ANNEX 4

REPORT OF THE WORKSHOP ON THE KRILL CPUE SIMULATION STUDY

(Southwest Fisheries Centre, La Jolla, California, USA 7 to 13 June 1989)

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SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

The Workshop provided the opportunity for participants to work closely with the Consultants on the details of their simulations and analyses.

2. In the light of these discussions, certain revisions of the models used were implemented and a variety of technical problems were identified and addressed.

3. The main conclusions of the Consultants' reports which, after revision, were accepted by the Group, involve a central distinction between information on the number, type and size of concentrations of krill and the information on the abundance of krill within concentrations.

4. The Workshop developed an operational classification of concentrations into three types, those of relatively dispersed, small, discrete swarms of krill, those of large aggregations of krill swarms and those of extensive layers of krill.

5. Data routinely collected by USSR survey vessels are amenable to analyses which estimate the number and size of concentrations in identified areas of ecological interest.

6. These analyses involve a number of uncertainties which could be resolved if supplementary information on the operation of the vessels were to be collected. The Workshop made recommendations for the collection of additional data so that these uncertainties could be resolved.

7. Data routinely collected by Japanese fishing vessels are in principle amenable to analyses which use the catch-per-unit searching time to estimate changes in krill abundance within concentrations. However, there are a number of difficulties involved in these analyses.

8. The Consultants' work on the Japanese fishery focussed on a distinction between time spent solely searching for krill aggregations and time when searching occurs, but other

activities continue. Japanese fishing vessels only operate in areas of high krill abundance and in these areas it is not practical to distinguish between these two modes of search.

9. Analyses at the Workshop involved assessing the sensitivity of different indices of CPUE to different types of change in krill abundance, namely: change in density within swarms, change in the size of swarms, and change in the number of swarms-per-unit area within a concentration.

10. Where a change in density within a swarm has occurred, this can be tracked by changes in an index based on catch-per-unit fishing time.

11. Where changes in swarm size or the number of swarms within a concentration have occurred, this can be tracked by changes in indices based on catch -per-searching time.

12. When krill was concentrated in layers, the relationship between krill abundance and CPUE was weak, i.e. a large change in the krill abundance was reflected by a small change in the CPUE index. In this case a strategy recommended by the Workshop was to estimate the abundance of concentrations which consist of large layers and to estimate the size of the concentrations and their density.

13. The Workshop concluded that a Composite Index of Krill Abundance could be constructed from information on krill concentrations derived from USSR survey vessels and on krill abundance within concentrations from Japanese fishing vessels. This Index would only be meaningful for identified ecological areas of the Southern Ocean where both survey and commercial fishing data are available. The task of identifying these areas should be taken up by the Working Group on Krill.

14. The general properties of the Index were such that small changes in krill abundance were unlikely to be detected, but any statistically significant change in the Index would imply that a major change in krill abundance had occurred. This has obvious implications for the deliberations of the Commission’s Working Group for the Development of Approaches to Conservation of Antarctic Marine Living Resources.

15. Although the general properties of the Index could be deduced, it was recognised by the Workshop that a detailed understanding of the quantitative behaviour of the Index was required. Accordingly, the Workshop recommended that the sensitivity of the Composite Index of Abundance to variation in parameter values should be further investigated.

16. A number of uncertainties in the behaviour of the CPUE indices could only be resolved by using information obtained from acoustic surveys of krill concentrations. The Workshop referred these problems to the Working Group on Krill.

Conclusions and Recommendations

17. The USSR and Japanese fisheries operate in different ways. The USSR fishery has survey vessels which detect fishable concentrations and call catching vessels to them, whereas the Japanese catching vessels operate more or less independently. The comments which follow relative to these two fisheries are assumed to be general, so that the fishing operations of other nations can be categorised accordingly.

18. The USSR fishery, although extensive, covers a relatively small proportion of the total area of the Southern Ocean. The fishing fleet is much smaller and covers a correspondingly smaller area. Within these limited areas of fishery operations, the Workshop demonstrated that CPUE was of some utility in providing information on krill abundance.

19. Data from survey vessels which operate in support of the USSR krill fishing fleet do provide useful information on the number and size of krill concentrations.

20. The Workshop developed an operational classification of concentrations into three types, those of relatively dispersed, small, discrete swarms of krill, those of large aggregations of krill swarms and those of extensive layers.

21. The Japanese fishery operates on the latter two types of these concentrations. Haul-by-haul data from the Japanese fishery could be used to estimate abundance within concentrations. The degree to and method by which this can be achieved depends on the type of concentration and the way in which krill abundance changes, i.e. changes in size of swarms, density within swarms or number of swarms in a concentration.

22. It is impossible to define Primary Searching Time (see paragraph 62) in the Japanese fishery adequately, and hence it is not possible to use this as an index of searching effort. However, the data that are currently collected on Japanese commercial vessels, namely the start and end times of fishing, are useful because they can be used to derive an effective search time.

23. Because krill abundance and the CPUE indices do not change proportionately, the detection of a change in an index implies that there has been a substantial change in mean abundance in the areas of interest.

24. There is considerable value in combining the results from the two approaches into a Composite Index of Abundance using the USSR data to determine the numbers and sizes of concentrations and the Japanese data to determine abundance within the concentrations. However, the application of this Composite Index of Abundance is limited due to the small area of operation of the Japanese fishery.

25. Care needs to be exercised in evaluating such a Composite Index as many of the component variables do not change in proportion to abundance and also because there are considerable uncertainties regarding how many of these variables are best estimated.

26. It is essential that, in order to improve the quality of the Composite Index, data collection should follow standard procedures.

27. Certain within-concentration parameters such as swarm size, the number of swarms-per-unit area of the concentration and interswarm distance are essential for monitoring abundance. These are best determined acoustically.

28. The Workshop therefore recommended that:

(i) Survey vessels operating in support of a fishing fleet should collect data in accordance with the bridge log format discussed in paragraph 73 and detailed in Appendix 5 of the Workshop Report. Data from these vessels should be analysed to provide estimates of the size and type of krill concentrations along the lines suggested in Appendix 5 and WS-KCPUE-89/6 Rev. 1.

(ii) All catching vessels should collect haul-by-haul data in the same way as the current Japanese fishery.

(iii) Haul-by-haul data should be analysed to provide appropriate indices of abundance based on catch-per-searching time within krill concentrations on a ten day reporting period. Such analyses could be undertaken either by CCAMLR or by the fishing nation concerned, and should be conducted annually.

(iv) The analytical procedures suggested above should be conducted on a trial basis and reviewed after three years.

(v) Acoustic data should be used to determine swarm size, the number of swarms-per-unit area of the concentration and interswarm distance within concentrations.

(vi) The detailed specification of the necessary acoustic data should be referred to the Working Group on Krill.

(vii) The following further activities be undertaken:

(a) Determination of the sensitivity of the Composite Index of Abundance to variation in parameter values. However, the utility of this is dependent on the ability of the Working Group on Krill to determine key parameter values and their distributions.

(b) The simulation model of the Japanese fishery should be changed by the Consultant so as to avoid the necessity to distinguish between Primary and Secondary Searching Time.

REPORT ON THE WORKSHOP

Introduction

29. The Workshop was held at the Southwest Fisheries Centre of the National Marine Fisheries Service in La Jolla, California, USA from 7 to 13 June 1989.

30. The Convener of the study, Dr J. Beddington (UK) chaired the meeting. A provisional agenda, distributed before the meeting, was amended to include a new item requested by the Chairman of the Commission’s Working Group for the Development of Approaches to Conservation of Antarctic Marine Living Resources. The revised agenda was then adopted (Appendix 1).

31. A list of those attending is given in Appendix 2.

32. The report was prepared by Miss M. Basson, Prof. D. Butterworth, Drs I. Everson and D. Powell.

33. Meeting documents received at the CCAMLR Secretariat were circulated to participants. Further papers were tabled at the meeting. The list of meeting documents is given in Appendix 3.

Activities Following SC-CAMLR-VII

34. Discussions following the presentation of the Consultants' reports to SC-CAMLR-VII indicated that modifications of the basic simulations were necessary, based on a more detailed understanding of the Japanese and USSR krill fisheries.

35. Dr J. Beddington (Convener) and Dr M. Mangel (Consultant) had both written to the Scientific Committee representative for the USSR for similar information, but neither had received a reply. No additional information on the USSR fishery was available to the meeting.

Computing

36. A VAX 11/780 mainframe computer was available to the meeting and the analyses undertaken were done in batch mode.

Major Tasks for the Workshop

37. The major tasks for the Workshop had been set out by the Scientific Committee (SC-CAMLR-VII, paragraph 2.41):

(i) to provide an opportunity for detailed and final discussions on the models developed by the Consultants and their implications for the potential use of CPUE to index krill abundance;

(ii) to consider refinements of the krill distribution model used in the Consultants' studies in the light of further analyses of existing krill research survey data to be tabled at the Workshop and to investigate whether such refinements altered the conclusions drawn from the existing studies;

(iii) to consider the practicality of the routine collection of various types of search time information in the light of analyses to be presented of experimental collection of such data that has already taken place on Japanese vessels and of some data from Soviet research vessels; and

(iv) to make recommendations to the Scientific Committee regarding the potential utility of CPUE to index krill biomass, the most effective and practical index or indices to be used and the consequent requirements for routine data collection in the krill fishery.

REVIEW OF CONSULTANTS' REPORTS

Japanese Fishery

38. Prof. Butterworth introduced his paper 'A Simulation Study of Krill Fishing by an Individual Japanese Trawler' (WS-KCPUE-89/4). This had been tabled at SC-CAMLR-VII. The study attempts to mimic the Japanese krill fishery during January and February, the period when peak fishing activity occurs.

39. The krill distributional model used in the study is one of 'patches within patches'. On the finest scale, krill are present in 'swarms'. Groupings of these swarms are termed 'concentrations'. Japanese data indicate that the swarms within a particular concentration tend to have the same characteristics with respect to krill size and feeding condition ('greenness').

40. The model simulates the initial searching strategy for a concentration as follows. It is assumed that a fishing vessel begins searching from a position about 100 n miles north of the ice-edge at the western end of a 600 x 600 n miles area considered, and proceeds towards the centre of the southern boundary. This initial search is in a straight line. Fishing is assumed to commence once the vessel's track-line intersects the boundary of a krill concentration. The Workshop was advised that in practice fishing vessels do move in a straight line towards the ice-edge, but whenever they encounter even slight indications of krill, they perform an intensive, localised search pattern to determine whether the detected concentration found is worth fishing. Swarms and therefore also concentrations are detected acoustically.

41. The search for concentrations on reaching the southern boundary or upon leaving the concentration most recently detected, is no longer modelled by simulating the vessel's track. Instead the random search formula is used. This has the advantage of making some allowance for the movement of concentrations with time. Field estimates of speeds of movement of krill aggregations (Kanda et al.,1982; Everson and Murphy, 1987) are not inconsistent with the value of 15 cm sec^{-1} used in the model. Japanese observations indicate that in the shelf slope region, the concentrations tend to remain in more or less the same location.

42. The random search formula used in the simulation is:

$$\text{Prob (detect concentration within time } \mathbf{t}) = 1 - \exp(wdvt) \quad (1)$$

where **d** is the density of concentrations (number per unit area) and **v** the vessel searching speed. Because echosounder and sonar search widths are small compared to concentration sizes, **w** was taken to be the median of the simulated concentration diameters. Generating a random number from a uniform distribution on [0,1] and solving formula above for **t**, yields the time taken to find the next fishable concentration (Concentration Searching Time, CST). If either the number or the typical size of concentrations decreased, CST would tend to increase because of the resultant smaller values of **d** or **w** respectively.

43. The vessel may terminate fishing on a concentration for one of three reasons: the need to return to a cargo vessel to off-load, the intervention of bad weather, or too low a catch rate. It is assumed that bad weather always causes a vessel to lose contact with the concentration and that the vessel is moved 50 n miles in a random direction. In reality, however, the vessel can often maintain contact with a good concentration even though fishing operations have to be suspended. In the model, random fluctuations of search times can lead to exceptionally long search times between fishable swarms and thus low catch rates. Concentration biomasses are much larger than the typical catch made by a trawler over the two-week period simulated, so that the catch made has a negligible effect on the catch rate. In reality, catch rates are likely to drop as a consequence of changes in the aggregation behaviour of krill over time; this feature was not incorporated in the model because of the absence of quantitative data regarding such behaviour.

