# A proposed new method for obtaining penguin moult count estimates

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## Abstract

A double Gaussian form is fit to annual moult count observations for both adult and juvenile penguins at Robben and Dassen Islands. While giving similar results for total moult numbers to the conventional linear interpolation approach in most cases, this new approach seems preferable for seasons where there are lengthly gaps between successive observations, and is accordingly proposed as a preferred approach. The approach is also used to provide coarse estimates of the precision of estimates of total moult numbers.

## Introduction

African penguins moult annually (Randall and Randall 1981) and are known to habitually moult at their breeding colonies (Randall 1983). Counts of moulting penguins have been used as population abundance estimates. A census of the two largest African penguin colonies in the Western Cape has been taken annually since the 1988/1989 moult season at Robben Island, and since the 1994/1995 moult season at Dassen Island (Wolfaardt *et al*. 2009). The moult season was chosen to run from 1 July until 30 June the following year since most birds moult during the months of November to January at these colonies (Underhill and Crawford 1999). The census has been conducted by separately summing the counts taken at two-week intervals of adult birds and immature birds in the feather-shedding phase of moult (Randall *et al*. 1986). These tallies are thought to give slightly conservative estimates for the total numbers of adult and immature birds moulting at the islands (Crawford and Boonstra 1994), since the mean duration of the feather-shedding phase of moult has been observed to be 12.7 days (Randall 1983), slightly less than the count interval of two weeks.

African penguins at a particular colony are known to synchronize their moult, usually peaking in late November at Dassen Island and early December at Robben Island (Wolfaardt *et al*. 2009). The peak is sharper at Robben Island, where 60% of adult birds moult within an eight week period, compared to eleven weeks at Dassen Island (Wolfaardt *et al*. 2009). Interannual variability in moult phenology is thought to be influenced by factors such as the success or failure of the previous breeding season, food availability and major oil spills (Crawford *et al*. 2006).

The juvenile moult season is often characterized by two peak periods. The first peak occurs in late spring, coincident with the peak period of the adult moult, and the second peak occurs late in the summer (Underhill and Crawford 1999). Wolfaardt *et al*. (2009) suggest that the first peak may comprise birds which delay moulting into their adult plumage until their second summer when they moult with the majority of the colony (“skippers”), while birds which fledge early in the year may moult during late summer or autumn, soon after they reach 12 months of age (“squeezers”) (Kemper and Roux 2005).

## Methods

Counts are not made daily, so interpolation needs to be used to estimate the number of birds moulting on days between counts. The simplest method is linear interpolation which can be used to estimate the number of birds moulting on each day of the year. The total number of moulters is then calculated by dividing the sum of daily moulters by 12.7, the mean length of the feather-shedding phase (Underhill and Crawford 1999).

However, a concern with this linear interpolation approach is that counts are not always made every two weeks, and sometimes the intervals between counts can be quite lengthly, rendering linear interpolation a rather coarse approach. An alternative approach is to model the expected number of birds moulting on each day  as the sum of two Gaussian functions:

 

where

 is the total number of moulting birds which would be counted if counts were made daily (if the moult season was “infinitely” long),

  and  are the days on which the two peaks of the moult season occur, and

  and  characterize the degree of synchrony of the moult.

The sum of two Gaussians was chosen because the juvenile penguin moult season is known to have two peaks, and the additional flexibility is useful as it can take account of asymmetric shapes of the overall distribution.

Values for the six parameters in equation are obtained by minimizing the negative log-likelihood for the Poisson process of sighting moulting birds given the data:

 

where  indexes each moult count with a total of  such observations made during the season. This method may be more robust than the linear interpolation method, both in the case of noisy data and when the intervals between consecutive counts are several weeks or even months.

