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*Title* **AN UPDATED DESCRIPTION AND PARAMETERISATION OF THE SPATIAL MULTI-SPECIES OPERATING MODEL (SMOM )**  
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#### ABSTRACT

An updated version of the Spatial Multi-species Operating Model (SMOM) of krill-predator-fishery dynamics is described. This has been developed in response to requests for scientific advice regarding the subdivision of the precautionary catch limit for krill among 15 small-scale management units (SSMUs) in the Scotia Sea, to reduce the potential impact of fishing on land-based predators. The model includes krill as prey and four predator groups (penguins, seals, fish and whales) in each of 15 SSMUs. A number of updates have been made to the model such as linking krill growth rate to sea surface temperature, and these are described here. Moreover, the methodology used to condition the model using the WG-SAM set of reference observations for Area 48 (the SAM calendar) is described. Alternative combinations of model parameters essentially try to bound the uncertainty in, for example, the choice of survival rate estimates as well as the functional relationships between predators and prey. An example is given of how this Operating Model can be used to develop a management scheme which includes feedback through management control rules.

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#### SUMMARY OF FINDINGS AS RELATED TO NOMINATED AGENDA ITEMS

<i>Agenda Item</i>	<i>Findings</i>
6.3	Description of the updated methodology of SMOM (Spatial Multi-species Operating Model), an Operating Model for use in a Management Procedure Framework for assisting in developing approaches to subdivide the precautionary catch limit for krill in Area 48.

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# **An updated description and parameterisation of the Spatial Multi-species Operating model (SMOM)**

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## **ABSTRACT**

An updated version of the Spatial Multi-species Operating Model (SMOM) of krill-predator-fishery dynamics is described. This has been developed in response to requests for scientific advice regarding the subdivision of the precautionary catch limit for krill among 15 small-scale management units (SSMUs) in the Scotia Sea, to reduce the potential impact of fishing on land-based predators. The model includes krill as prey and four predator groups (penguins, seals, fish and whales) in each of 15 SSMUs. A number of updates have been made to the model such as linking krill growth rate to sea surface temperature, and these are described here. Moreover, the methodology used to condition the model using the WG-SAM set of reference observations for Area 48 (the SAM calendar) is described. Alternative combinations of model parameters essentially try to bound the uncertainty in, for example, the choice of survival rate estimates as well as the functional relationships between predators and prey. An example is given of how this Operating Model can be used to develop a management scheme which includes feedback through management control rules.

## **INTRODUCTION**

The Spatial Multi-species Operating Model (SMOM) of krill-predator-fishery dynamics (Plagányi and Butterworth 2007, 2006a,b) has been developed in response to requests for scientific advice by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). Both SMOM and FOOSA (Watters *et al.* 2005, 2006) have been used to preliminarily explore alternative scenarios involving subdivision of the precautionary catch limit for krill (*Euphausia superba*) among 15 small-scale management units (SSMUs) in the Scotia Sea. The primary aim is to assess and to ameliorate current and future potential impacts

of fishing on land-based predators, given that krill catches may increase substantially in the future.

In 2007 WG-SAM defined a set of reference observations for validating and tuning proposed models to evaluate krill catch allocation options for Area 48 (the SAM calendar). The observations, which were endorsed by WG-EMM, were largely qualitative and relative, and these observations have recently been translated into numerical terms (the numerical calendar) (Hill *et al.* 2008). The validation of SMOM using this calendar of expected changes in predator and krill abundance in the Scotia Sea is described in an accompanying paper. This paper describes the methodology used and the implications of the tuning exercise for model parameterization and formulation. Whereas an earlier paper (Plagányi and Butterworth 2007) described the application of SMOM to comparing future fishing options, the focus of this paper is on conditioning SMOM to data for the historic period 1970-2006.

## **METHODS**

### **DATA**

#### *Sea Surface Temperature*

Historic sea surface temperature data were obtained from oceanic and air-sea interface data from the UMD Simple Ocean Data Assimilation Reanalysis (CARTON-GIESE SODA Version 2.0.2-3) for the period 1967 to 2006. The data were aggregated across a southern box (57°S-64°S; 30°W-70°W), spanning SSMUs 1-12 (Antarctic Peninsula to South Orkney Islands), and a northern box (50°S-57°S; 30°W-50°W), spanning SSMUs 13-15 (South Georgia) (Fig. 1). These data were used to modify the krill growth rate as described in Appendix 4.

#### *Historic catches*

The historic krill catches input to the model are given in Table 1. Total catches for the period 1973/74 to 1979/81 were obtained from the CCAMLR statistical bulletins. Catches by SSMU for the period 1980/81 to 2005/06 were taken from EMM 07-5 (provided by David Ramm). Where information was not given per area, estimated catches were derived by dividing the large scale catch (by area or subarea) among SSMUs in proportion to the distribution of catches over the whole period for which area-specific data were available.

Given that fish catches during the 1970's to 1980's were substantial, a historic catch series (1970 to 2006) for a generic fish was obtained as follows. Catch data for Area 48 and for each of the species included in the Hill *et al.* (2007) generic fish were extracted from the CCAMLR Statistical Bulletin volume 19. These annual totals were then apportioned between Subareas 48.1, 48.2 and 48.3 based on information in Kock (1992), which summarised the total catches for *N. rossii* and *C. gunnari* from 1978 to 1989 in Subareas 48.1 and 48.2. The balance of the catch was assumed to have been taken from Subarea 48.3. We apportioned these catches to each of the SSMUs, using data on shelf areas (from Hill *et al.* 2007), and assuming that catches are proportional to shelf area (Table 2).

## MODEL STRUCTURE

SMOM essentially builds on the modelling work of Thomson *et al.* (2000) and Mori and Butterworth (2004, 2006). The model includes all 15 SSMUs and uses a six-month (two seasons) timestep to update the numbers of krill in each of the SSMUs, as well as the numbers of predator species in each of these areas. The model currently includes four predator groups (penguins, seals, fish and whales) and a single prey group in the form of krill (Fig. 2). Future model versions may incorporate a link between seals and fish. Information such as abundance and total predator demand per SSMU (Table 3) is based on that provided in Hewitt *et al.* (2004).

The model is coded in AD Model Builder (AD Model Builder<sup>TM</sup>, Otter Research, Ltd.). An updated description of the Operating Model is given in Appendix 1 and a consolidated list of symbols used in this paper, together with their definitions, is given in Table 4. Values of parameters and their sources are listed in Table 5. The details of the illustrative Management Procedure and performance statistics are as given in Plagányi and Butterworth (2006b), with an illustrative summary presented in Appendix 2.

There are a number of ways in which predator performance could be linked to the abundance of krill. In the interests of constructing as simple a model as possible (a minimally realistic model) here, this is not effected through a consumption term. Rather it is assumed that breeding success is likely to be the most sensitive of the various demographic parameters to changes in prey abundance. A breeding success factor  $f(B_y^a)$  (see Equation A1.4) is thus formulated as a function of the available biomass of krill (i.e. krill in SSMU  $a$  in year  $y$ ) and acts as a multiplier

to the juvenile recruitment parameters, namely the reproductive rate  $P$  and/or the juvenile survival rate.

A single parameter value  $h$  (see Equation A1.11) determines the breeding success relationship for each area and predator species. It controls the “steepness” of the curve, and hence the level of krill abundance (relative to the carrying capacity) below which predator breeding success is negatively impacted. Given that this is not known or easily determined, a prudent approach adopted in previous applications involved selecting two values that roughly bound the likely range in this relationship by reflecting a near-linear decrease in breeding success as krill abundance decreases compared with a scenario in which predator breeding success is negatively impacted at relatively low levels of krill abundance only (see Fig. 3). These values are also used to compute  $B_j^a$  in the predator consumption term in the krill dynamics equation (Equation A1.1), effectively representing the krill biomass when the birth rate of predator species  $j$  in SSMU  $a$  drops to half of its maximum level. Moreover, rather than assuming a deterministic relationship, variability has been added such that the extent of variability about the curve can be changed by adjusting the parameter  $\sigma_{BR}$  (see Equation A1.10).

#### *Accounting for seasonality*

The CCAMLR WG suggested that these models include a seasonal component to temporally separate the fishery from predator demands, particularly for the South Georgia SSMU which is characterized by a fishery which operates during the winter months. In SMOM years are split into a “summer”  $s1$  season and “winter”  $s2$  season. The krill population in each SSMU is thus updated each year using two time-steps, with the possibility of setting different growth rates, catches/fishing proportions and movement rates for each of half years  $s1$  and  $s2$  (Equation A1.1). Moreover, whereas consumption estimates for  $s1$  are computed based on the numbers of predators present in each SSMU (and assumed confined to that SSMU because of their breeding), during  $s2$  the predators are assumed to range widely and to distribute themselves in the same proportions as the relative abundance of krill per SSMU at the end of  $s1$ .

#### *Modelling krill*

There are three different krill model options considered here when running SMOM over the historic period:

Model 1: This uses a fixed input series of krill biomass from the SAM calendar as a driving variable to generate predator trajectories for comparison with the SAM calendar.

