85	(.05)	0.90	(.05)	1.00	(.05)	0.94	(.05)
C.1: $TC/TFISHT^{+++}$		0.85	(.03)	0.88	(.03)	0.92	(.03)	0.92	(.04)	0.95	(.03)	0.96	(.03)	0.96	(.03)	0.97	(.02)	0.96	(.02)
2: $\overline{C/FISHT}^{+++}$		0.90	(.04)	0.90	(.04)	0.90	(.03)	0.92	(.04)	0.97	(.03)	0.99	(.03)	0.99	(.03)	1.00	(.03)	0.97	(.03)
3: $TC/TPST$		0.62	(.03)	0.65	(.03)	0.71	(.03)	0.76	(.03)	0.82	(.03)	0.86	(.02)	0.89	(.02)	0.94	(.02)	0.99	(.02)
4: $\overline{C/PST}$		0.74	(.04)	0.73	(.03)	0.78	(.03)	0.80	(.03)	0.87	(.03)	0.90	(.03)	0.93	(.03)	0.97	(.02)	1.01	(.03)
5: $TC/(TPST+TSST)^{+}$		0.73	(.02)	0.77	(.03)	0.81	(.02)	0.85	(.02)	0.89	(.02)	0.91	(.01)	0.93	(.02)	0.97	(.01)	0.99	(.02)
6: $TC/TCST^{+}$		0.24	(.20)	0.43	(.28)	0.34	(.20)	0.46	(.22)	0.78	(.28)	0.55	(.20)	0.72	(.22)	1.06	(.23)	1.11	(.28)
D.1: $TC/TFISHT/\overline{PST}$		0.56	(.05)	0.61	(.05)	0.68	(.04)	0.72	(.05)	0.80	(.04)	0.84	(.04)	0.88	(.03)	0.92	(.03)	0.96	(.03)
2: $TC/TFISHT/(\overline{PST+SST})^{+}$		0.66	(.04)	0.72	(.04)	0.77	(.03)	0.80	(.03)	0.87	(.03)	0.89	(.03)	0.92	(.03)	0.95	(.02)	0.96	(.02)
3: $TC/TFISHT/\overline{PST}/\overline{CST}$		0.29	(.16)	0.41	(.18)	0.39	(.15)	0.49	(.16)	0.67	(.17)	0.63	(.15)	0.82	(.16)	0.96	(.15)	0.96	(.17)
4: $TC/TFISHT/(\overline{PST+SST})/\overline{CST}^{+}$		0.34	(.16)	0.49	(.18)	0.46	(.15)	0.54	(.16)	0.73	(.18)	0.66	(.15)	0.86	(.16)	1.01	(.15)	0.94	(.17)
5: $TC/TFISHT/TAST^{++}$		0.58	(.07)	0.67	(.07)	0.69	(.06)	0.73	(.07)	0.82	(.07)	0.82	(.06)	0.89	(.06)	0.96	(.06)	0.96	(.07)
E.1: $[TNC^{+}]^{-1}$	*	1.00	(.06)	1.00	(.06)	0.96	(.06)	1.02	(.06)	1.04	(.06)	1.02	(.05)	0.96	(.06)	0.96	(.05)	1.06	(.06)
2: TH/TNC^{+}		0.59	(.08)	0.67	(.08)	0.70	(.08)	0.74	(.08)	0.84	(.08)	0.86	(.08)	0.84	(.08)	0.97	(.08)	1.01	(.08)
F.1: $\overline{C/H}^{+++}$		0.94	(.01)	0.95	(.01)	0.96	(.01)	0.97	(.01)	0.98	(.01)	0.99	(.01)	0.98	(.01)	0.99	(.01)	1.00	(.01)
2: $[\overline{FISHT}^{+++}]^{-1}$	*	0.93	(.01)	0.94	(.01)	0.96	(.01)	0.95	(.01)	0.99	(.01)	0.98	(.01)	0.99	(.01)	0.98	(.01)	0.98	(.01)
3: $[\overline{TOWT}^{++}]^{-1}$	*	0.95	(.01)	0.96	(.01)	0.97	(.01)	0.97	(.01)	0.99	(.01)	0.99	(.01)	0.99	(.01)	0.99	(.01)	0.99	(.01)
4: $[\overline{TBH}^{++}]^{-1}$	*	0.91	(.01)	0.93	(.01)	0.94	(.01)	0.95	(.01)	0.98	(.01)	0.98	(.01)	0.99	(.01)	0.99	(.01)	0.99	(.01)

Table 8: Abundance indices as a proportion of their values for the base case simulation model run. When the overall krill biomass is decreased to a fraction α of its base case level through a random combination of changes in N_c, L_c, D_c, r and δ. Results relate to the means over 100 simulations in every case. The figures in parenthesis are standard errors of the proportions estimated. Note that some of the indices listed are the inverses of those shown in Tables 4 and 5; the inverse has been taken whenever necessary to make the index an increasing function of α - such cases are indicated by *.

(b) More than one swarm per haul

INDEX \ α		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
A.1: TC^{+++}		0.36 (.07)	0.35 (.07)	0.43 (.08)	0.48 (.07)	0.57 (.07)	0.59 (.06)	0.77 (.06)	0.76 (.07)	0.93 (.06)
2: TH^{+++}		0.42 (.07)	0.40 (.07)	0.47 (.07)	0.52 (.07)	0.60 (.07)	0.62 (.06)	0.62 (.06)	0.78 (.07)	0.93 (.06)
B.1: $TFISHT^{+++}$		0.52 (.07)	0.49 (.06)	0.56 (.07)	0.61 (.06)	0.68 (.06)	0.69 (.06)	0.83 (.06)	0.81 (.06)	0.96 (.06)
2: TPST		0.60 (.08)	0.55 (.07)	0.59 (.07)	0.62 (.07)	0.67 (.06)	0.69 (.06)	0.81 (.06)	0.78 (.07)	0.92 (.06)
3: $TPST + TSST^{+}$		0.42 (.07)	0.40 (.07)	0.46 (.07)	0.50 (.07)	0.59 (.07)	0.61 (.07)	0.78 (.06)	0.76 (.07)	0.93 (.06)
4: $[TCST^{+}]^{-1}$	*	0.57 (.06)	0.56 (.06)	0.59 (.06)	0.60 (.06)	0.65 (.06)	0.66 (.06)	0.77 (.07)	0.78 (.07)	0.92 (.08)
5: $[TAST^{++}]^{-1}$	*	0.70 (.03)	0.69 (.03)	0.72 (.04)	0.73 (.04)	0.77 (.04)	0.77 (.04)	0.86 (.04)	0.87 (.04)	0.96 (.05)
C.1: $TC/TFISHT^{+++}$		0.71 (.03)	0.71 (.03)	0.79 (.03)	0.78 (.02)	0.83 (.02)	0.88 (.04)	0.91 (.02)	0.93 (.02)	0.94 (.02)
2: $\overline{C/FISHT}^{+++}$		0.72 (.06)	0.72 (.06)	0.81 (.06)	0.75 (.05)	0.79 (.04)	0.87 (.05)	0.89 (.04)	0.90 (.04)	0.87 (.04)
3: TC/TPST		0.66 (.04)	0.67 (.03)	0.74 (.03)	0.79 (.03)	0.86 (.02)	0.88 (.02)	0.97 (.02)	0.99 (.02)	1.01 (.02)
4: $\overline{C/PST}$		0.74 (.05)	0.73 (.05)	0.80 (.04)	0.83 (.04)	0.87 (.03)	0.88 (.03)	0.99 (.03)	0.99 (.03)	1.03 (.03)
5: $TC/(TPST+TSST)^{+}$		0.88 (.02)	0.90 (.02)	0.92 (.01)	0.96 (.01)	0.98 (.02)	0.98 (.01)	1.00 (.01)	1.01 (.01)	1.01 (.01)
6: $TC/TCST^{+}$		0.14 (.13)	0.14 (.14)	0.20 (.16)	0.26 (.23)	0.31 (.19)	0.29 (.14)	0.61 (.19)	0.64 (.19)	1.10 (.17)
D.1: $TC/TFISHT/\overline{PST}$		0.53 (.05)	0.54 (.05)	0.62 (.05)	0.66 (.04)	0.74 (.03)	0.79 (.04)	0.89 (.03)	0.93 (.03)	0.96 (.03)
2: $TC/TFISHT/(\overline{PST+SST})^{+}$		0.69 (.03)	0.72 (.04)	0.77 (.03)	0.79 (.02)	0.84 (.02)	0.88 (.03)	0.92 (.02)	0.94 (.02)	0.95 (.02)
3: $TC/TFISHT/\overline{PST}/\overline{CST}$		0.24 (.11)	0.24 (.12)	0.34 (.12)	0.38 (.12)	0.45 (.14)	0.44 (.10)	0.70 (.12)	0.74 (.12)	0.87 (.12)
4: $TC/TFISHT/(\overline{PST+SST})/\overline{CST}^{+}$		0.33 (.10)	0.32 (.11)	0.43 (.12)	0.47 (.11)	0.51 (.12)	0.50 (.10)	0.73 (.12)	0.76 (.11)	0.86 (.12)
5: $TC/TFISHT/TAST^{++}$		0.45 (.04)	0.45 (.05)	0.53 (.05)	0.55 (.05)	0.61 (.05)	0.65 (.05)	0.76 (.05)	0.80 (.05)	0.94 (.05)
E.1: $[TNC^{+}]^{-1}$	*	0.90 (.07)	0.96 (.07)	0.91 (.07)	0.84 (.06)	0.90 (.06)	0.96 (.06)	0.88 (.06)	0.94 (.06)	1.05 (.06)
2: TH/TNC^{+}		0.38 (.06)	0.38 (.06)	0.43 (.06)	0.44 (.07)	0.54 (.07)	0.56 (.07)	0.69 (.07)	0.73 (.07)	0.98 (.08)
F.1: $\overline{C/H}^{+++}$		0.86 (.01)	0.87 (.01)	0.91 (.01)	0.91 (.01)	0.95 (.01)	0.96 (.01)	0.98 (.01)	0.98 (.01)	1.00 (.01)
2: $[\overline{FISH}^{+++}]^{-1}$	*	0.80 (.01)	0.81 (.01)	0.85 (.01)	0.85 (.01)	0.89 (.01)	0.90 (.01)	0.94 (.01)	0.95 (.01)	0.97 (.01)
3: $[\overline{TOW}^{++}]^{-1}$	*	0.87 (.01)	0.87 (.01)	0.90 (.01)	0.90 (.01)	0.93 (.01)	0.94 (.01)	0.96 (.01)	0.97 (.01)	0.98 (.01)
4: $[\overline{TBH}^{++}]^{-1}$	*	0.88 (.01)	0.89 (.01)	0.92 (.01)	0.92 (.01)	0.94 (.01)	0.95 (.01)	0.97 (.01)	0.98 (.01)	0.98 (.01)

Table 9: Efficiency of abundance indices in detecting changes in krill biomass:

blank : 100 simulations detect no change significant at 5% level
+/_ : direction of change if difference significant at 5% level detected
* : index (or its inverse) drops by > 20%
* * : index (or its inverse) drops by > 45% (within 95% limits)

This table corresponds to Table 5a for the "One elongated (f=8) swarm per haul" case, except that concentration searching efficiency has been increased 7.5 times.

INDEX	$N_c \times 0.5$	$N_c \times 0.5$ + P.S.	$L_c \times 1/\sqrt{2}$	$D_c \times 0.5$	$r \times 1/\sqrt{2}$	$\delta \times 0.5$
A.1: TC^{+++}	-*			-	+	-**
2: TH^{+++}	-*			-	+	-*
B.1: TFISHT^{+++}	-*			-	-	
2: TPST	-*			+*	+*	+
3: $\mathrm{TPST + TSST}^{+}$	-*			+*	+*	-
4: TCST^{+}	+**					+*
5: TAST^{++}	+*			+		+
C.1: $\mathrm{TC/TFISHT}^{+++}$					+	-**
2: $\overline{\mathrm{C/FISHT}}^{+++}$					+	-*
3: $\mathrm{TC/TPST}$				-**	-*	-**
4: $\overline{\mathrm{C/PST}}$				-*	-*	-*
5: $\mathrm{TC/(TPST+TSST)}^{+}$				-*	-*	-*
6: $\mathrm{TC/TCST}^{+}$	-**			*	*	-**
D.1: $\mathrm{TC/TFISHT/}\overline{\mathrm{PST}}$				-**	-*	-**
2: $\mathrm{TC/TFISHT/(}\overline{\mathrm{PST+SST}}\mathrm{)}^{+}$				-*	-	-**
3: $\mathrm{TC/TFISHT/}\overline{\mathrm{PST}}\mathrm{/}\overline{\mathrm{CST}}$	-**			-**	-	-**
4: $\mathrm{TC/TFISHT/(}\overline{\mathrm{PST+SST}}\mathrm{)/}\overline{\mathrm{CST}}^{+}$	-**			-*		-**
5: $\mathrm{TC/TFISHT/TAST}^{++}$	-*			-	+	-**
E.1: TNC^{+}	-*			+	-	+*
2: $\mathrm{TH/TNC}^{+}$				-*	+	-**
F.1: $\overline{\mathrm{C/H}}^{+++}$					+	-
2: $\overline{\mathrm{FISHT}}^{+++}$	-			+	-	+*
3: $\overline{\mathrm{TOWT}}^{++}$		-		+	-	+*
4: $\overline{\mathrm{TBH}}^{++}$		-		+		+*

Table 10: A consolidated version of Table 4 for the six abundance indices selected for detailed comparison in section 3.6. Only the point estimates of the percentage difference from the estimated base case mean are given for the six alternative krill distribution scenarios (each corresponding to a 50% overall biomass drop). The first figure shown corresponds to the "One elongated (f=8) swarm per haul" and the second figure to the "More than one swarm per haul" model modification.

INDEX	$N_c \times 0.5$	$N_c \times 0.5$ + P.S.	$L_c \times 1/\sqrt{2}$	$D_c \times 0.5$	$r \times 1/\sqrt{2}$	$\delta \times 0.5$
A.1: TC^{+++}	-40; -41	+ 1; +25	-16; -10	-17; -62	+ 9; -51	-60; -64
C.1: $TC/TFISHT^{+++}$	- 8; + 0	- 2; - 0	- 4; + 0	- 0; -35	+15; -26	-42; -38
3: TC/TPST	- 1; + 3	+ 5; + 3	+ 1; + 5	-43; -51	-33; -30	-45; -36
D.1: TC/TFISHT/PST	- 6; + 3	+ 4; + 2	- 1; + 4	-42; -63	-24; -44	-62; -55
2: $TC/TFISHT/(PST+SST)^{+}$	- 3; - 0	+ 1; - 2	- 2; - 2	-30; -42	-11; -26	-52; -34
3: TC/TFISHT/PST/CST	-57; -45	+ 3; +85	-17; -11	-49; -76	- 8; -62	-77; -72

Table 11: Estimates of the percentage decrease in abundance indices incorporation PST for a 50% overall krill biomass drop are compared with and without random error (see text - section 3.6) in the allocation of within concentration search time between PST and SST. The comparisons are shown for the biomass drop due to falls in each of D_c, r and δ, and are for the "One elongated (f=8) swarm per haul" case.

	$D_c \times 0.5$		$r \times 1/\sqrt{2}$		$\delta \times 0.5$	
INDEX	No error	Error	No error	Error	No error	Error
B.2: TPST	+44	+32	+63	+55	-27	-27
3: TPST+TSST$^+$	+18	+ 5	+39	+32	-44	-43
|Difference|	26	27	24	23	17	16
C.3: TC/TPST	-43	-44	-33	-32	-45	-44
5: TC/(TPST+TSST)$^+$	-31	-31	-22	-21	-29	-29
|Difference|	12	13	11	11	16	15
D.1: TC/TFISHT/$\overline{\mathrm{PST}}$	-42	-47	-24	-23	-62	-61
2: C/TFISHT/$\overline{(\mathrm{PST+SST})}^+$	-30	-34	-11	-11	-52	-51
|Difference|	12	13	13	12	10	10
D.3: TC/TFISHT/$\overline{\mathrm{PST}}$/$\overline{\mathrm{CST}}$	-49	-61	- 8	-10	-77	-76
4: TC/TFISHT/($\overline{\mathrm{PST+SST}}$)/$\overline{\mathrm{CST}}^+$	-39	-51	+ 5	+ 4	-71	-69
|Difference|	10	10	13	14	6	7

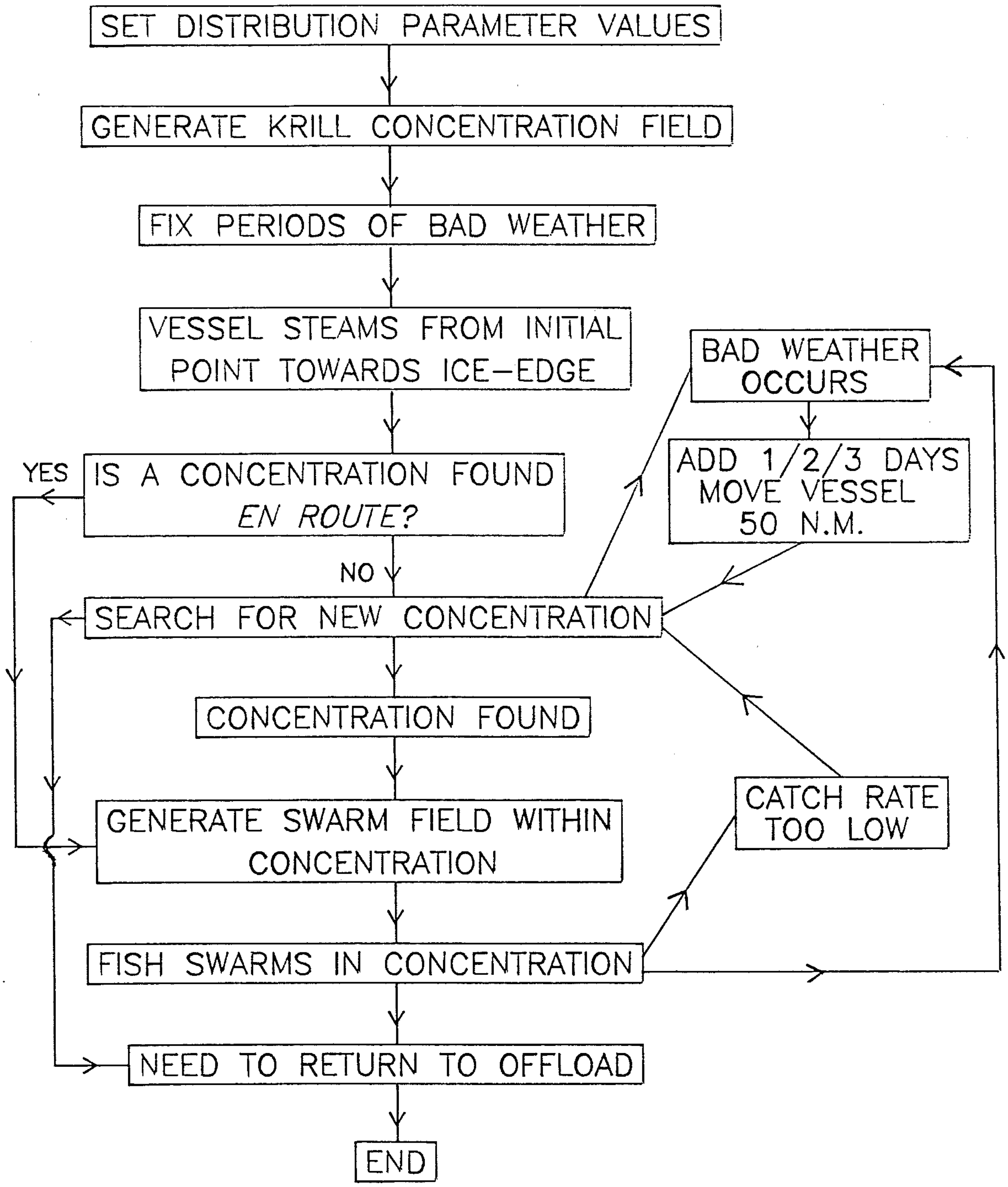


Figure 1: A flow diagram of the basic structure of the simulation model.

