Update of available data for the African Penguin *Spheniscus demersus* Model to be coupled to the pelagic OMP

Éva Plagányi and William Robinson
Department of Mathematics and Applied Mathematics, UCT

INTRODUCTION

This document serves as an updated compilation of all data currently available as inputs to the African penguin spatial model (MCM/2008/SWG-PEL/21b) which is to be coupled to the pelagic OMP. The data are presented here together with some comments as to how they are to be used in the model and notes on their derivation and potential reliability. Note that this is a working group document only and hence should be extended and improved in future, particularly as regards critical evaluation of different data sources.

The model presented thus far is spatial in that different populations of penguins are represented, and different levels of movement between these populations are modelled. The main focus of the model is on Dassen and Robben Islands, which were originally combined for reasons of simplicity and because of their close proximity to each other, suggesting that the effects of external factors such as food availability would be highly correlated between the two. However, data that have recently become available indicate differences between these two colonies which suggest that it may no longer be appropriate to pool the two; hence they are split in the model. The third population is Dyer Island because it has the next largest numbers of penguins, recent declines in the population there are of concern and it is considered an important breeding site for penguins given the eastward shift of sardines. The fourth population is Boulders. Although relatively small, this colony was considered important to include because of its position, its role as the focus of several other studies and because penguins are known to have moved from Dyer Island to Boulders, Robben and Dassen, and hence it is useful to quantify to what extent movement of birds away from Dyer Island could account for observed declines at Dyer and increases at these other colonies. An Algoa Bay component can also be linked to the model if required but the current model version focuses only on the western region.

A summary of all the breeding colonies of penguins in area i) is provided in Fig. 1 which also shows the relative abundance of breeding pairs in the different sub-areas, computed from data in Underhill *et al.* (2006). The regional penguin population is dominated (in terms of numbers) by two large colonies, namely Robben Island and Dassen Island; thus the model here has focused on these two colonies, with the next most important colony being Dyer Island.

Fig. 2 maps the extent of strata corresponding to pelagic fish biomass estimates used to link to penguin breeding success in the area i) model (which includes Dassen, Robben, Dyer Island and Boulders) and preliminary model for area iii) (St Croix).

The model time step is one year and hence average trends are modelled. Penguins in each sub-area are modelled starting from 1987.

DATA

Available Data - Penguins

A summary of the timeline assumed for an "average" penguin is given in Fig. 3.

A number of time series, both published and unpublished, are available and have been used both to compare with model trends and for use in estimating parameters by fitting to these data. The two main forms of data are counts of the numbers of moulting birds at the various colonies and counts of breeding pairs (Table 1). The data are from Underhill *et al.* (2006), and various published studies as well as recent updates provided by Les Underhill and Rob Crawford.

The moult count data are generally considered more precise as a population measure (based on c. 24 counts per year) than the breeding pairs count (one count per year aimed to hit the peak of the breeding season) (L. Underhill, pers. commn). The moult count measures the size of the adult-plumaged population whereas the nest count measures the number of breeding pairs (L. Underhill, pers. commn). There are two slightly different series available describing the number of birds moulting at Robben Island, and the series used here are the set considered the more accurate of the two because they account for missing information (see Underhill and Crawford 1999).

It has been highlighted (Rob Crawford, pers. commn) that the counts are of birds moulting around the coastline but that at Dassen Island, where many birds construct burrows, birds also moult in burrows and are not counted. Furthermore the counts at Dassen Island do not cover the interior where penguins may be found in appreciable numbers. Therefore, the count at Dassen Island is not of all birds moulting, just an index. Anton Wolfaardt and Les Underhill (pers. commn) have similarly confirmed that the Dassen Island moult counts should be treated as an index of abundance, and not as an estimate of the absolute number of penguins. Given that the moulting process takes two weeks, the sum of counts made at two week intervals provides an estimate of the total population moulting at the locality, following adjustments for the fact that the counts are not made at exactly this frequency. Crawford (pers commn) notes that moulters will be undercounted at Robben Island to a lesser extent than at Dassen Island.

As the model represents numbers of female penguins, an even sex ratio was assumed and the numbers of moulters halved to derive an index of the number of female moulters (Table 1). Separate moult count series are given in Table 1 for Robben and Dassen Islands given that these colonies are modelled separately.

It has been noted that the Dyer moult count data are unreliable for some years due to cholera outbreaks at the peak moult period (Underhill, pers commn). The following data from Dyer have thus been excluded from the analysis:

- 2001 (counts were not made in September and October 2000)
- 2003 (counts were not made in October and November 2002)
- 2005 (an important count is missing for the first half of October 2004, so the interpolation is not really satisfactory).

Data to provide insights into the age structure are provided by Les Underhill in the form of adult and juvenile (birds undergoing first moult) penguin moult counts at Dassen, Robben and Dyer Islands (Table 2). A combined index of the juvenile proportion for Robben and Dassen was derived by summing adult and juvenile numbers for all years for which data are available for both islands, and using just the Robben Island data for the remaining years.

It has been noted that, when considering Robben, Dassen and Dyer Islands, the number of female moulters per year is approximately the same or less, rather than substantially more, than the number of breeding females (Fig. 4). This indicates that only a proportion of the population is counted during the moult counts because, for example, counts do not cover the island interiors where penguins may be found in appreciable numbers. It is assumed in the modelling exercise that the proportion of counted to uncounted birds remains approximately constant from year to year and that the moult counts provide a reliable index of population trends even though only a proportion of the population is counted.

Using data on the numbers of breeding pairs (from Underhill *et al.* 2006), the observed trends in the Western Cape as a whole are compared in Fig. 5 with the trend obtained when summing the numbers of breeding pairs included in a model encompassing Dassen Island, Robben Island, Boulders and Dyer Island. This suggests that the model accounts for over 90% of all penguins in area (i) of the spatial model being developed for testing the pelagic OMP, and that the overall trend is the same as that for the Western Cape as a whole. The projected model will focus on Dassen and Robben Islands only which together currently account for 65% of all penguins in area (i), though the proportion has been 80-85% during the last 10 years.

Chick fledging success data

Data on the number of chicks fledged per pair per year were available for Robben Island based on values in Crawford *et al*. (2006) (Table 3), but with some recent updates and changes. Over the period 1989-2005 at Robben Island, penguin pairs fledged an average of 0.63 chicks annually, with a maximum of 0.97 in 1997 (Crawford *et al*. 1999, 2006 with changes to 2005 data and update for 2006 provided by Crawford pers commn.). There are no data for the year 2000, which corresponds to the year in which about 1900 birds died and breeding was disrupted following oiling in the *Treasure* spill (Crawford *et al*. 2000). Crawford *et al.* (2006) suggest that the increased mortality caused by the oil spill was ameliorated to a large extent by the high abundance of pelagic fish prey at the time.

