Preliminary model of the impact of pelagic fishing on the South African West Coast in the vicinity of seal and penguin colonies

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INTRODUCTION

Preliminary work is summarised here concerning the development of a model of the impact of pelagic fishing on the South African west coast in the vicinity of seal and penguin colonies, for report to the CCAMLR Scientific Committee to parallel and inform their similar initiative concerning krill fishing in the vicinity of krill-dependent predator colonies in the Antarctic Peninsula region through which there is a flux of krill. The decision to model the impact of the South African fishery on penguin and fur seal breeding colonies is because it is a topic of local interest and because of the readier availability of data from both predator studies and pelagic fish surveys, which can be used to provide flux estimates. A spatial modelling framework is used to assess what level and localisation of the fishing effort might negatively impact the predators. The models developed build to some extent on an earlier approach (Plagányi *et al*. 2000) to explore the effect of different geometric distributions and degrees of synchrony in the abundance of anchovy and its zooplankton prey off the South African west coast. That work made use of a spatial framework to explicitly model shoals of anchovy recruits feeding on patches of zooplankton prey, and quantified the fish's performance through temporal and spatial integration of periods and patches of prey abundance and shortage.

This work will be reported at a meeting of the WG-EMM subgroup of the CCAMLR Scientific Committee to inform and dovetail with their initiatives on the similar issue for krill fishing off the Antarctica Peninsula region, with subsequent modelling in this project then being directed to address this issue for krill.

The West Coast model has initially been constructed to be as simple as possible with greater complexity to be added in a stepwise fashion as required.

Pelagic fish overview

Anchovy *Engraulis capensis* and sardine individuals recruit to the fishery in their first year and support a purse seine fishery of considerable economic and social importance to the Southern Benguela upwelling region (Cochrane and Hutchings 1995). Anchovy spawn serially from October to January on the Agulhas Bank, and most eggs and larvae are transported northwards in a jet current (Hutchings *et al.* 1998). The larvae and juveniles migrate from the outer shelf region to a narrow coastal belt along the West Coast (Fig. 1), which acts as a nursery region before groups of shoals of recruits return south again to spawn on the Agulhas Bank the following spring/summer.

The mean recorded travelling speed of an anchovy is 1.7 $BL \cdot s^{-1}$ (James and Findlay 1989). The average caudal length of a recruit is about 8.42 cm in May (Waldron *et al*. 1992), which is midway through the model period (March - August). It follows that on average fish can travel about 6.2 km d^{-1}, under the assumption that they can travel for up to 12 hours per day (and rest and feed for the remaining period).

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Model spatial and temporal scales

The model area has been set as a 180 x 60 nautical miles rectangular block off the West Coast of South Africa, stretching from 31°S to 34°S latitude (Fig. 1). The rectangular model grid is divided into 4800 cells each measuring 1.5 x 1.5 nm^2 (approx. 2.8 x 2.8 km^2), with *x*-coords 1 – 40 and *y* coords 1 - 120. The model spatial resolution was selected after consideration of the average travelling speed of pelagic fish, as well as the need to use a small enough scale to simulate realistic fishing exclusion zones (Fig. 2). The resolution chosen is also adequate for simulating the foraging range of a number of predators: initial work will focus on fur seals as predators.

There is a western model boundary representing offshore water beyond the 200m isobath because pelagic fish recruits are typically in shallow inshore water. The eastern boundary represents the coast and includes St Helena Bay from which the largest pelagic catches are taken (Fig. 1). Fish enter the model area along the northern model boundary as well as the northwestern boundary and move in a generally southwards direction through the model area. The model time step is one day and the model is run over 180 days which represent the period from March to August. The choice of model time period is to coincide with the southward migration of pelagic fish recruits, catches by the fishery and peak breeding times of predators along the West Coast islands. For example, this time period includes the time female South African fur seals nurse their pups.

One or more islands will be simulated by locating the island/s within an appropriate cell with coords (x,y). The largest West Coast island is Dassen Island which is 4.5 km long and 2km wide and hence would occupy two model cells.

Boundary conditions

The eastern model boundary is represented by the coast and hence inshore shoals attempting to move eastwards are simply reflected back in either a westerly or south-westerly direction with equal probability. Shoals attempting to move beyond the western 200m isobath boundary are similarly reflected back into the model area.

