APPENDIX D

REPORT OF THE WORKSHOP ON PLAUSIBLE ECOSYSTEM MODELS FOR TESTING APPROACHES TO KRILL MANAGEMENT

(Siena, Italy, 12 to 16 July 2004)

CONTENTS

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INTRODUCTION

1.1 The Workshop on Plausible Ecosystem Models for Testing Approaches to Krill Management, which was established in the program of work for WG-EMM in 2001, was held at the University of Siena, Siena, Italy, from 12 to 16 July 2004. The meeting was convened by Dr A. Constable (Australia).

1.2 In 2003, the terms of reference for the workshop were agreed to be (SC-CAMLR-XXII, Annex 4, paragraph 6.17):

(i) to review the approaches used to model marine ecosystems, including:

   (a) the theory and concepts used to model food-web dynamics, the influence of physical factors on those dynamics and the operations of fishing fleets;

   (b) the degree to which approximations could be used to form 'minimally realistic' models[1];

   (c) the types of software or computer simulation environments used to implement ecosystem models;

(ii) to consider plausible operating models for the Antarctic marine ecosystem, including:

   (a) models of the physical environment;

   (b) food-web linkages and their relative importance;

   (c) dynamics of the krill fishing fleet;

   (d) spatial and temporal characteristics of models and their potential limitations in space and time;

   (e) bounding the parameters used in the models;

(iii) to advance a program of work to develop and implement operating models to investigate the robustness of different management approaches to underlying uncertainties in the ecological, fishery, monitoring and assessment systems, including:

   (a) the development and/or testing of software;

[1] A minimally realistic model of an ecosystem is one that includes just sufficient components and interactions to enable the key dynamics of the system to be realistically portrayed.

(b) specification of requirements of software, including diagnostic features, ability to test the efficacy of observation programs, such as different kinds of monitoring of predators, prey and the fishery;

(c) consideration of spatial and temporal characterisation of the physical environment (ice, oceanography) that could be used to parameterise the models.

1.3 A steering committee was established in 2003 and comprised Drs Constable (Coordinator) and C. Davies (Australia), P. Gasyukov (Russia), S. Hill (UK), Prof. E. Hofmann (USA), Drs G. Kirkwood and E. Murphy (UK), M. Naganobu (Japan), D. Ramm (Secretariat), K. Reid (UK), C. Southwell (Australia), P. Trathan (UK) and G. Watters (USA). Drs R. Hewitt (Convener, WG-EMM) and R. Holt (Chair, Scientific Committee) have been *ex officio* members of the steering committee (SC-CAMLR-XXII, Annex 4, paragraph 6.16).

1.4 Intersessional activities of the steering committee are reported in Item 2.

1.5 The Scientific Committee agreed to fund the attendance of two invited experts at the workshop, as well as providing some funding so that the invited experts could undertake some preparatory work which would at least involve reviewing the contributions to the workshop.

1.6 The workshop steering committee agreed to invite two external experts who could advise on important areas where sufficient expertise is not available from within the CCAMLR community, and who could help with the following key questions:

- To what extent is it necessary to represent all interactions in a food web?
- How can minimally realistic models be used safely?

1.7 Dr B. Fulton (CSIRO, Australia) was invited for her expertise in considering these questions in the context of the evaluation of management procedures (strategies). A second expert was invited but was unable to attend the workshop due to unexpected circumstances.

1.8 Dr Constable introduced the work of the workshop and provided a summary of the background to the workshop along with some expectations as to the outcomes to be achieved. These points were based on Part I of WG-EMM-04/24, and included:

(i) A discussion on how observations are the basis of making decisions.

(ii) A management procedure is a combination of observations, assessments, and decision rules that adjust harvest controls to achieve operational objectives.

(iii) Long-term planning is improved if the rules surrounding decisions are known and understood.

(iv) Assessments may comprise statistical estimation of a parameter/indicator, statistical comparisons, or more complex development of models and projections.

(v) Key questions about the assessments are:

(a) Are there sufficient samples to make the correct decision? This often relates to precision of the estimates, which could lead to statistical Type I and II errors (Andrew and Mapstone, 1987).

(b) Could the estimates be biased and/or confounded by variables or processes unrelated to the assumed cause of effects?

(vi) Precision can be handled by analyses of statistical power, such as those being done in the CEMP review.

(vii) The effect of bias and/or potential confounding on making decisions consistent with the precautionary approach can be addressed by building scenarios and determining whether the bias could lead to incorrect decisions. The issues of bias and confounding in relation to parameter estimation and in relation to the processes that link ecosystem elements to krill, either as food for krill or predators of krill, are more difficult to address. While some relationships could be explored using scenarios of logic, others will need to use more complicated simulations to explore the effects of different types of plausible relationships (structural uncertainty) as well as the effects of natural variation (system uncertainty).

(viii) A task of the workshop is to develop scenarios in order to help evaluate the potential for biases in our monitoring and in the assessment process and whether those biases could lead to incorrect decisions that would cause the Commission to fail to meet one or more of its objectives.

(ix) The primary aim of the workshop was to develop the specifications that will be used by programmers to produce the modelling framework in which plausible models of the Antarctic marine ecosystem can be simulated.

1.9 Dr Constable introduced the draft agenda (in WG-EMM-04/25) and the workshop agreed to add another item ‘Plausible scenarios for Antarctic marine ecosystems’. With this addition the agenda was adopted (Attachment 1).

1.10 In adopting the agenda, the workshop noted that the discussions would be drawing together information and concepts to provide a common framework for developing one or more ecosystem models for testing approaches to krill management. As such, the workshop acknowledged that the common framework developed in its report may not be using all of the information, concepts or understanding necessary for implementing ecosystem models. For example, the estimation and summary of parameters is not one of the intended outcomes of the workshop. As a result, some tables, figures or text may not be complete in their consideration or presentation of the issues. Nevertheless, the workshop agreed that the format of the workshop should provide the foundation for further development and implementation of ecosystem models for the work of WG-EMM.

1.11 The work was divided into the major sections of the agenda and coordinated by Dr Constable.

1.12 The report was prepared by Dr Constable, Prof. J. Croxall (UK), Drs Davies, Hill, Hewitt, S. Kawaguchi (Australia), Ramm, Reid, K. Shust (Russia), V. Siegel (Germany), Trathan, W. Trivelpiece (USA) and Watters. Workshop participants are listed in Attachment 2.

REPORT OF THE STEERING COMMITTEE ON INTERSESSIONAL ACTIVITIES

2.1 As agreed at WG-EMM in 2003, intersessional activities included:

(i) provision of advice on the potential contributions from experts in preparation for the workshop and in participating in the development of models at the workshop (Drs Hill and Murphy and Prof. Hofmann);

(ii) a review of relevant literature and information on the development of ecosystem models elsewhere as per the first term of reference (Prof. Hofmann and Dr Murphy);

(iii) compilation of a catalogue of available software and other simulation environments for ecosystem modelling (Drs Ramm, Watters and Gasyukov);

(iv) preliminary consideration of the requirements for datasets, estimates of parameters and other aspects related to the second term of reference (Drs Trathan, Reid and Naganobu);

(v) preliminary outline of the aims and specifications for ecosystem modelling as it relates to the development of management procedures for krill (Drs Constable, Davies and Kirkwood).

2.2 The results of this work are outlined in the report from the steering committee (WG-EMM-04/25).

Literature review on ecosystem models

2.3 A review of relevant literature and information on the development of ecosystem models elsewhere as per the first term of reference was prepared by Drs Hill, Murphy, Reid, Trathan and Constable. It was submitted as WG-EMM-04/67 and presented to the workshop under Item 3 (see also paragraphs 3.1 and 3.15).

2.4 The workshop had also been informed of other research and publications relevant to its evaluation of ecosystem models and processes.

2.5 The workshop requested that the recent evaluations of fishery management models (e.g. Plagányi and Butterworth, in press; Plagányi and Butterworth, in review) and of multispecies interactions in the Antarctic (Mori and Butterworth, in press) be submitted for the consideration of WG-EMM.

Available software and other simulation environments

2.6 A catalogue of available software and other simulation environments for ecosystem modelling was compiled by Drs Ramm, Gasyukov and Watters. It is summarised in Appendix A of WG-EMM-04/25.

2.7 Dr Gasyukov further outlined the availability of models through the Internet but noted that it would be preferable to develop software specifically for use by CCAMLR.

Data and parameter requirements

2.8 In preparation for the workshop, Drs Naganobu, Reid and Trathan were asked to make a preliminary consideration of the requirements for datasets, estimates of parameters and other aspects related to the second term of reference.

2.9 The workshop recognised that defining the data requirements for models that are not yet specified meant that there was a limit to the progress that could be made. Nevertheless there are a number of key areas of data that are likely to form the basic requirements of an ecosystem model of the Southern Ocean. In WG-EMM-04/25, a background synopsis of the availability of basic data is provided in the following categories:

- models of the physical environment
- food-web linkages and their relative importance
- dynamics of the krill fishing fleet.

2.10 The workshop noted that there was considerable information available with which to parameterise ecosystem models. However, the workshop also recognised that the availability and utility of data were not synonymous; for example, there are a large number of datasets of physical processes but the utility of these to ecosystem models was not yet defined. In order to progress the development of plausible ecosystem models for use in the management of the krill fishery, it would be necessary to ensure that adequate validated information was available to properly describe both food-web linkages and the dynamics of the krill fleet.

Aims and specifications for ecosystem modelling

2.11 Drs Constable, Davies, and Kirkwood undertook to consider aims and specifications for ecosystem modelling. Much of the discussion occurred at the Scientific Committee meeting last year, which was distributed in the first and second Scientific Committee circulars concerning the workshop.

2.12 Dr Kirkwood described his involvement in a project funded by the European Community developing fisheries-related models to evaluate management strategies. That work is being coordinated by Dr L. Kell (CEFAS) with much of the code being developed in the free-ware statistical language, R. A central theme of this work is to integrate many different kinds of operating and assessment models in a single framework, an approach similar to the one needed by WG-EMM. It was agreed that this work may provide some useful tools in the future.

2.13 Dr Constable described work undertaken at the Australian Antarctic Division to assist the workshop in initiating discussions on modelling different components of the Antarctic marine ecosystem. This work formed the basis of WG-EMM-04/24 as well as a number of working papers provided to WG-EMM to help initiate discussions.

Invited experts

2.14 Dr Constable welcomed Dr Fulton to the workshop and invited her to present illustrations of her use of models in CSIRO in evaluating management strategies for the marine environment. The following paragraphs summarise her presentation.

Management strategy evaluation (MSE)

2.15 The MSE approach is made up of a model of the biophysical system (or operating model); submodels of each of the important anthropogenic exploitation or impact activities; submodels for any monitoring activities; and submodels of the decisions process associated with management of each sector. The combined dynamics of these models are used to evaluate how the potential real system might respond to natural events and any human activities. The MSE models must be capable of reproducing historical trends and responses to major events, but they must also be capable of projecting the outcomes of a range of management strategies that have not been used in the past. This is done by ensuring that the main features of the natural system, including uncertainty, are captured in the model, as well as by realistic depiction of sector responses to management strategies. MSE is particularly useful for: (i) determining effective monitoring schemes; (ii) identifying management procedures robust to sampling and model uncertainty; (iii) finding effective compromises between different sectors (or interests) within the system; and (iv) identifying unanticipated problems, issues or dynamics.

2.16 MSE is a tool that has been used at the Australian CSIRO Marine Research (CMR) for nearly 20 years (e.g. Sainsbury, 1988). Over the last six years the approach has been extended from single and multispecies applications to ecosystem-level, multiple-use management MSE. The two marine ecosystem models currently used in this role by CMR are Atlantis and InVitro. Atlantis has been used to consider the effects of model complexity on model performance, and, in MSE, to test potential ecological indicators of the ecosystem effects of fishing (Fulton et al., in press). InVitro is currently being used as the basis of MSE for a range of multiple-use management procedures for the northwest shelf of Australia (Fulton et al., in prep.).

Atlantis

2.17 The Atlantis framework was developed from the 'Bay Model 2' ecosystem model (Fulton et al., 2004). It is a deterministic model that tracks the nutrient (nitrogen and silica) flow through the main biological groups (vertebrate and invertebrate) found in temperate marine ecosystems and three detritus groups (labile detritus, refractory detritus and carrion). The invertebrate and primary producer groups are simulated using aggregate biomass pools, while the vertebrates are represented using age-structured models. The primary processes considered in Atlantis are consumption, production, waste production, migration, predation, recruitment, habitat dependency, and natural and fishing mortality.

2.18 Atlantis is spatially resolved, with a polygonal geometry that matches the major geographical features of the simulated marine system (Figure 1). The size of each polygon reflects the extent of spatial homogeneity in the physical variables represented in the model (depth, seabed type (reef or flat), canyon coverage, porosity, bottom stress, erosion rate, salinity, light and temperature). Atlantis is also vertically structured. For the simulations of this study, there is one sediment layer and up to five water column layers within each box (Figure 1). The biological components mentioned above are replicated in each layer of each box, with movement among boxes and layers dealt with explicitly (for the migration of higher trophic levels), or by a simple transport model (for advective transfer).

2.19 The harvesting submodel in Atlantis allows for multiple fleets, each with differing characteristics (gear selectivity, habitat association, target, by-product and by-catch groups, effort dynamics and management structures). While not as sophisticated as fleet dynamic models that model the behaviour of individual vessels (e.g. Little et al., 2004), Atlantis does represent the dynamics of aggregate fleets and allows for behavioural responses to effects such as effort displacement due to the depletion of local stocks or the creation of marine protected areas.

2.20 The sampling model generates data with realistic levels of measurement uncertainty (bias and variance) based on the outputs from the operating model, given specifications for the precision of the data and how they are collected temporally and spatially. For example, fisheries-dependent data are aggregated spatially and temporally (e.g. total catch over the entire area per quarter), whereas fisheries-independent data (such as surveys or diet composition) are only available infrequently (annually to once every decade) from ‘snap shots’ taken at certain ‘sampling locations’ (Figure 1).

InVitro

2.21 The biophysical model that forms the operating model in InVitro reproduces the main physical and biological features of the natural marine ecosystem (e.g. bathymetry, currents, waves, seabed types, habitat-defining flora and fauna, and local and migratory populations of marine animals). The InVitro model also includes a representation of the impact of natural forces and activities by the various human sectors found on the northwest shelf of Australia (petroleum exploration and extraction, conservation, fisheries and coastal development). In the management submodel the relevant agencies observe the system produced by the biophysical model (imperfectly) and make decisions about the location and magnitude of the sector activities.

2.22 InVitro is a three-dimensional agent-based, or i-state-configuration, model (Caswell and John, 1992; DeAngelis and Gross, 1992). This form of model provides a convenient framework for dealing with many types of entities (e.g. individuals, populations and communities) – also known as agents. The behaviour of the various kinds of agents in the model can be either passive or on the basis of decision rules, depending on the form of the agent. A summary of the major agent types and the behaviours modelled for each type is given in Table 1. Mobile agents are represented as either individuals (turtles and fishers) or as aggregates (e.g. subpopulations of finfish, schools of sharks and prawn boils), while habitat-defining biological groups are all represented by more aggregate agents (e.g. entire seagrass beds and reefs). Functional and physical attributes are detailed for each of these agents and rules are specified for growth (at the appropriate scale), as well as for passive and active movement. This intertwining of classical age-structured population and typical agent-based models into hybrid form allows for an efficient representation of all critical spatial and interaction scales.

2.23 The environment of an agent is based on the bathymetry, currents, temperature, light intensity, chemical concentrations, habitat type and resident communities. The environmental attributes are updated so that active agents can evaluate their surroundings and take the appropriate (temporal and spatial) responses. A scheduler (which functions in much the same way as a multi-tasking operating system – assigning priorities to agents and splitting available time to give the illusion of concurrency) handles the timing of the agents' activities (and any interactions among the agents). This allows each agent to work at the time step best suited to its activities while ensuring temporal consistency (no agent may re-live the same instant), maintaining synchronicity (preventing the 'subjective' time of an agent straying far from that of its neighbours), and avoiding any potential for systematic advantage of a particular agent (or agent type) due to internal ordering of processes.

Model development

2.24 Ecosystem model development is an iterative, but largely two-stage process. Firstly the ecosystem must be scoped. The following list of checkpoints gives a good sense of the critical processes, components and scales in marine ecosystems:

- oceanography and climate;
- biogeochemistry;
- biogeography;
- biological components (dominant, keystone, vulnerable groups, age or size structuring required);
- links (trophic and otherwise, weights, multiple pathways);
- ecological processes;
- anthropogenic pressures and activities.

2.25 Once a conceptual model of the ecosystem has been sketched out (via multiple classification of the components and processes to allow for discernment of natural groupings), then the most critical step of model development commences – determination of the spatial, temporal and biological scales. Based on previous experience in a number of ecosystem modelling exercises around the world, it is likely that models incorporating mixed scales (with detail focused where it is needed rather than being applied homogeneously throughout the model) will prove to be the most effective.

DESIRABLE ATTRIBUTES OF ECOSYSTEM MODELS

Attributes of models in the literature

3.1 Dr Hill presented WG-EMM-04/67. This paper reviewed approaches to modelling ecosystems in the CCAMLR region with the aim of identifying issues and approaches of relevance to the development of models for evaluating approaches to the management of the krill fishery.

3.2 Models of krill population dynamics have generally addressed the causes of interannual variability in abundance in the Scotia Sea and around South Georgia. Both changes in large-scale distribution and local production seem to play a role. The krill yield model, which is used to set catch limits, uses a Monte Carlo approach to simulate fished krill populations. Parameter values for each year, including recruitment are independently drawn from statistical distributions but there is evidence of autocorrelation in krill recruitment.

3.3 There are various putative effects of environmental variables on aspects of krill biology, including recruitment dynamics and mortality. Most are modelled as simple correlations. A more complex model suggests that hatching of krill embryos on the continental shelf is limited by depth and presence of warm water (Hofmann and Hüsrevoğlu, 2003). Passive drift on ocean currents might be important in determining the large-scale distribution of krill, though active swimming could influence local distribution.

3.4 Early predator–prey models of the Southern Ocean were largely developed in response to the proposition that total krill consumption was reduced with the depletion of the baleen whale stocks. Laws (1977) estimated that this released a krill surplus of 147 million tonnes. The models of May et al. (1979) and others considered a multispecies system with exploitation of both krill and whales. They assumed that prey abundance was driven by predation and that competition and prey consumption were linearly proportional to predator abundance. Among the results of these models were illustrations of multispecies modelling issues.

3.5 Murphy (1995) developed a spatially resolved model of predator and prey dynamics in which krill recruitment was decoupled from predator abundance. The model showed the potential influence on predator dynamics of overlapping foraging ranges and krill concentration. It also illustrated the importance to land-based predators of the retention of krill around islands.

3.6 Butterworth and Thomson (1995) and Thomson et al. (2000) attempted to construct realistic models of the response of the best-studied predators to krill availability. These included non-linear performance responses to prey abundance. The models considered whether krill catch limits could be set on the basis of a target predator population size. There were biases in results due to parameter estimates or model structure. The workshop considered that such models were not sufficient to determine the level of krill escapement required to meet the conservation requirement for predators because they do not represent the overall krill requirement of all predators.

3.7 The models of Mangel and Switzer (1998) and Alonzo et al. (2003a, 2003b) considered the potential influence of behaviour on the dynamics of populations of krill and their predators. These models suggested that krill behaviour can amplify negative effects of krill harvesting on penguins. The authors suggested that predator behaviour might be used to indicate ecosystem status.

3.8 Models of krill fisheries were constructed by Mangel (1988) and Butterworth (1988a) to investigate the relationship between krill abundance and CPUE from the former Soviet and Japanese krill fisheries respectively. These incorporated the hierarchical structure of krill aggregations as patches within patches as described by Murphy et al. (1988). Marín and Delgado (2001) represented the fishery using a spatial automata model implemented in a GIS.

3.9 The earliest attempt to quantify biomass flow through a simplified food web was made by Everson (1977). Many of the pathways which could not be quantified remain data poor. Croxall et al. (1984) used detailed consideration of energy requirements to model prey consumption by predators. Three detailed ecosystem models have been constructed by Green (1975), Doi (1979) and Bredesen (2003), the latter using ECOSIM software. These models are limited by the availability of data. However they highlight the importance of pathways that do not involve krill or well-studied consumers. They also highlight the need for improved data on energy transfer and assimilation rates.

3.10 Constable (2001) presented a model to integrate ecosystem effects through summing biomass production in predator species arising from consumption of harvested species. This could be summed across predators to give an index of ecosystem status, which could be used to set ecosystem reference points. It could also be summed across prey species within predators to set reference points for individual predator populations.

3.11 Early models of long-term dynamics assumed the system was at equilibrium before harvesting. However, the past status of the ecosystem is likely to be impossible to establish. Also, the assumption of equilibrium in the past or the future might be unrealistic.

3.12 Krill is clearly of central importance, but the food web has pathways that do not include krill.

3.13 There is a need to improve the data available on important trophic interactions. Also, the question of how to manage fisheries when some parts of the ecosystem are difficult to observe needs to be addressed. Other important questions to consider are how to represent important environmental effects in models of the ecosystem, and how to integrate different models when they may give output at different scales.

3.14 Dr Hill requested workshop members to supply details of any relevant literature that was currently missing from the review. Dr Shust suggested the volume on krill distribution and oceanography (Maslennikov, 2003).

3.15 Dr Shust suggested that the estimation of unexploited krill biomass remains a problem. Dr V. Sushin (Russia) commented that there may be other ways to manage the ecosystem than through managing the krill fishery.

General attributes of models for evaluation of management procedures

3.16 Dr Constable presented discussion points on the general attributes of models for evaluating management procedures. This presentation was based primarily on Part II of WG-EMM-04/24. He noted that operating models are not intended to capture all of the dynamics of the physical and biological systems but should capture the important properties of the system as they relate to the effects of fishing and the possible monitoring programs (ecology, physical environment, fishery) that can be employed. The important properties to consider and discuss in more detail in WG-EMM-04/24 are:

- (i) the potentially important direct and indirect effects of fishing, thereby defining the characteristics of the ecosystem that may need to be measured in the simulations, whether or not they can be measured in the field;
- (ii) the types of field observations and monitoring programs that could be employed;
- (iii) the biological scales (taxonomic grouping and population subdivision into life stages – which may not be the same for each taxonomic group) required to promulgate the important interactions between species and to provide for monitoring;
- (iv) the spatial scales of interactions, taking account of differences in interactions between different types of locations as well as the potential for biogeographic differences, thereby influencing the degree to which space will need to be explicitly accommodated in the modelling framework and whether spatial units need to be uniform geographic units or may be implied by being represented as compartments accommodating different spatial areas and extents;
- (v) the temporal scales of interactions, taking account of differences in important interactions over time and the duration of different events, such as reproduction or other life stage characteristics, thereby influencing the duration of the time steps necessary to be accommodated;
- (vi) the degree to which interactions (cause and effect) are approximated or explicitly modelled, which may be influenced by the types of measurements able to be achieved in a monitoring program;
- (vii) the degree to which processes peripheral to the central processes concerned with the effects of fishing are simulated;
- (viii) the manner in which the boundaries of the model system are simulated, recognising that the system is unlikely to be a closed system and that processes occurring outside of the model system might impact on the function of that system.

3.17 The workshop agreed that these attributes are important to consider during the workshop and in the implementation of models for use by WG-EMM.

CONCEPTUAL REPRESENTATION OF ECOSYSTEM MODELS

General approach

4.1 As indicated in Item 2, Dr Constable had undertaken an exercise with scientists in the Australian Antarctic Division to develop conceptual models of various components of the Antarctic marine ecosystem. He introduced this item by summarising Part III of WG-EMM-04/24. The major points were:

- (i) the aim of developing conceptual models is to provide a flexible framework for considering how each taxon might be influenced by the rest of the ecosystem, thereby providing the means to explicitly decide how best that taxon should be represented in the model to evaluate krill management procedures;
- (ii) some taxa will need to be represented in some detail in order to simulate field monitoring and the local-scale effects of fishing;
- (iii) other taxa might be simulated in a very general way in order to save simulation time while ensuring that ecosystem responses are realistic;
- (iv) the approach is intended to provide a means for explicitly determining how to take account of structural uncertainties given the paucity of data on many aspects of the ecosystem. The approach is also designed to allow an assessment of the sensitivity of model outcomes to assumptions about the relationships between taxa.

