Ecography

E7330
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Supplementary material

APPENDIX 1 AERIAL SURVEY METHODS

The Royal Navy Lynx helicopter we used carried an external camera pod housing a Zeiss RMK aerial survey camera fitted with a 152-mm lens. Consecutive photographic images (240-mm frame size) overlapping by 60% were captured with either Kodak Aerochrome 2448 colour reversal film or Agfa Aviphot Pan 200 negative film. Our nominal survey height was 500 m, resulting in a photo-scale of approximately 1:3,300; a small number of flights were flown at 600 m, giving a photo-scale of approximately 1:4,010. All flights were undertaken during daylight hours when shadows were relatively short (10:30 am to 15:30 pm local time; GMT–3 hours). The survey flights were carried out during the females' long incubation shift while male birds were away from the colony foraging at sea. At this time there was minimum penguin traffic into and out of the colony as males were away for 10–20 days (Trathan 2004). In addition, penguin traffic associated with failed breeders was much reduced as many unpaired birds had returned to sea (Williams and Croxall 1991). Thus, on the dates flown, we assumed that each bird in the colony represented a single nesting site, and each nest site represented a breeding attempt. We assumed that a count of these breeding attempts represented the breeding population size. To minimize potential disturbance to penguins during helicopter over-flights, we positioned ground observers to monitor penguin activity within selected colonies (n=6). Each ground observer was in continual radio contact with the helicopter so that the pilot could abort the over-flight should the behaviour of birds indicate stress.

APPENDIX 1 REFERENCES

Trathan, P. N. 2004. Image analysis of color aerial photography to estimate penguin population size. *Wildlife Society Bulletin* **32,** 332-343.

Williams, T. D. and Croxall, J. P. 1991. Annual variation in breeding biology of macaroni penguins, *Eudyptes chrysolophus*, at Bird Island, South Georgia. *Journal Zoology* **223,** 189-202.

APPENDIX 2 AERIAL IMAGE PROCESSING

Colour film was developed using Eastman Kodak process AR5 with EA5 chemistry (Eastman Kodak Company, Rochester, N.Y.). Black-and-white film was developed using a variety of Kodak black-and-white developers (Eastman Kodak Company, Rochester, N.Y.). All penguin colonies identified on the film were digitally scanned at a resolution of 20 μm using a Vexcel VX400HT photogrammetric scanner (VXServices Corporation, Longmont, Co.). Nominal pixel size in images varied with terrain but was approximately 5 cm by 5 cm.

Each aerial image was analysed using the Image Processing Toolbox of the Matlab (version 6.0.0.88 release 12) software package (MathWorks Inc., Natick, Mass.). Analysis of colour film followed methods previously described (Trathan 2004). Analysis of black-and-white film followed these same methods, but routines were modified for gray-scale representation, rather than for colour. Each image was analysed only once. Application of the software depended upon operator interactions which were needed to account for shadows and image quality, nevertheless the software was able to generate repeatable counts for each image (Trathan 2004).

To assess how well the automated image-analysis routines identified individual penguins and how well they discriminated between birds and their background, we followed processes previously described (Trathan 2004). For this, randomly positioned areas ($n \approx 50$; each 225 pixels by 225 pixels) were selected within each colony. Selected areas covered a range of penguin densities and a range of terrain aspects. They also covered central regions and regions toward the edge of the colony. Within each area we manually counted the number of birds from the image and also estimated the number using the automated image-analysis routines. We used regression analysis to relate these paired observations.

The R^2 values from the linear regressions (1 for each colony) relating paired samples of automatic software counts and manual counts from the sampled colony images ($n \approx 50$; each 225 pixels by 225 pixels) showed that the automated image-analysis routines worked well. The mean R^2 value from the linear regressions was 0.960 (range from 0.680 to 0.999; median = 0.979; standard deviation = 0.058). Fig. A1 shows a histogram of R^2 values. Fig. A2 shows a linear regression of all the paired samples from all the colonies combined.