Fish enter the model area daily along the northern and north-western boundary, over a 3-month period starting from 1 March. The daily number of fish entering the northernmost cells during each of March, April and May are $p_1 * N_{Nov}$, N_{Nov} and $p_2 * N_{Nov}$ respectively, where p_1 and p_2 are inputs based on the birthdate distribution of anchovy (currently preliminarily set at $p_1 = p_2 = 0.5$) and N_{Nov} is estimated within the model as described in the "Estimable parameters" section below. (Alternatively this could be computed assuming the number of fish entering per day (for the first 90 days) = $N_{Nov}\sin(0.035t)$ i.e. a sine curve with period 180 days). Fish also enter the first 52 cells along the model's north-western boundary, with the number entering each of cells y = 1 to 52 given by:

$$Number(NW\ boundary)_y = N_{Nov}e^{-\kappa y} \qquad (1)$$

where $\kappa = 0.045$ is a fixed input, computed such that the number of fish entering the model area at the southernmost point is approximately 10% of that entering in the north.

Fish leaving the southern model boundary are assumed to continue on their southwards migration and hence do not re-enter the model area.

Fish dynamics

The dynamics of the pelagic fish population in each of cells *x,y* not on the model boundary is given by:

$$N_{x,y,t+1} = \left[\left(\omega N_{x,y,t} + D_{x,y,t} \right) \left(1 - F_{x,y,t} \right) e^{-M_b} \right] - Q_{x,y,t} \qquad (2)$$

and

$$D_{x,y,t} = \rho \left(N_{x-1,y-1,t} + N_{x-1,y,t} + N_{x-1,y+1,t} + N_{x,y-1,t} + N_{x,y+1,t} \right) \qquad (3)$$

where $N_{x,y,t}$ is the number of fish in cell (*x,y*) at the start of day *t*,

$D_{x,y,t}$ is the flux or movement of fish into cell (*x,y*) from neighbouring cells at the start of day *t* ;

ρ is the proportion of fish from each of the neighbouring cells that move into cell (*x,y*) at the start of day *t*,

$\omega = 1 - 5 * \rho$ is the proportion of fish retained within cell (*x,y*) on day *t*,

$F_{x,y,t}$ is the fishing "mortality" (i.e. the proportion which are caught) in cell (*x,y*) on day *t*,

M_b is the (time-invariant) background or basal daily natural mortality rate of fish, and

$Q_{x,y,t}$ is the loss due to predation on day *t* i.e. the number of fish consumed per day by predators on surrounding breeding colonies.

Fish are modelled in terms of numbers per model cell but should be visualised as one or more shoal groups travelling together. The movement of the fish is modelled as a southward flow combined with east-west diffusion.

The biomass of fish at time t is given by:

$$B_{x,y,t} = w_t N_{x,y,t} \qquad (4)$$

where w_t is the average mass (g) of a fish at time *t* (i.e. account is taken of the fact that individual fish increase in biomass over the 7-month model period).

The model assumes that at the start of each day fish diffuse, then fishing occurs, then predation occurs. The initial model includes the simplest possible predation term as follows:

$$Q_{x,y,t} = \frac{1}{w_t} \left(P_{x,y,t} \gamma \overline{R} \right) \qquad (5)$$

where $P_{x,y,t}$ is the number of predators feeding in cell (*x,y*) during day *t*;

$\overline{R}$ is the average daily ration in terms of biomass (g) of a predator; and

γ is the average proportion of pelagic fish in the predator's diet.

Notes:

1. $F_{x,y,t}$ is currently set to zero. The next step is to gradually increase the value from zero to (at least) the average value around a breeding colony, with values everywhere else equal to the average F ($\overline{F}_t$) required to achieve observed catches, i.e.

$$\overline{F}_t = \frac{C_t * 10^6}{w_t \sum N_{x,y,t}} \tag{6}$$

   where C_t is the observed daily pelagic catch (in tonnes) and the summation is over all non-boundary model cells in which fishing occurs. The model is set up such that it is possible to compute individual $F_{x,y,t}$ values instead, given spatially disaggregated catch information as inputs.