Data have also recently become available for Dassen Island from A. Wolfaardt (Table 3).
The Robben series is longer than the Dassen series, and the Dassen values are higher (average = 0.9; maximum = 1.08), possibly mainly because the Robben breeders are new, less experienced birds (Crawford pers. commn) (Fig. 6). One difficulty with these data is that the Dassen data are for one breeding attempt, not for one year, hence the fledgling success estimates per year should actually be slightly higher (A. Wolfaardt, pers. commn).

Crawford (pers. commn) notes as follows: "Averaging Anton's values for those re-breeding within 2.5 months (25% of successful; 36% of failed at incubation; 21% of failed at brood) gives 27% of birds having a second clutch, which as Anton points out is the same as observed in an earlier study at Robben Island (27% p. 143, Crawford et al. 1999). Therefore to get an estimate of chicks fledged per pair per year, I would multiply Anton's chicks produced per breeding attempt by 1.27." He notes further that differences between islands in breeding success may be due to island factors and not food effects, given for example that the cat population at Robben peaked in 1998. Moreover, Dassen Island is likely a more favourable breeding habitat than Robben Island.

Proportion that breed at various ages

African Penguins are known to breed for the first time when 4-5 years old (Randall 1983, Crawford *et al.* 1999, Whittington 2002). Based on data specifying the age at which known-age African penguins were first observed breeding at Robben Island, Crawford *et al.* (1999) assumed that the following proportions of birds of different ages were breeders:
Age 1 : 0.0; Age 2: 0.10; Age 3: 0.33; Age 4: 0.80 and Age 5+: 1.0.

Survival estimates

Table 4 summarises estimates of adult and first-year survival for African penguins available in the literature. These confirm the notion that juvenile survival is typically less than adult survival. As previously discussed, it is often practice in marine population modelling to estimate S by fitting to an index/indices of abundance for the species because of problems in quantifying biases in direct estimates of survival rates and of the sensitivity of population trends to the choice of an adult survival parameter *S*. Model simulations are conducted both with S fixed at values in the literature as well as by estimating *S* (as well as juvenile survival and recent decreases in *S*).

La Cock and Hänel (1987) computed survival rates based on ringing of 512 fledglings, 27 juveniles and rebanding of 86 adult penguins at Dyer Island in October/November 1978. They recaptured banded penguins during subsequent visits over the period 1982-1985 and computed survival from the formula:

$$\phi = \left(\frac{n_x}{n_1} \right)^{1/x}$$

where ϕ = survival coefficient;

n_1 = number banded in first year; and

n_x = number retrapped *x* years later.

They noted that their juvenile annual survival rate estimate of 69% was a minimum and was lower than rates for five of six penguin species examined by Croxall (1981).

Based on his study of penguins at St Croix Island over the period 1976-1982, Randall (1983) found post fledgling survival varied between years from 4% to 35%, with average second year survival being 90.5%. The post fledgling survival rate estimates are likely biased downwards because he notes that fledged chicks were often not seen back on the Island until their second or third years. Moreover he notes that the 1976 and 1977 seasons were characterised by exceptionally high post-fledgling mortalities. Adult annual survival based on resightings of known breeding age adults over a six-year period ranged from 87.8% to 95.7%, with an average of 91.1%. Furthermore, he notes that by the end of 1982 there were still large numbers of known age birds (158) aged 14 years or more, giving some idea of life expectancy i.e. it must be more than 14 years.

Whittington (2002) used the program MARK to evaluate annual survival rates using data on re-sightings of flipper-banded birds from seventeen penguin colonies. His results suggest mean annual adult survival of 0.81 for birds banded at Robben and Dassen Islands, and ranged between 0.1 and 0.8 (average = 0.35) for first year birds.

Altwegg (2006) computed penguin survival estimates for Dassen 1995 to 2004. These were all penguins that were oiled in 1994, rehabilitated and released again. It wasn't known how old they were when they were banded, nor whether the oiling had an effect on their long-term survival. His results indicated mean survival between 1995 and 2002 was 0.852 (se=0.018). The year-to-year variability measured by the standard deviation was sigma=0.054. This last estimate is corrected for sampling variance, and so is an estimate of the process variance only. If the years 2003 and 2004 are included, mean survival drops to 0.780 (se=0.054) and sigma=0.168.

Ricklefs (2000), using data from 34 studies comprising 32 bird species, demonstrated a strong correlation between annual fecundity (number of fledglings per year) and annual adult mortality. Using Ricklefs (2000) relationship and computing adult survival as $S = e^{-M}$, yields corresponding theoretical average and maximum survival estimates of 0.88 and 0.92 yr for African penguins. Moreover, Ricklefs (2000) found that mortality from fledging to maturity is a function of annual adult mortality, roughly suggesting from his relationship that prereproductive survival rates in this case are of the order 0.74 to 0.82/yr. First-year survival rates can naturally be expected to be less than this.

Many of the survival rate estimates provided in the literature are based on large-scale banding of penguins. However, some studies have shown that flipper-bands may have negative long-term effects on penguins (e.g. Jackson and Wilson 2002). For example, Gauthier-Clerc *et al.* (2004) report that for king penguins *Aptenodytes patagonicus* the survival rate of unbanded electronically tagged chicks after 2-3 years is approximately twice as large as that reported in the literature for banded chicks. They also found that banded birds arrived later at breeding colonies, and showed lower breeding probability and chick production. It is not known to what extent flipper banding of African penguins may have biased available survival estimates.

Immigration and Emigration

Adult African penguins very rarely breed at any other than the colony at which they first established breeding (Randall *et al.* 1987, Whittington 2002). However, first-time breeders are known to emigrate from natal colonies, likely in response to changing food availability (Whittington *et al.* 2005b). Based on re-sightings of flipper-banded chicks over the period 1989 to 1999, Whittington *et al.* (2005b) deduced that the predominant direction of movement of some young penguins was away from the south coast of the Western Cape (in the vicinity of Dyer Island), towards the western side of the Western Cape, centred on Robben and Dassen Islands.

Birds move regularly between Robben and Dassen Islands (Whittington *et al.* 2005c). Robben Island was recolonised by penguins in 1983 (Crawford *et al.* 2006). The mainland colonies of Boulders and Stony Point are considered to have been established through emigration of young penguins (Whittington 2002).

Based on resightings to October 1999 of birds banded as chicks, there were indications of little movement to the W Cape from the E Cape, with only one bird (out of a total of five observed moving) moving to the W Cape (Whittington *et al.* 2005b, Table 2). Approximately 71% of 14% of birds (10%) from Namibia moved to the W Cape. Crawford (pers. commn) notes that about 8000 pairs bred in Namibia in 1990 and about 6000 in 1999.

Whittington's study was conducted prior to very large increases in the anchovy and sardine abundance off the South African west coast, and hence if the penguins move around in response to local food availability, the movement patterns over the more recent period may have changed.