APPENDIX 2 REFERENCES

Trathan, P. N. 2004. Image analysis of color aerial photography to estimate penguin population size. *Wildlife Society Bulletin* **32,** 332-343.

Figure A1 Histogram of the R^2 values from the linear regressions (1 for each colony) relating paired samples of automated software counts with manual counts from the colony images from the aerial survey for macaroni penguins at South Georgia, 2000-03.

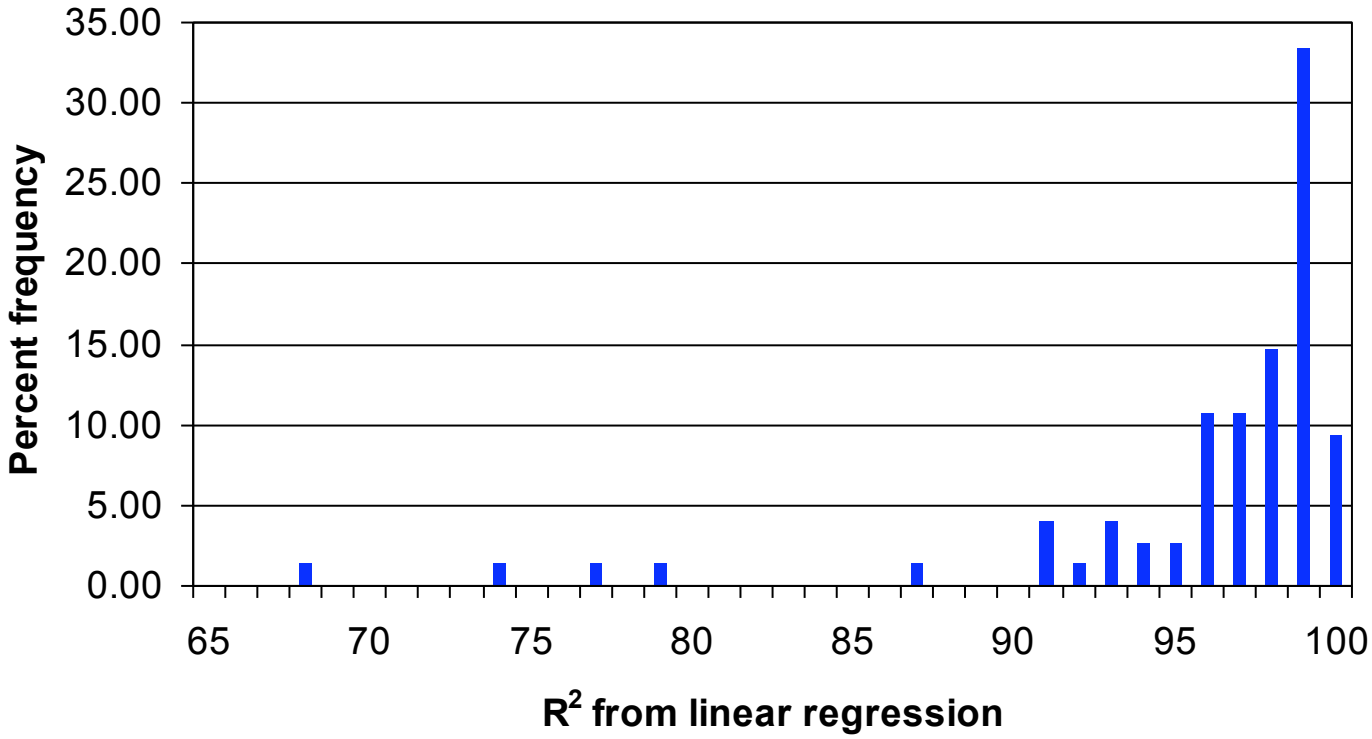
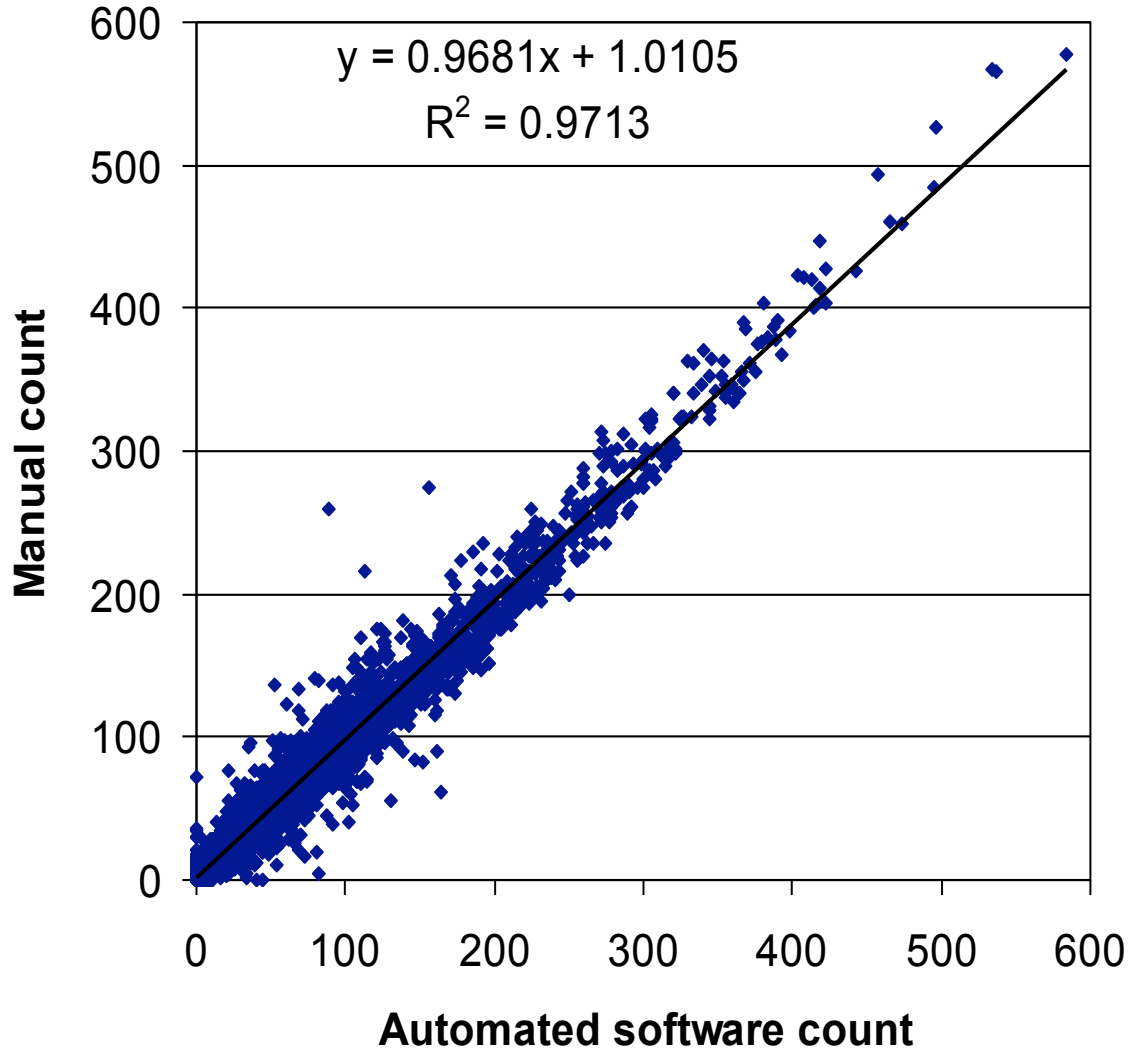


Figure A2 Plot of the linear regression (for all colonies combined) relating paired samples of automatic software counts with manual counts from the colony images from the aerial survey for macaroni penguins at South Georgia, 2000-03.



