

# An Emperor Penguin Population Estimate: The First Global, Synoptic Survey of a Species from Space

Peter T. Fretwell, Michelle A. LaRue, Paul Morin, Gerald L. Kooyman, Barbara Wienecke, Norman Ratcliffe, Adrian J. Fox, Andrew H. Fleming, Claire Porter, Phil N. Trathan

Published: April 13, 2012 • <https://doi.org/10.1371/journal.pone.0033751>

## Correction

**26 Apr 2012:** Fretwell PT, LaRue MA, Morin P, Kooyman GL, Wienecke B, et al. (2012) Correction: An Emperor Penguin Population Estimate: The First Global, Synoptic Survey of a Species from Space. PLOS ONE 7(4): 10.1371/annotation/32c246eb-3b73-4410-a44c-b41ddae11fc5. <https://doi.org/10.1371/annotation/32c246eb-3b73-4410-a44c-b41ddae11fc5> | [View correction](#)

## Abstract

Our aim was to estimate the population of emperor penguins (*Aptenodytes fosteri*) using a single synoptic survey. We examined the whole continental coastline of Antarctica using a combination of medium resolution and Very High Resolution (VHR) satellite imagery to identify emperor penguin colony locations. Where colonies were identified, VHR imagery was obtained in the 2009 breeding season. The remotely-sensed images were then analysed using a supervised classification method to separate penguins from snow, shadow and guano. Actual counts of penguins from eleven ground truthing sites were used to convert these classified areas into numbers of penguins using a robust regression algorithm.

We found four new colonies and confirmed the location of three previously suspected sites giving a total number of emperor penguin breeding colonies of 46. We estimated the breeding population of emperor penguins at each colony during 2009 and provide a population estimate of ~238,000 breeding pairs (compared with the last previously published count of 135,000–175,000 pairs). Based on published values of the relationship between breeders and non-breeders, this translates to a total population of ~595,000 adult birds.

There is a growing consensus in the literature that global and regional emperor penguin populations will be affected by changing climate, a driver thought to be critical to their future survival. However, a complete understanding is severely limited by the lack of detailed knowledge about much of their ecology, and importantly a poor understanding of their total breeding population. To address the second of these issues, our work now provides a comprehensive estimate of the total breeding population that can be used in future population models and will provide a baseline for long-term research.

**Citation:** Fretwell PT, LaRue MA, Morin P, Kooyman GL, Wienecke B, Ratcliffe N, et al. (2012) An Emperor Penguin Population Estimate: The First Global, Synoptic Survey of a Species from Space. PLoS ONE 7(4): e33751. <https://doi.org/10.1371/journal.pone.0033751>

**Editor:** André Chiaradia, Phillip Island Nature Parks, Australia

**Received:** September 19, 2011; **Accepted:** February 17, 2012; **Published:** April 13, 2012

**Copyright:** © 2012 Fretwell et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

**Funding:** The authors would like to acknowledge and thank funding and provision of imagery from the National Science Foundation (NSF-#1043681 and #0944220) which funded the U.S. component of this work. Imagery for the UK analysis was funded by the BAS Ecosystems/predators work package and UK Overseas Territories Fund (BAT601). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

**Competing interests:** The authors have declared that no competing interests exist.

## Introduction

An accurate assessment of the emperor penguin (*Aptenodytes fosteri*) population is urgently needed as recent research indicates that numbers may decrease significantly in coming decades [1], [2], [3]. These studies have highlighted the susceptibility of emperor penguins to changes in sea ice distribution. Recent recorded changes in sea-ice are substantial [4] and predictions suggest sea ice variation will increase with predicted climate change [5], [6]. The subsequent change in marine food webs [7], and other possible developments linked to climate change such as increased predation [8], increased competition, and an increasing

frequency of storm events is likely to impact on their breeding success and colony viability [4], [9], [10]. The loss of one colony has already been attributed to climatic warming and others are thought to be vulnerable [4], especially those in the north of the species' breeding range [2] or those currently experiencing regional climate change [8].

