SOME ASPECTS OF THE RELATION BETWEEN ANTARCTIC KRILL ABUNDANCE AND CPUE MEASURES IN THE JAPANESE KRILL FISHERY

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Abstract

The history of the Japanese krill fishery is reviewed briefly. Important aspects of the fishing operation are the constraints imposed by processing rate limitations on the vessels, and product quality considerations - in particular the increasing tendency to avoid catching "green" krill. These factors result in Catch-per-Day and Catch-per-Haul measures being unlikely to index krill abundance. During the high season, Catch-per-Towing-Time seems likely to index only within-swarm density. Search time data may be needed to assess the density of swarms in a concentration, but may be difficult to record in practice, and a number of other factors may complicate any analysis. The possibility of indexing the extent of the krill distribution through routine oceanographic monitoring merits attention. A data sample from the Japanese krill fishery statistics data-base has been selected for further studies.

Résumé

L'historique de la pêcherie de krill japonaise est résumée brièvement. Les aspects importants de l'opération de pêche sont les contraintes imposées par les limites du taux de traitement sur les navires et les considérations de qualité du produit - en particulier la tendance croissante à éviter le krill de "teinte verte". En raison de ces facteurs, les mesures de Prise-par-jour et de Prise-par-trait risquent d'être impropres à indiquer l'abondance du krill. Pendant la haute saison, la Prise-par-durée-de-trait n'indique vraisemblablement que la densité à l'intérieur des essaims. L'on pourrait avoir besoin de données sur le temps de recherche pour évaluer la densité d'essaims dans une concentration, mais, sur le plan pratique, il pourrait être difficile de les enregistrer, et un certain nombre d'autres facteurs pourraient compliquer l'analyse. La possibilité d'indiquer l'étendue de la distribution du krill par un contrôle océanographique régulier mérite d'être étudiée. Un échantillon de données provenant de bases de données statistiques de la pêcherie de krill japonaise a été sélectionné pour une étude ultérieure.

Резюме

Дается краткий обзор истории японского промысла криля. Наиболее важными аспектами промысла являются требования, вызванные ограничениями мощности судна по обработке криля и вопросами качества продукта - в частности увеличивающаяся тенденция избегать промысел "зеленого" криля. Результатом этих факторов является малая вероятность использования параметров "Улов за день" и "Улов за траление" в качестве показателей численности криля. В течение сезона, когда промысел достигает наивысшего размера, параметр "Улов за время траления", вероятно, служит показателем плотности криля только внутри скопления. Данные по времени поиска могут быть необходимы для оценки плотности скопления внутри концентрации, но, возможно, что их сбор будет на практике затруднен, а также ряд других факторов может осложнить анализ. Заслуживает внимания возможность получения индекса распределения криля на основе данных стандартных океанографических съемок. Для будущих исследований была сделана выборка данных из статистического банка данных по японскому промыслу криля.

Resumen

Se analiza brevemente la historia de la pesquería japonesa del krill. Los aspectos importantes de la operación pesquera son las restricciones impuestas por los límites de las tasas de procesamiento en los buques, y las consideraciones de calidad del producto - particularmente la tendencia creciente de evitar la captura del krill "verde". A razón de estos factores, las medidas Captura-por-día y Captura-por-lance pueden ser inadecuadas para indicar la abundancia del krill. Durante la temporada alta, parece que la Captura-por-tiempo-de-arrastre sólo indica la densidad en el interior de cardúmenes. Los datos del tiempo de búsqueda pueden ser necesarios para evaluar la densidad de cardúmenes en una concentración, pero en la práctica, pueden ser difíciles de registrar, además, otros factores pueden complicar cualquier análisis. La posibilidad de indicar la extensión de la distribución del krill por medio del control oceanográfico regular merece ser estudiada. Se ha seleccionado una muestra de datos de la base de datos de las estadísticas de la pesquería de krill japonesa para estudios ulteriores.

1. INTRODUCTION

This document summarises information provided in discussions held with Captains and other executives of Japanese krill fishing companies, and also Japan Fishing Agency officials and scientists involved in research on krill and the krill fishery, during October 1986. These discussions constituted the initial phase of a simulation study of krill distribution and the krill fishery to determine the utility of CPUE as an index of changes in krill abundance, which is being undertaken on a contractual basis for CCAMLR.

Details of the persons with whom discussions were held are listed in the Appendix. The material presented is drawn from those discussions and written information provided by Japanese scientists - in particular various documents authored by Dr Y. Shimadzu and Mr T Ichii. A number of the comments made during the discussions are anecdotal in nature, and should not be regarded as the conclusions of a detailed scientific analysis. Nevertheless they provide extremely useful background for developing an understanding of the way the fishery operates, and hence a basis to formulate hypotheses to test, and to choose the most appropriate approach for modelling purposes - such comments have been recorded and should be viewed in that context.