If  and/or  are large, the Gaussian functions have wide tails, resulting in values of  for days outside of the split year in question. This has been taken into account by subtracting the tails  and  of each of the Gaussian functions:

 

 

where the subscripts 1 and  indicate the first and last days or the moult year (1 July and 30 June respectively) and the complementary error function is defined as:

 

The total number of birds moulting in one year is then calculated as:

 

By using the optimization program ADMB to fit the double Gaussian curves to the annual moult counts, the Hessian-based CV  is readily obtainable for each estimate under the assumption that model errors are Poisson distributed. However, the actual errors are greater than this assumption suggests so that overdispersion must be accounted for when calculating realistic coefficients of variation. After grouping observations so that each , the overdispersion for the each annual estimate is calculated as:

 

where  is the number of observations in that year (after grouping) and  is the number of parameters estimated. CVs are then calculated as:

 

where  is the median of all overdispersion parameters calculated for each series.

An alternative to the maximum likelihood approach is to use the Markov-Chain Monte Carlo method to obtain a Bayes posterior distribution for . This was attempted for a few years and gave very similar results.

## Results

Double Gaussian functions were fitted to all the available adult and juvenile moult count data for Robben Island and Dassen Island. The number of observations, the estimated parameters and the overdispersion coefficients are given in Table 1 to Table 4.

The columns in to list series of moult count estimates from the linear interpolation analysis of Wolfaardt *et al*. (2009), unpublished data supplied by Rob Crawford, our own linear interpolation analysis which attempts replication of the earlier results, and the results of the double Gaussian method described above with coefficients of variation.

The only notable differences between our linear interpolation and Wolfaardt *et al*.’s results are for the 2001/2002 season when no counts were made from July to October at Robben Island, or for nine weeks during September and October at Dassen Island.

In most cases the fitted double Gaussian results are very similar to the linear interpolation results, but there are a few exceptions: Robben Island (1996/1997 and 2001/2002) and Dassen Island (2002/2003). The reasons underlying these are detailed below.

According to Underhill and Crawford (1999), “The abnormal pattern in 1996/97 was a result of errors in the November and December counts, which were undertaken by an inexperienced observer.” Consequently, three data points were excluded when fitting the double Gaussian function for this season (). The result is a 30% larger estimate for adult moulters and a 7% larger estimate for juvenile moulters for 1996/1997.

The 2001/2002 estimate for Robben Island is unreliable since only nine counts were taken during that year, with none before November ( and ). A decrease in moulters the year following the *Treasure* oil spill would perhaps be expected, as was the case in 1995/1996 following the sinking of the *Apollo Sea*. Compared to the linear interpolation estimates, the double Gaussian estimates given here are 21% and 27% lower for the adults and juveniles respectively.

At Dassen Island in 2002/2003, only one count was made between 8 October and 22 January, making it difficult to quantify the time or the extent of the peak of the moult season that year (). The linear interpolation method would certainly underestimate the number of moulters, especially if the peak was in mid to late November as usual. The double Gaussian estimate for the adults is 13% higher.

The double Gaussian fit failed to converge satisfactorily in three cases: Dassen Island adults in 1994/1995, Dassen Island juveniles in 2008/2009, and Robben Island adults in 2009/2010. In the latter two cases, a single Gaussian was fitted instead. This was not feasible for the Dassen Island adults in 1994/1995 because of the absence of data for the first half of the season, so no revised estimate is provided in that case.

## Discussion and conclusions

Results from deriving moult count estimates via the method of the fitted double Gaussian are in most cases similar to the results of linearly interpolating the count data. However, particularly in seasons where there are large gaps between some counts, the double Gaussian approach seems preferable. Accordingly it is proposed that the associated revised estimates be accepted for use for further modeling purposes.

The motivation for use of the double Gaussian was bimodality in the juvenile count distributions, and the corresponding  and  estimates in Table 3 and Table 4 are broadly consistent with a first peak in early summer and a second peak in late summer. The adult count fits (Table 1 and Table 2) do not show a similar pattern, and the justification of the use of two Gaussians there is more to provide greater overall shape flexibility. A more refined approach might consider fitting through the use of a Hermite polynomial series expansion, but this does not seem justified here as the double Gaussian approach achieves a sufficiently good fit to the data to provide estimates of reasonable accuracy for population modeling purposes.

