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Managing Southern Ocean Krill and Fish Stocks in a Changing Environment [and Discussion]

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Managing Southern Ocean krill and fish stocks in a changing environment

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SUMMARY

Management of Antarctic krill, *Euphausia superba*, and the mackerel icefish, *Champsocephalus gunnari* under the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) is discussed in relation to changes in their distribution and abundance arising from variation in circulation of the circumpolar current. It is concluded that on a Southern Ocean scale it is currently not possible to detect change but on a local scale, such as at South Georgia, major changes are detectable. These changes affect the krill fishery directly in terms of total catch and the way the fleets are deployed. Major local reductions in krill are thought to have a significant effect on natural mortality of the icefish.

1. INTRODUCTION

Management of Southern Ocean living resources is the responsibility of the Commission for Conservation of Antarctic Marine Living Resources, CCAMLR. This Commission, established in 1982, was different to other international fishery organisations because for the first time it was agreed that the resources should be managed on an ecosystem basis. The key clauses outlining this approach are in Article II which, in its first paragraphs, states that the objective of the Convention is conservation, a term which includes rational use, and then espouses three principles of conservation. These are firstly, the size of any harvested population should be prevented from decreasing below the size which ensures its stable recruitment, essentially the traditional single-species approach to management. Secondly, ecological relationships between harvested, dependent and related populations should be maintained, and the third principle is the prevention or minimisation of changes which are not reversible within 20 or 30 years. Article IX elaborates these principles into a mechanism for management which is in turn dependent on advice being provided by the Scientific Committee, SC-CAMLR, whose functions are set out in Articles XIV and XV.

In practical terms the Commission is seeking information from SC-CAMLR on how much of each resource may be safely harvested, where that resource can be harvested and the impact of that level of harvesting not only on the resource but also on dependent species. Management decisions are made, revised or confirmed annually while implementation often requires monitoring key parameters during the year. Changes in the status of individual resources, whether natural or induced by harvesting, will therefore in theory be covered by this review process.

The traditional approach to fisheries management has relied heavily on scientific advice being provided as a series of indices, such as the index catch per unit of effort (CPUE) which is often used as an index of abundance. When single species are being considered such an approach is perfectly valid. However, when groups of species are being managed together it becomes necessary to determine how an index for one species reacts with respect to indices for other species. This requirement has introduced an added complication into resource management on an ecosystem basis.

The types of scientific information needed to assess the status of living resources may be considered under a number of headings such as: distribution, standing stock, growth, mortality, recruitment, production, fishery catch and predator–prey interactions. In this paper the status, over recent years, of two resources, Antarctic krill (*Euphausia superba*) and the mackeral icefish (*Champsocephalus gunnari*) at South Georgia, is examined to determine how important a changing environment is to their management.

2. ANTARCTIC KRILL, *Euphausia superba*

(*a*) *Southern Ocean scale*

Krill have a circumpolar distribution being found south of the Polar Front and generally north of the ice edge in summer (Miller & Hampton 1989). They do occur under the pack ice in summer (Marschall 1989) but it is unclear whether these under-ice krill represent a significant proportion of the total population. Within this large general area are small regions of high krill concentration which tend to be close to the continental shelf and slope. Generally it is thought that krill are carried on the circumpolar current (Miller & Hampton 1989) although it has been

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Table 1. *Estimates of total standing stock for krill in the Southern Ocean*

standing stock (million tonnes)	comment	source
44.5	extrapolation of single observation (2.5 g m^{-2})	Marr (1962) (in Everson 1977)
521	extrapolation of single observation (28–29 g m^{-2})	Marr (1962) (in Everson 1977)
953–1350	method not indicated	Shevtsov & Makarov (1969)
750	assumes krill 50% zooplankton	Everson (1977) (from Gulland 1970)
5000–7000	based on assumed P:B ratio and krill 50% of the zooplankton	Moiseev (1970)

suggested that there are self maintaining groups in some regions (Siegel 1988). Proposals for a management system have been made by Everson (1977), who suggested expansion should be controlled up to an arbitrary but 'safe' level, an approach elaborated by Butterworth (1986, 1990).