Nomenclature in general use for the different types of krill aggregations is somewhat varied. The terminology in this document will be kept consistent with that of Butterworth and Miller (1987): krill aggregate into "concentrations"; different modes of concentration are a "number of swarms", a "layer", and a "super-patch". Swarms are typically several tens of metres long with densities between 10 and several hundred g/m^3; layers may exceed 1 000 m in length with densities of several tens of g/m^3; super-patches may extend over several km with densities of several hundred g/m^3. Conventional translations of certain of the standard Japanese terms differ somewhat from the above: they use the terms "patch" and "layer" for alternative manifestations of what is indicated above (and in what follows) as a "swarm" (see also Section 3.2).

Throughout this document attempts are made to relate the information presented to the question of obtaining a measure (or set of measures) from data collected (or potentially collected) in the fishery, which would provide an annual index of krill abundance. As discussed subsequently, the fishery provides no information on layers because their densities are too low for fishing on them to be economic, while fishing on super-patches seems a relatively rare phenomenon. Comments will accordingly be directed towards monitoring the abundance of krill aggregating in the "swarm" mode (K_s). Butterworth and Miller (1987) express this as:

$$K_s = A_t D_c A_{cs} d_s A_s \delta_{ks} \tag{1}$$

where
A_t = total management area
A_{cs} = average area of a concentration of swarms
A_s = average swarm area for swarms comprising a concentration of swarms
D_c = density of concentrations of swarms (no. concentrations per unit area)
d_s = average density of swarms within a concentration (no. swarms per total area of concentration)
δ_{ks} = average density of krill in a swarm (mass krill per surface area of swarm)

[Note: While these Butterworth and Miller (1987) symbols are used in this paper, a slightly different set are used in Butterworth (1988). Essentially the equivalences are, with the Butterworth (1988) symbols on the right hand sides:

$$
\begin{aligned}
A_{cs} &= \pi L_c^2 \\
A_s &= \pi r^2 \\
D_c A_t &= N_c \\
d_s &= D_c \\
\delta_{ks} &= \delta]
\end{aligned}
$$

Since changes in krill abundance could be reflected by changes in any one of the factors in equation (1) (see Section 4.5 for the sense in which a "change" in A_t is implied), it is important to attempt to relate data collected in the fishery to each of these factors. [Note that although δ_{ks} is defined as an areal density, subsequent discussions will for simplicity tacitly treat it as a volume density. Average swarm thickness is a further factor which should perhaps also be included in equation (1).]

This document first gives a brief overview of the history of the Japanese krill fishery, and then discusses details of the nature of the fishing operation. This is followed by a section on possible specific relations between data which are (or might be) routinely collected in the fishery and the factors in equation (1). A final section summarises the more important impressions, conclusions and recommendations.

2. AN OVERVIEW

2.1 A Brief Historical Perspective

The history of the Japanese fishery for Antarctic krill has been detailed by Shimadzu (1984) from 1972/73 to 1982/83. That document has been updated to cover the following two seasons by Shimadzu (1985).

In brief, some experimental fishing first took place in the 1972/73 season by a single vessel using side-towing nets designed for near-surface fishing, a method found to be inefficient. Commercial operations started in 1973/74 with stern trawlers using surface-midwater trawl nets. Unlike the USSR fishery, where catchers are guided by research vessels, the Japanese fishery has essentially been an individual ship operation (except for a five year period where a "mothership" also operated, as described in the next section). Between 1 and 10 vessels have operated on this individual basis from 1973/74 to 1984/85, and nearly all of these (90% of the vessel-years) have been 2 000-3 000 tonne class trawlers.

For the first three seasons, catches totalled only a few thousand tonnes, but rose rapidly over the next three years as effort expanded, including the introduction of the mothership operation in 1977/78. Since that time, seasonal catch totals have averaged 37 thousand tonnes, with a maximum of 50 thousand tonnes in 1983/84.

The fishery has been conducted in three areas, which are generally referred to as "off Enderby Land", "off Wilkes Land", and "the Scotia Sea". The greatest catches in these areas (Shimadzu 1985, Figure 4) have been taken between longitudes 50°E-70°E, 110°E-150°E, and 65°W-40°W (from the South Shetland to South Orkney islands) respectively, although effort has extended over wider ranges than these limits indicate. For the first three seasons the fishing took place off Enderby Land, but in 1976/77 started moving further east to the area off Wilkes Land. In 1979/80 further movement into the western hemisphere occurred, and since 1980/81 there has been an increasing transfer of fishing effort into the Scotia Sea area, which now contributes almost all the Japanese krill harvest. (The reasons for this are discussed in Section 3.5).

Although fishing has taken place from early November to the start of April, most activities have been concentrated in the mid-December to end-February period (i.e. an effective season of 70-80 days), for reasons primarily related to krill's swarming behaviour.

Further details of the history of the fishery are given in Shimadzu (1984), Shimadzu (1985), and Shimadzu and Ichii (1985).

2.2 The Mothership Operation

This operation took place during the five seasons from 1977/78 to 1981/82, fishing off Wilkes Land throughout this period. The venture was partly subsidised, and consisted of an 8 000 tonne class trawler with freezing and processing capabilities as the mothership, together with from 7-10 catchers (349 tonne class) each with limited freezing capacity.