Model 2: No movement scenario with krill dynamics determined by the combination of SST, historic removals by the fishery and predators, and density dependent effects.

Model 3: Movement assumed based on OCCAM and krill dynamics determined as described by other factors above.

Based on the SAM calendar, 1986 was set as an anomalous year, and in Models 2 and 3 a second scenario was explored in which there is a step-down in the average krill growth rate for all following years.

*Krill fishery:* The model assumes that the krill fishery does not operate in a SSMU once krill density falls below a threshold value, set for illustrative purposes at 20% of the starting level. This provides a rough way of accommodating an economic concern of the fishery regarding threshold krill densities below which fishing becomes uneconomical (CCAMLR 2006).

#### *Environmental forcing*

SMOM is capable of representing environmental forcing through the following mechanisms.

- a) The krill intrinsic growth rate  $r$  is modelled as a function of year, season and area (Equation A1.1). Several authors have suggested that there is a link between sea surface temperature (SST) and the variability in krill abundance, not only because of temperature's effect on growth but also possibly because SST is in turn an indicator of other mechanisms such as variability in regional sea-ice (Mackintosh 1972, Trathan *et al.* 2003, 2006). Historic SST data are used to modify the growth rate  $r$  for the summer and winter seasons  $s1$  and  $s2$ , and for the southern (Antarctic Peninsula/South Orkney) and northern (South Georgia) regions (Appendix 4).
- b) Different krill movement scenarios can be considered by amending Equation 2 to explore hypothesized changes in movement in response to environmental forcing.
- c) The predator adult survival rate is split into a "summer" and "winter" component such that, for example, decreased survival as a consequence of poorer environmental conditions during the winter months can be simulated.

#### *A Reference Case to Bound Uncertainty*

Given the numerous uncertainties regarding the choice of parameter values, a Reference Set is used in preference to a single Reference Case Operating Model (OM) (Rademeyer *et al.* 2007). The initial Reference Set used comprises 12 alternative combinations per predator that essentially try to bound the uncertainty in the choice of survival estimates as well as the

breeding success relationship. Sensitivity analyses showed that these are the most sensitive model parameters, and they are also the least well determined parameters based on a review of the literature.

For each predator species, the following parameter values are thus input:

- i) an average S2, low S1 and high S3 adult annual survival rate;
- ii) a low SJ1 and high SJ2 maximum juvenile annual survival rate; and
- iii) two alternative values ( $h_1$ ,  $h_2$ ) to roughly bound the likely “steepness” of the breeding success relationship.

This leads to a total of  $3 \times 2 \times 2 = 12$  alternative OMs to represent the dynamics of each predator. This number of combinations then needs to be raised to a power equal to the number of predators included, so that the number of OMs can become extremely large. Given computational constraints in the applications described thus far, the same ( $h_1$ ,  $h_2$ ) parameters were assumed for seals and penguins, and coupled low, medium and high survival scenarios assumed for penguins and seals, to restrict the number of operating models to 12. A total of ten replicates of each OM are typically run, yielding a total of 120 simulations per scenario. Ideally more replicates would be run, but time precluded this. Modifications to this format for the tuning process are described below.

## MODEL PARAMETERS

To facilitate model comparisons, wherever possible SMOM and KPFM have used the same model inputs in evaluations conducted as part of CCAMLR’s 2006 Workshop on Management Procedures to evaluate options for subdividing the krill catch among SSMU’s (CCAMLR 2006). Most of these inputs, including essential information on the total demand for krill from key predator species in each SSMU, are summarised in Hill *et al.* (2007). Parameters for different species were combined by Hill *et al.* (2007) to represent “generic” predators as this was considered the most pragmatic way to proceed, notwithstanding that individual species differences may be important to bear in mind.

### *Krill*

The basic krill intrinsic growth rate parameter is set at 0.4 (Mori and Butterworth 2006) and this is modified per year and per season as described in Appendix 4. The  $\lambda^j$  parameters are based on the estimates presented in Hewitt *et al.* (2004), when converting numbers to biomass

assuming an average krill mass of 0.46 g (Hill *et al.* 2007). Hewitt *et al.* (2004) give the total predator demand per SSMU (Table 3).

### *Predators*

To tune the model over the historic period, the growth rate estimates described in Hill *et al.* (2008) were used to set each of the predator growth rates  $R^j$ , so that the only parameter not yet accorded a value in Equation (A1.15) is the maximum breeding success parameter  $P^j$ . The average number of offspring per mature female that survive the first year of life is given by the product  $f(B_y^a) \cdot P^j \cdot S_{juv}^j$  which includes both intra- and inter-specific density-dependent components. In combination, these terms thus roughly capture the pregnancy rate, survival until fledging (for penguins) / until pups leave their natal colony (for seals) and survival of juveniles to the end of the first year of life. Density dependence in predators such as seals and penguins is assumed to primarily affect the youngest age classes.

## METHOD FOR CONDITIONING MODEL

A number of approaches were used to tune the model to the SAM calendar of expected changes in predator and krill abundances in the Scotia Sea. This included using Leslie matrix analysis (Appendix 3) to explore combinations of survival estimates (and other demographic parameters) capable of reproducing the observed growth rates as summarized in the SAM calendar. Secondly, the model was fitted (see Appendix 1 for method) to reference observations to assist in refining parameter estimates, with additional manual adjustment thereafter. The fitting exercise should not be seen as a formal fitting procedure but rather was used to assist with the tuning process. It was however particularly useful in informing on the following two aspects:

- a) For each of the three predator groups penguins, seals and whales, the parameter  $h$  was estimated, for each combination of survival values, that resulted in the best fit to the calendar numerical values.
- b) For fish, there were no calendar observations describing the change in the relative abundance over time, but an estimate of the recent abundance per SSMU is provided in Hewitt *et al.* (2004). Moreover, historic catch data were sourced (Table 2). The model was thus used to estimate the 1970 starting abundance of fish in each SSMU that would result in the recent abundance given the historic catch record and dynamics as described in Equation A1.4.



## **DISCUSSION**

The Spatial Multi-species Operating Model (SMOM) described here can potentially contribute to the provision of scientific advice regarding the subdivision of the precautionary catch limit for krill among 15 small-scale management units (SSMUs). This paper has outlined the methodology and summarised a number of updates that have been made to the model, such as linking krill growth rate to sea surface temperature (Appendix 4). Moreover, the methodology used to condition the model using the WG-SAM set of reference observations for Area 48 (the SAM calendar) is described.

Previous results under contrasting scenarios of no movement of krill, and extensive movement based on the OCCAM model, highlight the importance of checking the robustness of model conclusions to a wide range of krill transport assumptions – with increasing krill transport it is obvious that the demands of predators may be much more easily met in a SSMU. Given that whales, unlike the other predators in the model, are assumed to be much more mobile and able to integrate krill availability across all SSMUs, their dynamics do not differ much under different krill movement scenarios.

Simulations with the updated model suggested that some of the parameter settings are in need of further revision. The results of model simulations are provided in accompanying papers. This includes details concerning comparing SMOM outputs to the SAM calendar when running the model over the historic period 1970-2007. Secondly, the model is projected forwards 40 years to compare different fishing options and future levels of krill catch.

## **ACKNOWLEDGEMENTS**

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## APPENDIX 1 – MODEL EQUATIONS

### KRILL DYNAMICS EQUATION

The krill population is modelled following Mori and Butterworth (2006), with the following modifications to their discrete equation:

- (1) the krill catch is subtracted;
- (2) a net movement term is added which links the various SSMUs;
- (3) the consumption term is scaled upwards to account for the fact that mature predator numbers are calculated in terms of mature females only;
- (4) the consumption term is scaled upwards by a second factor ( $\mu^a$ ) which accounts for total consumption by predators not explicitly included in the model.

$$B_{t+1}^a = B_t^a + r_t^a B_t^a \left( 1 - \left( \frac{B_t^a}{K^a} \right) \right) - \sum_j \frac{1}{\omega_j} \frac{\lambda^j (B_t^a)^n N_{y,seas}^{j,a}}{(B_j^a)^n + (B_t^a)^n} - F_t^a B_t^a + D_t^a \quad (\text{A1.1})$$

where:

$B_t^a$  is the biomass of krill in SSMU  $a$  at time-step  $t$  (with the base-case model using two time-steps per year  $y$ ),

$r_t^a$  is the intrinsic growth rate of krill in SSMU  $a$  during time-step  $t$ ,

$K^a$  is the carrying capacity of krill in SSMU  $a$ ,

$\lambda^j$  is the maximum per capita consumption rate of krill by predator species  $j$ ,

$N_t^{j,a}$  is the number of mature females of predator species  $j$  in SSMU  $a$  during season  $seas$  ( $s1=summer, s2=winter$ ) in year  $y$ ,

$B_j^a$  is the krill biomass when the consumption and hence also birth rate of species  $j$  in SSMU  $a$  drops to half of its maximum level,

$n$  is a parameter that controls whether a Type II or a Type III functional response is assumed ( $n=1$  for Type II as assumed here;  $n=2$  for Type III),

$\omega_j$  is the proportion of the mature population for predator species  $j$  comprised of mature females;

$F_t^a$  is the fishing proportion (catch= $F_t^a B_t^a$ ) on krill in SSMU  $a$  at time-step  $t$ , and

$D_t^a$  is the net movement of krill (immigration-emigration) into SSMU  $a$  at time-step  $t$  (see below).