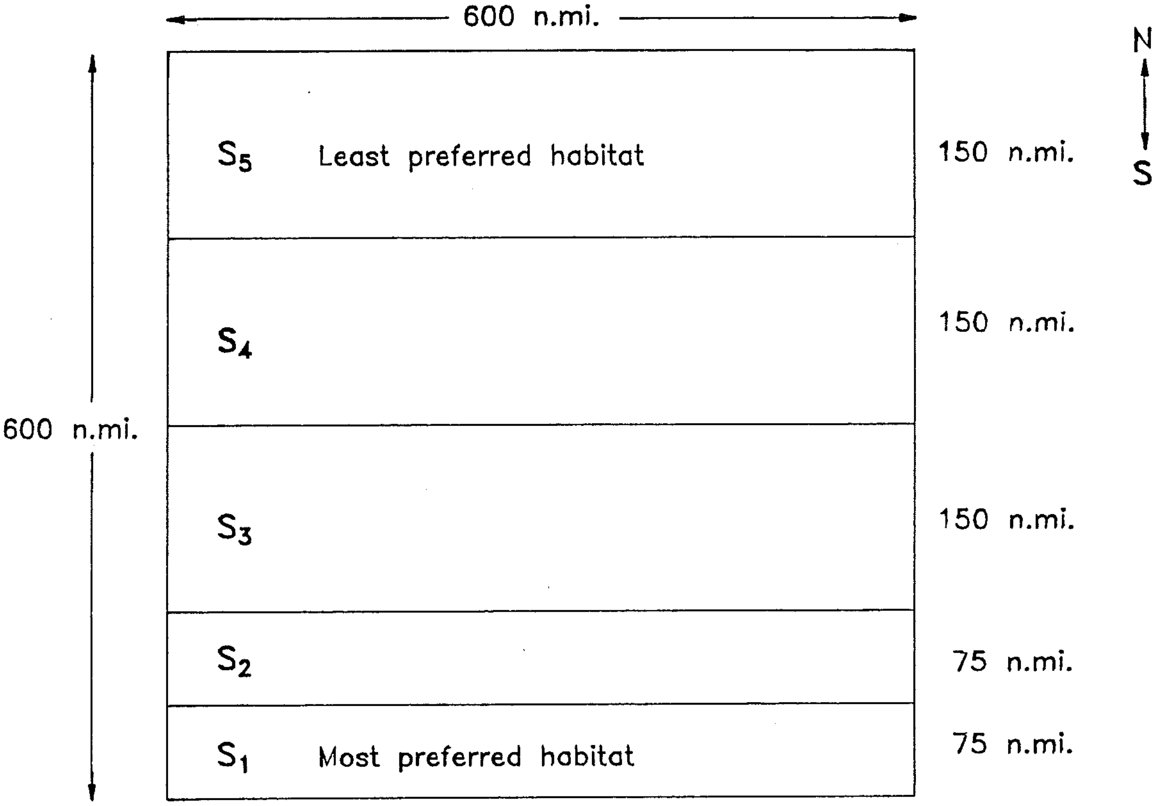


Figure 2: The stratified habitat chosen for the krill distribution model in a 600 n mile square sector of the Southern Ocean.

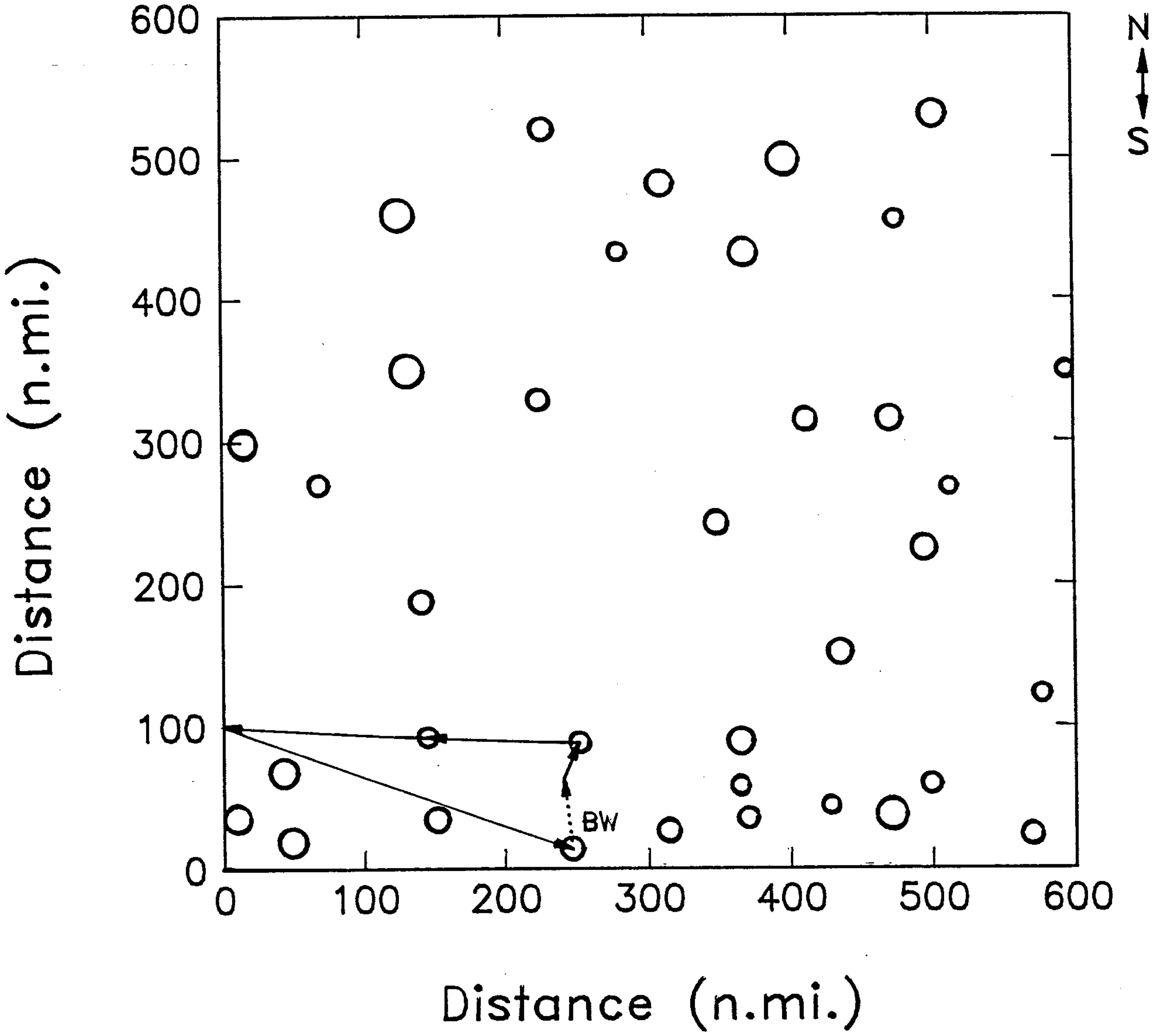


Figure 3: An example of the distribution of krill concentrations in the 600 n mile square Southern Ocean sector chosen, which has been generated as described in section 2.3. The radii of the concentrations are to scale. The arrowed lines indicate the concentrations fished sequentially during a half-month period. The dotted line represents movement during a period of bad weather (see section 2.4).

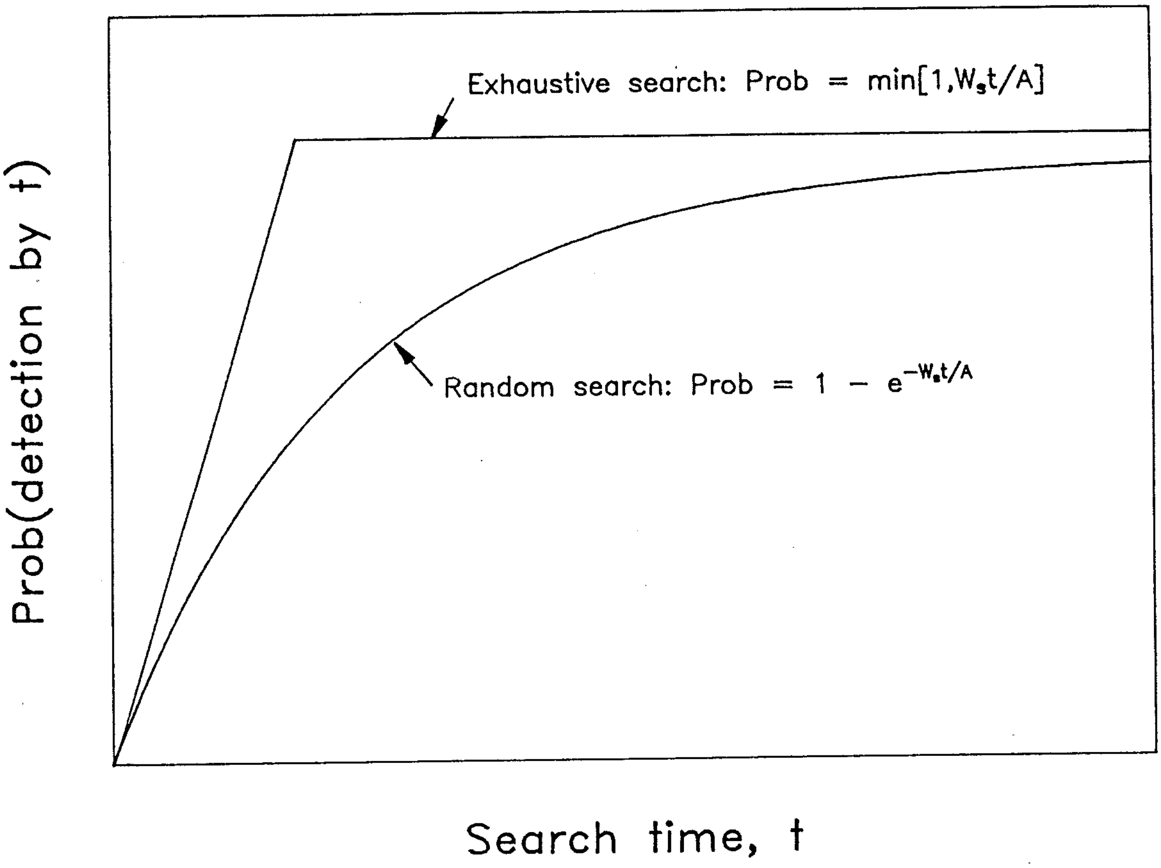


Figure 4: Detection probability as a function of time for the exhaustive search and random search models.

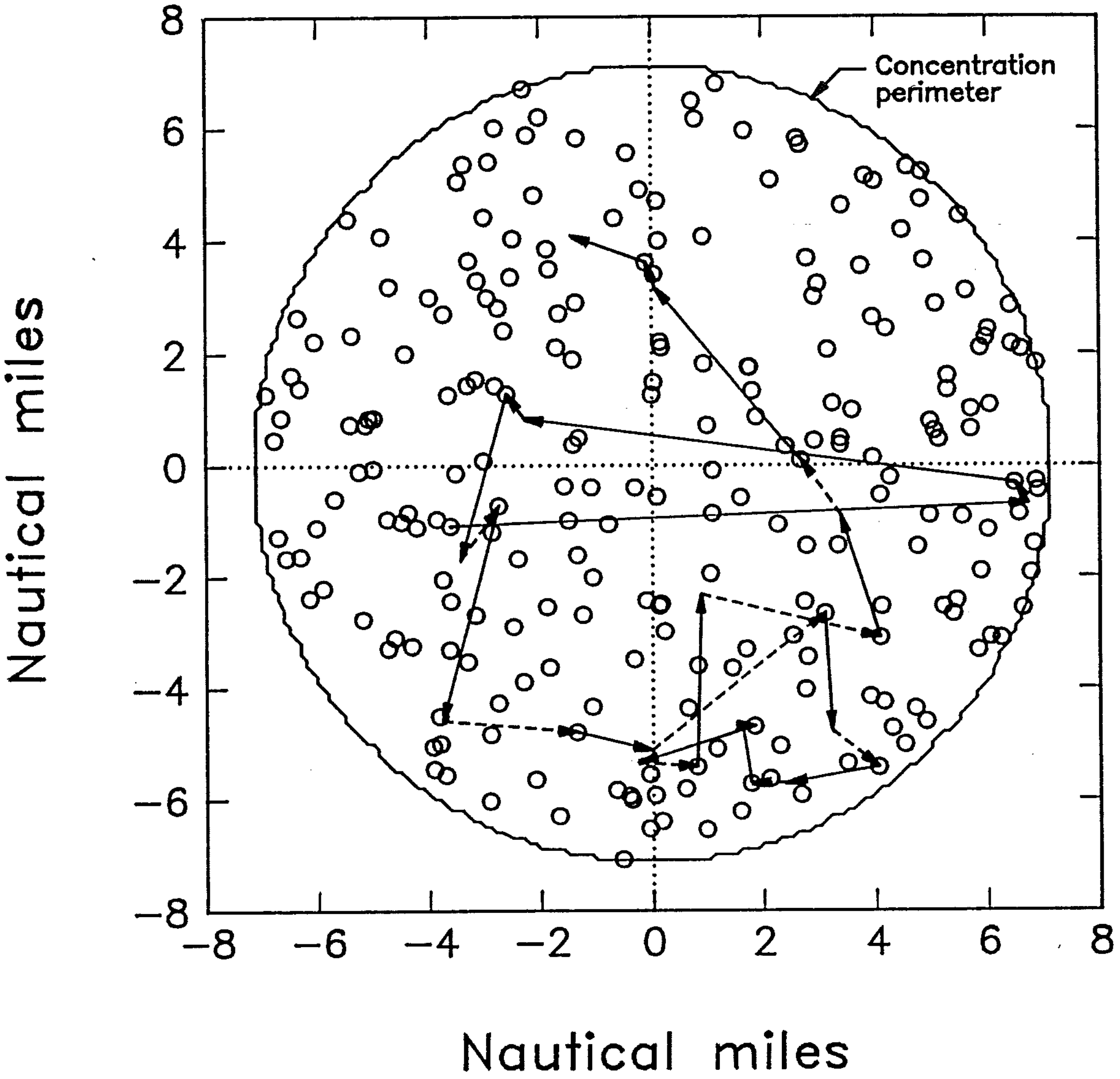


Figure 5: An example of the distribution of fishable swarms in a concentration, generated as described in section 2.7. The radii of the swarms are NOT to scale. This example corresponds to the "One elongated (f=8) swarm per haul" model modification, with the symbol for each fishable swarm placed at the centre point chosen for that swarm prior to elongation. The arrowed lines reflect the sequential towing of swarms in the concentration by a fishing vessel. Note that only the initial swarms are towed, even though these lines may intersect the symbols for other swarms. The full lines represent the length and direction of each haul (to scale), while the dashed lines indicate net movement in searching for the following swarm to tow.