Two detailed examples of this operation are provided in Shimadzu and Ichii (1985). Typically the catchers did not move more than 30 n.miles from the mothership (except for one vessel used for searching); this small radius was because processed product quality requirements necessitated their harvests to be transferred to the mothership within 2-3 hours of capture. Economically the operation did not compare favourably with the individual trawler performances - the fleet caught typically 200-300 tonnes per day compared to the 50-70 tonne average for a 3 000 tonne class vessel (Shimadzu, 1984) - and accordingly was discontinued.

Although this activity accounted for some 50% of the total Japanese catch while it operated, it is not felt appropriate to attempt a detailed model of the exercise. This is because the constraints of processing limitations would likely render interpretation of the data more difficult and the modelling quite complicated; further it seems unlikely that this operational mode would be recommenced by the Japanese in the future. This viewpoint might merit reconsideration if a detailed study would aid in analysing the USSR operation (which may have more similarities with this fleet-mode procedure), or if felt necessary to provide more information on areal swarm distribution than is available from individual fishing vessel records and research surveys.

3. THE FISHING OPERATION

3.1 Comparison with Other Trawling Operations

Gulland (1985) suggested that from a CPUE analysis perspective, the individual Japanese krill fishing vessels operate very much like a demersal trawler. Both the vessels used in the krill fishery and their Captains participate in mid-water or demersal trawling for other species over the remainder of the year, so the Captains present at the discussions were asked to comment on the differences in strategy between krill and other trawling operations.

The difference most strongly stressed was the limitations imposed by processing and quality considerations for krill. In other fisheries, maximising catch rate (in terms of total time) is the primary consideration. With krill, catches per haul are limited to prevent the product being crushed, and to allow time for processing while the krill remains fresh - generally only 2-3 hours for the fresh-frozen product. Towing times can therefore be quite short. This "quality" aspect and its implications for analysis are discussed further in Sections 3.3 and 4.1.

Another difference emphasised was that krill fishing involves much more searching (predominantly using an echo sounder). This contrasts with demersal operations where bottom features are considered of more importance in locating promising areas, and where there is in any case more accumulated experience on the location of preferential areas.

Comments were also made that krill trawling is sometimes very close to the surface, particularly with swarms so positioned in poor light conditions, and sonar is important in establishing the appropriate angle to tow through a swarm.

3.2 Fishing Strategies

The importance of the echosounder in locating swarms upon which to fish was stressed repeatedly. Ichii (1987) records this as the most frequent means of krill detection, both for surface and underwater swarms, and whether the area is of low or high abundance. Predator cues and direct sighting of swarms near the surface are location methods that appear not to be used very frequently.

The main role of sonar appears to be to determine the shapes and orientations of swarms and hence the appropriate towing direction. This also applies when swarms are small (generally earlier in the season), and tows are continued through a number of swarms. Sonar is also used for initial detection of underwater swarms, but is apparently limited in this role as it can be set to cover only a small depth range. Nevertheless one Captain ascribed the lack of success of the mothership operation as due in part to only one of the vessels having being equipped with sonar - echosounders having a much narrower horizontal effective search width. Another Captain commented that swarming behaviour was quite different in the Scotia sea (deep and dense swarms) compared to the near continuous echos off Wilkes Land; thus sonar was used far more in the Scotia Sea.

There are also favoured areas to find krill concentrations (the distribution is not random), and some relations between oceanographic features and the likelihood of finding krill swarms were suggested. Catch rates suffered in the earliest years until experience in these respects was developed.

Ichii (pers. commn) advises that such areas tend to be to the west of islands or glaciers (the downstream side in the East Wind Drift). Fronts and areas of water convergence (detected by observing movements of icebergs) were suggested as good signs, and water colour as a useful cue (clear water generally bad, green water generally good). Varying rather than flat bottom depth is another positive index, possibly because of associated upwelling currents carrying nutrients.

The vessels search at 10 knots, but the towing speed is only about 2 knots. Wind is an important aspect, and trawling requires a wind speed of less than 20 metres/sec (about 10 knots) for an average sized vessel. Ichii's (1985) report on repeated tows on the same swarm shows that such tows are nearly parallel to each other. The primary reason for this is that unless wind speeds are less than about 2-3 on the Beaufort scale (about 5-10 knots), the vessel must steam with the wind from behind when trawling. Accordingly the reverse traverse of the swarm is used to recheck the position of the swarm (which may be moving) and the optimum direction for towing; attempts are made to avoid the previous trackline when re-towing, as passage of the vessel tends to disperse the krill, although this can be difficult if the swarm has moved, and demarcation of the line may be problematic as air bubbles from the original tow vanish within 15 minutes. [The Soviet operations differ in this respect; their net design allows for faster towing at 4-5 knots, and they are less influenced by wind factors.]

In the initial part of the fishing season - until late December - krill swarms tend to be small and catch rates low. In the high season from late December to the end of February, the number of swarms and their sizes increase, and catch rates are high. In March icing starts, and after sunset the krill swarms rise to the surface and disperse with a consequent large drop in catch rates. The fishing takes place 24 hours a day, until later in the season when there is a period of darkness.