The estimates of overdispersion in Tables 1 to 4 always exceed 1, but are also very variable and sometimes very large. The last category generally arises from instances where counts are relatively high at the very beginning and/or very end of the 12 month period considered, which are times when the double Gaussian predicts very low values. Although these differences are not large in the context of the overall count estimate , they can influence the estimates of overdispersion  considerably. For this reason, CVs have been presented based on the median of the  estimates for each season. This is of course a somewhat coarse approach, but seems useful to provide some broad indication of the precision of the estimates obtained.

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Table : Estimated parameter values for equation for adult penguins moulting at Robben Island. Symbols are defined in the text.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Robben adults |  |  |  |  |  |  |  |  |
| 1988/1989 | 18 | 39248 | 13 Dec | 19.264 | 4828.4 | 19 Jan | 66.176 | 4.5 |
| 1989/1990 | 25 | 33982 | 13 Dec | 16.304 | 9164 | 07 Jan | 54.726 | 3.1 |
| 1990/1991 | 24 | 48582 | 12 Dec | 19.056 | 11425 | 11 Jan | 55.986 | 3.7 |
| 1991/1992 | 26 | 46954 | 12 Dec | 20.39 | 15806 | 11 Jan | 57.837 | 3.2 |
| 1992/1993 | 26 | 71918 | 10 Dec | 16.986 | 11210 | 04 Jan | 56.787 | 4.3 |
| 1993/1994 | 24 | 91001 | 12 Dec | 21.921 | 9547.1 | 16 Jan | 58.233 | 7.6 |
| 1994/1995 | 25 | 32469 | 12 Nov | 13.494 | 68284 | 23 Dec | 40.923 | 6.0 |
| 1995/1996 | 25 | 64385 | 08 Dec | 19.448 | 20401 | 11 Jan | 56.846 | 4.1 |
| 1996/1997 | 23 | 72095 | 17 Dec | 22.931 | 20668 | 20 Jan | 57.283 | 3.3 |
| 1997/1998 | 25 | 83273 | 05 Dec | 22.436 | 25436 | 08 Jan | 58.067 | 3.7 |
| 1998/1999 | 20 | 93079 | 16 Dec | 36.279 | 27583 | 22 Dec | 10.386 | 9.4 |
| 1999/2000 | 21 | 117280 | 06 Dec | 18.587 | 31249 | 12 Jan | 51.263 | 2.6 |
| 2000/2001 | 15 | 113540 | 22 Nov | 17.07 | 50074 | 22 Dec | 42.065 | 2.3 |
| 2001/2002 | 9 | 101810 | 27 Nov | 19.55 | 55507 | 06 Jan | 65.802 | 15.4 |
| 2002/2003 | 16 | 152490 | 04 Dec | 24.226 | 31588 | 19 Jan | 68.331 | 6.7 |
| 2003/2004 | 14 | 111400 | 30 Nov | 18.165 | 104350 | 11 Dec | 54.884 | 9.2 |
| 2004/2005 | 15 | 116200 | 30 Nov | 20.192 | 41817 | 01 Jan | 48.214 | 7.0 |
| 2005/2006 | 20 | 80941 | 01 Dec | 28.934 | 16646 | 29 Dec | 77.12 | 4.3 |
| 2006/2007 | 17 | 66480 | 29 Nov | 31.114 | 15793 | 15 Dec | 77.086 | 4.5 |
| 2007/2008 | 19 | 52628 | 04 Dec | 22.448 | 13021 | 02 Jan | 72.325 | 2.4 |
| 2008/2009 | 26 | 39798 | 11 Dec | 28.674 | 7820.5 | 06 Jan | 67.933 | 2.7 |
| 2009/2010\* | 26 | 56268 | 16 Dec | 44.341 | – | – | – | 6.8 |