Several types of change are possible in the Southern Ocean environment, but for this paper discussion is restricted to the implications of changes in oceanic circulation pattern as it might affect krill. It is assumed that the favoured temperature regime of the krill is present somewhere within its range and that there is sufficient primary production to maintain the krill. Following on from these assumptions we are left with distribution, standing stock, predator–prey interactions and the fishery as the key factors to consider in the management context.

Examples of total standing stock estimates for krill in the Southern Ocean that have been provided by several workers are set out in table 1. Several of the estimates in table 1 assume that krill make up half the standing stock of zooplankton in the Southern Ocean, a proportion that has been questioned by Voronina & Naumov (1968). There is increasing evidence that the contribution of krill to the overall Southern Ocean secondary production is very much less than that arising from the smaller zooplankton (Conover & Huntley 1991). The figures above may be used therefore as a guide but some are almost certainly overestimates, furthermore they cannot be used to indicate any trend that might have arisen as a result of environmental change.

The FIBEX survey of the BIOMASS programme provided the largest quasi-synoptic acoustic survey of krill (Everson & Miller 1992) which after recalculation using revised values of acoustic target strength gave the standing stock estimates shown in table 2 (Trathan *et al.* 1992). This gives a total of approximately 25 million tonnes for the 0.63 million square kilometres of that part of the survey. Trathan *et al.* (1992) note that there is considerable uncertainty as to how the German data, obtained at 50 kHz, relate to the remaining parts of the survey where 120 kHz echosounders were used and imply that the 10.4 million tonnes may be unrealistic. This leaves a total of 15 million tonnes in 0.41 million km^2 if that part is excluded.

Table 2. *Krill standing stock estimates*

location (subarea)	standing stock (million tonnes)	comment
48.1	14.20	including 10.4 million tonnes from German survey at 50 kHz.
48.2	9.38	
48.3	1.51	

The surveyed area in subareas 48.1, 48.2 and 48.3 was assumed to cover one of the assumed large areas of high krill concentration, hence extrapolating these values to the whole 36 million square kilometres of the Southern Ocean will almost certainly overestimate the total standing stock. Based on the BIOMASS results the standing stock of krill is therefore likely to be substantially less than 1429 or 1317 million tonnes, depending on whether the German results are included in the calculation.

The general equation:

$$Y = \lambda M B_0 \qquad (1)$$

is often used to estimate maximum sustainable yield (Y) when natural mortality rate (M), standing stock (B_0) and a proportionality factor (λ) are known. Several values of M have been suggested although currently 0.6 and 1.0 are thought to be the most realistic (Anon 1991). Beddington & Cooke (1983) demonstrated that are value of λ should be less than 0.5 and Butterworth & Basson (1991) based on the assumption that the krill growth season is only about a quarter of the year suggest that the value should be no greater than 0.4. Substituting these values in equation 1 gives the following values of Y:

	Y	
B_0	$M=0.6$ $\lambda=0.4$	$M=1.0$ $\lambda=0.4$
1429	343	572
1317	316	527

Estimates of krill production have also been made by summing the amount of krill consumed by predator species throughout the year. The most recent study of this type is Laws (1985) who estimates that the total amount of krill consumed by whales, seals, birds, fish and squid amounts to 470 million tonnes. Such a level of production would require a standing stock of between 1175 and 1958 million tonnes. This amount is similar to the values estimated from equation (1). Because the FIBEX estimates are extrapolations from an assumed high density region it indicates that the estimated predator consumption figures are too high relative to the acoustic estimates. The results do not

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Table 3. *Standing stock estimates for krill in the vicinity of South Georgia*

(Data from U.S.S.R. surveys reported to CCAMLR in Anon (1991)) compared with reported catches in the six months before and six months after the start of the survey (data from Anon 1991*b*).)

catch 2–6 months before survey	catch in 2 months before survey	survey biomass and date	catch during month of survey and one month later	catch 2–6 months after survey
		54 000 (June 1983)	10 008	3797
203	65	3800 (October 1984)	0	887
98 318	8120	607 000 (November 1986)	90	113 856
21 409	0	878 000 (February 1988)	24	168 048
4530	16 438	1 402 000 (May 1988)	88 926	106 272

indicate which is the more accurate or whether both are wrong. The important point is that, on a Southern Ocean scale, we are still unable to determine an average relationship between krill and its major predators. Until we have more sophistication in these estimates we are unlikely to be able to quantify a general relationship let alone determine how this is affected by a changing environment.