The records kept of the fishing operation distinguish between "patches" and "layers" (Japanese terminology); the separation is based on the ratio of vertical to horizontal dimensions of the aggregation - greater than 0.2 for a "patch", and less for a "layer". However either of these categorisations would seem to be "swarms" in the sense of Butterworth and Miller (1987). The larger dispersed "layers" [as defined by Butterworth and Miller (1987)] were indicated to be very common (though less so in the Scotia Sea), but their densities are too low to render fishing on them an economic proposition. Nevertheless, it is believed that these layers comprise a considerable fraction of the total krill biomass; since it seems that this component will not be sampled by the fishing vessels, some attention should perhaps be given to the possibilities of monitoring it during research activities.

Only one of the Captains with whom discussions were held, had experience of fishing on a super-patch (off the South Orkney islands during the 1985/86 season). Another stated that most super-patches were reported in the area off Enderby Land. From comments in Ichii (1985), it seems that the main difference in operational procedures when fishing on a super-patch, is the major reduction of the proportion of time spent actively searching.

3.3 Quality Aspects and "Green" Krill

Six types of products are prepared on the krill trawlers. Dried krill and boiled-and-peeled krill are very rare - the latter was only produced on an exploratory basis. Meal production is now increasing. The three major products are boiled-and-frozen krill (for human consumption), fresh-frozen krill (used as fishing bait and for food in rearing fish, though a part is used to produce a seasoning liquid for human consumption), and fresh-peeled krill consisting of the tail portion only (for human consumption). Processing constraints differ for the various products: fresh-frozen krill must be processed within 2-3 hours of capture, whereas peeled or boiled-and-frozen krill can wait for 3-4 hours.

The size of the krill is categorised by length class: LL (larger than 45 mm), L (between 35 and 45 mm), and M (below 35 mm in length). The largest size class has been targeted throughout the history of the fishery. This is because it is easier to peel, and the larger sizes are preferred both for human consumption and for use as bait.

However, in the course of time certain other important consumer preferences have developed. Over the past two years there has been a Government campaign to promote human consumption of krill, and the market has developed a clear preference for firm rather than soft krill.

The most important quality consideration though is (avoidance of) "green" krill. "Green" krill have been feeding intensively on phytoplankton, which accumulates in the head section (specifically in the hepatopancreas inside the carapace). This is of no relevance if fresh-peeled krill (or meal) is being produced, but "green" krill are actively avoided if the other two major products are required because they are dirty in appearance, smell bad on cooking, and are inferior in taste. The smaller sized krill tend to be less "green", so that L and M size classes may be fished preferentially if "green" krill are abundant. Egg-carrying females may also be sought in such circumstances, as this diminishes the greenish appearance.

Avoiding "green" krill was not always a feature of the fishery. The first season it became a factor was 1978/79. However, not all companies involved became concerned about this aspect simultaneously. A survey of the companies (Shimadzu, pers. commn) has indicated a steady progression with time in the number of companies taking "greenness" into account, with the final company joining this list as recently as the 1985/86 season; the market preference for "white" krill is now very strong. The first haul made by a vessel on moving to a new area is often small to provide a sample test for quality (both size and colour).

"Green" krill is more prevalent in the Scotia Sea than off Wilkes Land. It is more likely to be found early in the season, and closer inshore in relation to the Scotia Sea islands (possibly a consequence of upwelling). Swarms of krill in the Scotia Sea were reported usually to be close inshore and "green".

It seems very likely that any model of an individual trawler's operation would have to allow for change with time as krill "greenness" has become more relevant. Catch-length based analyses may also be affected, with age-specific-selectivity patterns influenced by this factor. Even though all the companies participating in the fishery are now "green" - sensitive however, this is not a constraint for all vessels at all times - it depends on the product(s) required on a particular day. For example, one multi-vessel company had one of its vessels dedicated to fresh-peeled krill production throughout the 1985/86 season, for which "greenness" would have been of no concern.

The data-base contains records of daily krill production by size category and product-type, though no details of "greenness". There seems to be a need to examine whether CPUE measures are substantially affected by desired-product-related targeting, and whether the existing data is adequate to allow targeting to be inferred - if not, a request might need to be made to consider possible routine recording of product-related targeting and "greenness" in future.

3.4 Cooperation with Other Vessels

The role of cooperative inter-vessel communication in determining fishing patterns is important to establish. The average time it takes to find a new swarm or new concentration upon which to trawl, may be an important contributing index in monitoring krill abundance trends (see Section 4.3); but this only applies to independent searching, which is quite different from moving directly to a high density region under the specific direction of another vessel already fishing there. Models of the fishing operation may yield very different results depending on the extent of such cooperation.

The Captains advised that during the first four seasons of the commercial fishery (essentially the operations off Enderby Land), there had been very frequent communication between the vessels, essentially to speed the development of expertise as all were then "new boys".

However the situation has since changed, and because of competition between the fishing companies, it seems that as a general rule there is no active communication between vessels from different companies. In contrast, vessels from the same company communicate and cooperate very closely - one company advised their vessels usually operate within sight of each other. The vessels from the company that also conducts whaling operations maintain close contact with the whaling fleet, which provides information on oceanographic conditions which may favour krill fishing as well as data on krill quality (size class) from minke whale stomach content inspection.