\*Single Gaussian only fitted

Table : Estimated parameter values for equation for adult penguins moulting at Dassen Island.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Dassen adults |  |  |  |  |  |  |  |  |
| 1994/1995 | 32 | – | – | – | – | – | – | – |
| 1995/1996 | 46 | 74569 | 11 Dec | 20.7 | 83645 | 18 Dec | 72.5 | 4.9 |
| 1996/1997 | 46 | 115650 | 09 Dec | 33.8 | 52007 | 12 Jan | 96.8 | 3.3 |
| 1997/1998 | 47 | 160090 | 17 Dec | 35.6 | 49142 | 31 Dec | 101.5 | 3.4 |
| 1998/1999 | 38 | 236770 | 12 Dec | 30.1 | 39748 | 26 Dec | 103.3 | 4.5 |
| 1999/2000 | 21 | 212580 | 01 Dec | 24.8 | 107320 | 23 Dec | 58.2 | 4.0 |
| 2000/2001 | 24 | 206590 | 22 Nov | 17.8 | 125940 | 28 Dec | 54.8 | 7.9 |
| 2001/2002 | 14 | 153100 | 10 Nov | 19.8 | 174200 | 16 Dec | 48.8 | 3.7 |
| 2002/2003 | 16 | 191000 | 11 Nov | 29.2 | 128960 | 29 Dec | 58.1 | 3.4 |
| 2003/2004 | 13 | 99884 | 21 Nov | 25.7 | 111710 | 12 Dec | 56.8 | 6.7 |
| 2004/2005 | 14 | 155310 | 22 Nov | 28.0 | 67374 | 27 Nov | 76.5 | 7.4 |
| 2005/2006 | 26 | 129690 | 02 Dec | 39.8 | 22384 | 02 Mar | 180.0 | 11.3 |
| 2006/2007 | 27 | 97285 | 29 Nov | 52.2 | 1565 | 10 Jul | 19.7 | 3.8 |
| 2007/2008 | 12 | 22651 | 01 Dec | 70.2 | 5140 | 23 Dec | 5.9 | 3.3 |
| 2008/2009 | 27 | 4555 | 26 Nov | 60.7 | 866 | 29 Apr | 39.8 | 1.9 |
| 2009/2010 | 31 | 1001 | 08 Nov | 13.2 | 3426 | 27 Dec | 85.2 | 1.8 |

Table : Estimated parameter values for equation for penguins in immature plumage moulting at Robben Island.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Robben immatures |  |  |  |  |  |  |  |  |
| 1988/1989 | 18 | 6653.7 | 01 Dec | 11.397 | 3516.1 | 23 Feb | 42.084 | 2.7 |
| 1989/1990 | 25 | 7306.2 | 30 Nov | 29.083 | 3618.1 | 11 Mar | 27.788 | 4.8 |
| 1990/1991 | 24 | 7432.3 | 06 Dec | 24.247 | 3985.5 | 21 Mar | 32.822 | 2.2 |
| 1991/1992 | 26 | 17413 | 12 Dec | 34.509 | 2422.3 | 29 Mar | 25.246 | 7.1 |
| 1992/1993 | 26 | 8730 | 07 Dec | 7.5553 | 12011 | 24 Dec | 58.991 | 3.9 |
| 1993/1994 | 24 | 7689.8 | 28 Jan | 58.923 | 12337 | 03 Dec | 13.426 | 2.3 |
| 1994/1995 | 25 | 6711.3 | 28 Dec | 13.961 | 10692 | 15 Jan | 57.606 | 2.6 |
| 1995/1996 | 25 | 9058.8 | 28 Nov | 32.168 | 8806.8 | 02 Mar | 31.532 | 2.6 |
| 1996/1997 | 23 | 23047 | 19 Dec | 22.949 | 5979.3 | 24 Mar | 31.406 | 4.5 |
| 1997/1998 | 25 | 17602 | 25 Nov | 25.31 | 12716 | 20 Jan | 63.506 | 2.9 |
| 1998/1999 | 20 | 18893 | 28 Nov | 26.224 | 15954 | 21 Jan | 60.217 | 4.2 |
| 1999/2000 | 21 | 24849 | 30 Nov | 20.834 | 10851 | 03 Mar | 26.816 | 2.8 |
| 2000/2001 | 15 | 22735 | 15 Nov | 27.734 | 8068.2 | 17 Mar | 33.422 | 2.8 |
| 2001/2002 | 9 | 21905 | 26 Nov | 12.387 | 12698 | 27 Feb | 48.978 | 5.5 |
| 2002/2003 | 16 | 33711 | 03 Dec | 23.522 | 11640 | 26 Mar | 27.483 | 9.0 |
| 2003/2004 | 14 | 29882 | 25 Nov | 26.849 | 12374 | 01 Mar | 17.726 | 6.8 |
| 2004/2005 | 15 | 20585 | 02 Dec | 17.468 | 11360 | 04 Jan | 64.789 | 2.4 |
| 2005/2006 | 20 | 29868 | 28 Nov | 24.744 | 4206.3 | 15 Mar | 26.326 | 7.5 |
| 2006/2007 | 17 | 22349 | 13 Nov | 47.549 | 2038 | 03 Apr | 47.503 | 3.8 |
| 2007/2008 | 19 | 6238.2 | 06 Dec | 13.25 | 11576 | 19 Dec | 76.042 | 2.3 |
| 2008/2009 | 26 | 16314 | 04 Dec | 30.565 | 6649.6 | 02 Mar | 28.871 | 2.6 |
| 2009/2010 | 26 | 17413 | 29 Nov | 28.318 | 4858.9 | 11 Mar | 23.352 | 5.5 |