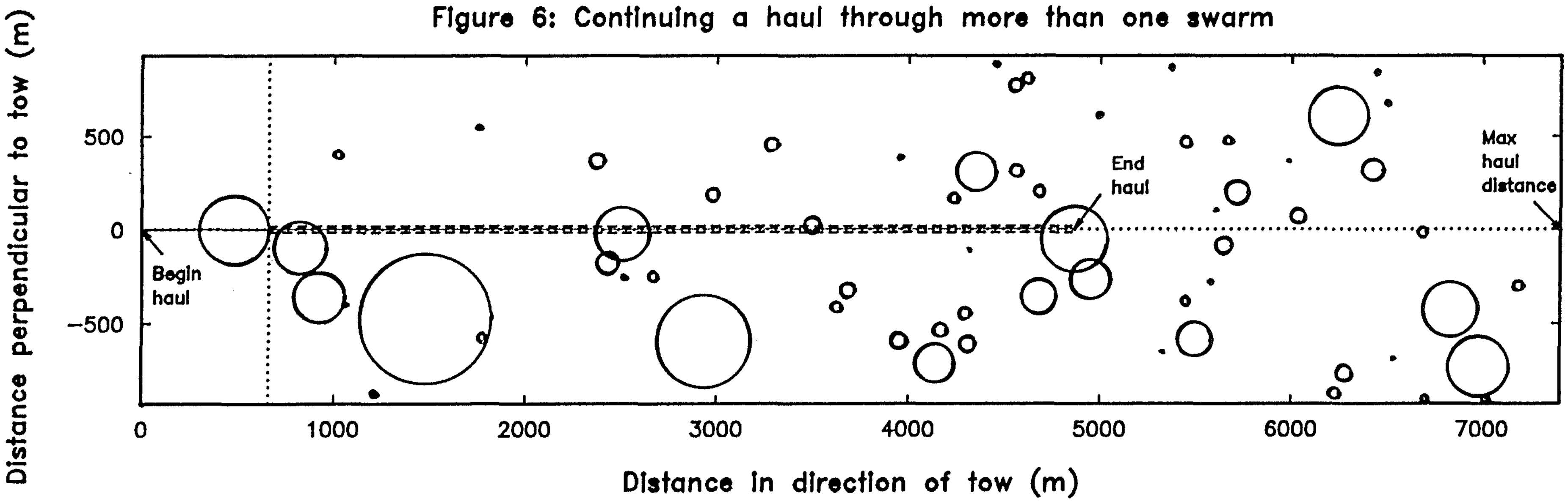
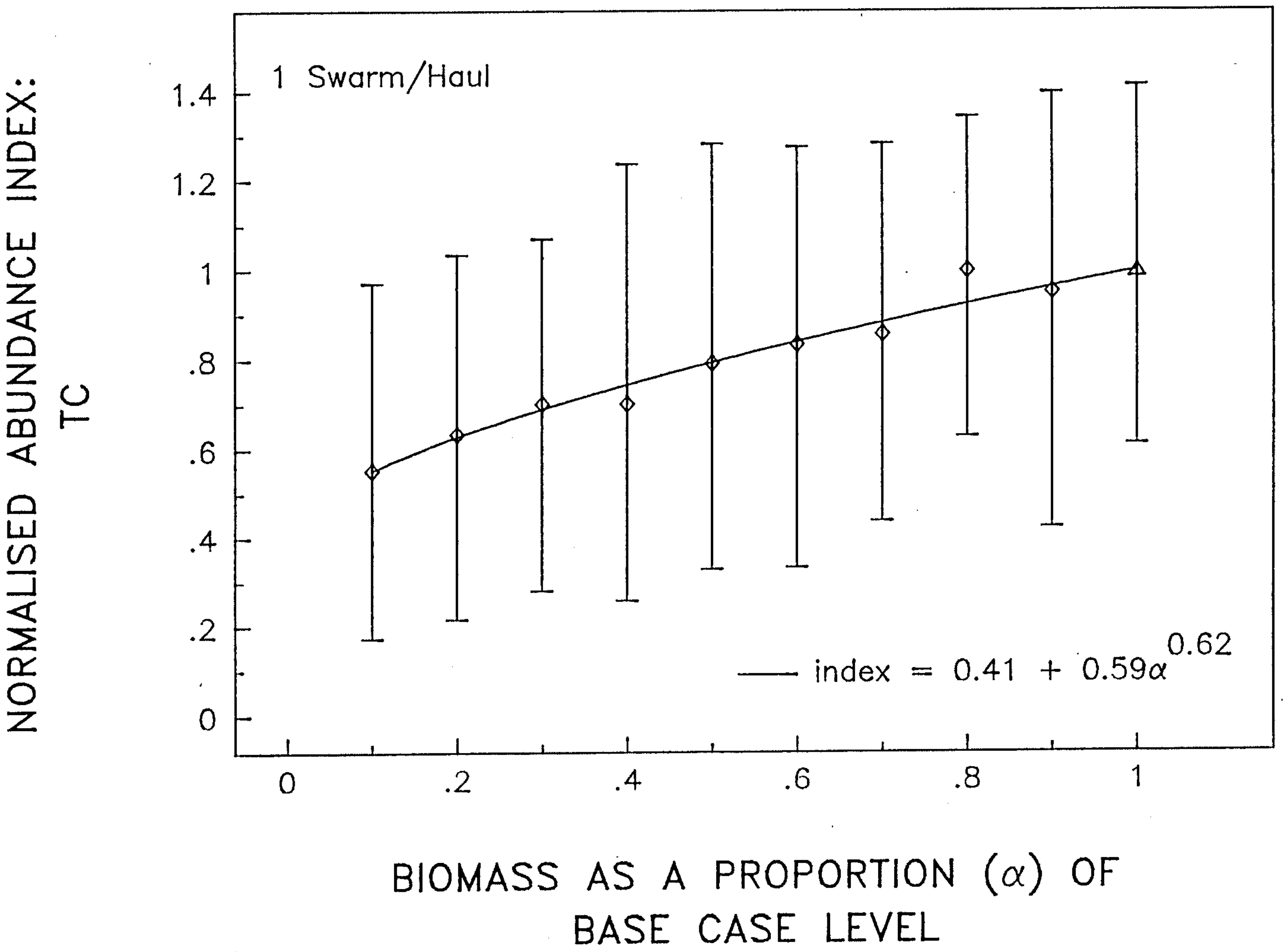


Figure 6: An example of a single haul for the model modification where more than one swarm may be towed per haul (see sections 2.8 and 3.3). The swarms shown are to scale. While the initial swarm towed is a "fishable" swarm in terms of criterion (20), <u>all</u> swarms in the area to the right of this original swarm are shown. The dashed lines to the right of the initial swarm define the "sonar band"; swarms intersecting this band are also fished until the haul is ended because (in this example) the Captain estimates the catch has reached 10 tonnes.

Figure 7: Plots of abundance indices as a function of α (the proportion of the base case level to which the krill biomass has been reduced), where biomass reduction occurs as a result of a random combination of decreases in the distribution parameters N_C, L_C, D_C, r and δ. The abundance indices have been normalised to their estimated base case mean levels. The error bars shown represent estimates of the central 68% of the distribution of the index in question for a vessel-half-month, while the symbol is the estimate of the distribution mean, for each particular value of α. A formula is shown for the curve fitted to the relationship between the index and *a* by the method described in section 3.5. Plots a) and b) are for the "One elongated (f=8) swarm per haul" and "More than one swarm per haul" model modifications respectively, and correspond to the indices :

(i) TC
(ii) TC/TFISHT
(iii) TC/TPST
(iv) TC/TFISHT/$\overline{\text{PST+SST}}$
(v) TC/TFISHT/($\overline{\text{PST+SST}}$)
(vi) TC/TFISHT/$\overline{\text{PST/CST}}$

Figure 7 i) a)



1 Swarm/Haul
NORMALISED ABUNDANCE INDEX: TC
1.4
1.2
1
.8
.6
.4
.2
0
.2
.4
.6
.8
1
index = 0.41 + 0.59α^0.62
BIOMASS AS A PROPORTION (α) OF BASE CASE LEVEL

Figure 7 i) b)

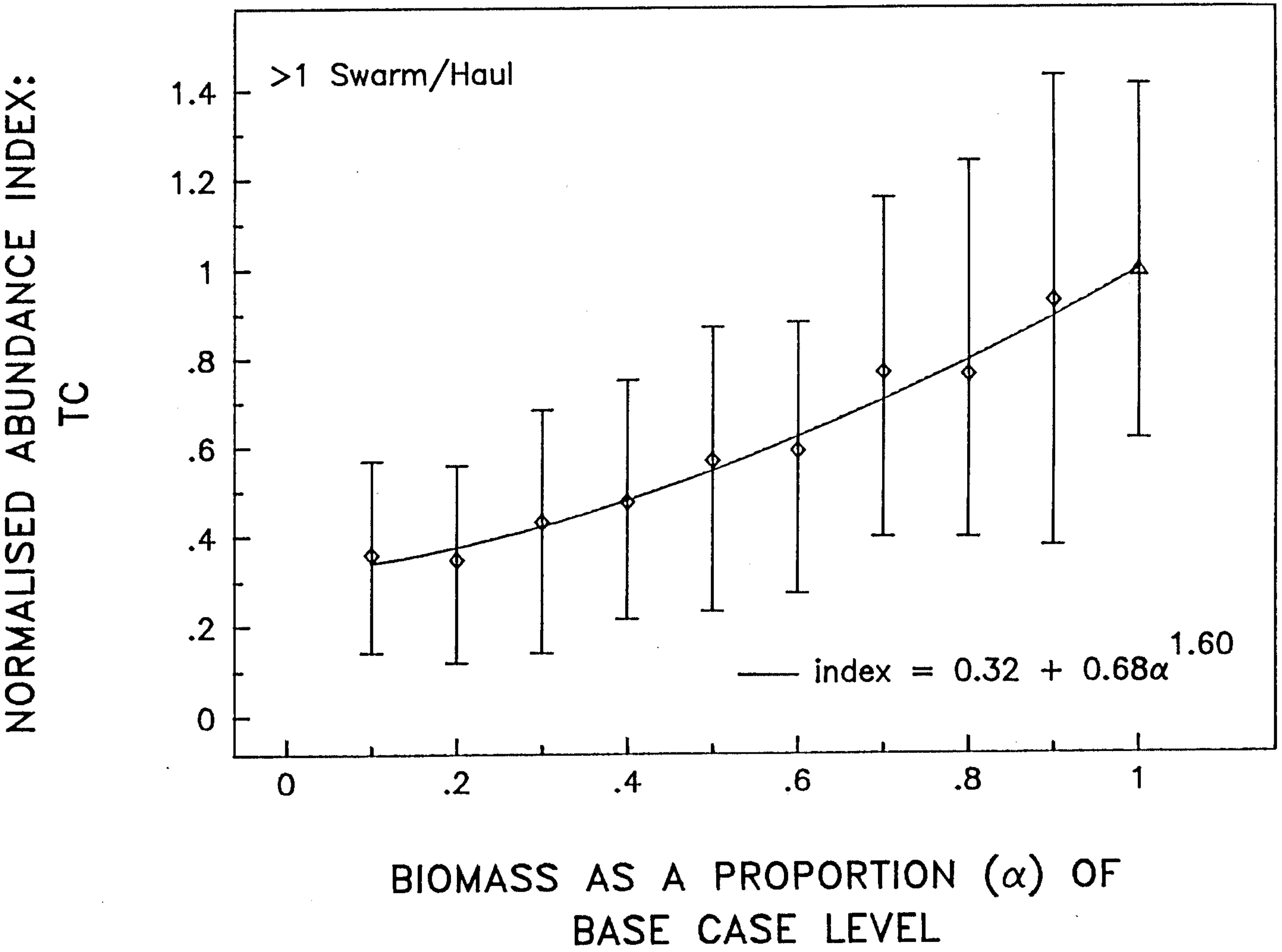

>1 Swarm/Haul
NORMALISED ABUNDANCE INDEX:
TC
1.4
1.2
1
.8
.6
.4
.2
0
0
.2
.4
.6
.8
1
index = 0.32 + 0.68α^1.60
BIOMASS AS A PROPORTION (α) OF
BASE CASE LEVEL

Figure 7 ii) a)

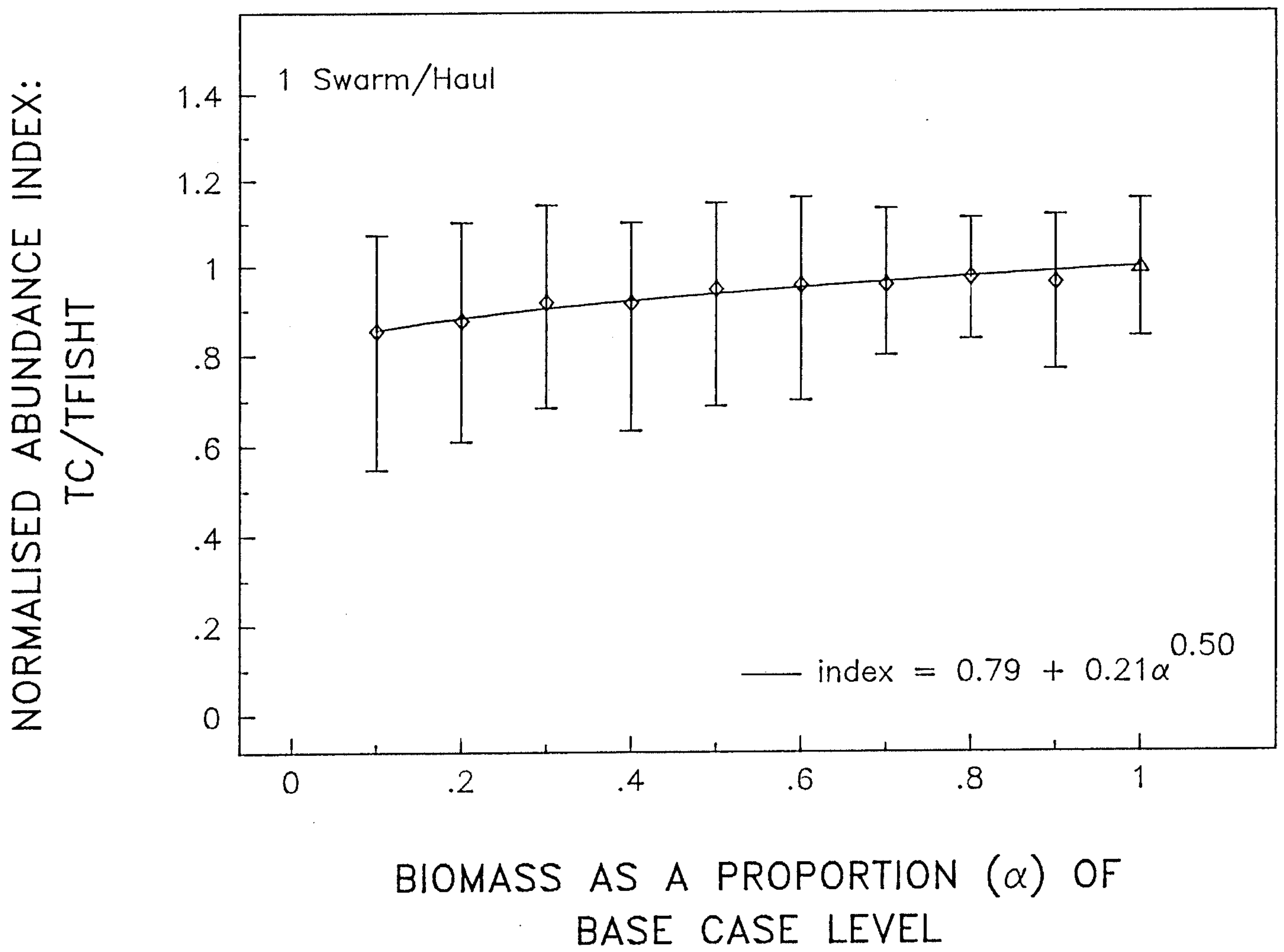

1 Swarm/Haul
NORMALISED ABUNDANCE INDEX:
TC/TFISHT
1.4
1.2
1
.8
.6
.4
.2
0
0
.2
.4
.6
.8
1
index = 0.79 + 0.21α^0.50
BIOMASS AS A PROPORTION (α) OF
BASE CASE LEVEL

Figure 7 ii) b)

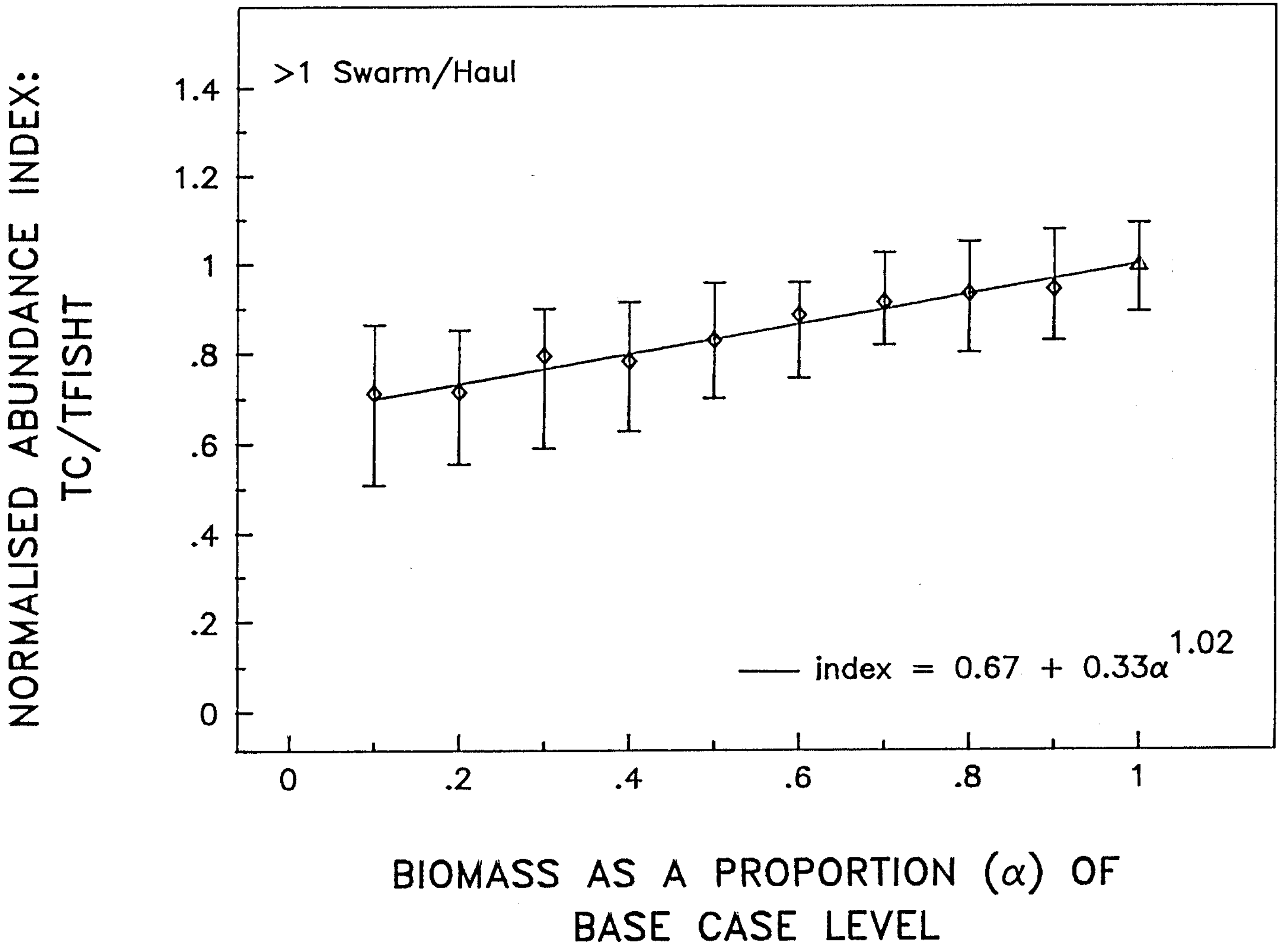

>1 Swarm/Haul
NORMALISED ABUNDANCE INDEX:
TC/TFISHT
1.4
1.2
1
.8
.6
.4
.2
0
— index = 0.67 + 0.33α^1.02
0
.2
.4
.6
.8
1
BIOMASS AS A PROPORTION (α) OF
BASE CASE LEVEL

Figure 7 iii) a)

