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Title **A COMPILATION OF PARAMETERS FOR A KRILL-FISHERY-PREDATOR MODEL OF THE SCOTIA SEA AND ANTARCTIC PENINSULA.**

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ABSTRACT

We describe the compilation and derivation of parameters for use in krill-fishery-predator models of the Scotia Sea – Antarctic Peninsula region. The primary aim is to provide input for the model developed by Watters et al. (2006), which we use to define the required parameters. However, these parameters should be applicable to other models of the system. Our methods include the use of weighted averages to derive “generic” parameters from multiple species in a taxonomic group, and the derivation of potential krill transport rates from the OCCAM global ocean circulation model. This parameter set, like most others, is associated with considerable uncertainty, which must be taken into account when it is used. We have therefore documented our sources, assumptions and calculations at every stage of the compilation process. Our calculations suggest that myctophid fish are the major consumers of Antarctic krill in the Scotia Sea – Antarctic Peninsula region.

SUMMARY OF FINDINGS AS RELATED TO NOMINATED AGENDA ITEMS

Agenda Item Findings We provide a compilation of parameters required to run the updated KPFM. This compilation may also be useful for other models of the system.

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A COMPILATION OF PARAMETERS FOR A KRILL-FISHERY-PREDATOR MODEL OF THE SCOTIA SEA - ANTARCTIC PENINSULA REGION.

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ABSTRACT

We describe the compilation and derivation of parameters for use in krill-fishery-predator models of the Scotia Sea – Antarctic Peninsula region. The primary aim is to provide input for the model developed by Watters *et al.* (2006), which we use to define the required parameters. However, these parameters should be applicable to other models of the system. Our methods include the use of weighted averages to derive “generic” parameters from multiple species in a taxonomic group, and the derivation of potential krill transport rates from the OCCAM global ocean circulation model. This parameter set, like most others, is associated with considerable uncertainty, which must be taken into account when it is used. We have therefore documented our sources, assumptions and calculations at every stage of the compilation process. Our calculations suggest that myctophid fish are the major consumers of Antarctic krill in the Scotia Sea –Antarctic Peninsula region.

INTRODUCTION

The work program of CCAMLR’s working group on Ecosystem Monitoring and Management includes the evaluation of options for allocating krill catch limits amongst small-scale management units (SSMUs) in the Scotia Sea –Antarctic Peninsula region (Hewitt *et al.* 2004a). This process will involve simulating the effects of candidate options on krill and its predators using one or more spatially resolved ecosystem models.

The krill-fishery-predator model (KPFM2) developed by Watters *et al.* (2006) represents krill and predator populations at the spatial scale of SSMUs. It requires

parameters describing life-history characteristics and interactions with krill for up to four predator populations in each of these units. It also requires parameters describing the abundance, size and non-predation mortality rate of krill, historical catch levels and the minimum density of krill required to sustain fishing in each of these units. The model can also be used to explore hypotheses about the importance of krill transport on ocean currents, the relative competitive abilities of predators and the role of climatic forcing in krill recruitment, each of which require further optional parameterisation.

In this paper we compile and derive parameters required for KPFM2, with particular attention to those describing predator populations and krill transport. We derive parameters for two seasons, corresponding to the six months from 1st October, which we refer to as summer (or season 1 in KPFM2 input) and the six months from 1st April, which we refer to as winter (season 2 in KPFM2 input).

Although our primary purpose is to parameterise KPFM2, these parameters should be applicable to other models of the system. Our intention is to produce the best parameter set available. However it is important to recognise that this is not a definitive set but rather one that reflects current knowledge of the system. We provide details of our sources, methods and assumptions, which serve as an audit trail. This is intended to provide the information required to stimulate debate and research that will challenge our assumptions and address important gaps in this knowledge. The derivation of some parameters, such as the krill movement matrix is described in self-contained sections of the main text. However, the derivation of many parameters required specific calculations, which we have detailed in accompanying notes.

SSMU AREAS

The basic spatial unit of KPFM2 and the current parameter set is the SSMU. The model includes additional spatial units, known as “bathtubs” that border these management units and represent the spatial boundaries of the model. In this parameterisation we consider three bathtubs corresponding to areas in the Bellinghousen Sea, the Drake Passage and the Weddell Sea respectively (Fig 1). These bathtubs are essentially boxes fitted around the furthest distances that particles originating in the SSMUs could travel over six months, and the furthest distances from which particles could reach the SSMUs in six months. These values were calculated by tracking particle advection in model velocity fields on a horizontal grid of resolution 0.25° latitude by 0.5° longitude (see next section).

The area within each SSMU was provided by the CCAMLR secretariat and was calculated from the global seafloor topography database of Smith & Sandwell (1997). and bathtub areas were calculated from the GEBCO bathymetric database (IOC *et al.*, 2003). In compiling some parameters, we distinguished between two types of marine habitat in each SSMU. Waters with depth $\leq 500\text{m}$ were defined as “shelf” areas and waters deeper than 500m were defined as “off-shelf” areas. Basic information on each SSMU, including the total krill catch from 1988 to 2002 is given in Table 1.

KRILL PARAMETERS

The mean body mass of individual krill caught in nets during the CCAMLR 2000 survey was calculated from data supplied by Volker Siegel (Sea Fisheries Institute, Hamburg, Germany). The total wet mass of 193,723 krill from 93 hauls was 88,729g, giving a mean mass of 0.46g. We assumed a non-predation mortality rate (M0) of zero. SSMU specific krill parameters are listed in Table 2.

The v-matrix describes the instantaneous rate of movement of krill between areas and is used to explore ideas about the role of krill flux in the dynamics of the krill-predator system. We derived parameters for the hypothesis that the rate of krill movement between areas equals the rate of passive drift on ocean currents by tracking particle movements in velocity fields output from the OCCAM global numerical ocean circulation model. This model has 66 vertical levels, with a horizontal resolution of $1/4^\circ \times 1/4^\circ$ (Coward & de Cuevas, 2005). We used a subset of output, covering the model domain $45^\circ\text{---}75^\circ\text{S}$, $100^\circ\text{---}20^\circ\text{W}$ and the upper 100 m of the water column (upper 14 model levels). For each calendar month, we calculated a depth-weighted mean velocity field over a 19 year run of this model (1985 to 2003). Prior to use in the advection scheme, the monthly mean velocity fields were modified according to Killworth (1996) to avoid errors associated with linear interpolation between mean fields.

The particles were advected using a second order Runge-Kutta advection scheme, following Murphy *et al* (2004). The advection scheme used a timestep of 0.1 day and did not explicitly include diffusion. The scheme applies a no slip boundary condition at coasts and, once particles leave the model domain, they take no further part in the simulations. Particles were released on a regular grid within predefined areas of the SSMUs and bathtubs, with resolution of 0.25° lat x 0.5° lon. The particles were advected through the velocity fields for 183 days (~6 months) beginning on either 1st October or 1st April to parameterise the summer and winter matrices respectively.

The value of each cell in the v-matrix was calculated as follows:

$$v_{i,j \neq i} = -\log_n \left(1 - \frac{\theta_{i,j}}{\tilde{\theta}_i} \right) \quad [1a]$$

$$v_{i,i} = 0 \quad [1b]$$

where $\tilde{\theta}_i$ is the number of particles released in area i at the beginning of the advection period and $\theta_{i,j}$ is the number of these particles that were found in area j at the end of the period. The resulting summer and winter matrices are given in Tables 3 and 4.

GENERIC PREDATORS

KPFM2 allows the analyst to specify up to four types of predator per SSMU. We compiled parameters for four important groups of vertebrates that prey on krill: baleen whales, seals, penguins and fish. Each of these groups is composed of several species

in the Scotia Sea – Antarctic Peninsula region, and the members of some groups, particularly fish, have very different characteristics. We calculated parameters for generic members of each group based on the averages of relevant characteristics weighted by the krill consumption of the initial population of each species within the group. The basic calculation for a generic predator parameter was:

$$\tilde{P}_{t,a} = \frac{\sum_{i=1}^s D_{i,a} P_{i,a}}{\sum_{i=1}^s D_{i,a}} \quad [2]$$

where $\tilde{P}_{t,a}$ is the generic value of parameter P for taxon t , $P_{i,a}$ is its value for the i 'th of s species in taxon t in area a , and $D_{i,a}$ is the total annual krill consumption of species i in area a .