(*b*) *South Georgia region*

Having demonstrated that we are unable currently to follow changes on a Southern Ocean scale we need to consider whether this is possible on a smaller scale. For this analysis I will concentrate on the southwest Atlantic sector and in particular the South Georgia region, subarea 48.3, because this is the best documented.

In 1991 CCAMLR adopted its first conservation measure with respect to krill (Anon 1991*a*, para. 10.4) which set a precautionary catch limit of 1.5 million tonnes for the three subareas 48.1, 48.2 and 48.3. This level was arrived at by applying equation (1) to a provisional re-evaluation of the FIBEX results for these subareas (Anon 1991, Annex 5, Table 6). It assumes that there is a major flow sequentially from subarea 48.1 to 48.2 and thence to 48.3 with a smaller flow in the opposite direction. Determination of the relationship between the standing stock and rate of change arising from transport in the circumpolar current are beyond the scope of the present paper although these factors need to be taken into account in any management plan.

There have been many papers, reviewed by Everson (1988), which contain information on standing stock of krill. However, when comparing the results from different surveys it is important that all methods are fully standardized. The requisite level of standardization is most likely to be present in surveys undertaken by the same organization. At South Georgia there have been a series of krill surveys undertaken by the former U.S.S.R. in recent years; those in the past decade have been during a period of large-scale fishing in the area. Survey estimates, reported to CCAMLR by U.S.S.R., include values from all times of the year and in several seasons, and are shown in table 3.

There is a great deal of variation between these individual survey estimates. Part of this variation is due to natural variation arising within the survey; no survey variances are provided. A large amount of variation, however, is likely to be due to real differences in standing stock between the surveys. Unfortunately no information is available which describes the survey design or the method of assessment, but assuming that all surveys have been undertaken and analysed in the same way we can infer that significant changes do occur that are sometimes of great magnitude. Such an assumption is reasonable because it is known that there are major changes in local krill standing stock with time (Everson 1984). Even though there is this large variation between surveys, suggesting major changes in local standing stock over a period of months it is important to consider how long particular concentrations remain in an area. Such an assessment should give an indication of how useful such surveys are for management.

Although krill are widespread in their distribution, concentrations suitable for commercial harvesting tend to be found over the continental shelf. Everson & Goss (1991), from an analysis of commercial data reported from 'finescale rectangles' half a degree of latitude by a degree of longitude, demonstrated that the U.S.S.R. krill fishery was highly localized and

Table 4. *Catches of krill from subareas 48.2 South Orkneys) and 48.3 (South Georgia) for the 1986–87 and 1987–88 seasons reported to CCAMLR by U.S.S.R.*

(Data from Anon (1991*b*). An asterisk indicates the month during which a krill survey was undertaken around South Georgia.)

month	subarea 48.2	subarea 48.3
October 1986	669	1748
November 1986*	1131	32
December 1986	6609	58
January 1987	5342	16 974
February 1987	316	16 098
March 1987	2912	15 608
April 1987	0	65 176
February 1988*	14 579	14
March 1988	21 459	10
April 1988	40 681	16 428
May 1988	650	41 025
June 1988	0	47 901

tended to concentrate around South Georgia during the winter months, moving south to the South Orkneys as the ice retreats. During the fishing season at South Georgia the data in Everson & Goss (1991) indicate that the fleets appear to be operating within only about four 'finescale' rectangles. These 'finescale data' are only available for the most recent seasons and do not cover the whole period of the surveys in table 3. Monthly catch rates have been reported since 1983 and annual catches from before then. Examination of the monthly catch rates provides an indication of how the fleet has made use of the survey information.