Given that there is likely to be substantial movement of krill between areas, it is important to include a term in Equation (A1.1) to describe this. However, there is limited information available on which to base this term. There are two alternative movement models included in SMOM. In the first, a simplistic movement term has been developed by assuming that the net annual immigration in each area is randomly determined in such a way that the total immigration between areas approximately equals the total emigration, i.e. there is conservation of krill in the overall area considered. The parameter  $Em$  represents the average proportion of krill that emigrate from an area into other areas each year. By varying  $Em$ , a range of movement hypotheses can be tested, from an assumption of zero movement to extensive movement. In initial simulations this parameter is set to zero as the addition of movement complicates interpretation of the dynamics. Mathematically:

$$D_t^a = -Em * B_t^a + I_t^a \quad (\text{A1.2})$$

where  $I_t^a$  is the randomly-determined number of immigrants into SSMU  $a$  at time  $t$ , scaled such that (on average) in each year:

$$\sum_a I_t^a \approx Em \sum_a B_t^a \quad (\text{A1.3})$$

The second option for modelling krill movement in SMOM is based on the method used by KPFM (Watters *et al.* 2006), based on outputs from the Ocean Circulation Climate Advanced Modelling Project (OCCAM). Hill *et al.* (2007) present summer and winter matrices detailing the instantaneous transport rate between SSMUs and three adjacent “bathtub” areas. These matrices are here rescaled by a parameter  $\phi$  such that the rescaled values in matrices  $\underline{M}^{summer}$  and  $\underline{M}^{winter}$  represent the proportion of krill in each SSMU and bathtub that immigrate to or emigrate from every other SSMU and bathtub at each time-step. The proportions remain constant over time as they represent the relative amounts of krill that can be expected to move between different SSMUs. These proportions are in each case multiplied by the absolute numbers of krill in the different areas, with the numbers in the bathtub regions assumed to remain constant over time. Both the parameter  $\phi$  and the bathtub krill abundance values can be adjusted to increase or decrease krill movement in the model.

## PREDATOR DYNAMICS EQUATION

The same delay difference equation is used for all predators (penguins, seals, fish) except whales, with the number of mature females (i.e. adult females past the age-at-first-parturition or laying) at the start of year  $y$ , where year  $y$  is assumed to commence on the first day of the “summer” season  $s1$ , given by:

$$N_{y+1}^{j,a} = N_y^{j,a} \sqrt{(S_{s1}^j)(S_{s2}^j)} + (N_{y-T+1}^{j,a}) \cdot q^j \cdot f(B_{y-T+1}^a) \cdot P^j \cdot S_{juv}^{*,j} \left( 1 - \frac{N_y^{j,a}}{K^{*,j,a}} \right) \left( (S_{s1}^j)(S_{s2}^j) \right)^{(T-1)/2} \quad (\text{A1.4})$$

and the number of mature females at the start of winter season  $s2$  given by:

$$N_{y,s2}^{j,a} = N_y^{j,a} \sqrt{(S_{s1}^j)} + (N_{y-T+1}^{j,a}) \cdot q^j \cdot f(B_{y-T+1}^a) \cdot P^j \cdot S_{juv}^{*,j} \left( 1 - \frac{N_y^{j,a}}{K^{*,j,a}} \right) (S_{s1}^j)^{(T-1)/2} (S_{s2}^j)^{(T-2)/2} \quad (\text{A1.5})$$

where:

- $N_y^{j,a}$  is the number of predator species  $j$  in SSMU  $a$  at the start of season  $s1=summer$  in year  $y$ ,
- $N_{y,s2}^{j,a}$  is the number of predator species  $j$  in SSMU  $a$  at the start of season  $s2=winter$  in year  $y$ ,
- $S_{s1}^j$  is the post-first-year annual survival rate of predator species  $j$  in season  $s1$  (assumed to be independent of area),
- $S_{s2}^j$  is the post-first-year annual survival rate of predator species  $j$  in season  $s2$ ,
- $T$  is the average age at first parturition or laying, assumed here for simplicity to be one year more than the age at maturity (i.e. a common gestation period of 1 year is assumed, though clearly this is less for some of the predator species considered),
- $q^j$  is the fraction of chicks/pups that are female,
- $P^j$  is the maximum number of fledged chicks or pups leaving the natal colony per adult female past the age of first parturition or laying of predator species  $j$  per year;
- $f(B_y^a)$  is a breeding success factor (multiplier for  $P$  or  $S_{juv}$ ) which is a function (see below) of the biomass of krill in SSMU  $a$  in year  $y$ ,

$S_{juv}^{*,j}$  is the maximum first year post-fledging or post-weaning (juvenile) survival rate of predator species  $j$ , and

$K^{*,j,a}$  is a carrying capacity-related term for predator species  $j$  in SSMU  $a$ , used to introduce density dependence into the predator dynamics through the dependence of  $S_{juv}$  on predator abundance  $N$ .

Note from the above that it is possible to set different adult survival values  $S^j$  for each of the 6-month seasons. Births are assumed to occur at the start of the summer season. The second term on the right hand side of Equation (A1.4) represents animals born  $T+1$  years ago that are now reproducing for the first time, and is slightly different in Equation (A1.5) because the adult survival rate is only applied for half (i.e. the summer half) of the last pre-maturity year in order to estimate the numbers of animals present at the start of the winter (the survivors from these maturing animals will be assumed to give birth at the start of the following summer).

Note that during the “summer” months, the number of predators feeding in each SSMU is simply given by:

$$N_{y,summer}^{j,a} = N_y^{j,a} \tag{A1.6}$$

However, predators in the Antarctic Peninsula region are not confined to their SSMUs during the winter months (CCAMLR 2006). In the model they are assumed to distribute themselves according to the relative abundance of krill in the region, and then to return again to their natal SSMUs at the start of spring/summer. To compute the impact of predators on krill in each SSMU during season  $s2$ , the number of predators feeding in each SSMU is thus calculated as:

$$N_{y,winter}^{j,a} = \frac{B_{s2}^a}{\sum_a B_{s2}^a} \times \sum_a N_{y,s2}^{j,a} \tag{A1.7}$$

The “breeding success” factor in the model above is essentially related to the first-year or juvenile survival rate  $S_{juv}$ . It is not adequate in a model of this form to assume that survival depends on prey abundance without also introducing density dependence into the predator dynamics through the dependence of  $S_{juv}$  (say) on  $N$ . If  $S_{juv}$  is a decreasing function of  $N$ , as well as an increasing function of prey abundance  $B$ , the model behaviour will yield broadly stable

levels of predator abundance for a range of prey abundances. Density dependence in predators such as seals and penguins is assumed to primarily affect the youngest age classes.

The selected density-dependent formulation is based on the form suggested in Thomson *et al.* (2000) adapted as follows:

$$S_{juv} \rightarrow S_{juv}^* \left( 1 - \frac{N_y}{K^*} \right) \quad (\text{A1.8})$$

Note that the value of the density dependent multiplier lies between zero and 1, so that, for example, when the population size is very small relative to the carrying capacity related term  $K^*$ , this term approaches 1. If at any stage  $N_y > K^*$ , the whole term is set to zero. Estimating or specifying the value of  $S_{juv}^*$  is not straightforward: one approach is to set this value based on the maximum realistic population growth rate (see Appendix 3). The value for  $K^*$  is computed as explained in the next section.

A breeding success factor  $f(B_y^a)$  is formulated as a function of the available biomass of krill, which can be determined either as the krill in SSMU  $a$  during season  $sI$  or the average krill in SSMU  $a$  during year  $y$ . It acts as a multiplier to the reproductive rate  $P$  in Equation (A1.4) but could also be thought of as acting as a multiplier for the juvenile survival rate  $S_{juv}$  or a multiplier of the product of  $P$  and  $S_{juv}$ . To reduce the number of parameters in the model, the breeding success factor is scaled such that it is 1 when the local krill abundance is at the carrying capacity level for an area, i.e. breeding success is at a maximum in these circumstances. A useful functional form to use is that classically referred to as a Beverton-Holt form when used for a stock-recruitment relationship; this is applied here to represent breeding success as a function of krill biomass  $B_y^a$ :

$$f(B_y^a) = \frac{\alpha^a B_y^a}{\beta^a + B_y^a} \quad (\text{A1.9})$$

where  $\alpha^a$  and  $\beta^a$  are parameters for SSMU  $a$ , with  $\beta^a = (\alpha^a - 1) \cdot K^a$ .