PREDATOR RECRUITMENT PARAMETERS

Our recruitment parameters were largely assumed. However we were able to calculate limits for the maximum per capita recruitment at low abundance, α , for some groups as follows:

$$\alpha_{\max} = r_{\max} + 1 - e^{-M_A} \quad [3a]$$

$$\alpha_{\min} = \Lambda \cdot e^{-M_J \cdot \rho} \quad [3b]$$

where M_A and M_J are the adult and pre-recruit mortality rates, r_{\max} is the maximum observed rate of population increase, Λ is the observed number of live offspring produced per breeding adult per year and ρ is the age at recruitment to the adult population.

FISH

The krill eating fish fauna is composed largely of demersal members of the order Perciformes (mainly families Nototheniidae and Channichthyidae, the icefish) and pelagic members of the family Myctophidae. We assumed that off-shelf areas were populated by a generic myctophid and that shelf areas were populated by a generic perciform. We therefore began by calculating parameters for generic fish within these taxa. We calculated abundance and krill consumption parameters for perciform fish from data in Kock (1985) (Table 5, note F1) and we used life history parameters for *Champocephalus gunnari* (Table 7, note F3) which was the main krill consumer identified in that study. We calculated generic myctophid parameters from data in Pusch *et al.* (2004) describing *Electrona antarctica* and *Gymnoscopelus nicholsi*, the two main krill eating myctophids identified in that study (Table 6, notes F2 & F3).

Our generic fish parameters for each SSMU were the weighted averages of these generic perciform and myctophid parameters (Tables 7 & 8, notes F4 & F5). As table 7 shows, the body mass and mortality rates of these two taxa are very different, so the characteristics of generic fish varied with the relative area of the two habitats in each SSMU.

We assumed the stock-recruit parameters for generic fish on the basis that myctophids are probably capable of rapid population growth at low densities. KPFM2 input parameters for fish are given in tables 9 and 10.

SEALS

We considered only one species of seal, the Antarctic fur seal, *Arctocephalus gazella*. There are considerable differences between the sexes of this species, in characteristics including age at first reproduction, body size and mortality rate (Table 11). In addition, a substantial proportion of adult females do not breed each year, and these non-breeders are likely to have lower food requirements than those nursing pups. We therefore calculated average characteristics across these three different groups of adult fur seals. This required the construction of a simple demographic projection to calculate sex ratios (Table 12, note S2). We obtained estimates of the annual krill requirements of fur seal pups and adult males and females from Boyd (2002a) (see note S3) and life-history parameters from McCann & Doidge 1987, Boyd *et al.* (1995), Wickens & York (1997) and Boyd (2002b). We converted annual requirements to seasonal requirements using assumed proportions of the annual requirement taken in each season (Table 11, note S4). We also added the first season requirement of pups to that of breeding females.

SC-CAMLR (2002) lists the position of fur seal breeding colonies and the abundance of breeding females in each colony. We assigned these colonies to the SSMUs they were located in and scaled up the abundance estimates to include males and non-breeding females (Table 13).

We calculated $\alpha_{\max} = 0.39$ (equation 3a, note S4) for seals on the basis of an observed 16.8% population growth rate at South Georgia (Payne, 1977) and $\alpha_{\min} = 0.28$ (equation 3b, note S4) on the basis of the parameters listed in table 11 and assuming an even sex ratio at birth. KPFM2 input parameters for seals are given in tables 14 and 15.

PENGUINS

We calculated generic penguin parameters using specific parameters for adélie, (*Pygoscelis adeliae*) chinstrap (*Pygoscelis antarctica*), gentoo (*Pygoscelis papua*) and macaroni (*Eudyptes chrysolophus*) penguins. We added data for four additional adélie penguin colonies to those listed in SC-CAMLR 2002 provided by the CCAMLR secretariat (Table 16). We assigned the colonies, which were derived largely from Woehler (1993), to SSMUs on the basis of location (Table 17). We obtained basic life-history parameters from Williams (1995). However, we were unable to find adult mortality rates for chinstrap penguins, or juvenile mortality rates and the proportion of non-breeding adults for all species, so we assumed these values (notes P1 to P3). We calculated the seasonal krill requirements of adélie, chinstrap and gentoo penguins from the krill consumption estimates and population structures in Croll & Tershy

(1998) (note P4). We assumed a 1:1 sex ratio in the adult population and that the individual krill requirements of adults were constant throughout the year. We also added chick requirements during the breeding season to those of adults (notes P5, P6). We halved the annual krill demand estimates for macaroni penguins in Boyd (2002) to obtain seasonal requirements (Table 18, note P6)

We calculated α_{\min} for each penguin species on the basis of the parameters listed in table 16 and used these to calculate generic values for each SSMU. Generic penguin abundance and demand estimates are given in table 19 while KPFM2 input parameters for penguins are given in tables 20 and 21.

WHALES

Reilly *et al.* (2004) estimated the abundance and krill requirements of fin (*Balaenoptera physalus*), humpback (*Megaptera novaeangliae*), minke (*B. bonaerensis*) and southern right whales (*Eubalaena australis*) as well as the overall abundance of “large baleen” whales including humpback, fin, southern right, blue (*B. musculus*) and sei (*B. borealis*) whales in the strata corresponding to the Scotia Sea and Antarctic Peninsula regions. We used these data, together with life-history parameters from Laws (1977) and Boness *et al.* (2002) to estimate generic parameters for each region (Tables 22 to 24, notes W1 to W8). We were unable to find a mortality estimate for Southern Right Whales, so we assumed this value. Reilly *et al.* (2004) did not distinguish between blue and sei whales and we assumed that the ratio of sei to blue whales was 10:1 (note W1). We multiplied the area of each SSMU by the density of generic baleen whales in the relevant strata to obtain the abundance in each SSMU (Table 25).

We calculated generic values of α_{\min} for the two strata on the basis of the parameters listed in table 22. KPFM2 input parameters for whales are given in tables 26 and 27.

FURTHER ASSUMPTIONS AND PARAMETER TUNING.

The calculations described above resulted in estimates of predator abundance, mortality, maximum recruit production and maximum krill consumption. The other parameters required in the functional response and recruitment functions are not readily derived from the literature. We arrived at values for these additional parameters through a combination of assumptions, sensitivity analysis and an iterative tuning process.

The functional response (describing the relationship between krill density and the potential per-capita consumption of krill by predators) includes the parameters κ (the krill density at which predators achieve half of the maximum potential per-capita consumption) and q (a shape parameter determining whether the functional response is asymptotic or sigmoidal). We were unable to find any functional responses for the relevant predators so we assumed that κ should be smaller for predators with low daily food requirements (fish) and for wide-ranging species (whales), and generally higher for the predators that are central place foragers during part of the year

(penguins and seals). We assumed that all predators have a Type II (asymptotic) functional response and, thus, set $q_i = 0$ for all areas.

The predator recruitment function in KPFM2 requires the analyst to specify the parameters α (maximum per-capita recruitment when all adults breed), R_{peak} (the maximum recruitment when all adults breed), $Speak$ (the adult abundance that produces maximum recruitment) and φ (a shape parameter determining the effect of krill availability on the proportion of adults that breed). To estimate $Speak$ and R_{peak} for each predator species, we held all other parameters constant, and used a graphical procedure to set $Speak$ at a value that maximizes recruitment. A plot of recruitment versus $Speak$ has an apex whose position relative to $Speak$ is insensitive to the value of R_{peak} . We therefore set $Speak$ to coincide with this apex and then iteratively adjusted the value of R_{peak} until the number of recruits balanced the number of deaths.

To calculate the parameters presented in this paper we used a value of $\varphi=2$ for all predators. This describes an exponential relationship between krill availability and the proportion of adults that breed, so the latter is sensitive to small changes in the former (“hyper-depletion”). This is an important structural consideration that requires more investigation. We were able to produce plausible dynamics with φ values of 0.2 (hyper-stable), 1 (linear), and 2 (hyper depleting). A value of 5 resulted in strong and persistent oscillations in most of the predator dynamics.

Once we had obtained a complete parameter set for each predator we used KPFM2 simulations, with constant krill recruitment and no krill transport (all $v_{i,j}=0$), to identify a value of α for krill such that krill recruitment balanced predator demand: We ran two, one beginning in the first season (summer) and one beginning in the second season (winter). We then summed the initial predator demand in each SSMU from each simulation to obtain the annual demand in each SSMU. Finally, we divided by the mean mass of individual krill to obtain demand in terms of krill numbers, which was also our estimate of α for krill.