APPENDIX 3 VIRTUAL ECOLOGIST ROUTINES

We used a "virtual ecologist" model (Ratcliffe et al. 2008, Grimm et al. 2006, 2010) to adjust the observed colony counts, and produce confidence intervals to reflect uncertainty around these estimates that is attributable to seasonal variation in the availability of count units. Using R (version 2.11.1) we first developed an individual-based simulation model of a virtual macaroni penguin colony comprising 1,000 breeding pairs. This allocated each pair a random start date at which they initiated their first breeding attempt, drawn from a normal distribution defined by the mean 'A' egg laying date of 19 October and a standard deviation of 3.2 days (Williams 1995). Colonies in shade have average laying dates 9 days later than those exposed to mid-day sun, based on observations at 3 colonies with varying aspect on Bird Island, 2 on the Willis Islands and 2 on the Barff Peninsula (P.N. Trathan, personal observation). Hence, we examined the macaroni penguin colony and hill shade layers of the South Georgia GIS map (www.sggis.gov.gs; accessed on 1 June 2011) to determine which colonies were shaded and delayed laying dates at each of these by 9 days. Following laying, we determined whether each nest survived each day by testing whether a random probability was less than the appropriate stage or age-dependent survival rates until they either failed or the chicks reached an age of 25 days old, when they left the nest to join a crèche. We assumed nest survival rate was a constant 0.994 throughout the 39 day incubation period, and chick survival to vary with their age according to a logistic regression line with an intercept of 3.6 and slope of 0.1. Over the 39 day incubation period and 60 day fledging period these values resulted in hatching and fledging success values of 0.79 and 0.75 respectively. These are well within the range of values reported for macaroni penguins on South Georgia (Williams 1995), and equate to a breeding success of 0.59, as recorded on Bird Island in 2002 (mean = 0.51

over the past 25 years; BAS, unpublished data). The model made no allowance for re-nesting, as this has not been recorded in macaroni penguins (Williams 1995).

On the date that a real colony count occurred, we assigned a virtual ecologist to conduct a count of a virtual colony with an aspect that matched that of the real one. Within the model, we achieved this by adding 1 to a running total for every nest that was present on the allocated census date. We divided this virtual census total by 1,000 (the known number of nests in the virtual colony) to estimate the proportion of nests available to count. We then divided the observed nest count by this value to produce an adjusted estimate. We repeated this procedure to produce 10,000 adjusted counts for each colony. We calculated the sum of all colony counts for each of the iterations to estimate 10,000 adjusted census totals for the whole of South Georgia. We took the average, 2.5 and 97.5 percentiles of these vectors to produce an adjusted estimate of nests for each colony and for the whole of South Georgia with 95% confidence intervals. The availability of macaroni penguin nests to aerial surveys in relation to calendar date is shown in Fig. A3.