For the period immediately prior to each survey there is no significant correlation between the reported catch and the estimated survey standing stock (table 3). Immediately after the survey the picture is quite different. The winter survey in 1983, even though it indicated a fairly low standing stock, was followed by a large catch. The following year the standing stock was extremely low, a result confirmed by Priddle *et al.* (1988), also there was a very low catch prior to the survey and in the succeeding months. The 1986 survey followed a period when a large catch was reported but, at the time of the survey the fleet had moved to the South Orkneys where, during November and December the total reported catch was 7740 tonnes (Anon 1991*b*). This is less than had been caught at South Georgia in the preceeding months amd probably indicated better conditions there than at the South Orkneys. Examination of the reported catches for that season, shown in table 2, indicates that one month following completion of the survey, much of the fleet appears to have returned to South Georgia resulting in the very high catches, ten times that reported for the South Orkneys, during the first four months of 1987. A similar pattern followed the February 1988 survey (table 4).

The February 1988 survey is the only one to have been undertaken by a research vessel, all the others were by commercial vessels. This survey, which followed two months of zero catches, indicated that the standing stock was very high. The fleet at this time was operating around the South Orkneys where in the month of the survey 15410 tonnes were reported (Everson & Goss 1991). Even though high catches were reported from the South Orkneys part of the fleet moved to South Georgia, where following a second survey, this time by a commercial vessel, high catches were achieved. The least squares regression equation for the relationship between the survey standing stock and the reported krill catch (table 3) during the six months following the survey is:

$$\text{catch} = 12.0 + 0.147 \times \text{standing stock} \quad (n=5,\ r^2=0.949).$$

To summarize from this very limited series, the winter surveys, when the fleet is presumably restricted by ice to the South Georgia region, were followed by immediate fishing. Summer surveys, which are undertaken when catch reports indicate that the fleet is generally at the South Orkneys were followed by a two month period of low catches and then a period of high catch rates lasting several months. Seen together these facts indicate that the survey is being used to identify the extent and density of concentrations, this information is then transmitted to the fleet who, after about a further month, regroup in the new area. For such an operational scheme to be effective a local high standing stock must remain in an area for several months. In the context of krill management we need to determine where and when such concentrations occur and how they are replenished.

Current thinking is that there is a relationship between krill in subareas 48.1, 48.2 and 48.3 such that krill are transported at an unknown rate towards the east. Maintenance of fishable concentrations in the vicinity of South Georgia, as indicated by the survey data and reported catches in table 3 means that either (i) krill are arriving in 'pulses' which remain at South Georgia for several months; or (ii) there is a continual supply of krill at low density that becomes concentrated on the shelf.

Both of these options are controlled by the effects of the circumpolar current, which, depending on how far north the krill containing component is at any particular time, has a strong influence on whether water masses containing krill arrive at South Georgia. Changes in the distribution of surface water masses can be determined from satellite images as demonstrated by Hunt *et al.* (1991). How the distribution of surface water relates to krill distribution remains unclear even though Hunt *et al.* (1991) noted changes in the distribution of birds, some of which feed on krill, that reflected the changes in surface isotherms. A krill patch remained more or less stationary at the western end of South Georgia throughout the first half of February 1986 (Everson *et al.* 1992) while large changes were taking place in the distribution of surface isotherms. Even though the distribution of surface temperature may indicate circulation patterns in surface water, perhaps down to 100 m, of the deep ocean, the situation over the shelf may not be representative of water more than a few metres from the surface, due to the shallow complex bottom topography. A similar conclusion was drawn by Atkinson & Peck (1990) when considering the residence times of zooplankton on the South Georgia shelf. Clearly this is a topic for further study before variation in the oceanic circulation can be incorporated into a management model.

3. MACKEREL ICEFISH, *Champsocephalus gunnari*, at SOUTH GEORGIA

Mackerel icefish are restricted to the shelf region of the Antarctic Peninsula, South Orkneys, South Georgia and other subantarctic islands. The species has supported major fisheries at Kerguelen and South Georgia and more limited fisheries in the South Orkneys and Antarctic Peninsula. The fish are fast growing and 50% reach sexual maturity when three years old at about 22 cm total length (Kock *et al.* 1985). The fishery is concentrated on three to five year old fish and in many years one year class dominates the population. Conservation measures are in force speci-