While the distinctions just indicated seem to be the case on a "microscale", and probably provide an appropriate basis for the stratification of data from various vessels in initial modelling exercises, they should not be understood to imply that vessels from different companies are kept completely ignorant of the activities of each other. The Captains advised that they are eager to collect information from other companies on catch rates and catch compositions (size and quality) in previous seasons. While fishing is in progress, general information about whether an area is good or bad for catching may be passed on if vessels accidentally approach each other, or hints of appropriate areas to which to move may be relayed to vessels following communication between company offices in Japan. The vessels are aware of each other's approximate positions, and may consult with others before deciding whether to move east or west in searching for a new fishing area. "Areas" in this sense may be typically of the order of 100 n.miles apart, i.e. reflecting different "concentrations" as the term is used in this document.

Ichii (1987), following observations on a krill trawler off Wilkes Land, reports that communication with another vessel (from a different company in this instance) was the primary determinant of fishing area location in about 20% of cases - a not insubstantial proportion.

3.5 Macroscale Ground Selection

Ichii (1987) contrasts the features of the fishing grounds in the Scotia Sea and off Wilkes Land. In broad terms, the quality of krill off Wilkes Land is better: there is less "green" krill, and the krill tend to be transparent and firm rather than of red-pink colour and soft, so that processing of the fresh-frozen product need only be completed in 3 hours, compared to 2 hours in the Scotia Sea. By-catches of salps and of fish larvae are also problems in the Scotia Sea.

In this context, the almost complete transfer of effort from off Wilkes Land to the Scotia Sea over the past few years may seem surprising, but has been brought about for more important logistic/economic reasons. Recent increased product demand has been primarily for peeled krill, for which "greenness" is not relevant; and the better catch rates (and also larger sized krill) in the Scotia Sea compared to those off Wilkes Land are important favourable factors.

The profit levels in the krill fishery are not high, so that cost-reducing strategies are adopted. The various companies' vessels operating in the Scotia Sea generally share the same freezer-cargo ship, reducing the options for more widespread operation. (The whaling factory ship is used in this capacity off Wilkes Land). In earlier years many of the trawlers were based in Japan, so that the grounds off Enderby and Wilkes Lands involved the least transit times. Now most of the vessels involved are engaged in other fishing activities off New Zealand, Africa and South America over the remainder of the year (for example, squid fishing off the Falklands/Malvinas); the vessels are based in foreign ports (in Chile, for example) so that fishing in the Scotia Sea for krill becomes a much more practical proposition.

4. THE RELATION BETWEEN CATCH RATES AND ABUNDANCE

4.1 The Utility of Catch-per-Haul and Catch-per-Towing-Time Indices

Catch-per-day holds little promise as a krill abundance indicator, because of limitations imposed by vessels' processing capabilities. Also it seems very clear that Catch-per-Haul will not constitute a usable index in monitoring abundance trends. When vessels move to a new area, the first haul is usually deliberately small, as the immediate concern is to determine the quality of the krill at that location. But more importantly, hauls are generally kept to a maximum of 5-10 tonnes (assessed while towing by use of net sounders). This is for two reasons: product quality suffers in larger hauls because the krill is crushed, and operations need to be linked to the vessel's processing rate capabilities. Thus Catch-per-Haul exhibits a form of gear saturation.

Gulland's (1985) initial impression of the Japanese krill fishery was that it was rather similar to demersal trawlers operating on dispersed fish, and that fishing on a single swarm was far from being the standard practice. Accordingly he concluded that Catch-per-Towing-Time might give a fair index of krill density over a wide area. In consequence Butterworth and Miller (1987) suggested that Catch-per-Towing-Time would index within-concentration krill density ($d_sA_s\delta_{ks}$) rather than within swarm density (δ_{ks}) alone.

However, following discussions, the author suspects that this conclusion may be incorrect. Shimadzu (1984) reports the average number of swarms trawled per haul as 1.5. One company advised that a single swarm was generally adequate to obtain the maximum catch required in a single haul (though also quoted the South Shetland Islands area in 1985/86 as an exception); another advised that about 80% of hauls in the high season were made on a single swarm alone. Clearly this needs to be investigated in detail by analysis of the Japanese krill data base, but the immediate implication seems to be that Catch-per-Towing-Time will provide only an index of within swarm density (δ_{ks}) - the data base contains records of the number of swarms trawled each haul, so that multi-swarm tows could be excluded when making such a calculation.

The situation may be different in the earlier part of the season when swarms are smaller, and hauls tend rather to traverse a number of swarms. Sonar (forward range 1/2-1 km) is used to detect swarms ahead of the vessel. Responses differed as to the strategy adopted if no further swarms were immediately visible on the sonar once towing through a particular swarm was complete: some advised it was more efficient to keep towing the net in such circumstances; others stated that in areas with a small number of swarms, it was preferable to increase the number of hauls rather than keep the net in the water. The latter instance would complicate interpretation of Catch-per-Towing-Time as an index of within-concentration krill density ($d_s\ A_s\ \delta_{ks}$).