Although this process produced a parameter set in which krill recruitment generally matches predator demand, predator demand exceeded current krill density estimates for SSMUs 1 (Antarctic Peninsula Pelagic Area) and 14 (South Georgia West). As a consequence, the dynamics in SSMU 1 did not reach a static equilibrium but, rather, stable limit cycles.

FORAGING MATRIX

KPFM2 allows the analyst to specify, for each predator population in each SSMU, the proportion of its seasonal krill requirement that it attempts to obtain from each other area in the model (SSMUs and bathtubs). We assumed that all predators forage exclusively in their home SSMUs during the summer season and that fish remain resident year round. We assumed that baleen whales do not feed in the SSMUs or bathtubs in the winter and we did not parameterise their winter foraging distribution. For penguins and fur seals we assumed the distribution of winter foraging amongst the different habitat types shown in table 28, and we calculated values for generic

penguins in each SSMU using equation 2. We then divided krill demand amongst SSMUs according to the proportion of relevant habitat types in each:

$$P_j(\Gamma_i) = I_j \cdot P_i(\Gamma_i) + \frac{C_j}{\sum_{k=1}^s C_k} \cdot P_c(\Gamma_i) + \frac{O_j}{\sum_{k=1}^s O_k} \cdot P_o(\Gamma_i) \quad [4]$$

where $P_j(\Gamma_i)$ is the proportion of its krill requirement that a predator from SSMU i attempts to obtain from SSMU j , and $P_c(\Gamma_i)$ and $P_o(\Gamma_i)$ are the proportions it attempts to obtain from shelf and off-shelf areas respectively; I_j has value 1 if $i=j$ and 0 otherwise, C_k is the total shelf area and O_k the total off-shelf area in SSMU k and s is the total number of SSMUs. The resulting winter foraging matrices for seals and penguins are shown in tables 29 and 30.

DISCUSSION

We have compiled a set of parameters for the KPFM that represents currently available information about Antarctic krill and its vertebrate predators in the Scotia Sea – Antarctic Peninsula region. We have compiled information about a number of species taken from studies at a range of spatial and temporal scales into a coherent and spatially resolved view of the regional krill-based foodweb. This can be used to parameterise models of this foodweb, but it should also be a useful reference for other analyses of the system at the regional and SSMU scales. We have also illustrated a practical method for linking output from a numerical ocean model to an ecosystem dynamics model. Such links between models operating at different scales are likely to be essential in the use of ecosystem models to evaluate the likely effects of fisheries management.

The complexity and scale of the system and its dynamics ensure that it will be impossible to ever describe it fully. Therefore while our parameters might summarise the best available information about selected krill predators, they should not be considered definitive. Analysts and resource managers using these parameters should be aware of their associated uncertainties. We have tried to provide a clear audit-trail of our sources, methods and assumptions to facilitate the necessary scrutiny, and we recommend this as good practice in the compilation of similar parameter sets.

Our parameter set does not include traditional estimates of the uncertainty associated with parameter values. In part this is because such estimates are often misleading, evaluating only the natural variability or measurement error in the source data. These estimates do not provide any indication of other sources of uncertainty that might affect model results, such as extrapolations from limited studies or assumptions about the processes controlling the system's dynamics. We advocate the quantification of all sources of uncertainty, and we suggest that the most appropriate way to do this is through the comparison of contrasting parameter sets that describe bounds on likely values. We therefore devote most of this discussion to highlighting some uncertainties associated with the current parameter set.

We have compiled empirical values from a variety of studies focusing on different, but limited, temporal and spatial scales. These studies inevitably represent a

“snapshot” of conditions that might not apply to other scales. In particular, our abundance estimates for the various predators may represent different states in the system’s dynamics. Also, we have extrapolated myctophid fish diets and densities from the shelf slope near King George Island to all waters deeper than 500m. Our extrapolations and assumptions of contemporaneity do not imply that the system is homogenous and stable at these scales. They merely highlight a lack of suitable information on its heterogeneity and dynamics.

KPFM2 considers up to four predator types per area, and this constraint is reflected in our choice and parameterisation of generic predators. The taxonomic groups include the “krill dependent” penguins and seals that are an important focus of the CCAMLR Ecosystem Monitoring Program, the baleen whales, and fish. This combination is intended to represent current interest in the conservation of endothermic predators and the maintenance of viable fish stocks, and to capture important sources of krill consumption. However, this is not a comprehensive survey and we have not included other potentially important consumers such as crabeater seals and squid, as there are few data to assess their abundance and krill requirements.

Myctophid and perciform fish have very different life histories and adult body sizes. There is also much variation within the diverse perciform fauna, and *C. gunnari* might not be representative, especially in terms of its longevity and age at maturity. The differences between myctophids and perciforms have resulted in very different generic fish parameters for pelagic areas and shelf areas. Therefore, while our generic parameters attempt to describe the key characteristics of the fish fauna in each SSMU, they are not suitable for simulating the dynamics of specific fish stocks.

We envisage using KPFM2 primarily to assess the effects of various management options on a krill-predator system in which krill production initially balances predator demand. KPFM2 represents krill production through local recruitment, which might be augmented by krill transport from other areas. For simplicity, the model does not include krill growth or spatial differences in mean size. Therefore while data are available to describe these processes, they are not applicable to the current implementation of the KPFM2.

Our v-matrix parameters represent an upper bound on possible krill transport scenarios. That is, the hypothesis that krill are advected as passive particles on ocean currents. The contrasting extreme is that there is no krill movement between SSMUs. That is, a v-matrix in which every cell has value zero.

Other issues include, for example: (1) Different whale species may have very different patterns of habitat use and baleen whale distribution might therefore differ from our assumptions. (2) Breeding and non-breeding members of the same species also have different spatial distributions, so the total adult size may not always scale linearly with the breeding population size. (3) Most of the studies used to estimate krill consumption were conducted in the austral summer. We therefore have very few data on winter diets. (4) We also have few data on the winter distribution of predators, and those studies that have been conducted through tracking a small number of individuals are not suitable for estimating the distribution of whole populations. (5) Model estimates of krill demand are sensitive to their assumptions, such as the number of hours spent feeding per day.

Our calculations suggest that fish are the most important krill consumers in the Scotia Sea – Antarctic Peninsula region, with an annual demand accounting for 83% of that for the four groups of predators that we considered (c. 69 million tonnes before parameter tuning). Myctophids alone are responsible for 65% of the total demand, penguins for 11% and whales and seals for 3% each. These figures must be interpreted in the light of the above caveats, but they suggest that krill demand outstrips estimated biomass, implying that most demand is met by short-term production. They also suggest that establishing a better picture of myctophid distribution and krill consumption is a high priority in terms of understanding the dynamics of this system.

The catch allocations in Hewitt *et al.* (2004a) were based on SSMU-specific estimates of predator abundance and krill demand that we have up-dated in the current paper. Consequently, the catch allocations must also be updated and it should be remembered that KPFM2 evaluates the catch allocations implied by its input parameters, which are likely to be different from those in Hewitt *et al.* (2004)

In conclusion, we have used a combination of empirical data, published models, informed estimates, parameter tuning and sensitivity analysis to obtain parameter values. This exercise has produced a compilation of parameters that will be useful in parameterising models of krill and predator dynamics in the Scotia Sea – Antarctic Peninsula region. However, there are many uncertainties associated with these parameters, which must be taken into account when they are used. KPFM2 is designed to investigate the implications of differing assumptions and parameter values and we recommend that full use is made of this facility.

This exercise also highlights some limitations of the available data on issues addressed by KPFM2. An idealised shopping list of data would include simultaneous estimates of the abundance and krill consumption of each of the main predator groups and of the density of krill. However, a more tractable but equally worthwhile project would be to assess variability in the abundance and krill requirements of myctophid fish throughout the region.

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NOTES

Fish

F1. Kock (1985) included data from a third survey at South Georgia in the 1980/81 season, which we omitted to allow comparability between areas when calculating averages. We replaced Kock's (1985) krill consumption estimates for *P. georgianus* at South Georgia in 1977/78, *C. gunnari* at the South Orkneys in 1975/76 and *C. rastropinosus* at the South Orkneys in 1977/78 with the values shown in Table 5 to maintain a constant relationship between trawlable biomass and krill consumption in each area.