44. Searching for swarms within a concentration is also modelled as a random search process as follows:

$$\text{Prob (detect swarm within } \mathbf{t} \text{ hours)} = 1 - \exp(-\lambda t) \quad (2)$$

where $\lambda = 4$ (hours)$^{-1}$. The formula is adjusted when the number of swarms-per-unit area of the concentration drops, so that the Primary Searching Time (PST) to find the next swarm increases. Decreases in swarm radius (r) and the density of krill within a swarm (δ) also cause an increase in PST because of a decline in the proportion of swarms considered large enough to be worth fishing (see paragraph 48 following).

45. The value of **t** in equation 2 was chosen to give an average search time (λ^{-1}) of about 15 minutes, corresponding to time budget data collected for a Japanese trawler during the 1986/87 season. Mr Ichii advised that in good concentrations, Japanese vessels took only about 5 minutes to find a swarm; the balance of the 15 minutes is used for positioning to commence the haul. The simulation study results thus reflect an overestimation of the proportion of time spent on primary search. An average search time of 5 minutes corresponds to $\lambda = 12$. This is more compatible with estimates of parameters **w, d** and **v** (see paragraph 43) for searching for swarms, which indicated that $\lambda = wdv$ would lie in the range of 14–60.

46. Equation 2 assumes that fishing is directed at discrete swarms. When fishing takes place in concentrations comprised of extensive layers, the search time is essentially zero. The Workshop noted that a considerable portion of the Japanese krill fishing effort may be directed at concentrations of this type, and that the results of the simulation study would not be appropriate to such activities.

47. Fishing does not usually commence immediately after a good swarm is found. Initially some time is required to complete processing of an appropriate proportion of the catch from the previous haul. This is because krill quality deteriorates rapidly. Consequently, the catch-per-haul is usually maintained at a level of about 10 tonnes or less so that it can be processed sufficiently quickly. This waiting time, during which some further search is carried out, is termed Secondary Searching Time (SST).

48. Krill swarm size and density distribution parameters were selected from information obtained during the FIBEX survey and data in Kalinowski and Witek (1983). Catches from unselective tows on such swarms would average 1.5 tonnes, compared to the catches of 6–8 tonnes realised in the Japanese fishery from hauls on single swarms. This is attributed in the simulation study to deliberate selection on the part of the vessel's captain, who would tow only on swarms considered to be sufficiently large or dense, i.e. fishable.

Soviet Fishery

49. Dr Mangel introduced his paper 'Analysis and Modelling of the Soviet Southern Ocean Krill Fleet' (WS-KCPUE-89/5), which had been tabled at SC-CAMLR-VII.

50. The operational procedure for the USSR fishing fleets is quite different to that of the Japanese vessels which operate individually. The USSR fishing fleets operate in concert with survey vessels. The survey vessels continually search for new concentrations and inform the fishing vessels when new fishable concentrations are located. The fishing vessels do not move to all the concentrations that are detected. USSR fishing fleets tend to work in groups travelling more or less from west to east. The vessels travel together, often for as much as 100 n miles before returning to cover the same area.

51. For these reasons, it was considered that search time data from USSR fishing vessels will be unlikely to provide valid estimates of changes in krill abundance because their strategy is cooperative and would not approximate random search. However, echosounder charts for such activities may provide information on swarm parameters (see paragraphs 64 and 65).

52. Dr Mangel then introduced the paper WS-KCPUE-89/6 which reported an analysis of a sample of data from survey vessels accompanying the USSR fishing fleet. This analysis indicated that such data could be used to determine the size and location of concentrations. The concentrations so indicated were similar in size and location to those reported in analyses of Japanese data. It was clear from examination of Soviet data that USSR survey vessels remained within a particular concentration for some time and occasionally returned to it following activity in an adjacent area.

53. The paper proposed that these survey vessel data could be used to provide estimates of the number ($\mathbf{N_c}$) and size of concentrations in a region. In the former respect, the formula suggested is:

$$N_c = n_c/[1-\exp(wvt/A)] \qquad (3)$$

where $\mathbf{n_c}$ is the number of concentrations encountered, **w** is the detection width, **v** is the vessel's search speed, **t** is the search time and **A** is the area of the region being searched. Estimates of $\mathbf{N_c}$ from this formula are sensitive to the values used for the parameters **w**, **t** and **A**. Considerable discussion took place as to how best to refine their estimation; the results of this discussion are reflected in paragraphs 66 to 67.

Other Analyses Tabled

54. Mr Ichii and Dr Endo (WS-KCPUE-89/7) raised three problems concerning Prof. Butterworth's simulation study (WS-KCPUE-89/4) of the Japanese krill fishery. Firstly, they reported that Japanese vessels often operated on layers rather than swarms during the peak fishing season. The sizes of these layers are much larger than the swarms detected during FIBEX surveys, whereas the simulation study had used krill distribution parameter values based on the FIBEX results. Very little searching time is spent in concentrations comprised of such layers. Accordingly, they queried whether CPUE indices based on searching time would be as useful as indicated by the simulation study. Secondly, they queried the utility of indices based on the sum of Primary and Secondary Searching Time (PST + SST), because the processing time needs reflected by SST are markedly dependent on the product being produced, and the product mix varies substantially from one season to the next. Finally, they alluded to the unrealistic behaviour of the simulation model in respect of the values used for the minimum catch rate required to remain in a concentration, and suggested that the distribution model used for the simulation did not adequately reflect the actual situation of few harvestable amongst many unharvestable krill concentrations.

55. The authors suggested that experiments to test the viability of collection of PST data needed to be carried out, together with model tests of robustness to recording errors, before considering the routine implementation of search time data collection. They further suggested that improvement of the krill distribution model used was necessary before the study could be considered to have demonstrated that the routine collection of such data was warranted.

56. In discussion, it was suggested that keeping a record in the log book of the product being produced at a particular time might help resolve the second problem detailed in paragraph 54.

57. Drs Endo and Shimadzu (WS-KCPUE-89/9) reported information on the krill aggregations fished by a Japanese trawler in January 1988 in the region north of Livingston Island (north of the Antarctic Peninsula). The trawler fished during a cooperative survey with the research vessel *Kaiyo Maru* over a four day period. The aggregations fished were layers rather than swarms, and in 88% of the hauls only a single layer was fished. The mean length towed during fishing was 3.25 km, the mean layer thickness (i.e. depth dimension) detected acoustically was 13.3 m and the mean surface density estimated from catch data was 228 g/m^2. Thus these layers were 44.5 times longer, 2.7 times thicker, but 25% less dense than typical swarms dimensions calculated from acoustic data collected during FIBEX surveys.

The largest layer reported in the paper was 18.5 km in length, and the longitudinal length of the concentration exceeded 52 km.

58. Mr Ichii and Dr Endo (WS-KCPUE-89/8) considered CPUE data together with krill size and condition information from the operations of seven trawlers in the region north of Livingston Island during January–March 1988. The nature of the aggregations fished was such that there was essentially no Primary Searching Time. Catch-per-haul data appeared to depend on the end product from the catch, not the abundance of krill and showed no variation with time. Catch-per-fishing time indices showed no significant differences with time, although different vessels showed peaks in these indices at different times. The total catch taken from the area was only about 7% of the estimated krill biomass. There were no significant differences in mean body length of krill during the season. The proportion of green krill recorded was highly variable among the trawlers; the authors doubted that the routine collection of 'greenness' data would improve abundance indices.

59. Mr Ichii and Dr Shimadzu (WS-KCPUE-89/9) reported examples of time budget data recorded by a Japanese trawler in the 1986/87 season. The average proportions of time spent on cargo transfer, net handling, fishing, confirming swarm sizes and searching for swarms were presented for various periods from November to March, and further parameters of the distributions of some of these statistics were also reported. Searching times were greater and fishing times less in November and early December, but thereafter there was little trend in any of the statistics reported over the remainder of the fishing season.

Practicality of Data Collection

60. The simulation study of the Japanese krill fishery (WS-KCPUE-89/4) indicated that CPUE indices which utilise Primary Searching Time (PST) are much more effective for detecting changes in krill abundance within concentrations than those in which Primary and Secondary Searching Time were combined (PST + SST). The latter statistic could probably be recorded routinely, since they can be obtained by subtraction of the time required for other activities such as cargo transfer, net handling and fishing which are clearly defined. However, the practicality of discriminating between PST and SST was questioned and was thoroughly discussed.

61. Mr Ichii advised that for most concentrations in which substantial fishing activity took place, processing requirements were the principal determinant of the period of time between ending one haul and starting the next. Some form of searching took place throughout this

period, but the detection of the next fishable swarm to be fished was easily and rapidly achieved. It was effectively impossible, however, to identify exactly what proportion of this period should be considered as ‘Primary Searching Time’.

62. The Workshop agreed that the collection of Primary Searching Time as used in the simulation study was impractical as no operational definition would be possible. Accordingly, any attempt to use search time data from this fishery in CPUE indices would need to utilise PST+ SST or some adaptation thereof.

63. Unfortunately, since no Soviet scientists were present at the Workshop, it was not possible to comment on the practicalities of data collection from the Soviet krill fisheries. For a similar reason, no comments could be offered on this matter for the fleets of other nations participating in the krill fishery.

MATTERS ARISING FROM DOCUMENTS DISCUSSED AND ANALYSES OF RESULTS

Concentration Types

64. Advice from Mr Ichii served to emphasise that not all concentrations of krill are fishable. The majority of concentrations, whether consisting of swarms or of layers, are too ‘poor’ to be fished. Generally, Japanese fishing vessels keep no records of any ‘poor’ concentrations encountered. Only ‘good’ concentrations are fished, and interpretation of the fishing statistics collected would depend on whether such concentrations consist of swarms or layers. Accordingly, it was considered important to provide more specific definitions of what constituted ‘poor’ or ‘good’ concentrations as perceived by the fishermen. Broad definitions of a ‘poor’ concentration (consisting either of swarms or layers), a ‘good layer’ concentration and a ‘good aggregation’ concentration were agreed and are set out in Appendix 4.

65. Because interpretation of reported fishing statistics depends on whether a good layer or a good aggregation was being fished, it becomes important to ascertain whether such a characterisation could be achieved on board a fishing vessel for routine recording purposes. The Workshop agreed that this should be possible through inspection of echocharts. The matter of developing an operational definition to characterise concentrations (which would include the provision of some typical echochart examples) was referred to the Working Group on Krill.

Estimating the Number of Concentrations ($\mathbf{N_c}$)

66. Data obtained from Japanese fishing vessels cannot be used for estimating the number of concentrations for three reasons. First, the vessels do not search randomly. Second, the vessels operate in a relatively small region. Third, the vessels operate in just a few concentrations per year (often returning to the same concentration after unloading).

67. Dr Mangel suggested a formula that could be used to provide an estimate of $\mathbf{N_c}$ from Soviet survey vessel data (equation 3). Application of this equation requires estimates for **w**, **v**, **t** and **A**. The value of the searching speed **v** is known and records could readily be kept of the search time **t** between concentrations if appropriate definitions were provided. An estimate of **A** is dependent on the perceived limits of the krill distribution, but may also be refined by reference to oceanographic features and bottom topography. There is evidence that the survey vessels tend to restrict their activities to frontal zones and topographic features. This is likely to lead to positive bias in the estimate of $\mathbf{N_c}$ because the density (number-per-unit area) of concentrations over the whole area (**A**) may not be as high as that within the concentrated fishing zone. The effective search width **w** is equivalent to the diameter of the concentrations (assuming that they are circular). The estimation of average concentration radius and a bias that arises in this process are discussed in paragraphs 68 to 72 below. Further details concerning the estimation of $\mathbf{N_c}$ in this manner are detailed in Appendix 5.

Estimating the Size of Concentrations (Effective Circular Radius $\mathbf{L_c}$)

68. The size of fishable concentrations could be determined by plotting the positions of the various hauls made in that concentration. This information could be obtained from Soviet and Japanese vessels. For example, the centroid of the haul positions could be calculated and the root-mean-square distance of the individual positions from this centroid evaluated. Mathematical analysis for various shapes could indicate an appropriate value for a constant which, when multiplying this root-mean-square distance, would provide an estimate of effective radius $\mathbf{L_c}$. This in turn, would provide the estimate required for **w** in the proceeding paragraph. Even if the resultant estimate was biased, the $\mathbf{N_c}$ value obtained could still be used to provide a relative, if not an absolute, index of krill abundance.