2. M_b = 0.0025 d^{-1} (corresponds to juvenile annual mortality rate of 0.9 – Cunningham and Butterworth 2004) – value will be estimated in later model versions.
3. The consumption term $Q_{x,y,t}$ - this will be zero for all cells except those around breeding colonies. Initially this variable will simply be computed based on the number of predators on an island, their total daily ration and their foraging range (Equation 5). Later model versions may use more complex formulations in which e.g. per capita consumption is density dependent and a saturation term is included.
4. Later model versions may include modifications to take into account the greater retention of fish in some coastal areas/around islands due to oceanographic features.

Estimable parameters

The current model version (which is still preliminary) has three estimable parameters as follows:

1. N_{Nov} which determines the flux of fish into the model area;
2. ρ which describes the rate of movement of the fish through the model area and hence the flux of fish past islands with breeding predators; and
3. M_b – the background mortality rate.

These parameters are estimated within the model using the following information. Recruitment estimates for anchovy and sardine are available from annual surveys conducted in ± May each year (Table 1). The model uses in the first instance the May (anchovy + sardine) survey estimate, namely $Surv_{May}(2003) = 5.32$ billion (Table 1), as a snapshot of the number of recruits present along the west coast at the time, ignoring those fish that have not yet entered the system or have already exited in the south. The model area includes about 90% (CHK VALUE) of the total fish surveyed. A corresponding model "survey" date is fixed at 15 May. Hence the corresponding model estimates of this quantity is:

$$\hat{S}_{May} = \sum N_{x,y,t=75} \tag{7}$$

where the summation is over all non-boundary model cells.

The second set of information is based on the results from the South African anchovy model (Cunningham and Butterworth 2004). The Cunningham and Butterworth model provides an estimate of the number of 1-yr old pelagic fish (anchovy + sardine) in November of a year - $N^{obs}_{age=1,Nov\,2003}$ (Table 1). These are the number of 0-yr olds that have survived from the November of the previous year, i.e. surviving $N^{obs}_{age=0,Nov\,2002}$ taking into account the total catch of the 0-yr olds and the assumed juvenile mortality rate M_{juv} = 0.9 yr^{-1}.

The model parameters N_{Nov}, ρ (which are correlated to some extent and control the flux of fish through the model area) and M_b will be estimated by minimising the objective function:

$SS = \left(a_1 * Surv_{Nov} - \hat{S}_{Nov}\right)^2$ + term fitting model estimate to difference between number of fish that entered area and remained over at the end of the year

where a_1 = 0.9 (in the current model version) is the ratio of the model area to the survey area.

RESULTS

No results are currently available as the model is still being developed and comments being sought regarding the model structure. The model is being coded in AD Model Builder^{TM}, (Otter Research, Ltd.).

As an example of model outputs, simulations will be conducted under various levels of fish numbers/biomass and fishing mortalities to estimate the biomass and flux of fish around islands of breeding predators. Different levels of fishing in the model will then be simulated over a range of distances around an island to determine whether or not this has an appreciable impact on penguin and fur seal breeding colonies.

The point of this modelling exercise is thus to see how, as F in the colony square is increased (and also the numbers of predators there is varied), the ratio of the consumption rate by predators to local density of prey varies. Changes in the ratio suggest that the predators are potentially impacted by fishing versus the alternative scenario in which diffusion/transport processes are sufficient to replenish prey in the area and hence little difference is made.

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Table 1. Recruitment estimates for anchovy and sardine (from Cunningham and Butterworth 2004) showing the May recruitment survey estimates and November model estimates from the model of Cunningham and Butterworth (2004).

	Anchovy Recruitment Numbers (in billions)			Sardine Recruitment Numbers (in billions)		
Year	Observed	Time Of Survey	November	Observed	Time of Survey	November
1984			198.738			6.747
1985	91.736	106.286	419.114	3.143	3.180	7.684
1986	121.755	221.230	236.710	4.754	3.511	7.326
1987	115.694	107.812	214.166	8.040	3.291	9.526
1988	111.836	105.379	75.821		4.634	12.314
1989	29.395	27.851	164.839		6.220	9.716
1990	45.517	77.278	413.512		5.489	22.194
1991	82.699	252.487	251.544	5.245	12.908	23.963
1992	101.114	143.325	119.871	13.836	13.804	25.873
1993	98.691	68.343	65.412	24.671	14.604	19.529
1994	30.071	36.997	139.443	6.210	11.252	42.128
1995	134.256	71.584	55.704	38.583	22.192	20.604
1996	26.772	29.462	136.499	8.191	10.804	27.414
1997	111.890	83.577	178.996	42.850	15.884	50.757
1998	136.740	103.281	302.618	14.540	28.569	59.104
1999	161.110	187.164	844.231	12.000	34.858	83.111
2000	550.110	513.574	1030.883	36.390	48.050	106.526
2001	631.950	645.859	358.095	69.280	63.775	102.535
2002	460.050	222.776	435.767	71.780	61.174	90.466
2003	379.520	265.854		63.450	52.264	