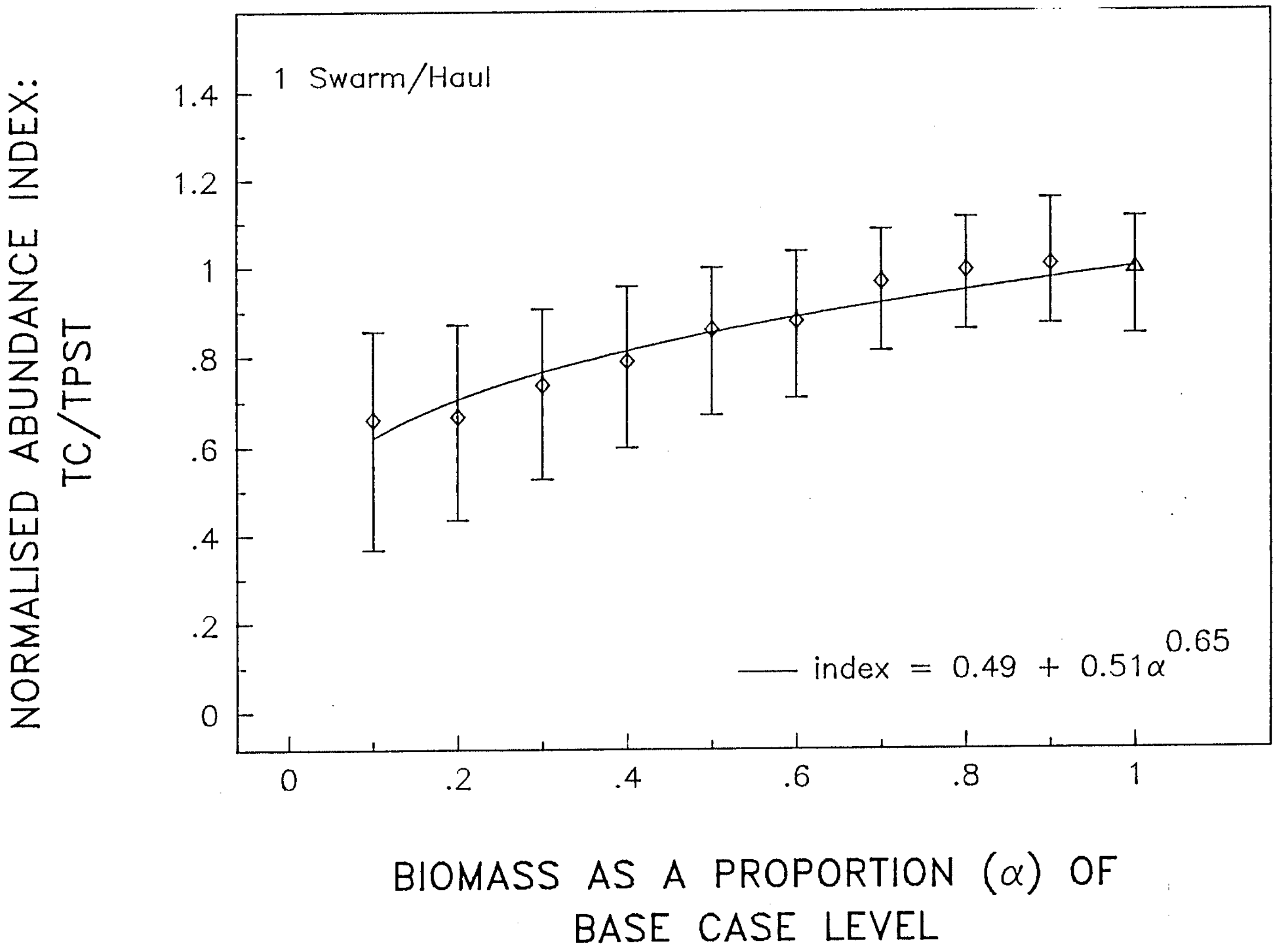


Figure 7 iii) b)

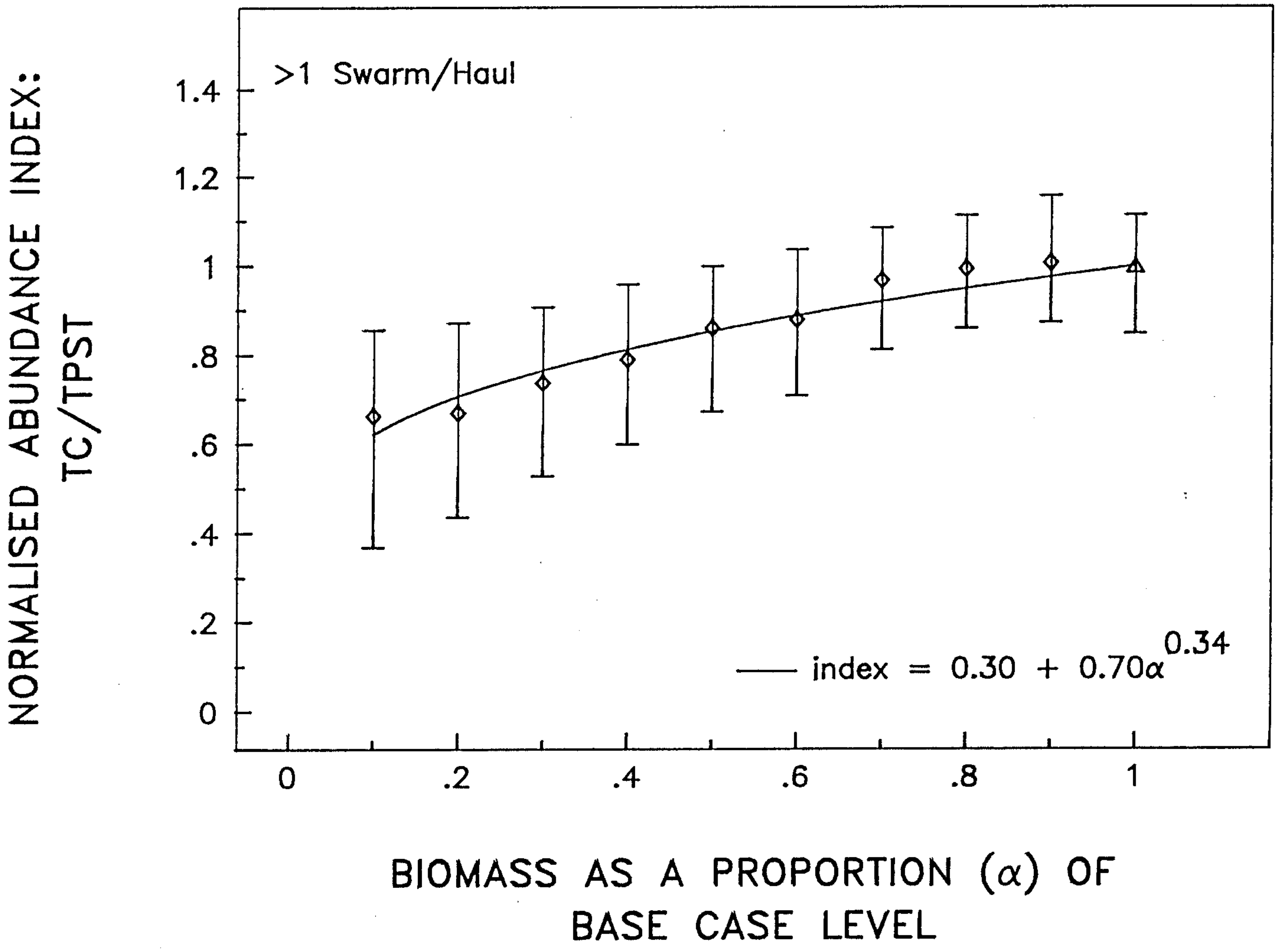


Figure 7 iv) a)

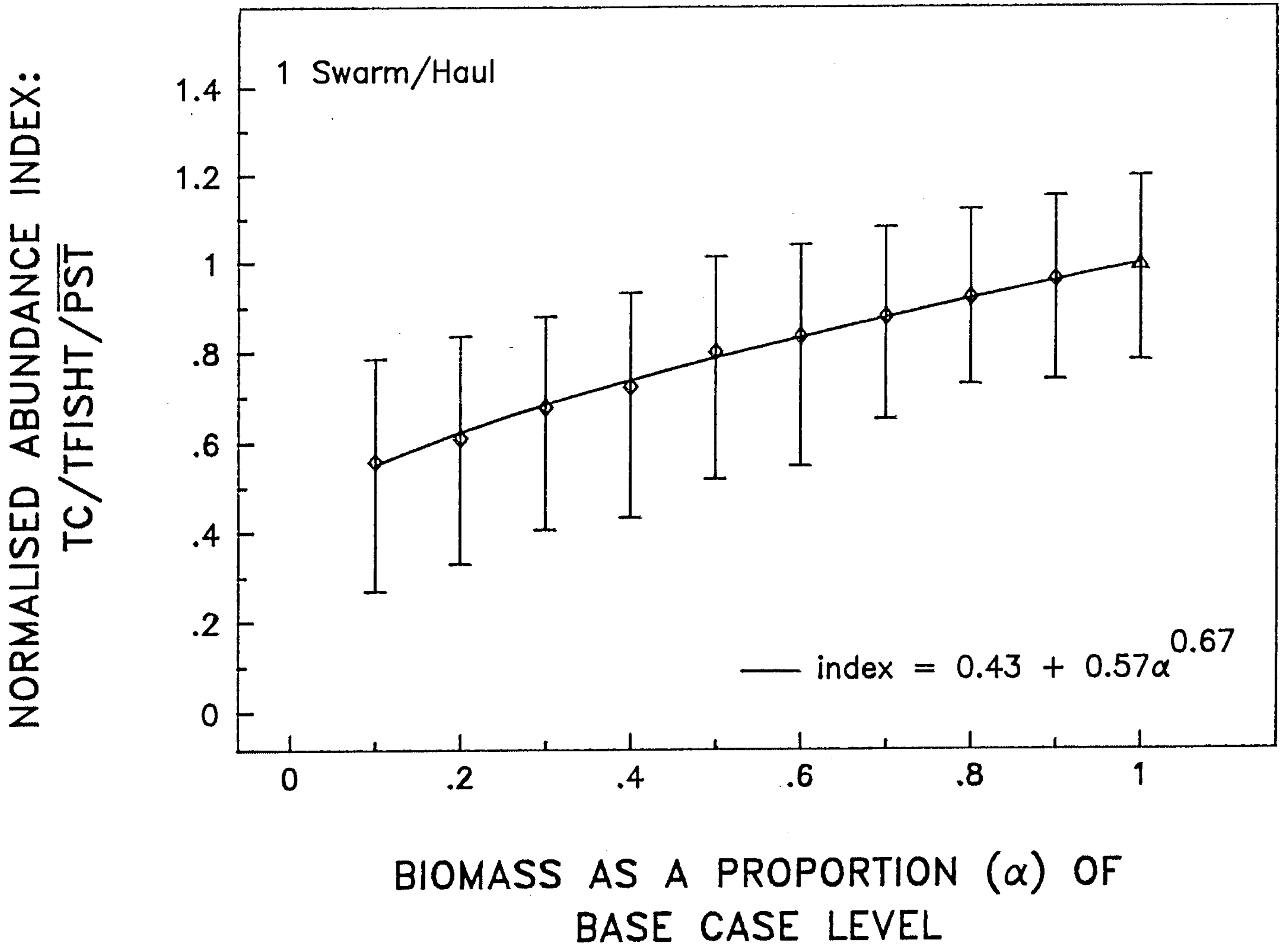

1 Swarm/Haul
NORMALISED ABUNDANCE INDEX:
TC/TFISHT/$\overline{PST}$
1.4
1.2
1
.8
.6
.4
.2
0
0
.2
.4
.6
.8
1
index = 0.43 + 0.57$\alpha^{0.67}$
BIOMASS AS A PROPORTION (α) OF
BASE CASE LEVEL

Figure 7 iv) b)

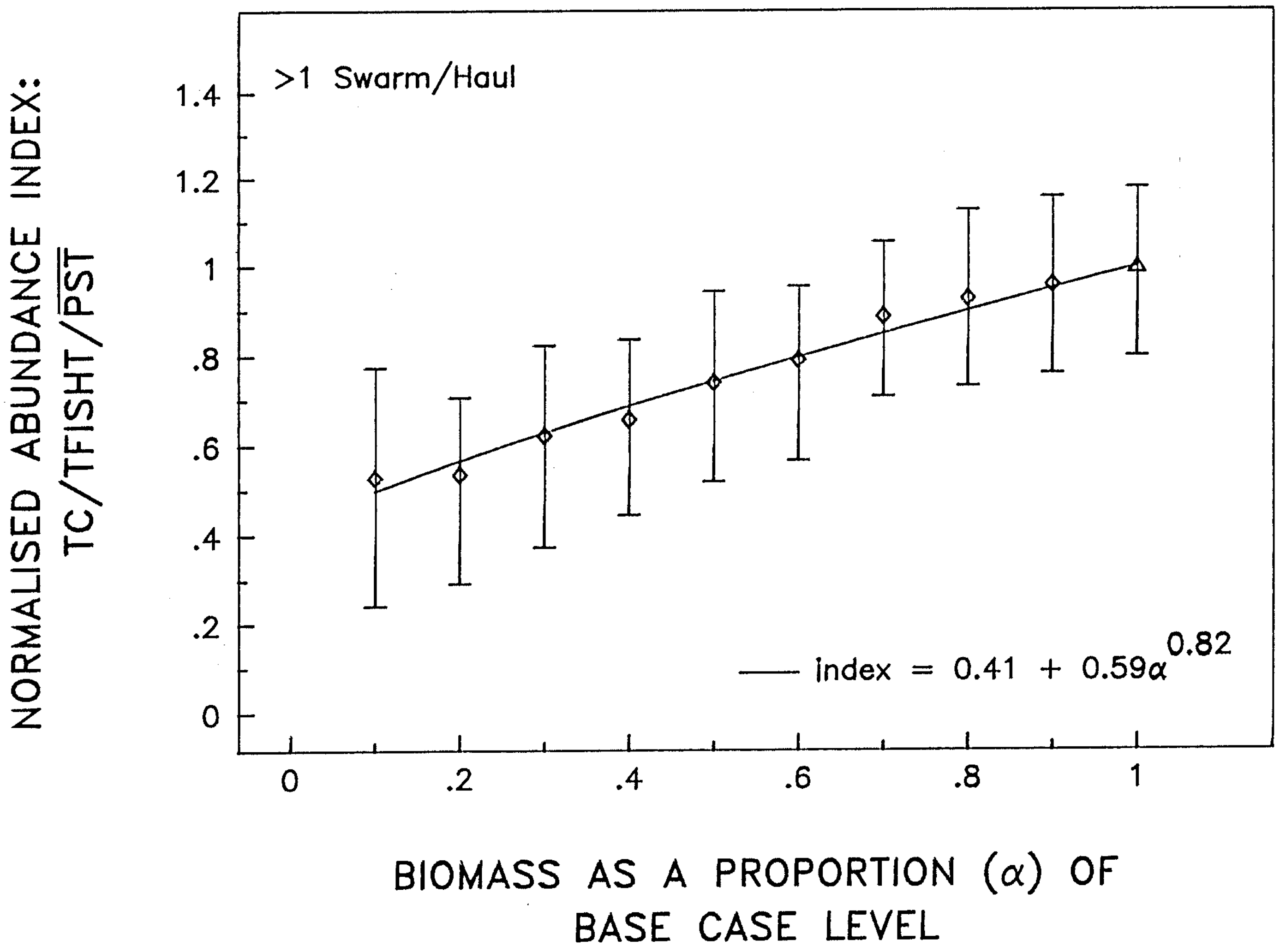

>1 Swarm/Haul
NORMALISED ABUNDANCE INDEX:
TC/TFISHT/$\overline{PST}$
1.4
1.2
1
.8
.6
.4
.2
0
0
.2
.4
.6
.8
1
index = 0.41 + 0.59$\alpha^{0.82}$
BIOMASS AS A PROPORTION (α) OF
BASE CASE LEVEL

Figure 7 v) a)

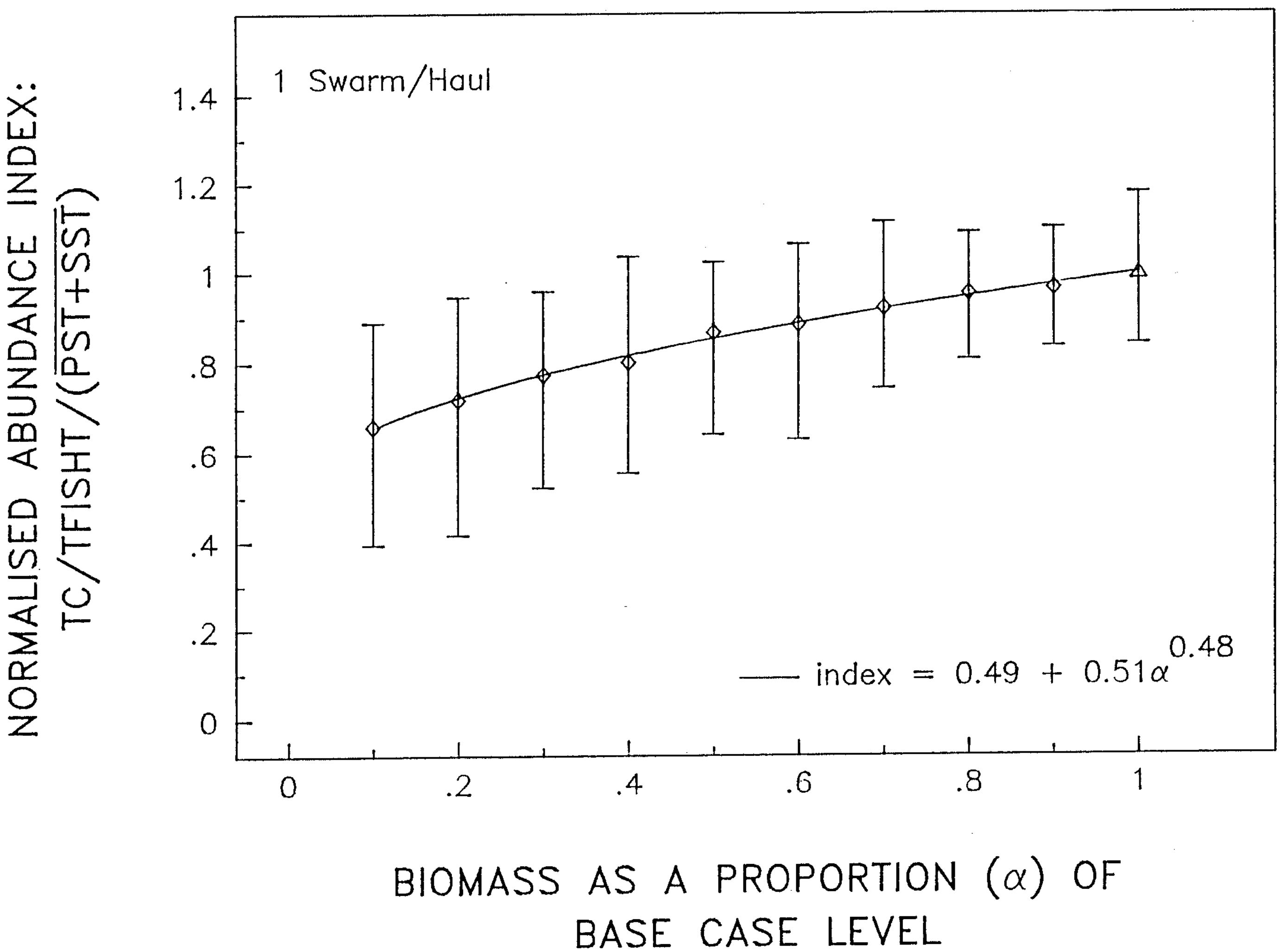

NORMALISED ABUNDANCE INDEX:
$TC/TFISHT/(\overline{PST+SST})$
1 Swarm/Haul
1.4
1.2
1
.8
.6
.4
.2
0
0
.2
.4
.6
.8
1
index = $0.49 + 0.51\alpha^{0.48}$
BIOMASS AS A PROPORTION (α) OF
BASE CASE LEVEL