Major oil spills

The Apollo Sea oil spill in 1994 and Treasure oil spill in 2000 resulted in the death of approximately 5000 and 2000 breeding adults, mostly from Robben and Dassen Islands (Underhill *et al.* 1999, 2006, Crawford *et al.* 2000). As this is an important additional source of mortality, in the model it is assumed that an additional 2500 and 1000 breeding females from Dassen/Robben died in these years, with the number assumed dead from each age class computed on the assumption of proportionality to the abundance of that age class.

It is also assumed that a proportion (set at 0.5 in the current model version) of fledged chicks died at Robben and Dassen in these years.

Available Data – Pelagic fish

The diet of African penguins is dominated by anchovy and sardine (Hockey *et al*. 2005), and the breeding success of penguins is thought to be correlated with the abundance of these two pelagic fish species. Current model versions use assessment model predicted estimates of the biomass and recruitment series for anchovy and sardine combined. Janet Coetzee and Carryn De Moor kindly provided data on the abundance of anchovy and sardine spawners and recruits. Data from Coetzee were in the form of May recruit survey biomass for the various strata. Inshore and offshore estimates were summed for each stratum and combined biomass series computed by summing over the strata corresponding to the area west of Cape Aguhlas (stratum A-E in Fig. 2). These biomass and recruit abundances are presented in Table 6. The data from J. Coetzee were used to compute the proportion of the total anchovy and sardine biomasses in the west of Cape Agulhas region (i.e. model area (i)). The model biomass estimates from C. de Moor were used as input series to the penguin model, and in each case the abundance estimates for a series were divided by the maximum observed value for that series, yielding relative abundance series. These indices are given in Table 7 and are shown in Fig. 7.

A large number of correlations were explored between penguin breeding success parameters and the sardine and anchovy series (Fig. 7), either in combination or individually, and using a range of different time lags, to assist in informing which series are the most appropriate to use. For illustrative purposes, correlations of fledging success at Robben Island with both pelagic biomass west of Cape Agulhas and recruitment abundances are shown in Fig. 8. The relationships obtained were similar for anchovy and sardine on their own rather than combined, such that it was difficult to discriminate as to one or the other of anchovy or sardine playing a relatively more important role. Although Fig. 8(a) will be redone so as to use an AIC criterion for model selection, the linear regression fit obtained was non-significant at the 5% level. It should be noted that although there are indications of a linear relationship, there is considerable variability with some of the highest fledging success values being achieved at very low pelagic biomass levels. There are too few available fledging success data from Dassen Island to similarly explore the functional relationships as has been done for Robben Island. As explained in the accompanying model description paper, the penguin model fits a Beverton-Holt relationship to the breeding success data, and the parameters of the best fit relationship are then used when projecting the penguin population into the future.

DISCUSSION

Previously arguments have been made by the task group that Dassen and Robben Island should show the same response to changing environmental conditions, and hence these two colonies were lumped in the initial model version. However, data on fledgling success (Fig. 6) suggest that this is not necessarily the case. Given the difference in these two fledging success data series, together with the fact that Robben Island is a relatively "new" colony (i.e. the average age of birds is likely to be less than at Dassen), it is perhaps surprising that the proportion of juvenile to total moulters at these two islands is remarkably similar (Table 2 and figure below). Note that the proportion of juveniles at Dyer Island is substantially less, possibly indicative of emigration of young birds away from the island. A further problem with lumping Robben and Dassen Islands is that the ratio of the numbers breeding to the numbers moulting at these two islands is very different, particularly for recent years (see Fig. 4). For these reasons, these two colonies are modelled separately.

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Table 1. Summary of data input to model. Data kindly provided by R. Crawford and L. Underhill. Counts of the numbers of moulting birds have been halved to represent the number of female moulters per year, so as to make them comparable with the numbers of breeding pairs, which also comprises a count of the numbers of breeding females per year.

	Female moulters			Breeding pairs				
	Robben	Dassen	Dyer	Robben	Dassen	Dyer	Boulders	Western Cape
1987				476	4588		7	23504
1988				849			34	23077
1989	1729			829	8428		38	22236
1990	1696			1278		8349	54	20395
1991	2365			1879	9012	6115	131	18971
1992	2458			2027	7563	7579	158	19015
1993	3269			2176	7199	2374	241	13109
1994	4001			2799	9389	4649	359	19245
1995	3974	6180		2279	9792	4260	366	18219
1996	3282	6111		3097	9502	3279	416	17716
1997	2804	6477		3336	8651	2745	726	17060
1998	4348	8148		3467	10918	1963	555	18386
1999	4699	10719		4399	15155	2363	906	24278
2000	5882	12537	2289	5705	15598	2220	949	26238
2001	6681	13048		6723	21409	2088	1054	33633
2002	8219	12809	2108	7252	22883	2145	1083	35274
2003	7368	11255		6433	20319	1929	1033	31389
2004	8712	8796	3088	8524	24901	2216	1196	38610
2005	6435	9149		7152	22687	2053	1227	34840
2006	3884	5672	1674	3697	13283	2057	1075	21319
2007	3314		1472	6749	11785	1513	824	21962
2008				2241	5719	1605	913	12126

Table 2. Summary of penguin moult counts (from L. Underhill). The counts have been halved so that they represent females only (for comparison with the breeding pairs data). The proportion of juveniles (birds undergoing first moult) is computed as the number of juveniles (not shown) divided by the total number of moulters.

	Number of female moulters			Proportion juveniles : total moulters		
	Robben	Dassen	Dyer	Robben	Dassen	Dyer
1989	1729			0.196		
1990	1696			0.203		
1991	2365			0.161		
1992	2458			0.245		
1993	3269			0.196		
1994	4001			0.165		
1995	3974	6180		0.147	0.113	
1996	3282	6111		0.176	0.126	
1997	2804	6477		0.276	0.271	
1998	4348	8148		0.213	0.173	
1999	4699	10719		0.232	0.281	
2000	5882	12537	2289	0.192	0.252	0.055
2001	6681	13048		0.161	0.204	
2002	8219	12809	2108	0.193	0.246	0.088
2003	7368	11255		0.184	0.194	
2004	8712	8796	3088	0.165	0.18	0.037
2005	6435	9149		0.169	0.219	
2006	3884	5672	1674	0.255	0.161	0.046
2007	3314		1472	0.234		0.057

Table 3. Breeding success data from R. Crawford for Robben Island representing the average numbers of chicks fledged per pair (i.e. per female) per year. The breeding success data from A. Wolfaardt for Dassen Island represent the average numbers of chicks fledged per pair (i.e. per female) per breeding attempt, and thus are expected to be lower than estimates per year. The third last column shows a derived Dassen Island series (for purposes of experimenting within the model before a functional relationship has been determined) that assumes the trends are similar at Robben and Dassen, but scales the Robben data for missing years at Dassen by multiplying by the average ratio of the Dassen to Robben values. Values for 2000 are considered unreliable because of the 2000 oil spill and hence these data have been omitted. The last column shows the Dassen series multiplied by 1.27 to convert them (making them comparable to the Robben Island data) from indices of mean chicks fledged per breeding attempt to mean chicks fledged per year.