69. Some indication of likely concentration shapes is needed to perform the analysis suggested in the preceding paragraph. Plots of haul positions from fisheries data (such as those examined by Dr Mangel in Appendix 5) might assist in this regard. Concentrations may

be associated with hydrographic features which could give rise to particular shapes. It was suggested that a better understanding of the conditions under which concentrations occur would help determine the sorts of shapes to be expected.

70. It was pointed out that an estimate of $\mathbf{L_c}$ from observed or encountered concentrations is likely to be positively biased because larger concentrations are more likely to be detected than smaller ones. An attempt was made to quantify the magnitude of this bias for the search model used in the simulation studies. These studies assumed that concentrations are circular with radii distributed uniformly over the range (5.6, 11.3) n miles. Analytical as well as simulation results evaluated during the Workshop, showed that for the parameters used in the search model, the bias in the estimate of $\mathbf{L_c}$ is of the order of ±10%. This bias affects not only the estimate of $\mathbf{L_c}$ itself, but also the estimate of $\mathbf{N_c}$ which depends on this value (see paragraphs 53 and 67).

71. The extent of the bias discussed in the preceding paragraph is determined by the statistical distribution of concentration radii, as well as the effective detection width of the search vessel (i.e. the width over which its sonar and echosounder can locate krill). It was suggested that the characteristics of the observed concentrations be summarised in terms of a size frequency histogram to give a better estimate of this distribution. It was noted, however, that this empirical distribution would be biased towards the larger concentrations. The Workshop agreed that further mathematical analyses to assess the magnitude of the bias in $\mathbf{L_c}$ and $\mathbf{N_c}$ should wait until a more detailed picture of the size distributions of concentrations has been built up from fisheries and survey data.

72. The problem of possible double counting of concentrations in analyses of Soviet survey vessel data had been raised by Dr Mangel in WS-KCPUE-89/6. This is not a problem if search is truly random, but creates difficulties in the circumstances of directed search (i.e. deliberate attempts to relocate a concentration found at an earlier time). It was recognised that the primary objective of the operations of the Soviet survey vessels is not to obtain an unbiased estimate of $\mathbf{N_c}$. It was noted, however, that a directed search component may not matter if only a relative abundance index for a well-defined subarea is required.

73. The Workshop considered that the finest scale on which catch data are currently reported to CCAMLR (on a grid approximately 30 n miles x 30 n miles in size) was still too coarse to be adequate to estimate concentration sizes. The matter of the additional data which would need to be collected by survey vessels to allow $\mathbf{N_c}$ and $\mathbf{L_c}$ estimations as described above was discussed in detail, and suggestions for the development of a bridge log are given in Appendix 5.

ESTIMATION OF KRILL DISTRIBUTION PARAMETERS WITHIN GOOD CONCENTRATIONS FROM CPUE DATA

Good Aggregations

74. After considering a number of modifications to the Consultant's study (WS-KCPUE-89/4) as detailed in Appendix 6, the Workshop agreed that while there was still uncertainty regarding a number of the inputs to the simulation model, the results obtained indicated that CPUE indices using a modification of time between trawling called Pseudo Primary Searching Time, PPST, may be able to provide information on changes in biomass within a good-aggregation concentration. Such indices can detect changes that might not be detected by indices using only fishing time data. It was noted that national laboratories could in principle construct such an index using data for the times at which fishing begins and ends for each haul. This is already routinely recorded by some nations. Some minor additional annotations would be required in existing log books to indicate changes in the product being produced, and whether the normal activities of searching and fishing were interrupted by some other occurrence such as bad weather.

Good Layers

75. For practical purposes it was agreed that areal coverage of krill is virtually uninterrupted within concentrations comprised of good layers. Therefore, the only within-concentration distribution parameter for which an estimate is required is the krill surface density (δ). This is indexed by catch-per-fishing time, for which data are already collected routinely.

CONSTRUCTION OF A COMPOSITE ABUNDANCE INDEX

76. Results in the Tables of Appendix 6 indicate that for good aggregations even the best of the CPUE indices for which data could be collected in practice has only poor ability to detect a decrease in swarm radius (**r**). Decreases in krill surface density (δ) are well detected by indices involving fishing time. It appears that indices using Pseudo Primary Searching Time have the potential to detect decreases in the number of swarms-per-unit area within the concentration ($\mathbf{D_c}$). Generally the CPUE indices have the property that as the biomass drops, the value of the index falls by a smaller proportion (this is referred to as non-linear behaviour).

77. The error bars in the Figure in Appendix 6 give an indication of the precision with which changes of abundance could be detected by the index shown from one year to the next by a fishery similar in scale to the current Japanese fishery (approximately 10 vessels fishing for two to three months). These results suggest that the detection of statistically significant changes in CPUE indices will be difficult to achieve. Taken together with the non-linear behaviour of these CPUE indices discussed in the preceding paragraph, this means that detection of any statistically significant reduction in a CPUE index is likely to imply that a substantial reduction in krill biomass has occurred.

78. In view of the poor ability of CPUE indices to detect changes in swarm radius **r**, it was considered that the Meeting of the Working Group on Krill could valuably discuss the possibilities of using acoustic data (from either or both fishing vessels and vessels conducting scientific surveys) to detect such changes.

79. The components of a Composite Index of Abundance, and the sources of data required to monitor their changes, are detailed in Appendix 7. A study of the likely precision with which such a Composite Index of Abundance could estimate krill biomass and more particularly relative changes in the krill biomass in a region, was recommended. The framework for such an exercise is also given in Appendix 7.

80. It was noted that the proposed method of assessing $\mathbf{N_c}$ would take account of the possibility of a decrease in krill biomass being associated with a contraction in the areal extent of the overall krill distribution, even though the local abundance of krill in the fishing area was little affected. However, it was also appreciated that the proposed Composite Index took no account of the amount of krill in poor concentrations; this might not vary in proportion to that in good concentrations as the overall krill abundance changed. Data from Soviet survey vessels may provide some information in this regard.

81. The Workshop noted that especially useful information to refine this approach could be obtained if data were available for an area in which Japanese trawlers, Soviet survey vessels and scientific survey vessels (performing systematic survey) operated simultaneously.

FURTHER ANALYSES REQUIRED

82. The likely variance of the Composite Index suggested in paragraph 79 should be assessed from estimates of the precision with which component parameters could be measured (see Appendix 7).

83. Refinement of existing analyses of krill distribution data from scientific surveys (such as FIBEX) was not seen as high priority at present. It was considered rather that more data from the fishery on the distributional parameters of aggregations fished (as provided, for example, by Drs Endo and Shimadzu in WS-KCPUE-89/9) should be obtained and analysed.

84. Information on temporal trends in krill distribution parameters (i.e. the rates at which good aggregations formed and dispersed) was also not seen as immediate priority. While such information is desirable to more closely model the process of Japanese trawlers deciding to leave concentrations when catch rates drop to a level considered to be too low, this is relevant only to the estimation of $\mathbf{N_c}$ and $\mathbf{L_c}$ from concentration searching time. However, this does not seem practical from the Japanese fishery data for other reasons.

85. A modification to the simulation model of the Japanese fishery was suggested which avoids the distinction between Primary and Secondary Searching Time. This could be achieved by fixing the total searching time between hauls on the basis of required processing time. The number of swarms detected in this period would be generated stochastically and the best of these swarms would be chosen for the following haul. It was recommended that this possibility be explored.

IMPLICATIONS OF RESULTS FOR A CONSERVATION STRATEGY

86. There were two broad results from the Workshop which were of relevance to this agenda item:

(a) the ability to detect decreases in krill abundance from CPUE data is relatively limited; and

(b) should a statistically significant decrease in a Composite Index of Krill Abundance be detected, this would imply that a substantial fall in krill biomass has already occurred.

The implications of these results for a conservation strategy was a matter for the attention of the Working Group on Krill in the first instance.

CLOSE OF MEETING

87. The Workshop agreed to adopt the report of its activities. The Chairman thanked the participants and the staff of the Southwest Fisheries Centre for hosting the meeting and assisting with related activities, particularly Drs R. Hewitt and R. Holt for general arrangements, Gaye Holder for typing and Susie Jacobson for assistance with the runs of the simulation model undertaken on the computer. The Workshop participants thanked the Chairman for the efficient and effective manner in which he had conducted the meeting.

APPENDIX 1

AGENDA

Workshop on the Krill CPUE Simulation Study
(Southwest Fisheries Centre, La Jolla, California, USA, 7 to 13 June 1989)

1. Opening: Convener's remarks

2. Adoption of the agenda

3. Appointment of rapporteurs

4. Review of documents and computing facilities

5. Review of Consultants' reports
   - (a) Analyses
     - (i) Japanese fishery
     - (ii) Soviet Fishery
   - (b) Recommendations
     - (i) Japanese fishery
     - (ii) Soviet fishery

6. Adjustment to Krill Distributional Model
   - (a) Likely effect on simulation results
   - (b) Spatial aspects
   - (c) Temporal aspects

7. Practicality of Data Collection
   - (a) Search time for Japanese fishery
   - (b) Soviet research vessels
   - (c) Fleets of other nations

8. Further Analyses Required
   - (a) Utilisation to provide composite abundance index
   - (b) Distributional data
   - (c) Simulation studies

9. Request by the Chairman of the Working Group for the Development of Approaches to Conservation of Antarctic Marine Living Resources

10. Recommendations
    (a) Utility of CPUE measures to provide an index of krill abundance
    (b) Data collection
    (c) Further analyses

11. Adoption of report

12. Close of meeting.

APPENDIX 2

LIST OF PARTICIPANTS

Workshop on the Krill CPUE Simulation Study
(Southwest Fisheries Centre, La Jolla, California, USA, 7 to 13 June 1989)

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APPENDIX 3

LIST OF MEETING DOCUMENTS

Workshop on the Krill CPUE Simulation Study
(Southwest Fisheries Centre, La Jolla, California, USA, 7 to 13 June 1989)

Papers received in advance of the meeting:

WS-KCPUE-89/1	Agenda for the Krill CPUE Workshop
WS-KCPUE-89/2	Annotated agenda
WS-KCPUE-89/3	Some aspects of the relation between Antarctic krill abundance and CPUE measures in the Japanese krill fishery. (Component of SC-CAMLR-VI/BG/4) (D.S. Butterworth)
WS-KCPUE-89/4	A simulation study of krill fishing by an individual Japanese trawler (SC-CAMLR-VI/BG/37) (D.S. Butterworth)
WS-KCPUE-89/5	Analysis and modelling of the Soviet Southern Ocean krill fleet (SC-CAMLR-VII/BG/12) (M. Mangel)
WS-KCPUE-89/6	Analysis and modelling of the Soviet Southern Ocean krill fleet, II: Estimating the number of concentrations and analytical justification for search data (M. Mangel)
WS-KCPUE-89/7	Brief comments on the simulation study made by Prof. Butterworth on krill fishing by an individual Japanese trawler (T. Ichii and Y. Endo)
WS-KCPUE-89/8	CPUEs, body length and greenness of Antarctic krill during 1987/88 season in the fishing ground north of Livingston Island (T. Ichii and Y. Endo)

The following papers were tabled during the meeting:

WS-KCPUE-89/9	Some examples of time budget data recorded by a Japanese trawler *Ehiko Maru* in 1986/87 season (T. Ichii and Y. Shimadzu)
WS-KCPUE-89/10	Size and density of krill layers fished by a Japanese trawler in the waters north of Livingston Island in January 1988 (Y. Endo and Y. Shimadzu)
WS-KCPUE-89/11	Krill aggregation characteristics: spatial distribution patterns from hydroacoustic observations. Polar Biology (in press) (D.G.M. Miller and I. Hampton)
WS-KCPUE-89/12	Some examples of time budget data recorded by a Japanese trawler, *Ehiko Maru* in 1986/87 season (Anon., Far Seas Fisheries Laboratory, Shimizu, Japan)

Other References:

Everson, I. and Murphy, E. 1987. Mesoscale variability in the distribution of krill *Euphausia superba*. Marine Ecology, Progress Series, 40, No. 1: 53-60.

Kalinowski, K. and Witek, Z. 1983. Elementy biologii, formy grupowego wystepowania i zasoby antarktycznego kryla *Eupahusia superba* (Dana/Crustacea). Sea Fisheries Institute, Gdynia, 207 pp.