4.2 Figure 9 in WG-EMM-04/24 illustrated the components/functions of a single element in a food-web model discussed in that paper. An element was defined as the lowest, indivisible quantity in the food-web model and had the following attributes:

- (i) taxon – the group to which the element belongs, which could be a population, species, guild, ecological group, sex or some other category;
- (ii) stage – the life stage of the element, whether it be age, life stage or some other subdivision of the taxon needed to provide for distinguishing ecological characteristics (below) from other stages;
- (iii) units – the type of units used to measure/monitor the quantity of the element, such as number, biomass, area or some other measure;
- (iv) location – if needed, the spatial compartment or cell in which the element resides;
- (v) depth – if needed, the depth stratum in which the element resides.

4.3 The state of an element is largely governed by its magnitude (abundance) but some knowledge of its age may be important if the proportion of animals of a certain life stage advancing to another life stage is not constant and governed by the present age structure.

4.4 The workshop noted that the conceptual models will require consideration of the characteristics of elements, even though each characteristic may not be explicitly incorporated as separate parts of a model.

4.5 In the first instance, the workshop agreed to undertake the following work in developing conceptual representations of key components:

(i) develop pictorial representation, as appropriate, of key population processes, primary locations of individuals relative to features in the physical environment and spatial foraging patterns;

(ii) identify key parameters and processes that will need to be considered in the representation of each element in the ecosystem model, including population dynamics, foraging behaviours and spatial and temporal distributions;

(iii) undertake initial consideration of:

(a) the interactions between taxa and between taxa and the environment;

(b) the representation of space, time and depth in ecosystem models;

(c) consideration of the requirements for modelling field observations, which will be undertaken in the evaluation process.

4.6 The workshop noted that the major considerations for the development of operating models are with respect to

- physical environment
- primary production
- pelagic herbivores and invertebrate carnivores
- target species
- mesopelagic species
- marine mammals and birds.

4.7 Other taxa may need to be considered in future, such as demersal and bathypelagic species, including *Dissostichus* spp., *Macrourus* spp., skates and rays. It was noted that the current framework was sufficient for initiating work on evaluating approaches to krill management.

4.8 The remainder of this section sets out the results of discussions on conceptual representation of these components.

4.9 The Antarctic marine ecosystem considered at the workshop is primarily that ecosystem south of the Sub-Antarctic Front (SAF), including most of the Polar Frontal Zone (PFZ) and the ocean south of that zone, which comprises the west–east flow of the Antarctic Circumpolar Current (ACC) and the east–west flow of the Antarctic coastal current. This is primarily contained within the CCAMLR Convention Area, although some features of the

PFZ occur to the north of the CCAMLR Convention Area (Figures 2 and 3). The workshop noted that the boundaries of the ACC described by Orsi et al. (1995) are also important features to consider. In that respect, the subtropical front, which is to the north of the primary area of interest, was also considered important for flying birds.

4.10 The other main feature of the Antarctic marine ecosystem is the annual progression and retreat of the pack-ice zone (Figure 4). In this respect, the MIZ at the edge of the pack-ice as well as the role of pack-ice to predators needing haul out locations and as a substratum for productivity need to be considered.

4.11 A view of the biological productivity of the Southern Ocean can be viewed using SeaWifs data (Figure 5).

4.12 The main biotic components considered by the workshop were primary production, pelagic herbivores and invertebrate carnivores, target species (*Euphausia superba* and *Champsocephalus gunnari*), mesopelagic species (myctophid fish and squid) and widely distributed and migratory species, the marine mammals and birds (Table 2).

Physical system

4.13 The workshop considered those elements of the physical environment that it noted were of potential importance in the operation of the Southern Ocean marine ecosystem and that would also be of considerable utility in a coupled ecosystem model. The workshop considered these various elements from a number of perspectives.

4.14 Firstly, it considered a range of environmental factors each with a set of properties and each with a set of motivating forces; secondly, it considered a set of dynamic processes and how these structure the environment; thirdly, it considered seasonality and how this affects a number of the environmental factors; and finally it considered the natural spatial properties of the ecosystem. The results of these deliberations are contained in Tables 3 to 6. The workshop agreed that considerably greater detail could be included, but it recognised that, for a first attempt, the identified elements were sufficient to scope the modelling process.

4.15 The workshop noted that, conceptually, the physical environment provides four main ecological functions in the Antarctic marine ecosystem:

(i) a substratum for production, with the attendant physical conditions in space, depth and time;

(ii) stratification of the physical environment into natural units, including oceanic zones, depth zones, bathymetric features and ice;

(iii) substratum for transport between areas and depths;

(iv) sources of mortality, such as extreme atmospheric conditions.

4.16 At each stage of the process, the workshop identified which of these ecological functions and processes was affected; examples of potential functional impact are identified in square brackets ([ ]) in Tables 3 and 4.

4.17 The workshop considered physical factors in different seasons (Table 5). It recognised that the division of the calendar year into seasons depended on latitude. Initially it decided to focus on two seasons, winter and summer.

4.18 The workshop also recognised that the Southern Ocean had a number of natural spatial divisions (Table 6).

4.19 The workshop attempted to develop a conceptual model of the environment and how the various factors and processes interacted. This is illustrated in Figure 6.

4.20 The workshop recognised that there were a number of areas where environmental models would be of considerable utility in a coupled ecosystem model. These included:

(i) Delineating two-dimensional areas and three-dimensional polygons of spatial operation; these would potentially delineate a framework of habitats for use elsewhere in the ecosystem framework. The workshop recognised that direct coupling of a physical general circulation model may not be necessary, so long as inputs and outputs could be defined at appropriate spatial and temporal scales. These outputs would need to encompass the ecosystem functions described in paragraph 4.15.

(ii) The delineated habitats and processes should relate to the intended biological complexity of the model.

(iii) There could be utility in considering separate frameworks for each of continental, island and low-latitude situations.

Primary production

4.21 As part of its deliberations the workshop considered primary production, recognising that there was only general (and not specific) expertise within the group. Some consideration of primary production is given in WG-EMM-04/24. It noted that the formation of particulate matter for secondary producers could arise from primary production, particulates in the microbial loop as well as particulate detritus (Figure 7). The workshop also considered the factors that might influence primary production discussed in that paper (Figure 8, Table 7). It noted that remotely sensed ocean colour data, such as from SeaWiFS or MODIS, had the potential to help partition the Southern Ocean for the purposes of building an ecosystem model coupled with a physical oceanographic model. An example of summer Chl-*a* distribution from SeaWiFS is shown in Figure 5.

4.22 The workshop noted that future work will be needed in developing models of primary production, including reviews of the forcing functions provided in WG-EMM-04/24 as well as alternative formulations available in other models. The workshop recognised that, at some future point, it would also need to consider more detailed primary production models that included successional elements and seasonal elements.

Invertebrate herbivores and carnivores

4.23 Five taxonomic groups were considered as important pelagic herbivores and carnivores: salps, copepods, mysids, amphipods and euphausiids (other than *E. superba*).

4.24 Salps are open-water pelagic filter feeders and include several species, the most important of which is *Salpa thompsoni*. Copepods include approximately 60 species, of which 10 to 15 are common. Mysids include three common epibenthic species associated with continental shelves, shelf breaks and canyons. Hyperiid amphipods include approximately six common species, the most important of which may be *Themisto gaudichaudii*. Important euphausiids other than *E. superba* include *E. crystallorophias* and *Thysanoessa macrura*.

4.25 Attributes that were considered to be important with regard to the functioning of the pelagic ecosystem included spatial distribution, diet, generation time and depth distribution.

4.26 With regard to spatial distribution, it was recognised that distinct zooplankton communities were difficult to identify in the Southern Ocean, that there was a general decline in the number of species and their abundance progressing from north to south. Nevertheless, three non-exclusive species groupings were recognised: namely oceanic, island shelf and high-latitude shelf groups with large overlaps between them. Species indicative of the ocean group include salps; species indicative of the island shelf group include mysids; and species indicative of the high-latitude shelf group include *E. crystallorophias*.

4.27 With regard to diet, salps were considered to be primarily herbivores. Copepods, depending on species, were considered to include herbivores, carnivores and omnivores. Mysids and amphipods were considered to be carnivores. Euphausiids were considered to be omnivores.

4.28 With regard to generation time, salps and copepods were considered to be capable of responding the fastest to favourable conditions with generation times of 0.5 to 1 year. Mysids were considered to have a generation time in the order of 2 years; amphipods 1 to 2 years and euphausiids 2 years.

4.29 With regard to depth distribution, three depth zones were defined: the epipelagic from 0 to 400 m depth, the mesopelagic greater than 400 m depth, and the epibenthic within 50 m of the bottom in water depths of 100 to 400 m. During the summer months all taxa were considered to occupy primarily the epipelagic zone, with the exception of mysids, which occupy the epibenthic zone. Little is known of the winter-time depth distribution of these zooplankton.

4.30 The above attributes are summarised in Table 8.

Target species

4.31 The workshop considered WG-EMM-04/24, 04/50 and 04/59 for its deliberations to define elements of target species to be used in ecosystem models for testing approaches to krill management. Discussions concentrated on two species, the icefish (*C. gunnari*) and krill (*E. superba*). It considered that *Dissostichus* species might be incorporated in the modelling framework in the future but these species were not considered further at this workshop.

Icefish

4.32 The properties of *C. gunnari* for inclusion in the general structure of the Antarctic ecosystem model are summarised in Table 9.

4.33 *C. gunnari* is one of the key components in the sub-Antarctic marine ecosystem in the Scotia Sea and northern Kerguelen Plateau areas. *C. gunnari* has a high biomass within its distribution range, although this can vary widely between locations and over time. The workshop noted that the species has a disjunct distribution within the sub-Antarctic region; a population in the South Atlantic region around South Georgia and Shag Rocks, South Orkney and South Shetland Islands and the tip of the Antarctic Peninsula (Figure 9); and populations on the northern part of the Kerguelen Plateau around Kerguelen and Heard Islands.

4.34 Within its distribution range *C. gunnari* is restricted to shelves around islands. Subpopulations in each major distribution area show distinct biological properties, e.g. maximum size, growth, fecundity, spawning season and fluctuations in abundance. Abundance is highly variable at any location, and fluctuations are not synchronised between areas. The variability in abundance in this species appears to derive both from large variations in recruitment strength as well as changes in abundance of adult fish between years. The documented high degree of variability in year-class strength in all populations is presumably driven by environmental factors. These may include:

- poor feeding conditions leading to a low proportion of mature fish reaching spawning condition, e.g. in the South Georgia area;

- low hatching rate of eggs due to sub-optimal temperatures or predation;

- low larval survival due to inadequate food supply, advection by currents from nursery grounds, or predation.

Although the processes behind this are not well understood, the workshop felt it necessary that variability in recruitment should be included in the modelling framework.

4.35 *C. gunnari* could be modelled as length- and age-structured populations, the methods of which are well described in the literature. While there is sufficient information to develop length-structured dynamic models that could be overlayed on bathymetric features, the workshop indicated that this species could be modelled as three life stages – early life-history stages, juveniles and adults (Figure 10).

4.36 It was recognised that icefish is a component of two different prey environments:

- In the South Atlantic area, the principal food item is *E. superba*. Larval as well as juvenile and adult icefish feed on various stages of krill from furcilia larvae to adult individuals. During times when krill is scarce, all stages of *C. gunnari* can switch prey to *T. macrura* or amphipods and mysids.

- On the Kerguelen Plateau, where *E. superba* does not exist, the principal diet component is *E. vallentini* with *T. gaudichaudii* being a secondary component.

4.37 In the Atlantic sector predators include other fish species, albatross in certain years and penguins. Fur seals increase the proportion of *C. gunnari* in their diet in those years when krill is scarce. In the Kerguelen Plateau area, predation appears to be less intense.

4.38 Since the late 1990s, fisheries have resumed for this species at South Georgia and Heard Island. It has been suggested that the nature of the ecosystem may have changed since the period of intensive fishing in such a way as to reduce the carrying capacity of *C. gunnari*. Whether this phenomenon is a result of unsustainable fishing in the past or of environmental change or other ecosystem change has not been established. A decline in the *C. gunnari* fishery at Kerguelen during the last 10 years has been attributed to a southward shift of the Polar Front (WG-EMM-04/59).

4.39 Regular surveys of *C. gunnari* around South Georgia suggest a highly heterogeneous distribution, which may be important to include in models.

4.40 The workshop considered that in each geographic location *C. gunnari* should be considered as at least three elements (larvae, juveniles and adults). It was also considered that it may be worth considering eggs as an additional element if there was reason to believe that predation on eggs is an important factor to consider.

Krill

4.41 The properties of *E. superba* for inclusion in the general structure of the Antarctic ecosystem model are summarised in Table 10.

4.42 The workshop noted that, although krill has a circumpolar distribution, the highest concentrations of the species and the broadest latitudinal distribution range are found in the Southwest Atlantic (Figures 11 and 12). Two different views were expressed on the distribution of krill size groups/developmental stages (the juvenile and spawning adult component):

(i) Existing concepts of krill distribution on the onshore–offshore separation of juveniles, the breeding stock and larvae were generalised as a conceptual life-history model in WG-EMM-04/50. The model attempted to take into account the observed relationships between properties of Antarctic krill and its biotic and abiotic environment, focusing on the effect of environmental forces such as sea-ice properties and gyre systems (Figures 13 and 14). The workshop recognised that there is some debate as to whether the South Georgia region should be regarded as an area where successful spawning of krill does not occur and the degree to which the source of recruitment is from outside South Georgia.

(ii) An alternative view was also presented for the South Orkney Islands and considered (Figure 15).

4.43 For the purposes of the model, the workshop agreed that krill could be modelled as four life stages – eggs, larvae, juveniles, adults – because of their spatial separation and that the fishery targets primarily adult krill. The life-history strategy of krill places the developing embryos and larvae in locations distinct from the adult population which avoids competition for food, but also prevents predation on larval krill by adults.

4.44 Two alternative conceptual horizontal distributions were discussed:

(i) The first alternative described krill distribution as a coherent flow across large scales including some high-density retention areas where local production was important.

(ii) The second alternative described krill distribution as a set of discrete populations restricted to the major gyre systems of the Southern Ocean (WG-EMM-04/50).

4.45 The workshop discussed alternative hypotheses regarding seasonality in the horizontal movement of krill in the Southwest Atlantic; the workshop concluded that an operating model of the krill-centric ecosystem could be useful to explore the possible alternatives:

(i) The first hypothesis suggests that krill are advected from west to east with the flow of the ACC during the summer. Further, that transport of krill slows (or ceases) as the sea surface freezes during the early winter. Krill are then distributed within 50 m of the underside of the ice where they utilise ice algae as a food source and experience reduced predation. When the ice retreats the following spring, krill are again exposed to advection by the ACC.

(ii) An alternative hypothesis would be that over shelf areas with little sea-ice cover, krill move to the bottom and reside there during the winter months.

4.46 Additional to the two-dimensional dispersion of krill, plausible ecosystem models must also account for the diel vertical migration (DVM) pattern. This DVM has a seasonal and latitudinal component which is probably linked to the prevailing light regime (evolutionary), but may also reflect a response to predators (avoidance behaviour).

4.47 DVM behaviour of *E. superba* during the summer appears to vary with latitude. In the northern part of their distribution (South Georgia) krill migrate between 0 and 150 m. Further south krill appear to migrate less, and in the southern part of their distribution (Ross Sea, Weddell Sea) krill do not appear to migrate at all. It is hypothesised that the tendency to migrate vertically is related to summertime changes in daylight (greatest at lower latitudes, least at high latitudes). A general picture of DVM behaviour during the winter is less obvious. During the winter months krill trawlers set their nets deeper at South Georgia and krill have been observed in swarms close to the bottom, although it is not known how typical this behaviour may be. Diel variation in krill catches during a recent wintertime research cruise to the Weddell Sea suggests vertical migration between 0 and at least 200 m.

4.48 Interannual abundance and recruitment vary substantially. The population is driven by reproductive output and larval survival over winter. The important key variable is sea-ice, which is probably an indicator for food resources in winter (ice-algal) and spring (ice-edge bloom).

4.49 Adult krill are viewed as indiscriminate feeders on suspended matter in the pelagic zone, consuming autotrophs, small heterotrophs and detrital material, and because of their aggregating nature, they can have the effect of locally clearing particulate material from the euphotic zone. The critical feeding periods for krill larvae are in the late summer through until spring whereas for adults it is in spring through to late summer. This further avoids competition for food resources between the life-history stages.

4.50 The workshop noted that sufficient data are available to characterise the population to implement the conceptual model summarised in Tables 3 and 4. This includes the life cycle, the interaction between ice and oceanographic features and the different life stages, as well as important components in demography and food-web linkages.

4.51 The hierarchical structure of krill aggregations is understood to consist of individuals within swarms within patches within concentrations. This structure will influence the interactions between krill, their predators and the fishery (see also paragraph 4.94).

Mesopelagic species

Mesopelagic fish

4.52 The workshop had WG-EMM-04/24 and 04/58 on which to base considerations of how to structure mesopelagic fish in an operating model for the Antarctic ecosystem.

4.53 For the purposes of the operating model the workshop considered that mesopelagic fish could be divided into four elements based on:

- the distributions of taxa between those associated with the PFZ and those distributed from the PFZ to the south;
- the differences between distributions on the shelves of islands and the Antarctic continent and those associated with high-productivity frontal features in offshore waters.

A summary of the rationale for the division is provided in Table 11. The properties of each element are provided in Tables 12(a) to 12(c).

4.54 This categorisation was considered to be appropriate given the information and expertise available to the workshop. It may be that future consideration may elaborate on this categorisation in terms of taxon included (e.g. species), distribution, size classes, sexual maturity, or other considerations. The workshop suggested that this task (reviewing this categorisation) could usefully be referred to WG-FSA.

Questions for further consideration

4.55 Should we include benthic fish, e.g. notothenids and *Dissostichus* spp. as a separate component in the model?

4.56 The extent to which predators based on the Antarctic Continent, e.g. breeding birds and seals tend to consume squid, notothenioid fish and krill over or near the continental shelf (WG-EMM-04/59).

Squid

4.57 The workshop had WG-EMM-04/24 and 04/28 on which to base considerations of how to include squid in an operating model for the Antarctic ecosystem.

4.58 For the purposes of the operating model the workshop considered that squid could be divided into five elements based on:

1. Onychoteuthid squid – juveniles
2. Onychoteuthid squid – adults
3. Ommastrephid squid – juveniles
4. Ommastrephid squid – adults
5. Small to medium nektonic squid.

The properties of each element are provided in Tables 13(a) to 13(c).

4.59 In the case of both onychoteuthid and ommastrephid squid, the workshop considered that it was necessary to have juvenile and adult elements, given the size differences, the spatial separation and the different prey and predators of each of the life-history stages.

4.60 In the case of the ommastrephid squid it was noted that the spawning grounds and distribution of juveniles from the dominant species in the Southwest Atlantic are on the Patagonian shelf, outside the CCAMLR Convention Area. Consideration will need to be given to how this spatial separation is modelled. It was also noted that there was research suggesting that some species of onychoteuthid squid may have a two-year life cycle, rather than an annual cycle.

4.61 The workshop noted that there is generally thought to be a high degree of cannibalism in squid, although there is little data available to determine the extent. The workshop suggested that it would be important to include predation functions that allow the implications of different assumptions about cannibalism to be explored.

4.62 The workshop also noted that the larger species of squid, such as *Mesonychoteuthis hamiltoni*, may represent a functional equivalent to large pelagic vertebrate predators in temperate and tropical systems, such as the Scombridae. The workshop considered that it would be important to explore the implications of assuming different functional roles for such squid in trophic pathways.

4.63 While the above categorisation of squid was considered to be appropriate given the information and expertise available to the workshop, further review of the roles of psychroteuthid, galiteuthid and cranchid squid would be appropriate. The role of epibenthic cephalopods might also warrant consideration.

Marine mammals and birds

4.64 Marine mammals and birds potentially forage widely in the Southern Ocean. This large group of animals was divided into two broad categories associated with the degree of distributional constraint imposed by breeding:

(i) those that have a part of their life cycle in which they are constrained to be central-place foragers (i.e. they have a requirement to breed on land where the dependent offspring remains until independence; one or both parents make repeated foraging trips from that point to provision the offspring), e.g. Antarctic fur seals, penguins and flying birds;

(ii) those that have pelagic distribution (i.e. cetaceans) or come on land or ice to pup, such as phocid seals.

4.65 The life-history characteristics of these two groups also reflect the extent to which species are income breeders, those species that acquire the resources required to provision offspring during the offspring rearing period (e.g. Antarctic fur seal), or capital breeders, those species for which the resources required to provision offspring are acquired prior to offspring birth (e.g. Southern elephant seal).

4.66 The workshop considered WG-EMM-04/22 (shags), 04/24 (general and migratory species), 04/53 (Adélie penguins) and 04/65 (marine mammals) to help describe the elements of these taxa.

4.67 The workshop concentrated on:

(i) identifying the important elements/components of each of the major groups;

(ii) developing visual representations of the conceptual models of the dynamics of each group, including the functions that might cause transition from one life stage to another and the locations of the main foraging areas relative to the main oceanographic and topographic features of the Southern Ocean. Examples of these are given in Figures 16 to 20;

(iii) developing the framework for considering the estimation of parameters and functions required in population transition matrices and in the spatial and temporal foraging activities of the predators;

(iv) identifying future work to validate the conceptual models and for obtaining appropriate parameters.

4.68 These were considered for the following species/taxa:

1. Central-place foragers:

   (i) Adélie, chinstrap, gentoo, macaroni, emperor and king penguins
   (ii) Antarctic fur seal
   (iii) black-browed, grey-headed, wandering and light-mantled sooty albatrosses
   (iv) giant petrels
   (v) large petrels (white-chinned, cape, snow, Antarctic, Antarctic fulmar etc.)
   (vi) small petrels (prions, diving petrels, storm petrels)
   (vii) skuas, gulls, terns, shags.

2. Non-central-place foragers:

   (i) baleen whales
   (ii) toothed whales (sperm whale and small cetaceans)
   (iii) killer whale
   (iv) pack-ice seals (crabeater, Ross and leopard seals)
   (v) Weddell seal
   (vi) southern elephant seal.

Life-history characteristic and demography

Birds

4.69 The workshop noted that the conceptual model provided in WG-EMM-04/53 provided the basis for describing transitions between the different elements in a generalised life cycle of a bird. The generalised model is shown in Figure 21. Further consideration may be needed for some birds as to whether pre-breeders might become non-breeders (either in good or poor condition) as a result of having a different size, foraging behaviours or factors influencing survivorship.

Penguins

4.70 Adélie, chinstrap, gentoo, macaroni, emperor and king penguins were considered by the workshop to have a period during breeding when they are central-place foragers (Figure 22). Some pre-breeders and non-breeders may also be central-place foragers for a period. This is because they can be found in colonies along with the breeders, however, the costs/constraints are unlikely to be equivalent to those of breeding birds (WG-EMM-04/53). The demography of these populations could be summarised in a manner shown in Figure 23. The workshop considered that these attributes may need to be further refined for Adélie penguins in areas other than Béchervaise Island and for other penguins.

4.71 For Adélie penguins, the workshop reviewed the conceptual model in WG-EMM-04/53 and developed some options for the various functions that might influence the dynamics of Adélie penguin populations. To that end, the transition matrix in Table 14 provided the basis for these discussions.

4.72 Points for consideration in respect of the transition matrix for Adélie penguin are:

(i) survival in first winter is low:

   (a) where $S_{1,t}$ = f(FA, biomass of population and other competitors, condition, predation), where FA is food availability;

   (b) the relationship between $S_{1,t}$ and FA is sigmoidal and with biomass of the population and competitors is a sigmoidal decay;

(ii) survival up to breeding, which may be over a period of three to five winters, has an expectation of an increased survivorship compared to the first year;

(iii) transition from pre-breeder to breeder is governed by the condition after winter and FA;

(iv) transition from non-breeder to breeder is likely to be high because few birds are non-breeders for two consecutive years;

(v) winter survival of breeders is likely to be higher than that of fledglings;

(vi) summer survival of the breeders is influenced by leopard seal predation, energetic costs and other factors, with the breeders expected to have a lower survivorship than non-breeders;

(vii) breeding success is influenced by age and experience of the breeders (step function), FA (increasing sigmoidal), predation by skuas (exponential decrease) and weather (step function).