Even if this measure could be used to index $d_s\ A_s\ \delta_{ks}$ in the earlier part of the season, this may nevertheless prove to be of limited utility. One company advised that operations are now being concentrated in the high-season (January-February), primarily to maximise efficiency by taking advantage of higher catch rates at that time. Thus in future years, data pertinent to the early part of the season may well be very sparse.

Accordingly the existing data collection procedures seem likely only to provide an index of within-swarm krill density (δ_{ks}), through Catch-per-Towing-Time. While searching time measures may allow monitoring of average swarm density within a concentration (d_s) (see Section 4.3), a concern is that this would nevertheless leave average swarm area (A_s) unmeasured (in the high season maximum haul sizes apparently usually being obtained, and nets being raised, before the whole swarm has been traversed).

4.2 Reasons for Vessel Movement

If the density of swarms within a concentration (d_s), or the density of concentrations (D_c), are to be indexed by operational data other than Catch-per-Towing-Time, it is important that the various reasons that may lead to movement of a vessel be appreciated. Accordingly one question asked of the Captains was what were the main determinants of a decision to move to another "area" to fish. Although the question was intended to apply both to within-concentration and between-concentrations scales, the author suspects that most of the comments made were more applicable to the latter.

The principal consideration appears to be an economic one. However, comments differed as to whether catch rate or krill quality (white rather than green, large size class, and avoidance of by-catch of salps and/or fish larvae) was the dominant factor in the economic equation. This must depend on the final product required, which may differ from vessel to vessel, and even for the same vessel at different times of the season. If catch rate or quality (whichever is relevant at the time) is satisfactory, a vessel will attempt to keep track of the swarm while completing processing to allow for subsequent re-towing, but will otherwise undertake searching for new swarms.

Bad weather also plays a role; the low power of vessels restricts their ability to catch in adverse conditions (see Section 3.2), so they will move to avoid these unless the area being fished is particularly good. Further, poor weather is often accompanied by a change in the distribution of the krill swarms, so that searching may have to be started anew once such periods are over, although the echosounder is monitored continually through these periods despite towing being impossible.

Communication with other vessels (see Section 3.4) can lead to a decision to move to another area. Also movements must take into account the need to transfer catch and take on fuel and water from a freezer-cargo vessel (or whaling factory ship for some vessels) - this occurs typically 5 times for a vessel during one krill fishing season. The opening strategy is often to move to an area where good catches were made the previous season, although locations favoured by krill can change from year to year.

From observations made aboard one particular vessel, Ichii (1987) lists the following relative frequencies of reasons to move to new fishing areas:

Areas that provided good yields the previous season:	34%
Communication with other vessels:	22%
Return to areas previously located that season (in the hope, perhaps, of quality improvement):	22%
Cues to krill concentrations (e.g. ice conditions, predators)	22%

The reason for leaving an area during the period of these observations was usually poor catch rates.

Ichii (1985) provides an example of fishing on a super-patch. Vessel movement on that occasion appears essentially to have involved no more than maintaining contact with the super-patch in its counter-migration against the current.

4.3 Time Budgeting and Search Time

As discussed in Section 4.1, it appears that in the high season for krill fishing, Catch-per-Towing-Time is likely to relate only to the average density of krill within a swarm (δ_{ks}), rather than the product $d_s A_s \delta_{ks}$ representing the density of krill within a concentration of swarms. Some index is needed of the density of swarms within a concentration (d_S) (as well as, if possible, the density of concentrations, D_c). For example, one company stated that in the vicinity of the South Orkney islands in the 1985/86 season, although the within swarm density was very high, the number of swarms per unit area had been rather low; thus Catch-per-Towing-Time alone might give an over-optimistic impression of the krill abundance in that area on that occasion.

Measuring the search time to find swarms could provide an index of d_s (and also possibly D_c). Certainly a large fraction of operational time is spent searching, and the Captains emphasised that the echosounder is watched all the time (even when transferring cargo). One Captain (who had previous experience of the time budget data recorded in whaling operations) had had his quartermaster keep records in a notebook on a similar basis over the krill fishing season. His vessel's time had been divided as follows:

Searching:	45%
Net handling (entry to and withdrawal from water):	24%
Towing:	18%
Idling (due to bad weather, engine kept going):	6%
Transferring cargo:	4%
Drifting (engine stopped):	3%

Note: (a) The searching time above was not measured directly, but was obtained by subtracting the time spent on other activities from the total operation time. It includes both "primary" and "secondary" searching (as defined subsequently in this section).

(b) The towing time refers only to when catching is taking place, as indicated by the net recorder; about 1.5% of the total time was spent adjusting the net to the desired water depth, and this is included in the searching time above. Drifting occurs for several reasons, for example engine repair; only a small proportion of this time corresponds to waiting to end processing (without searching) because swarms are known to be in the area.

This indicates that the great majority of the time is spent in searching and net handling. A Captain from a different company independently offered this comment, although not possessing as detailed quantitative data.