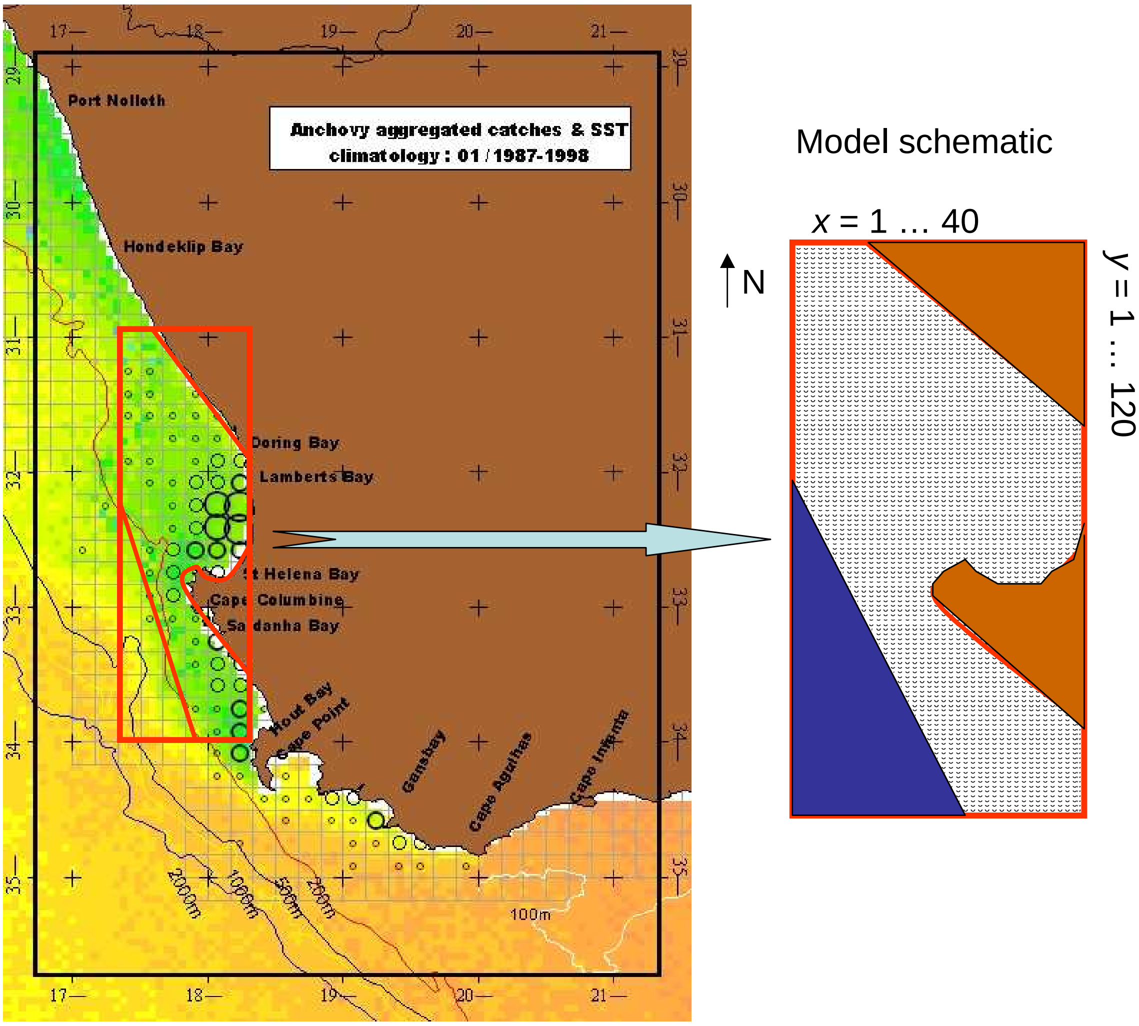

Fig. 1. Model spatial grid shown superimposed on GIS map of the West Coast of South Africa showing aggregated anchovy catches over the period 1987-1998 (from IDYLE – REFS Freon et al**). The model area includes the inshore (within 200m isobath) area from about 31°S to 34°S latitude where anchovy catches are greatest and in which a number of islands with breeding fur seals and seabirds are located. The model spatial resolution is 1.5 nm x 1.5 nm.