Figure 7 v) b)

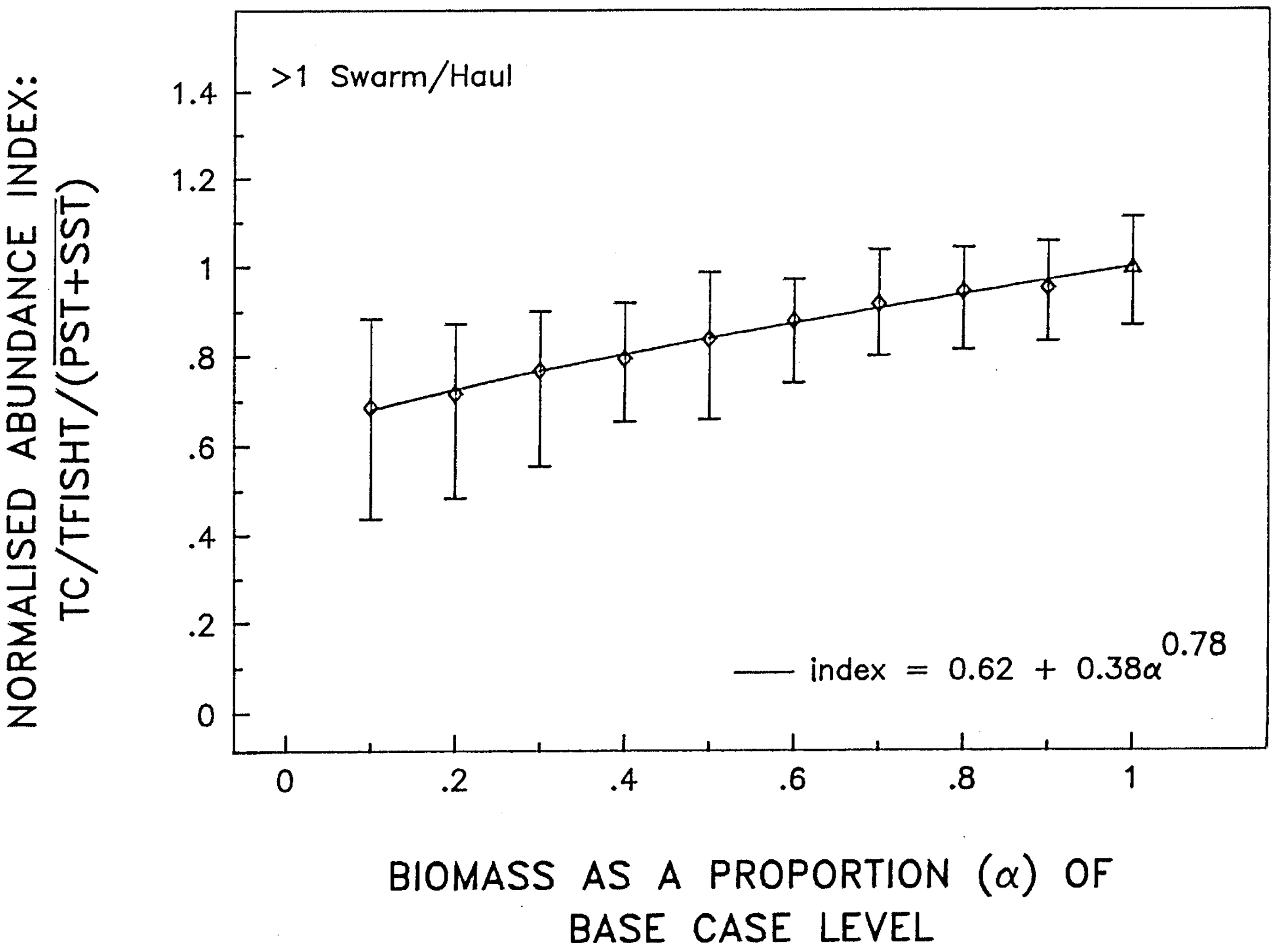
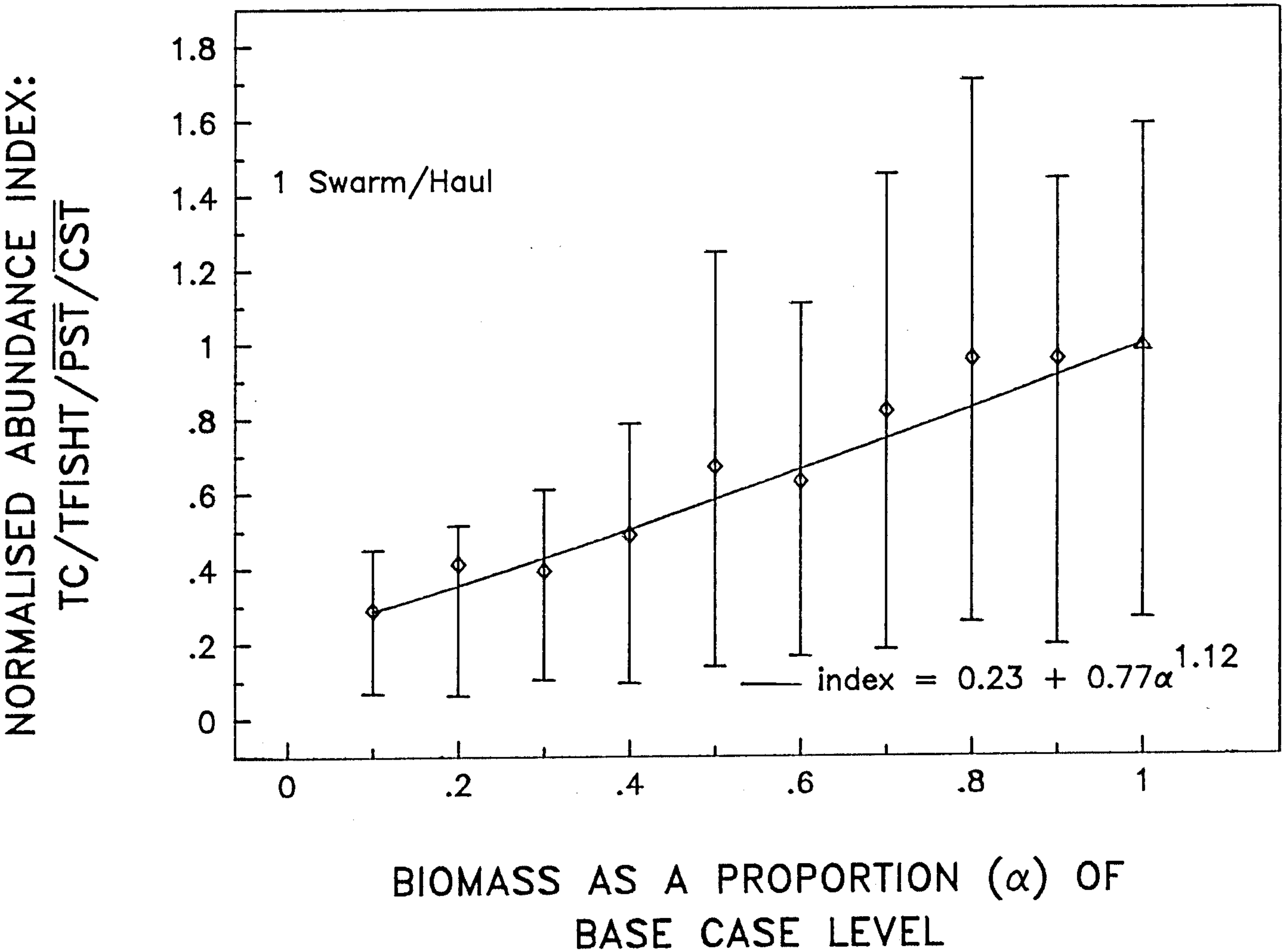

>1 Swarm/Haul
NORMALISED ABUNDANCE INDEX:
TC/TFISHT/(PST+SST)
1.4
1.2
1
.8
.6
.4
.2
0
index = 0.62 + 0.38α^0.78
0
.2
.4
.6
.8
1
BIOMASS AS A PROPORTION (α) OF
BASE CASE LEVEL

Figure 7 vi) a)



NORMALISED ABUNDANCE INDEX:
$TC/TFISHT/\overline{PST}/\overline{CST}$
1.8
1.6
1.4
1.2
1
.8
.6
.4
.2
0
1 Swarm/Haul
index = $0.23 + 0.77\alpha^{1.12}$
0
.2
.4
.6
.8
1
BIOMASS AS A PROPORTION (α) OF
BASE CASE LEVEL

Figure 7 vi) b)

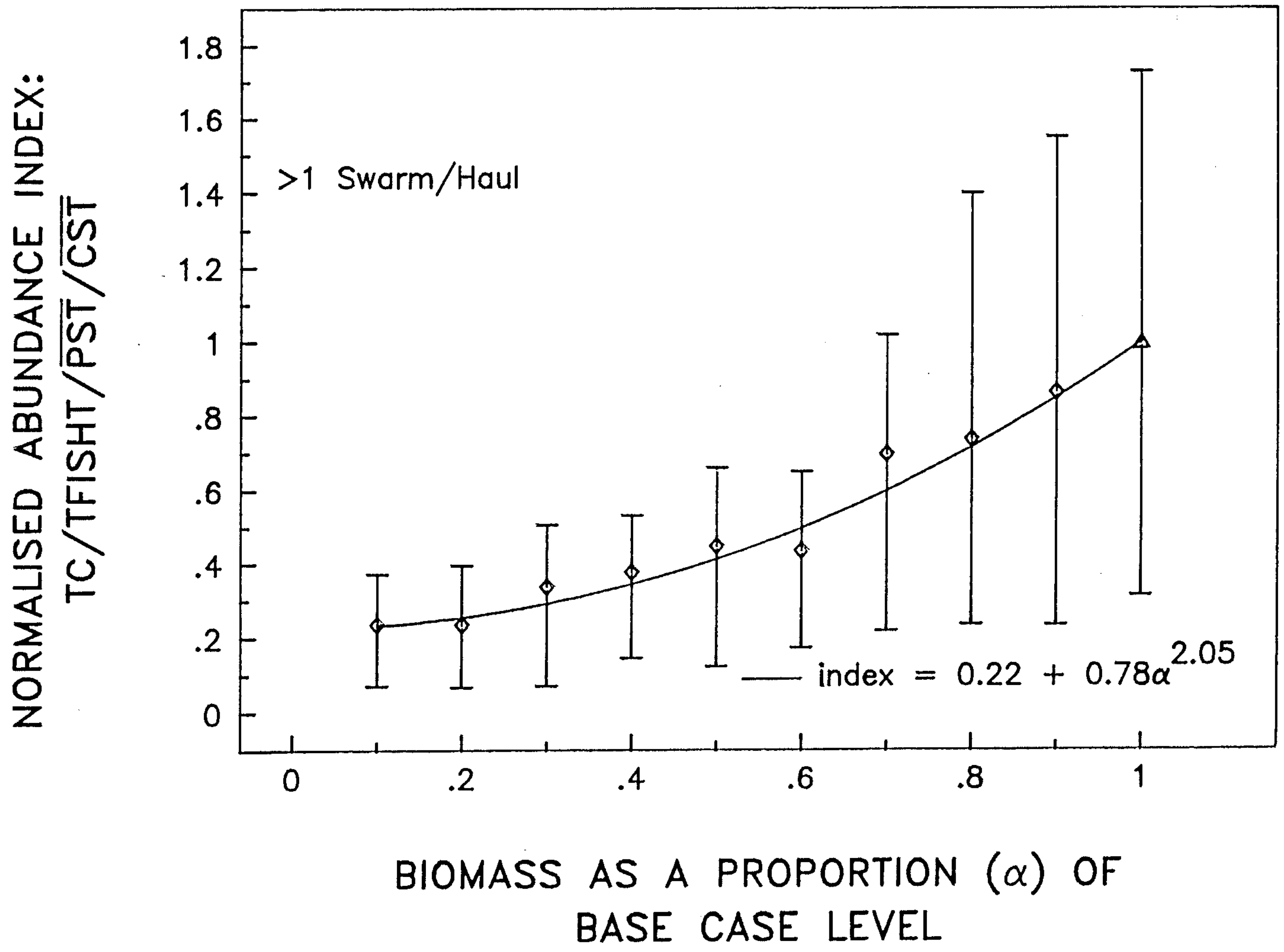

NORMALISED ABUNDANCE INDEX:
TC/TFISHT/$\overline{PST}$/$\overline{CST}$
1.8
1.6
1.4
1.2
1
.8
.6
.4
.2
0
>1 Swarm/Haul
index = 0.22 + 0.78α^2.05
0
.2
.4
.6
.8
1
BIOMASS AS A PROPORTION (α) OF
BASE CASE LEVEL

Figure 8: Plots of (i) total half-monthly catch (TC) and (ii) number of concentrations fished (TNC) against the minimum catch rate per overall elapsed time (CR_{min}) required to be achieved for a vessel not to leave a concentration. The plots are for the base case krill distribution and the "One elongated (f=8) swarm per haul model modification. The error bars indicate one standard deviation.

Figure 8 i) TC *vs* CR_{min}

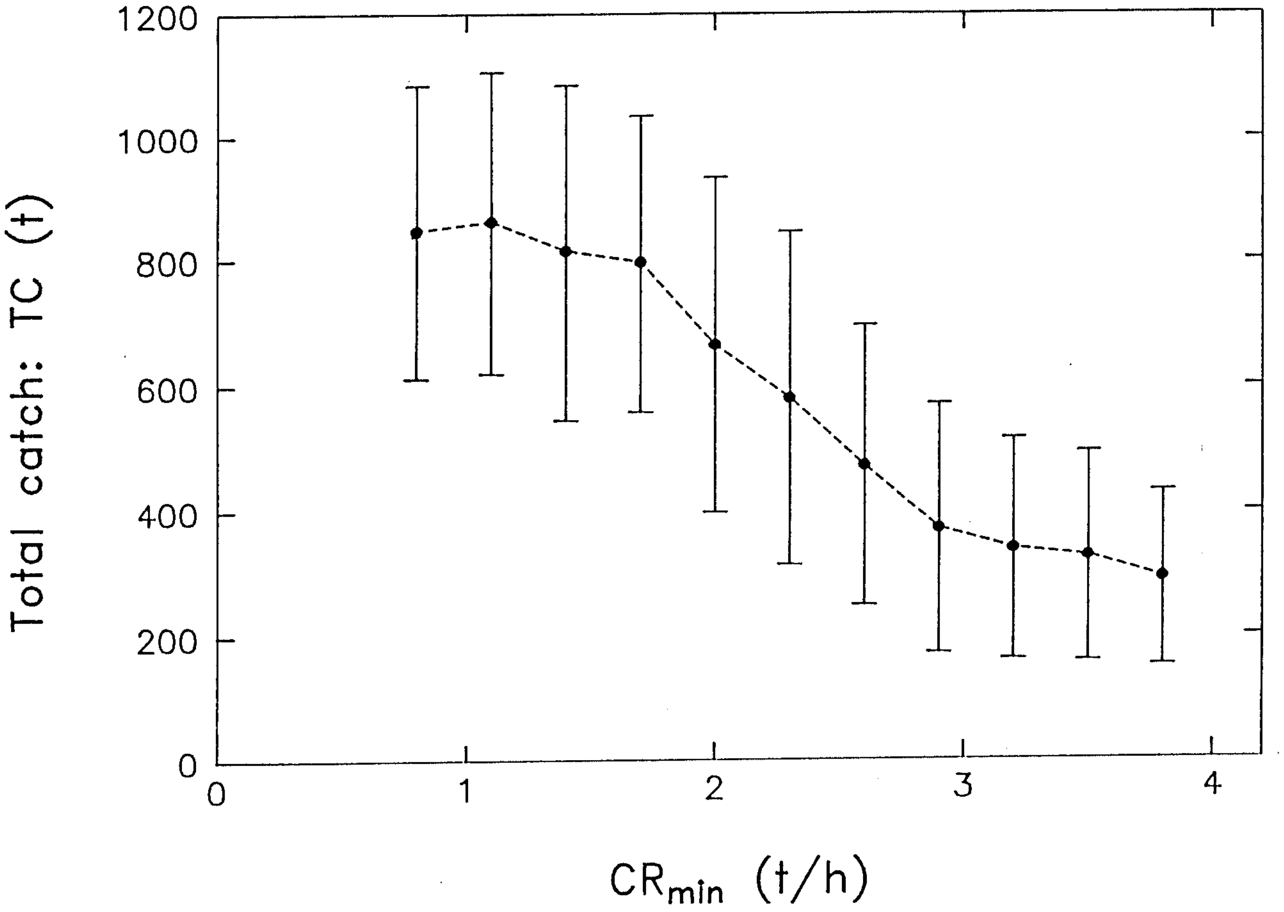


Figure 8 ii) TNC *vs* CR_{min}

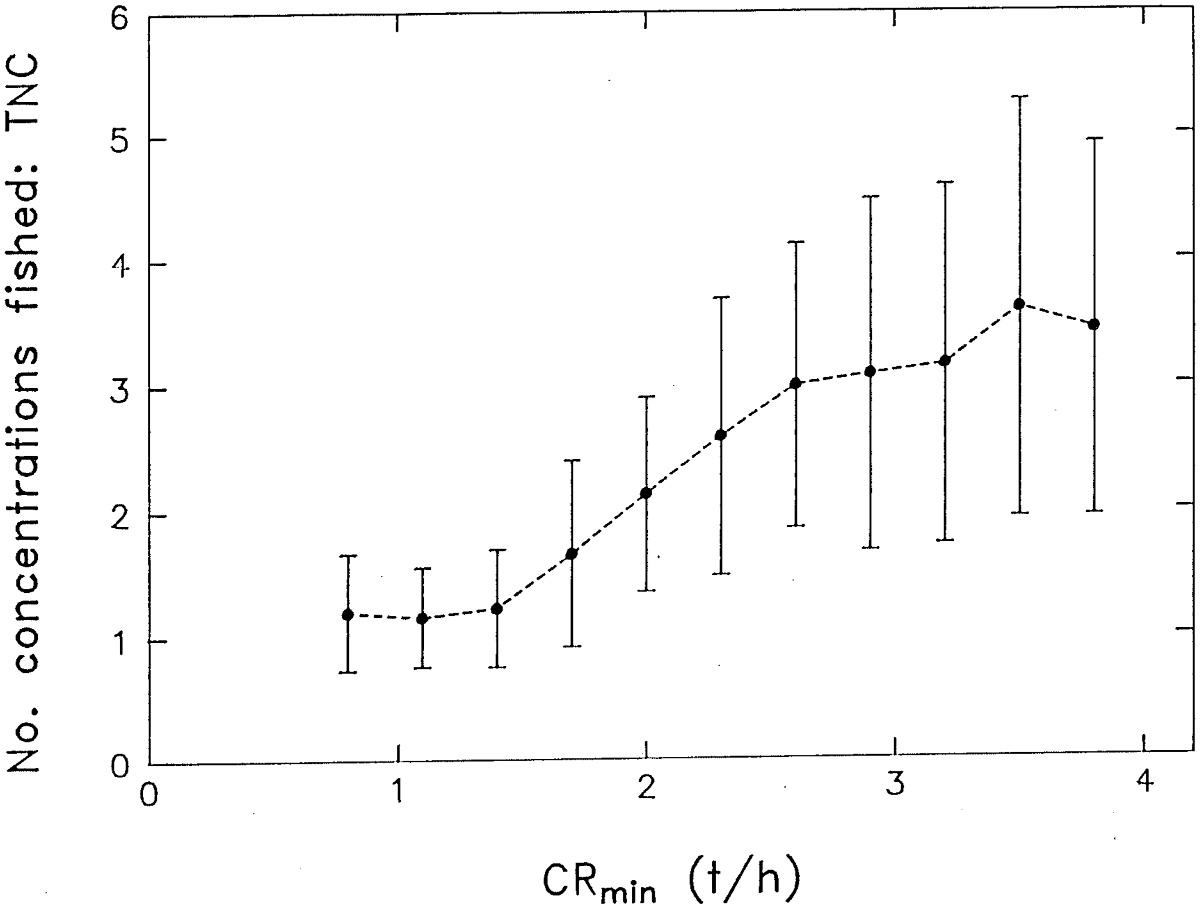


Figure 9: Plots of abundance indices against α as in Figure 7, except that the overall biomass decline is the result of a change in krill swarm surface density δ only. The plots are for the "One elongated (f=8) swarm per haul" model modification, and correspond to the indices :