	Crawford BR(Rob)	Wolfaardt BR(DAS)	Wolfaardt BR(DAS)		Wolfaardt BR(DAS)
	Chicks/pr/year	Chicks/pr	Chicks/pr		Chicks/pr/year
	Robben	Dassen	Dassen extrapolated series		1.27*Dassen extrapolated series
1989	0.42		0.590		0.75
1990	0.32		0.454		0.58
1991	0.59		0.841		1.07
1992	0.59		0.839		1.07
1993	0.54		0.761		0.97
1994	0.45		0.634		0.80
1995	0.38	0.650	0.650	1.70	0.82
1996	0.65	0.805	0.805	1.23	1.02
1997	0.97	0.929	0.929	0.96	1.18
1998	0.75	1.057	1.057	1.41	1.34
1999	0.60	1.083	1.083	1.81	1.38
2000					
2001	0.84		1.195	Ave=	1.52
2002	0.90		1.281	1.42	1.63
2003	0.57		0.812		1.03
2004	0.72		1.016		1.29
2005	0.90		1.279		1.62
2006	0.58		0.824		1.05
Max	0.97	1.08	1.28		1.63
Average	0.63	0.90	0.89		1.12
Median	0.59	0.93	0.84		1.07

Table 4. Summary of adult and juvenile survival rates estimated for African penguins.

Adult survival rate

Value	Locality	Period	Source
0.91	St Croix Island	1976-1982	Randall 1983
0.69	Dyer Island	1979-1985	La Cock and Hänel 1987
0.82 model estimate	Robben Island	1993-1994	Crawford *et al*. 1999
0.80	Dassen Island	1990-1999	Whittington 2002
0.82	Robben Island	1990-1999	Whittington 2002
0.852 (SE = 0.018)	Western Cape	1994-2002	Altwegg 2006
0.69	Robben Island	Apr 2005 – Apr 2006	L. Underhill pers commn

Juvenile survival rate

Value	Locality	Period	Source
0.32 ?	St Croix Island	1976-1982	Randall 1983
0.69 minimum	Dyer Island	1979-1985	La Cock and Hänel 1987
0.31	Robben Island	1987-1999	Whittington 2002
0.38	Dassen Island	1987-1999	Whittington 2002

Table 5. Summary of anchovy biomass and recruit abundance estimates. Inshore and offshore data is combined from surveys (from J. Coetzee, MCM). The proportion observed west of Cape Aguhlas each year is calculated by summing over the relevant strata and dividing by the total abundance (see Fig. 2 for summary of strata). The proportions were used to calculate the predicted biomass west of Cape Aguhlas from the assessment model data (provided by C. De Moor).

Anchovy

	Observed November Biomass ('000t)	Proportion west of Cape Aguhlas	Assessment Model Predicted November Biomass ('000t)	Predicted November Biomass west of Cape Aguhlas ('000t)	Observed May Recruitment (billions)	Assessment Model Predicted May Recruitment (billions)
1984	1553.8128		1153.7744			
1985	1366.2940	0.7423	911.1184	676.3328	83.46	85.7047
1986	2568.6249	0.7703	1562.6934	1203.7674	139.30	204.0785
1987	2108.7712	0.8851	1403.5837	1242.2830	124.44	124.4138
1988	1607.0598	0.8025	1038.0111	832.9773	129.01	105.7320
1989	751.5293	0.6883	559.2242	384.9258	33.14	27.8143
1990	651.7107	0.5260	534.1841	280.9907	51.15	53.4545
1991	2327.8344	0.5389	1412.9058	761.3475	113.58	232.8424
1992	2088.0249	0.4964	1152.7044	572.2492	93.71	120.0435
1993	916.3593	0.4792	744.1190	356.5830	115.07	71.2202
1994	617.2755	0.5022	445.6822	223.8111	30.56	35.2907
1995	601.2710	0.7795	359.9410	280.5666	110.40	72.2617
1996	162.0485	0.1836	412.1100	75.6541	25.76	24.8274
1997	1482.6329	0.2547	778.2067	198.2286	90.40	93.3011
1998	1229.1325	0.1681	978.7562	164.5038	136.52	98.5186
1999	2052.1557	0.3616	1407.1490	508.7577	199.23	180.3506
2000	4653.7788	0.4212	3126.4020	1316.8070	624.68	514.5177
2001	6720.2870	0.3425	3786.4650	1297.0339	627.20	525.1798
2002	3867.6492	0.5219	3301.2493	1722.9596	520.41	247.5233
2003	3563.2316	0.3255	2534.1007	824.9597	430.31	218.6538
2004	2044.6151	0.3490	1903.2127	664.2201	238.57	130.4449
2005	3077.0014	0.2178	1912.7858	416.6873	176.92	175.8352
2006	2106.2732	0.4829	1501.3663	725.0733	117.46	103.3005
2007						

Table 6. Summary of sardine biomass and recruit abundance estimates. Inshore and offshore data is combined from surveys (from J. Coetzee, MCM). The proportion observed west of Cape Aguhlas each year is calculated by summing over the relevant strata and dividing by the total abundance (see Fig. 2 for summary of strata). The proportions were used to calculate the predicted biomass west of Cape Aguhlas from the assessment model data (provided by C. De Moor).

Sardine

	Observed November Biomass ('000t)	Proportion west of Cape Aguhlas	Assessment Model Predicted November Biomass ('000t)	Predicted November Biomass west of Cape Aguhlas ('000t)	Observed May Recruitment (billions)	Assessment Model Predicted May Recruitment (billions)
1984	48.3776		118.3660			
1985	45.0130	0.5656	154.9848	87.6523	3.60	6.0473
1986	299.7966	0.7946	160.9513	127.8982	3.71	3.8472
1987	111.2848	0.8462	275.2657	232.9195	8.06	8.8766
1988	134.3622	0.9530	227.9686	217.2475	0.44	2.5776
1989	256.6549	0.7727	307.3733	237.5205	2.26	9.4388
1990	289.9315	0.8585	405.4688	348.0908	2.50	11.8377
1991	597.8583	0.8651	390.9247	338.1715	1.90	7.7860
1992	494.1574	0.5014	482.0023	241.6621	5.59	14.8302
1993	560.0194	0.8586	619.7646	532.1176	15.43	27.9850
1994	518.3538	0.7519	714.5811	537.2657	2.70	8.9562
1995	843.9444	0.4308	1194.2418	514.4382	26.04	44.8689
1996	529.4559	0.4868	1212.2987	590.2016	3.49	13.3297
1997	1224.6322	0.7879	2013.8980	1586.6637	40.72	78.4402
1998	1607.3283	0.6735	2035.3427	1370.8176	10.72	36.7095
1999	1635.4105	0.4329	2059.3382	891.5630	10.38	43.0682
2000	2292.3798	0.3168	1882.1271	596.2609	20.00	62.4662
2001	2309.6003	0.2899	3009.5812	872.5613	60.07	191.7623
2002	4206.2505	0.2817	3787.5933	1066.7956	49.15	144.2469
2003	3564.1709	0.2782	5458.5166	1518.7201	36.45	89.4883
2004	2615.7153	0.1113	3170.8419	352.8518	4.09	12.3107
2005	1048.9909	0.0704	1866.9521	131.5045	1.69	8.7501
2006	712.5527	0.2457	1400.2385	344.0404	9.56	33.1512
2007						

Table 7. Summary of relative anchovy and sardine biomass and recruitment model predicted abundance estimates after dividing values by the maximum for each series so that the indices shown represent a proportion of the maximum observed value over the time series. (Model outputs were provided by C. De Moor).