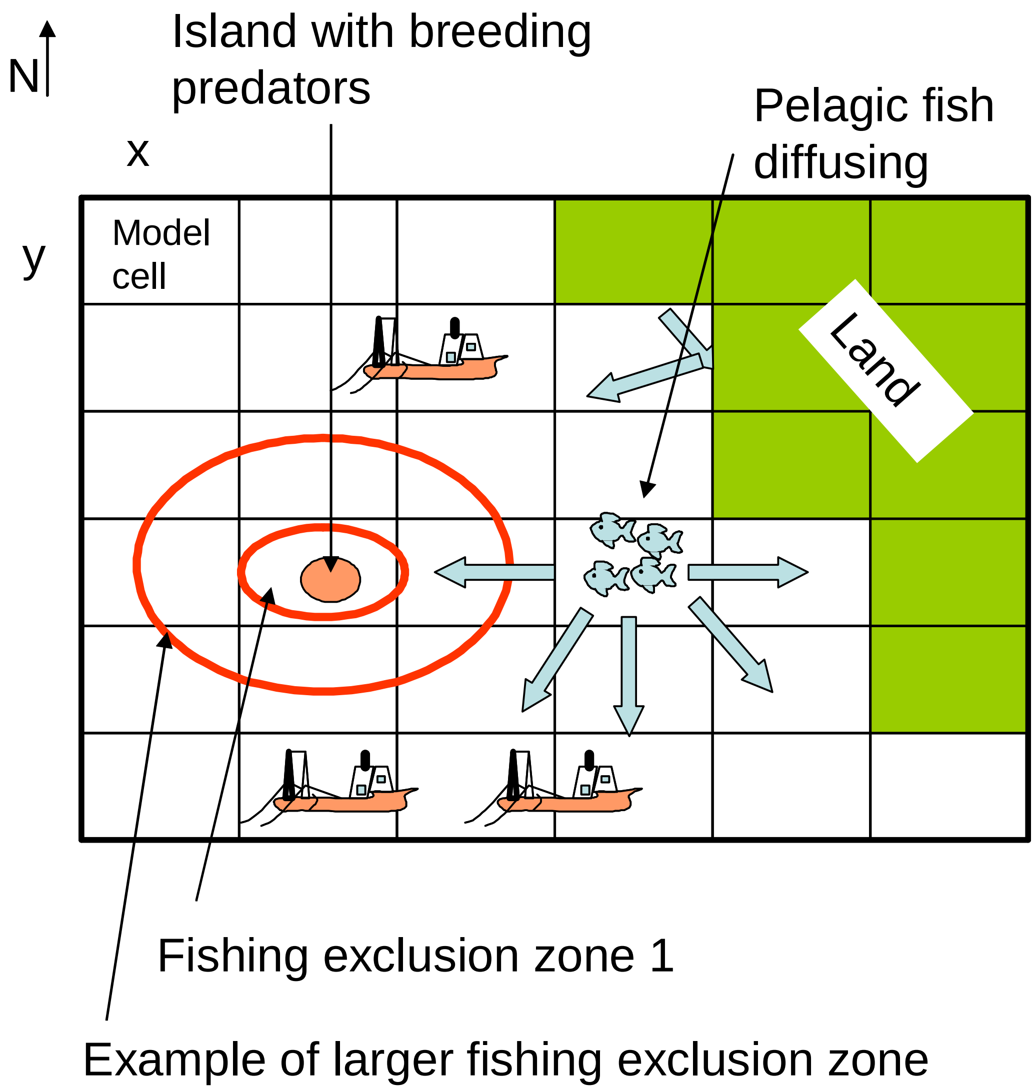

Fig. 2. Close-up schematic of model structure illustrating generally southwards diffusion of pelagic fish, reflection from model boundary and situation of island with fishing exclusion zones to be simulated. Model cells are 1.5 nm x 1.5 nm.