APPENDIX 3 REFERERENCES

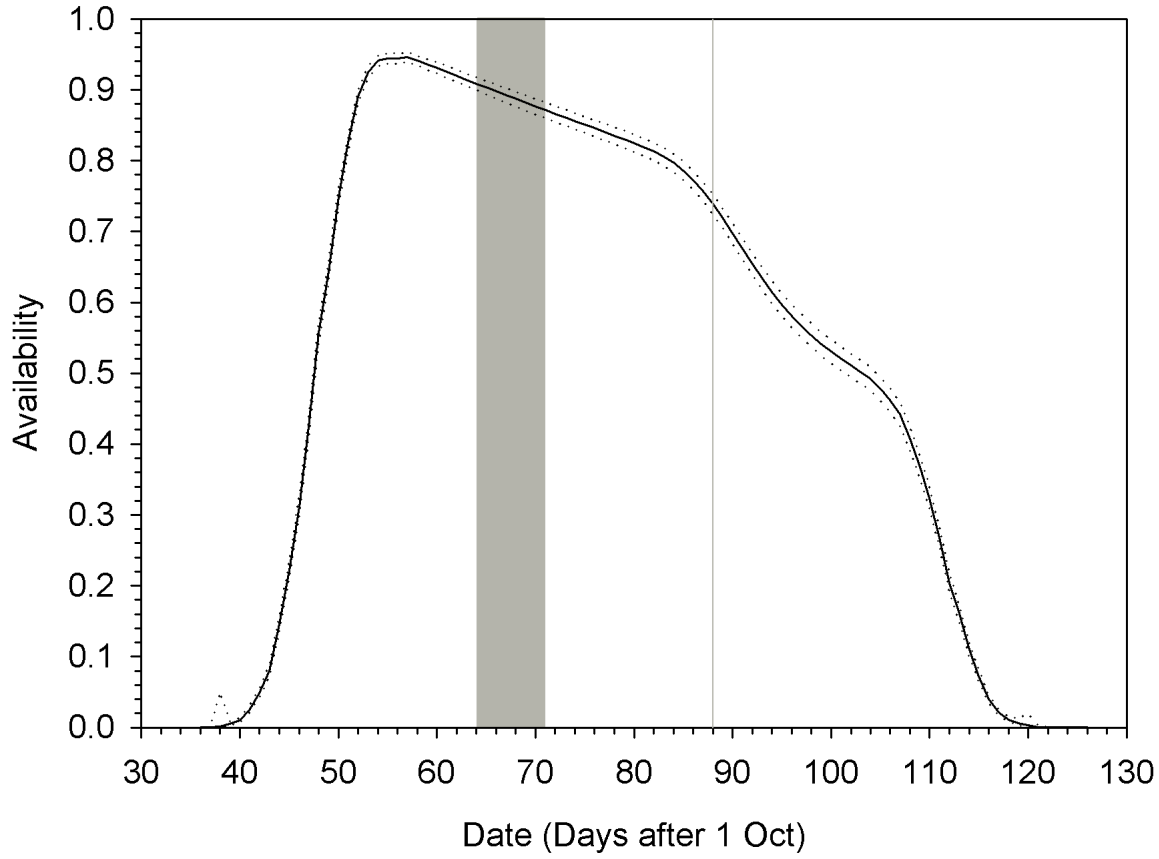
Grimm, V. et al. 2006. A standard protocol for describing individual-based and agent-based models. *Ecological Modelling* **198,** 115–126.

Grimm, V. et al. 2010. The ODD protocol: a review and first update. *Ecological Modelling* **221,** 2760–2768.

Ratcliffe, N. et al. 2008. Resolving the status of Ascension frigatebird using a "virtual ecologist" model. *Ibis* **150,** 300-306.

Williams, T. D. 1995. *The Penguins*. Oxford, Oxford University Press.

Figure A3 Plot showing the results from the virtual ecologist simulation for the availability of macaroni penguin nests to aerial surveys. The solid black line represents the mean availability in relation to calendar date and the dotted lines the standard errors. The grey shading represents the actual period when all survey counts took place, with the exception of the main island of Clerke Rocks, which was surveyed on the date represented by the narrow grey line.



APPENDIX 4 AERIAL SURVEY FOR MACARONI PENGUINS AT SOUTH GEORGIA

Table A1. Observed and adjusted counts of macaroni penguins at colonies on South Georgia. Shade denotes whether the colony was shaded (1) or not (0); Date is when the images were taken (nc denotes no count was made); Observed is the observed count; Adjusted is the adjusted count; and LCI and UCI are the lower and upper 95% confidence limits of the adjusted count that relate to uncertainties in availability of count units to census.