F2. We calculated the mean weight of myctophid species as biomass over individuals, and biomass per unit area as 0.6 times biomass per 1,000m³ on the assumption that myctophids occupy a depth range of 600m. Daily krill consumption is based on 10 hours feeding per day. This value was multiplied by 365 to obtain annual consumption per unit biomass, and further multiplied by biomass density to obtain annual consumption per unit area.

F3. We calculated myctophid mean mass as the average of the two species in Table 6 weighted by their daily krill consumption densities. The mean mass of perciforms is based on *C. gunanri* in age classes 3+ to 7+ using the von Bertalanffy growth parameters of North (2005), the length weight relationship of Agnew *et al* (1998) and assuming constant recruitment and annual mortality rate of 0.48. The annual mortality rates are those for *E. antractica* (Konstantinova 1987, cited in Kock 1992) and *C. gunanri* (Agnew *et al.* 1998) and the ages at first reproduction were assumed. Myctophid biomass density is the sum of values for the two species in Table 6 and perciform biomass density is the sum of biomass values divided by twice the sum of areas in Table 5.

F4. We assumed that each taxon consumes two thirds of its annual krill requirement in summer and the remaining third in winter. We calculated the annual krill requirement per unit biomass of myctophids as the sum of values for the two species in Table 6 and that of perciforms as summed consumption over summed biomass from Table 5. We multiplied these values by mean body mass to calculate the requirements of individual fish.

F5. We calculated the abundance of individual fish taxa as biomass density multiplied by habitat area (shelf or off-shelf) divided by mean body mass. We multiplied these figures by individual krill requirements to calculate total demand. We divided total demand by the individual requirements of generic fish to calculate the abundance of generic fish.

Seals

S1. Annual natural mortality rates were calculated from survivorship estimates in Boyd (2002b) for males (0.5) and Boyd *et al.* (1995) for females (0.83). The value for pups was assumed equal to that for adult females. The ages at first breeding for each sex, the maximum breeding age of females (reproductive longevity = 23 years), and the proportion of non-breeding females (pregnancy rate = 77.4%) were taken from Wickens & York (1997).

S2. The female:male ratio (1:0.16) was calculated from the simple demographic model in Table 12, based on the mortality, recruitment age and longevity parameters in Table 11. The male mortality rate was assumed to be equal to the female mortality rate until the males joined the breeding population. The distribution of annual demand between summer and winter was assumed for all classes.

S3 Annual krill demand was estimated using data from Boyd (2002a). We divided the total annual krill demand (3.84 million tonnes) amongst the different sexes and age classes in Table 3 of Boyd (2002a) according to the sum of carbon flux and sequestration (growth) for each age class in each sex.

S4: We calculated the overall mortality rate as the average of male and female rates

i.e. $M_G = \frac{oM_M + M_F}{1 + o}$ where o is the number of adult males (aged ≥ 7 years) per

adult female and M_M and M_F are the male and female mortality rates. We set the value of α at a level that gives a population growth rate (calculated as $e^{-M_G} + \alpha - 1$) of approximately 17% (Payne, 1977), and we used arbitrary values for the division of krill demand amongst seasons. Seasonal per-capita krill consumption was calculated

as $Q_i^* = \frac{\omega_J \cdot P_i(\omega_J) + \omega_M \cdot P_i(\omega_M) \cdot m + \omega_F \cdot P_i(\omega_F) \cdot (1+n)}{1 + n + m}$

where n is non-breeding females per breeding female, m is males per breeding females, ω_J is the annual krill demand of juveniles and $P_i(\omega_J)$ is the proportion of this demand taken in season i .

Penguins

P1: Individual body mass estimates were calculated from SC-CAMLR (2002) as Biomass/(2*Number of pairs)

P2. Where possible, penguin life history parameters were obtained or derived from Williams (1995). Adult M for adélie and gentoo penguins was estimated as the negative log of the average of the minimum and maximum adult survivorship values quoted (0.809 to 0.907 and 0.75 to 0.85 respectively). Adult M for macaroni penguins was estimated from an assumed survivorship of 0.92, which is based on 78% of breeders returning to colonies the next year and a maximum 14% of the population not breeding. Juvenile M was assumed for all species. The number of chicks fledged per breeding adult for adélie penguins was the middle of the quoted range for Signy Island (0.77 to 1.27 per pair), that for chinstrap penguins was the average of five

quoted values (1.83,0.016,0.36,1.02,0.56 per pair), that for gentoo penguins was an 11 year average for South Georgia (0.85 per pair) and that for macaroni penguins was the middle of the range quoted for South Georgia (0.34 to 0.52) per pair. The proportion of non-breeding adults was assumed for all species based on the following figures: 2 to 14% of macaroni penguins, 4-26% of male adélie penguins and 2-18% of female adélie penguins join colonies but do not breed.

P3: Fledging chicks per adult was calculated as chicks per breeding adult * (1- the proportion of non-breeders). α , the maximum per capita recruitment was calculated using equation 3b.

P4. Information on the krill demand of adélie, chinstrap and gentoo penguins was obtained from Croll & Tershy (1998). Table 2 of Croll & Tershy (1998) contains an apparent error in the krill requirements for adélie penguin chicks, so we recalculated this value from the energy requirements given in the same table.

P5. The number of chicks per breeding pair was calculated as chicks/breeding adults/2. Summer per-capita demand (representing the mean krill requirement of an adult penguin and its dependent offspring) for adélie, chinstrap and gentoo penguins was calculated as

$$Q_s = 0.5 \left(1.52(q_m + q_f) + \left(2 - \frac{1}{1 - P_n} \right) q_c C \right)$$

where q_m , q_f and q_c are the krill demands of males, females and chicks respectively, P_n is the proportion of non-breeders and C is the number of chicks per pair. The factor 1.52 scales the 120 day period of Croll & Tershy's (1998) estimates to half a year. Winter demand was calculated as $Q_w = 0.5(1.52(q_m + q_f))$.

P6. Krill demand by macaroni penguins was taken from Boyd (2002), who estimated that 17,876,000 adults consumed 8.08 million tonnes of krill in one year. We divided the total demand equally between summer and winter.

Whales

W1: Reilly *et al.* (2004) estimated the abundance of fin, humpback, minke and southern right whales as well as the overall abundance of "large baleen" whales including humpback, fin, southern right, blue and sei whales in the strata listed in Table 22. Our abundance estimate for "blue & sei" whales is the "large baleen" estimate minus the individual estimates for fin, humpback and southern right whales. Other parameters for "blue & sei" whales are calculated from parameters for the individual species on the assumption that the ratio of sei to blue whales is 10:1, though the ratio of confirmed sightings in Reilly *et al.* (2004) was 7:1.

W2: Consumption estimates were taken from Reilly *et al.* (2004). Estimates for minke whales are based on the consumption rates and population structure suggested by Tamura *et al.* (1997) while those for other species are based on Reilly *et al.*'s (2004) revised version of the Innes *et al.* (1986) model

W3: Mean whale body mass estimates were taken from Reilly *et al.* (2004).

W4: Estimates of the annual mortality rate for baleen whales were taken from Laws (1977) except the value for Southern Right whales, which we assumed.

W5: The age at first parturition is the lowest age quoted by Boness *et al.* (2002). The inter-birth interval is the middle of the range quoted by Boness *et al.* (2002).

W6: Biomass was calculated as the sum of products of the abundance and mean body mass of individual species given in Table 22. This was divided by stratum area to give biomass density.

W7: Baleen whales were assumed to feed on krill for 120 days in the summer (Reilly *et al.* 2004). Total summer consumption was therefore the sum of products of individual daily krill consumption and abundance of each species multiplied by 120. This was divided by the biomass of baleen whales to give krill consumption per unit baleen whale biomass for each stratum.

W8: Per-capita demand is the product of consumption per unit biomass and mean individual body mass.

W9: Baleen whale biomass and demand parameters for individual SSMUs were estimated by scaling the regional estimates in Table 23 by SSMU area (Table 1) over stratum area for the relevant region (Table 23). SSMUs 1 to 8 were assigned generic parameters for the Antarctic Peninsula region and SSMUs 9 to 15 were assigned values for the Scotia Sea region.

TABLES

Table 1. SSMU and bathtub names, areas and krill catch (1988 to 2002). Shelf area is the area of water with depth $\leq 500\text{m}$ and off-shelf area is the area of water with depth $> 500\text{m}$. SSMU areas were calculated from the Smith & Sandwell (1997) dataset, bathtub areas were calculated from the GEBCO dataset (IOC *et al.*, 2003) and krill catch data were taken from Hewitt *et al.* (2004a).