4.73 A number of potential functions were also considered by the workshop concerning the impacts of various factors on survivorship and reproductive success. These included those related to:

(i) fledgling survival in the first winter; these functions may be related to:

(a) condition at fledging (possibly a skewed distribution)
(b) food availability (possibly a positive sigmoidal function)
(c) predation (possibly a negative sigmoidal function);

(ii) ice extent and density (may increase food availability, alternatively it may reduce foraging habitat, therefore associated functions may take various forms).

Flying birds

4.74 Similar principles and processes will affect the transition matrices of the different groups of flying birds. Additional factors of particular (or potential) relevance to the group might include effects of incidental mortality (both within and outside the Convention Area), and availability of supplementary food through waste and/or discards from the fisheries.

4.75 The workshop noted that the following factors might influence different life stages of flying birds, including:

(i) effects on chick survivorship include disease in the sub-Antarctic, exposure, provisioning, scavengers, other predators and, primarily, starvation;

(ii) fledglings will be influenced by food supply, which could result in mortality from starvation;

(iii) immatures and adults at sea will be influenced by predation, as well as anthropogenic effects from longlining (especially large species and white-chinned petrels) and pollutants, but scavengers will also benefit from discards and waste.

4.76 Following the example given in Table 14, a matrix of taxonomic categories and their potential states was developed to provide a basis for developing appropriate transition matrices for these taxa (Table 15).

Marine mammals

4.77 Seals have a similar process of transition between states to that depicted in Figure 22, however, they differ from birds in respect of sexual size dimorphism and the relative contribution of the different sexes to the costs of offspring rearing. In the case of Antarctic fur seals, there is a similar constraint of central-place foraging for breeding females, however, in the case of phocid seals and cetaceans these particular constraints will not apply.

4.78 Following the example given in Table 14, a matrix of taxonomic categories and their potential states was developed to provide a basis for developing appropriate transition matrices for these taxa (Table 15).

Trophic dynamics

4.79 Representation of trophic dynamics is required for all the relevant species/species-groups and will include characterisation of:

(i) diet
(ii) distribution (horizontal and vertical as appropriate).

Both of these may vary by time of year and region.

Diet

4.80 Table 16 provides an example of various potential levels of detail required to characterise the main prey types in the diet of predators. Table 17 provides a qualitative illustration of how diet categories might be allocated at the level of predator species and other species groups. Consideration of diet, including relating it to the desired levels of temporal and spatial subdivision, is an important element of future work.

Spatial scales of distribution and foraging movements by depth

4.81 A generalised model of the vertical foraging distribution of air-breathing predators was developed for several taxonomic groups (Figure 24). In general, those predators found in the upper 100 m are predominantly krill-feeding species, whilst those that consume fish and squid are predominantly found at greater depth.

4.82 With respect to the conceptual diving model in Figure 24 the penguins, seals (other than southern elephant seal) and flying birds, i.e. groups 1–7, can be characterised as surface-dwelling species that make excursions from the surface to feed. Southern elephant seals and odontocete whales can be characterised as species that live and feed at depths of 500–1 500 m and make excursions to the surface to breathe. The arrows on the figure indicate the direction of movement from the primary location in which the foragers spend the greater part of their time budget.

4.83 The horizontal distribution of the species/taxa considered at different life-history stages is considered for breeding and non-breeding periods in Tables 18 and 19. The workshop also considered the importance of boundary conditions for any operational model to allow for the dispersal and seasonal migrations of marine mammals and birds that takes account of the time spent inside/outside the Convention Area.

Fisheries

4.84 The workshop considered WG-EMM-04/24 and 04/51 during its deliberations to define elements of fisheries that can be used in ecosystem models for testing approaches for ecosystem management. The discussion focused on two fisheries: the krill fishery and the icefish fishery.

Krill fishery

4.85 The nature of the krill fishery was considered based on the behaviour of the Japanese krill fishery reported in WG-EMM-04/51. The workshop recognised that the kind of information provided, such as the decision-making processes made by the skipper according to changing circumstances during the course of the fishing season (Table 20), is an important factor when considering the development of a model of the krill fishery.

4.86 In Area 48, fishing areas usually occur adjacent to the islands. Some of these fishing areas are further divided into local fishing grounds (Figure 25).

4.87 Throughout the fishing season, there is a preference by the Japanese fleet for using fishing areas closer to the ice edge rather than using any of the other areas available (Figure 26). The fishing patterns were further characterised according to seasonal succession of physical and biological properties at the fishing grounds (Figure 27).

4.88 Individual vessels moved frequently between local fishing grounds, and sometimes moved to different fishing areas seeking suitable aggregations (e.g. density, structure, krill condition etc.) to fish.

4.89 Properties of the krill fishery were considered by the workshop; firstly, by identifying possible options for taxon, stage and units as outlined in WG-EMM-04/24. Following this exercise, the options for basic model elements, the types of decision made, and the different factors affecting fishery behaviour, were discussed.

4.90 Although krill fishing vessels tend to operate in national fleets, the behaviour of each vessel is strongly influenced by individual skippers. The 'taxon' should be defined at the level of individual vessels to reflect these behavioural differences between vessels. This is particularly appropriate as there are few vessels (5–10) and some of the observation data are available at vessel level. These properties are detailed in Table 21.

4.91 The fishing patterns examined by the workshop were derived from data from the Japanese krill fishery. Given the fact that there may be national/fleet differences in preference for fishing area as well as strategies for fishing operations (Figure 28) (CCAMLR-XXI), the workshop agreed that such differences may need to be included in any model of the krill fishery. The workshop recommended that this type of analysis should be undertaken for krill fisheries of other nations.

4.92 Overall, the workshop recognised that the fishing patterns considered were related to fishing under current fishery levels and regulations. Recalling that the aim of plausible models of the Antarctic marine ecosystem would be to evaluate krill management scenarios, the workshop thought it essential that any model should be capable of testing management scenarios by reproducing fisheries behaviour under various regulation scenarios, including catch limits set at smaller spatial and/or temporal scales than those defined by the conservation measures presently in force.

4.93 In order to achieve this, the fishery model may need to simulate individual vessels fishing under different operational strategies and requirements (see paragraphs 4.22 and 4.51). Therefore, the operational model may need to:

(i) generate regional concentrations of krill that would constitute the 'local fishing grounds' including:

    (a) concentrations corresponding to 'known' fishing grounds
    (b) concentrations in currently unfished areas;

(ii) characterise the types and distributions of aggregations within local fishing grounds well enough to allow discrimination between the results of the different fishing strategies of the different fleets;

(iii) model the effect of fishing on aggregations (e.g. reduced abundance and size of aggregations resulting from removals or dispersion; reforming of swarms after catching/dispersal, flux etc.) in order to:

    (a) be able to handle the effects of different fleet fishing strategies
    (b) describe the effects on predator feeding success;

(iv) model factors which affect catch quality such as phytoplankton and salp distributions at the level of resolution that allows the model to represent vessel behaviour in response to these properties.

4.94 With respect to 4.93(iii), the workshop noted that some work has captured the properties of krill aggregations to examine catch per unit effort in krill fisheries (Butterworth, 1988b; Mangel, 1988; Kasatkina and Latogursky, 1990; Kasatkina and Ivanova, 2003; Litvinov et al., 2002; Litvinov et al., 2003, WG-EMM-03/31), as discussed in WG-EMM-04/24 and 04/67. A number of studies have also been carried out on the effects of predation on krill concentrations, including WG-EMM-96/20, WG-EMM-96/67, Boyd et al. (1997), WG-EMM-97/28, 97/64, Murphy et al. (1988), Miller and Hampton (1989) and Alonzo et al. (2003a, 2003b). The Workshop agreed that it may be possible to examine the effects of fishing activities on predator foraging by integrating these approaches. It also recognised that further work was needed on these aspects and noted also that issues of model detail, complexity and scale would need to be considered when incorporating these interactions into the overall ecosystem model.

Icefish fishery

4.95 The Data Manager described general properties of this fishery drawing on his knowledge of CCAMLR data holdings.

4.96 It was recognised that fishing in Area 48 is currently permitted only around South Georgia and that the size of the current fishing fleet is small (<5 vessels in any season). However, in the past, the icefish fishery was larger (>80 000 tonnes), and was also present around the South Orkney Islands and the South Shetland Islands. The use of bottom trawling is prohibited in this fishery and icefish are largely taken by pelagic trawl (Figure 29).

4.97 Icefish fisheries have also operated in Area 58 and the fishing in Division 58.5.2 is regulated under Conservation Measure 42-02.

4.98 One of the significant differences between icefish fisheries and krill fisheries is that icefish fisheries are assessed annually by WG-FSA and strict management regulations are in place. In Subarea 48.3, these regulations include a temporal spatial closure during the spawning season, a move-on rule to minimise the catch of fish <240 mm in length and catch limits for by-catch species (Conservation Measures 33-01 and 42-01).

4.99 Properties of the icefish fishery were considered following the procedure for the krill fishery. These properties are detailed in Table 22.

4.100 In order to be able to model the icefish fishery operations, the operational model may need to be able to:

(i) generate realistic age structure and distribution in relation to the bottom topography;

(ii) model the dynamics of by-catch species.

PLAUSIBLE SCENARIOS FOR THE ANTARCTIC MARINE ECOSYSTEM

5.1 The workshop considered the types of scenarios that need to be considered in evaluating the robustness of krill management procedures to structural uncertainties of the model. This discussion focused on two broad topics. The first was concerned with the plausibility of the model and the second with questions of ecosystem dynamics that could be explored with the model.

5.2 With regard to model plausibility, several questions were raised. These include:

(i) How sensitive is the model to alternate hypotheses regarding critical processes?

(ii) What data and/or research are required to distinguish between important alternatives?

(iii) How closely should model ecosystem behaviour match observations?

(iv) What level of detail will be required to make a plausible model?

5.3 Examples of the above questions include consideration of:

(i) various hypotheses on interactions between species (e.g. whales and seals)
(ii) various hypotheses on trophic pathways
(iii) use of different life-history parameter values (e.g. demographies)
(iv) use of alternate component formulations.

5.4 With regard to questions of ecosystem dynamics, it was recognised that it was important to limit the number of scenarios to be explored. The possible scenarios were organised into a series of topics. These include:

(i) Response of the model system to changes in environmental forcing factors. This would require a choice of forcing factors, the degree and direction of change. For example, the response of the model to gradual climatic change versus a more abrupt regime shift could be explored. More specific examples include system response to a change in formation of Antarctic bottom water or change in Antarctic surface circulation; rapid reduction of winter ice extent or large changes in primary production occurring over decadal time scales; enhanced ultraviolet radiation and its subsequent effect on epipelagic organisms such as krill larvae.

(ii) Sensitivity and dynamics of the model system to various starting conditions and/or artificial forcing functions. For example, different starting population sizes of baleen whales and fur seals, or an initial excess krill production could be explored. The effects of random noise or periodic cycles in forcing functions could be explored.

(iii) The effects on the model system of external processes and boundary conditions. Examples of this include processes affecting the population dynamics of whales, squid and birds outside the CCAMLR Convention Area. Another possible class of examples includes the invasion of temperate species due to ocean warming and/or changes in currents.

(iv) The required behaviour of the model system to achieve a specified state. For example, recovery of depleted whale or seal populations.

(v) Effects on the model system of developments in various fisheries. These might include expansion of the krill fishery, overfishing of toothfish, expanded harvest of icefish, as well as developments in fisheries external to CCAMLR.

(vi) Effects of system feedback on modelled populations. Examples include changes over time in life-history traits, genetic selection, spatial distribution and other density-dependent population effects.

5.5 After some discussion, the workshop concluded that the following scenarios should be accorded the highest priority:

(i) behaviour of the model system in response to artificial (i.e. known) forcing functions in order to better understand the properties of the model;

(ii) effects of alternative formulations of krill transport on ecosystem dynamics;

(iii) effects of climate change on primary production and/or ocean circulation.

5.6 The workshop also requested guidance from the Scientific Committee with regard to the priorities for exploring realistic scenarios and future work.

MODEL FORMULATION AND SPECIFICATION

6.1 The workshop discussed a number of items that relate to the formulation and specification of ecosystem models in general (paragraphs 6.2 to 6.4) and to Antarctic ecosystems in particular (paragraphs 6.5 to 6.25).

6.2 The workshop agreed that it would be desirable to develop an ecosystem model as a set of connected modules rather than a single, large piece of software. Individual modules might be used to model various oceanographic processes (e.g. separate modules for ocean currents and the seasonal development of sea-ice) and the population dynamics of individual taxonomic groups (e.g. separate modules for Antarctic krill and fur seals). The modular approach described here would facilitate:

(i) the development of population dynamics models that are consistent with the data and knowledge available for each taxonomic group (e.g. to simultaneously use an age-structured model for one group and a biomass-dynamics model for another group);

(ii) the construction and implementation of modules that describe processes differently (e.g. comparing foraging models that are based on functional relationships or individual decision making);

(iii) the construction and implementation of modules that describe alternative hypotheses (e.g. regional variations in krill biomass being determined by advection or local population dynamics);

(iv) the implementation, where appropriate and helpful, of existing models;

(v) the progress of model development regardless of whether modules describing the dynamics of all taxonomic groups or forcing mechanisms are complete.

6.3 Although a modular approach to model building has distinct advantages, the workshop recognised that such an approach would introduce specific technical issues that will need to be addressed. These issues include:

(i) the need to reconcile processes that are modelled on different scales using accepted ecosystem structuring rules like thermodynamic laws and particle-size distributions;

(ii) the need to manage overall model complexity by ensuring that individual modules are developed with reasonable intuition and a focus that relates to specific questions of interest;

(iii) the need to develop protocols, software, and database architectures that link and manage the flow of information among modules.

6.4 The workshop recognised that linking modules describing oceanographic process and population dynamics to observation models will also be necessary. These links can be developed by ensuring that various modules within the operating model describe variation in state variables that are typically (or might eventually be) observed in the field. For example,

(i) a module describing the dynamics of Antarctic krill should describe spatial variation in the distribution of swarms, concentrations etc. with sufficient detail to provide reasonable linkage to observation models describing hydroacoustic surveys and krill fisheries;

(ii) modules describing the dynamics of some predator populations should describe variation in reproductive performance with sufficient detail to link to observation models describing data collection under CEMP;

(iii) a module describing ocean currents might characterise variation in the contribution of different water masses to a region of particular interest and thereby link to observation models describing the results of an oceanographic survey within that region;

(iv) modules describing the dynamics of fish populations might describe variation in the size (or age) composition of the population and thereby link to observation models describing the size (or age) composition of trawl survey or fishery catches.

Modelling interactions between species

6.5 Ecosystem models typically describe interactions between species and taxonomic groups in the context of predator–prey and competitive interactions (although many other types of interactions are possible), and the manner in which such interactions are characterised typically has profound effects on the behaviour of, and predictions from, ecosystem models.

6.6 The workshop focused its discussion on predator–prey interactions, but recognised that competitive interactions should also be considered during future developments of Antarctic ecosystem models. In this regard, the workshop drew a distinction between competition that might occur within and among taxonomic groups and competition that might occur among krill predators and krill fisheries. The processes by which such competitive interactions might occur, if they occur at all, would potentially be different. In the first case, some animals might, for example, use aggressive behaviours to compete with other animals for food. In the second case, substantive localised removals of krill by a fishery might limit availability of food for predators. Developing appropriate models of competition will also be important for understanding the degree to which krill 'surpluses' caused by the removal of one predator can result in the expansion of another predator population.

6.7 The workshop summarised the predator–prey interactions described throughout Section 4 of this report by developing conceptual illustrations of various Antarctic food webs. These webs are presented in Figures 30 to 34. Each of the arrows illustrated in these figures represents a possible predator–prey interaction that might need to be modelled, and the workshop recognised that the interactions illustrated in these figures might increase or decrease after further review and consideration. The workshop further recognised that modelling all of the predator–prey interactions illustrated in these figures may not be necessary to describe how most energy flows through the food web. Care needs to be taken that the dynamics of any taxonomic group are not necessarily dominated by weak predator–prey links.

6.8 The easiest way to consider the trophic linkages is to subdivide them based on geographic location and central prey type. The workshop discriminated two major web-types based on geographical area: continental (including high-latitude seamounts) and island based (which includes the Scotia Sea). This split is also reflected in the respective taxonomic composition of these webs. The continental shelf webs are further subdivided into krill-centric and squid-centric subwebs. Similarly, the island-based webs are subdivided into krill-centric, squid-centric and fish-centric subwebs. The workshop was less confident in its ability to characterise the squid- and fish-centric subwebs than in its ability to characterise the krill-centric subwebs, and the group 'other fish' reflects a recognition that many predator groups probably consume a fish fauna that is less well described. Despite increased uncertainty regarding the structure of the squid- and fish-centric subwebs, it will be important to consider these alternative energy pathways because they are likely to have a marked effect on model predictions.

6.9 The age and size-dependent links included in the food webs illustrated in Figures 30 to 34 indicate two processes. The first is ontogenetic shifts in the spatial distributions of predator or prey. The second is when predators take only a certain size range of prey resulting in prey outside this range (either smaller or larger) being safe from that predator. If these food webs were redrawn with the life stages for each group explicitly represented, such age- and size-dependent links might be clearer.

6.10 Depth structuring is a potentially important aspect of the trophic links in Antarctic food webs that is not illustrated in Figures 30 to 34. The trophic structure shown in these figures has greater resolution at the surface and in mid-water than in deep water. This is not an issue if the focus of the study and the dynamics of the ecosystem do not change. However, predictions by models developed from the links illustrated in Figures 30 to 34 may be misleading if the research and management focus or system dynamics become dominated by processes that occur in deep water (e.g. demersal or benthic groups and processes). It would be worthwhile to consider whether any of the ecological, environmental, or fisheries scenarios identified in Section 5 of this report would be affected by this potential problem.

6.11 With respect to Figures 30 to 34, the workshop also noted that some food webs which are not presented in this report (e.g. entirely pelagic webs or webs associated with deep seamounts like those in the Ross and Weddell Seas which are dominated by toothfish, rajids and oceanic squids) may need to be developed to completely represent the full range of major food webs in the Antarctic.

6.12 The workshop considered two methods of modelling predator–prey interactions: functional response curves and individual foraging models. Functional response curves describe the relationship between prey abundance (or density) and the per capita consumption of that prey by a group of predators. Individual foraging models describe predator–prey relationships by modelling the decisions that predators and prey make in response to the abundance (or density) and distribution of each other and to variations in environmental conditions.

6.13 It was agreed that both methods of describing predator–prey interactions should be investigated and the workshop commented on each approach.

6.14 Two types of functional response curves might be useful for describing many predator–prey interactions in Antarctic ecosystems: Type II and Type III response curves. These two types of curves are illustrated in Figure 35. For those predators whose foraging is based on interactions with individual prey organisms (e.g. a killer whale that forages on a seal), Type II response curves might be appropriate. For those predators whose foraging is based on interactions with prey organisms that must be aggregated into some threshold density (e.g. a baleen whale that forages on krill), Type III curves might be appropriate. When considering Type III curves, the workshop recognised that prey abundance (or density) might need to be measured on different scales. For example, foraging by baleen whales might be influenced more by the density of swarms within an area of relatively high krill concentration than by the density of krill within a swarm, but this might be reversed for other predators.

6.15 The workshop noted that a single functional response curve might not be appropriate for any given species or taxonomic group. Functional responses might change over the course of a reproductive cycle, be dependent on an animal's condition, age, or sex, and vary in response to the predator's perceived risk of themselves becoming prey. Although such refinements to functional response models will complicate this approach to modelling predator–prey interactions, they may be more realistic.

6.16 Foraging models based on individual decision making have previously been developed for penguins and krill fisheries (Alonzo and Mangel, 2001; Alonzo et al., 2003a, 2003b;

Mangel and Switzer, 1998). The predictions from this work were reviewed in WG-EMM-04/67, and the workshop considered that such models might, after additional review and modification, be useful dynamic modules to include in operational models of Antarctic ecosystems.

6.17 The workshop noted that multiple cues can be used by predators to make individual foraging decisions. These cues are not necessarily related to the absolute abundance or density of prey and probably include, but are not likely limited to, habitat features (e.g. the shelf break), previous experience (e.g. travelling back to the last location where prey were successfully captured and eaten) and variation in the local retention of prey. It might be particularly important to recognise when foraging decisions are based on group dynamics (e.g. when animals adopt foraging strategies like their neighbours or when they cue on aggregations of other predators).

6.18 The workshop noted that foraging models based on individual decision making are often generated from data collected during foraging trips, and some care should be taken in making inferences from these data. Animals that forage in the Antarctic adopt a variety of foraging strategies. As a result of these strategies, foraging events might be uniformly or randomly distributed in space and time. Alternatively, foraging events might be aggregated in space and time, and such aggregation might occur over a range of scales (e.g. at both diurnal and annual scales). For example, diving behaviours might occur in bouts when animals are foraging on shoaling/swarming species, and a single foraging trip might include several periods with and without dive bouts. Inferences from data collected during foraging trips can be facilitated by considering the physiological and ecological context in which the data were collected (e.g. time-energy budgets can be useful for understanding the foraging behaviour of animals that are provisioning offspring).

6.19 Unfortunately, data on foraging behaviours are not available for many species in the Antarctic, and this lack of information will make it difficult to construct decision-based models. The workshop noted that it may be possible to alleviate this problem by looking for information on analogous species outside the Antarctic.

6.20 In concluding its discussion of predator–prey interactions, the workshop agreed that two items of future work would be useful. First, sensitivity analyses should be done to explore how predictions from Antarctic ecosystem models change in response to different assumptions about predator–prey interactions (e.g. assuming a Type II or Type III functional response or assuming different decision criteria in individual-based foraging models) and to different ways of modelling these interactions (i.e. using functional response curves or individual (group) based foraging models). Second, studies should be done to determine whether, and under what conditions, functional response curves can be satisfactory approximations of individual-based foraging models. Although the latter approach may be more realistic, the former approach is likely to be more efficient in a modelling context.

Modelling space

6.21 The workshop had considerable discussion regarding appropriate spatial resolution for operating models of Antarctic ecosystems. It was agreed that spatially explicit models would be appropriate in many circumstances. The workshop considered that, at a minimum, it would be useful to resolve differences between high-Antarctic and sub-Antarctic areas and between pelagic areas and areas on or near the continental shelf (e.g. Figures 30 to 34). It was noted, however, that substantially greater spatial resolution might be appropriate in many instances. Cases in which greater spatial resolution might be warranted are identified throughout section 4 of this report.

6.22 The workshop recognised that spatial resolution can vary among the modules that are developed as components of operating models of the Antarctic ecosystem (i.e. a fixed spatial resolution is not required by the envisioned approach). It was also recognised that having module-specific spatial resolution would further increase the need to address the issues identified in paragraph 6.3. The workshop noted that modules with varying spatial resolution have successfully been implemented in the Atlantis and InVitro models (see section 2).

6.23 The workshop also considered the degree to which depth should be resolved in operating models of Antarctic ecosystems. In contrast to the minimum horizontal resolution identified in paragraph 6.21, the workshop did not identify a minimum vertical resolution. This was difficult because there is considerable overlap in the depths used by animals that spend time in Antarctic waters. Nevertheless, resolving processes across depths may be critical for describing the spatial overlap of predators and prey. Information on depth distributions is provided throughout section 4 of this report.

Modelling time

6.24 The workshop considered that the temporal resolution of the operating model should, at a minimum, discriminate summer from winter. Such discrimination is sensible for a variety of reasons, including the resolution of breeding/spawning seasons and seasons in which most observational data are collected. Finer temporal resolution might, however, be required to adequately describe the dynamics of various oceanographic processes and taxonomic groups. Thus, temporal resolution can also be module-specific, and the workshop reiterated the points that were raised in paragraph 6.22.