Area	Colony Name	Shade	Date	Observed	Adjusted	LCI	UCI
1	Willis Islands Main Island 1	1	05-Dec-02	7,568	7,984	7,875	8,103
1	Willis Islands Main Island 2	1	05-Dec-02	2,879	3,037	2,996	3,082
1	Willis Islands Main Island 3	1	05-Dec-02	20,717	21,856	21,558	22,181
1	Willis Islands Main Island 3	1	05-Dec-02	6,752	7,123	7,026	7,229
1	Willis Islands Main Island 3	1	05-Dec-02	14,543	15,343	15,133	15,571
1	Willis Islands Main Island 4	1	05-Dec-02	3,981	4,200	4,143	4,262
1	Willis Islands Main Island 5	1	05-Dec-02	16,925	17,856	17,612	18,121
1	Willis Islands Main Island 6	1	05-Dec-02	6,127	6,464	6,376	6,560
1	Willis Islands Main Island 7 & 8	1	05-Dec-02	7,985	8,424	8,309	8,549
1	Willis Islands Main Island 9, 10 & 11	1	05-Dec-02	4,684	4,942	4,874	5,015
1	Willis Islands Main Island 12	0	05-Dec-02	4,000	4,400	4,315	4,489
1	Willis Islands Main Island 13	0	05-Dec-02	1,386	1,525	1,495	1,556
1	Willis Islands Main Island 14	0	05-Dec-02	3,348	3,683	3,612	3,758
1	Willis Islands Main Island 15, 16 & 17	0	05-Dec-02	914	1,005	986	1,026
1	Willis Islands Main Island 18	0	05-Dec-02	34,894	38,384	37,642	39,163
1	Willis Islands Main Island 19	0	05-Dec-02	6,845	7,529	7,384	7,682
1	Willis Islands Trinity Island 1	0	05-Dec-02	4,269	4,696	4,605	4,791
1	Willis Islands Trinity Island 2	0	05-Dec-02	3,004	3,304	3,241	3,371
1	Willis Islands Trinity Island 3	0	05-Dec-02	3,853	4,238	4,156	4,324
1	Willis Islands Trinity Island 4	0	05-Dec-02	35,926	39,519	38,755	40,321
1	Willis Islands Trinity Island 5	1	05-Dec-02	31,030	32,737	32,289	33,223
1	Willis Islands Trinity Island 6 & 7	0	05-Dec-02	4,729	5,202	5,101	5,308
1	Willis Islands Trinity Island 8	0	05-Dec-02	4,378	4,816	4,723	4,914
1	Willis Islands Trinity Island 9	1	05-Dec-02	27,873	29,406	29,004	29,843
1	Willis Islands Trinity Island 10	1	05-Dec-02	39,078	41,228	40,664	41,839
1	Willis Islands Trinity Island 11	0	05-Dec-02	598	658	645	671
1	Willis Islands Verdant Island 1 & 2	0	05-Dec-02	448	493	483	503
1	Willis Islands Verdant Island 3	0	05-Dec-02	314	345	339	352
1	Willis Islands Verdant Island 4	0	05-Dec-02	58,654	64,519	63,273	65,829
2	Bird Island Mac Cwm	0	04-Dec-02	10,895	11,913	11,690	12,146
2	Bird Island Fairy Point	0	04-Dec-02	469	513	503	523
2	Bird Island Goldcrest Point	1	04-Dec-02	35,103	37,242	36,719	37,827
3	Elsehul	0	05-Dec-02	2,118	2,330	2,285	2,377
4	Welcome Islands 1	0	05-Dec-02	421	463	454	473
4	Welcome Islands 2 & 3	0	05-Dec-02	4,783	5,261	5,160	5,368
5	Bjelland Point 1			nc			
5	Bjelland Point 2	0	05-Dec-02	2,888	3,177	3,115	3,241
5	Bjelland Point 3	0	05-Dec-02	5,067	5,574	5,466	5,687
5	Hercules Bay 1	0	05-Dec-02	36,681	40,349	39,570	41,168
5	Hercules Bay 2	0	05-Dec-02	37,569	41,327	40,528	42,165
5	Hercules Bay 3	0	05-Dec-02	2,929	3,222	3,160	3,287