By scaling as above, multiplying through by the krill carrying capacity  $K_a$  and adding a term to allow for fluctuations about this relationship, Equation (A1.9) becomes:

$$f(B_y^a) = \frac{\alpha^a B_y^a / K^a}{(\alpha^a - 1) + B_y^a / K^a} e^{(\zeta_{ay} - \sigma_{BR}^2/2)} \quad (\text{A1.10})$$

where

$\zeta_{ay}$  reflects fluctuation about the expected curve for area  $a$  in year  $y$ , which is assumed to be normally distributed with standard deviation  $\sigma_{BR}$  (whose value is input in the applications considered here). Note that values of  $\sigma_{BR}$  considered are such that the product  $f(B_y^a) \cdot P^j$  does not exceed biologically plausible limits (e.g. the annual seal pup production for females does not exceed 1).

In order to work with estimable parameters that are more meaningful biologically, Equation (A1.10) is re-parameterised in terms of the maximum krill biomass,  $B_{MAX}^a$ , and the “steepness”  $h$  of the relationship, where “steepness” is the fraction of, for example, maximum fledging success that results when  $B_y^a$  drops to 20% of its maximum level, from which it follows that:

$$h = \frac{\alpha}{5\alpha - 4} \quad (\text{A1.11})$$

By ignoring the random variation term and choosing a single parameter value  $h$ , the fledging success relationship can thus be specified. The parameter  $h$  may be thought of as controlling the level of prey biomass below which breeding success is negatively impacted (Fig. 3).

For the deterministic case, Equation (A1.10) can also be used to calculate  $B_j^a$  in Equation (A1.1) given that it represents the krill biomass when the birth rate (as a proxy for consumption) of species  $j$  in SSMU  $a$  drops to half of its maximum level. Equation (A1.10) is thus used to solve for  $B_y^a / K^a$  when  $f(B_y^a) = BR = 0.5$ , yielding:

$$B_j^a = \frac{0.5 \cdot K^a \cdot (\alpha^a - 1)}{(\alpha^a - 0.5)} \quad (\text{A1.12})$$

Given values for all the other parameters in Equation (A1.1) (including  $n=1$ ), and assuming that krill have shown a steady growth rate  $R$  over the past few years, and that  $y$  represents the start year of the period to be modelled (i.e. start year predator numbers is the average over the recent period), the value of  $K_a$  can be calculated by rewriting Equation (A1.1) (and assuming zero net immigration/emigration) as:

$$R = r^a \left( 1 - \left( \frac{B_y^a}{K_a} \right) \right) - \sum_j \frac{\lambda^j N_y^{j,a}}{q^j (B_j^a + B_y^a)} - F_y^a \quad (\text{A1.13})$$

and hence solving for  $K_a$  for each SSMU as follows:

$$K_a = B_y^a \left/ 1 - \frac{R + F_y^a + \mu^a}{r^a} \right/ \sum_j \frac{\lambda^j N_y^{j,a}}{q^j (B_j^a + B_y^a)} \quad (\text{A1.14})$$

Analogous to the method outlined above for krill, if the predators in each SSMU have shown a fixed growth rate  $R^j$  over the past few years, the values of  $K^{*,j,a}$  can be calculated by rewriting Equation (A1.4) as:

$$(1 + R^j)^T = (1 + R^j)^{T-1} \sqrt{(S_{s1}^j)(S_{s2}^j)} + q^j \cdot f(B_y^a) \cdot P^j \cdot S_{juv}^{*,j} \left( 1 - \frac{N_y^{j,a}}{K^{*,j,a}} \right) \left( (S_{s1}^j)(S_{s2}^j) \right)^{(T-1)/2} \quad (\text{A1.15})$$

and rearranging to solve for  $K^{*,j,a}$  as:

$$K^{*,j,a} = N_y^{j,a} \left/ 1 - \frac{(1 + R^j)^T - (1 + R^j)^{T-1} \sqrt{(S_{s1}^j)(S_{s2}^j)}}{q^j \cdot f(B_y^a) \cdot P^j \cdot S_{juv}^{*,j} \left( (S_{s1}^j)(S_{s2}^j) \right)^{(T-1)/2}} \right/ \quad (\text{A1.16})$$



## WHALE DYNAMICS EQUATION

A similar delay difference equation to Equation (A1.4) is used to represent whales, with two main differences. Given the large movements undertaken by whales, the dynamics of whales are not determined at the individual SSMU scale but rather based on the total prey abundance across all the SSMUs. Hence the number of mature female whales at the start of year  $y$  is given by:

$$N_{y+1}^w = N_y^w \sqrt{(S_{s1}^w)(S_{s2}^w)} + (N_{y-T+1}^w) \cdot q^w \cdot f(B_{y-T+1}^w) \cdot P^w \cdot S_{juv}^{*,w} \left(1 - \frac{N_y^w}{K^{*,w}}\right) \left((S_{s1}^w)(S_{s2}^w)\right)^{(T-1)/2} \quad (\text{A1.17})$$

To incorporate the effect of whales on krill abundance in each SSMU during the summer months, it is assumed that whales distribute themselves according to the relative abundance of krill in the region, such that:

$$N_{y,summer}^{w,a} = \frac{B_{s1}^a}{\sum_a B_{s1}^a} \times N_y^w \quad (\text{A1.18})$$

As for simplicity, all whales are assumed to migrate north during winter, it follows that:

$$N_{y,summer}^{w,a} = 0 \quad (\text{A1.19})$$

## ALTERNATIVE FUNCTIONAL FORMS

In conditioning the model to historic data, it became clear that the predators were likely represented as oversensitive to prey (krill) abundance as well as to intra-specific density dependent effects. Options were thus introduced into the model to allow for the following alternative representations of  $f(B_y^a)$  and  $S_{juv}$ :

$$S_{juv} \rightarrow S_{juv}^* \left(1 - \frac{N_y}{K^*}\right)^c \quad (\text{A1.20})$$

$$f(B_y^a) = \left[ \frac{\alpha^a B_y^a}{\beta^a + B_y^a} \right]^c \quad (\text{A1.21})$$

where  $c$  is a constant (set at 0.5 here) which has the effect of dampening the multiplier functions.

## THE LIKELIHOOD FUNCTION

The complete negative log-likelihood function minimized to estimate parameters  $h^j$  for all the predator species  $j$ , and  $N_{1970}^{j,a}$  for fish, is:

$$-\ln L = LL_{peng} + LL_{seal} + LL_{whal} + LL_{fish}$$

where this function ( $-\ln L$ ) is comprised of the likelihood contributions from each predator species  $j$  as given below.

### *Penguins*

The likelihood component  $LL_{peng}$  that relates the model estimated penguin abundance to the observed “calendar” abundance values (for SSMUs with penguins) is computed as ( $j = penguins$ ):

$$LL_{peng} = \frac{1}{2\sigma_j^2} \left[ \sum_{a=1}^{N_{ssmu}} \left( \ln N_{2007}^{p,a} - \ln(\hat{N}_{2007}^{p,a} / \omega_j) \right)^2 + \sum_{a=14}^{15} \left( \ln N_{1980}^{p,a} - \ln(\hat{N}_{1980}^{p,a} / \omega_j) \right)^2 + \sum_{a=1}^{12} \left( \ln N_{1977}^{p,a} - \ln(\hat{N}_{1977}^{p,a} / \omega_j) \right)^2 \right]$$

where  $\sigma_j$  represents a typical CV associated with observed abundance estimates, taken for current purposes to be the same for all predators and areas. A realistic value of 0.5 was chosen based on typical known CVs associated with fur seal abundance estimates.

### *Seals*

$$LL_{seal} = \frac{1}{2\sigma_j^2} \left[ \sum_{a=1}^{N_{ssmu}} \left( \ln N_{2007}^{s,a} - \ln(\hat{N}_{2007}^{s,a} / \omega_j) \right)^2 + \sum_{a=3}^7 \left( \ln N_{1995}^{p,a} - \ln(\hat{N}_{1995}^{p,a} / \omega_j) \right)^2 + \sum_{a=14}^{15} \left( \ln N_{1988}^{p,a} - \ln(\hat{N}_{1988}^{p,a} / \omega_j) \right)^2 \right]$$

where  $j = seals$ .

### **Whales**

$$LL_{seal} = \frac{1}{2\sigma_j^2} \left[ \left( \ln N_{2007}^w - \ln(\hat{N}_{2007}^w / \omega_j) \right)^2 + \left( \ln N_{2000}^w - \ln(\hat{N}_{2000}^w / \omega_j) \right)^2 + \left( \ln N_{1980}^w - \ln(\hat{N}_{1980}^w / \omega_j) \right)^2 \right]$$

where this component is computed by comparing model and calendar estimates summed over all SSMUs and  $j = whales$ .