Peripheral processes and boundary conditions

6.25 The workshop discussed peripheral processes and boundary conditions in the context of animals that move in and out of the spatial arena described by operating models. How such processes and conditions are modelled must be case-specific because operating models of Antarctic ecosystems might cover a range of spatial arenas, potentially varying on scales from the entire CCAMLR Convention Area down to SSMUs. Nevertheless, the workshop noted that the key to dealing with such processes and conditions is to recognise:

(i) how much time animals spend outside a model's spatial arena (e.g. see Tables 18 and 19);

(ii) what processes (e.g. recruitment) occur when animals are outside the spatial arena;

(iii) how both physical and biological conditions outside the spatial arena might contribute to variation in processes that ultimately occur inside the arena.

Dealing with peripheral processes and boundary conditions will require future work.

FUTURE WORK

Further development of plausible models

7.1 The workshop agreed that its work has achieved a foundation for conceptual models of the physical environment and taxa of the Southern Ocean ecosystem and how to place these into a modelling framework. It recognised that future work will entail validating the work presented here and further developing conceptual models as indicated in sections 4, 5 and 6. As such, the workshop recommended continued refinement of these conceptual models and encouraged their implementation in the modelling framework.

7.2 An important task is to collate the appropriate parameter values for implementing functions and model components derived from these conceptual models. In this respect, the workshop noted that reviews of available information would be useful and that a common database of available parameters could be developed to facilitate a coordinated use of such parameters and information.

7.3 The workshop also recognised that there was a lack of expertise and time at the meeting to fully develop the components concerned with fish, squid and fisheries. The workshop therefore requested WG-FSA to review the details provided and develop component details for toothfish and demersal species. These include:

(i) check the existing details on icefish life history as listed in paragraphs 4.32 to 4.40 providing changes where appropriate;

(ii) check that the existing details listed in paragraphs 4.95 to 4.100 have correctly captured the dynamics of the icefish fishery;

(iii) check the existing details on mesopelagic fish and squid life history as listed in paragraphs 4.52 to 4.63, providing changes where appropriate;

(iv) develop similar profiles (tables, figures and text) for *D. eleginoides* and *D. mawsoni* as target species (i.e. as for species in paragraphs 4.52 to 4.63);

(v) develop similar profiles (tables, figures and text) for the *D. eleginoides* and *D. mawsoni* fisheries (i.e. as for fisheries in paragraphs 4.84 to 4.100);

(vi) develop a new key component of the ecosystem which includes the other demersal fish species (e.g. macrourids, rajids, other nototheniids etc.);

(vii) check food webs for interactions including toothfish, icefish, other demersal fish, myctophids and *Pleuragramma antarcticum*.

7.4 The workshop recommended that the Working Group seek guidance from the Scientific Committee with regard to the priorities for exploring realistic scenarios and future work (paragraph 5.6).

Further development of a modelling framework

7.5 The workshop agreed that the it has provided a suitable framework to continue the development of plausible ecosystem models for testing approaches to krill management. It recognised that the development of complex models will take some time to complete.

7.6 With respect to next year's workshop on evaluating candidate management procedures, the workshop noted that initial exploration of management options could be achieved using spatially structured krill population models that allow exploration of the interaction between

- the krill population
- spatial catch limits and the fishery
- krill predators
- transport of krill.

This may be feasible next year with the further development of existing models and new basic models taking account of outcomes of this workshop.

7.7 The workshop noted that further development of the framework and the implementation of one or more ecosystem models will require coordinated work. It recommended that the Working Group consider establishing a steering committee to coordinate this work. Such a committee will need to consider, among other things,

(i) framework
 data, parameters, database
 code, platforms, components, protocols
 model architecture, modularity, flexibility
 the process of validation of the models to ensure appropriate application;

(ii) collaboration
 timetable
 authorship and ownership issues
 components;

(iii) role of the Secretariat;

(iv) coordination with the conveners of next year's workshop.

7.8 The workshop noted that a number of research groups of CCAMLR Members are developing ecosystem models for the Southern Ocean. It recommended that the Working Group establish the steering committee as quickly as possible in order to have the work coordinated among groups as far as is practicable as well as taking advantage of the momentum generated from this workshop.

7.9 It was noted that the development of models for next year's workshop is a different task from the longer-term work. Nevertheless, it was recommended that the conveners of next year's workshop coordinate the preparatory work for the workshop with the coordinator of the steering committee. This will help provide the opportunity for modelling work for next year to be developed in such a way that it might contribute to the longer-term modelling work.

ADOPTION OF THE REPORT

8.1 The report, with figures, tables and attachments, was adopted.

CLOSE OF THE WORKSHOP

9.1 The Convener of WG-EMM, Dr Hewitt, thanked Dr Constable for his hard work in convening the workshop and his guidance throughout in ensuring its success.

9.2 Dr Constable thanked all the participants, rapporteurs and members of the workshop steering committee for their contributions to the workshop. He also thanked Dr Fulton, the invited expert, for her valuable contribution and for her guidance during the discussions. Dr Constable thanked the Secretariat for their support both intersessionally and at the workshop, and Prof. S. Focardi (Italy) and his team for hosting the workshop.

9.3 The workshop closed on 16 July 2004.

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Table 1: InVitro: Summary of the major agent types and behaviours that may be modelled in the InVitro Northwest Shelf (Australia) management strategy evaluation model. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

Agent type	Description	Instances (species or groups)	Behaviours and characteristics
Population	Age-structured sub-populations of mobile species	Finfish (small and large lutjanids, lethrinids, nemipterids and saurids)	Ageing through age classes, growth, feeding, mortality, movement to preferable habitat, spawning and recruitment to age class zero.
Animal	Individuals or schools of mobile species	Prawns (banana and king prawns), turtles, sharks, dugongs, seabirds	Ageing, growth, mortality, feeding, evasion, movement to preferable habitat, spawning and recruitment of new individuals or schools.
Larva	Larval (or infant) and juvenile stages of other agent types	Finfish (small and large lutjanids, lethrinids, nemipterids and saurids)	Advection, settling, growth, mortality, consumption, movement to recruiting sites, recruitment.
Polyorganisms	Large patches (or mean field representations) of high turnover rate species or groups	Oyster leases, ponyfish schools	Movement, feeding, mortality, reproduction, advective and dispersive growth.
Benthic	Mosaic of habitat-defining patches	Macrophytes (seagrass and macroalgae), reefs (sponge and coral), mangroves	Mortality, depth and sediment-type dependent reproduction and patch growth (may be resource limited), vertical growth into larger size/age classes.
Vessel	Ore carriers	Cargo vessels	Route following, cargo content, fuel load, state (port operations, steaming, dithering).
Boat	Fishing vessels	Trawlers, trappers, fishing survey boats	Cargo content, fuel load, state (port operations, steaming, dithering), licences, past fishing sites, effort allocation, gear types.
Recfisher	Recreational fisher area of influence	Recreational fishers	Access points, fishing pressure (dependent on human population size and distance to port).
Catastrophe	Infrequent, large-scale events	Cyclones, spills, dredging	Damage (potentially fatal) to all appropriate agents in the path of impact (dependent on intensity and type of event).
Environment	Physical environmental characteristics	Temperature, light, depth, seabed type, currents	Current flow, advection, diffusion, absorption, erosion.
Tracker	Monitoring or sampling bodies	Buoy, monitoring sites, random samples of catch	Drift (if appropriate), monitoring.
Fixtures	Fixed locations	Ports, rigs, pipelines	Production, capacity, population size.
Fisheries management authority	Fisheries assessment and management body	FMA	Stock assessment, decision procedures, management rules, enforcement, monitoring.

(continued)

Table 1 (continued)

Agent type	Description	Instances (species or groups)	Behaviours and characteristics
Environmental protection agency	Water quality and contamination assessment and management body	EPA	Monitoring, decision procedures, management rules, enforcement.
Port Authority	Port capacity and vessel traffic assessment and management body	Department of Transport Department of Primary Industries	Monitoring, decision procedures, management rules, enforcement.

Table 2: List of taxa considered at the workshop (* represents suitable future work). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

General grouping	Taxa		
Primary production	Phytoplankton	Microbial loop	
Pelagic herbivores and invertebrate carnivores	Microzooplankton * Copepods Euphausids (excluding *E. superba*)	Mysids Amphipods	Salps Jellyfish *
Target species	*Euphausia superba* *Champsocephalus gunnari*	*Dissostichus eleginoides* * *Dissostichus mawsoni* *	
Mesopelagic species	*Pleuragramma antarcticum* Myctophid species	Squid – ommostrephids Squid – onychoteuthids	Squid – other *
Demersal fish species *	Skates * Other demersal species	Rays *	*Macrourus* spp. *
Penguins	Adélie Chinstrap	Macaroni Gentoo	Emperor King
Seals	Antarctic fur Southern elephant	Crabeater Ross	Leopard Weddell
Baleen whales	Minke Humpback Other baleen whales – high latitudes	Southern right Fin Other baleen whales – sub-Antarctic	
Toothed whales	Sperm	Orca	Other small cetaceans
Large flying birds	Wandering albatross Light-mantled sooty albatross	Grey-headed albatross Black-browed albatross	Giant petrel
Small flying birds	White-chinned petrel Cape petrel Antarctic petrel	Snow petrel Diving petrel Storm petrel	Antarctic fulmar Antarctic prion Other prions
Other birds	Skuas, gulls etc.	Shags	

Table 3: Factors in the physical environment that are of potential importance in the operation of the Southern Ocean marine ecosystem and that would also be of considerable utility in a coupled ecosystem model; each factor has a set of properties and a set of motivating forces. Roman numerals in square brackets ([ ]) refer to the subparagraphs in paragraph 4.15 outlining the main ecological functions of the physical environment. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

Factor	Properties	Motivating forces
Sea-ice [i, ii, iv]	Ice texture, e.g. brine channels Ice cover – aerial density Ice extent Ice duration	Temperature Salinity Wind stress Ocean currents Local geography
Ocean currents [i, ii, iii]	Magnitude (volume flow) Magnitude (spatial dimensions) Direction Eddies (variance) Fronts (dimensions)	Temperature Salinity Bathymetry Wind stress
Light [i]	Magnitude Duration – daily/seasonal Wavelength	Latitude Water column depth Ice cover Cloud cover Season
Nutrients [i]	Micronutrients (Fe etc.) Macronutrients (N, P etc.) Form (NH_4, NO_3 etc.)	Distance from land Biological cycling
Bathymetry [ii]	Depth – pressure	

Table 4: Processes in the physical environment that are of potential importance in the operation of the Southern Ocean marine ecosystem and that would also be of considerable utility in a coupled ecosystem model; each process has a set of motivating forces. Roman numerals in square brackets ([ ]) refer to the subparagraphs in paragraph 4.15 outlining the main ecological functions of the physical environment. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

Processes	Motivating forces
Vertical exchange in water column [ii, iii]	Upwelling/down-welling/mixing
Atmospheric deposition [i]	Wind Precipitation
Stratification [ii]	Wind Ocean currents
Ekman transport [ii]	Wind
Polynya formation [i, ii]	Upwelling Wind Ocean currents
Local processes [i, ii, iv]	Glacial rock flour Ice scour Land run off – rivers, nutrients, pollution
Nutrient depletion/enrichment [i]	Biological cycling Run off from predator breeding colonies
Climatic forcing [iv]	El Niño Southern Oscillation Antarctic Circumpolar Wave Drake Passage Oscillation Index
External boundaries [i, ii, iii, iv]	Land Water mass Atmosphere

Table 5: Potential variation in some physical factors between winter and summer seasons. Seasons may vary in time with latitude. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

Seasonality		
Winter months April–November		Summer months December–March
Low	Temperature	High
High	Ice cover	Low
Low intensity	Light	High intensity
Short day	Day length	Long day
Higher at surface	Salinity	Lower at surface
Magnitude/breadth/shifts	Ocean currents	Magnitude/breadth/shifts
Change in patterns (latitude)	Wind	Change in patterns (latitude)

Table 6: Natural spatial divisions in the Southern Ocean that may affect the operation of the Southern Ocean marine ecosystem. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

NATURAL SPATIAL DIVISIONS	
Latitude	High ←--→Low
Land	Continent vs Islands and peninsulas
Sea	Nearshore vs Shelf vs Slope vs High Sea vs Fronts Depth Bottom ←--→Surface
Ice cover	Land vs Ice shelf vs Permanent ice vs Seasonal ice vs MIZ vs Never freezes

Table 7: Factors related to primary productivity that are of potential importance in the operation of the Southern Ocean marine ecosystem and that would also be of considerable utility in a coupled ecosystem model; each factor has a set of properties and a set of motivating forces. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

Factor	Properties	Motivating forces	
Size fractionation	Species composition	Micronutrients (e.g. Fe)	Temperature
		Macronutrients (e.g. N, Si)	Salinity
		Distance from land	Light regime
		Water mass	Light wavelength
		Proximity to fronts	Ice cover
		Winds	Ice retreat
		Stratification	Grazers
Species distribution	Species composition	Micronutrients (e.g. Fe)	Temperature
		Macronutrients (e.g. N, Si)	Salinity
		Distance from land	Light regime
		Water mass	Light wavelength
		Proximity to fronts	Ice cover
		Winds	Ice retreat
		Stratification	Grazers

Table 8: Summary of attributes of the main pelagic invertebrate herbivores and carnivores in the Southern Ocean, excluding *Euphausia superba*. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

Taxa	Habitat	Diet	Generation time (years)	Summer depth zone
Salps	Oceanic	Herbivore	0.5–1	Epipelagic
Copepods	Oceanic	Herbivore Carnivore Omnivore	0.5–1	Epipelagic
Mysids	Island shelf	Carnivore	2	Epibenthic
Hyperiid amphipods	Oceanic, Island shelf	Carnivore	1–2	Epipelagic
Euphausiids				
e.g. *Thysanoessa macrura*	Oceanic	Omnivore	2	Epipelagic
Euphausia crystallorophias	High-latitude shelf	Omnivore	2	Epipelagic

Table 9: Properties of *Champsocephalus gunnari* for inclusion in the general structure of the Antarctic ecosystem model. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

Parameter		Stage		
		Larvae	Juveniles	Adults
Geographic distribution			South Georgia to Antarctic Peninsula, Kerguelen/Heard	South Georgia to Antarctic Peninsula, Kerguelen/Heard
Spatial distribution	Features of the physical environment that are important to this life stage		Pelagic in near-shore waters	Benthopelagic in shelf waters to about 350 m depth
	Factors/functions influencing spatial coverage, including temporal changes to distribution		Prey availability and oceanic variability likely to influence spatial coverage, but no relationships have yet been determined. Ontogenetic descent down slope influences temporal distribution.	Prey availability and oceanic variability likely to influence spatial coverage, but no relationships have yet been determined. Ontogenetic descent down slope influences temporal distribution.
	Depth		0–150 m	150–350 m
	Factors/functions influencing depth distribution, including temporal changes to distribution		Gradually spreads over inner plateau in pelagic zone and occupies lower position in water column.	Arrives at feeding grounds when about 2 years old. Diurnal vertical migrations from bottom during day into water column at night.
Age structure			0–2 years	2–5 years

(continued)

Table 9 (continued)

Parameter		Stage		
		Larvae	Juveniles	Adults
Condition	Size		<240 mm	240–>350 mm
	Reproduction		Immature	Mature
Input	Reproduction		-	Generally autumn/winter spawners but spawning season varies with locality. Estimated total fecundity 1 294–31 045.
	Mortality		Highly variable juvenile population, which is a result of variable spawning success and juvenile survival.	Mortality probably relatively low in 2 and 3 year olds, then rising abruptly in 4 year olds. Few fish remain after 5 years.
Output	Predators		Larval stages probably prey for a wide range of planktonic (e.g. Chaetognaths) and nektonic (e.g. fish) predators, but no direct data. Later stages same as for adults.	Fur seals, king penguins are main predators but rate varies between years, depending on abundance of icefish and/or of krill. Other fish, birds and mammals prey on icefish to some extent.
	Exploitation		By-catch of trawl fisheries but rate limited by conservation measures.	Target of trawl fisheries.
	Death (other sources of mortality)		-	Rapid disappearance of 4+ year olds not attributable to fishing or completely top predation.
Consumption	Classification, e.g. generalist or specialist feeders		Specialist feeder on aggregating zooplankton.	Specialist feeder on aggregating zooplankton.
	Food types		Crustaceans (in particular euphausiids and amphipods). *Euphausia superba* in Atlantic sector.	Crustaceans (in particular euphausiids and amphipods). *E. superba* in Atlantic sector.

Table 10: Properties of *Euphausia superba* for inclusion in the general structure of the Antarctic ecosystem model. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

			Stage			
			Eggs	Larvae	Juveniles/Immatures	Adults
Spatial distribution	Features of the physical environment that are important to this life stage	Intrusion of upper CDW Water depth Water temperature		Ice cover Intrusion of upper CDW Water temperature	Ice cover Water temperature Position of frontal systems	Circulation Water temperature Position of frontal systems
	Spatial extent of distribution	Position of frontal systems Water temperature		Position of frontal systems Water temperature	Position of frontal systems Water temperature	Position of frontal systems Water temperature
	Spatial area of distribution			Extent of water masses Sea-ice extent	Extent of water masses Sea-ice extent	Extent of water masses Sea-ice extent
	Factors/functions influencing spatial coverage, including temporal changes to distribution	Water mass intrusions Advection Displacement		Extent of water masses Sea-ice extent Water mass intrusions Advection Displacement	Extent of water masses Sea-ice extent Water mass intrusions Advection Displacement	Extent of water masses Sea-ice extent Water mass intrusions Advection Displacement
	Depth (if applicable)	0–1 500 m		<500 m	<500 m	<500 m
	Factors/functions influencing depth distribution, including temporal changes to distribution	Spawning locations Developmental descent		Spawning locations Developmental ascent	DVM with latitudinal and temporal changes (predator escapement – evolutionary or behavioural reaction) Ontogenetic migrations	DVM with latitudinal and temporal changes (predator escapement – evolutionary or behavioural reaction Ontogenetic migrations

(continued)

Table 10 (continued)

			Stage			
			Eggs	Larvae	Juveniles/Immatures	Adults
Condition	Size	Function or estimate of size for the stage (e.g. growth curve or set size)		Developmental pathway known, size at stage structure thought to be fixed (Ikeda, 1984). Effect of food supply and temperature (Ross et al., 1988; Yoshida et al., 2004).	Growth curves published (Ikeda, 1985; Hofmann and Lascara, 2000). Question of shrinkage. Age structure still problematic. Length/weight, seasonal differences (Siegel, 1992). Effect of food supply and temperature on growth.	Growth curves published (Rosenberg et al., 1985; Siegel, 1987; Hosie, 1988). Question of shrinkage (Ikeda and Dixon, 1982). Effect of food supply and temperature on growth.
	Reproduction	Function relating, as appropriate, food availability (carrying capacity), environmental conditions, abundance of conspecifics and other competitors				Female reproduction dependent on very high food intake, length of season and conditions in winter/spring.
	Health	Function relating, as appropriate, the effect of food consumption		After critical point larvae die.	Reduced food can lead to cessation of growth or shrinkage.	Reduced food can lead to cessation of growth or shrinkage.
	Waste	As appropriate, function defining the production of waste based on activity, consumption and environment		Excretion, defecation and moulting rates estimated (Quetin and Ross, 1991).	Excretion, defecation and moulting rates estimated (Ikeda and Thomas, 1987).	Excretion, defecation and moulting rates estimated (Ikeda and Mitchell, 1982; Clarke et al., 1988).

(continued)

Table 10 (continued)

			Stage			
			Eggs	Larvae	Juveniles/Immatures	Adults
Input	Reproduction	Function relating to reproductive condition, environment and abundance of breeding individuals, e.g. stock-recruitment relationship modified by condition, or fecundity modified by feeding condition.				See above
	Physical movement	Relative locations in space and rates of movement between locations, including movement over the course of a year.	Eggs spawned offshore	Larvae must move inshore as they metamorphose into juveniles.	Generally found inshore.	Distribution centred on shelf break, gravid females move offshore to spawn, all adults may move inshore in winter.
		Relative locations in depth and rates of movement between depths, including movement over the course of a year.	Eggs laid at surface, embryos sink	Early larvae swim upwards as they develop, later larvae stay in surface waters and probably under ice in winter.	Undergo DVM in summer.	Undergo DVM in summer. May vary between regions (daylight length?).

(continued)

Table 10 (continued)

			Stage			
			Eggs	Larvae	Juveniles/Immatures	Adults
Output	Predators	Identify predators, including, as appropriate, relative importance at different locations, depths and times.			Land-based predators restricted to foraging area, seabirds and pelagic predators less restricted in range.	Land-based predators restricted to foraging area, seabirds and pelagic predators less restricted in range.
	Exploitation	Identify, as appropriate, the degree of exploitation at different locations, depths and times and by which types of methods.				Along shelf break-slope, close to ice edge. In summer exploitation by midwater trawl at 20–80 m depth, in autumn 30–150 m depth and in winter ~400 m depth.
Consumption	Food types	Identify prey, including, as appropriate, relative importance at different locations, depths and times.		Phytoplankton, zooplankton and under ice microbial community. First feeding stage calyptopis, 30 days after spawning.	Most particles >5 µm in diameter in surface 200 m. In deeper water probably detrital food. Under-ice feeding in late winter.	Most particles >5 µm in diameter in surface 200 m. In deeper water probably detrital food. Under-ice feeding in late winter.
	Functional feeding relationships for different prey	Include, as appropriate, variations in the feeding relationships likely to be experienced in different locations, depths and/or times or influenced by environmental features (e.g. ice).			Maximum retention efficiency >30 µm. Functional response curves described for different food types and concentrations (Ross and Quetin, 2000).	Maximum retention efficiency >30 µm. Functional response curves described for different food types and concentrations (Quetin and Ross, 1985; Ross et al., 2000).

Table 11: Rationale and characterisation of elements for mesopelagic fish. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

Element	Description	Dominant species	Questions/Issues
Sub-Antarctic shelf	Restricted to insular shelves of sub-Antarctic islands.	*Champsocephalus gunnari*	May be equivalent to *C. gunnari* element. Question of whether it is important to consider taxa other than *C. gunnari*.
Sub-Antarctic mesopelagic	Broadly distributed in off-shelf pelagic environment north of the southern boundary of the ACC.	*Electrona carlsbergi* *Krefftichthys anderssoni*	Other species may be important depending on location. Is it necessary to include *Nototheniops larseni*?
Antarctic neritic	Restricted to insular shelves of the Antarctic continent.	*Pleuragramma antarcticum* *Chaenodraco wilsoni*	Suggested as functional alternative to icefish for Antarctic continental shelf. Question of whether other taxa need to be considered.
Antarctic mesopelagic	Broadly distributed in off-shelf pelagic environment south of the southern boundary of the ACC.	*Electrona antarctica* *Gymnoscopelus nicholsi*	

Table 12: Properties of pelagic fish for inclusion in the general structure of the Antarctic ecosystem model. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

(a) Sub-Antarctic mesopelagic fish (e.g. *Electrona carlsbergi*, *Krefftichthys anderssoni*).

Geographic distribution		Circumpolar
Spatial distribution	Features of the physical environment that are important to this life stage	Broadly distributed in off-shelf pelagic environment north of the southern boundary of the ACC.
	Factors/functions influencing spatial coverage, including temporal changes to distribution	Spatial, seasonal and depth distribution influenced by water temperature/water mass. Main feeding grounds in the Polar Front. Greatest abundances associated with Polar Front.
	Depth	50–200 m depth in areas south of 50°S depending on DVM. Progressively deeper to the north of the Polar Front (500–600 m) towards the STC (>1 000 m).
	Factors/functions influencing depth distribution, including temporal changes to distribution	Water temperature/water masses (i.e. position of the Polar Front). DVM: migrates from 80–140 m to the surface at 18:00h. Found at 200–250 m during the day.
Age structure		Unknown, <5–6 years maximum age
Condition	Size	70–100 mm maximum size, growth thought to be approximately 30 mm per year for first 2–3 years.
	Reproduction	Size at maturity ~75mm Age at maturity ~2–3 years Serial spawning in late winter/early spring or summer/autumn to the north of the Polar Front.
Input	Reproduction	Suggest lognormal distribution with potential for correlation with environment.
	Mortality	-
Output	Predators	Primary: king, royal/macaroni, rockhopper and gentoo penguins, Antarctic fur seals depending on geographic location, squid (?), *Dissostichus eleginoides*. Secondary: *C. gunnari* at Heard Island and other fish species (?).
	Exploitation	Historical commercial trawl fishery.
	Death (other sources of mortality)	Unknown
Consumption	Classification, e.g. generalist or specialist feeders	Generalist (?)
	Food types	Principal components copepods with smaller amounts of hyperiids, euphausiids, pteropods and ostracods. Two main feeding periods: an extended evening period and a shorter morning period.