Table 5. *Standing stock estimates (tonnes) for the Champsocephalus gunnari in subarea 48.3*

(Data from SC-CAMLR-X, p. 226. The CV for the South Georgia part of the survey is indicated in parentheses. The 1989 survey did not include Shag Rocks.)

	survey	estimates	
season	Spain	U.K.–Poland–U.S.A.	U.S.S.R.
1987	222 160 (95)	55 256 (18)	
1988		16 225 (21)	
1989		22 328 (50)	
1990		149 598 (63)	442 168 (69)
1991		26 204 (16)	192 114 (44)

fying minimum mesh sizes and closed seasons and a total allowable catch (TAC) is set each year by CCAMLR.

Standing stock estimates for the South Georgia region are available from all the recent seasons and these are summarised in table 5.

Like the krill surveys, there is a large variation from year to year. The 1987 survey was based on midwater trawl data whereas all the other surveys used bottom trawls. The highest standing stock estimates tend to have the highest associated coefficient of variation (CV) and this is largely because those surveys were characterized by a large number of low density catches and a small number of very high catches. These large catches exert great influence on the mean. The surveys labelled U.K.–Poland–U.S.A., as one series, have some commonality in the scientists involved, research vessels and the gear. Inter year comparisons are therefore valid between these surveys. The same is also probably true of the two U.S.S.R. surveys. Both these series indicate a major decline between 1990 and 1991. The U.K.–Poland–U.S.A. series also indicates a large increase from 1989 to 1990. Two points warrant detailed consideration; were the indicated increases from 1989 to 1990 and the subsequent decline in the following season real or an artefact of sampling?

The February 1989 survey indicated that one year old fish made up over three quarters of the population and in the following season 72% of the population were two years old, indicating that an unusually strong yearclass was passing through the population (Parkes 1991). The presence of dominant yearclasses in fish populations is well documented and has been a feature of this species at Kerguelen, the other region in which intensive fishing has taken place. The increase in standing stock at South Georgia in 1990 can therefore be explained in part by population dynamics.

The high estimated standing stock in 1990 was justification for CCAMLR to set a total allowable catch (TAC) of 26 000 tonnes for the 1991 season; this TAC would have been even higher had not consideration of the bycatch of *Notothenia gibberifrons* in the fishery been taken into account (Anon 1990, para 13.13 *et seq.*). Reported catches for the 1991 season were very low, 49 tonnes by U.S.S.R., 41 tonnes by Poland and 3 tonnes by the U.K. (taken in the course of the survey). These low catch figures indicate that a major change had taken place. Several explanations are possible, and these are summarized below.

1. There had been a massed emigration of *Champsocephalus* from the South Georgia area.
2. There had been large scale commercial fishing at South Georgia.
3. The localized high concentrations had dispersed to produce widespread low densities over all the shelf.
4. There had been a high natural mortality of fish between the two surveys.

Champsocephalus are normally restricted to the shelf region. There is a considerable distance between the South Georgia shelf and the nearest suitable adjacent areas, therefore, it seems unlikely, but not impossible, that a large scale migration had taken place. No large-scale fishing was reported from the area (Anon 1991) indicating that, in this case, fishing was probably not the cause of the decline. Dispersion over the shelf is possible but this would have increased the estimated mean density; such an increase was not noted in the survey results. This leaves a high natural mortality as the most likely cause. Two pieces of evidence point to this being the case, firstly the stomach contents of fish caught during the survey contained proportionately less krill than had been the case in previous years (Kock *et al.* 1991) and secondly relatively few of the fish, large enough to be sexually mature were coming into spawning condition (Everson *et al.* 1991). Both of these factors are strongly suggestive of a krill shortage being the root cause.

A brief period of food shortage, such as a week, will be recognisable from examination of the stomach contents of the fish but, such a short term effect is unlikely to affect the final maturation of gonads several months prior to spawning, which normally occurs in March to May. The poor gonad condition is indicative of poor food availability several months prior to the survey and is strongly suggestive that krill had been in short supply over that period.