Area	Name	Shelf area (km ²)	Off-shelf area (km ²)	Total area (km ²)	Krill catch (t)
1	Antarctic Peninsula Pelagic Area (APPA)	80,971	341,105	422,076	25,376
2	Antarctic Peninsula West (APW)	26,901	8,159	35,060	7,400
3	Drake Passage West (APDPW)	6,799	8,269	15,068	227,741
4	Drake Passage East (APDPE)	7,973	7,611	15,584	103,169
5	Bransfield Strait West (APBSW)	11,243	9,773	21,017	11,463
6	Bransfield Strait East (APBSE)	14,763	12,684	27,447	5,952
7	Elephant Island (APEI)	8,141	27,182	35,322	94,930
8	Antarctic Peninsula East (APE)	55,325	3,379	58,704	25
9	South Orkney Pelagic Area (SOPA)	12,303	796,861	809,163	6,248
10	South Orkney West (SOW)	2,591	12,978	15,569	217,374
11	South Orkney North East (SONE)	2,585	7,666	10,251	15,856
12	South Orkney South East (SOSE)	13,636	1,318	14,954	19,531
13	South Georgia Pelagic Area (SGPA)	5,307	914,227	919,534	7,822
14	South Georgia West (SGW)	16,286	25,832	42,119	31,436
15	South Georgia East (SGE)	19,225	34,510	53,735	208,870
16	Bathtub 1 (Bellinghausen Sea)	1,880,955			
17	Bathtub 2 (Drake Passage)	779,869			
18	Bathtub 3 (Weddell Sea)	523,502			

Table 5. Estimated biomass and annual krill requirements of seven species of perciform fish in three areas of the Scotia Sea during surveys in the mid-1970s, and the shelf area (depth <=500m) of non-pelagic SSMUs in these areas. Biomass and krill consumption data are from Kock (1985) (see note F1). Area data are from table 1.

Area	Shelf area (km ²)	Season	<i>Notothenia rossii</i>	<i>N. gibberifrons</i>	<i>N. larseni</i>	<i>Champscephalus gunnari</i>	<i>Chaenocephalus aceratus</i>	<i>Pseudochaenichthys geogianus</i>	<i>Chionodraco rastrospinosus</i>
<i>Trawlable biomass (tones)</i>									
South Georgia	21,593	1975/76	35,682	40,094	449	141,469	18,719	36,401	-
		1977/78	9,326	20,100	422	34,713	18,399	31,057	-
South Orkneys	18,812	1975/76	133	68,430	562	140,000			8,759
		1977/78	284	29,187	505	40,000	9,854	8,270	
Elephant Island	8,141	1975/76	9,370	16,471	100	20,000			
		1977/78	15,663	17,824	90	20,000	1,249		1,015
<i>Krill consumption (tones)</i>									
South Georgia	-	1975/76	160,800	18,000	1,000	630,000	33,700	131,000	-
		1977/78	42,000	9,000	900	156,200	33,100	111,800	-
South Orkneys	-	1975/76	1,100	30,700	1,300	1,197,000	-	-	31,500
		1977/78	2,400	13,100	1,100	342,000	17,700	29,800	-
Elephant Island	-	1975/76	80,100	7,400	200	171,000	-	-	-
		1977/78	133,900	8,000	200	171,000	2,200	-	3,700

Table 6. Density, mean body mass and krill requirements of the two main krill eating myctophids sampled in slope waters near King George Island in 1996. Data from Pusch et al. (2004). See note F2 for further details.

Species	Individuals per 1000m ³	Biomass (g) per 1000m ³	Mean body mass (g)	Biomass density (kg.km ⁻²)	Daily krill intake as % fish wet weight	Annual krill consumption per unit biomass	Annual krill consumption (kg.km ⁻²)
<i>Electrona antarctica</i>	0.5948	4.0798	6.86	2,448	1.06	3.87	947,085
<i>Gymnoscopelus nicholsi</i>	0.0420	1.3681	32.57	0,821	0.65	2.37	194,749

Table 7. Further assumptions and parameters used to calculate generic fish parameters. See notes F3 and F4 for further details.

Taxon	Habitat	Mean mass (g)	M	Rage	Biomass density (t/km2)	Krill demand (g/fish/season)	South Georgia	Elsewhere
Myctophidae	Off-shelf waters (>500m)	11.24	1.14	2	3.27	Summer		46.79
						Winter		23.40
Perciformes	Shelf waters (<500m)	358.94	0.480	3	8.18	Summer	821.20	1317.70
						Winter	410.60	658.85
Details		F3	F3	F3	F3		F4	F4

Table 8. Estimated abundance and krill requirements of krill-eating perciform, myctophid and derived “generic” fish. Winter demand was assumed to be half of summer demand. See note F5 for further details.

SSMU	Perciform abundance	Myctophid abundance	Perciform summer demand (t)	Myctophid summer demand (t)	Total annual demand (t)	Fish biomass (t)	Generic fish abundance
APPA	1.85E+09	9.92E+10	2,432,726	4,639,443	10,608,253	1,777,659	1.46E+10
APW	6.13E+08	2.37E+09	808,222	110,972	1,378,791	246,830	7.90E+08
APDPW	1.55E+08	2.40E+09	204,268	112,466	475,101	82,671	3.66E+08
APDPE	1.82E+08	2.21E+09	239,543	103,522	514,597	90,131	3.67E+08
APBSW	2.56E+08	2.84E+09	337,794	132,929	706,084	123,962	4.91E+08
APBSE	3.37E+08	3.69E+09	443,535	172,523	924,088	162,281	6.41E+08
APEI	1.86E+08	7.90E+09	244,579	369,702	921,421	155,473	1.11E+09
APE	1.26E+09	9.82E+08	1,662,192	45,963	2,562,232	463,829	1.33E+09
SOPA	2.81E+08	2.32E+11	369,626	10,838,282	16,811,862	2,705,417	1.26E+11
SOW	5.91E+07	3.77E+09	77,830	176,519	381,524	63,623	5.84E+08
SONE	5.89E+07	2.23E+09	77,659	104,263	272,882	46,211	3.09E+08
SOSE	3.11E+08	3.83E+08	409,690	17,924	641,421	115,907	3.38E+08
SGPA	1.21E+08	2.66E+11	99,365	12,434,604	18,800,953	3,031,801	2.37E+11
SGW	3.71E+08	7.51E+09	304,939	351,352	984,436	217,727	1.61E+09
SGE	4.38E+08	1.00E+10	359,966	469,380	1,244,018	270,145	2.17E+09

Table 9. KPFM2 first season parameter set for fish. This table follows KPFM2 input conventions with the parameters named as in the model code on the first line and the season listed on the second line. The parameters and units are as follows: R_{age} is age on joining the adult population (years), init.type describes the units of init.value where N is number, init.value in this case is the initial population size (number of generic fish), M is the mean rate of natural mortality, M_{switch} and M_{prop} are explained in Watters *et al.* (2006) but are not parameterised in the current paper, R_{alpha} is the maximum per-capita recruitment at low adult abundance when all adults breed (number of recruits), R_{speak} is the adult abundance that produces maximum recruitment (number of adults), RR_{peak} is the maximum recruitment when all adults breed (number of recruits), R_{phi} is the shape parameter determining the proportion of adults that breed, Q_q is the functional response shape parameter, Q_{max} is the maximum potential per-capita consumption, Q_{k5} is the krill density at which half of maximum potential per capita consumption is reached (g.m⁻²).