(i) TC
(ii) TC/TFISHT
(iii) TC/TPST
(iv) TC/(TPST+TSST)

(v) TC/TFISHT/$\overline{\text{PST+SST}}$

(vi) TC/TFISHT/$\overline{\text{PST/CS}}$T

Figure 9 i)

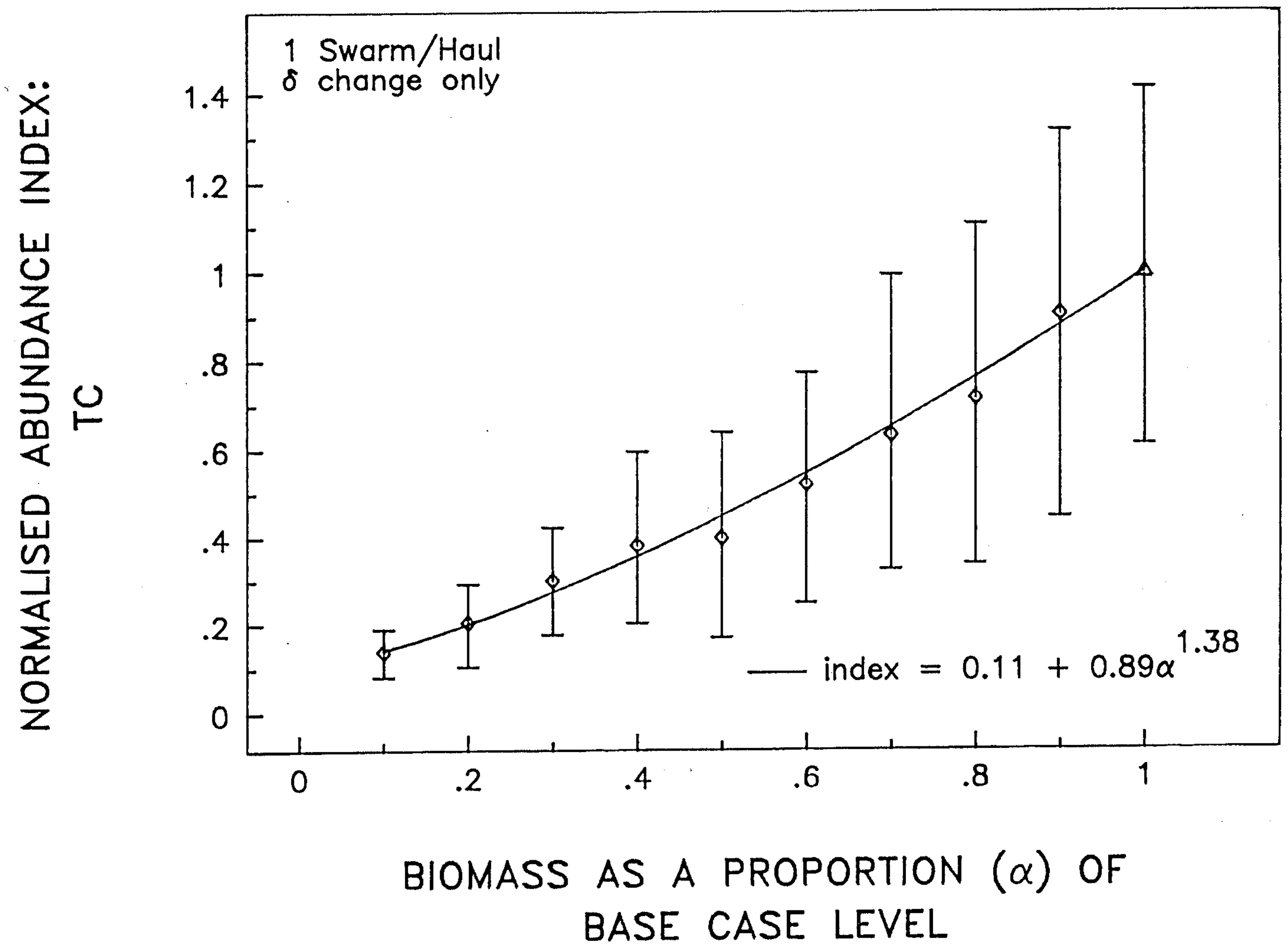

1 Swarm/Haul
δ change only
NORMALISED ABUNDANCE INDEX:
TC
1.4
1.2
1
.8
.6
.4
.2
0
— index = 0.11 + 0.89α^1.38
0
.2
.4
.6
.8
1
BIOMASS AS A PROPORTION (α) OF
BASE CASE LEVEL

Figure 9 ii)

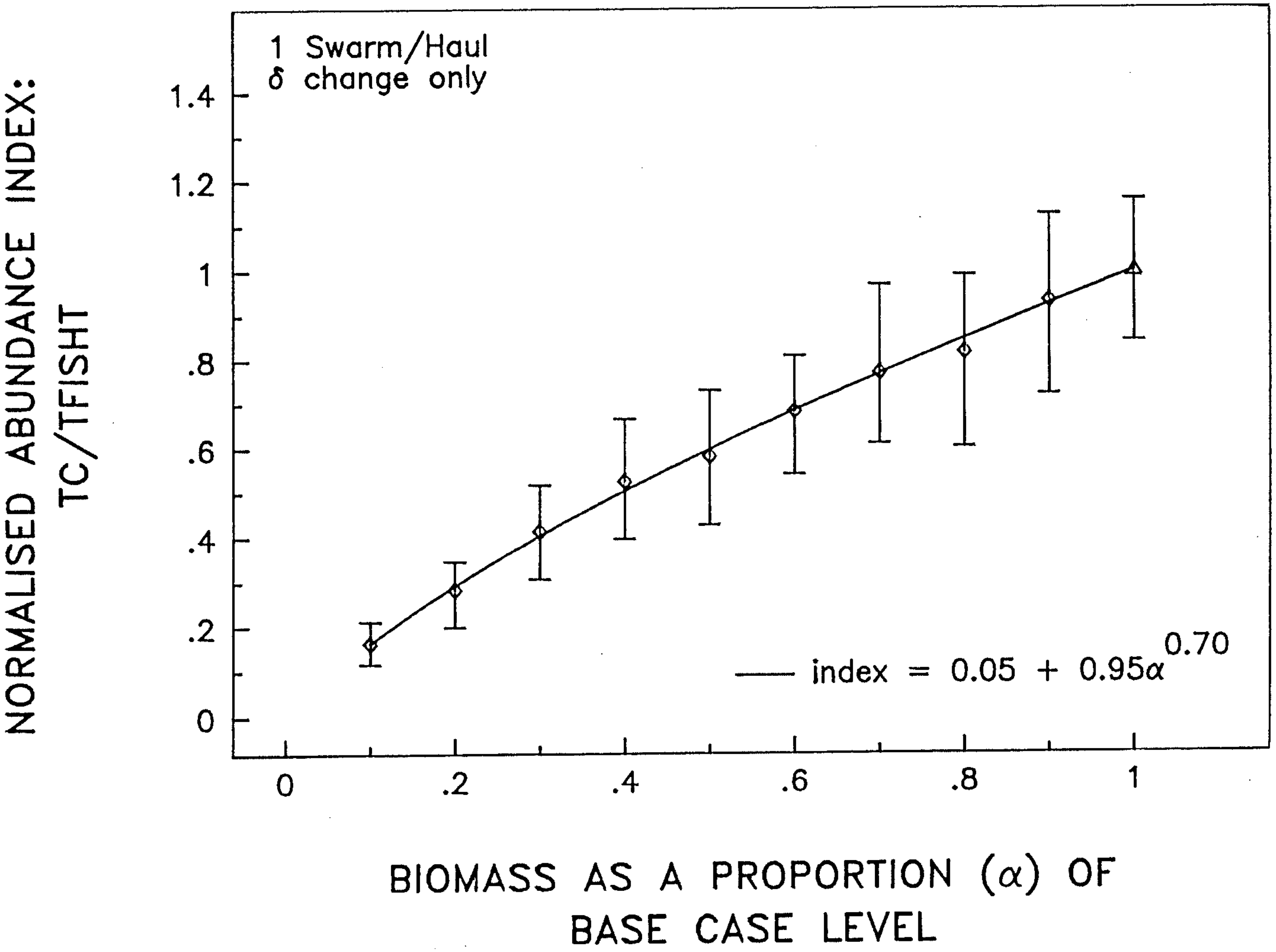

1 Swarm/Haul
δ change only
NORMALISED ABUNDANCE INDEX:
TC/TFISHT
1.4
1.2
1
.8
.6
.4
.2
0
— index = 0.05 + 0.95α^0.70
0
.2
.4
.6
.8
1
BIOMASS AS A PROPORTION (α) OF
BASE CASE LEVEL

Figure 9 iii)

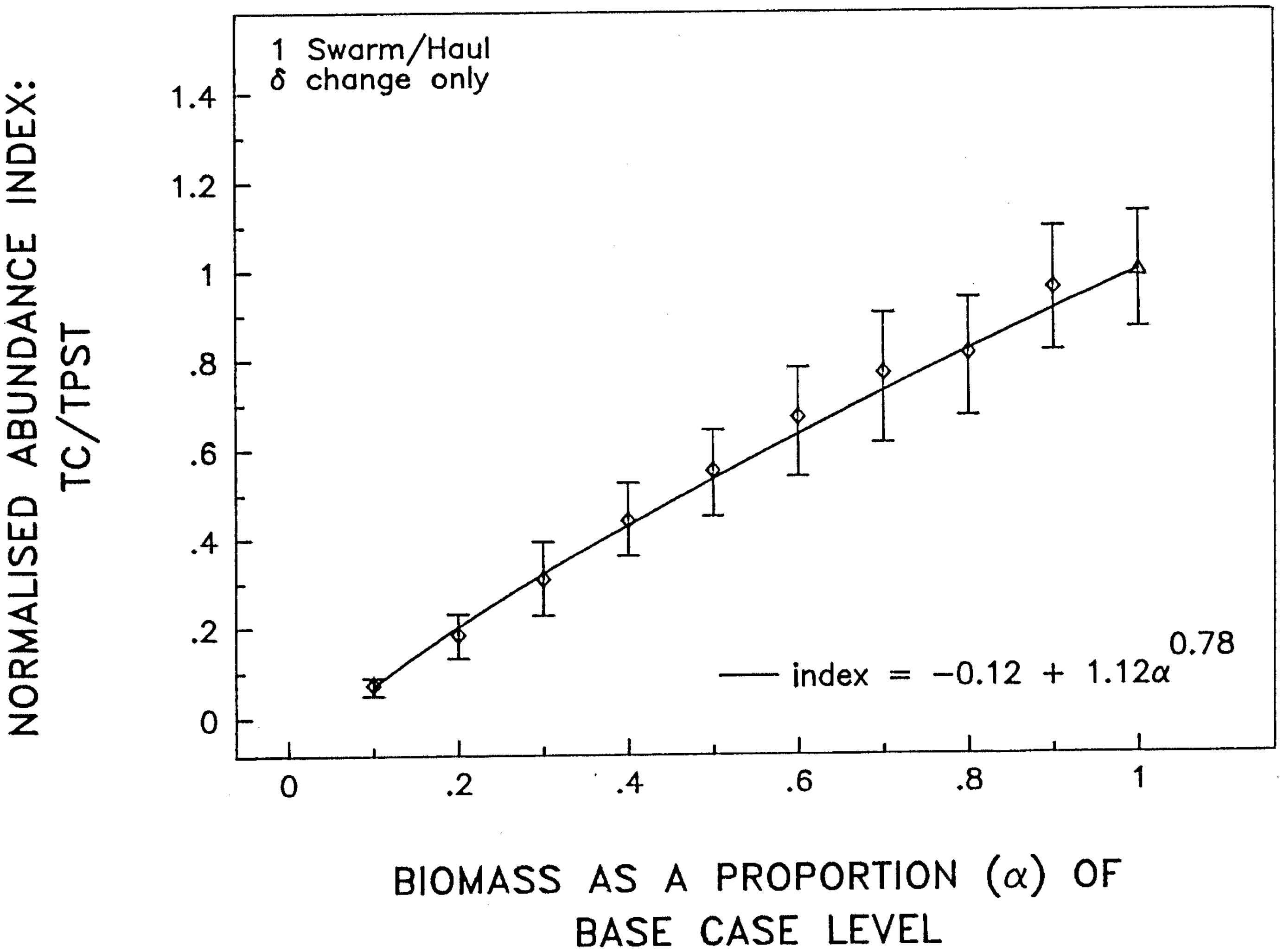

1 Swarm/Haul
δ change only
NORMALISED ABUNDANCE INDEX: TC/TPST
1.4
1.2
1
.8
.6
.4
.2
0
0
.2
.4
.6
.8
1
index = $-0.12 + 1.12\alpha^{0.78}$
BIOMASS AS A PROPORTION (α) OF BASE CASE LEVEL

Figure 9 iv)

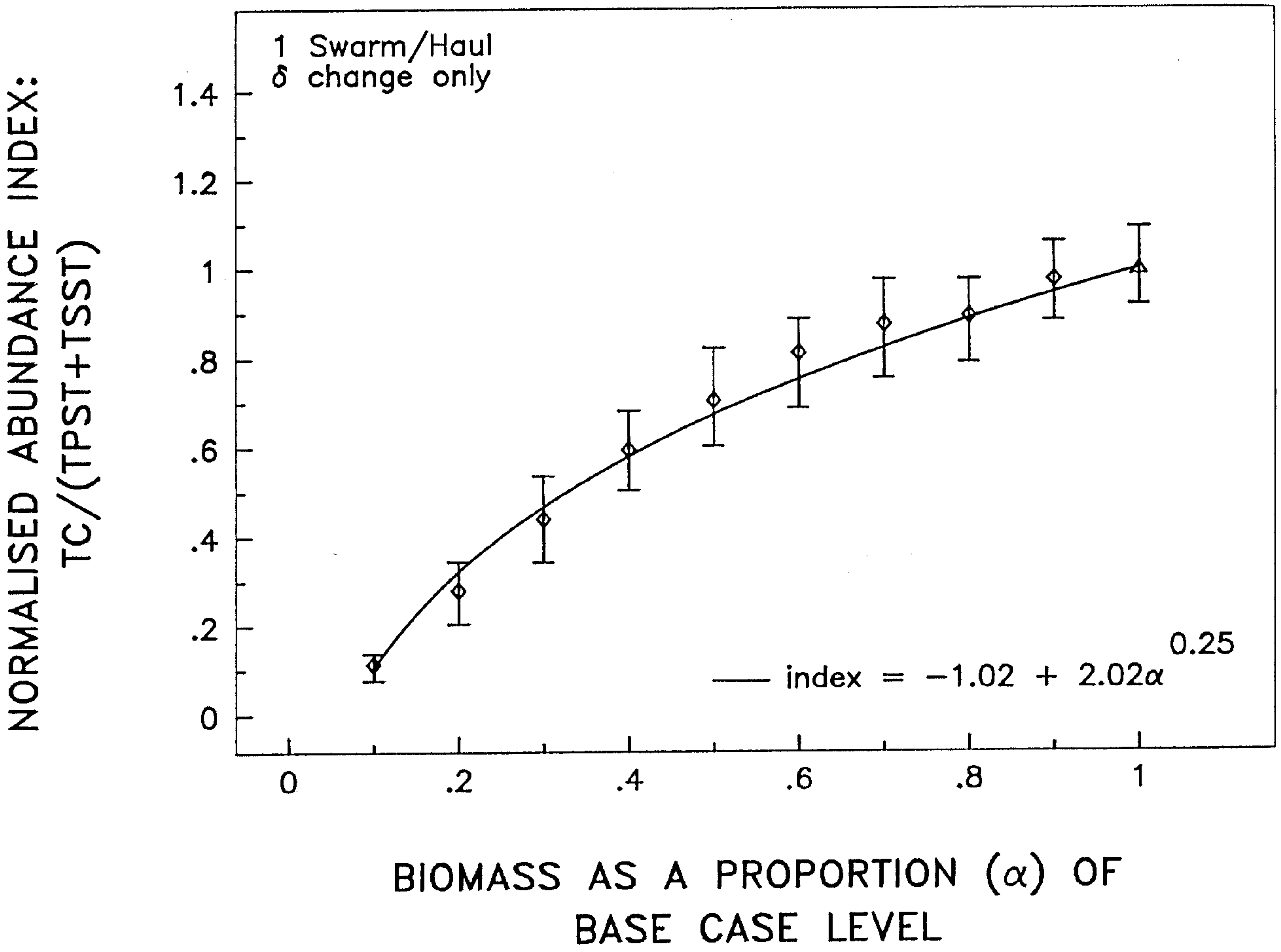

1 Swarm/Haul
δ change only
NORMALISED ABUNDANCE INDEX:
TC/(TPST+TSST)
1.4
1.2
1
.8
.6
.4
.2
0
0
.2
.4
.6
.8
1
— index = −1.02 + 2.02α^0.25
BIOMASS AS A PROPORTION (α) OF
BASE CASE LEVEL