Area	Colony Name	Shade	Date	Observed	Adjusted	LCI	UCI
5	Hercules Bay 4	0	05-Dec-02	738	812	796	828
5	Hercules Bay 5	0	05-Dec-02	4,656	5,122	5,023	5,226
5	Hercules Bay 6			nc			
5	Hercules Bay 7	1	10-Dec-02	1,413	1,518	1,494	1,544
6	Lucas Point 1, 2 & 3	0	10-Dec-02	9,087	10,304	10,074	10,566
6	Rookery Point 1	0	10-Dec-02	3,236	3,669	3,584	3,763
7	Calf Head	0	10-Dec-02	18,773	21,288	20,813	21,829
8	Cape Charlotte 1	0	10-Dec-02	18,394	20,858	20,370	21,388
8	Cape Charlotte 1	0	10-Dec-02	27,332	30,993	30,302	31,781
8	Cape Charlotte 2			nc			
8	Cape Charlotte 3	0	10-Dec-02	16,680	18,914	18,492	19,395
8	Cape Charlotte 4	0	10-Dec-02	164	186	182	191
8	Cape Charlotte 5	0	10-Dec-02	948	1,075	1,051	1,102
8	Cape Charlotte 6			nc			
9	Cooper Bay Little Mac	0	10-Dec-02	3,936	4,463	4,364	4,577
9	Cooper Bay Big Mac 1	1	10-Dec-02	21,031	22,587	22,232	22,985
9	Cooper Bay Big Mac 2	0	10-Dec-02	664	753	735	772
10	Cooper Island 1	1	10-Dec-02	6,020	6,465	6,364	6,579
10	Cooper Island 2	1	10-Dec-02	25,837	27,748	27,312	28,237
10	Cooper Island 3	0	10-Dec-02	44,247	50,175	49,054	51,450
10	Cooper Island 4 & 5	0	10-Dec-02	7,557	8,569	8,378	8,777
10	Cooper Island 6 & 7	0	10-Dec-02	8,765	9,939	9,717	10,192
11	Shannon Point 1	1	11-Dec-02	17,245	18,630	18,326	18,971
11	Shannon Point 2	1	11-Dec-02	14,402	15,558	15,305	15,844
11	Rumbolds Point 1 & 2	0	10-Dec-02	17,919	20,319	19,844	20,836
11	Rumbolds Point 3	0	10-Dec-02	7,071	8,018	7,831	8,222
11	Rumbolds Point 4 & 5	0	10-Dec-02	17,722	20,096	19,647	20,607
11	Smaaland Cove	0	10-Dec-02	751	852	832	873
11	Stensholt Bay	1	11-Dec-02	8,782	9,487	9,333	9,661
11	Green Island	0	11-Dec-02	7,130	8,134	7,949	8,339
11	Cape Disappointment 1			nc			
11	Cape Disappointment 2			nc			
11	Brode Rock			nc			
11	First Rock	0	11-Dec-02	1,924	2,195	2,145	2,250
12	Pickersgill Islands 1	0	11-Dec-02	2,605	2,972	2,904	3,047
12	Pickersgill Islands 2	0	11-Dec-02	1,206	1,376	1,344	1,411
13	Annenkov Island 1	0	11-Dec-02	3,067	3,499	3,419	3,587
13	Annenkov Island 2	0	11-Dec-02	4,580	5,225	5,106	5,357
13	Annenkov Island 3	0	11-Dec-02	4,416	5,038	4,923	5,165
13	Annenkov Island 4	1	11-Dec-02	2,932	3,167	3,116	3,226
13	Annenkov Island 5	0	11-Dec-02	180	205	201	210
13	Annenkov Island 6	0	11-Dec-02	2,335	2,664	2,603	2,731
13	Annenkov Island 7			nc			
13	Annenkov Island 8	0	11-Dec-02	417	476	465	488
14	Cape Paryadin	0	05-Dec-02	1,733	1,906	1,869	1,945
15	Cape North	1	05-Dec-02	5,790	6,108	6,025	6,199
16	Sheathbill Bay			nc			
17	Clerke Rocks Main Island	0	28-Dec-02	6,600	8,498	8,209	8,777
17	Office Boys West, North & Middle	0	10-Dec-02	3,952	4,481	4,381	4,595
17	Office Boys East	0	10-Dec-02	6,515	7,388	7,223	7,576
	South Georgia Total			855,377	938,017	920,601	956,997