### **Fish**

There are no historic calendar estimates for fish, and it is important to ensure a sufficiently large starting number of fish in 1970 ( $N_{1970}^{f,a}$ ) so that the fish trajectories do not reflect extinction when attempting to account for the sometimes large historic fish catches. Hence  $N_{1970}^{f,a}$  is estimated by fitting to the Hewitt *et al.* (2004) estimates of recent fish biomass ( $j = fish$ ):

$$LL_{fish} = \frac{1}{2\sigma_j^2} \left[ \sum_{a=1}^{N_{ssmu}} \left( \ln N_{2007}^{f,a} - \ln(\hat{N}_{2007}^{f,a} / \omega_j) \right)^2 \right]$$

## APPENDIX 2 – ILLUSTRATIVE CONTROL RULE

To test a dynamic feedback management rule, “future data” in the form of, for example, CEMP indices of abundance are required by the MP program to calculate the krill allotment per SSMU for each of the years in the projection period. These data are generated from the operating model, assuming the same error structure as in the past, and are passed to the MP which in turn passes information back to the operating model.

For illustrative purposes, an example is provided in which it is assumed future monitoring data are available annually as follows:

- i) A krill abundance index available for all SSMUs.
- ii) An index of abundance available for penguins in all SSMUs except the three pelagic areas: 1 (APPA), 9 (SOPA) and 13 (SGPA) as these include fishing areas not in the vicinity of land-breeding predators.
- iii) An index of predator performance (e.g. duration of fur seal cow foraging) available for seals in SSMUs 3 and 14 (Indices no. 13 and 14).

It is assumed for illustrative purposes that the CVs associated with Indices 1-12 are the average of the CVs associated with historic CEMP data from Bird Island and Stranger Point (Ramm and Turner 2005), namely 0.34, whereas the seal index “future” CV of 0.42 is similarly based on observed CVs associated with the CEMP data from Bird Island (Ramm and Turner 2005). These CVs are used when accounting for observation error i.e. noise in the CEMP monitoring data.

The initial MP developed here is ‘model-free’ (data-based, empirical) (see Rademeyer *et al.* 2007) and hence uses the data directly, for example in the form of recent upward or downward trends in abundance indices, to feedback appropriately through krill catch allocation changes in the same direction.

The recommended krill catch per SSMU fed back to the operating model is computed as follows:

$$Y_y^a = \Delta \cdot Y_{y-1}^a + (1 - \Delta) * \sqrt{h(CEMPRat_y^{j,a})h(KRILLRat_y^a)} * Y_{y-1}^a \quad (A2.1)$$

where

$Y_y^a$  is the precautionary krill catch limit in SSMU  $a$  in year  $y$ , renormalized after application of this equation to ensure that  $Y = \sum_a Y_y^a$ ,

$\Delta$  is a control parameter which moderates the extent of the  $Y_y^a$  annual variations, and is set to 0.5 for the computations reported here,

$h(\text{CEMPRat}_y^{j,a})$  is a function which adjusts  $Y_y^a$  depending on the ratio of the CEMP index  $\text{CEMP}_y^{j,a}$  for predator  $j$  in SSMU  $a$  (averaged over the most recent three years after the first 3 years of the projection) compared to the starting index value (i.e that immediately preceding application of the MP), and

$h(\text{KRILLRat}_y^{j,a})$  is a function which adjusts  $Y_y^a$  depending on the ratio of the krill survey index  $\text{KRILL}_y^{j,a}$  in SSMU  $a$  (averaged over the most recent three years in the projection) compared to the starting index value (i.e that immediately preceding application of the MP).

The functions  $h(\text{CEMPRat}_y^{j,a})$  and  $h(\text{KRILLRat}_y^{j,a})$  which control the precautionary krill catch limit in SSMU  $a$  in year  $y$  depending on these ratios ( $I_y^{\text{rat}}$ ) are:

$$\text{CEMPRat}_y^{j,a} = \left( \frac{\frac{1}{3} \sum_{y'=y-3}^{y-1} \text{CEMP}_y^{j,a}}{\text{CEMP}_{2004}^{j,a}} \right) \quad (\text{A2.2})$$

$$\text{KRILLRat}_y^{j,a} = \left( \frac{\frac{1}{3} \sum_{y'=y-3}^{y-1} \text{KRILL}_y^{j,a}}{\text{KRILL}_{2004}^{j,a}} \right) \quad (\text{A2.3})$$

and

$$h(I_y^{\text{rat}}) = \begin{cases} r1 & \text{if } 0 < I_y^{\text{rat}} \leq r1 \\ I_y^{\text{rat}} & \text{if } r1 < I_y^{\text{rat}} \leq r2 \\ r2 & I_y^{\text{rat}} > r2 \end{cases} \quad (\text{A2.4})$$

There are a number of different options that can be tested in cases where there is more than one predator abundance index per SSMU. For example, one could take the average of the  $\text{CEMP}_y^{j,a}$

values (normalized, to take account of different scales). From initial trials, a better (and more conservative) approach proved to be to use only the minimum of the  $CEMP_y^{j,a}$  values.

*Control parameters:*

The values of  $r1$  and  $r2$  used in the results presented here are respectively 0.7 and 1.1. Additional constraints were also imposed such that the maximum permissible decrease/increase in the krill catch in one SSMU from one year to the next were both 10%.

After some initial experimentation, the method chosen to allocate the krill catch between SSMUs was as follows:

- 1) For all SSMUs for which “future” data were assumed available, an updated krill catch for the respective SSMUs was computed using Equation (A1.1) and the associated constraints.
- 2) If no data were available for a SSMU with land-breeding predators, future catches remained at their existing level;
- 3) Once changes to all the SSMUs with land-breeding predators were computed, the differences between the  $Y_{y+1}^a$  and  $Y_y^a$  values were totaled and then shared equally between the three pelagic areas (APPA, APE and SGPA) such that  $Y = \sum_a Y_y^a$ .

The results and candidate MP presented here are still in the early stages of development. Further work would include testing the robustness of candidate MPs to a wide range of alternative hypotheses. For example, it is possible to use robustness tests (see Rademeyer *et al.* 2007) as part of the framework presented here to test the effect of future environmentally-driven changes, such as a change in the overall carrying capacity of krill.

### APPENDIX 3 - Leslie matrix computation of life history parameters

In earlier model versions, parameter values were sourced from Hill *et al.* (2007) or from other available literature sources. However it was found that several of these parameter combinations were inconsistent in that, for example, they could not yield the maximum growth rates observed as summarised in Hill *et al.* (2008). As a preliminary tuning step, Leslie matrix analysis was used as this approach provides values of the maximum steady annual growth rate ( $R$ ) of which a population is possible given values for its demographic parameters. These are obtained by solving the following equation (which is a derivation of a simplified version of Equation A1.4 for each predator in turn:

$$\exp[RT] = \exp[R(T-1)]S + q P S_{juv} S^{T-1} \quad (\text{A3.1})$$

- $S$  is the post-first-year annual survival rate of a predator species,
- $T$  is the average age at first parturition or laying, assumed here for simplicity to be one year more than the age at maturity,
- $q$  is the fraction of chicks/pups that are female,
- $P$  is the maximum number of fledged chicks or pups leaving the natal colony per pair of predator species  $j$  per year, and
- $S_{juv}$  is the maximum first year post-fledging or post-weaning (juvenile) survival rate of a predator species.

In this analysis, values of  $P$ ,  $T$  and  $q$  were fixed, and alternative combinations of  $S$  and  $S_{juv}$  explored that would produce both the average growth rates and the maximum values of 10% and 15% for penguins and seals as described in Hill *et al.* (2008). For whales, a maximum rate of 10% was tested: surveys of humpback whales migrating off the west and east Australian coasts show recent growth rates close to this figure (Bannister and Hedley 2001; Noad *et al.* 2008), as do the IWC's IDCR/SOWER surveys for blue whales in the Antarctic (Branch 2008a); this value is also near to the upper limit demographically achievable for these species (Zerbini *et al.* 2008; Branch 2008b). Note that maximum values were sought as in the model described in Appendix 1 the juvenile survival rate is an upper limit because it is multiplied by a density dependent parameter, and the reproductive rate is simply modified (downwards) based on food availability.

Table A3.1. Summary of two alternative combinations of  $S$  and  $S_{juv}$  for each predator group that yields the maximum growth rate  $R$  as shown when  $P$  and  $T$  are fixed, and assuming  $q = 0.5$ .