Figure 9 v)

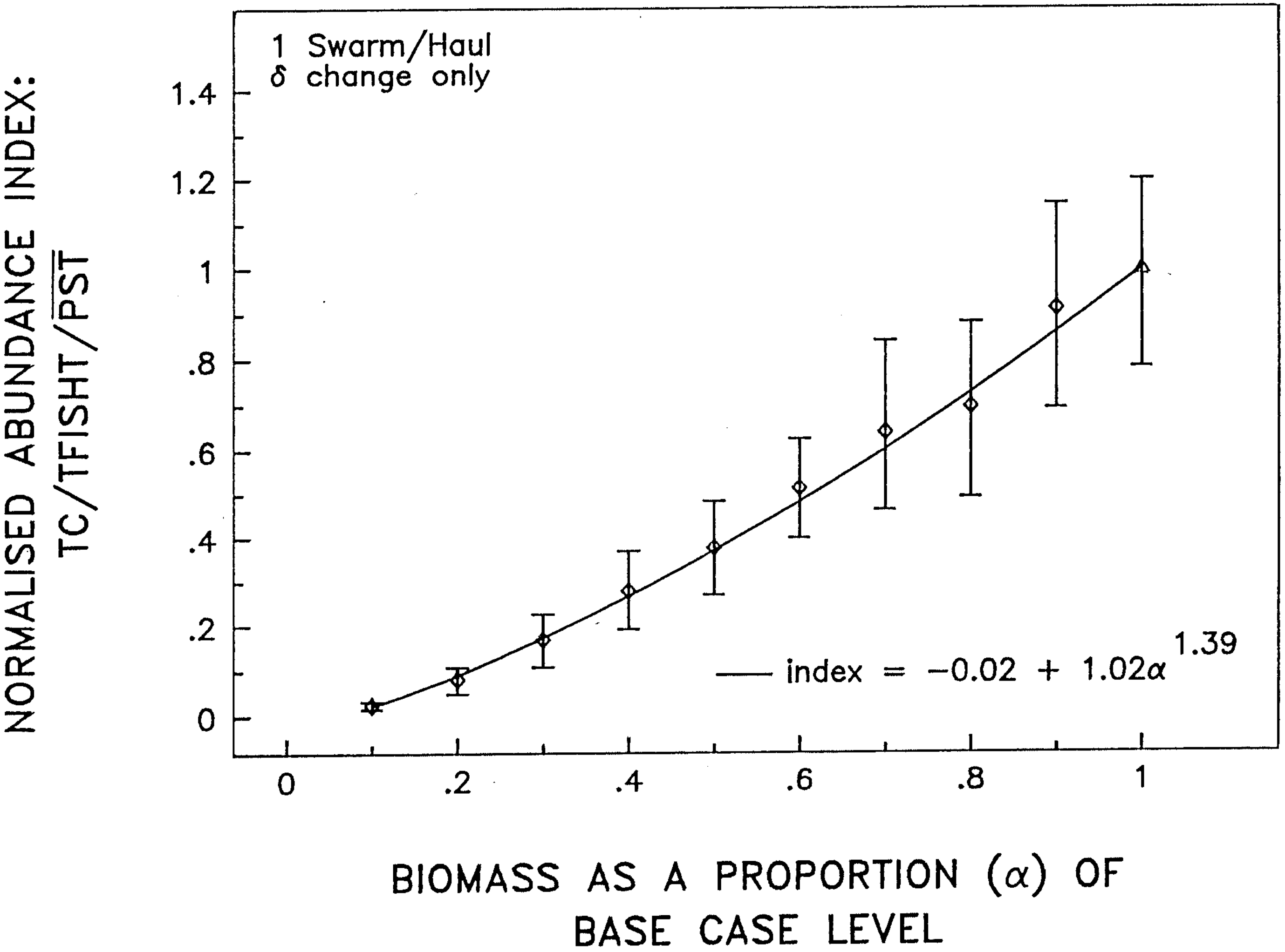
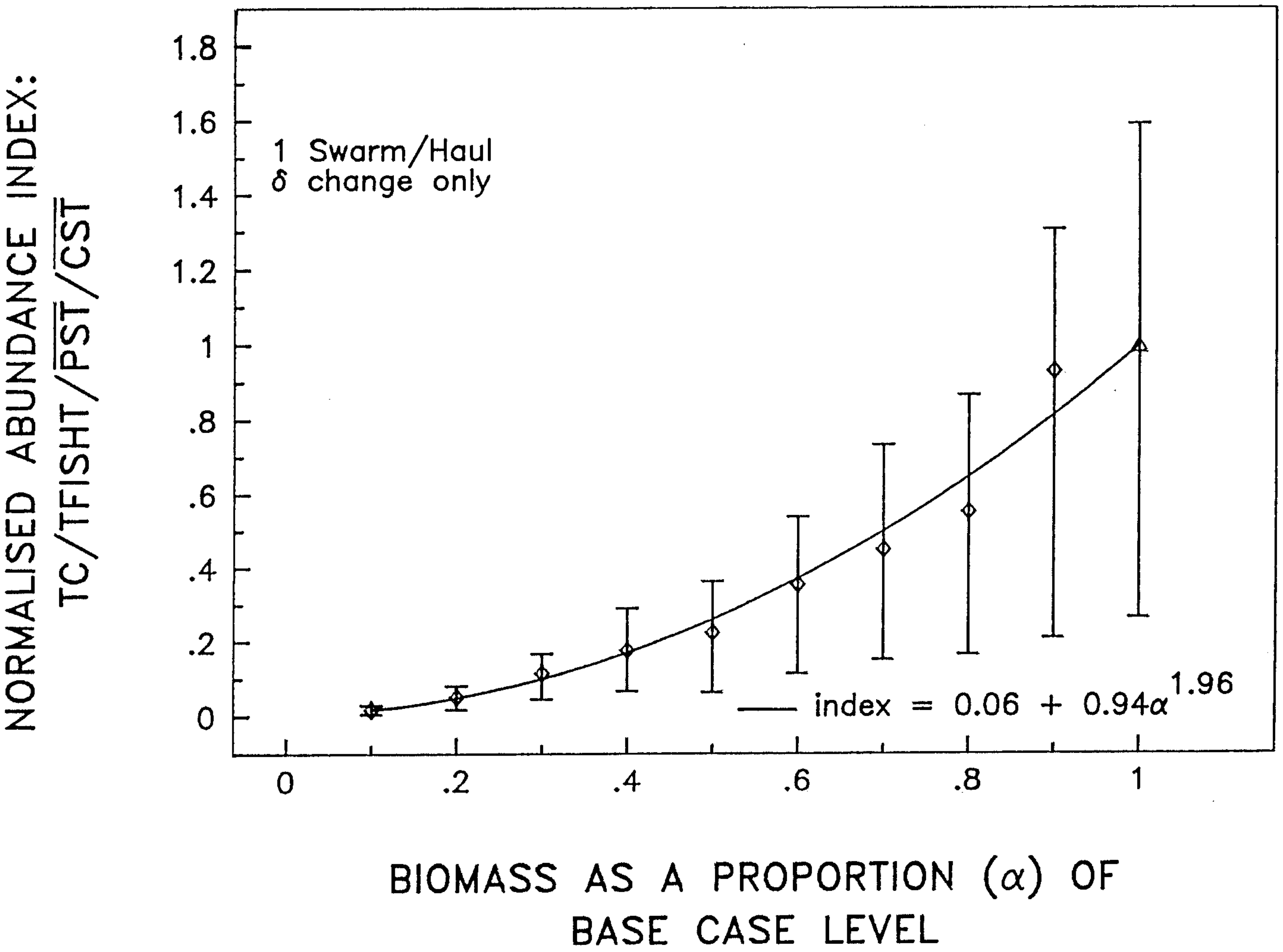

1 Swarm/Haul
δ change only
NORMALISED ABUNDANCE INDEX:
TC/TFISHT/$\overline{\text{PST}}$
1.4
1.2
1
.8
.6
.4
.2
0
0
.2
.4
.6
.8
1
— index = −0.02 + 1.02α^1.39
BIOMASS AS A PROPORTION (α) OF
BASE CASE LEVEL

Figure 9 vi)


NORMALISED ABUNDANCE INDEX:
TC/TFISHT/$\overline{PST}$/$\overline{CST}$
1.8
1.6
1.4
1.2
1
.8
.6
.4
.2
0
1 Swarm/Haul
δ change only
— index = 0.06 + 0.94α^1.96
0
.2
.4
.6
.8
1
BIOMASS AS A PROPORTION (α) OF
BASE CASE LEVEL

Légendes des tableaux

Tableau 1 Statistiques de synthèse d'un échantillon de données recueillies par un chalutier industriel de krill japonais. Un nombre suivi par un autre entre parenthèses correspond à une moyenne (écart-type), sauf indication contraire ou lorsqu'une seule statistique est en jeu.

Tableau 2 Valeurs des paramètres d'opérations de pêche pour différentes modifications de modèle. Lorsqu'une valeur d'un paramètre "partiellement affiné" est mise entre parenthèses carrées, la valeur n'a pas été ajustée pour cette modification, mais égalisée à la valeur ajustée pour une modification connexe.

Tableau 3 Comparaison de statistiques pour la pêcherie commerciale japonaise de krill établies à partir de l'échantillon de données reçues et d'autres sources, avec les résultats du modèle de simulation du cas de base. Les résultats du modèle de simulation reflètent la moyenne sur 100 cas. (NB: Toutes les statistiques ont trait à une période d'un demi-mois.) Les chiffres entre parenthèses sont les coefficients de variation sauf les pourcentages de bilan temporel qui sont les écarts-types.

Tableau 4 Comparaison des indices d'abondance pour l'expérience du modèle de simulation du cas de base avec ceux de six autres scenarios de répartition du krill, correspondant chacun à une baisse totale de 50% de la biomasse. Pour le cas de base, la moyenne sur les 100 simulations est représentée avec l'erreur standard de cette moyenne entre parenthèses. Pour les autres scenarios, la différence de pourcentage du cas de base moyen est donnée entre parenthèses, avec l'erreur standard. (Les unités, le cas échéant, sont en combinaisons tonne-heure.)

(a) Un Essaim Allongé (f=8) Par Trait

(b) Plus d'Un Essaim Par Trait

Tableau 5 Efficacité des indices d'abondance à détecter les changements de la biomasse de krill:

blanc : 100 simulations ne détectent pas de changement significatif à un intervalle de confiance de 5%
+ / - : significative à un intervalle de confiance de 5%
* : indice (ou son inverse) baisse de > 20%
* * : indice (ou son inverse) baisse de > 45% (dans des limites de 95%)

(a) Un Essaim Allongé (f=8) Par Trait

(b) Plus d'Un Essaim Par Trait

Tableau 6 Statistiques comparatives complémentaires de 100 expériences de modèles de simulation pour le cas de base et pour six autres scenarios correspondant chacun à une baisse totale de 50% de la biomasse. Le format est le même que celui du tableau 4 mais les valeurs entre parenthèses pour le cas de base sont les écarts-types (et non pas les erreurs standard de la moyenne.)

(a) Un Essaim Allongé (f=8) Par Trait

(b) Plus d'Un Essaim Par Trait

Tableau 7 Statistiques comparatives supplémentaires des expériences de modèles de simulation pour le cas de base et six autres scenarios correspondant chacun à une baisse totale de 50% de la biomasse. Les valeurs données sont des moyennes sur 100 expériences, avec les erreurs standard de ces moyennes données entre parenthèses.

(a) Un essaimallongé (f=8) par trait

(b) Plus d'un essaim par trait

Tableau 8 Indices d'abondance comme proportion de leurs valeurs pour l'expérience de modèle de simulation du cas de base quand la biomasse totale de krill est réduite à une fraction a de son niveau du cas de base par une combinaison au hasard de changements en N_c, L_c, Dc,r et δ. Les résultats se rapportent aux moyennes sur 100 simulations dans chaque cas. Il faut noter que quelques uns des indices mentionnés sont les inverses de ceux indiqués sur les tableaux 4 et 5; l'inverse a été utilisé si nécessaire, pour faire de l'indice une fonction croissante de α - ces cas sont indiqués par un *.

(a) Un Essaim Allongé (f=8) Par Trait

(b) Plus d'Un Essaim Par Trait

Tableau 9 Efficacité des indices d'abondance à détecter les changements de la biomasse de krill:

blanc : 100 simulations ne détectent pas de changement significatif à un intervalle de confiance de 5%
+/- : direction de changement en cas de détection d'une différence significative à un intervalle de confiance de 5%
* : indice (ou son inverse) baisse de > 20%
* * : indice (ou son inverse) baisse de > 45% (dans des limites de 95%)

Tableau 10 Une version consolidée du Tableau 4 pour les six indices d'abondance selectionnés pour une comparaison détaillée dans la section 3.6. Seules les estimations ponctuelles de différence de pourcentage par rapport à la moyenne estimée du cas de base sont données pour les six autres scenarios de répartition du krill (correspondant chacun à une baisse totale de 50% de labiomasse). Le premier chiffre indiqué correspond à "Un essaim allongé(f=8)-par-trait" et le second chiffre à la modification du modèle "Plus d'un essaim-par-trait".

Tableau 11 Des estimations de la baisse du pourcentage des indicesd'abondance incorporant le temps de recherche primaire(PST)pour une baisse totale de 50% de la biomasse de krill sont comparées avec et sans erreur aléatoire (voir texte - section 3.6) dans l'allocation du temps de recherche de concentrations entre temps de recherche primaire et secondaire (PST et SST). Les comparaisons sont indiquées pour la baisse de la biomasse dûe à des baisses en D_c, r et δ respectivement, et sont pour le cas d'"Un essaim (f=8)allongé-par-trait".

Légendes des figures

Figure 1	Organigramme de la structure de base du modèle de simulation.
Figure 2	L'habitat stratifié choisi pour le modèle de répartition du krill dans un secteur de 600 milles nautiques carrés de l'océan Austral.
Figure 3	Un exemple de la répartition des concentrations de krill dans le secteur choisi de l'océan Austral de 600 milles nautiques carrés qui a été engendré selon la description de la section 2.3. Les rayons de concentrations sont représentés à l'échelle. Les lignes fléchées indiquent les concentrations pêchées séquentiellement pendant une période d'un demi-mois. La ligne pointillée représente le mouvement pendant une période de mauvais temps (voir sectionè.4).
Figure 4	Probabilité de détection comme fonction de temps pour la recherche approfondie et les modèles de recherche au hasard.
Figure 5	Un exemple de la répartition d'essaims pêchables dans une concentration engendrée selon la description de la section 2.7. Les rayons d'essaims ne sont PAS représentés à l'échelle. Cet exemple correspond à la modification du modèle "Un essaim allongé (f=8) par trait", avec le symbole, pour chaque essaim pêchable, placé au point central choisi pour cet essaim avant l'élongation. Les lignes fléchées reflètent le chalutage séquentiel de bancs dans la concentration par un navire de pêche. Il faut noter que seuls les bancs initiaux sont chalutés, bien que ces lignes puissent entrecouper les symboles d'autres bancs. Les lignes continues représentent la longueur et la direction de chaque trait (à l'échelle), tandis que les lignes en tirets indiquent le mouvement net de recherche du prochain essaim à chaluter.
Figure 6	Un exemple d'un seul trait pour la modification du modèle lorsque plus d'un essaim peut être chaluté par trait (voir sections 2.8 et 3.3). Les bancs représentés sont à l'échelle. Tandis que le premier banc chaluté est un banc "pêchable" en termes de critère (20), tous les bancs dans la zone à la droite de ce banc d'origine sont représentés. Les lignes en tirets à la droite de l'essaim initial délimitent la "bande de sonar"; les essaims intersectant cette bande sont aussi pêchés jusqu'à ce que le trait soit terminé parce que (dans cet exemple) le Capitaine estime que la capture a atteint 10 tonnes.
Figure 7	Courbes des indices d'abondance comme fonction d' a (la proportion du niveau du cas de base auquel la biomasse de krill a été réduite), où la réduction de la biomasse se produit par suite d'une combinaison au hasard de baisse dans les paramètres de distribution N_c, Lc, Dc, r et δ. Les indices d'abondance ont été normalisés à leurs niveaux moyens estimés pour le cas de base. Les barres d'erreur représentent les estimations des 68% centraux de la distribution de l'indice en question pour un navire par demi-mois, tandis que le symbole est l'estimation de la moyenne de distribution pour chaque valeur particulière de α. Une formule est présentée pour la courbe ayant trait à la relation entre l'indice et a par la méthode décrite dans la section 3.5. Les courbes a) et b) se rapportent respectivement aux modifications du modèle "Un essaim allongé (f=8) par trait" et "Plus d'un essaim par trait" et correspondent aux indices:

(i) TC
(ii) TC/FISHT
(iii) TC/TPST
(iv) TC/TFISHT/$\overline{\text{PST+SST}}$
(v) TC/TFISHT/($\overline{\text{PST+SST}}$)
(vi) TC/TFISHT/$\overline{\text{PST/CST}}$

Figure 8 Courbes de (i) capture totale par demi-mois (TC) et (ii) nombre de concentrations pêchées (TNC) par le taux de capture minimum par temps total écoulé (CR_{min}) requis pour qu'un navire n'abandonne pas une concentration. Les courbes ont trait à la répartition du krill du cas de base et à la modification du modèle "Un essaim allongé (f=8) par trait". Les barres d'erreur indiquent un écart-type.

Figure 9 Courbes des indices d'abondance par α sur la figure 7, sauf que le déclin de la biomasse totale provient uniquement d'un changement de la densité δ de surface d'un banc de krill. Les courbes sont celles de la modification du modèle "Un essaim allongé (f=8) par trait", et correspondent aux indices:

(i) TC
(ii) TC/FISHT
(iii) TC/TPST
(iv) TC/(TPST+TSST)
(v) TC/TFISHT/$\overline{\text{PST+SST}}$
(vi) TC/TFISHT/$\overline{\text{PST/CST}}$

Заголовки к таблицам

Таблица 1 Сводка избранных статистических данных, полученных с японского коммерческого крилевого траулера. Цифра с последующей в скобках другой цифрой соответствует среднему числу (среднему квадратическому отклонению), за исключением тех примеров, где цифры стоят в другом порядке, или где приведен только один показатель.