	Anchovy biomass	Sardine biomass	Anchovy and Sardine biomass	Anchovy recruitment	Sardine recruitment	Anchovy and Sardine recruitment
1985	0.3925	0.0552	0.2739	0.1632	0.0315	0.1280
1986	0.6987	0.0806	0.4773	0.3886	0.0201	0.2900
1987	0.7210	0.1468	0.5288	0.2369	0.0463	0.1859
1988	0.4835	0.1369	0.3765	0.2013	0.0134	0.1511
1989	0.2234	0.1497	0.2231	0.0530	0.0492	0.0520
1990	0.1631	0.2194	0.2255	0.1018	0.0617	0.0911
1991	0.4419	0.2131	0.3941	0.4434	0.0406	0.3356
1992	0.3321	0.1523	0.2918	0.2286	0.0773	0.1881
1993	0.2070	0.3354	0.3186	0.1356	0.1459	0.1384
1994	0.1299	0.3386	0.2728	0.0672	0.0467	0.0617
1995	0.1628	0.3242	0.2850	0.1376	0.2340	0.1634
1996	0.0439	0.3720	0.2387	0.0473	0.0695	0.0532
1997	0.1151	1.0000	0.6398	0.1777	0.4090	0.2395
1998	0.0955	0.8640	0.5503	0.1876	0.1914	0.1886
1999	0.2953	0.5619	0.5020	0.3434	0.2246	0.3116
2000	0.7643	0.3758	0.6857	0.9797	0.3257	0.8048
2001	0.7528	0.5499	0.7777	1.0000	1.0000	1.0000
2002	1.0000	0.6724	1.0000	0.4713	0.7522	0.5464
2003	0.4788	0.9572	0.8401	0.4163	0.4667	0.4298
2004	0.3855	0.2224	0.3646	0.2484	0.0642	0.1991
2005	0.2418	0.0829	0.1965	0.3348	0.0456	0.2575
2006	0.4208	0.2168	0.3832	0.1967	0.1729	0.1903

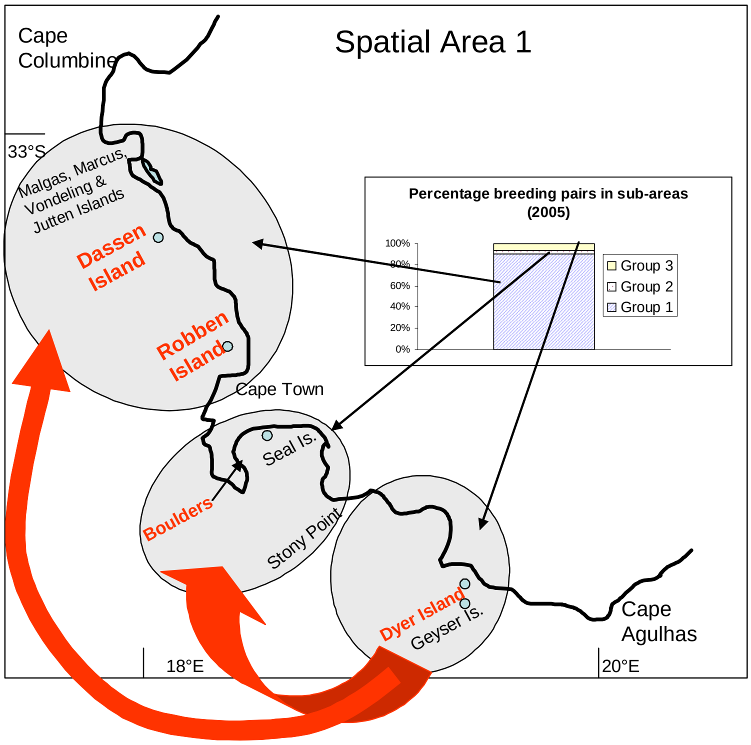


Fig. 1. Map showing location and possible grouping of penguin colonies in the "western" area (area i)). The colonies currently included in the model are shown in bold red text. The arrows represent movement of penguins from Dyer Island to Boulders, as well as movement to Robben and Dassen Islands as is explored in the model.

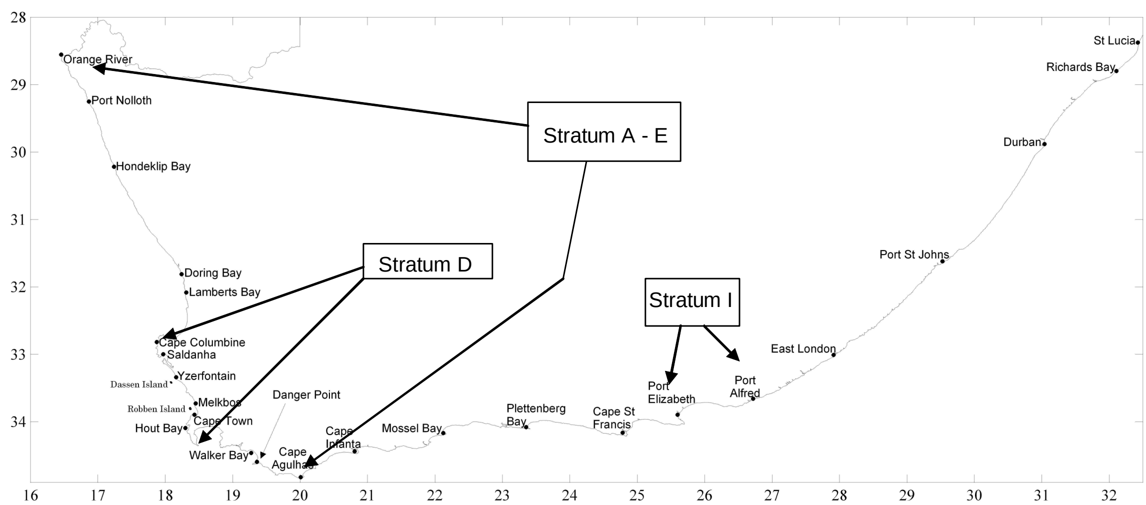


Fig. 2. Map showing extent of strata corresponding to pelagic fish biomass estimates used to link to penguin breeding success in the area i) model (which includes Dassen, Robben, Dyer Island and Boulders) and preliminary model for St Croix in area iii). Basic map provided by Janet Coetzee (MCM).