(continued)

Table 12 (continued)

(b) Antarctic neritic fish (e.g. *Pleuragramma antarcticum*, *Chaenodraco wilsoni*)

Geographic distribution		Circumpolar (?)
Spatial distribution	Features of the physical environment that are important to this life stage	Restricted to insular shelves of the Antarctic continent. Suggest that *P. antarcticum* may represent a functional alternative to *C. gunnari* for Antarctic continental shelf. Question of whether other taxa need to be considered.
	Factors/functions influencing spatial coverage, including temporal changes to distribution	-
	Depth	100–500 m
	Factors/functions influencing depth distribution, including temporal changes to distribution	DVM: yes 100 (night) to 200 m (day)
Age structure	maximum of 10 years	Unknown
Condition	Size	Adult size = 120–250 mm
	Reproduction	Mature at 3–4 years Spawning period October–December
Input	Reproduction	Suggest lognormal distribution with potential for correlation with environment.
	Mortality	-
Output	Predators	*D. mawsoni*, other fish, seals (?)
	Exploitation	Historical trawl fishery for *C. wilsoni*.
	Death (other sources of mortality)	Unknown
Consumption	Classification, e.g. generalist or specialist feeders	Generalist zooplankton feeder (?)
	Food types	*E. superba* (?), other krill (?), copepods (?)

(continued)

Table 12 (continued)

(c) Antarctic mesopelagic fish (e.g. *Electrona antarctica*, *Gymnoscopelus nicholsi*).

Geographic distribution		Circumpolar
Spatial distribution	Features of the physical environment that are important to this life stage	Abundant south of the Polar Front to the shelf of the continental slope.
	Factors/functions influencing spatial coverage, including temporal changes to distribution	Concentrated along shelf and the Polar Front during spring–summer.
	Depth	Upper 250 m during spring and summer, 350–700 m during winter.
	Factors/functions influencing depth distribution, including temporal changes to distribution	Suggested that there is a seasonal pattern of: (i) concentration in surface 100–200 m at shelf break, or Polar Front during spring and summer; (ii) movement to deeper water (350–700 m) in winter. Suggested that the seasonal movement is in response to movement of invertebrate food sources.
Age structure	Maximum of 5–6 years	Unknown
Condition	Size	Size range of species (*E. antarctica, G. nicholsi*) 100–200 mm TL with *G. nicholsi* being at the upper end of the range. 15–51 g <5 years Growth rate 27–34 mm per year May be worth considering having two classes based on size and maturity.
	Reproduction	Winter spawners
Input	Reproduction	Suggest lognormal distribution with potential for correlation with environment.
	Mortality	-
Output	Predators	Primary: king penguin, Antarctic fur seals. Secondary: royal/macaroni and gentoo penguins, Antarctic fur seals, black-browed and grey-headed albatrosses, white-chinned and snow petrels, *D. eleginoides*, cormorants at Heard Island.
	Exploitation	Historical trawl fishery
	Death (other sources of mortality)	
Consumption	Classification, e.g. generalist or specialist feeders	Generalist
	Food types	Feeds on any abundant organisms, principally copepods and euphausiids, but also includes amphipods, pteropods, ostracods. Proportion of euphausiids increases in larger fish.

Table 13: Properties of the five elements of squid for inclusion in the general structure of the Antarctic ecosystem model. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

(a) Onychoteuthid squid

		Juveniles	Adults
Geographic distribution		Circumpolar in the sub-Antarctic and Antarctic.	Circumpolar in the sub-Antarctic and Antarctic.
Spatial distribution	Features of the physical environment that are important to this life stage	Shelves and slopes of landmasses in the sub-Antarctic and Antarctic.	Slopes of landmasses in the sub-Antarctic and Antarctic.
	Spatial extent or area of distribution	Shelf/slope (see above)	Slope (see above)
	Factors/functions influencing spatial coverage, including temporal changes to distribution	Prey availability and oceanic variability likely to influence spatial coverage, but no relationships have yet been determined. Ontogenetic descent down slope influences temporal distribution.	Prey availability and oceanic variability likely to influence spatial coverage, but no relationships have yet been determined. Ontogenetic descent down slope influences temporal distribution.
	Depth (if applicable)	0–1 000 m	400 – ≥ 2 000 m
	Factors/functions influencing depth distribution, including temporal changes to distribution	Undergoes ontogenetic descent down slope over time with increasing size/maturation. Diurnal vertical migrations have not been recorded. Clarify whether DVM occur in other species (e.g. Rodhouse and Clarke, 1986), and/or include as an alternative to no DVM.	Undergoes ontogenetic descent down slope over time with increasing size/maturation. Diurnal vertical migrations have not been recorded.
	Does pack-ice affect distribution?	Distribution includes pack-ice zone; relationship with pack-ice extent and retreat unknown.	Distribution includes pack-ice zone; relationship with pack-ice extent and retreat unknown.
Age structure (if applicable)		-	-
Units		Biomass	Biomass
Condition	Size	See WG-EMM-04/26, Figure 8	See WG-EMM-04/26, Figure 8
	Reproduction	-	-
	Health	-	-
	Waste	-	-

(continued)

Table 13(a) (continued)

		Juveniles	Adults
Input	Reproduction	-	Two spawning peaks per year (late summer and late winter). Estimated total fecundity (i.e. ovarian egg number estimates) for *Moroteuthis ingens*: 84 379–286 795.
	Physical movement	Ontogenetic descent down slope over course of life stage.	Ontogenetic descent down slope over course of life stage.
	Movement between life stages	All juveniles (minus those lost to predation, by-catch and natural mortality) move into adult life stage after 6–7 months (approximately 200 days).	100% natural mortality of all adults (minus those lost to predation and by-catch) after approximately 1 year. Possibility of two-year life-cycle for some species of Antarctic squid (see Ommastrephids below)
Output	Predators	Cephalopod and vertebrate predators foraging in epipelagic and upper mesopelagic in shelf/slope environments from the sub-Antarctic to the Antarctic.	Cephalopod and vertebrate predators foraging in the mesopelagic and bathypelagic in slope environments from the sub-Antarctic to the Antarctic.
	Exploitation	By-catch of trawl fisheries in shelf/slope environments.	By-catch of trawl fisheries in shelf/slope environments.
	Death (other sources of mortality)	-	-
Consumption	Classification, e.g. generalist or specialist feeders	Opportunistic, generalist predator.	Opportunistic, generalist predator.
	Food types	Crustaceans (in particular euphausiids, also amphipods and copepods), small cephalopods and juvenile fish. Important to consider potential for higher predation (via cannibalism) on second cohort by first cohort within a season and, in the case of a two-year life-cycle, one year class on the following year class.	Myctophids, other mesopelagic fish, e.g. *Bathylagus antarcticus*, cephalopods including juvenile onychoteuthids.

(continued)

Table 13(a) (continued)

		Juveniles	Adults
Consumption (continued)	Functional feeding relationships for different prey	Minimum prey size >10 mm; maximum prey size <200 mm. Will only take pelagic, mobile prey.	Minimum prey size >10 mm; maximum prey size = approx. size of the (mantle length? of) individual squid. Will only take pelagic, mobile prey.

(b) Ommastrephid squid

Geographic distribution			Circumpolar in the sub-Antarctic and Antarctic but not high Antarctic.
Spatial distribution	Features of the physical environment that are important to this life stage	Shelves	Shelves (for spawning) and slopes of landmasses and in the open ocean for feeding.
	Spatial extent or area of distribution	In the southwest Atlantic juvenile distribution is largely outside the area (Patagonian shelf). Distribution outside the southwest Atlantic not known/uncertain.	Large proportion of biomass associated with the Polar Front.
	Factors/functions influencing spatial coverage, including temporal changes to distribution	Spawning occurs on the (Patagonian) shelf where juveniles develop.	Feeding and spawning migrations influence spatial distribution. Aggregations often associated with oceanic frontal systems. Distribution varies significantly over time and space.
	Depth (if applicable)	0–200 m	0–≥ several hundred metres.
	Factors/functions influencing depth distribution, including temporal changes to distribution	DVM on shelf	Diurnal vertical migrations to approach surface during darkness.
	Does pack-ice affect distribution?	No, because juveniles occur elsewhere.	Not known to be distributed in the high Antarctic, pack-ice unlikely to affect distribution.
Age structure (if applicable)			-
Units		Biomass	Biomass

(continued)

Table 13(b) (continued)

		Juveniles	Adults
Condition	Size		See WG-EMM-04/26, Figure 9
	Reproduction	-	-
	Health	?	-
	Waste	?	-
Input	Reproduction	Spawns throughout the year, potential fecundity per individual female estimated at 115 000–560 000 (from ovarian egg number estimates).	Incoming juveniles, minus consumption.
	Physical movement	Juveniles passively migrate with current systems away from spawning grounds to feed.	Adult population actively migrates to spawning ground to spawn, which in the southwest Atlantic is the Patagonian shelf.
	Movement between life stages	Size-based progression between juvenile and adult.	Die/consumed
Output	Predators		Cephalopod and vertebrate predators foraging in epipelagic and upper mesopelagic in shelf/slope environments and in the open ocean. Total predation in the Scotia Sea estimated at 326 000–381 000 tonnes per year.
	Exploitation	-	By-catch of other squid jig fisheries around Falkland/Malvinas Islands and on Patagonian shelf, is occasionally a direct target for commercial jiggers in Subarea 48.3.
	Death (other sources of mortality)		100% natural mortality of remaining adult population after spawning.
Consumption	Classification, e.g. generalist or specialist feeders	Opportunistic, generalist predator.	Opportunistic, generalist predator.

(continued)

Table 13(b) (continued)

		Juveniles	Adults
Consumption (continued)	Food types	?? assume smaller zooplankton and larval fish, conspecifics.	Myctophids (particularly *Krefftichthys anderssoni*), cephalopods including cannibalism on conspecifics, crustaceans including *E. superba* and amphipod *T. gaudichaudii*.
	Functional feeding relationships for different prey	Will only take pelagic, mobile prey. An individual squid may take prey as large as itself while continuing to take smaller prey??	Will only take pelagic, mobile prey. An individual squid may take prey as large as itself while continuing to take smaller prey.

(c) Small to medium nektonic squid

Geographic distribution		Uninterrupted circumpolar distribution throughout the sub-Antarctic and Antarctic.
Spatial distribution	Features of the physical environment that are important to this life stage	Shelves and slopes of landmasses and in the open ocean from the sub-Antarctic to the high Antarctic. Ubiquitous distribution throughout.
	Spatial extent or area of distribution	See above
	Factors/functions influencing spatial coverage, including temporal changes to distribution	Until further data are available, the spatial coverage of this model group should remain static throughout the sub-Antarctic to the high Antarctic. (For species-specific differences see WG-EMM-04/26, Figure 8.)
	Depth (if applicable)	0 – ≥ 2 000 m
	Factors/functions influencing depth distribution, including temporal changes to distribution	Until further data are available, the depth distribution of this model group should remain static throughout the sub-Antarctic to the high Antarctic. (For species-specific differences see WG-EMM-04/26, Figure 8.)
	Does pack-ice affect distribution?	Distributed within pack-ice zone, pack-ice not known to affect distribution.
Age structure (if applicable)		-
Units		Biomass
Condition	Size	See WG-EMM-04/26, Figure 1
	Reproduction	-
	Health	-
	Waste	-
Input	Reproduction	Spawns throughout the year, on shelf breaks/slopes in the sub-Antarctic and high Antarctic and in the open ocean.
	Physical movement	-
	Movement between life stages	-

(continued)

Table 13(c) (continued)

Output	Predators	Important dietary component for many vertebrate predators in the southwest Atlantic; ≥ 3 squid species co-occur in the diets of 11 predators including penguins, albatrosses, seals, whales and fish. Also preyed on by other cephalopods.
	Exploitation	Occasional by-catch, discarded.
	Death (other sources of mortality)	100% natural mortality of remaining adult population after spawning.
Consumption	Classification, e.g. generalist or specialist feeders	Opportunistic, generalist predators.
	Food types	Small mesopelagic fish, small cephalopods, zooplankton including euphausiids, copepods and amphipod *T. gaudichaudii*.
	Functional feeding relationships for different prey	Will only take pelagic, mobile prey. An individual squid may take prey as large as itself while continuing to take smaller prey.

Table 14: Possible transition matrix for Adélie penguins. Numbers refer to functions and discussion in the text. (X represents a transition probability; Time represents the amount of time spent in the stage on the left; Function represents the ecological or physical function that results in the transition probability.) Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

	Fledgling	Pre-breeder (Itinerant)	Pre-breeder (Colony)	Non-breeder (Itinerant)	Non-breeder (Colony)	Breeder
Chick	X Time: Function:					
Fledgling		X Time: 1 year Function: 1	X Time: 1 year Function: 1			
Pre-breeder (Itinerant)		X Time: Function:	X Time: Function:			X Time: 3–5 winters Function: 2, 3
Pre-breeder (Colony)		X Time: Function:	X Time: Function:			X Time: 3–5 winters Function: 2, 3
Non-breeder (Itinerant)				X Time: annual Function:	X Time: annual Function:	X Time: annual Function:
Non-breeder (Colony)					X Time: annual Function:	X Time: annual Function:
Breeder					X Time: annual Function:	X Time: annual Function:

Table 15: Potential transition matrix categories for other taxa of marine mammals and birds. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

Albatrosses and large petrels	Small petrels	Antarctic fur seals	Pack-ice seals (crabeater, Ross and leopard seals)	Weddell seals	Southern elephant seals	Baleen whales	Toothed whales
Chick	Chick	Pup	Pup	Pup	Pup	Calves	Calves
Fledgling	Fledgling	Juvenile	Juvenile	Juvenile	Juvenile	Juvenile	Juvenile
Juvenile	Juvenile	Sub-adult male	Non-breeder	Non-breeder	Sub-adult male	Non-breeder	Non-breeder
Breeder	Breeder	Non-breeder male	Breeder	Breeder	Non-breeder male	Breeder	Breeder
Failed breeder	Failed breeder	Breeder male			Breeder male		
Non-breeder	Non-breeder	Breeder female			Breeder female		
		Failed breeder female			Failed breeder female		

Table 16: Classification of components of the diet of seabirds and marine mammals. [ ] show general guide but these will need to be refined further. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

Diet category	Level of classification	
Copepod	[large, small]	
Amphipod	Themisto, other	
Mysids	[taxon]	
Krill	[sex, status, size]	
Squid	[large, small; alive, dead]	Onychoteuthid Ommastrephid Other
Fish	[adult, juvenile]	Toothfish Icefish Myctophid Other [large, small]
Carrion	[taxon]	
Birds	[taxon]	
Marine mammals	[taxon]	

Table 17: Qualitative analysis of prey of marine mammals and birds in the Atlantic sector of the Southern Ocean. Predators are listed in the left column. Other columns represent prey groups based on the classification in Table 4.16. The number of X's corresponds to potential importance of prey. (X) means present occasionally. L – large, S – small. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

	Copepods	Amphipods	Krill	Squid		Icefish	Myctophids	Other fish		Carrion	Seals	Seabirds
				S/live	L/dead			L	S			
Large flying birds												
Wandering albatross					XX			X		XX		
Light-mantled sooty albatross			X	X	X			X		X		(X)
Grey-headed albatross			X	XX			X					
Black-browed albatross			XX	X			X			X		
Giant petrel			X		X					XXX		X
Small flying birds												
White-chinned petrel			XX	XX			XX		X			
Antarctic prion	XX	X	XX									
Cape petrel			XX				X	XX				
Antarctic fulmar			XX	X				X				
Antarctic petrel			XX	X				X				
Snow petrel			XX					X				
Diving petrel	XX	X	XX									
Storm petrel	XX	X	X				X					
Penguins												
King				X			XXX					
Emperor			X	X				XXX				
Gentoo			XX			XX		X	X			
Adélie/chinstrap			XXX				X					
Macaroni		X	XXX									
Marine mammals												
Whales:												
Baleen			XXX									
Toothed				XX				XX				
Sperm				XXX								
Killer								X			XXX	
Seals												
Fur			XXX			XX	X		X			
Crabeater			XXX									
Weddell				XX				XXX				
Leopard			XX					XX			XX	
Ross				XX	X			XX				
Elephant				XX	XX			XX				

Table 18: Foraging locations for marine mammals and birds during the respective breeding seasons. A – adult, M – male adult, F – female adult, PB – pre-breeder, NB – non-breeder, I – incubation, B/G – brood/guard, R – rearing, S – shelf, SB – shelf break, O – offshore, SBACC – southern boundary of the ACC, SACCF – southern Antarctic Circumpolar Current Front, PF – Polar Front, SAF – sub-Antarctic Front, STF – sub-tropical front. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

Group	Taxon	Life stage	Part of year/ breeding cycle	Sea-ice				Coastal current			Antarctic Circumpolar Current														
											Antarctic Zone						Polar Frontal Zone					Sub-Antarctic Zone			
				Polynya	Pack	MIZ	Off-MIZ	S	SB	O	Shore	SBACC	SACCF	S	SB	O	PF	SAF	S	SB	O	STF	S	SB	O
Large flying birds	Wandering albatross	A	I													X					X	X		X	X
		A	B/G																X	X	X				
		A	R				X									X				X	X	X		X	X
	Light-mantled sooty albatross	A	I										X			X					X				
		A	B/G													X					X				
		A	R													X									
	Grey-headed albatross	A	I										X		X	X	X			X	X				
		A	B/G										X		X		X			X	X				
		A	R										X		X	X									
	Black-browed albatross	A	I										X	X	X	X	X				X				
		A	B/G										X	X	X	X	X				X				
		A	R										X	X	X	X	X				X				
	Giant petrel	M	I								X			X	X	X									
			B/G								X			X	X				X	X					
			R								X			X	X	X									
	Giant petrel	F	I								X			X	X	X									
			B/G								X			X	X	X									
			R				X				X			X	X	X									
Small flying birds	White-chinned petrel	A	I										X		X	X	X			X					
			B/G										X	X	X	X	X								
			R				X						X		X	X	X			X					
	Antarctic prion	A	Breeding										X	X	X	X									
	Other prions	A	Breeding				X							X	X	X	X		X	X	X				
	Cape petrel	A	Breeding			X	X			X			X	X	X	X									

(continued)

Table 18 (continued)

Group	Taxon	Life stage	Part of year/ breeding cycle	Sea-ice				Coastal current			Antarctic Circumpolar Current														
											Antarctic Zone						Polar Frontal Zone					Sub-Antarctic Zone			
				Polynya	Pack	MIZ	Off-MIZ	S	SB	O	Shore	SBACC	SACCF	S	SB	O	PF	SAF	S	SB	O	STF	S	SB	O
Small flying birds (cont.)	Antarctic fulmar	A	Breeding	X	X	X			X	X			X	X	X	X									
	Antarctic petrel	A	Breeding	X	X	X			X	X			X												
	Snow petrel	A	Breeding						X	X			X												
	Diving petrel	A	Breeding											X		X									
	Storm petrel	A	Breeding		X	X		X	X	X			X	X	X	X									
Penguins	Adélie – Peninsula	A	I						X	X															
		A	B/G						X	X															
		A	Crèche						X	X															
		NB			X	X			X	X															
		PB			X	X			X	X															
	Adélie – East Antarctic	A	I		X	X	X	X	X	X															
		A	B/G		X	X	X	X	X																
		A	Crèche		X	X		X	X																
		NB			X	X		X	X	X															
		PB			X	X		X	X	X															
	Adélie – Ross Sea	A	I		X	X	X	X	X	X															
		A	B/G		X	X	X	X	X																
		A	Crèche		X	X		X	X																
		NB			X	X		X	X	X															
		PB						X	X	X															
	Chinstrap	A	I					X	X	X		X	X												
		A	B/G					X	X	X															
		A	Crèche					X	X	X															
		NB						X	X	X		X	X												
		PB						X	X	X		X	X												
	Gentoo – Peninsula	A	I					X																	
		A	B/G					X																	
		A	Crèche					X																	
		NB						X																	
		PB						X																	

(continued)

Table 18 (continued)

Group	Taxon	Life stage	Part of year/ breeding cycle	Sea-ice				Coastal current			Antarctic Circumpolar Current														
											Antarctic Zone						Polar Frontal Zone					Sub-Antarctic Zone			
				Polynya	Pack	MIZ	Off-MIZ	S	SB	O	Shore	SBACC	SACCF	S	SB	O	PF	SAF	S	SB	O	STF	S	SB	O
Penguins (cont.)	Gentoo – sub-Antarctic	A	I											X											
		A	B/G											X											
		A	Crèche											X											
		NB												X											
		PB												X											
	Macaroni	A	I													X	X	X			X				
		A	B/G										X	X	X										
		A	Crèche										X	X	X	X									
		A	Premoult											X	X	X	X								
		NB														X	X	X			X				
		PB														X	X	X			X				
	King	A	Breeding													X	X	X			X				
		NB														X	X	X			X				
		PB		X	X	X										X	X	X			X				
	Emperor	A	Breeding	X	X	X																			
		NB		X	X	X																			
		PB																							
Seals	Antarctic fur	F	Breeding			X	X	X	X	X		X	X	X	X	X	X	X		X					
		M	Breeding					X	X	X		X	X	X	X	X	X	X		X					
	Southern elephant	A	Breeding		X	X		X	X	X		X	X	X	X	X	X	X	X	X	X				X
	Crabeater	A	Breeding		X																				
	Ross	A	Breeding		X	X																			
	Weddell	A	Breeding		X	X	X																		
	Leopard	A	Breeding																						
Baleen whales	Minke	?	?																						
	Humpback	?	?																						
	Southern right	?	?																						
	Fin	?	?																						
Toothed whales	Sperm	?	?																						
	Orca	?	?																						
	Other small cetaceans	?	?																						

Table 19: Foraging locations for marine mammals and birds during the respective non-breeding seasons (see Table 18 for explanation of abbreviations). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

Group	Taxon	Life stage	Part of year/ breeding cycle	Sea-ice				Coastal current			Antarctic Circumpolar Current													
											Antarctic Zone					Polar Frontal Zone					Sub-Antarctic Zone			
				Polynya	Pack	MIZ	Off-MIZ	S	SB	O	SACCB	SACCF	S	SB	O	PF	SAF	S	SB	O	STF	S	SB	O
Large flying birds	Wandering albatross	Adult	Sabbatical													X			X	X			X	X
	Light-mantled sooty albatross	Adult	Winter				X					X			X	X				X				
	Grey-headed albatross	Adult	Sabbatical													X	X			X	X			X
	Black-browed albatross	Adult	Winter																	X		X	X	
	Giant petrel	Adult	Winter															X		X		X		X
Small flying birds	White-chinned petrel	Adult	Winter												X	X	X			X	X	X	X	X
	Antarctic prion	Adult	Winter											X	X									
	Other prions	Adult	Winter													X	X			X				
	Cape petrel	Adult	Winter				X								X	X	X	X	X	X		X	X	X
	Antarctic fulmar	Adult	Winter				X								X	X	X	X	X	X		X	X	X
	Antarctic petrel	Adult	Winter	X		X	X								X									
	Snow petrel	Adult	Winter	X		X	X								X									
	Diving petrel	Adult	Winter										X	X	X									
	Storm petrel	Adult	Winter									X			X			X	X	X	X	X	X	X
Penguins	Adélie	Adult	Winter		X	X		X	X	X														
	Chinstrap	Adult	Winter			X	X	X	X	X	X	X												
	Gentoo	Adult	Winter	X			X	X					X											
	Macaroni	Adult	Winter													X	X			X				
	King	Adult	Sabbatical													X	X			X				
	Emperor	Adult	Winter		X																			

(continued)

Table 19 (continued)

Group	Taxon	Life Stage	Part of Year/ Breeding Cycle	Sea-ice				Coastal Current			Antarctic Circumpolar Current													
											Antarctic Zone					Polar Frontal Zone					Sub-Antarctic Zone			
				Polynya	Pack	MIZ	Off-MIZ	S	SB	O	SACCB	SACCF	S	SB	O	PF	SAF	S	SB	O	STF	S	SB	O
Seals	Antarctic fur	Female	Winter			X	X	X	X	X	X	X	X	X	X	X	X			X		X	X	X
		Male	Winter			X	X	X	X	X	X	X	X	X	X									
	Southern elephant	Adult	Winter					X	X	X	X	X	X	X	X	X	X	X	X	X				X
	Crabeater	Adult	Winter		X	X																		
	Ross	Adult	Winter		X																			
	Weddell	Adult	Winter		X	X																		
	Leopard	Adult	Winter		X	X	X						X	X										
Baleen whales	Minke	?	?																					
	Humpback	?	?																					
	Southern right	?	?																					
	Fin	?	?																					
Toothed whales	Sperm	?	?																					
	Orca	?	?																					
	Other small cetaceans	?	?																					