Kanda, K., Takagi, K. and Seki, Y. (1982). Movement of larger swarms of Antarctic krill *Euphausia superba* population off Enderby Land during 1976-1977 season. J. Tokyo Univ. Fish 68: 25-42.

APPENDIX 4

DEFINITIONS OF KRILL CONCENTRATIONS

Type	Name	Qualitative Description	Inter-Aggregation Distance	Aggregation Diameter	Comment
1	Poor	Swarms widely spaced Diffuse aggregations	Several to 10’s km	Several to 10’s m	
2	Good Layer	Dense continuous layer	0	Several to 10’s km	Both horizontal and vertical separation is possible
3	Good aggregation	Close groups of dense swarms	10’s m	10 – 100’s m	

ESTIMATING THE NUMBER OF CONCENTRATIONS IN A REGION

This appendix addresses a number of issues raised during the Workshop using data from the 1980-81 cruise of a research vessel *Mys Tihiy* as an example.

2. The ‘concentration map’ for this cruise, taken from Figure 5 of WS-KCPUE-89/6, is shown in Figure 1. The actual individual hauls are shown in Figure 2. In this figure, hauls are separated according to size (greater or less than 1 000 kg of krill). Figures 3 and 4 show the distribution of hauls within individual concentrations 4 and 8. From these figures, one sees that it is difficult to group hauls together to form concentrations. WS-KCPUE-89/6 used a ‘50 n miles’ rule for defining a concentration, but this was an *ad hoc* choice based on the considerations from simulations. Alternatively, one could attempt to define concentrations in the geometrically smallest way possible (e.g. defining concentrations as ellipses rather than circles).

3. Some of the difficulties are best illustrated in Figure 4. Here the majority of hauls took place in the region around 64.5° S and 140° E, with a few hauls of 65.5° S and 138° E. Given the fishing log book data, it is difficult to determine if the gap in Figure 4 corresponds to a region that is lacking krill or to one in which krill were present, but the vessel simply did not sample those krill.

4. An area of future work should be refinement of the operational definitions of concentrations for use in statistical analysis and krill abundance estimation.

5. Given this kind of difficulty, a subgroup of the Workshop participants considered the development of bridge logs to be used by survey vessels. The following is an example of such a log:

VESSEL NAME: ______________________
DATE: ______________________

Hour	Position		Speed	Course	Concentration			Tow
	S	E			Type	Same/Different	Fishable/Otherwise	
01								
02								
...								
24								

The entries in this log are the following:

Position: Usual latitude and longitude

Speed: This entry is the average speed of the vessel during the reporting period

Course: This entry describes the course type of the vessel during the reporting period:

1 - Straight course
2 - Highly variable course
3 - Hove to (bad weather)
4 - Stationary
5 - In transit, but not recording on the echosounder

Concentration:

Type: This entry is the type of concentration as defined in Appendix 4:

0 - Not in a concentration of krill
1 - Poor concentration
2 - Good layer concentration
3 - Good aggregation concentration

Same/Different:

This entry describes whether the vessel is in the same concentration as in the previous reporting period:

1 - Same concentration
0 - Different concentration

Fishable/Otherwise:

This entry describes whether or not the survey vessel considered the concentration fishable:

1 - Fishing vessels present or contacted regarding this concentration
2 - Otherwise

This variable is important, because it provides an operational definition of fishable concentrations.

Tow: This entry describes whether towing occurred during the reporting period:

1 - Towing occurred
2 - No towing

6. It is proposed that survey vessels fill out such log sheets every day from the time that they enter the Convention Area until the time that they leave the Area. On days in which the vessel is anchored, bad weather occurs, or the vessel is not surveying for other reasons, the vessels should fill out the log sheet header, with a notation indicating why survey activity did not occur that day.

7. Even with the limited data available in the log books from the cruise of *Mys Tihiy*, it is possible to answer certain questions about estimation of the number of concentrations.

Can Concentrations be Separated According to Poor or Good Concentrations?

8. Presumably catch per fishing time in the concentration will be used as a measure of the quality of the concentration. For the 14 concentrations surveyed by *Mys Tihiy*, the catch per fishing time (defined to be from the start to end of fishing, as denoted in the logbook) is shown below:

Concentration	Catch/Fishing Time (kg/hr)
1	41
2	1530
3	359
4	879
5	907
6	184
7	531
8	629
9	918
10	395
11	1250
12	578
13	6
14	136

9. Adopting the definition that a concentration is poor if the catch is less than about 500 kg/hr suggests that concentrations 1, 3, 6, 10, 13 and 14 (nearly half of the concentrations) are poor concentrations.

How variable are Concentration Radii?

10. Using the east-west and north-east extents given in WS-KCPUE-89/6, one can convert the effective rectangle to an equivalent radius. The results of such a computation are shown below:

Concentration	Effective Radius (n miles)
1	8.95
2	3.91
3	5.52
4	34.2
5	14.5
6	62.9
7	31.2
8	35.1
9	1.2
10	13.3
11	12.7
12	2.68
13	.85
14	24.3

11. When considering these numbers, it is important to consider the following issues:

- The '50 mile rule' is used to define the concentrations, and this will affect concentration size.

- There will be a bias for the radii of detected concentrations, because larger concentrations are more likely to be detected. Running the survey portion of the model developed in WS-KCPUE-89/5 for the Soviet survey operation showed that the mean radius of detected concentrations was about 8.9 n miles, while the mean radius of all concentrations was about 8.4 n miles; this is a relatively minor bias. For a simpler one-dimensional problem, one can show that the ratio of the expected radii of detected concentrations to expected radii of all concentrations is $\mathbf{1 + CV^2}$, where **CV** is the coefficient of variation of the distribution of concentration radii.

12. For the data shown above, the range of concentration radii is 0.85 n miles to 62.9 n miles, the mean is 17.9 n miles and the standard deviation is 17.1 n miles. This gives a coefficient of variation of 0.95. Figure 5 shows a histogram of the distribution of concentration radii.

How Does the Estimation Formula Depend Upon Parameters?

13. Based on the random search formula, the estimated number of concentrations $\mathbf{N_c}$ in a sector of size **A** is given by

$$N_c = \text{int} [\, n_c/(1 - \exp(-wvt/A)) \,] \qquad (1)$$

14. In this equation, **int[Z]** denotes the largest integer smaller than z and

N_c = estimated number of concentrations in the region
n_c = number of concentrations encountered
w = detection width of concentrations
v = searching speed of the vessel
t = total search time between concentrations

Dependence Upon the Area of the Sector

15. Figure 6 shows the results of applying Eqn(1) to the data collected by *Mys Tihiy*, using **w** = twice the average concentration radius, **v** = 10 knots, and the search time reported in WS-KCPUE-89/6. As the sector area ranges from 90 000 square n miles to 45 000 square n miles, the value of $\mathbf{N_c}$ ranges from 14 to 24.

Dependence Upon **w**, **v** and **t**

16. From Eqn(1), it is clear that the value of $\mathbf{N_c}$ depends upon the product **wvt**, thus compounding changes in individual values of the parameters. The general result is that if any of **w**, **v**, or **t** increase, then the estimate of $\mathbf{N_c}$ will decrease. Similar, if **A** decreases, then the estimate of $\mathbf{N_c}$ will decrease. This can be seen from the dependence of $\mathbf{N_c}$ on the value of **wvt/A**.

17. The searching speed $\mathbf{v}$ and total search time between concentrations $\mathbf{t}$ can be estimated accurately, since they are operational parameters. The general effect of varying either $\mathbf{v}$ or $\mathbf{t}$ will be analogous to the effect of varying $1/\mathbf{A}$; hence Figure 6 can be interpreted as the effect of increasing $\mathbf{v}$ or $\mathbf{t}$ as $\mathbf{A}$ decreases.

18. The dependence upon $\mathbf{w}$ is more problematical, since $\mathbf{w}$ is most likely a random variable and, in addition, is not fully observed. There are two biases that will tend to increase $\mathbf{w}$ (thus decreasing the estimated number of concentrations $\mathbf{N_c}$):

- Larger concentrations are more likely to be detected than smaller concentrations, hence increasing the estimated value of $\mathbf{w}$.

- If concentrations move and the vessel(s) follows the movement of the concentration, the net effect will be an increase in the estimated value of $\mathbf{w}$.

19. One should thus consider the estimated number of concentrations $\mathbf{N_c}$ to be a function of $\mathbf{w}$, so that $\mathbf{N_c} = \mathbf{N_c}(\mathbf{w})$, where $\mathbf{w}$ is a random variable. Since $\mathbf{N_c}(\mathbf{w})$ is, by Eqn(1), a nonlinear function of $\mathbf{w}$, there will be a bias in the estimate of $\mathbf{N_c}$. This bias can be computed as follows. Consider the difference between $\mathbf{N_c}(<\mathbf{w}>)$, the estimated value of $\mathbf{N_c}$ using the average value of $\mathbf{w}$, and $<\mathbf{N_c(w)}>$. the average value of $\mathbf{N_c(w)}$, where the average is taken over the (unknown) distribution of $\mathbf{w}$. Standard methods show that

$$<N_c(w)> = N_c(<w>) + (1/2)N_{c,ww}(<w>)\mathrm{Var}(w) \qquad (2)$$

where $\mathbf{N_{c,ww}}$ is the second derivative of $\mathbf{N_c}(\mathbf{w})$ with respect to $\mathbf{w}$ and $\mathbf{Var}(\mathbf{w})$ is the variance of $\mathbf{w}$.

20. Figure 6 also shows the corrected estimated number of concentrations, using Eqn(2), as a function of assessed area of the sector. In order to apply this correction, one has to estimate the variance of the concentration radii. In the light of the results of the survey simulation which showed relatively small bias in detected radii relative to all radii, the observed value of $\mathbf{Var}(\mathbf{w})$, for the *Mys Tihiy* data, was used in constructing Figure 6. The net effect is relatively small, ranging from 0 for smaller values of $\mathbf{A}$ to 3 for the largest value of $\mathbf{A}$.

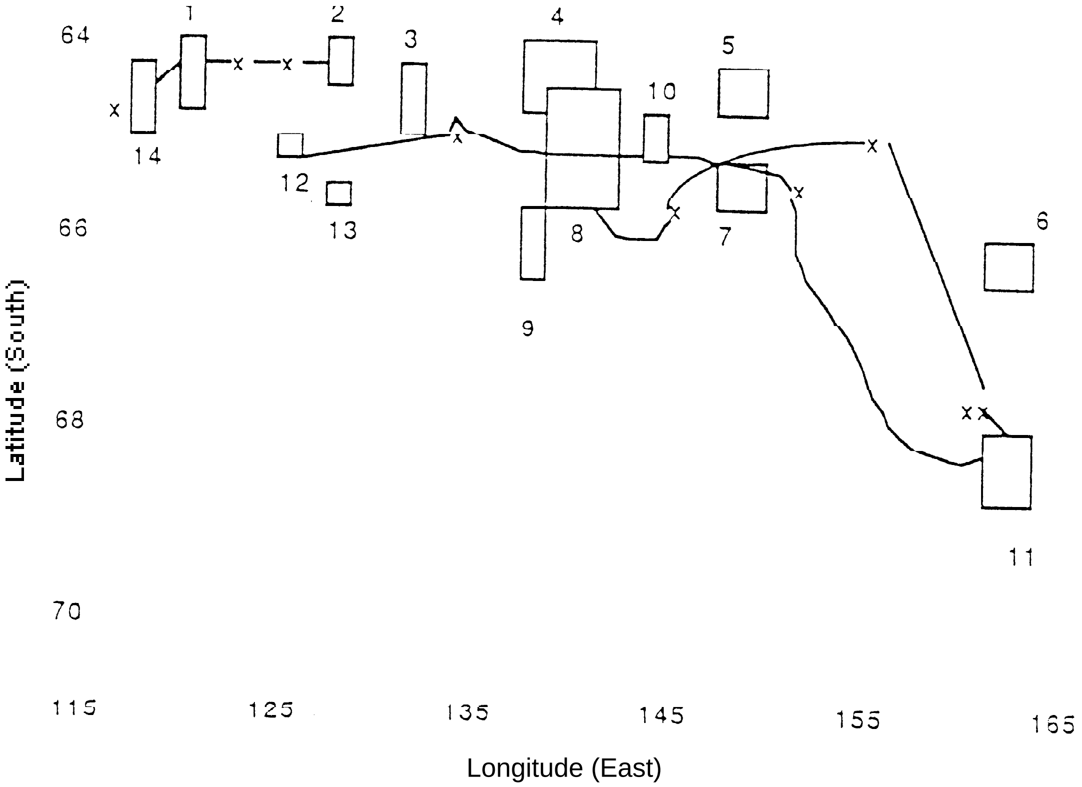

Figure 1: Concentration Map for data from research vessel *Mys Tihiy*. Concentrations are not drawn to scale. Data are taken from Mangel (WS-KCPUE-89/6).