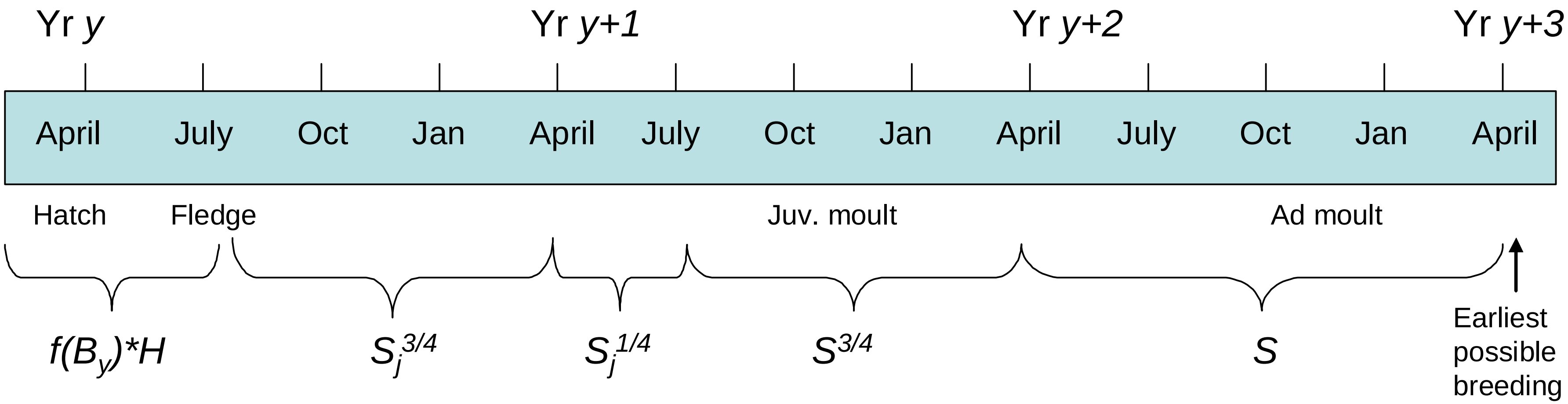


Fig. 3. Schematic summary of timeline detailing life history of an average penguin, to illustrate different survival factors applied in the modelling analyses.

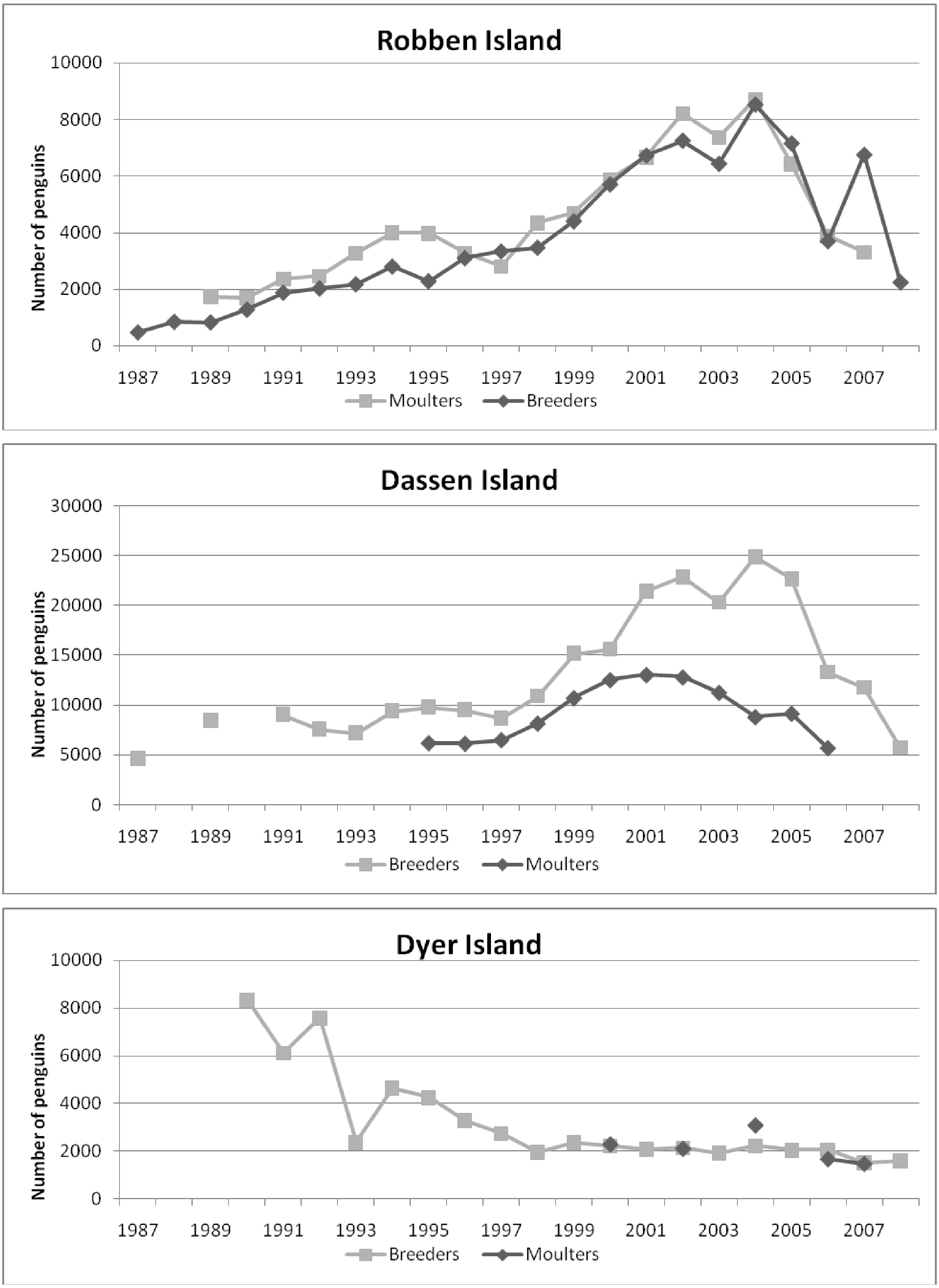


Fig. 4. Numbers of female moulters (assuming a 50:50 sex ratio) and numbers of breeding pairs of penguins at Robben, Dassen and Dyer Island. The number of adult moulters includes all animals aged (approximately) two years and older whereas breeding females are aged approximately three years and older. The latter index would thus be smaller than the former if both reflected complete censuses.