Таблица 2 Значения параметров промысловой операции для различных модификаций модели. Там, где значение частично "приведенного в соответствие" параметра показано в квадратных скобках, означает, что значение не было приведено в соответствие для данной модификации, а было оставлено равным приведенной в соответствие величине для соседней модификации.

Таблица 3 Сравнение статистических результатов, касающихся японского коммерческого промысла криля, полученных из выборки данных и других источников, с выходными данными имитационной модели для базисного варианта. Результаты имитационной модели отражают среднюю величину, полученную за 100 прогонов модели. (Примечание: Вся статистика относится к периоду полумесяца.) Цифры в скобках являются коэффициентами вариации, за исключением процентных величин затраченного времени, где они соответствуют среднему квадратическому отклонению.

Таблица 4 Сравнение индексов численности для имитационной модели базисного варианта с индексами численности, полученными из шести различных комбинаций параметров распределения криля, каждая из которых соответствует общему уменьшению биомассы на 50%. Для базисного варианта дается средняя величина, полученная в результате 100 прогонов модели, в скобках указана средняя квадратическая ошибка этой средней величины. Для различных комбинаций параметров распределения криля дается процентная разница по отношению к средней величине базисного варианта, в скобках указана средняя квадратическая ошибка этой процентной разницы. (Единицы в сответствующих местах выражены в тоннах/час.).

(a) одно удлиненное (f=8) скопление за одно траление.

(b) больше одного скопления за одно траление.

Таблица 5 Показатель эффективности индексов численности при обнаружении изменений в биомассе криля:

пустое место	:	за 100 прогонов модели никаких статистически значимых изменений не обнаружено при 5% уровне
+/-	:	направление изменений, когда статистически значимое различие обнаружено при 5% уровне
*	:	индекс (или обратная величина индекса) снижается на > 20%
**	:	индекс (или обратная величина индекса) снижается на > 45% (в пределах 95%)

(a) одно удлиненное (f=8) скопление за одно траление.

(b) больше одного скопления за одно траление.

Таблица 6 Дополнительная сравнительная статистика по 100 прогонам имитационной модели для базисного варианта и для шести различных комбинаций параметров, соответстующих общему уменьшению биомассы на 50%. Обозначения те же, что и в таблице 4 кроме того, что цифры в скобках для базисного варианта являются средними квадратическими отклонениями (а не средними квадратическими ошибками средней величины).

(a) одно удлиненное (f=8) скопление за одно траление.

(b) больше одного скопления за одно траление.

Таблица 7 Дополнительная сравнительная статистика по прогонам имитационной модели для базисного варианта и для шести различных комбинаций параметров, соответствующих общему уменьшению биомассы на 50%. Данные значения являются средними числами, полученными за 100 прогонов модели, в скобках указаны средние квадратические ошибки этих значений.

(a) Одно удлиненное (f=8) скопление за одно траление.

(b) Больше одного скопления за одно траление.

Таблица 8 Индексы численности, выраженные в процентном отношении к их величинам, для прогона имитационной модели базисного варианта, когда общая биомасса криля уменьшается до доли α от ее базисного уровня вследствие случайного сочетания изменений в N_c, L_c, D_c, r и δ. В каждом случае результаты относятся к средним числам, полученным за 100 прогонов имитационной модели. Цифры в скобках являются средними квадратическими ошибками подсчитанных средних величин. Обратите внимание, что некоторые из нижеследующих индексов являются обратными величинами индексов, указанных в таблицах 4 и 5; когда необходимо превращать индекс в возрастающую функцию α дается его обратная величина, такие примеры отмечены значком *.

(a) одно удлиненное (f=8) скопление за одно траление.

(b) больше одного скопления за одно траление.

Таблица 9 Показатель эффективности индексов численности в обнаружении изменения биомассы криля:

пустое место : за 100 прогонов модели никаких статистически значимых изменений не обнаружено при 5% уровне

+/- : направлениеизменений, когда статистически значимое различие обнаружено при 5% уровне

* : индекс (или обратная величина индекса) снижается на > 20%

** : индекс (или обратная величина индекса) снижается на > 45% (в пределах 95%)

Эта таблица соответствует таблице 5a ("одно удлиненное (f=8) скопление за одно траление"), за исключением того, что эффективность концентрированного поиска увеличена в 7.5 раз.

Таблица 10 Обобщенный вариант таблицы 4 для шести индексов численности, выбранных для подробного сравнения в разделе 3.6. Для шести различных комбинаций параметров распределения криля (каждая такая комбинация соответствует общему уменьшению биомассы на 50%) дается только оценка процентного различия отдельных результатов базисного варианта Первая цифра соответствует модификации модели "одно удлиненное (f=8) скопление за одно траление", вторая цифра - "больше одного скопления за одно траление".

Таблица 11 Сравнение оценок процентного снижения индексов численности (с ошибкой случайного выбора и без нее), включающих первичное время поиска (PST), соответствующее 50% снижению биомассы криля при распределении в пределах времени поиска концентрации от первичного времени поиска (PST) до вторичного времени поиска (SST). Сравнения касаются уменьшения биомассы вследствие понижения в каждом из D_c, r и δ и относятся к случаю "одно удлиненное (f=8) скопление за одно траление".

Подписи к рисункам

Рисунок 1	Схема основной структкры имитационной модели.
Рисунок 2	Стратифицированный ареал обитания криля, использованный для модели его распределения в участке Южного океана площадью 600 квадратных морских миль.
Рисунок 3	Пример распределения концентраций криля в выбранном квадратном участке Южного океана площадью 600 квадратных морских миль, рассчитанный как показано в разделе 2.3. Радиусы концентраций пропорциональны. Линии со стрелками показывают концентрации, последовательно облавливаемые в течение полутора месяцев.Точечная линия изображает передвижение в период плохой погоды (см. раздел 2.4).
Риунок 4	Вероятность обнаружения как функция времени для моделей всеобъемлющего и случайного поиска.
Рисунок 5	Пример распределения скоплений промыслового размера в пределах концентрации рассчитан как описано в разделе 2.7. Радиусы скоплений НЕ пропорциональны. Этот пример соответствует модификации модели "одно удлиненное (f=8) скопление за одно траление", где обозначение для каждого пригодного для промысла скопления находится в центральной точке, выбранной для этого скопления до его удлинения. Линиями со стрелками.показано последовательное траление промысловым судном скоплений в пределах этой концентрации. Обратите внимание на то, что, хотя эти линии могут пересекать обозначения для других скопленйй, облавливаются только исходные скопления. Непрерывные линии обозначают длину и направление каждого траления (пропорциально), а пунктирные линии изображают движение сети в ходе поиска следующего скопления для лова.
Риунок 6	Пример отдельного траления для модификации модели, где улов может составить больше одного скопления за одно траление (см. раздел 2.8 и 3.3). Данные скопления пропорциальны. Хотя, в соответствии с критерием 20, только исходное скопление является "пригодным для промысла", показаны все скопления, находящиеся в районе направо от этого исходного скопления. Пунктирные линии направо от исходного скопления определяют "звуковую полосу"; скопления, пересекающие эту полосу также облавливаются, так как (в этом случае) капитан оценивает улов в 10 тонн.
Рисунок 7	Графики индексов численности как функция α (процентная величина базового уровня, к которому сведена биомасса криля), где уменьшение биомассы является результатом случайного

сочетания снижений параметров распределения N_C, L_C, D_C, r и δ. Индексы численности были приведены к вычисленным средним уровням базисного варианта. Размер указанных на графике статистических ошибок представляет собой оценки центральной части распределения 68% данного индекса для судна в течение полумесяца, а обозначение является оценкой средней величины распределения для каждого отдельного значения α. Дается формула для кривой, скорректированной в отношение связи между индексом и α по методу, описанному в разделе 3.5. Графики (a) и (b) соответственно относятся к модификациям модели "одно удлиненное (f=8) скопление за одно траление" и "больше одного скопления за одно траление", и соответствуют нижеследующим индексам:

(i) TC
(ii) TC/TFISHT
(iii) TC/TPST

(iv) TC/TFISHT/$\overline{\text{PST+SST}}$

(v) TC/TFISHT/($\overline{\text{PST+SST}}$)

(vi) TC/TFISHT/$\overline{\text{PST/CST}}$

Рисунок 8 Графики (i) общего улова в течение полумесяца (TC) и (ii) количества облавливаемых концентраций (TNC) по отношению к минимальному коэффициенту уловистости на единицу общего протекшего времени ($КУ_{мин}$), который необходимо достичь для того, чтобы судно не отплыло от концентрации. Графики касаются распределения криля базисного варианта и модификации модели "одно удлиненное (f=8) скопление за одно траление". Размер указанных на графике статистических ошибок свидетельствует об одном среднем квадратическом отклонении.

Рисунок 9 Графики индексов численности по отношению к α такие же, как на рисунке 7, за исключением того, что общее уменьшение биомассы является результатом изменения только в плотности поверхностного слоя скопления криля δ. Графики касаются модификации модели "одно удлиненное (f=8) скопление за одно траление", и соответствуют нижеследующим индексам:

(i) TC
(ii) TC/TFISHT
(iii) TC/TPST

(iv) TC/TFISHT/$\overline{\text{PST+SST}}$

(v) TC/TFISHT/($\overline{\text{PST+SST}}$)

(vi) TC/TFISHT/$\overline{\text{PST/CST}}$

Encabezamientos de las Tablas

Tabla 1 Resumen de las estadísticas de una muestra de datos de un arrastrero comercial de krill japonés. Un número seguido de otro, entre paréntesis, corresponde a un promedio (desviación estándar), salvo indicación contraria o donde una sola estadística está implicada.

Tabla 2 Valores de los parámetros de operaciones de pesca para diferentes modificaciones del modelo. Donde el valor de un parámetro "parcialmente ajustado" se indica en corchetes, el valor no fue ajustado para esta modificación, pero igualado al valor ajustado para una modificación relacionada.

Tabla 3 Comparación de las estadísticas para la pesquería comercial japonesa del krill a partir de una muestra de datos suministrada y de otras fuentes con los resultados del modelo de simulación para el caso de base. Los resultados del modelo de simulación reflejan el promedio sobre 100 ejecuciones. (NB: Todas las estadísticas se aplican a un período de 15 días). Los números entre parémtesis con coeficientes de variaciones, excepto los porcentajes del presupuesto temportal que son desviaciones estándar.

Tabla 4 Comparación de los índices de abundancia para la ejecución del modelo de simulación del caso de base con aquellos de los seis escenarios alternativos de la distribución del krill, correspondiendo cada uno a un descenso del 50% del total de la biomasa. Para el caso de base, se indica el promedio sobre las 100 simulaciones, junto con el error estándar de este promedio entre paréntesis. Para los escenarios alternativos, se da la diferencia del porcentaje del caso de base promedio, junto con el estándar de error de esta diferencia entre paréntesis. (Las unidades, cuando corresponda, son combinaciones de toneladas-hora).

(a) Un cardumen por lance alargado (f=8)

(b) Más de un cardumen por lance

Tabla 5 Eficiencia de los índices de abundancia para detectar cambios en la biomasa del krill:

blanco : 100 simulaciones no detectan un cambio importante al nivel del 5%
+ / - : dirección de cambio si se detecta una diferencia importante al nivel del 5%
* : índice (o su inverso) baja un > 20%
* * : índice (o su inverso) baja un > 45% (dentro de los límites del 95%)

(a) Un cardumen por lance (f=8)

(b) Más de un cardumen por lance

Tabla 6 Estadísticas comparativas adicionales de 100 ejecuciones del modelo de simulación para el caso de base y para seis escenarios alternativos, cada uno correspondiendo a un descenso del 50% del total de la biomasa. El formate es el mismo que el de la tabla 4 excepto que los valores entre paréntesis para el caso de base son desviaciones estándar (no errores estándar del promedio).

(a) Un cardumen por lance alargado (f=8)

(b) Más de un cardumen por lance

Tabla 7 Estadísticas comparativas adicionales de las ejecuciones del modelo de simulación para el caso de base y seis escenarios alternativos cada uno correspondiendo a un descenso del 50% de la biomasa total. Los valores dados son promedios sobre 100 ejecuciones, con los errores estándar de estos promedios dados entre paréntesis.

(a) Un cardumen por lance alargado (f=8)

(b) Más de un cardumen por lance

Tabla 8 Indices de abundancia como una proporción de sus valores para la ejecución del caso de base del modelo de simulación, cuando la biomasa total del krill disminuye a una fracción α del nivel del caso de base a través de una combinación aleatoria de cambios en N_c, L_c, D_c r y δ. Los resultados se relacionan a los promedios sobre 100 simulaciones en cada caso. Las cifras entre paréntesis son errores estándar de las proporciones estimadas. Observese que algunos de los índices en la lista son los inversos de los indicados en las Tablas 4 y 5; el inverso se ha tomado siempre que ha sido necesario para hacer del índice una función creciente de α - tales casos están indicados con un *.

(a) Un cardumen por lance alargado (f=8)

(b) Más de un cardumen por lance.

Tabla 9 Eficiencia de los índices de abundancia para detectar cambios en la biomasa del krill:

blanco : 100 simulaciones no detectan un cambio importante al nivel del 5%
+ / - : dirección de cambio si se detecta una diferencia importante al nivel del 5%
* : el índice (o su inverso) desciende un > 20%
* * : el índice (o su inverso) desciende un > 45% (dentro de los límites del 95%)

Esta Tabla corresponde a la Tabla 5a del caso "Un cardumen alargado (f=8) por lance" excepto que la eficiencia de búsqueda de la concentración ha sido aumentada 7.5 veces.

Tabla 10 Una versión consolidada de la Tabla 4 para los seis índices de abundancia seleccionados para una comparación detallada en la sección 3.6. Sólo se dan las estimaciones de la diferencia del porcentaje del promedio del caso de base estimado para los seis escenarios alternativos de distribución del krill (correspondiendo cada uno a un descenso del 50% del total de la biomasa). La primera cifra indicada corresponde a "Un cardumen-por-lance" alargado (f=8) y la segunda cifra a la modificación del modelo "Más de un cardumen-por-lance".

Tabla 11 Se comparan estimaciones de la disminución del porcentaje en los índices de abundancia que incorporan PST para un descenso del 50% del total de la biomasa del krill con y sin error aleatorio (ver texto -sección 3.6) en la adjudicación de tiempo de búsqueda entre PST y SST dentro de una concentración. Las comparaciones se indican para el descenso de la biomasa debido a disminuciones en cada uno de D_c , r y δ, y son para el caso de "Un cardumen por lance" alargado (f=8).

Leyendas de las Figuras

Figura 1 Un diagrama de flujo de la estructura básica del modelo de simulación.

Figura 2 Habitat estratificado seleccionado para el modelo de distribución del krill en un sector de 600 millas náuticas cuadradas del Océano Austral.

Figura 3 Un ejemplo de la distribución de las concentraciones de krill en el sector seleccionado del Océano Austral de 600 millas náuticas cuadradas, el cual ha sido producido tal como se describe en la sección 2.3. Los radios de las concentraciones están a escala. Las flechas indican las concentraciones pescadas secuencialmente durante un período de 15 días. La línea de puntos representa movimiento durante un período de mal tiempo (ver sección 2.4).

Figura 4 Probabilidad de detección como una función de tiempo para los modelos de búsqueda exhaustiva y búsqueda aleatoria.

Figura 5 Un ejemplo de la distribución de los carúmenes explotables en una concentración, producidos tal como se describe en la sección 2.7. Los radios de los cardúmenes NO están a escala. Este ejemplo corresponde a la modificación del modelo "Un cardumen por lance" alargado (f=8), con el símbolo para cada cardumen explotable situado en el punto central escogido para este cardumen antes del alargamiento. Las flechas reflejan el arrastre secuencial de los cardúmenes en la concentración por un buque de pesca. Observese que sólo los cardúmenes iniciales son arrastrados, aunque las líneas pueden cruzar los símbolos para otros cardúmenes. Las líneas sólidas representan la longitud y dirección de cada lance (a escala), mientras las líneas quebradas indican movimiento de las redes en la búsqueda del cardumen que se arrastrará a continuación.

Figura 6 Un ejemplo de un solo lance para la modificación del modelo donde más de un cardumen puede ser arrastrado por lance (ver las secciones 2.8 y 3.3). Los cardúmenes representados están a escala. Aunque el cardumen inicial arrastrado es un cardumen "explotable" en términos de criterio (20), todos los cardúmenes situados a la derecha de este cardumen original están representados. Las Líneas quebradas a la derecha del cardumen inicial determinan la "banda sonar"; los cardúmenes que cruzan esta banda también se pescan hasta que el lance termina porque (en este ejemplo) el Capitán estima que la captura ha alcanzado las 10 toneladas.

Figura 7 Curvas de los índices de abundancia como una función de α (la proporción del nivel del caso de base para el cual la biomasa del krill ha sido reducida), donde la reducción de la biomasa ocurre como un resultado de una combinación aleatoria de disminuciones en los parámetros de distribución N_c , L_c , D_c r y δ. Los índices de abundancia han sido normalizados a sus niveles promedios estimados para el caso de base. Las barras de error representadas indican estimaciones del 68% central de la distribución del índice en cuestión para un buque durante una quincena, mientras el símbolo es la estimación del promedio de la distribución, para cado valor particular de α. Se presenta una fórma para la curva ajustada a la relación entre el índice y α por el método descrito en la sección 3.5. Las curvas (a) y (b) corresponden a las modificaciones del modelo "Un cardumen por lance" alargado (f=8) y "Más de un cardumen por lance" respectivamente, y corresponden a los índices:

(i) TC
(ii) TC/TFISHT
(iii) TC/TPST
(iv) $TC/TFISHT/\overline{PST+SST}$
(v) $TC/TFISHT/(\overline{PST+SST})$
(vi) $TC/TFISHT/(\overline{PST/CST})$

Figura 8 Curvas de (i) captura total en una quincena (TC) y (ii) número de concentraciones pescadas (TNC) como función de la tasa de captura mínima por el tiempo total transcurrido (CR_{min}) requerido para que un buque no abandone una concentración. Las curvas corresponden a la distribución del krill del case de base y al modelo de modificación "Un cardumen por lance (f=8) alargado". Las barras de error indican una desviación estándar.

Figura 9 Curvas de los índices de abundancia como una función de α como en la Figura 7, excepto que la disminución total de la biomasa es solamente el resultado de un cambio en la densidad de superficie del cardumen de krill. Las curvas corresponden a la modificación del modelo "Un cardumen por lance" alargado (f=8), y corresponde a los índices:

(i) TC
(ii) TC/TFISHT
(iii) TC/TPST
(iv) TC/(TPST+TSST)
(v) $TC/TFISHT/\overline{PST+SST}$
(vi) $TC/TFISHT/\overline{PST/CST}$