Table 20: Seasonal succession of reasons to decide on fishing locations by skippers across months in Subareas 48.1, 48.2 and 48.3 (WG-EMM-04/51). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

	Reasons for the decision						
	Month	Density	Change in krill size	Krill too green	Too many salps	Ice conditions	Transhipping
South Shetland Islands Subarea 48.1	December	16	0	1	0	0	0
	January	34	2	14	1	0	3
	February	19	2	9	5	0	0
	March	37	1	6	2	0	2
	April	46	4	4	0	0	2
	May	32	2	0	0	4	1
	June	10	1	0	0	2	0
	July	5	0	0	0	2	1
South Orkney Islands Subarea 48.2	December	3	0	2	0	0	0
	January	0	0	2	0	0	1
	February	2	0	1	0	1	0
	March	7	0	1	0	2	0
	April	4	1	1	0	0	0
	May	3	1	0	0	3	0
	June	4	1	0	0	7	0
South Georgia Subarea 48.3	May	1	0	0	0	0	0
	June	4	0	0	0	0	0
	July	0	0	0	0	0	0
	August	1	1	0	0	0	0
	September	3	0	0	0	0	0

Table 21: Properties of the krill fishery. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

Taxa	Krill fishing vessels in general Nations Fleets Individual vessels Vessel size Factory type (products) Factory capacity (raw krill basis) Type of gear
Stage	Learning, established
Units	Numbers (vessel), number of hauls (effort), catch (tonnes), length of operation (days, hours)
Fishing ground formation	Relation to environmental features • ice edge • bottom topography (distance relative to the shelf edge) • hydrodynamic characteristics of the area → complex currents around islands together with topographically induced effects; • krill flux, krill spatial distribution pattern Area 48 fishing areas South Georgia, South Orkney Islands, Elephant Island, King George and Livingston Islands, Antarctic Peninsula and within these fishing areas, there are several local fishing grounds
Decision making	Skippers Based on experience and accumulation of information (biological, environmental, regulation, physical, logistics) Company (market demand, price, remaining stocks, economy, logistics)
Factors affecting behaviour	Physical aspects • Non-seasonal → bottom topography (depth and space) • Seasonal → weather Biological • Krill → distribution, colour (green, red/white), size, maturity, aggregation size, type • Other species → salp, fish, predators Communication with other vessels, or monitoring Logistics → cargo transfer, emergencies

Table 22: Properties of icefish fishery. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

Taxa	Icefish fishing vessels in general
	    Nations
	        Fleets
	            Individual vessels
	                Vessel size
	                    Factory type (products)
	                    Type of gear

Stage	Learning, established
Units	Numbers (vessel), number of hauls (effort), catch (tonnes), length of operation (days, hours)

Fishing ground formation	Relation to environmental features
	    bottom topography (shelf area)
	Biological features
	    aggregation
	Area 48 fishing area
	    Subarea 48.3
	Area 58 fishing area
	    Divisions 58.5.1 and 58.5.2

Decision making	Skippers
	    Based on experience and accumulation of information
	    (Biological, environmental, regulation, physical, logistics)
	Company (market demand, price, remaining stocks, economy, logistics)

Factors affecting behaviour	Physical aspects
	    • Non-seasonal → bottom topography (depth and space)
	    • Seasonal → ice, weather
	Biological
	    • Icefish → distribution, size, maturity
	    • Aggregation → size, type
	    • Other species → by-catch species
	Communication with other vessels, or monitoring
	Logistics → cargo transfer, emergencies
	Regulations → temporal spatial closure, minimum size, by-catch.

Figure 1: Example of the horizontal and vertical spatial geometries used to define an ecosystem in Atlantis. Vertically, if the depth of the polygon is less than the maximum vertical depth, the water column layer(s) are truncated to match (e.g. a box in B that is 100 m deep would have 2 x 50 m water column layers). Any open ocean cells in B that are >1 800 m deep have no epibenthic or sediment layers, and are treated as having an open boundary under the deepest water column layer. Note that fine black lines indicate the boundaries of model boxes, thick black lines mark the edges of management zones, and sampling locations (used in the observation model) are indicated by black dots (reproduced from Fulton et al., in press). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

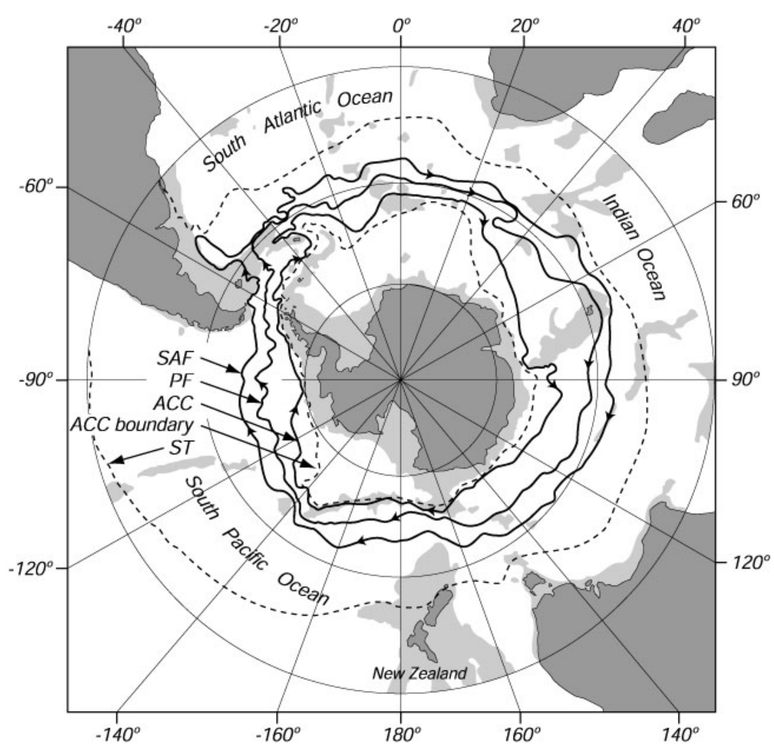


Figure 2: Main frontal features in the Southern Ocean (Orsi et al., 1995) and the CCAMLR boundaries (figure obtained from http://oceanworld.tamu.edu/resources/ocng_textbook/chapter13/Images/Fig13-13.htm). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

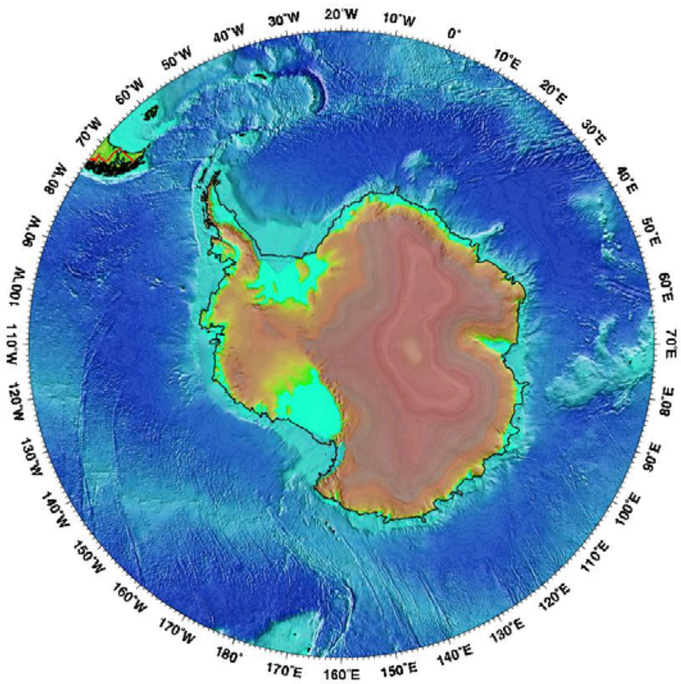


Figure 3: Main topographic features of the Southern Ocean (figure obtained from http://oceancurrents.rsmas.miami.edu/southern/img_topo2/antarctic-coastal2.jpg). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

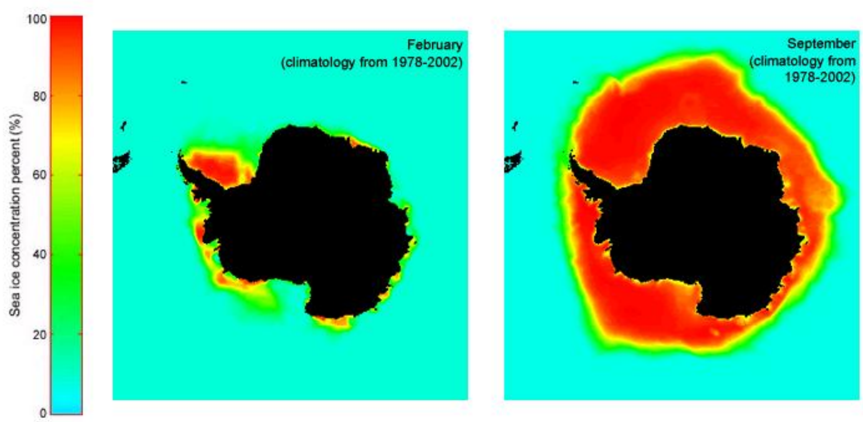


Figure 4: Seasonal extent of pack-ice around Antarctica in summer and winter (figures obtained from http://nsidc.org/sotc/sea_ice.html). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

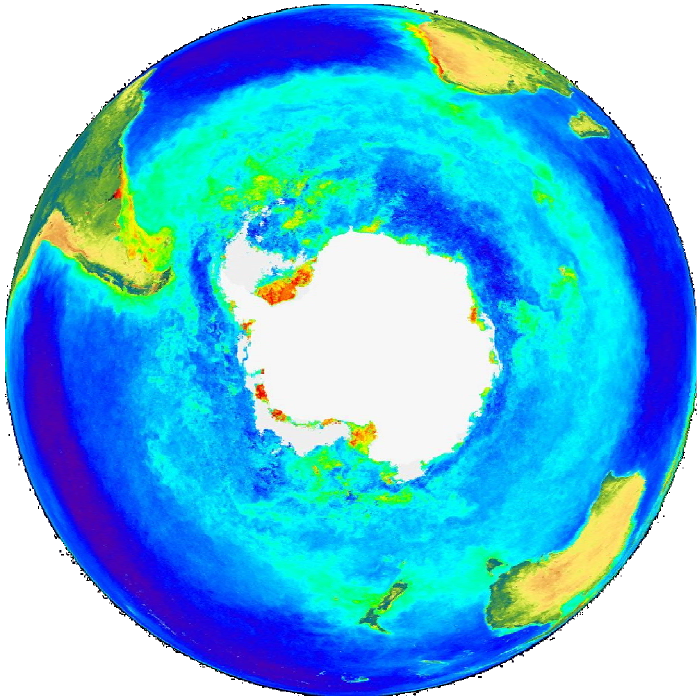


Figure 5: Average chlorophyll distribution in the polar region from SeaWiFS September 1997–July 1998 (figures obtained from http://seawifs.gsfc.nasa.gov/SEAWIFS.html). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

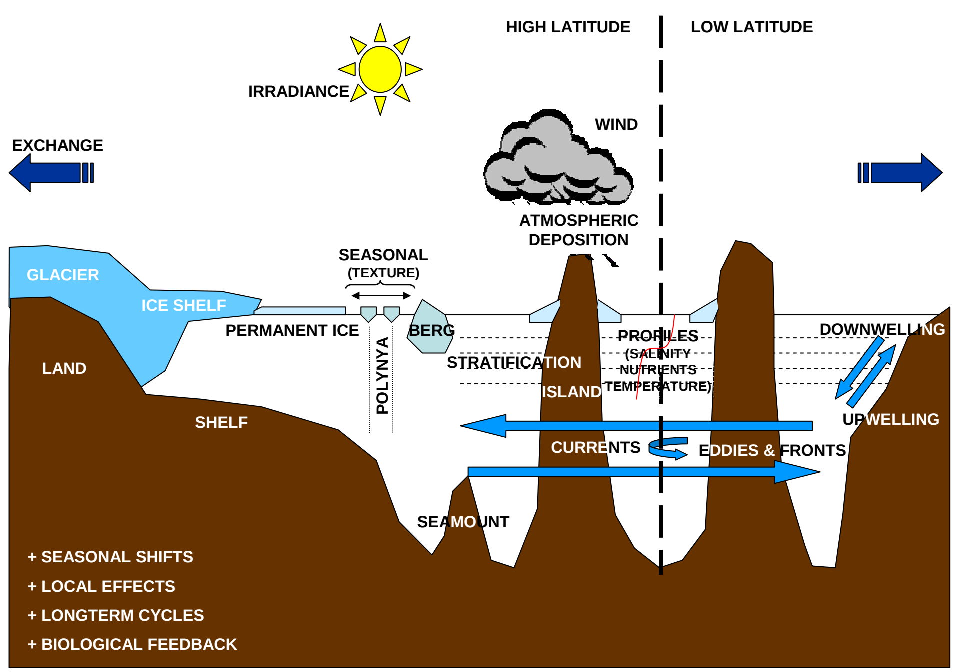


Figure 6: Conceptual diagram of major physical factors and processes affecting the Southern Ocean marine ecosystem. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

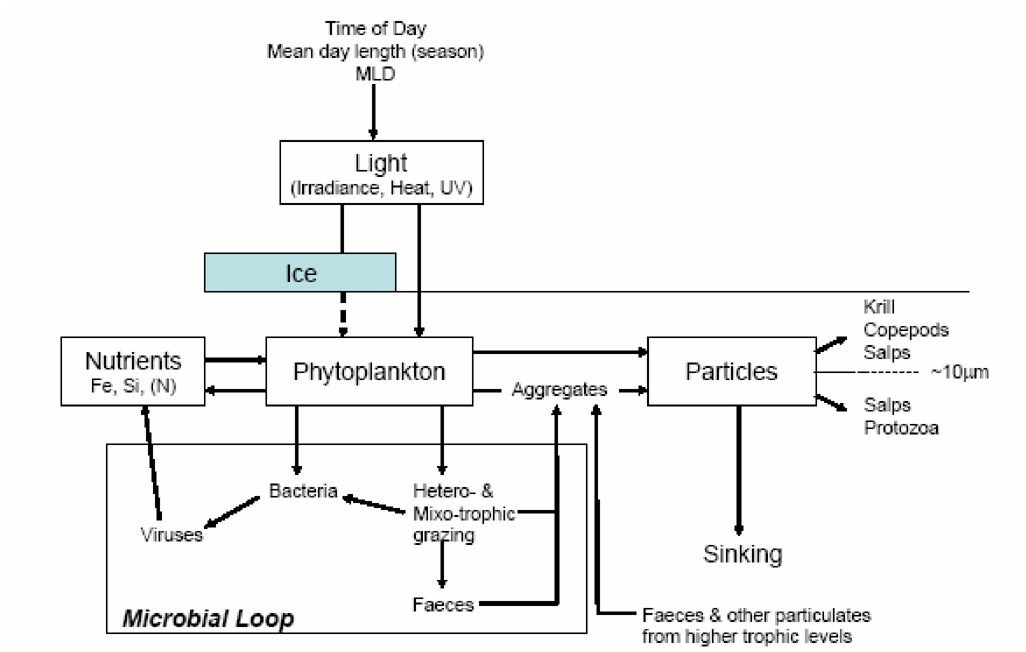


Figure 7: Conceptual model of the important linkages influencing production of particulates used as food by zooplankton. MLD – mixed layer depth. Note that Dissolved Organic Matter (DOM) is a waste product from all organisms, and DOM and Particulate Organic Matter are an important source of carbon in winter (from WG-EMM-04/24). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

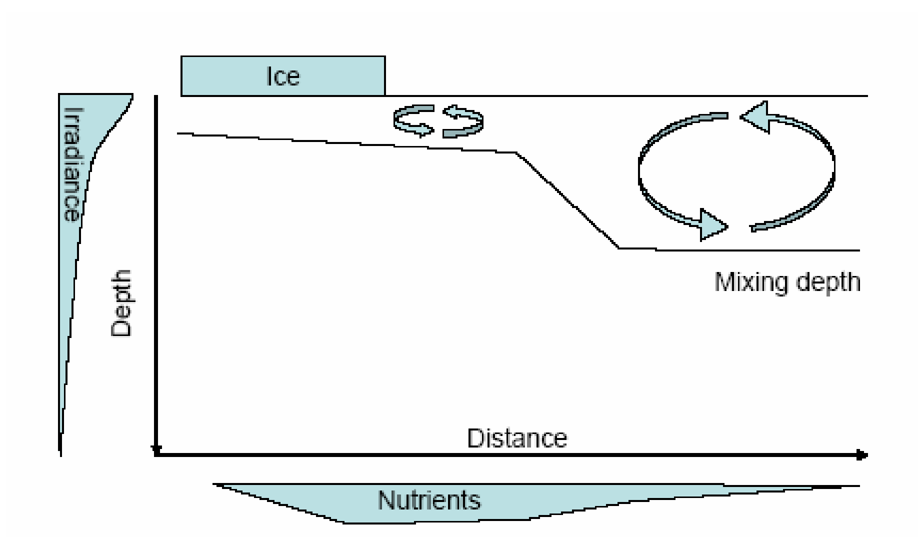


Figure 8: Diagrammatic representation of how the spatial characteristics of the environment might influence primary production in the ice-edge region. Arrows indicate possible mixing. The width of the shapes surrounding nutrients and irradiance indicate the quantities that might be available to phytoplankton given proximity to ice and the depth of the mixing layer (from WG-EMM-04/24). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

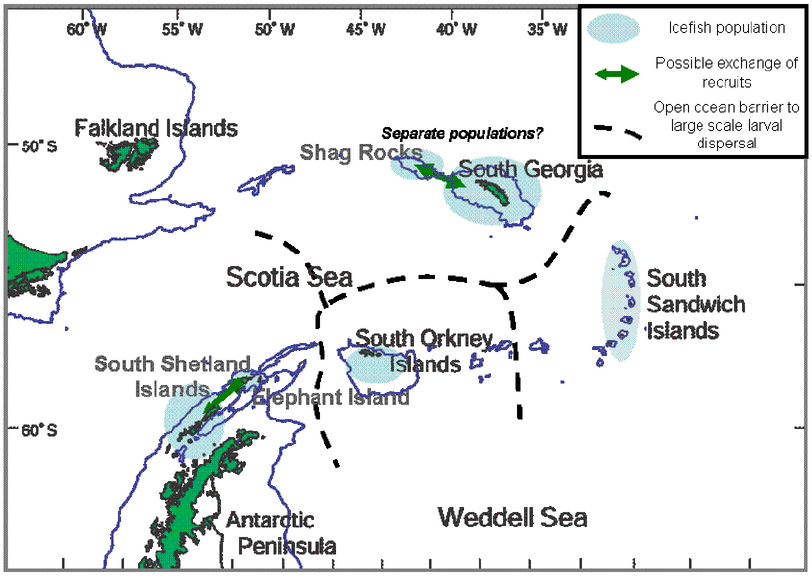


Figure 9: Conceptual model of the distribution of *Champsocephalus gunnari* in the southwest Atlantic. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

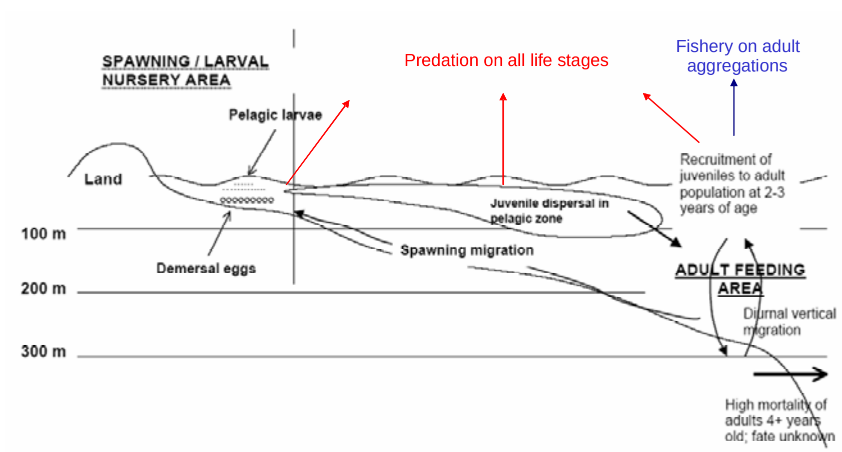


Figure 10: Summary of life history of *Champsocephalus gunnari* (modified from WG-EMM-04/59). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

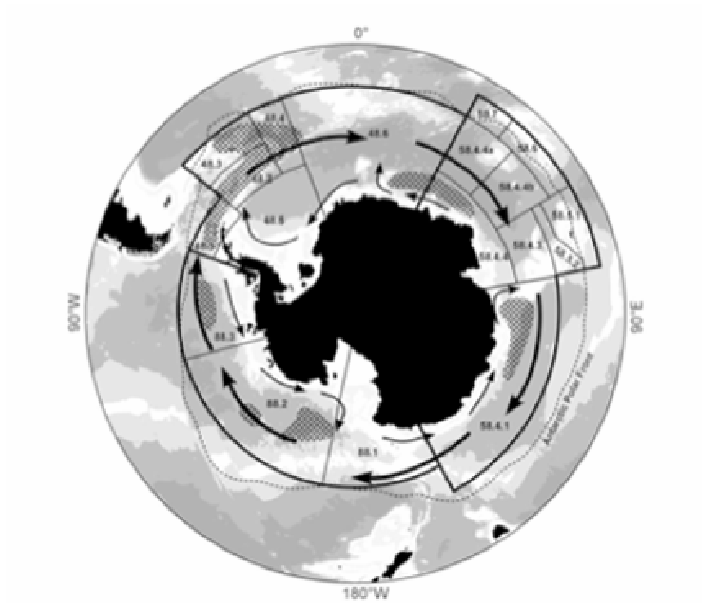


Figure 11: Antarctic Polar Front, CCAMLR boundaries, FAO statistical areas, areas of high krill densities (cross-hatched), ACC (West Wind Drift) and East Wind Drift (sources: CCAMLR, Hobart, Australia; Laws, 1985; Amos, 1984; Mackintosh, 1973). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

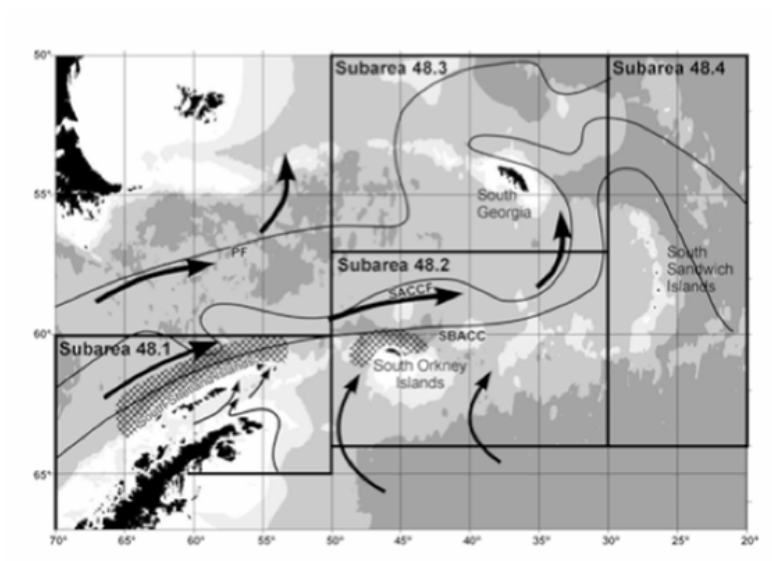


Figure 12: Krill spawning areas (cross-hatched), major currents and frontal zones in the southwest Atlantic sector of the Southern Ocean; PF – Polar Front, SACCF – Southern Antarctic Circumpolar Current Front, SBACC – southern boundary of the ACC (sources: Marr, 1962; Orsi et al., 1995; Hofmann et al., 1998). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