Table : Estimated parameter values for equation for penguins in immature plumage moulting at Dassen Island.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Dassen immatures |  |  |  |  |  |  |  |  |
| 1994/1995 | 32 | 9190 | 23 Dec | 20.0 | 8571 | 10 Mar | 37.1 | 3.2 |
| 1995/1996 | 46 | 15822 | 27 Dec | 48.8 | 6632 | 20 Mar | 33.0 | 3.3 |
| 1996/1997 | 46 | 33242 | 14 Dec | 24.8 | 29510 | 15 Mar | 32.2 | 5.4 |
| 1997/1998 | 47 | 5798 | 02 Dec | 18.5 | 37212 | 20 Jan | 60.9 | 3.0 |
| 1998/1999 | 38 | 48715 | 08 Dec | 22.7 | 57059 | 16 Jan | 52.9 | 3.7 |
| 1999/2000 | 21 | 75465 | 04 Dec | 23.5 | 31201 | 01 Mar | 24.8 | 5.0 |
| 2000/2001 | 24 | 60807 | 22 Nov | 24.8 | 24543 | 16 Mar | 30.7 | 4.1 |
| 2001/2002 | 14 | 72519 | 19 Nov | 30.1 | 32959 | 12 Mar | 24.2 | 3.2 |
| 2002/2003 | 16 | 48807 | 02 Dec | 25.8 | 23324 | 25 Feb | 32.0 | 5.5 |
| 2003/2004 | 13 | 25358 | 05 Dec | 37.5 | 24364 | 03 Mar | 23.7 | 6.5 |
| 2004/2005 | 14 | 44738 | 30 Nov | 29.4 | 18833 | 10 Mar | 28.7 | 7.9 |
| 2005/2006 | 26 | 15003 | 02 Dec | 28.1 | 12757 | 11 Mar | 31.3 | 1.9 |
| 2006/2007 | 27 | 4926 | 22 Nov | 17.7 | 16935 | 06 Jan | 58.7 | 1.6 |
| 2007/2008 | 12 | 6254 | 17 Dec | 60.6 | 1617 | 26 Feb | 15.8 | 0.6 |
| 2008/2009\* | 27 | 969 | 12 Jan | 69.2 | – | – | – | 1.9 |
| 2009/2010 | 31 | 1053 | 16 Nov | 28.6 | 517 | 03 Feb | 33.6 | 2.4 |

 \*Single Gaussian only fitted.

Table 5: Estimates of the number of penguins in adult plumage moulting at Robben Island. The Double Gaussian estimates correspond to the parameters in .