Data from "*Mys Tihiy* 1980-81"

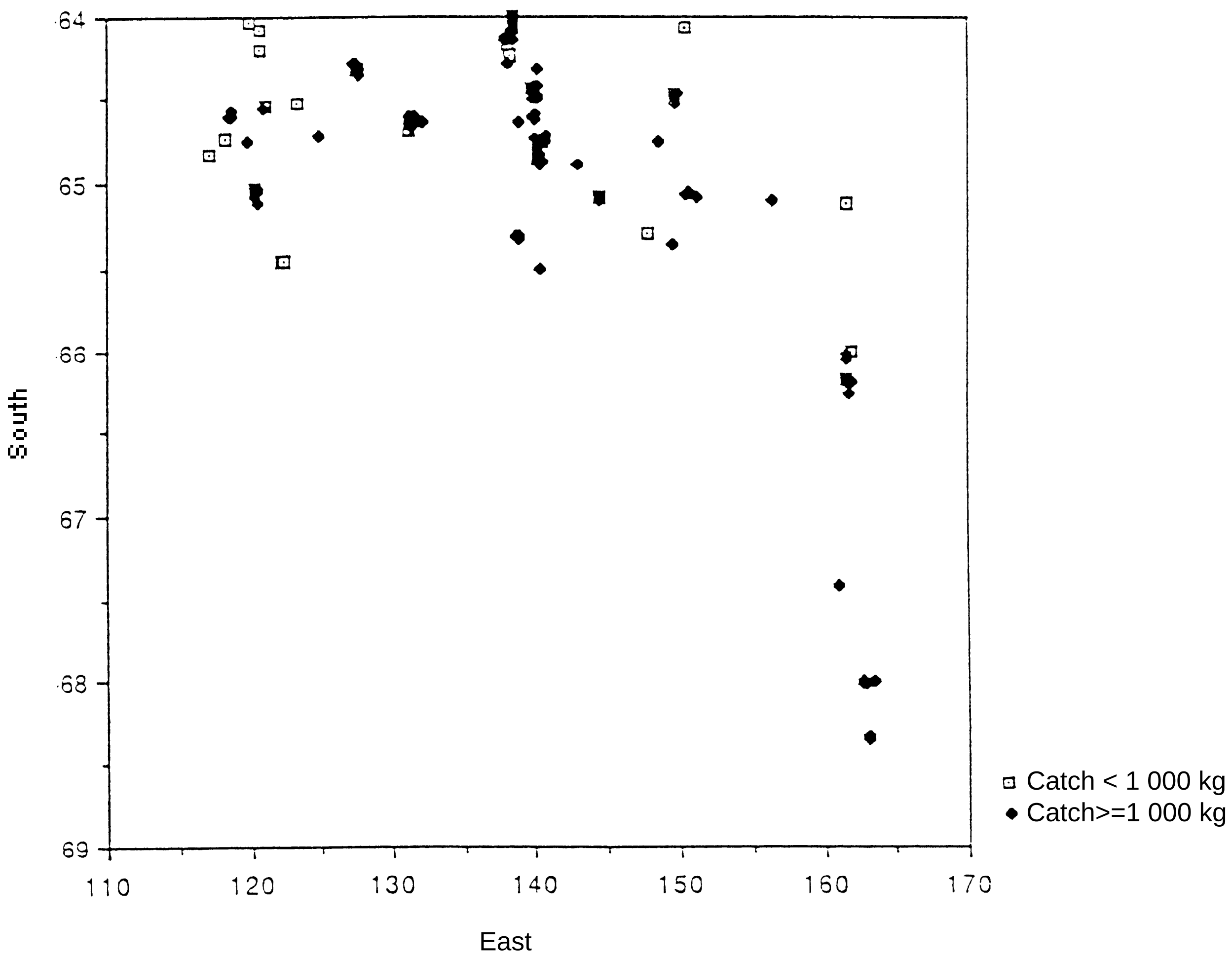

Figure 2: Haul-by-haul plot of the data used to generate the concentration map, with hauls separated by catch.

Data from "*Mys Tihiy* 1980-81", Concentration 4

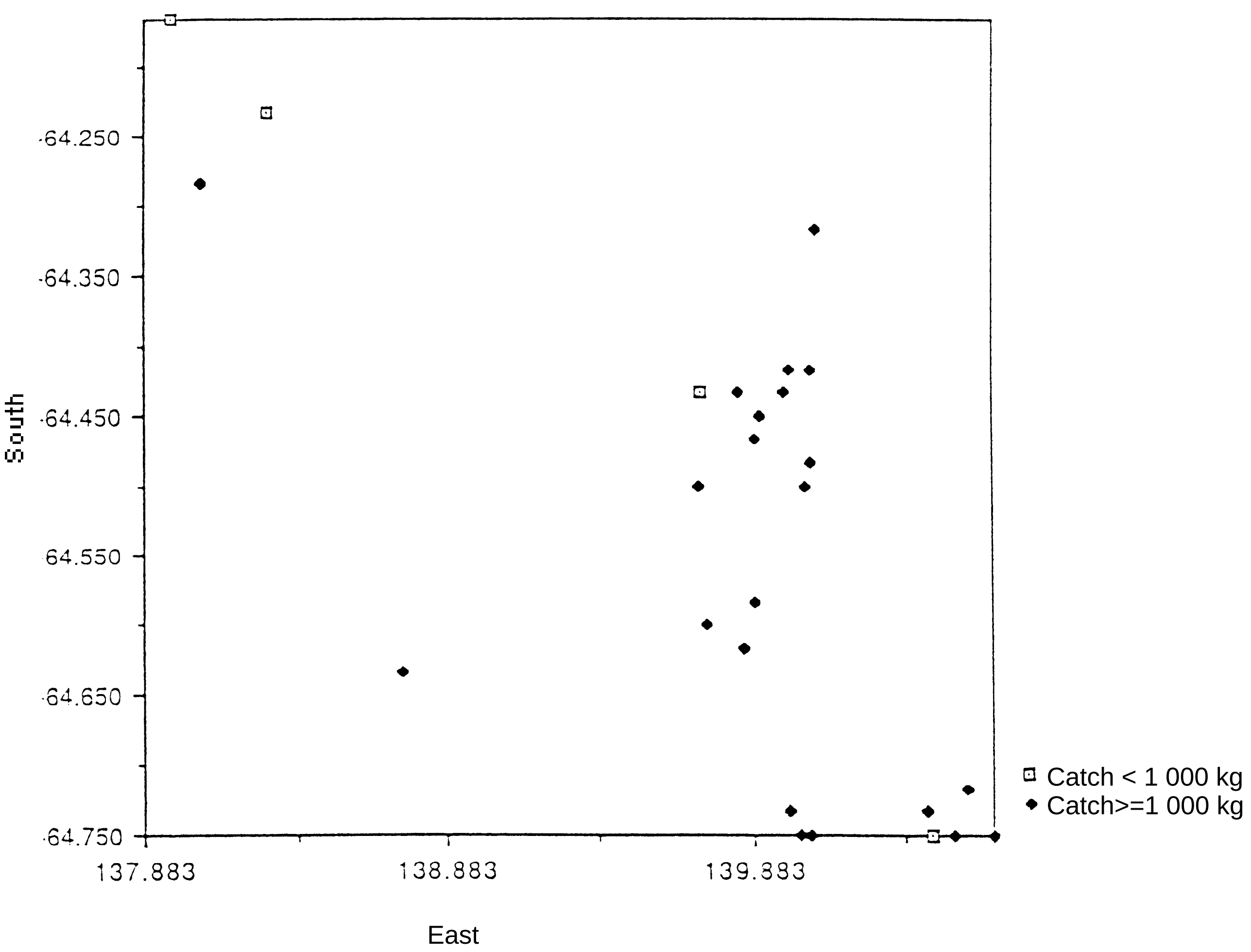

Figure 3: Haul-by-haul plot of the data from concentration 4.

Data from "*Mys Tihiy* 1980-81", Concentration 8

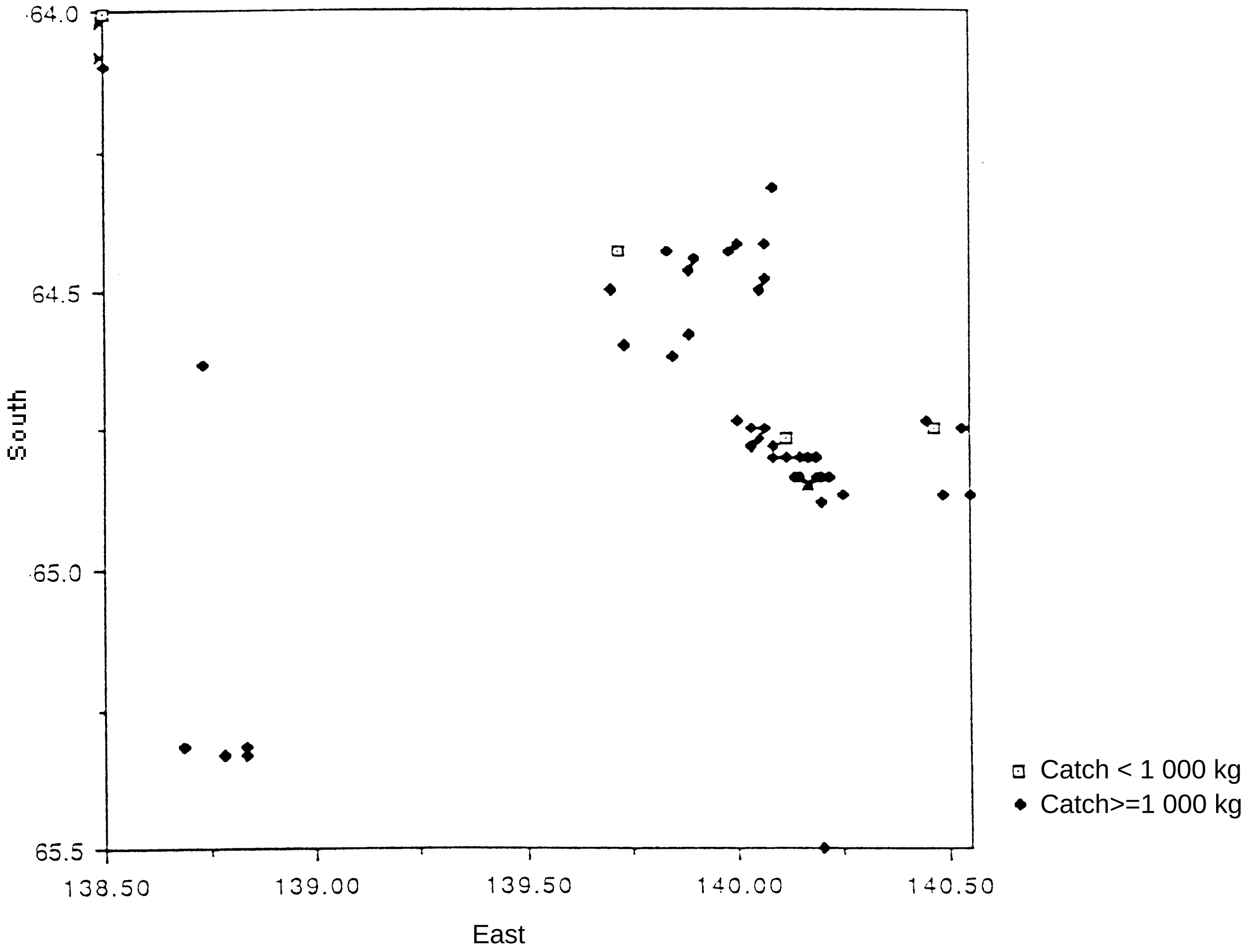

Figure 4: Haul-by-haul plot of the data from concentration 8

Data from “*Mys Tihiy* Conc Radii”