However, the definition of searching is not as straightforward as the tabulation above suggests, in particular since it is only the "primary searching" component of this time relating to finding a new swarm (or new concentration) that is relevant as an index of d_s (or D_c). Ichii (1987) comments that while searching time is almost equivalent to the time between finishing one haul and starting the next in low density areas, definition becomes very difficult in higher densities when the constraint imposed by processing time requirements delays the onset of further trawling. Sometimes the trawl net may be deliberately kept under water until processing of the catch from the previous tow has been completed. Also Ichii (1985) suggests that judgements that repeated towing on a patch is taking place (such data has been recorded since 1984/85) may not be entirely reliable.

The Captains, while appreciating the relevance of a measure of primary searching effort, were doubtful how practical it would be to record this. One problem (unlike in the case of whaling) is that it would not always be possible to decide easily and unequivocally what a vessel's primary activity was at a particular time. Further, it was stressed that the quartermaster already has considerable data recording duties to which to attend, and would not welcome further work; this aspect has to be kept in mind, as unrealistic further requests of the crews may lead only to a decline in data quality.

Nevertheless because of the importance of this issue, two experimental recording procedures were discussed with Dr Shimadzu and his colleagues, and Dr Shimadzu was to investigate further whether it might be possible to implement them during the 1986/87 season. (Shimadzu, pers. commn, advises that some trial recordings similar to those discussed below were duly made.)

The first was to request all vessels to keep a record of the start and end times of periods of "primary searching effort" during a limited period of the fishing season (mid-January to mid-February during the high season was suggested). "Primary searching" was defined as the time spent looking for a new swarm on which to trawl, and excluding time spent preparing to tow again on the same swarm or to complete processing after a new swarm had been found. It would be requested that if there were periods when the crew was too busy to record this information, they note such times on the forms to be provided. The objective of this exercise was to serve as a feasibility study of whether primary searching information could be collected in practice and would prove suitable for use in calculations.

The second experiment would involve a request to the company whose vessel had collected time budget data previously (as summarised above) to continue this exercise using a form that would facilitate subsequent encoding and analysis of the data. This would constitute continuous recording of the vessel's operational activity. In discussion with Dr Shimadzu and colleagues after the meetings with company personnel, the following provisional list of activities was constructed:

(I) Searching:

- (a) Primary searching:
  - (i) Searching for new swarm within concentration
  - (ii) Searching for new concentration (undirected)
  - (iii) Searching following external communication
  - (iv) Searching in transit to/from cargo transfer
- (b) Secondary searching:
  - (i) Confirming swarm dimensions after finding it
  - (ii) Searching for swarm just trawled to trawl again
  - (iii) Maintaining contact with swarm until processing ends

(II) Net Handling:

- (a) Net entering water
- (b) Aiming net to correct depth
- (c) Withdrawing net from water onto deck

(III) Towing (actively fishing)

(IV) Idling (due to bad weather)

(V) Transferring cargo

(VI) Drifting (engine off):

- (a) Drifting while finishing processing, with swarms in the area
- (b) Drifting because of bad weather
- (c) Drifting for other reasons (e.g. engine repair).

The objective of this was again a feasibility study of the practicality of collecting such information. The resultant data could be used, for example, to develop a model such as that of Cooke and Christensen (1983) to assess the magnitude of possible non-linearities in the CPUE-abundance relation arising from catchability fluctuations.

4.4 Large-scale Density Trends

Another component in the expression to calculate total krill abundance is the total management area (A_t). A concern is that changes in total abundance could be reflected mainly by expansions or contractions of the overall extent of the krill concentrations, rather than in the smaller scale features [such as within-swarm density (δ_{ks})] to which indices discussed earlier would relate (Butterworth and Miller, 1987). Information on larger-scale trends in krill density is therefore of interest.

The close vicinity of the continental ice-edge was not regarded by the Captains as necessarily a preferred area to catch krill, but this must be considered in the context that drifting ice is avoided because of the danger of damage to the fishing gear. One strategy when new concentrations are sought, is to move to the ice-edge and then search northwards, which is suggestive of a large-scale general fall-off in density moving away from the ice.

A feature mentioned more than once is that krill remains within the cold water masses as the ice retreats in the early stages of the season, so that fishing tends to move closer to the continent with time. The prospects that a routine monitoring of oceanographic features might provide an annual index of the overall krill distributional area perhaps merit attention.

In the Scotia Sea, most fishing is carried out within sight of an island. Islands can be approached to within 1/2 n.mile for fishing, but the nearer regions tend to be avoided because of the greater likelihood of encountering "green" krill. Fishing extends to about 30 n.miles from shore in the South Orkneys, and as far as 80 n.miles in the South Shetlands. The Captains could not suggest any general trend in density within these areas, though a belief was expressed that krill were rather far from the islands at the start of January, and tended to move closer as the season progressed. However, the distribution in the zone between the South Shetlands and South Orkneys was described as very sparse, suggesting that there must be a fall off in density once a certain distance from the islands is exceeded.