	$P$	$T$	$S$	$S_j$	Max.growth rates $R$
Penguins	0.91	3	0.88	0.8	0.1
	0.91	3	0.9	0.7	0.1
Seals	0.88	4	0.92	0.8	0.15
	0.88	4	0.96	0.6	0.15
Whales	0.5	5	0.98	0.8	0.1
	0.5	5	0.97	0.91	0.1



#### APPENDIX 4 – Krill temperature model

As a preliminary means of relating krill growth to SST in the model, a functional relationship was derived as follows. Based on Atkinson *et al.* (2006) and Wiedenmann *et al.* (2008), the instantaneous growth rate formula for krill is:

$$L(t+1) = L(t) + L(t) \times \delta \times G(t) \quad (\text{A4.1})$$

where  $L(t+1)$  and  $L(t)$  are respectively post- and pre-moult length;

$\delta$  is 0 or 1 to index if  $t$  corresponds to a moult; and

$G(t)$  is the growth increment, assumed to depend on length, temperature and food concentration  $f(t)$  as follows:

$$G(t) = \beta_0 + \beta_1 L(t) + \beta_2 L(t)^2 + \frac{\beta_3 f(t)}{\beta_4 + f(t)} + \beta_5 T(t) + \beta_6 T(t)^2 \quad (\text{A4.2})$$

where  $\beta_0$  to  $\beta_6$  are constants, as given in Table A4.1 ; and

$T(t)$  is the average ambient temperature at time  $t$ .

An average value of  $f(t) = 0.25$  (from Wiedenmann *et al.* 2008) was substituted given that the primary purpose here was to establish the relationship between krill growth and SST. Equation (A4.2) was used to simulate the difference in krill growth rates under temperatures ranging from  $-1^\circ\text{C}$  to  $5^\circ\text{C}$ , and for average krill lengths from 2mm (0 years) to 60 mm (6 years). Age-length conversions were effected using the von Bertalanffy equation given in Siegel (1987). From the above, a general relationship between growth rate and SST was derived as shown in Fig. A4.1, and a functional form for a growth rate multiplier  $GRM(T)$  estimated by fitting the following equation:

$$GRM(T) = -\alpha_1(T(t) - 1) + \alpha_2 \quad (\text{A4.3})$$

where  $T$  is the average SST at time  $t$ ;

$\alpha_1, \alpha_2$  are constants as listed in Table A4.1.

The available SST data for the historic season were used to compute  $GRM(T)$  for each season of each of the historic years, and this was in turn applied as a multiplier to the krill growth rate parameter  $r$ .

Table A4.1. Parameter values for krill growth model, with  $\beta_0$  to  $\beta_6$  as given in Wiedenmann *et al.* (2008).  $\alpha_1, \alpha_2$  are constants used to describe the relationship between relative growth rate and SST (see Fig. A4.1).

Parameter	Value
$\beta_0$	6.6
$\beta_1$	-0.385
$\beta_2$	0.00259
$\beta_3$	17.53
$\beta_4$	0.332
$\beta_5$	0.595
$\beta_6$	-0.477
$\alpha_1$	0.016
$\alpha_2$	1.047

### Temperature vs growth relationship

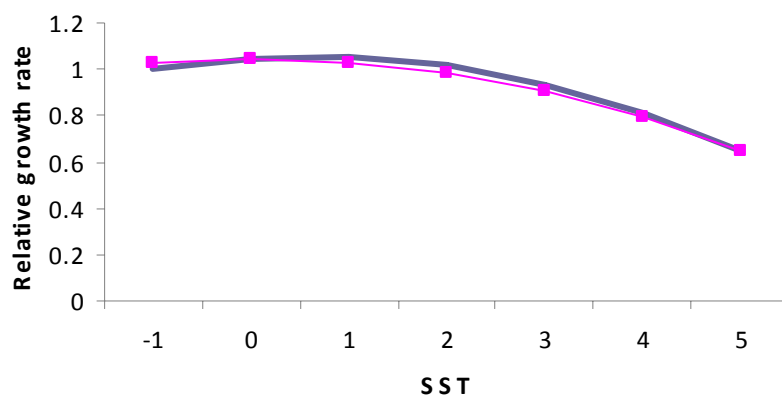


Fig. A4.1. Derived relationship between relative krill growth rate and SST.

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Table 1. Table of historic krill catches (t). Total catches 1973/74 to 1979/81 from CCAMLR statistical bulletin. Catches by SSMU 1980/81 to 2005/06 from EMM 07-5 (provided by David Ramm). Grey boxes are estimated catches based on dividing the large scale catch (by area or subarea) among SSMUs in proportion to the distribution of catches over the whole period (as indicated by summing and then averaging the white boxes).

Year/SSML	APBSE	APBSW	APDPE	APDPW	APE	APEI	APPA	APW	SGE	SGPA	SGW	SONE	SOPA	SOSE	SOW
1973/74	0	0	3	7	0	4	2	0	15	2	2	2	7	1	15
1974/75	124	122	1032	2273	1	1435	493	63	4939	613	567	500	2221	171	4781
1975/76	266	261	2206	4860	2	3068	1055	135	10561	1310	1212	1069	4749	366	10223
1976/77	10	10	83	182	0	115	40	5	396	49	45	40	178	14	384
1977/78	484	475	4015	8847	3	5585	1920	246	19222	2385	2206	1946	8643	667	18607
1978/79	536	526	4447	9798	3	6185	2126	272	21288	2641	2443	2155	9572	738	20607
1979/80	1691	1661	14036	30927	10	19523	6712	860	67195	8337	7711	6802	30215	2331	65045
1980/81	2657	51	35633	18142	130	16053	17494	3557	0	0	0	3945	17522	1352	37721
1981/82	0	1	10495	17537	0	6268	32752	1141	0	0	0	997	239257	0	18342
1982/83	0	0	0	6	0	5	2273	11	1618	201	186	1873	48174	0	10025
1983/84	200	13	10392	5294	16	5015	9000	300	59	7	7	3709	29	3	6491
1984/85	44	0	4854	499	0	5846	1595	96	49017	6081	5625	18293	5109	41	114912
1985/86	54	0	12504	4642	0	19664	2536	1648	89275	11076	10245	40285	1192	0	185619
1986/87	12	1	11780	1807	0	53373	3296	0	312134	0	0	684	1026	0	16718
1987/88	0	43	10459	41584	0	24580	2223	30	105990	105636	24	4357	4555	19296	70073
1988/89	0	21	10065	47176	0	42857	5401	33	157204	1412	0	14	72890	0	15197
1989/90	11	0	11432	7336	0	24894	1071	8	89225	11359	7230	12657	81808	0	129067
1990/91	1014	437	8245	26272	0	29684	4012	1	85719	8352	7598	12947	5051	201	141785
1991/92	92	451	9031	54004	0	6266	5703	18	47805	1136	15305	3870	48696	0	65236
1992/93	0	45	530	30286	0	2365	37	3	3478	124	11139	4240	1248	0	7182
1993/94	0	146	708	26569	0	17652	5	4	19908	381	11	147	4	1303	17806
1994/95	0	399	2646	13834	0	15030	6256	0	46624	473	325	1273	27	24	47509
1995/96	0	1470	4149	37701	25	12613	6007	0	23596	63	2793	4	51	0	2679
1996/97	13	211	15656	22646	0	9138	1179	0	26605	0	106	6	29	2	62
1997/98	86	2162	18054	23602	0	5828	3953	2889	22930	314	3532	290	505	0	5877
1998/99	914	107	10608	11400	0	8976	2981	3909	795	99	91	3379	984	12422	45291
1999/2000	2959	6104	19980	30816	0	10673	1344	101	14600	8425	2532	1130	3145	1493	11123
2000/01	576	3379	16273	21803	0	4131	5	611	36333	630	15461	22	2	3846	1111
2001/02	94	290	1150	4830	0	4132	146	3	30562	3202	9517	3856	70	1170	66963
2002/03	18	390	1627	32174	0	1040	67	62	52003	791	14131	54	509	44	14821
2003/04	1683	350	1348	4493	0	5477	311	220	23527	331	33971	754	280	10	45412
2004/05	0	375	2000	4605	0	37	12	66	45029	23	210	1439	2410	26	70805
2005/06	18511	11981	10566	40142	0	2479	5197	0	6542	0	8069	123	0	0	2979

Table 2. Historic catch series (1970 to 2006) for a generic fish constructed as described in the text, and based on catch data for Area 48 extracted from the CCAMLR Statistical Bulletin volume 19. and apportioned to each of the SSMUs, using data on shelf areas (from Hill *et al.* 2007), and assuming that catches are proportional to shelf area. Catches are shown in units of tons and are converted to numbers within the model by dividing by an average fish mass of 0.11 g (Hill *et al.* 2007).