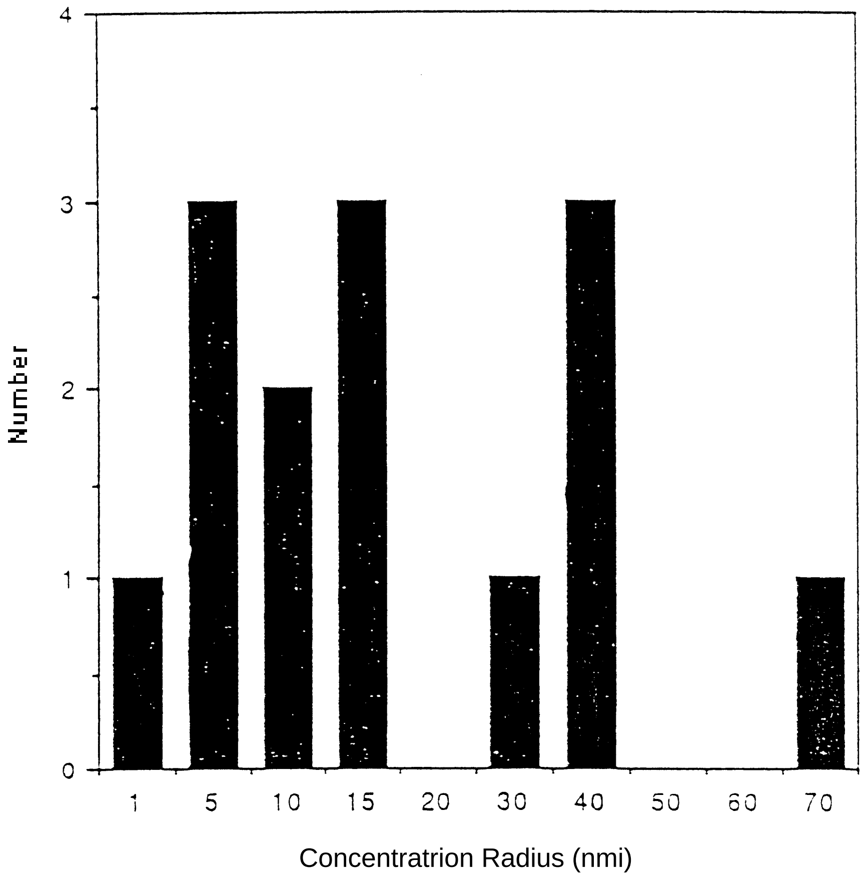

Figure 5: Histogram of concentration radii

Data from “*Mys Tihiy* Estimation”

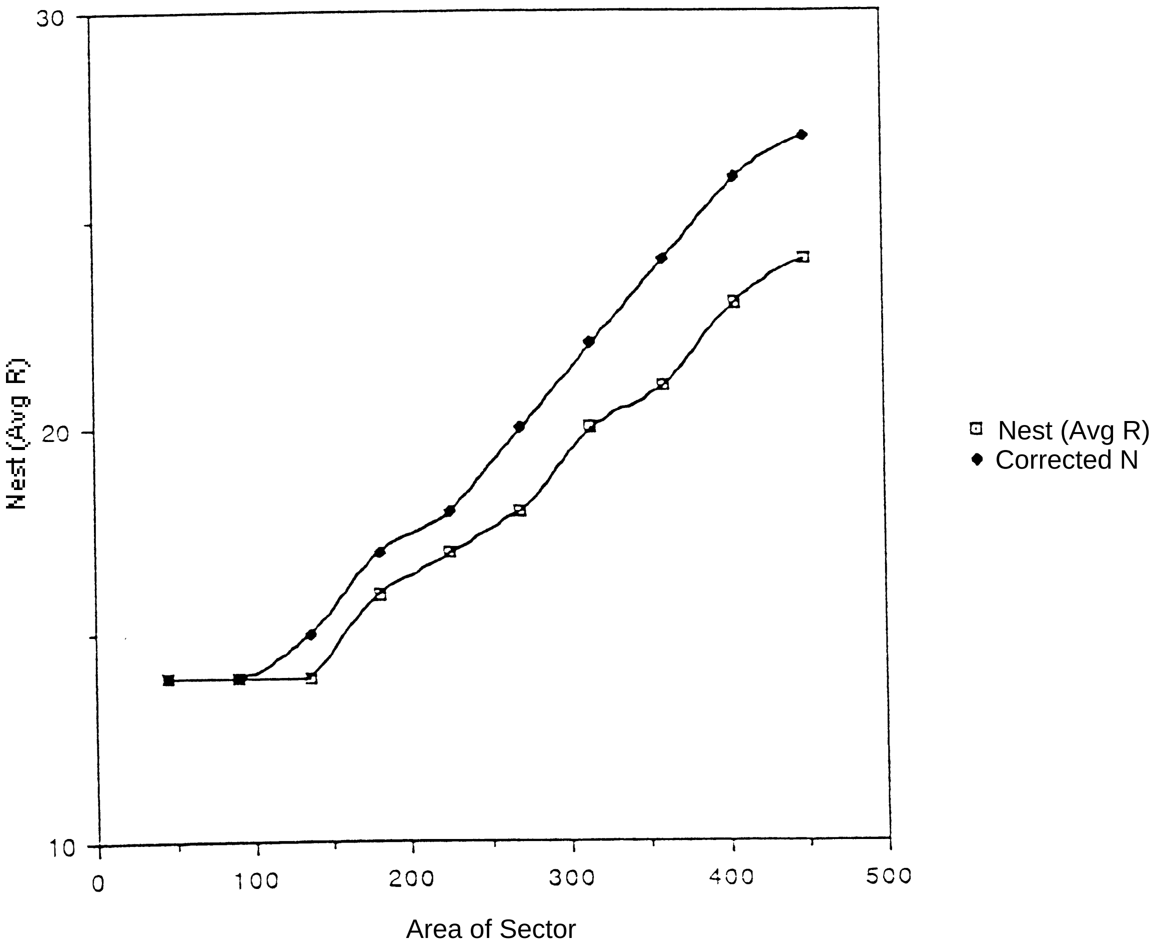

Figure 6: Estimated number of concentrations in the sector, $N_{c,est}$ (Avg R), using the average concentration radius, as a function of area of the sector. The lower curve corresponds to results from Eqn(1) and the upper curve corresponds to the results for Eqn(2), correcting the bias caused by a distribution of concentration radii.

APPENDIX 6

DETAILS OF MODIFICATIONS TO AND RESULTS FROM THE SIMULATION MODEL OF THE JAPANESE KRILL FISHERY UNDERTAKEN DURING THE WORKSHOP

INTRODUCTION

A particular problem that arose in the simulation study of the Japanese krill fishery (WS-KCPUE-89/4) was that the typical simulated fishing time required to make a catch from a single swarm was only about 15 minutes compared to the average period of one hour customarily reported for Japanese operations. Two reasons were offered during the Workshop to explain this anomaly. Firstly, the reported Japanese statistics were heavily influenced by results from fishing on good layers which require long tows, whereas fishing times on swarms in good aggregations are rather less than one hour. Secondly, swarms are not randomly distributed over these concentrations, but tend to clump together, i.e. there is positive spatial correlation of swarms in good aggregations. A group of swarms close together would be adjudged by the fishing vessel to be a single swarm with spatial dimensions much larger than those reported from scientific surveys and used in the simulation studies. The Workshop therefore addressed the questions of how this grouping effect could be taken into account by modifying the model, and whether this would change certain conclusions about the potential utility of various CPUE indices.

MODEL MODIFICATIONS

2. The major modification effected was to increase the median swarm radius (**r**) of 50 m used to describe the krill distribution in the simulation studies. Runs were carried out in turn for median **r** values of 100, 150 and 300 m. The motivation for this change was that groups of swarms seen as single units would be larger than the individual swarms, so that increasing the median **r** value in this way would be a simple (albeit approximate) way of taking this into account in the model.

3. However, increasing the median **r** value alone is inappropriate, as this soon leads to a proportional coverage of a concentration by krill swarms of more than 100% if no other distribution parameters are changed. Therefore, as median **r** was increased, the number of

swarms per unit area ($\mathbf{D_c}$) was decreased in such a way that the product $\mathbf{D_c r^2}$ remained constant. This means that the biomass of krill in the concentration and the proportion of the concentration covered by swarms remains the same as **r** is increased. This procedure was chosen because the objective of changing **r** was no more than to represent grouping of swarms within a concentration in a manner that would have the simulation model correspond to the fishermens' perception of 'swarms' within a good aggregation concentration. The values of **r** and $\mathbf{D_c}$ used in the analyses are shown in Table 1.

4. The original random search formula basis for computing primary search time (see paragraphs 44 and 45) was retained, although parameter values were adjusted as described below. The assumption of random search *per se* is questionable, because search in these concentrations may be more of the nature of directed search. However, even if search is directed, the time to travel from one group of swarms to another will increase if krill biomass drops because of a decrease in $\mathbf{D_c}$ and consequent increase in distance between groups of swarms. The random search formula gives similar results in these circumstances, so that it may be an adequate approximation for the purposes of this investigation.

5. The formula used to determine primary searching time was therefore:

Prob (detect swarm in time **t**) = 1-exp(-wdvt)

where **v** = search speed (10 knots)

d = number of fishable swarms per unit area

w = $\mathbf{w_{sonar}} + 2\,\mathbf{\bar{r}_{fs}}$

$\mathbf{w_{sonar}}$ = 2000 m

$\mathbf{\bar{r}_{fs}}$ = mean radius of fishable swarms.

When a haul is repeated on the same swarm, a fixed 'primary searching' time of 10 minutes was used.

6. The effective search width was formulated as shown above to take account of the fact that larger swarms are more likely to be detected. As median **r** is increased, the typical size of swarms considered to be fishable would increase so that **w** would increase. The values used for $\mathbf{\bar{r}_{fs}}$ were taken from the simulation model, though this parameter could be estimated from actual data if the radius of each swarm that is fished could be recorded. The parameter **d** is the product of two terms: the number of swarms per unit area ($\mathbf{D_c}$) and the proportion of these which are considered to be fishable. As median **r** is increased the first of these (S)

terms will decrease, but the second will increase. The net resultant effect is shown in Table 1 which also shows how the mean primary searching time (**wdv**)$^{-1}$ changes as median **r** is varied.

7. Only one other change to the parameters of the krill distribution model used in the Consultants studies (equation 11 of WS-KCPUE-89/4) was made. This involved the value chosen for the number of swarms per unit area ($\mathbf{D_c}$). The proportional coverage of the area of a concentration by krill swarms for the parameters used in these studies (50%) was felt to be unrealistically high. The problem was resolved by using the mean rather than the median swarm radius in calculating $\mathbf{D_c}$. For the case of a median **r** of 50 m, the mean radius is larger (90 m) because the distribution of radii is skewed. This mean value gives an estimate of approximately 10 swarms per n miles^2 when substituted in equation 10 of WS-KCPUE-89/4, compared to the 20 swarms per n miles^2 used in the calculations of WS-KCPUE-89/4. This new value for $\mathbf{D_c}$ implies a somewhat more realistic value of 25% for the proportional coverage of the concentration area by krill.

8. The particular model of the fishery for which computations were carried out during the Workshop is the 'one swarm per haul - no elongation' version described in WS-KCPUE-89/4. The fishing operation parameter values (both fixed and partially tuned) that were utilised are those of the first column of Table 2 of WS-KCPUE-89/4 with the following two exceptions. The minimum catch rate to remain in a concentration was set to a low value that would not be attained during the simulations. This was because only within-concentration statistics were of interest, so that there was no need to generate between-concentration search statistics. The repeat-haul-on-a-swarm criterion was changed from 50 tonnes/hour to 40 tonnes/hour to better reflect the reported estimate of a repeated haul attempt rate of 40% (see Table 3, WS-KCPUE-89/4) for the range of krill distribution parameters considered. Only 50 rather than 100 simulations were run for each scenario considered to save on computer time costs. This still provides adequate precision for estimates of within-concentration statistics.