Examination of the *Champsocephalus* population at South Georgia leads to the conclusions that at times when krill are abundant the fish population dynamics can be explained by the traditional models, such as Virtual Population Analysis (Parkes 1991) which in the case of this species are highly sensitive to recruitment and natural mortality. When krill are scarce this appears to have a dramatic effect on the population affecting natural mortality and spawning stock. Furthermore, the implications from the 1990–91 season are that the scarcity of krill must have persisted for several months. Such a situation, with respect to krill, was also reported in August 1983 by Heywood *et al.* (1985), a conclusion in line with the krill survey results in table 3.

4. CONCLUSIONS

1. At present we are unable to monitor krill on a Southern Ocean scale. However, providing assessments are made in key areas of exploitation and

predator–prey interaction these should provide sufficient indices to give some indication of the status of the resource.

2. Concentrations of krill at South Georgia appear to persist for several months. Periods of krill scarcity also appear to persist for several months. The most likely cause of changes in abundance is variation in the pattern of the circumpolar current in the Scotia Sea and East Pacific sector of the Southern Ocean. It is also unclear whether the concentrations persist because they arise as 'pulses' of krill being brought into the area that are retained on the shelf, or whether they are part of a continuous stream flowing past the island.

3. Seen from the fishery viewpoint the analysis presented in this paper indicates that the U.S.S.R. krill fishery has been managed by deployment of catching vessels following resource surveys. This has involved moving vessels from other fishing grounds. Such an operational scheme indicates that the whole fishery might be managed on the basis of fishing effort rather than on catches.

4. The local changes in krill abundance do have significant effects on dependent species such as fish (this paper), avian and mammalian predators (Croxall, this symposium).

5. The ability to identify when such environmental changes have taken place would improve the quality of management decisions. The ability to predict such situations would allow management to be more proactive, an aim fully in line with the objectives of CCAMLR.

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Discussion

B. Stonehouse (*Scott Polar Research Institute, Cambridge, U.K.*). Is the krill fishery market led? If so, does Dr Everson see any signs of changing demand? (A few years ago it was accepted wisdom that demand was limited by the lack of appeal of the product as human food, and that once food technologists had got to work and turned it into a high value food, demand would be insatiable.)

I. Everson. A variety of products have been developed ranging from low unit value bulk products such as krill meal to high unit value small quantity products for direct human consumption. In recent years the largest catches have been reported by the former U.S.S.R.; initially much of this must have gone to fish meal but in recent years they have been making great efforts to produce high quality products aimed at western markets.

Krill fishing is undertaken in regions that are remote from main port facilities and hence the operating cost is initially quite high, although currently there are no licence fees. I would suspect that the krill meal market will depend on movements of fish meal prices world wide. High value products are likely to have much more limited markets although I have no information to indicate whether any of these are currently at saturation level.

D. J. Drewry (*British Antarctic Survey, Cambridge, U.K.*). There are several areas of environmental change which are likely to have effects on biological productivity relevant to fisheries. These might include inter-annual and longer-term sea-ice variations, and related changes in brine drainage, salinity and deep convection. There is also an increasing body of output from models such as FRAM and other Ocean Circulation models on ocean variability and response to climate forcing. Have any of these issues or factors been considered for inclusion in management plans?

I. Everson. Yes, all of these have been considered, but, because none of them operate in a predictable fashion they do not loom large in Conservation Measures. This meeting has shown the high level of uncertainty associated with them which highlights the need for more research into those factors of greatest influence on Southern Ocean living resources.

P. F. Barker (*British Antarctic Survey, Cambridge, U.K.*). How is fishing managed, as opposed to being merely monitored, when the natural variation of the estimated population from year to year is so large? Is it necessary to manage, as opposed to monitor, at this stage?

I. Everson. In its first ten years CCAMLR has gone from a tentative initial phase into a much more proactive phase of applying Conservation Measures to all harvested resources. The krill fishery is one where continued monitoring is needed and this is being done in parallel with prudent management. The finfish stocks, many of which were severely depleted before the existence of CCAMLR, require protection and monitoring to allow the stocks to rebuild. The ecosystem approach, the cornerstone of CCAMLR, is now a significant part of the monitoring work that hopefully will lead to further Conservation Measures. The next phase involves the thorny question of compliance and I am quite optimistic that this can be resolved.