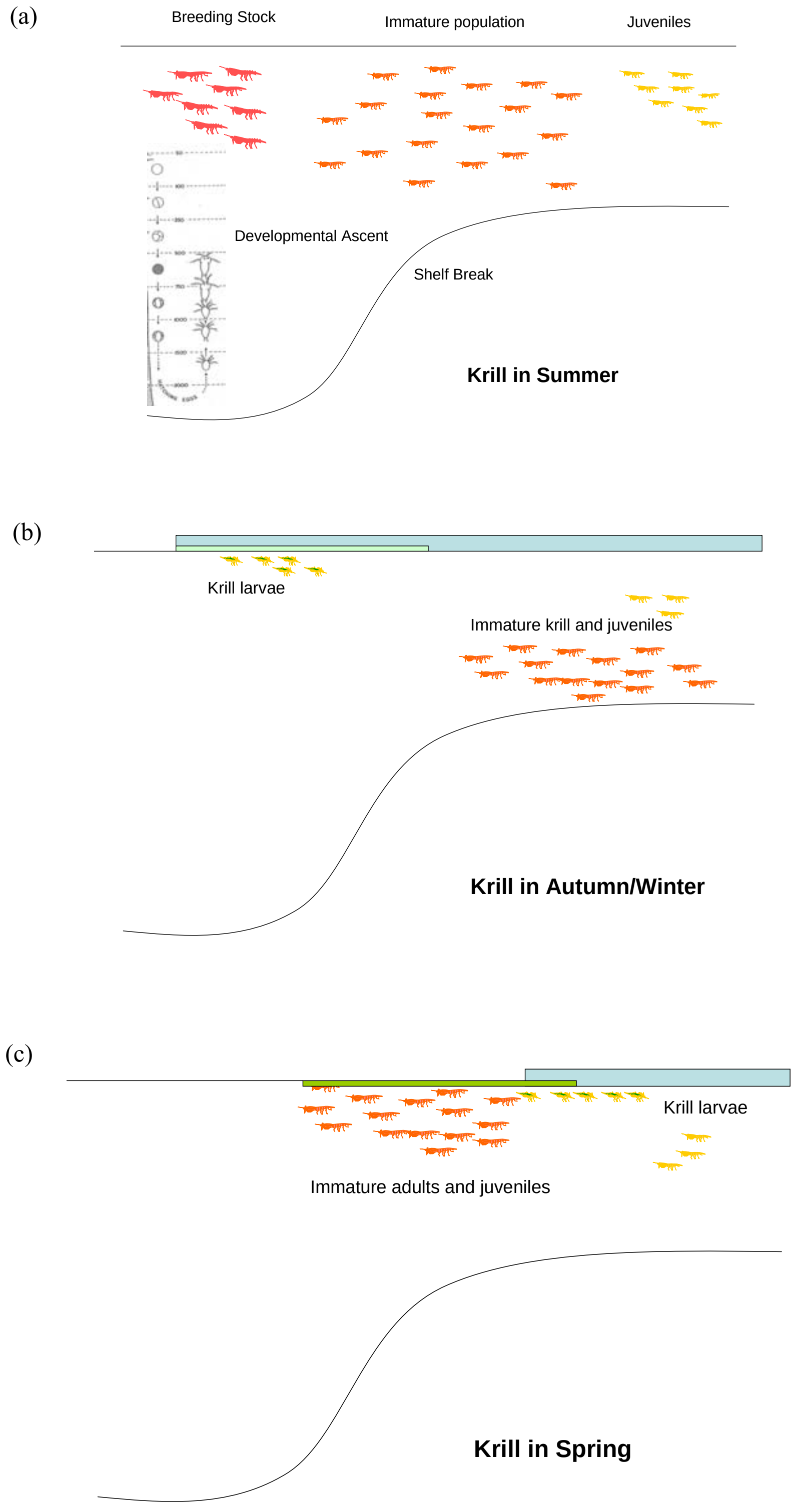


Figure 13: Conceptual model of krill population in summer and winter (modified from WG-EMM-04/50). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

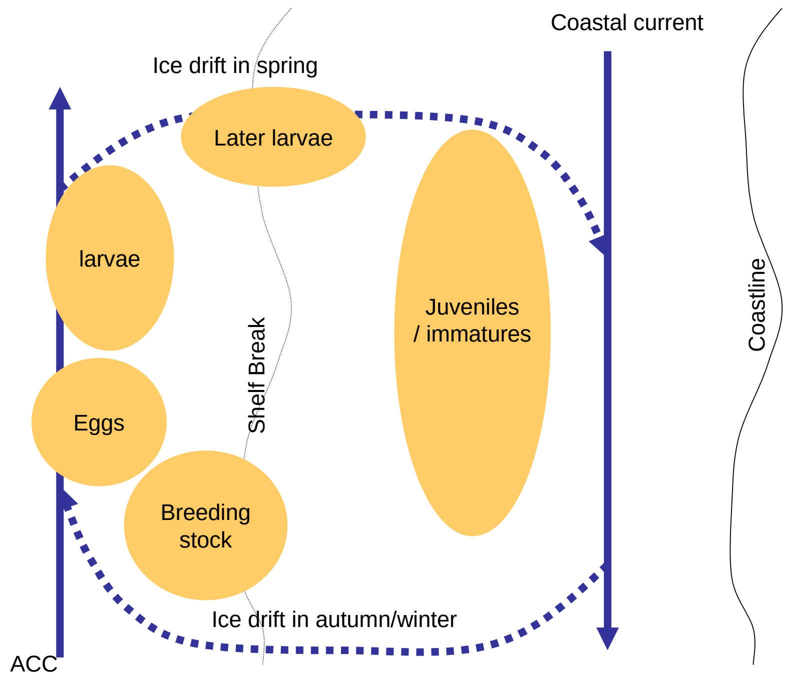


Figure 14: Conceptual model of krill in spring and plan view of ontogenetic migration pattern (modified from WG-EMM-04/50). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

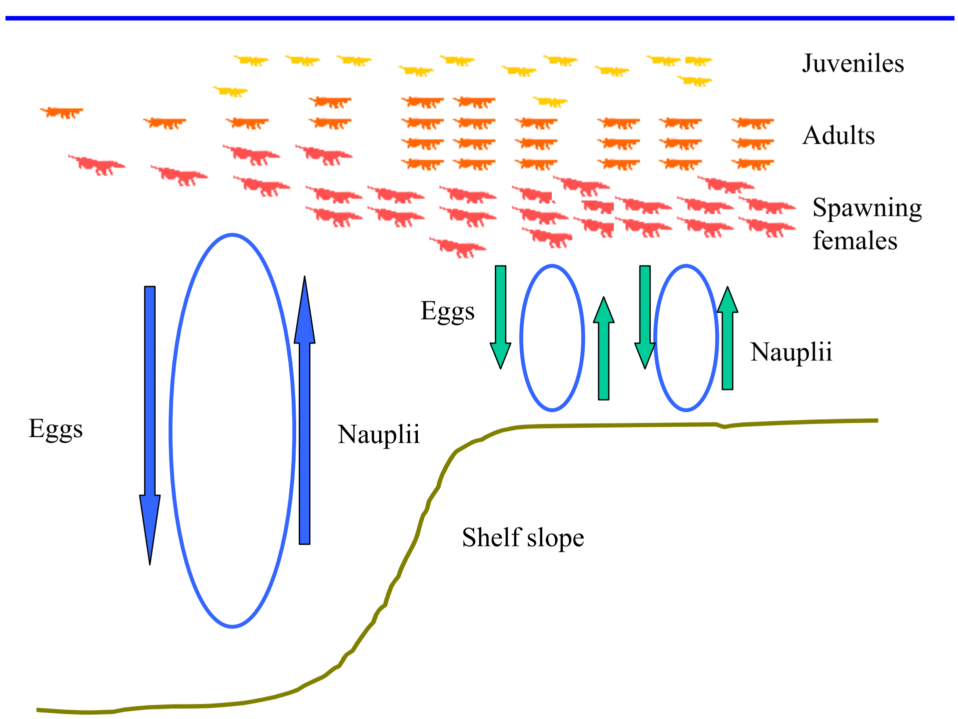
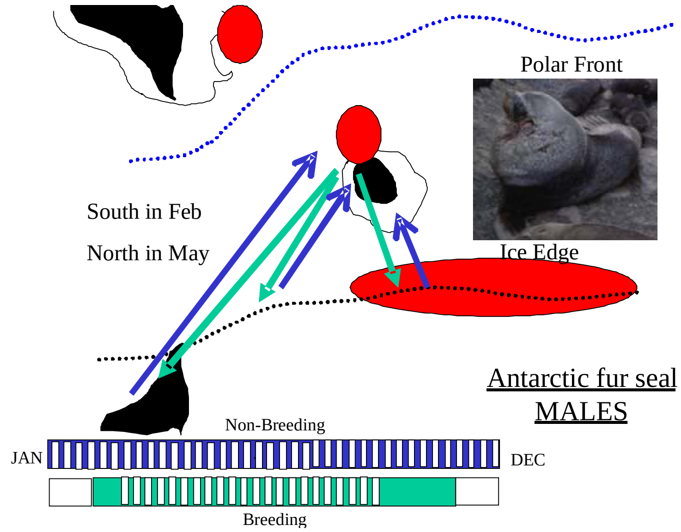


Figure 15: Alternative summer distribution of krill at South Orkney Islands. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.



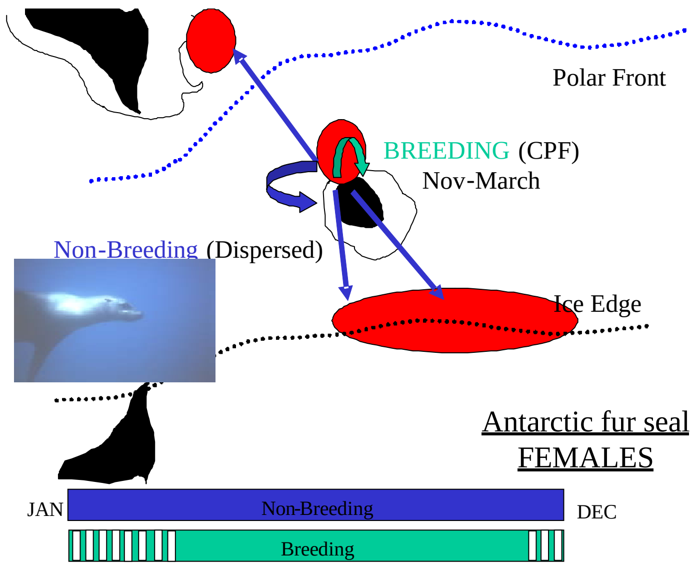


Figure 16: Conceptual model of the seasonal distribution of Antarctic fur seals associated with a sub-Antarctic island in Area 48. Top panel shows males. Bottom panel shows females. The lower bars in each panel indicate the time spent at sea by non-breeding and breeding individuals. For male seals there is a southward dispersal away from the breeding site in January with a northward return in early winter. Female seals that are central-place foragers during the breeding season disperse away from the island to other foraging areas (indicated by the filled ellipses) outside the breeding season. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

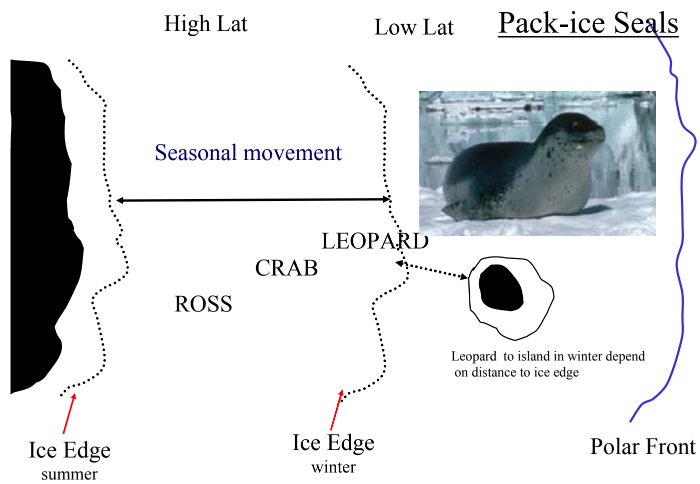


Figure 17: The spatial and temporal distribution of pack-ice seals that follow the seasonal advance and retreat of the pack-ice and the extent of the dispersal of leopard seals to sub-Antarctic islands as a function of the proximity of the pack-ice edge. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

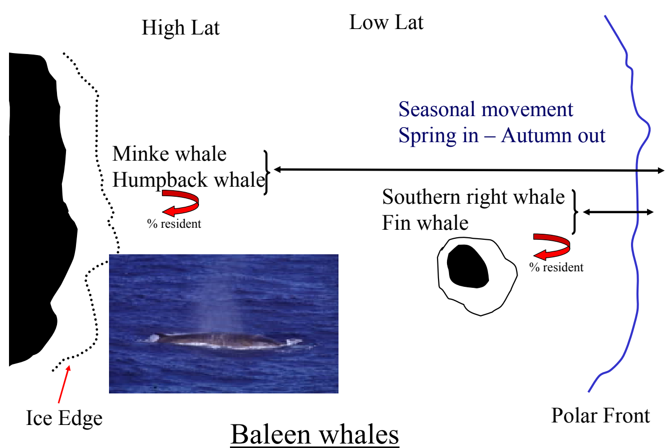


Figure 18: The spatial and temporal distribution of baleen whales separated into a high-latitude group comprising minke and humpback (possible also blue) and a lower latitude group, associated with the sub-Antarctic, comprising fin and southern right whale categories (possibly also sei). The straight arrows indicate the major migration directions, the looped arrows indicate a small proportion that stay over winter in the system. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

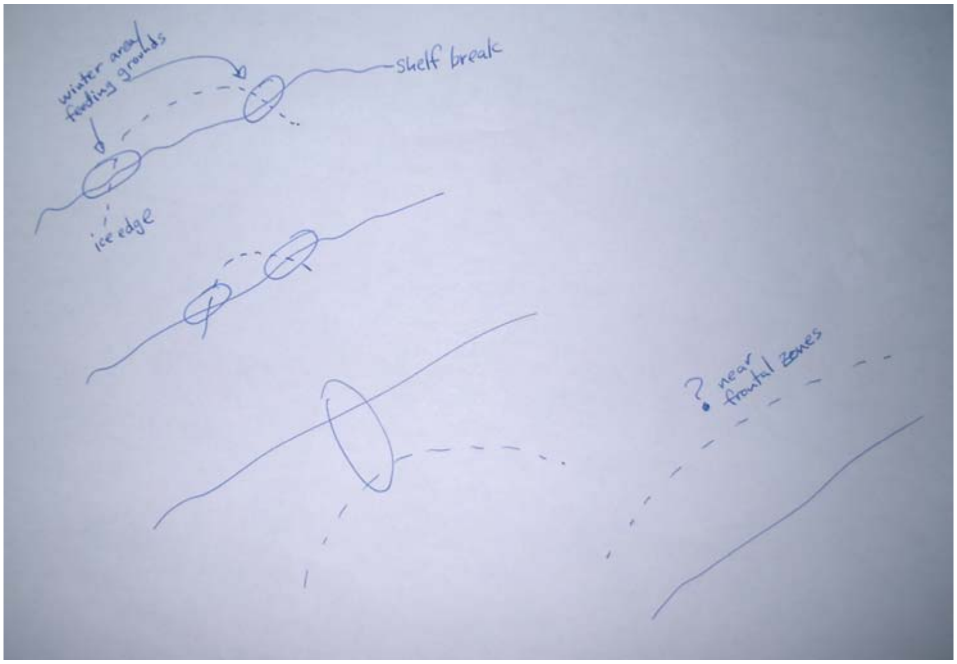


Figure 19: Graphical representation of Adélie penguin foraging locations relative to the ice-edge and shelf break. In the absence of ice, the penguins are expected to forage on the shelf break. Otherwise they would be expected to forage near the ice-edge. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

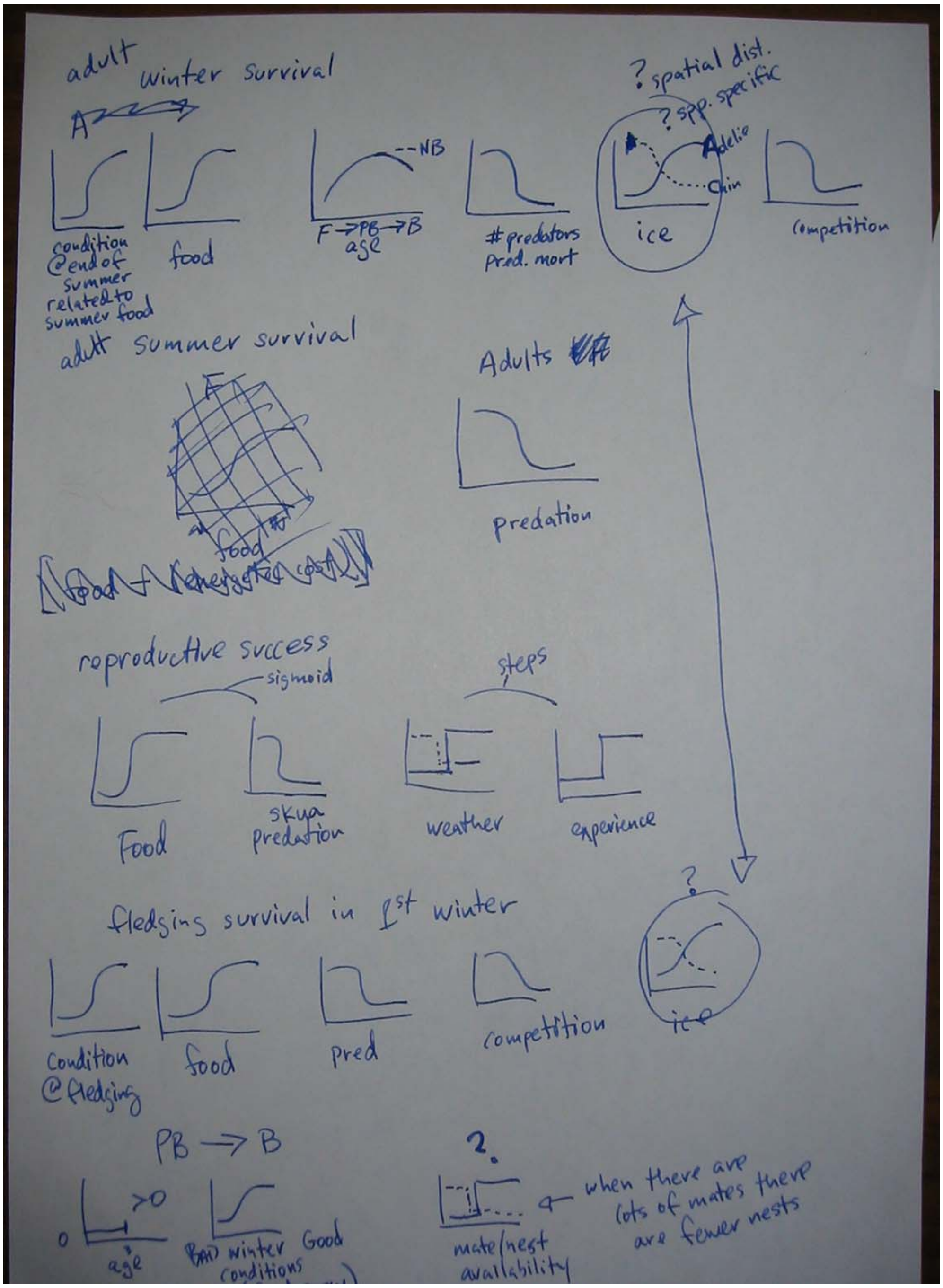


Figure 20: Graphical representations of the form of relationships affecting Adélie penguin demography. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

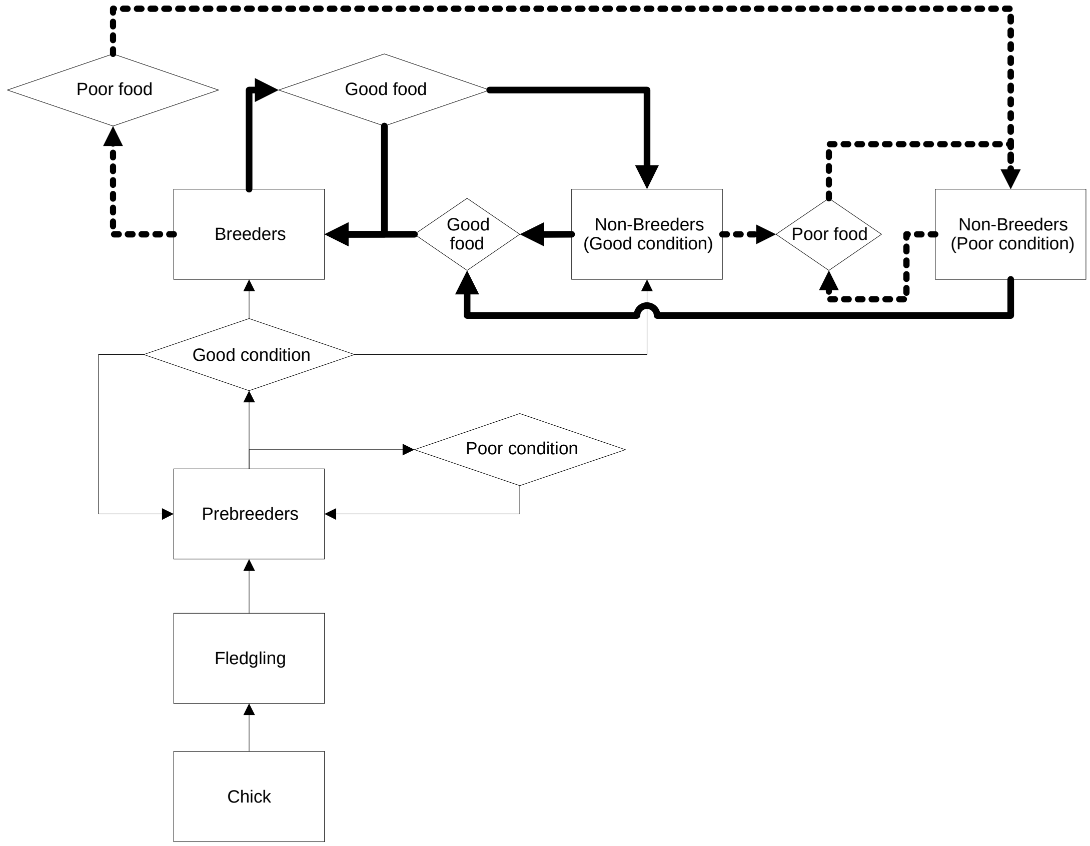


Figure 21: A generalised conceptual model of the transition between different phases in birds. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