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Robben adults | Wolfaardt *et al*. (2009) | Crawford (unpub.) | Linear interpolation | Double Gaussian MLE |
| Year |  |  |  |  | CV (%) |
| 1988/1989 | 3459 | 3125 | 3562 | 3468 | 8.3 |
| 1989/1990 | 3392 | 3015 | 3391 | 3397 | 8.5 |
| 1990/1991 | 4730 | 4378 | 4725 | 4724 | 6.1 |
| 1991/1992 | 4915 | 4626 | 4917 | 4939 | 5.8 |
| 1992/1993 | 6538 | 5909 | 6535 | 6544 | 4.4 |
| 1993/1994 | 8002 | 7213 | 7998 | 7915 | 3.6 |
| 1994/1995 | 7948 | 7159 | 7948 | 7933 | 3.6 |
| 1995/1996 | 6563 | 6350 | 6568 | 6674 | 4.3 |
| 1996/1997 | 5608 | 5235 | 5607 | 7300 | 3.9 |
| 1997/1998 | 8696 | 8556 | 8695 | 8556 | 3.4 |
| 1998/1999 | 9397 | 9710 | 9395 | 9501 | 3.0 |
| 1999/2000 | 11765 | 10667 | 11768 | 11694 | 2.5 |
| 2000/2001 | 13362 | 12059 | 13187 | 12883 | 2.2 |
| 2001/2002 | 16439 | 11549 | 15646 | 12362 | 2.3 |
| 2002/2003 | 14737 | 12607 | 14627 | 14469 | 2.0 |
| 2003/2004 | 17424 | 15774 | 17419 | 16975 | 1.7 |
| 2004/2005 | 12871 | 12640 | 12852 | 12442 | 2.3 |
| 2005/2006 | 7769 | 7286 | 7749 | 7660 | 3.8 |
| 2006/2007 |  | 5138 | 6494 | 6453 | 4.5 |
| 2007/2008 |  | 5229 | 5197 | 5157 | 5.6 |
| 2008/2009 |  | 3378 | 3740 | 3745 | 7.7 |
| 2009/2010 |  | 3738 | 4309 | 4430 | 6.5 |

Table : Estimates of the number of penguins in adult plumage moulting at Dassen Island. The Double Gaussian estimates correspond to the parameters in Table 2.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Dassen adults | Wolfaardt *et al*. (2009) | Crawford (unpub.) | Linear interpolation | Double Gaussian MLE |
| Year |  |  |  |  | CV (%) |
| 1994/1995 | 12360 | 12360 | 12390 | – | – |
| 1995/1996 | 12222 | 12222 | 12243 | 12373 | 2.8 |
| 1996/1997 | 12953 | 12954 | 12943 | 12950 | 2.6 |
| 1997/1998 | 16296 | 16296 | 16223 | 16195 | 2.2 |
| 1998/1999 | 21438 | 21438 | 21375 | 21531 | 2.6 |
| 1999/2000 | 25074 | 25074 | 25098 | 25174 | 2.9 |
| 2000/2001 | 26095 | 26096 | 26008 | 26175 | 2.9 |
| 2001/2002 | 25619 | 25618 | 29605 | 25767 | 10.2 |
| 2002/2003 | 22511 | 22510 | 22373 | 25177 | 5.8 |
| 2003/2004 | 17592 | 17592 | 17605 | 16642 | 5.4 |
| 2004/2005 | 18298 | 18298 | 18298 | 17385 | 3.7 |
| 2005/2006 | 11345 | 11344 | 11345 | 11377 | 3.9 |
| 2006/2007 |  | 7159 | 7878 | 7729 | 4.1 |
| 2007/2008 |  | 1827 | 2319 | 2160 | 14.7 |
| 2008/2009 |  | 449 | 433 | 420 | 18.5 |
| 2009/2010 |  |  | 342 | 340 | 22.6 |