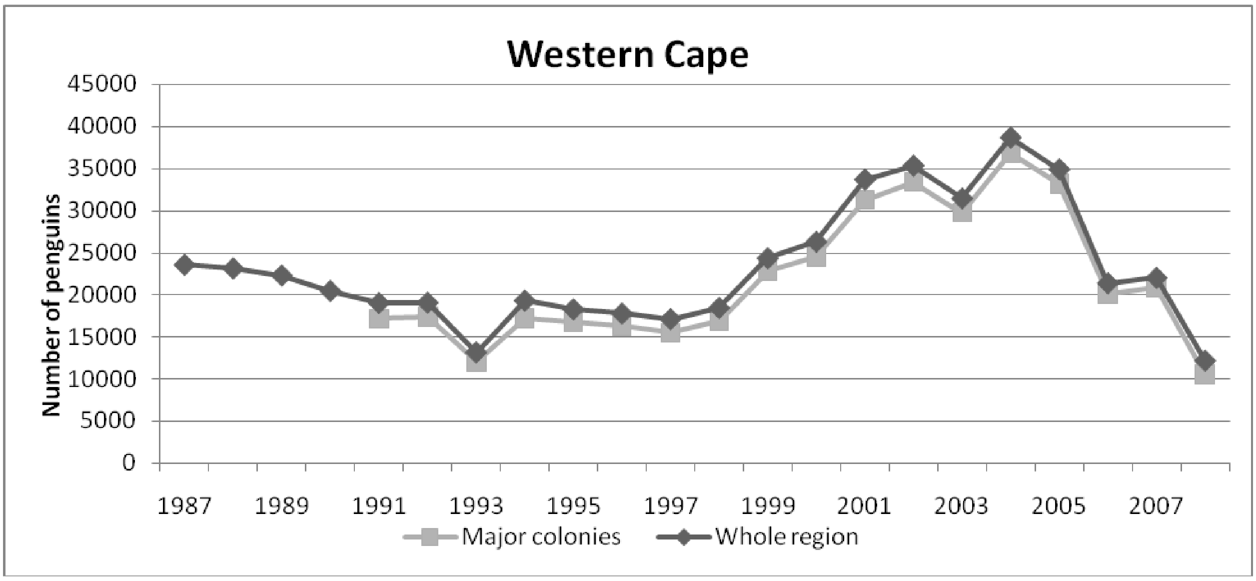


Fig. 5. Comparison of numbers of breeding pairs (from Underhill *et al.* 2006) and observed trends in the Western Cape as a whole and the numbers of breeding pairs included in a model encompassing Dassen Island, Robben Island, Boulders and Dyer Island.

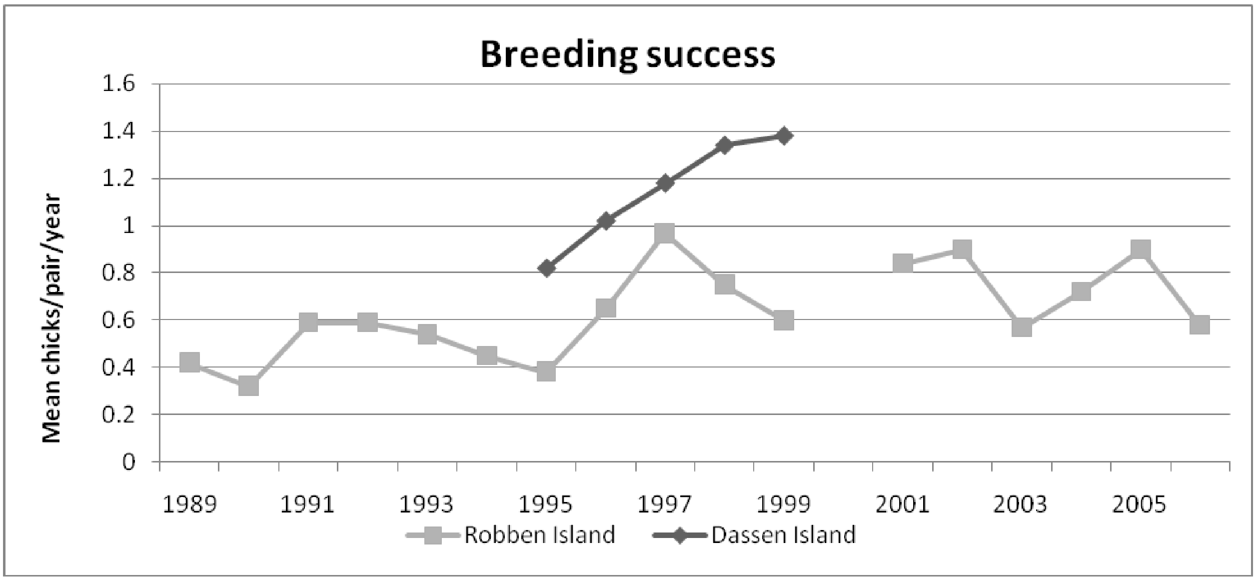


Fig. 6. Plots of chick fledging success data representing the average numbers of chicks fledged per pair (i.e. per female) per year for Robben Island (from R. Crawford) and for Dassen Island (derived by scaling data from A. Wolfaardt to account for multiple breeding attempts in the same year).