RESULTS

9. The results of runs of the Japanese fishery simulation model modified as above in terms of the behaviour of CPUE indices are shown in Table 2. As the median **r** is increased from 50 m to 300 m, the average length of a swarm through which a haul is made, increases from about 0.3 n miles to 0.6 n miles and the average fishing time per haul (the time the net is at the desired depth, excluding lowering and raising times) increases from about 13 minutes to 23 minutes. Mr Ichii advised that although tows on good layers involved an average

fishing time of one hour, fishing times of about 20 minutes were typical for tows on good aggregations.

10. It seemed, therefore, that increasing the median **r** value did lead to model estimates of fishing time that were comparable to reality in good aggregation concentrations.

11. Table 2 shows that the efficiency of the CPUE indices listed to detect biomass reductions is hardly affected as the median **r** value is increased. It is clear that the performance of indices using Primary Searching Time (PST) only is much superior to those using the combination of Primary and Secondary Search Time (PST + SST). The latter have hardly any utility except a very weak ability to detect decreases in $\mathbf{D_c}$. Unfortunately (see paragraph 62 of the Workshop Report), only the latter combination could be collected routinely, as the PST component could not be distinguished in practice.

12. Thus, although indices involving fishing times could be used to monitor biomass reductions that are the result of a decrease in δ, use of indices based on total-within-concentration searching time (PST + SST) do not appear to be adequate to detect changes in **r** or $\mathbf{D_c}$.

INDICES BASED ON A MODIFICATION OF TOTAL SEARCHING TIME

13. Results given in Table 11 of WS-KCPUE-89/4 had shown that indices based on PST still performed well even if PST was estimated with considerable error, provided the estimation was unbiased.

14. This suggested that an approximate means of inferring the PST component from data on PST + SST might provide indices whose performance in detecting biomass reductions might not be substantially reduced from that of the (impractical) PST-based indices.

15. What is required is to subtract some estimate of SST from the PST + SST combination which can be measured. The SST required depends on the size of the catch from the previous haul because of processing time requirements, so that an approximate estimate of SST might be provided by some multiplier (μ) of this catch. Thus, Pseudo Primary Searching Time (PPST) was defined as the time between the end of one haul and the beginning of the next, less μ times the previous catch (**C**). The specific formula used was:

$$\text{PPST} = \max \begin{cases} \text{PST} + \text{SST} - \mu\,(C - 0.75 \times 5) \\ 3 \text{ minutes} \end{cases}$$

The reason that **C** is reduced by 3.75 tonnes is to allow for the fact that the simulation model starts the next haul (i.e. ends SST) 0.75 hours before processing of the last catch (at a rate of 5 tonnes per hour) is complete. The multiplication factor μ was chosen empirically to be 0.17 to provide good performance of the resultant CPUE indices. The minimum value of PPST for each haul of 3 minutes was introduced to avoid unrealistically small (or negative) values of PPST. It was recognized that an analysis of this sort constituted only an examination of whether such an approach might work in principle. In any practical implementation, the multiplier would need to be changed depending on the product being produced.

16. The results of the runs carried out for indices based on PPST are also shown in Table 2. Although these indices are not as effective as those using PST at detecting changes in $\mathbf{D_c}$, they perform considerably better than those which used PST + SST. Further, the efficiency of these indices improves as median **r** is increased above 50 m, which is considered to be a more realistic representation of krill distribution in a good aggregation concentration. Similar comments apply to the ability of PPST based indices to detect changes in **r**, except that the sensitivity is not as large as for $\mathbf{D_c}$.

17. The value of μ chosen for the calculations carried out was selected to attempt to achieve the best possible results in terms of sensitivity of PPST indices to biomass reductions for the particular simulation model used to represent the fishery. In reality, the parameters of this model would not be known exactly so that the value of μ used may not be optimal. Therefore, the sensitivity of the results regarding detection of changes in $\mathbf{D_c}$ was investigated for different values of μ.

18. Calculations were repeated for a number of smaller values for μ. The results of these calculations are shown in Table 3. In the simulation, the inverse of the processing rate was 0.20 hours per tonne. The value of μ is bounded above by this inverse rate, and the results show that indices involving PPST are reasonably responsive to changes in $\mathbf{D_c}$ for values of μ down to at least 0.10, which is one half of this upper bound. This wide range suggests that indices based upon PPST would retain their utility even if a value for μ which is not ideal was used.

19. Thus it seems that there is potential for search time information to be used to detect changes in $\mathbf{D_c}$ and **r.** The search time data required will involve little more data collection

than is already carried out in the Japanese fishery. These operations routinely record the time at which fishing ends for one haul and the time it begins for the next. The difference between these times is (PST + SST + the time required to raise then lower the net). These last net handling times are relatively constant from one haul to the next. Therefore PPST could be calculated simply from these data, provided information was also recorded on changes in processing rate and interruptions to the normal searching and fishing activities. Different values of μ would need to be used as the processing rate changes because a different product is being produced. Interruptions may occur, for example, because of bad weather.

LIKELY PRECISION OF CPUE INDICES INVESTIGATED

20. Figure 1 shows the relationship between the CPUE index TC/TFISHT and biomass, where the biomass changes as a result of a change in within-swarm krill areal density δ only. The non-linearity of the relationship is clear from the plot. The change in TC/TFISHT does not reflect the full extent of any biomass reduction.

21. Error bars, corresponding to 95% confidence intervals, are also shown in Figure 1. These have been derived from estimates for the standard error of the mean of the index for 50 simulation runs of the model each corresponding to a 15 day period. This is equivalent to 25 vessel-months, which is approximately the effort currently being expended by the Japanese Antarctic krill fishing fleet.

22. The specific confidence intervals illustrated in the plot correspond to the ratio of the CPUE index over two years. Thus, if δ dropped by 50% from one year to the next, these results indicate that for the level of catch taken by the Japanese fleet, the TC/TFISHT index would be 95% certain to drop by between 31% and 41%.

Table 1: Parameters used in random search formula for swarms as median **r** is increased. The search speed **v** is 10 knots throughout. The selectivity is fixed throughout, with fishable swarms being those within a biomass greater than 50 tonnes, which constitute a fraction **S** of the total number of swarms. The average Primary Searching Time for a swarm is $\bar{\mathbf{t}}$.

Median r m	$\bar{r}_{fs}$ m	$w=2000+2\bar{r}_{fs}$ m	D_c n miles^{-2}	S	$d=D_cS$ n miles^{-2}	$\bar{t}=(wdv)^{-1}$ min
50	372	2744	10	.076	0.760	5.3
100	515	3030	2.5	.183	0.458	8.0
150	628	5256	1.11	.277	0.307	11.1
300	936	3872	.278	.475	0.132	21.7

Table 2: Sensitivity **s** of various CPUE indices **I** for different biomass change scenarios. If **I(1)** is the value of the index for the base case distribution parameters, and **I(0.5)** corresponds to a biomass decrease of 50% through a change in the parameter indicated, then:

$$s = 2(1- I(0.5)/ I(1))$$

Thus **s=0** means that the index shows no change when the biomass is reduced in this manner, whereas **s=1** means that the index value falls by the same relative amount as the biomass (as would be the case for a linear CPUE-biomass relationship). The meanings of the components of the CPUE index are as follows:

TC =	Total catch	TSST =	Total secondary searching time
TFISHT =	Total fishing time	$\overline{PST}$ =	Average primary searching time per haul
TPST =	Total primary searching time*	TPPST =	Total pseudo primary searching time (μ = 0.17 hr/tonne)

(a) Biomass reduction through swarm radius $r \rightarrow r/\sqrt{2}$

Median r (m)	50	100	150	300
Index				
TC/TFISHT	-.19	-.30	-.27	-.26
TC/TPST*	.57	.50	.57	.45
TC/(TPST+TSST)	.05	.07	.11	.14
$TC/(TFISHT*\overline{PST})$*	.43	.29	.38	.23
$TC/(TFISHT*\overline{PST+SST})$	-.14	-.19	-.13	-.13
TC/TPPST	.20	.28	.37	.43
$TC/(TFISHT*\overline{PPST})$	.02	.03	.16	.20

* Collection not practical

(b) Biomass reduction through krill areal density as within-swarm $\delta \rightarrow \delta/2$

Median r (m)	50	100	150	300
Index				
TC/TFISHT	.61	.72	.79	.67
TC/TPST*	.77	.89	.84	.64
TC/(TPST+TSST)	-.05	-.02	.08	.16
$TC/(TFISHT*\overline{PST})$*	1.02	1.11	1.12	.90
$TC/(TFISHT*\overline{PST+SST})$	.35	.38	.53	.53
TC/TPPST	.47	.72	.78	.68
$TC/(TFISHT*\overline{PPST})$	.77	.97	1.07	.94

* Collection not practical

Table 2 continued

(c) Biomass reduction through number of swarms per unit area $D_c \rightarrow D_c/2$

Median r (m)	50	100	150	300
Index				
TC/TFISHT	.06	.07	-.20	-.10
TC/TPST*	.78	.83	.90	.87
TC/(TPST+TSST)	.10	.13	.30	.41
$TC/(TFISHT*\overline{PST})$*	.80	.83	.82	.80
$TC/(TFISHT*\overline{PST+SST})$	.13	.12	.20	.35
TC/TPPST	.40	.57	.67	.81
$TC/(TFISHT*\overline{PPST})$	.42	.56	.57	.74

* Collection not practical

Table 3: Sensitivity **s** of PPST-based CPUE indices to a reduction in $\mathbf{D_c}$ to $\mathbf{D_c/2}$ for various values of the multiplier μ of the catch subtracted from total searching time.

Index	TC/TPPST		$TC/(TFISHT*\overline{PPST})$	
μ (hr/tonne)	Median r = 50 m	Median r = 300 m	Median r = 50 m	Median r = 300 m
0.17	.40	.81	.42	.74
0.15	.29	.71	.32	.65
0.10	.18	.56	.20	.50
0.05	.13	.47	.15	.41

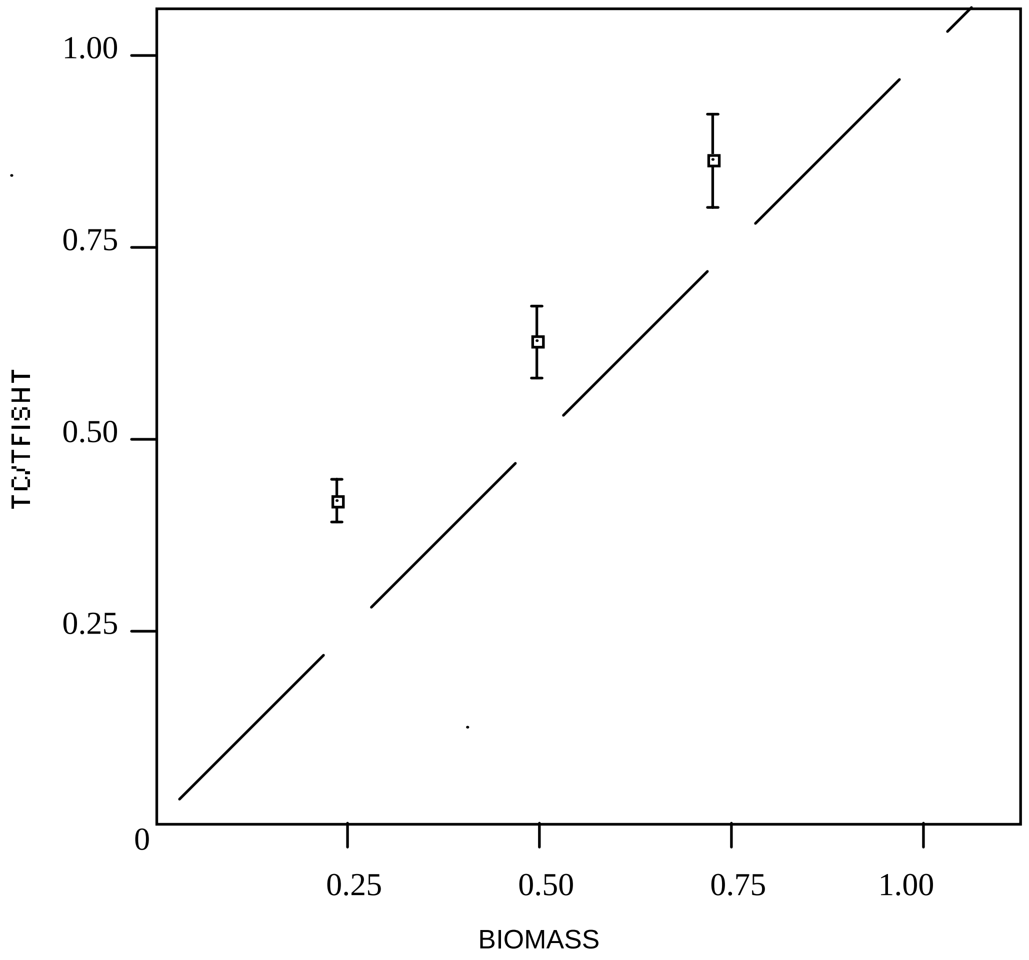

Figure 1: Plot of the TC/TFISHT index as a function of biomass when the biomass reduction is as a result of a decrease in within swarm krill areal density δ. The variables on both axes are shown as fractions of their base case levels for median **r=100 m**.