		R _{age}	init.type	init.value	M	M _{switch}	M _{prop}	R _{alpha}	R _{speak}	RR _{peak}	R _{phi}	Q _q	Q _{max}	Q _{k5}
SSMU	SSMU	NA	NA	NA	1	1	1	1	1	1	1	1	1	1
1	APPA	2	N	1.4613E+10	0.46	0	0	10	1.52E+10	2.85E+10	2	0	1052.1	5
2	APW	3	N	789505257	0.28	0	0	10	8.00E+08	5.63E+08	2	0	2531.01	5
3	APDPW	3	N	365563864	0.36	0	0	10	3.70E+08	3.40E+08	2	0	1883.53	5
4	APDPE	3	N	367229904	0.34	0	0	10	3.70E+08	3.20E+08	2	0	2030.86	5
5	APBSW	3	N	490947932	0.33	0	0	10	5.00E+08	4.15E+08	2	0	2084.36	5
6	APBSE	3	N	640533357	0.33	0	0	10	6.60E+08	5.43E+08	2	0	2090.85	5
7	APEI	2	N	1111198021	0.44	0	0	10	1.12E+09	1.27E+09	2	0	1201.76	5
8	APE	3	N	1330853538	0.25	0	0	10	1.35E+09	8.40E+08	2	0	2790.22	5
9	SOPA	2	N	1.26E+11	0.56	0	0	10	1.30E+11	2.14E+11	2	0	192.83	5
10	SOW	2	N	583793827	0.47	0	0	10	5.80E+08	6.05E+08	2	0	947.14	5
11	SONE	2	N	308699524	0.43	0	0	10	3.10E+08	2.91E+08	2	0	1281.12	5
12	SOSE	3	N	338187162	0.25	0	0	10	3.36E+08	1.81E+08	2	0	2748.76	5
13	SGPA	2	N	2.37E+11	0.57	0	0	10	2.40E+11	4.09E+11	2	0	115.06	5
14	SGW	2	N	1614055111	0.42	0	0	10	1.65E+09	1.75E+09	2	0	883.93	5
15	SGE	2	N	2165898810	0.43	0	0	10	2.20E+09	2.41E+09	2	0	832.41	5

Table 10. KPFM2 second season parameter set for fish.

SSMU	SSMU	M	Mswitch	Mprop	Ralpha	RSpeak	RRpeak	Rphi	Qq	QQmax	Qk5
		2	2	2	2	2	2	2	2	2	2
1	APPA	0.46	0	0	0	99	99	2	0	526.05	5
2	APW	0.28	0	0	0	99	99	2	0	1265.51	5
3	APDPW	0.36	0	0	0	99	99	2	0	941.77	5
4	APDPE	0.34	0	0	0	99	99	2	0	1015.43	5
5	APBSW	0.33	0	0	0	99	99	2	0	1042.18	5
6	APBSE	0.33	0	0	0	99	99	2	0	1045.42	5
7	APEI	0.44	0	0	0	99	99	2	0	600.88	5
8	APE	0.25	0	0	0	99	99	2	0	1395.11	5
9	SOPA	0.56	0	0	0	99	99	2	0	96.42	5
10	SOW	0.47	0	0	0	99	99	2	0	473.57	5
11	SONE	0.43	0	0	0	99	99	2	0	640.56	5
12	SOSE	0.25	0	0	0	99	99	2	0	1374.38	5
13	SGPA	0.57	0	0	0	99	99	2	0	57.53	5
14	SGW	0.42	0	0	0	99	99	2	0	441.97	5
15	SGE	0.43	0	0	0	99	99	2	0	416.21	5

Table 11. Parameters for Antarctic fur seals. See notes S1 to S4 for further details. Parameter names are explained in the legend to table 9.

	Male	Female	Pup	Species	Source
M	0.69	0.19	0.19		0.26 S1/S4
Rage	7	3			4 S1
Maximum breeding age		26			S1
Proportion of adults that do not breed					0.23 S1
Non-breeding females per breeding female					0.29 S1
Adult males per female					0.16 S2
Adult males per breeding female					0.21 S2
Ralpha					0.39 S4
Annual krill demand (kg)	3,997	1,778	1,225		S4
Proportion of annual demand that happens in first season	0.5	0.5	0.7		S4
Proportion of annual demand that happens in second season	0.5	0.5	0		S4
Qqmax (summer) (g)					1,615,385 S4
Qqmax (winter) (g)					1,044,677 S4

Table 12. Simple demographic projection for Antarctic fur seals used to calculate sex ratios (see note S2).

Age	Male	Female
3		1
4		0.83
5		0.69
6		0.57
7	0.47	0.47
8	0.24	0.39
9	0.12	0.33
10	0.06	0.27
11	0.03	0.23
12	0.01	0.19
13	0.01	0.16
14	0.00	0.13
15	0.00	0.11
16	0.00	0.09
17	0.00	0.07
18	0.00	0.06
19	0.00	0.05
20	0.00	0.04
21	0.00	0.03
22	0.00	0.03
23	0.00	0.02
24	0.00	0.02
25	0.00	0.02
26	0.00	0.01
Totals	0.95	5.82
Males/female	0.16	

Table 13. Population size and krill demand of Antarctic fur seals in each SSMU. Female population size data from SC-CAMLR 2002.

	Number of breeding females	Annual krill demand (t)	Total population size
APPA	-	-	-
APW	-	-	-
APDPW	9,138	36,531	13,733
APDPE	158	632	237
APBSW	-	-	-
APBSE	-	-	-
APEI	750	2,998	1,127
APE	-	-	-
SOPA	-	-	-
SOW	-	-	-
SONE	-	-	-
SOSE	-	-	-
SGPA	-	-	-
SGW	457,540	1,829,123	687,624
SGE	4,560	18,230	6,853

Table 14. KPFM2 first season parameter set for seals.

SSMU	SSMU	Rage NA	init.type NA	init.value NA	M 1	Mswitch 1	Mprop 1	Ralpha 1	RSpeak 1	RRpeak 1	Rphi 1	Qq 1	QQmax 1	Qk5 1
1	APPA	4	N	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2	APW	4	N	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
3	APDPW	4	N	13733	0.13	0	0	0.39	15500	9800	2	0	3511706	20
4	APDPE	4	N	237	0.13	0	0	0.39	290	197	2	0	3511706	20
5	APBSW	4	N	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
6	APBSE	4	N	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7	APEI	4	N	1127	0.13	0	0	0.39	1320	860	2	0	3511706	20
8	APE	4	N	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
9	SOPA	4	N	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
10	SOW	4	N	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11	SONE	4	N	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
12	SOSE	4	N	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
13	SGPA	4	N	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
14	SGW	4	N	687624	0.13	0	0	0.39	7.45E+05	4.50E+05	2	0	3511706	20
15	SGE	4	N	6853	0.13	0	0	0.39	7.70E+03	4.75E+03	2	0	3511706	20

Table 15. KPFM2 second season parameter set for seals.

SSMU	SSMU	M 2	Mswitch 2	Mprop 2	Ralpha 2	RSpeak 2	RRpeak 2	Rphi 2	Qq 2	QQmax 2	Qk5 2
1	APPA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2	APW	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
3	APDPW	0.13	0	0	0	99	99	2	0	2271037	20
4	APDPE	0.13	0	0	0	99	99	2	0	2271037	20
5	APBSW	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
6	APBSE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7	APEI	0.13	0	0	0	99	99	2	0	2271037	20
8	APE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
9	SOPA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
10	SOW	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11	SONE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
12	SOSE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
13	SGPA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
14	SGW	0.13	0	0	0	99	99	2	0	2271037	20
15	SGE	0.13	0	0	0	99	99	2	0	2271037	20

Table 16. Population size data for four adélie penguin colonies that were not included in SC-CAMLR (2002).

Species	Centre No	Long	Lat	Number of pairs	Biomass
Adélie penguin	104	-45.0333	-60.7333	16,750	150,750
	105	-44.4000	-60.7167	94,462	850,158
	106	-45.9167	-60.6333	5,700	51,300
	107	-44.6833	-60.7667	24,600	221,400

Table 17. Biomass (kg) by species of breeding penguins in each SSMU. Data from SC-CAMLR (2002) and table 16.

SSMU	Adélie	Chinstrap	Gentoo	Macaroni
APPA				
APW	395,289	300,792	230,688	
APDPW	18	229,320	42,240	
APDPE		3,735,280	77,424	
APBSW		3,948,656	145,296	
APBSE	512,019	363,808	195,516	
APEI	18	4,922,560	31,200	
APE	2,767,041		9,432	
SOPA				
SOW		8,000		
SONE	1,921,716	40,000	12,120	
SOSE	1,284,525	5,575,160	134,640	
SGPA				
SGW			673,008	28,501,245
SGE			903,192	1,607,940

Table 18. Parameters for individual penguin species. See notes P1 to P6 for further details.