	Antarctic Peninsula Pelagic	Antarctic Peninsula West	Drake Passage West	Drake Passage East	Bransfield Strait West	Bransfield Strait East (APBSE)	Elephant Island (APEI)	Antarctic Peninsula East	South Orkney Pelagic	South Orkney West	South Orkney North East	South Orkney South	South Georgia Pelagic	South Georgia West	South Georgia East	TOTAL
1970	12348	4102	1037	1216	1714	2251	1241	8437	40247	8476	8456	44607	34299	105256	124250	397937
1971	3468	1152	291	341	482	632	349	2369	11304	2381	2375	12528	9633	29562	34896	111763
1972	102	34	9	10	14	19	10	69	331	70	70	367	282	866	1022	3274
1973	57	19	5	6	8	10	6	39	184	39	39	204	157	482	569	1822
1974	8	3	1	1	1	1	1	5	26	5	5	28	22	67	79	253
1975	23	8	2	2	3	4	2	16	75	16	16	83	64	196	232	743
1976	866	288	73	85	120	158	87	592	2824	595	593	3130	2406	7384	8717	27918
1977	3393	1127	285	334	471	619	341	2318	11059	2329	2324	12258	9425	28923	34143	109350
1978	6163	2048	518	607	856	1124	620	4211	20089	4231	4221	22265	17120	52537	62018	198624
1979	2529	840	212	249	351	461	254	1728	8243	1736	1732	9136	7025	21558	25448	81503
1980	2382	792	200	235	331	434	240	1628	7766	1635	1632	8607	6618	20309	23974	76781
1981	1147	381	96	113	159	209	115	783	3737	787	785	4142	3185	9774	11538	36953
1982	1871	622	157	184	260	341	188	1279	6100	1285	1282	6761	5198	15952	18831	60310
1983	6056	2012	509	596	841	1104	609	4138	19739	4157	4147	21878	16822	51623	60939	195172
1984	1724	573	145	170	239	314	173	1178	5619	1183	1181	6228	4788	14695	17347	55556
1985	316	105	27	31	44	58	32	216	1030	217	216	1142	878	2694	3180	10186
1986	863	287	72	85	120	157	87	589	2812	592	591	3116	2396	7353	8680	27799
1987	2673	888	224	263	371	487	269	1826	8713	1835	1831	9657	7425	22787	26899	86151
1988	1373	456	115	135	191	250	138	938	4476	943	940	4961	3814	11705	13818	44254
1989	64	21	5	6	9	12	6	43	207	44	44	230	177	542	640	2051
1990	336	112	28	33	47	61	34	229	1094	230	230	1213	932	2861	3377	10817
1991	3	1	0	0	0	1	0	2	9	2	2	10	8	24	29	92
1992	0	0	0	0	0	0	0	0	1	0	0	2	1	4	4	14
1993	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	1	0	0	0	0	0	0	0	2	0	0	2	2	6	7	22
1995	0	0	0	0	0	0	0	0	2	0	0	2	1	4	5	15
1996	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1998	0	0	0	0	0	0	0	0	1	0	0	1	1	2	2	7
1999	8	3	1	1	1	2	1	6	28	6	6	31	24	72	85	274
2000	127	42	11	13	18	23	13	87	414	87	87	459	353	1083	1279	4096
2001	30	10	3	3	4	5	3	20	98	21	21	108	83	255	301	965
2002	83	28	7	8	12	15	8	57	271	57	57	301	231	710	838	2684
2003	62	20	5	6	9	11	6	42	201	42	42	222	171	525	620	1984
2004	83	28	7	8	12	15	8	57	270	57	57	300	230	707	835	2673
2005	7	2	1	1	1	1	1	5	23	5	5	25	20	60	71	227
2006	68	23	6	7	9	12	7	46	221	47	47	245	189	579	684	2189

Table 3. Data from Hewitt *et al.* (1994), Hill *et al.* (2007) and S. Hill and G. Watters (pers. commn) showing the estimated number of krill per SSMU as well as the current krill catch (in kgs). The middle columns show estimates of the numbers of penguins, seals, fish and whales per SSMU, calculated from annual predator demand estimates from data provided in Hewitt *et al.* 2004. The final columns show annual predator demand in terms of numbers of krill, with these being converted to biomass of krill within the model. The penguin and seal predator demand estimates in Hewitt *et al.* (2004) considered only Adélie, chinstrap, gentoo and macaroni penguins, as well as lactating female Antarctic fur seals.

Area	SSMU	Area.(m2)	Catch (kg)	Penguins (no.)	Seals (no.)	Fish (no.)	Whales (no.)	Qmax(penguins)	Qmax(seals)	Qmax (fish)	Qmax(whales)
1	APPA	4.22E+11	2.54E+07	0	0	1.46E+10	1.12E+04	0	0	1.05E+03	1.31E+08
2	APW	3.51E+10	7.40E+06	2.37E+05	0	7.90E+08	9.30E+02	6.70E+05	0	2.53E+03	1.31E+08
3	APDPW	1.51E+10	2.28E+08	7.57E+04	1.36E+04	3.66E+08	4.00E+02	5.54E+05	3.50E+06	1.88E+03	1.31E+08
4	APDPE	1.56E+10	1.03E+08	1.11E+06	2.35E+02	3.67E+08	4.13E+02	5.47E+05	3.50E+06	2.03E+03	1.31E+08
5	APBSW	2.10E+10	1.15E+07	1.19E+06	0	4.91E+08	5.57E+02	5.48E+05	0	2.08E+03	1.31E+08
6	APBSE	2.74E+10	5.95E+06	2.79E+05	0	6.41E+08	7.28E+02	6.77E+05	0	2.09E+03	1.31E+08
7	APEI	3.53E+10	9.49E+07	1.45E+06	1.12E+03	1.11E+09	9.37E+02	5.46E+05	3.50E+06	1.20E+03	1.31E+08
8	APE	5.87E+10	2.50E+04	7.25E+05	0	1.33E+09	1.56E+03	7.97E+05	0	2.79E+03	1.31E+08
9	SOPA	8.09E+11	6.25E+06	0	0	1.26E+11	7.54E+03	0	0	1.93E+02	1.50E+08
10	SOW	1.56E+10	2.17E+08	2.35E+03	0	5.84E+08	1.45E+02	5.46E+05	0	9.47E+02	1.50E+08
11	SONE	1.03E+10	1.59E+07	5.17E+05	0	3.09E+08	9.50E+01	7.91E+05	0	1.28E+03	1.50E+08
12	SOSE	1.50E+10	1.95E+07	2.00E+06	0	3.38E+08	1.39E+02	5.89E+05	0	2.75E+03	1.50E+08
13	SGPA	9.20E+11	7.82E+06	0	0	2.37E+11	8.56E+03	0	0	1.15E+02	1.50E+08
14	SGW	4.21E+10	3.14E+07	7.58E+06	6.80E+05	1.61E+09	3.92E+02	4.94E+05	3.50E+06	8.84E+02	1.50E+08
15	SGE	5.37E+10	2.09E+08	5.97E+05	6.78E+03	2.17E+09	5.00E+02	5.29E+05	3.50E+06	8.32E+02	1.50E+08

Table 4. List of model parameters and descriptions.

<b>Parameter / Variable</b>	<b>Description</b>
$B_y^a$	Biomass of krill in SSMU $a$ in year $y$
$r_t^a$	Intrinsic annual growth rate of krill in SSMU $a$ at time $t$
$K_a$	Carrying capacity of krill in SSMU $a$
$\lambda^j$	Maximum per capita annual consumption rate of krill by predator species $j$
$N_y^{j,a}$	Number of predator species $j$ in SSMU $a$ in year $y$
$B_j^a$	Krill biomass when the consumption and hence also birth rate of species $j$ in SSMU $a$ drops to half of its maximum level
$n$	Parameter that controls whether a Type II or a Type III functional response is assumed ( $n=1$ for Type II assumed here)
$\omega$	Proportion of mature females in the mature population of predator species $j$
$F_y^a$	Fishing proportion (catch= $F_y^a B_y^a$ ) on krill in SSMU $a$ in year $y$
$D_y^a$	Net movement of krill (immigration-emigration) into SSMU $a$ in year $y$
$Em$	The average proportion of krill that emigrate from an area to other areas each year
$N_y^{j,a}$	Number of predator species $j$ in SSMU $a$ in year $y$
$S^j$	Post-first-year annual survival rate of predator species $j$
$T$	Average age at first maturity, taken for simplicity to be one less than the age at first reproduction (i.e. assuming a one year gestation period)
$q^j$	Fraction of chicks/pups that are female
$P^j$	Maximum number of fledged chicks or pups leaving the natal colony per pair of predator $j$ per year
$f(B_y^a)$	Breeding success factor (multiplier for $P$ ) which is a function of the biomass of krill in SSMU $a$ in year $y$
$S_{juv}^{*,j}$	Maximum first year (juvenile) survival rate (post-fledging or post-weaning) of predator species $j$
$K^{*,j,a}$	Carrying capacity-related term for predator species $j$ in SSMU $a$
$\alpha^a, \beta^a$	Parameters for breeding success function for SSMU $a$ , with $\beta = (\alpha - 1) \cdot K_a$
$h$	“Steepness” parameter for breeding success function
$c$	Constant to dampen density dependent multipliers
$R$	Krill steady annual growth rate
$R^j$	Steady annual growth rate of predator $j$



Table 5. Parameter values and their sources as used in the basic model.