APPENDIX 7

FRAMEWORK FOR A SIMULATION STUDY OF A COMPOSITE INDEX OF KRILL ABUNDANCE

The majority of discussion in this appendix concerns the Composite Index of Krill Abundance in good aggregation concentrations. An index of krill abundance in good layer concentrations is described at the end of this section.

2. A Composite Index of Krill Abundance should be constructed only on an area by area basis. The selected area should have a number of properties:

- It should be relatively homogeneous, so that one can justify 'multiplying up' the data collected in this area;
- Both survey and fishing vessels should operate in this area.

3. The Composite Index will be a relative measure of biomass, and hence should be constructed in ecologically sensitive areas. An example of such a region is the shelf boundary.

4. The Composite Index is given by

$$CI = N_c L_c^2 D_c r^2 \delta \qquad (1)$$

In this equation, **CI** denotes the Composite Index and

N_c = number of concentrations in the area of interest
L_c = characteristic radius of concentrations
D_c = number of swarms per unit area in a concentration
r = characteristic radius of swarms in concentrations
δ = areal density of krill within swarms. (2)

5. The purpose of the simulation study of a Composite Index is to determine if such an index can monitor krill biomass effectively. It is most likely that the Composite Index will be a nonlinear function of krill biomass. The nonlinearity is likely to be such that if the index

shows a statistically significant change, then the biomass has changed by an even greater amount than the index so that krill abundance has altered markedly.

6. Since the variance of the Composite Index will depend upon the variance of the underlying variables, it is crucial to understand how these parameters both vary and can be estimated and how errors in the estimates affect the Composite Index. That is, the actual Composite Index is not given by Eqn(1), but is given by

$$CI = N_{c,est}\, L^2_{c\ ,est}\, D_{c,est}\, r^2_{e\ st}\, \delta_{est} \qquad (3)$$

where the subscript 'est' on each of the variables on the right hand side indicates that these variables are estimated.

7. The Composite Index of Krill Abundance when krill are in layers is given by

$$CI_{layer} = N_{cl}\, L^2_{c\ l}\, \delta \qquad (1')$$

where $\mathbf{N_{cl}}$ is the number of concentrations in which krill are in layers, $\mathbf{L_{cl}}$ is the characteristic length of such concentrations and δ is the density of krill in such concentrations. The general principles described below apply to krill in layers, with appropriate modification.

CURRENT KNOWLEDGE ABOUT UNDERLYING PARAMETERS, SOURCES OF UNCERTAINTY AND ESTIMATION

Number of Concentrations

8. Survey vessel data can, with appropriate mathematical analyses, be used to estimate the number of concentrations in a region. By adapting the methods described in Mangel and Beder (1985) to the situation in which depletion does not occur, one can compute the probability distribution of $\mathbf{N_{c,est}}$ as a function of the number of discoveries by the survey vessel.

9. Difficulties with the estimation of $\mathbf{N_c}$ include:

(i) double counting concentrations during the survey process;

(ii) accurate determination of vessel search speed and searching time;

(iii) accurate and confident determination of the effective detection width of concentrations; and

(iv) the non-random distribution of concentrations and associated stratification of search effort.

10. Currently, very little is known about the distribution of concentrations in ecologically sensitive areas. To improve knowledge of this variable, concentrations should be defined while at sea using the echochart, rather than *post-hoc* in a statistical analysis.

Characteristic Length of Concentrations

11. The use of a single characteristic length for concentrations presumes that either concentrations are symmetrical (e.g. circles or squares), or are not symmetrical (e.g. ellipses) but that if abundance changes then all axes of the ellipse will change in the same proportion. It is not known whether this assumption is valid and this matter deserves further attention.

12. The characteristic length of concentrations can be determined by using the detailed location data from Soviet and Japanese fishing activities. In particular, such vessels could attempt to determine:

- concentration shape; and
- concentration characteristic length.

13. At the present time, very little is known about the distribution of sizes and shapes of concentrations. In their simulation models, the Consultants assumed that diameters were uniformly distributed over the approximate range of 11 n miles to 22 n miles. Discussions at the Workshop suggest a number of modifications:

- good concentrations are at least 25 n miles in diameter;

- concentration radii have a skewed distribution, rather than a uniform distribution; and

- in a region such as the shelf edge, the relevant variable is the width of the concentration across the shelf, rather than length along the shelf.

Density of Swarms Within Concentrations

14. The density of swarms within concentrations (i.e. the number of swarms per unit area) can be estimated using Japanese logbook data or using acoustic data collected by scientific survey vessels. In poor concentrations, the distance between swarms may follow a negative exponential distribution (e.g. Miller and Hampton, 1989). In good aggregations, the negative binomial distribution, a typical aggregated distribution, might be used to model $\mathbf{D_c}$.

15. The Consultants assumed that $\mathbf{D_c=20exp(X_{.1})}$ swarms/ n miles^2, where $\mathbf{X_\sigma}$ is a normally distributed random variable with mean 0 and variance σ^2. The general feeling at the Workshop was that:

- The distribution of densities of swarms within concentrations should be relatively easily determined from echocharts.

16. In addition, there should be only modest variation in density of swarms within concentrations. If krill are indeed in swarms (versus layers), then the density cannot be too low, since in that case the krill would not be in a ‘good’ (i.e. fishable) concentration. Similarly, if the value of density is very high, then the krill are not in swarms, but are essentially in layers. These effects will constrain the variance.

Characteristic Radius of Swarms within Concentrations

17. This variable would be most effectively determined using acoustic information collected by survey vessels, although data collected by fishing vessels could be used as well. Full discussion of the distributional properties of **r** was referred to the Working Group on Krill. However, the following points emerge.

18. The Consultants assumed that $\mathbf{r= 50\ exp(X_{1.1})\ m}$, which leads to considerable skewness in the value of **r**. Six examples of towed swarm size distributions are given by Ichii (1987). In a region that was approximately 60 n miles in north-south extent and 60 n miles in east-west extent, Ichii’s data (Figure 1) suggest four instances of swarm radii following an apparently negative exponential distribution, one instance of swarm radii following an approximately uniform distribution and one instance of swarm radii following a highly skewed distribution with minimum size 3 000 m. These kinds of results suggest that swarm radii may vary considerably over relatively small geographic areas and that the accurate determination of this variability is important.

Krill Density Within Swarms

19. The areal density of krill within swarms (i.e. g/m^2) can be determined from both Soviet and Japanese fishing vessels, using catch per fishing time as an index. Acoustic data could also be used, but **only if mean volume backscattering strength is reported**. This is required, even for a relative abundance index, in order to calibrate data from one vessel to the next.

20. The Consultants assumed that **$\delta = 150 \exp(X_{1.4})$ g/m^2**, which leads to considerable skewness in the distribution of densities. In concentrations that are fished, however, the density may be less variable, since the fishermen select concentrations on the basis of achieving a satisfactorily high catch rate. This same operational behaviour will reduce the ability of a Composite Index to detect changes in abundance.

GENERAL CONSIDERATIONS REGARDING THE COMPOSITE INDEX

21. Since $\mathbf{L_c}$ and $\mathbf{r}$ are squared in the Composite Index, uncertainties in either of these values will have proportionately greater effects than uncertainties in $\mathbf{N_c}$, $\mathbf{D_c}$ or δ.

22. At the current time, there is little known about the correlation between parameters. For example, it might be that krill biology forces the product $\mathbf{D_c\ r^2}$ to be approximately constant.

23. There is also little current knowledge about the way that abundance changes may be manifest. That is, each of the five underlying variables may change independently, or there may be considerable covariation between them.

24. Since the Composite Index will most likely be a nonlinear function of abundance, the variance properties of the index become extremely important if it is to be used for monitoring abundance.

A PROTOCOL FOR A SIMULATION STUDY OF THE COMPOSITE INDEX

25. A possible protocol for a simulation study of the Composite Index involves the following steps:

(a) Choose fundamental values for the underlying distribution parameters. These can be viewed, for example, as the means or medians of these parameters;

(b) For each iteration of the simulation, use the distributional properties just described to determine particular values for each of the underlying parameters in that iteration. The biomass index **BI** for this particular run of the simulation will then be given by Eqn(1). Note that **BI** is the 'true' abundance index, as distinct from **CI** which is an estimate of this index;

(c) For each iteration of the simulation, use the distributional properties of the estimated variables and models developed by the Consultants to determine estimated values of the underlying variables, given the true values of the underlying variables. Once these estimated variables are constructed, the 'observed' Composite Index is given by Eqn(3); and

(d) Study the properties of **CI/BI** as a function of **BI** and as the underlying parameters are varied. In this way, one can consider both the nonlinearity and the variance of the Composite Index.

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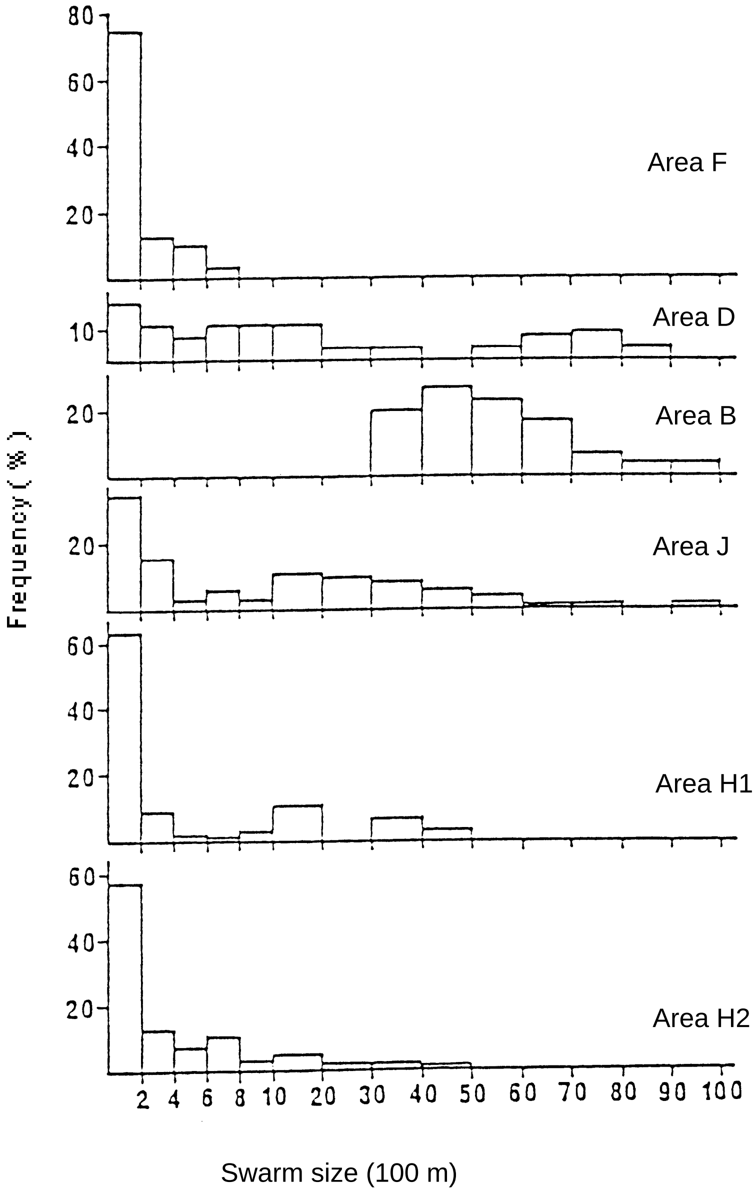

Figure 1: Frequency distributions of swarm sizes towed in each fishing area (Ichii, 1987)