	Adelie	Chinstrap	Gentoo	Macaroni	Sources
Body mass (kg)	4.5	4.0	4.0	6.0	4.5 P1
Annual M (adults)	0.12	0.17	0.17	0.22	0.07 P2
Annual M (juveniles)	0.20	0.20	0.20	0.20	0.12 P2
Rage	4	2	2	2	5 P2
Average fledging chicks/individual	0.51	0.38	0.38	0.43	0.22 P2
prop non breeders	0.15	0.15	0.15	0.15	0.15 P2
fledging chicks/adult	0.43	0.32	0.32	0.36	0.18 P3
α_{min}	0.23	0.25	0.25	0.28	0.12 P3
Individual requirements for 120 days during breeding season					
male (kg)	162	142	142	128	P4
female (kg)	158	130	130	128	P4
chick (kg)	152	113	113	103	P4
Population structure					
adults	131,000	1,620,000	1,620,000	18,000	P4
chicks	129,000	770,000	770,000	19,100	P4
Chicks per pair	1.97	0.95	0.95	2.12	P5
Demand A: Per capita, for whole breeding season (g)	366,920	251,065	251,065	284,674	226,000 P5/P6
Demand B: Per capita for remaining 6 months (g)	243,333	206,833	206,833	194,667	226,000 P5/P6

Table 19. Krill demand of Antarctic and number of generic penguins each SSMU.

SSMU	Total annual demand (t)	Generic penguin abundance
APPA	0	0
APW	125,257	237,045
APDPW	34,857	75,734
APDPE	510,329	1,113,793
APBSW	545,445	1,189,859
APBSE	149,062	279,200
APEI	665,886	1,453,934
APE	442,350	725,259
SOPA	0	0
SOW	1,077	2,353
SONE	313,123	516,551
SOSE	968,432	2,001,976
SGPA	0	0
SGW	3,431,245	7,583,268
SGE	274,900	597,473

Table 20. KPFM2 first season parameter set for penguins.

SSMU	SSMU	Age NA	init.type NA	init.value NA	M 1	Mswitch 1	Mprop 1	Ralpha 1	RSpeak 1	RRpeak 1	Rphi 1	Qq 1	QQmax 1	Qk5 1
1	APPA	0	N	0	NA	NA	NA	0.25	NA	NA	NA	NA	NA	NA
2	APW	3	N	237045	0.08	0	0	0.26	2.60E+05	1.00E+05	2	0	669537.3	20
3	APDPW	2	N	75734	0.09	0	0	0.25	8.40E+04	3.70E+04	2	0	553799.3	20
4	APDPE	2	N	1113793	0.09	0	0	0.25	1.20E+06	5.30E+05	2	0	546789.3	20
5	APBSW	2	N	1189859	0.09	0	0	0.24	1.30E+06	5.60E+05	2	0	547542.9	20
6	APBSE	3	N	279200	0.07	0	0	0.25	3.00E+05	1.03E+05	2	0	676578.2	20
7	APEI	2	N	1453934	0.09	0	0	0.23	1.58E+06	6.90E+05	2	0	546101.7	20
8	APE	4	N	725259	0.06	0	0		8.00E+05	2.25E+05	2	0	797196.4	20
9	SOPA	0	N	0	NA	NA	NA	0.25	NA	NA	NA	NA	NA	NA
10	SOW	2	N	2353	0.09	0	0	0.23	2.40E+03	565	2	0	545793.5	20
11	SONE	4	N	516551	0.06	0	0	0.25	5.20E+05	8.10E+04	2	0	791093.5	20
12	SOSE	2	N	2001976	0.08	0	0		2.10E+06	4.17E+05	2	0	589005.3	20
13	SGPA	0	N	0	NA	NA	NA	0.12	NA	NA	NA	NA	NA	NA
14	SGW	5	N	7583268	0.04	0	0	0.17	7.90E+06	1.51E+06	2	0	493524	20
15	SGE	4	N	597473	0.06	0	0	0.25	6.50E+05	1.84E+05	2	0	529111.9	20

Table 21. KPFM2 second season parameter set for penguins.

SSMU	SSMU	M	Mswitch	Mprop	Ralpha	RSpeak	RRpeak	Rphi	Qq	QQmax	Qk5
		2	2	2	2	2	2	2	2	2	2
1	APPA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2	APW	0.08	0	0	0	99	99	2	0	479183.6	20
3	APDPW	0.09	0	0	0	99	99	2	0	446750.1	20
4	APDPE	0.09	0	0	0	99	99	2	0	449277.2	20
5	APBSW	0.09	0	0	0	99	99	2	0	449004.4	20
6	APBSE	0.07	0	0	0	99	99	2	0	484048.9	20
7	APEI	0.09	0	0	0	99	99	2	0	449526.7	20
8	APE	0.06	0	0	0	99	99	2	0	528715.7	20
9	SOPA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
10	SOW	0.09	0	0	0	99	99	2	0	449637.7	20
11	SONE	0.06	0	0	0	99	99	2	0	526691.6	20
12	SOSE	0.08	0	0	0	99	99	2	0	462599.2	20
13	SGPA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
14	SGW	0.04	0	0	0	99	99	2	0	490119	20
15	SGE	0.06	0	0	0	99	99	2	0	471114.2	20

Table 22. Parameters for individual baleen whale species. See notes W1 to W5 for further details.

Species	Scotia sea abundance	Antarctic Peninsula abundance	Daily krill consumption (kg)	Body mass (kg)	M	Rage	Inter-birth interval
Fin	3,180	1,492	693	48,768	0.04	5	2.5
Humpback	2,493	6,991	497	26,924	0.07	5	2.5
Minke	10,730	7,395	224	6,272	0.10	6	2.5
Southern Right	1,712	43	748	55,880	0.10	9	4.0
Blue & Sei (note W1)	1772	261	444	23,830	0.07	8	2.5
Source	W1	W1	W2	W3	W4	W5	W5

Table 23. Estimated total abundance and krill consumption by stratum in the survey reported by Reilly et al. (2004).

	Stratum area	Biomass (t)	Biomass density	Total consumption (t)	Consumption / biomass	QQmax (g)
Scotia Sea	1,591,926	427,398	0.27	949,514	2.22	69,129,805
Antarctic Peninsula	473,318	315,993	0.67	757,636	2.40	60,366,665
Source	Hewitt et al (2004b)	W6	W6	W7	W7	W8

Table 24. Generic whale parameters for two regions.

	Body mass (kg)	M	Rage	Inter-birth interval	Ralpha
Scotia Sea	31,117	0.08	6	3	0.12
Antarctic Peninsula	25,178	0.07	5	3	0.14
Source					

Table 25. Total krill demand and generic whale abundance by SSMU

SSMU	Total annual demand (t)	Generic baleen whale abundance
APPA	675,614	11,192
APW	56,120	930
APDPW	24,119	400
APDPE	24,946	413
APBSW	33,641	557
APBSE	43,934	728
APEI	56,540	937
APE	93,967	1,557
SOPA	520,869	7,535
SOW	10,022	145
SONE	6,598	95
SOSE	9,626	139
SGPA	591,916	8,562
SGW	27,112	392
SGE	34,590	500

Table 26. KPFM2 first season parameter set for whales.

SSMU	SSMU	Rage NA	init.type NA	init.value NA	M 1	Mswitch 1	Mprop 1	Ralpha 1	RSpeak 1	RRpeak 1	Rphi 1	Qq 1	QQmax 1	Qk5 1
1	APPA	5	N	11192	0.04	0	0	0.14	1.40E+04	8.30E+03	2	0	1.31E+08	15
2	APW	5	N	930	0.04	0	0	0.14	1.05E+03	165	2	0	1.31E+08	15
3	APDPW	5	N	400	0.04	0	0	0.14	460	73	2	0	1.31E+08	15
4	APDPE	5	N	413	0.04	0	0	0.14	480	75	2	0	1.31E+08	15
5	APBSW	5	N	557	0.04	0	0	0.14	640	100	2	0	1.31E+08	15
6	APBSE	5	N	728	0.04	0	0	0.14	830	130	2	0	1.31E+08	15
7	APEI	5	N	937	0.04	0	0	0.14	1070	168	2	0	1.31E+08	15
8	APE	5	N	1557	0.04	0	0	0.14	1780	278	2	0	1.31E+08	15
9	SOPA	6	N	7535	0.04	0	0	0.12	8.70E+03	1.90E+03	2	0	1.5E+08	15
10	SOW	6	N	145	0.04	0	0	0.12	150	15	2	0	1.5E+08	15
11	SONE	6	N	95	0.04	0	0	0.12	100	10	2	0	1.5E+08	15
12	SOSE	6	N	139	0.04	0	0	0.12	150	14	2	0	1.5E+08	15
13	SGPA	6	N	8562	0.04	0	0	0.12	9.80E+03	2.20E+03	2	0	1.5E+08	15
14	SGW	6	N	392	0.04	0	0	0.12	450	72	2	0	1.5E+08	15
15	SGE	6	N	500	0.04	0	0	0.12	570	90	2	0	1.5E+08	15

Table 27. KPFM2 second season parameter set for whales.