Parameter	Value	Source
$r_t^a$	$r_t^a$ (max) = 0.4;	Mori and Butterworth (2006)
$K_a$	Computed; Whales initial $N/K = 0.2$	
$\lambda^j$	See Table 3	Hill <i>et al.</i> (2007)
$n$	1	-
$\omega$	0.5 (penguins); 0.67 (seals); 0.5 (fish); 0.5 (whales)	Hill <i>et al.</i> (2007)
$c$	0.5	-
$S^{penguins}, S^{seals}, S^{fish}, S^{whales}$	0.88 – 0.9; 0.92 – 0.96; 0.6 – 0.72; 0.97 – 0.98	See Table A3.1
$T$	3 (penguins); 4 (seals); 3 (fish); 5 (whales)	Hill <i>et al.</i> (2007)
$q^j$	0.5	-
$P^j$	0.91 (penguins); 0.88 (seals); 3.0 (fish); 0.5 (whales)	Crawford <i>et al.</i> (2006); Boyd <i>et al.</i> (1995); Taylor <i>et al.</i> (2007)
$S_{juv}^{*,penguins}, S_{juv}^{*,seals}, S_{juv}^{*,fish}, S_{juv}^{*,whales}$	0.7 – 0.8; 0.6-0.8; 0.6-0.67; 0.8-0.91	See Table A3.1
$R, R^j$	0.0	Working Group

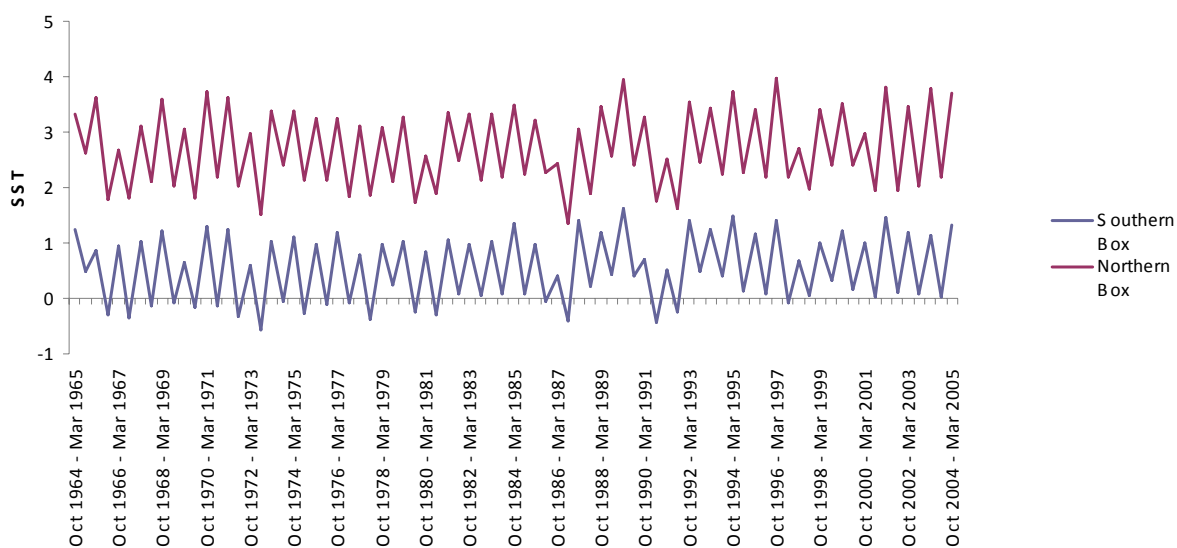


Fig. 1. Historic sea surface temperature data (CARTON-GIESE SODA Version 2.0.2-3) for the period 1967 to 2006. The data were aggregated across a southern box (57°S-64°S; 30°W-70°W), spanning SSMUs 1-12 (Antarctic Peninsula to South Orkney Islands), and a northern box (50°S-57°S; 30°W-50°W), spanning SSMUs 13-15 (South Georgia)

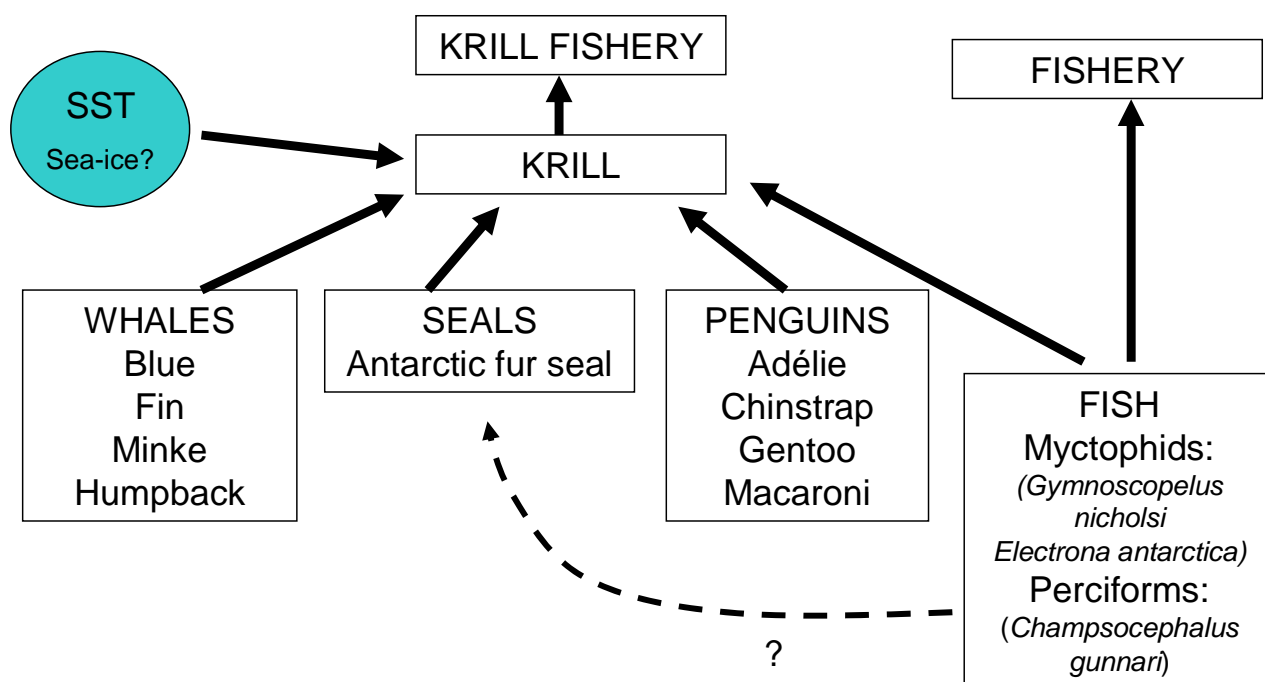


Fig. 2. Schematic summary of interactions included in SMOM. The composition of each of the four generic predators varies per SSMU. Krill is the only prey species, although future model versions may include a link between seals and fish. Sea surface temperature (SST) is included as a forcing function of krill, and indirectly represents sea ice extent.

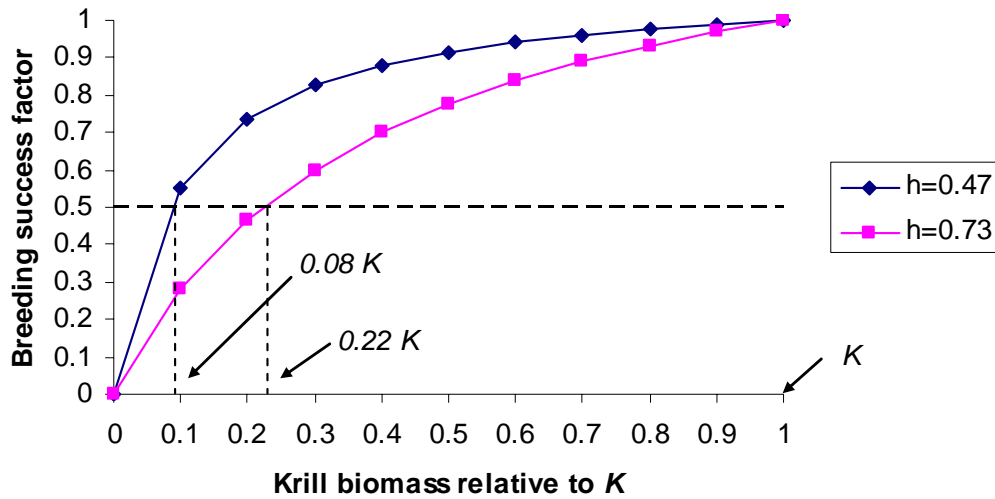


Fig. 2. Plot of the modelled relationship between predator breeding success and krill abundance relative to the krill carrying capacity level  $K$  in each SSMU. The shape of the curve is determined by the steepness parameter  $h$  (see Equation 11). The illustrative curve shows examples of a near-linear decrease in breeding success as krill abundance decreases (square symbol) and a scenario in which predator breeding success is negatively impacted at relatively low levels of krill abundance only (diamond symbol). Thus in the former case breeding success drops to half its maximum level when krill biomass is 22% of  $K$  compared with a much lower 8% of  $K$  in the latter case. These values are also used to compute  $B_j^a$  in the predator consumption term in the krill equation, effectively representing the krill biomass when the birth rate of predator species  $j$  in SSMU  $a$  drops to half of its maximum level .