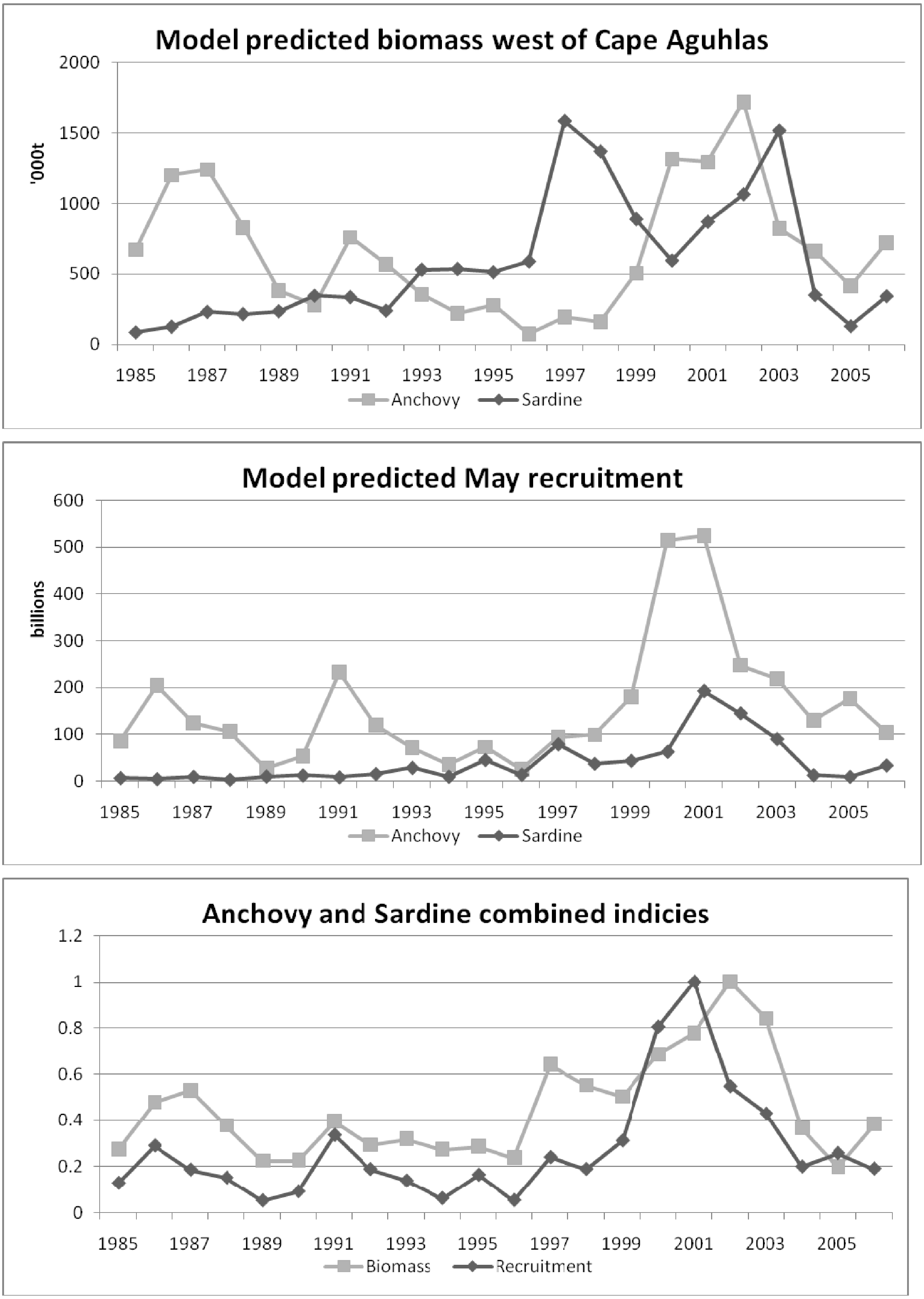
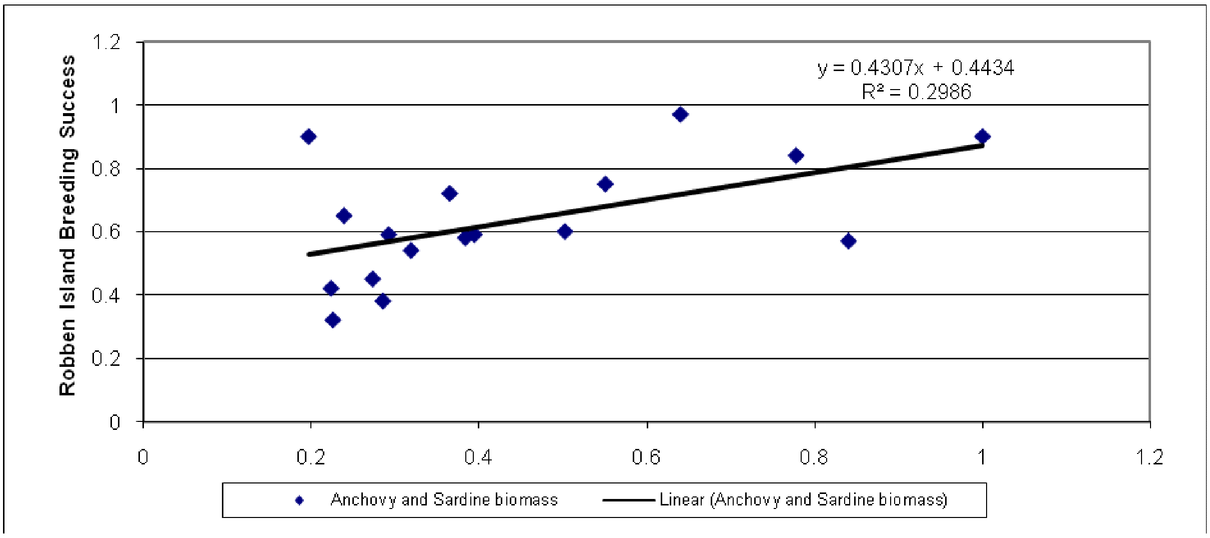


Fig. 7. Predicted anchovy and sardine biomass (top) and recruit (middle) abundances (from C. De Moor). The predicted biomass proportions west of Cape Aguhlas are plotted, calculated using the historic proportions (from J. Coetzee). The relative abundances of the combined series are plotted on the bottom graph.

(a)



(b)

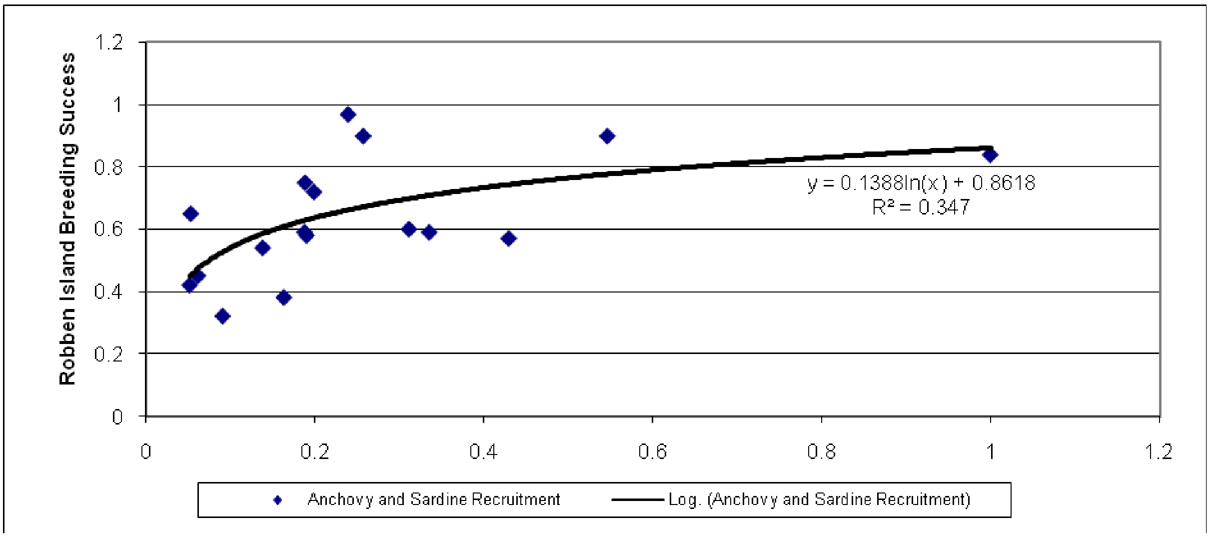


Fig. 8. Functional relationships between breeding success at Robben Island and (a) anchovy and sardine combined biomass west of Cape Aguhlas and (b) anchovy and sardine combined recruits in the same year. The correlations with the combined series were better than using only the anchovy or sardine series.