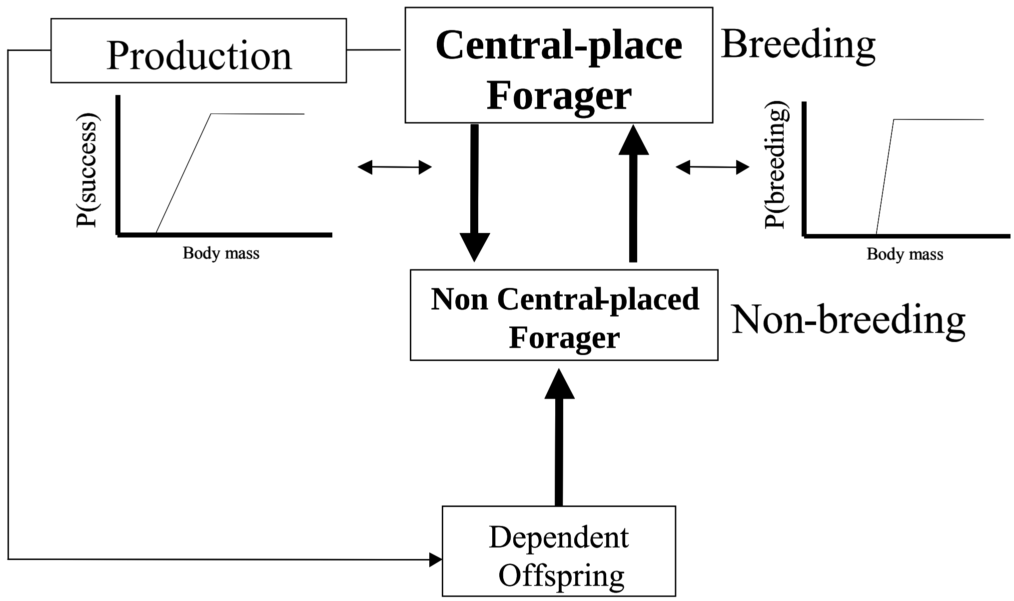


Figure 22: Diagram showing the three main elements of an investment breeder – dependent offspring, non-breeder (wide foraging distribution) and breeder (central-place forager). The transition from non-breeding to breeding depends on the non-breeder being a minimum age; thereafter its body condition will influence whether it can become a breeder, shown by the function of probability of breeding with body condition (substituted by body mass in this case) prior to the breeding season. Successful breeding will depend on the maintenance of body mass during the breeding season. The transition to having non-breeding foraging behaviours will occur at the time at which it no longer has dependent offspring, i.e. when the pup/chick dies or weans/fledges. This transition may be determined by a condition function in a similar way to that described above. Body condition will be affected by the costs of different activities, such that parental investment could be a substantial cost to a breeder (i.e. relative costs of activities comparing breeders to non-breeders might be in the order of 2:1, with dependent offspring not having any cost). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

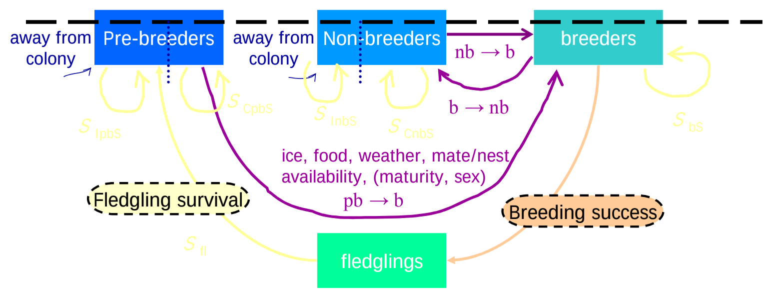


Figure 23: Demography of Adélie penguins at Béchervaise Island (WG-EMM-04/53). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

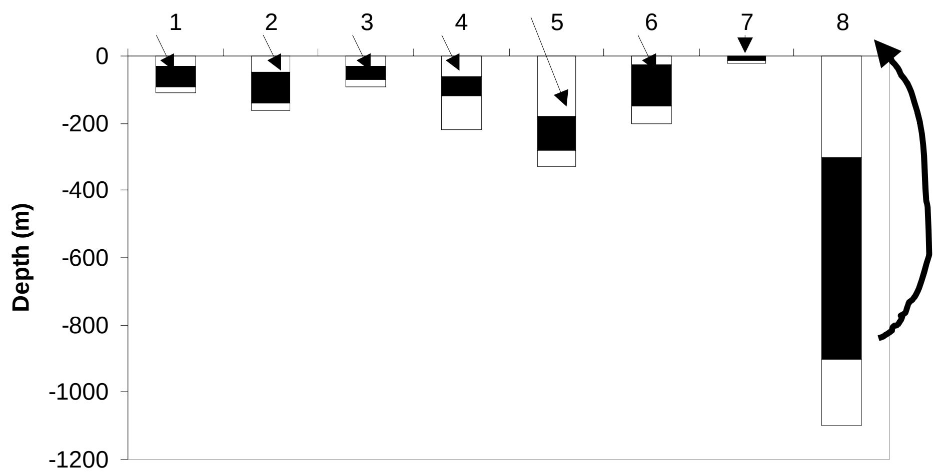


Figure 24: Generalised conceptual model of the vertical foraging distribution of air-breathing predators. The filled sections of the bars indicate the depth region of highest frequency, the upper and lower quartiles of the dive depths are indicated by the unfilled sections. The arrows on the figure indicate the direction of movement from the primary location in which the foragers spend the greater part of their time budget. The numbers refer to the taxonomic grouping:

1 – chinstrap, Adélie and macaroni penguins, 2 – gentoo penguins, 4 – Antarctic fur, leopard and crabeater seals, 5 – king and emperor penguins, 6 – Weddell seals, 7 – baleen whales, 8 – flying birds, 9 – southern elephant seals and odontocete whales.

Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

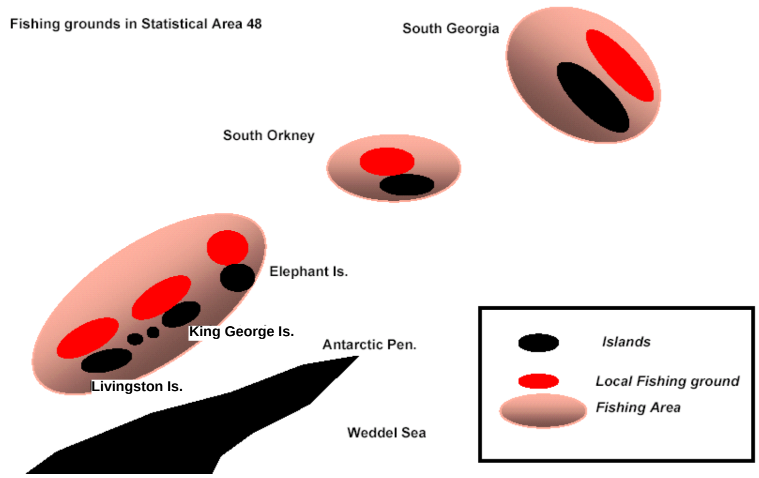


Figure 25: Conceptual illustration of krill fishing areas and grounds in Area 48 (WG-EMM-04/51). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

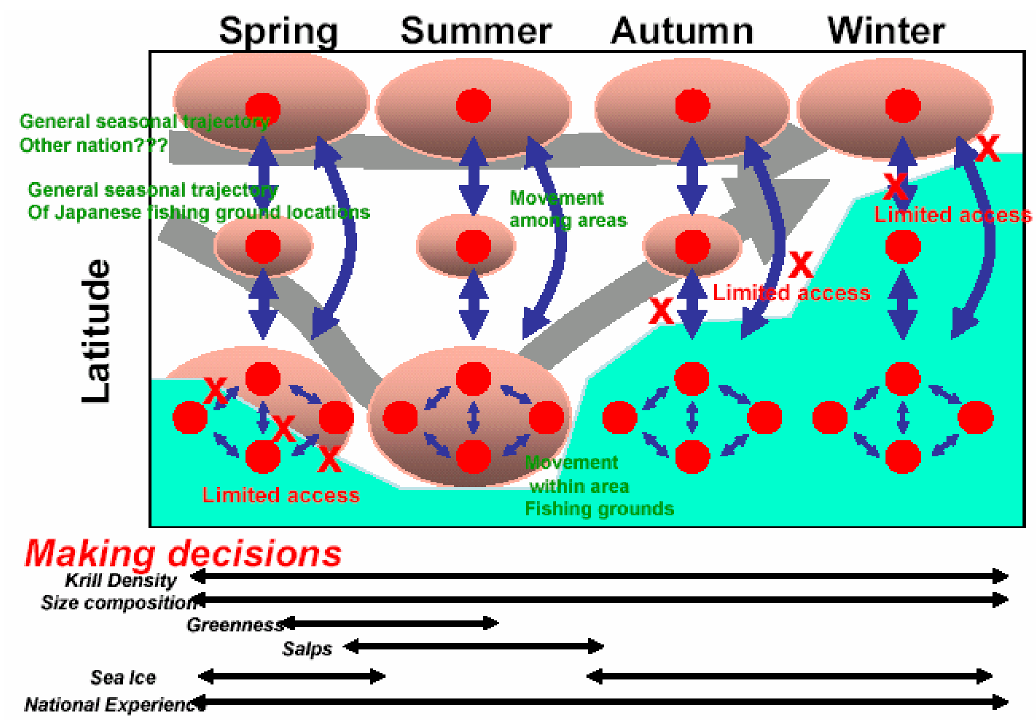


Figure 26: A conceptual illustration of the behaviour of the krill fishery through a season, and related major decision rules (WG-EMM-04/51). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

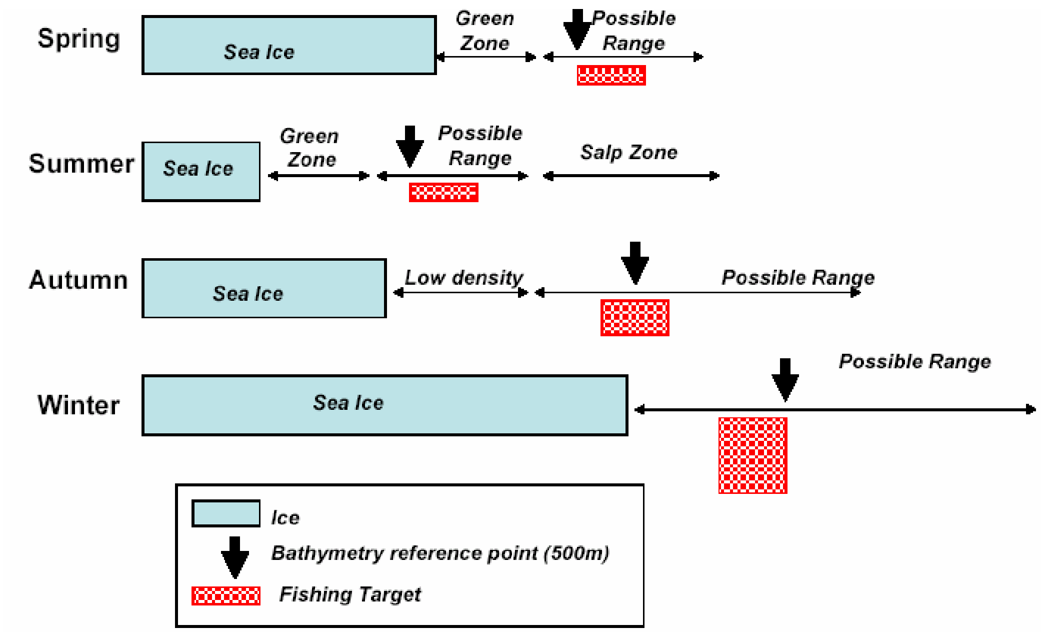


Figure 27: Krill fishing patterns characterised according to seasonal succession of physical and biological properties around the fishing grounds (generated according to information in WG-EMM-04/50). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

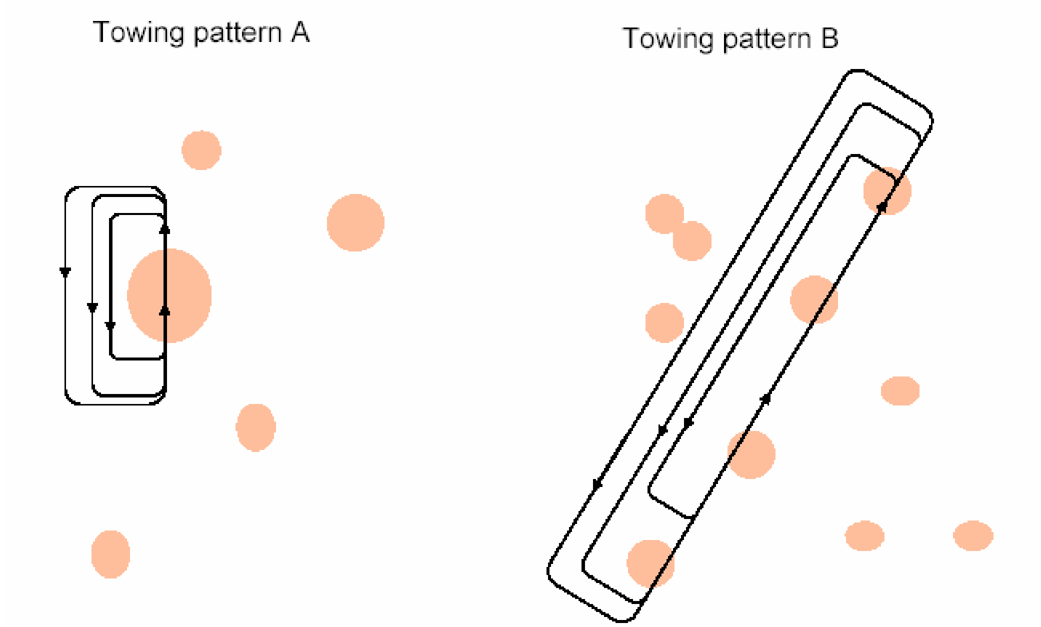


Figure 28: Different strategies of fishing operational pattern at same regional krill density but under different aggregation structure (generated according to information in WG-EMM-04/50). Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

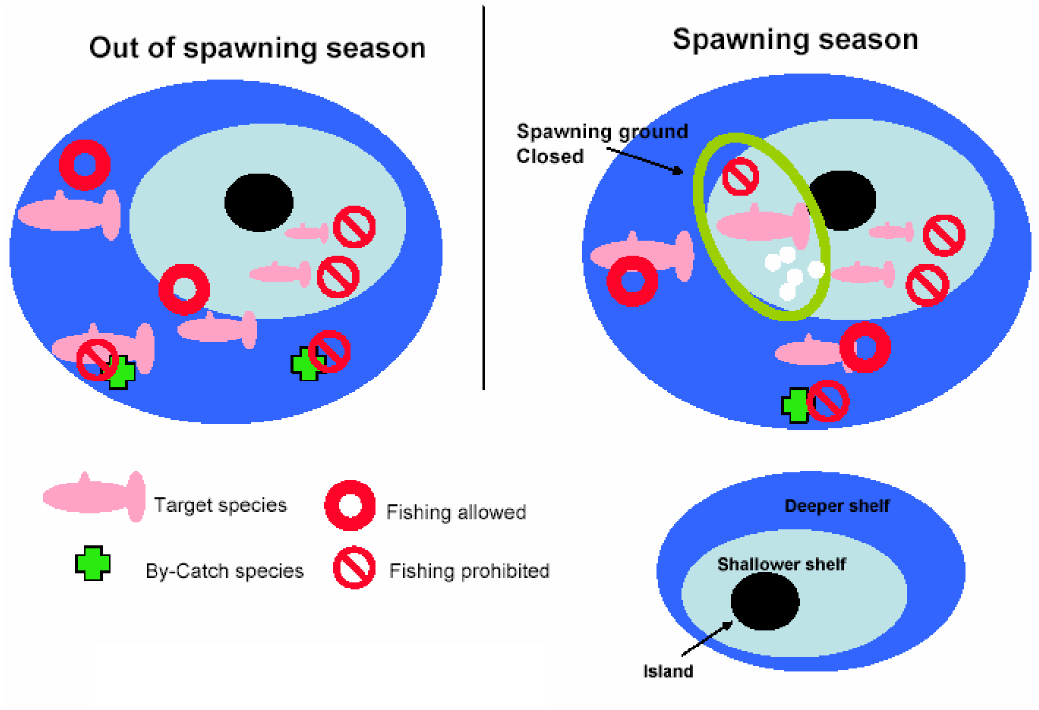


Figure 29: Conceptual illustration of an icefish fishing ground. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

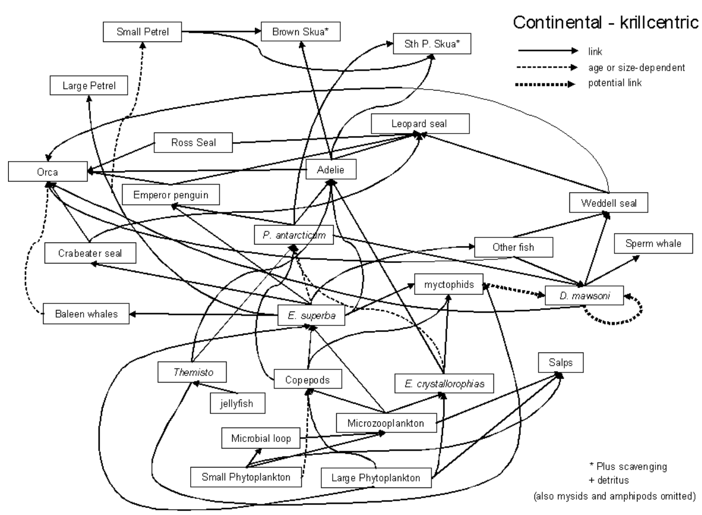


Figure 30: Schematic representation of the krill-centric food web around the Antarctic continent. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

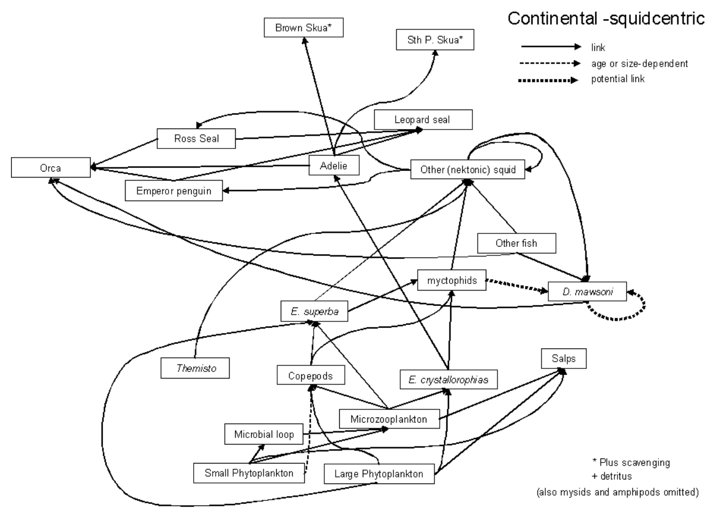


Figure 31: Schematic representation of the squid-centric food web around the Antarctic continent. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

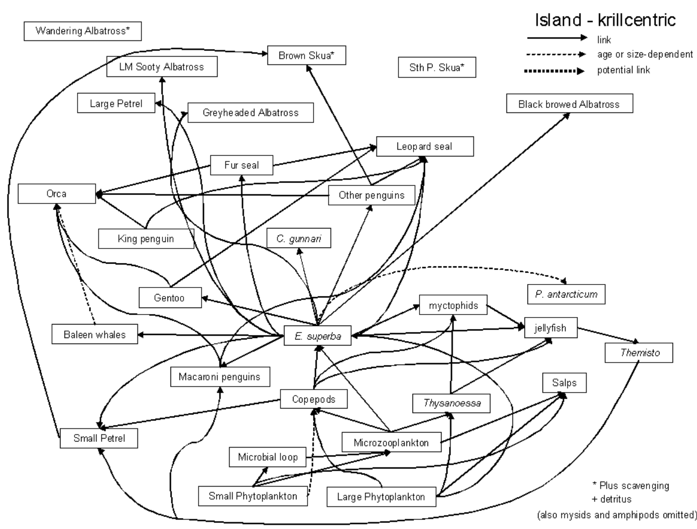


Figure 32: Schematic representation of the krill-centric food web around sub-Antarctic islands. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

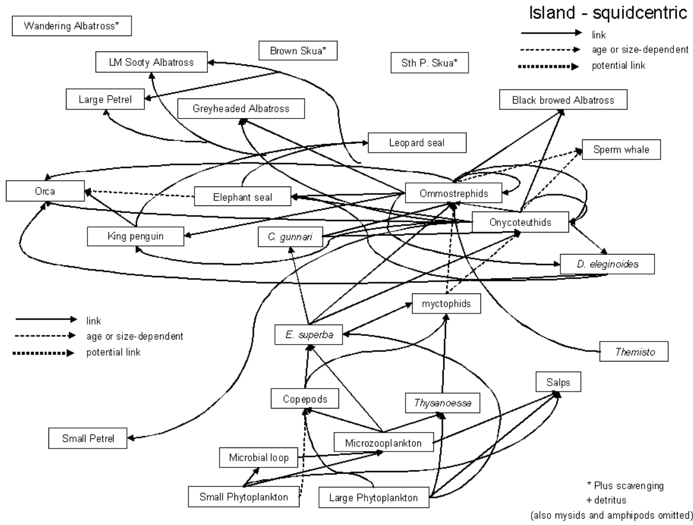


Figure 33: Schematic representation of the squid-centric food web around sub-Antarctic islands. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

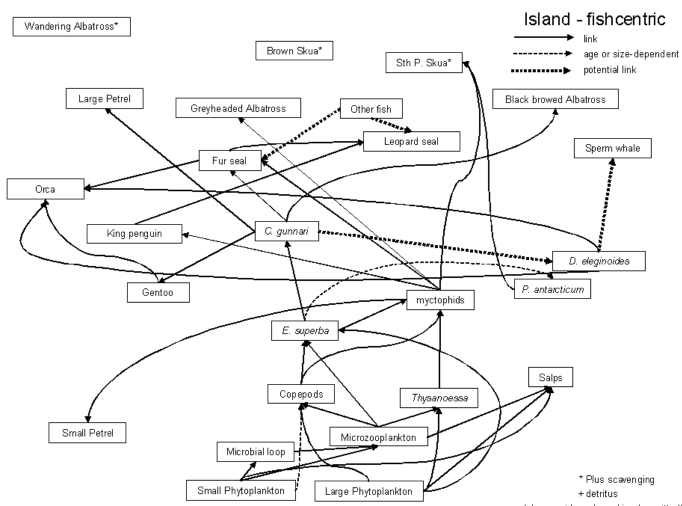


Figure 34: Schematic representation of the fish-centric food web around sub-Antarctic islands. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

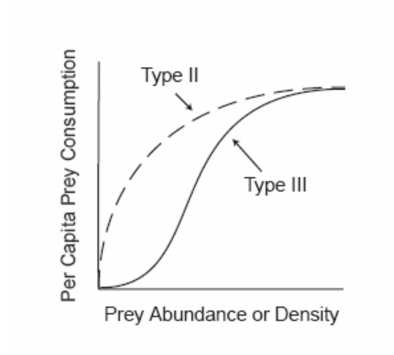


Figure 35: Functional responses that could be used to describe foraging by predators in Antarctic ecosystems. Not to be cited except for the purpose of CCAMLR: only the main features considered at the workshop are shown and, as such, this may be incomplete.

ATTACHMENT 1

AGENDA

Workshop on Plausible Ecosystem Models
for Testing Approaches to Krill Management
(Siena, Italy, 12 to 16 July 2004)

1. Opening of the workshop
   - 1.1 Purpose of the workshop
   - 1.2 Rapporteurs

2. Report from the Steering Committee on intersessional activities
   - 2.1 Invited experts
   - 2.2 Literature review of ecosystem models
   - 2.3 Catalogue of available software
   - 2.4 Existing data and estimates of parameters
   - 2.5 Aims and specifications for ecosystem modelling as it relates to the development of management procedures for krill

3. Desirable attributes of ecosystem models
   - 3.1 Attributes of models in the literature
   - 3.2 General attributes of models for evaluation of management procedures

4. Conceptual representation of key components
   - 4.1 General approach
     - 4.1.1 Biological scales
     - 4.1.2 Important attributes to consider
     - 4.1.3 Identifying needs for 'field observations'
     - 4.1.4 Direct and indirect effects of fisheries
   - 4.2 Physical environment
   - 4.3 Primary production
   - 4.4 Pelagic herbivores and invertebrate carnivores
   - 4.5 Target species
   - 4.6 Mesopelagic species
   - 4.7 Central point foragers within the system
   - 4.8 Widely distributed and migratory species
   - 4.9 Fisheries

5. Plausible scenarios for Antarctic marine ecosystems

6. Model formulation and specification
   - 6.1 Modelling interactions between species
   - 6.2 Handling space
   - 6.3 Handling time
   - 6.4 Peripheral processes and boundary conditions

7. Future work
   - 7.1 Tools available
   - 7.2 Software development
   - 7.3 Software requirements
   - 7.4 Coordination

8. Report adoption

9. Close of workshop.

ATTACHMENT 2

LIST OF PARTICIPANTS

Workshop on Plausible Ecosystem Models
for Testing Approaches to Krill Management
(Siena, Italy, 12 to 16 July 2004)

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