4.5 The Choice of a Data Sample for Further Studies

The CCAMLR Scientific Committee has requested that Japan make available a sample of the detailed data that has been collected on their krill fishing operations, to facilitate further investigations in this study. In choosing such an initial sample, the primary consideration was to search for a vessel whose operation was categorised by as few complicating factors as possible. Any initial model of the fishing operation needs to be kept simple; the data choice strategy was intended in that sense, to enhance the possibility of identifying the basic features of the operation - attempts to take account of complicating factors can be made later.

The sample chosen comprised the operation of a particular vessel off Wilkes Land in the 1980/81 and 1981/82 seasons. The vessel is only slightly larger than the average, both in terms of size and its harvest in each of the two seasons. Also the nets used by the vessel were virtually identical over the two seasons. The vessel's parent company had previous Antarctic krill fishing experience prior to the 1980/81 season.

There are several advantages to this particular choice:

(i) This was the only vessel operated by its parent company over those two seasons, so that searching behaviour was probably influenced relatively little by inter-vessel communication.

(ii) The parent company indicates the "green" krill catch quality aspect was not a factor it took into consideration until some years after these two seasons.

(iii) The vessel fished for a lengthy period in both seasons (about 3.5 months - late November to mid-March - in each case), which allows scope for inter-month comparisons.

(iv) Another vessel from the same company fished in the same area in 1982/83 - this allows for further comparisons in future work.

(v) The area off Wilkes Land does not have the complications of the numerous islands of the Scotia Sea; krill distribution and fishing patterns in the Scotia Sea seem to be closely linked to these islands, which would complicate modelling.

(vi) There is a longer history of Japanese operations off Wilkes Land compared to the Scotia Sea.

However the choice also has some disadvantages:

(i) The great majority of current Japanese krill fishing takes place in the Scotia Sea, rather than off Wilkes Land as previously.

(ii) Little of the fishing area off Wilkes Land was surveyed by research vessels in the FIBEX and SIBEX programmes.

(iii) Records have been kept of whether a tow was on a new swarm or repeated on the same swarm - but only from the 1984/85 season. Such data would be useful for modelling.

Consideration was given to choosing the vessel for which certain time-budget data had been collected (see Section 4.3). However it was felt that this was offset by the complications of that vessel's searching behaviour being influenced by communication with the whaling fleet, and being sensitive to a certain extent to "green" krill quality considerations.

5. SUMMARY OF CONCLUSIONS

(a) Investigations of the Japanese krill fishery should concentrate on the analysis of individual vessel activities. The mothership-type operation was complicated by processing constraints, would be difficult to model, and seems unlikely to be repeated in the immediate future.

(b) Catch-statistics analysis will be concerned with fishing on concentrations of swarms. Super-patches seem to be relatively rare. Layers of krill are of densities that are too low for fishing to be economic; consideration should be given to the possibilities of monitoring these layers during research activities.

(c) It seems likely that future krill fishing will be concentrated in the January-February "high-season" period, which yields the best catch-rates. Modelling should therefore concentrate on the circumstances typical of this period.

(d) Processing rate limitations are a major feature of the krill fishery, so that Catch-per-Day indices are unlikely to relate to abundance.

(e) Product quality considerations lead to haul sizes being restricted, so that Catch-per-Haul is not a reliable index of abundance.

(f) Advice was that most tows in the high-season are completed before the first swarm fished has been traversed completely. This merits checking against available data, and would imply that Catch-per-Towing-Time is likely to index only within-swarm density (δ_{ks}).

(g) Primary search time information (pertaining to finding a new swarm) would be desirable to obtain to attempt to index within concentration swarm densities (d_s), and perhaps also the density of concentrations (D_c). However, there are practical and definition difficulties in recording such data. Some feasibility experiments in this regard may be attempted (and were indeed subsequently instituted, Shimadzu, pers. commn). Other important difficulties for analysis of this aspect are:

  (i) The overall krill distribution is non-random; there are favoured areas, possibly linked to oceanographic features.

  (ii) There is communication between vessels. Vessels from the same company cooperate very closely, but on the other hand communication between vessels from different companies is very limited.

  (iii) Searching often has to start "*ab initio*" after bad weather.

  (iv) Over the years, market preference development has led to an increasing tendency to avoid catching "green" krill, unless the fresh-peeled product is required. Analysis should attempt to determine the extent to which this influences various CPUE measures, and whether routine recording of "greenness" and product-targeting is needed. This aspect of the fishing strategy may also have implications for catch-length-frequency-based assessment methods such as Virtual Population Analysis.

(h) A concern is that high-season catch rates and associated data seem unlikely to index average swarm area (A_s) (see 6. above), or the average area of a concentration of swarms (A_{cs}).

(i) There are indications that (in a very broad sense) krill density falls-off moving north from the continental ice-edge, and away from island coastlines in the Scotia Sea. The possibility of routine oceanographic monitoring being used to demarcate and so index the extent of the krill distribution (reported to remain within the cold water masses as they retreat during the fishing season) should be investigated.

(j) Data from an individual vessel which operated off Wilkes Land in the 1980/81 and 1981/82 seasons have been selected for initial study; the choice was aimed at an operation affected by as few complicating factors as possible, to simplify initial modelling attempts.

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