Table : Estimates of the number of penguins in immature plumage moulting at Robben Island. The Double Gaussian estimates correspond to the parameters in Table 3.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Robben immature | Wolfaardt *et al*. (2009) | Crawford (unpub.) | Linear interpolation | Double Gaussian MLE |
| Year |  |  |  |  | CV (%) |
| 1988/1989 | 842 | 759 | 807 | 800 | 19.7 |
| 1989/1990 | 866 | 752 | 866 | 860 | 18.4 |
| 1990/1991 | 911 | 827 | 914 | 899 | 17.6 |
| 1991/1992 | 1598 | 1481 | 1599 | 1562 | 10.1 |
| 1992/1993 | 1597 | 1447 | 1596 | 1631 | 9.7 |
| 1993/1994 | 1585 | 1425 | 1583 | 1574 | 10.0 |
| 1994/1995 | 1373 | 1198 | 1373 | 1369 | 11.5 |
| 1995/1996 | 1403 | 1279 | 1413 | 1407 | 11.2 |
| 1996/1997 | 2138 | 2006 | 2138 | 2285 | 6.9 |
| 1997/1998 | 2351 | 2289 | 2350 | 2381 | 6.6 |
| 1998/1999 | 2834 | 2824 | 2833 | 2739 | 5.8 |
| 1999/2000 | 2803 | 2484 | 2810 | 2811 | 5.6 |
| 2000/2001 | 2565 | 2236 | 2521 | 2425 | 6.5 |
| 2001/2002 | 3921 | 3141 | 3737 | 2719 | 5.8 |
| 2002/2003 | 3330 | 3051 | 3291 | 3571 | 4.4 |
| 2003/2004 | 3440 | 3104 | 3431 | 3327 | 4.7 |
| 2004/2005 | 2617 | 2615 | 2606 | 2511 | 6.3 |
| 2005/2006 | 2654 | 2740 | 2647 | 2683 | 5.9 |
| 2006/2007 |  | 1621 | 1927 | 1911 | 8.3 |
| 2007/2008 |  | 1377 | 1443 | 1387 | 11.4 |
| 2008/2009 |  | 1614 | 1804 | 1808 | 8.7 |
| 2009/2010 |  | 1304 | 1707 | 1754 | 9.0 |

Table : Estimates of the number of penguins in immature plumage moulting at Dassen Island. The Double Gaussian estimates correspond to the parameters in Table 4.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Dassen immature | Wolfaardt *et al*. (2009) | Crawford (unpub.) | Linear interpolation | Double Gaussian MLE |
| Year |  |  |  |  | CV (%) |
| 1994/1995 | 1578 |  | 1580 | 1398 | 6.7 |
| 1995/1996 | 1767 |  | 1776 | 1767 | 6.9 |
| 1996/1997 | 4823 |  | 4825 | 4940 | 6.1 |
| 1997/1998 | 3418 |  | 3414 | 3374 | 4.3 |
| 1998/1999 | 8380 |  | 8320 | 8324 | 3.6 |
| 1999/2000 | 8462 |  | 8406 | 8399 | 4.4 |
| 2000/2001 | 6683 |  | 6655 | 6720 | 4.8 |
| 2001/2002 | 8380 |  | 8934 | 8305 | 5.7 |
| 2002/2003 | 5409 |  | 5485 | 5680 | 8.5 |
| 2003/2004 | 3864 |  | 3899 | 3915 | 7.4 |
| 2004/2005 | 5134 |  | 5134 | 5006 | 7.1 |
| 2005/2006 | 2184 |  | 2213 | 2186 | 6.8 |
| 2006/2007 |  |  | 1698 | 1719 | 7.6 |
| 2007/2008 |  |  | 622 | 618 | 23.5 |
| 2008/2009 |  |  | 77 | 76 | 36.8 |
| 2009/2010 |  |  | 133 | 124 | 33.4 |

Figure : Comparison of previously derived moult count estimates with proposed revisions for Robben Island adult penguins.

Figure : Comparison of previously derived moult count estimates with proposed revisions for Dassen Island adult penguins.

Figure : Comparison of previously derived moult count estimates with proposed revisions for Robben Island penguins in immature plumage.

Figure : Comparison of previously derived moult count estimates with proposed revisions for Dassen Island penguins in immature plumage.

Figure 5: Counts of adult penguins at Robben Island in the 1996/1997 season, showing the double Gaussian curve fitted with the three indicated counts excluded.

Figure 6: Counts of moulting adult penguins at Robben Island in the 2001/2002 season, showing the double Gaussian curve fitted.

Figure 7: Counts of moulting penguins in immature plumage at Robben Island during the 2001/2002 season, showing the double Gaussian curve fitted.

Figure 8: Counts of moulting adult penguins at Dassen Island during the 2002/2003 season, showing the double Gaussian curve fitted.

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