SSMU	SSMU	M	Mswitch	Mprop	Ralpha	RSpeak	RRpeak	Rphi	Qq	QQmax	Qk5
		2	2	2	2	2	2	2	2	2	2
1	APPA	0.04	0	0	0	99	99	2	0	0	15
2	APW	0.04	0	0	0	99	99	2	0	0	15
3	APDPW	0.04	0	0	0	99	99	2	0	0	15
4	APDPE	0.04	0	0	0	99	99	2	0	0	15
5	APBSW	0.04	0	0	0	99	99	2	0	0	15
6	APBSE	0.04	0	0	0	99	99	2	0	0	15
7	APEI	0.04	0	0	0	99	99	2	0	0	15
8	APE	0.04	0	0	0	99	99	2	0	0	15
9	SOPA	0.04	0	0	0	99	99	2	0	0	15
10	SOW	0.04	0	0	0	99	99	2	0	0	15
11	SONE	0.04	0	0	0	99	99	2	0	0	15
12	SOSE	0.04	0	0	0	99	99	2	0	0	15
13	SGPA	0.04	0	0	0	99	99	2	0	0	15
14	SGW	0.04	0	0	0	99	99	2	0	0	15
15	SGE	0.04	0	0	0	99	99	2	0	0	15

Table 28. Assumed winter foraging distributions of penguins and fur seals. The values represent the proportion of total krill demand that each species attempts to obtain from the listed area or habitat type.

	Adélie	Chinstrap	Gentoo	Macaroni	Fur seal
Home area	0.10	0.00	0.50	0.50	0.00
Bathtub 1 (West Antarctic Peninsula)	0.45	0.00	0.00	0.00	0.10
Bathtub 2 (Drake Passage, Southwest Atlantic)	0.00	0.00	0.00	0.00	0.30
Bathtub 3 (Weddell Sea)	0.45	0.00	0.00	0.00	0.10
Pelagic Areas	0.00	0.86	0.00	0.43	0.43
Shelf Areas	0.00	0.14	0.50	0.07	0.07

Table 29. Winter foraging matrix for seals. The values represent the proportion of total krill demand that seals from each SSMU (rows) attempt to obtain from each SSMU or bathtub (columns).

	APPA	APW	APDPW	APDPE	APBSW	APBSE	APEI	APE	SOPA	SOW	SONE	SOSE	SGPA	SGW	APW	B1	B2	B3
APPA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
APW	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	0.09	0.01	0	0	0	0.01	0.01	0.01	0.16	0	0	0	0.18	0.01	0.01	0.1	0.3	0.1
APDPW																		
APDPE	0.09	0.01	0	0	0	0.01	0.01	0.01	0.16	0	0	0	0.18	0.01	0.01	0.1	0.3	0.1
	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
APBSW																		
APBSE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
APEI	0.09	0.01	0	0	0	0.01	0.01	0.01	0.16	0	0	0	0.18	0.01	0.01	0.1	0.3	0.1
APE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
SOPA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
SOW	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
SONE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
SOSE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
SGPA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
SGW	0.09	0.01	0	0	0	0.01	0.01	0.01	0.16	0	0	0	0.18	0.01	0.01	0.1	0.3	0.1
SGE	0.09	0.01	0	0	0	0.01	0.01	0.01	0.16	0	0	0	0.18	0.01	0.01	0.1	0.3	0.1

Table 30. Winter foraging matrix for penguins.

	APPA	APW	APDPW	APDPE	APBSW	APBSE	APEI	APE	SOPA	SOW	SONE	SOSE	SGPA	SGW	APW	B1	B2	B3
APPA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
APW	0.08	0.15	0	0	0.01	0.01	0.01	0.03	0.1	0	0	0.01	0.11	0.01	0.01	0.23	0	0.23
	0.17	0.02	0.07	0.01	0.01	0.01	0.01	0.04	0.28	0.01	0	0.01	0.32	0.02	0.02	0	0	0
APDPW																		
APDPE	0.17	0.02	0.01	0.01	0.01	0.01	0.01	0.03	0.31	0.01	0	0.01	0.35	0.02	0.02	0	0	0
	0.17	0.02	0.01	0.01	0.02	0.01	0.01	0.03	0.31	0.01	0	0.01	0.35	0.02	0.02	0	0	0
APBSW																		
APBSE	0.07	0.01	0	0	0.01	0.13	0.01	0.02	0.1	0	0	0.01	0.11	0.01	0.01	0.25	0	0.25
APEI	0.17	0.02	0.01	0.01	0.01	0.01	0.02	0.03	0.32	0.01	0	0.01	0.36	0.02	0.02	0	0	0
APE	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0.45	0	0.45
SOPA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
SOW	0.17	0.02	0.01	0.01	0.01	0.01	0.01	0.03	0.32	0.01	0	0.01	0.36	0.02	0.02	0	0	0
SONE	0	0	0	0	0	0	0	0	0.01	0	0.1	0	0.01	0	0	0.44	0	0.44
SOSE	0.13	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.24	0	0	0.04	0.27	0.01	0.02	0.1	0	0.1
SGPA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
SGW	0.09	0.01	0	0	0	0.01	0.01	0.02	0.16	0	0	0	0.18	0.51	0.01	0	0	0
SGE	0.11	0.02	0.01	0.01	0.01	0.01	0.01	0.04	0.11	0	0	0.01	0.12	0.02	0.52	0	0	0

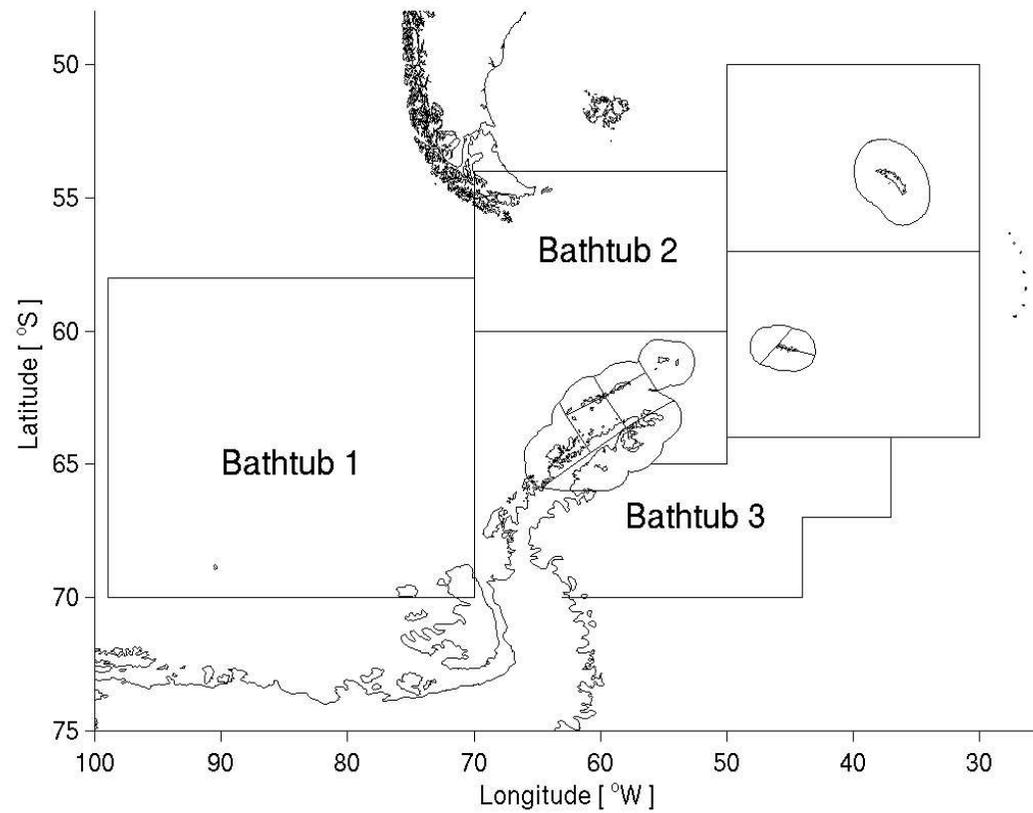


Figure 1. The Scotia Sea –Antarctic Peninsula Region, showing the SSMU and bathtub area.