One of the most important parameters of any population assessment model is knowledge of the extant population size and status of the breeding colonies [11], [12]. These parameters are the starting point for any demographic model. For emperor penguins this knowledge is limited; only five colonies are monitored each year, but these colonies are geographically restricted to the Ross Sea area and the East Antarctic coast between longitudes 20°E and 140°E. The regional nature of climate change in Antarctica [5] means that a more extensive knowledge of population and population dynamics is required, particularly in those areas where climate change is most evident. For much of the emperor penguins geographic range we have little or no information on demographic change. The paucity of data regarding population status of emperor penguins is largely due to the logistical difficulties of accessing potential emperor penguin breeding habitat in areas of Antarctica that are not in close proximity to research stations. The last global population estimate of 135,000–175,000 pairs [13], compiled nearly two decades ago, was based on a compendium of previous reports. However, the accuracy and validity of many of the counts used to compile this figure have been questioned [14]. Further, many colonies have not previously been counted, including the ten new locations reported in a recent Landsat survey [15] and the new colonies found in our study. Also, many of the colonies where counts do exist were last counted several decades ago (Table 1), while other counts rely on estimates from late in the breeding season (i.e. after an unknown number of eggs and chicks had already been lost and adults may have already departed from the colony) [16]. These concerns over the lack of a baseline population figure for the species have led to the suggestion that emperor penguins should be re-classified by the IUCN from 'of least concern' to 'data deficient' [14].

Name	long	lat	Image date	area (km <sup>2</sup> )	BE	Image notes	PLC	source	notes
Adelie Island, Edward VII Peninsula	-127.7	-71.14	12/10/2009	12,862	17,648	good	6359	176	
Robert Coast	-143.3	-75.39	26/10/2009	1680	1038	good	Unrecorded		See ice gaps before image date
Little Bay	not known	not known	0	0	0	Unrecorded	176		Probable snow only late in the season
Thurston Glacier, McMurdo	-124.827	-70.2	10/10/2009	3255	2895	good	2100	176	(1) chick estimate
East Peninsula	-174.24	-74.32	18/11/2009	2918	3491	good	Unrecorded		
Emerson Islands	-103.84	-74.35	18/11/2009	4146	1732	good	Unrecorded		Many guano
Stately Peninsula	-184.45	-75.31	13/11/2009	3651	2044	good	Unrecorded		Many guano
Trinity	-162.3	-72.2	12/11/2009	4936	4067	good	Unrecorded		
Spain	-164.83	-74.37	26/10/2009	4347	4634	good	Unrecorded		
Chickman	-164.43	-75.01	26/10/2009	1757	1628	good	Unrecorded		Small part of colony nesting in image
Stanford	-127.44	-84.32	26/10/2009	2321	2344	good	3845	176	
Waller	-147.68	-77.21	14/10/2009	4923	4024	good	7329	176	
Lyford	-134.4	-77.07	12/11/2009	4849	3436	good	Unrecorded		
Duncan	-118.67	-76.32	13/10/2009	2769	2287	good	11766		Agglin uncounted 843 square 1986
Willey	-127.43	-75.34	27/10/2009	24127	22318	good	14380		Agglin uncounted 843 square 1986
Stewart	-123.69	-74.12	21/10/2009	5849	5455	fair	3050		Small amount of Agglin uncounted 843 square 1986
Donner	-174.34	-72.82	04/10/2009	2469	2325	fair	6656	176	No guano, analysis on perched/roost band only
Wain	-113.33	-72.32	22/10/2009	4286	4613	fair	5969	176	High chick count
Wain	-82.38	-76.67	26/10/2009	3992	2642	good	8969	176	
Saner	-142	-79	26/10/2009	3423	3116	good	113	176	
Ward	8.27	-69.85	26/11/2009	1467	1388	good	Unrecorded		See image column study document
Lawson	15.25	-69.72	11/10/2009	891	921	fair	4323	176	
Highland	27.24	-69.62	10/10/2009	746	806	good	Unrecorded		
Common	34.38	-69.72	01/10/2009	4989	4622	fair	7089	176	
Widdowson	42.67	-69.76	26/10/2009	176	146	good	237	176	
Amundsen Bay	50.15	-69.74	10/10/2009	84	88	good	216	176	Small, difficult to count
Weka Point	57.28	-69.44	13/11/2009	3121	3245	good	4396	176	
Eastland	102.19	-67.02	14/10/2009	228	213	good	348	176	
Light House	103.68	-67.07	11/10/2009	336	318	fair	259	176	Some standing near colony
Avon	43.98	-67.59	01/10/2009	8422	7954	poor	11009	176	
Cape Denney	66.7	-67.86	12/10/2009	3713	3462	good	3493	146	
Amundsen Bay Island	76.89	-69.27	12/10/2009	773	693	good	9000	176	
Island Island	82.62	-68.52	12/10/2009	942	1247	poor	1746		Multi-layered image but, overlaid with perched/roost band
Shepherd Ice Shelf	96.22	-68.86	10/10/2009	6927	6671	good	Unrecorded		Good image
McMurdo Island	100.82	-68.12	10/10/2009	719	749	good	Unrecorded		
Penner Bank	112.23	-63.92	24/11/2009	0	0	NA	1060	176	Late image, colony almost
Delaney Glacier	124.74	-66.03	12/10/2009	12017	12474	fair	Unrecorded		Analysis of perched/roost only
Frank Gattuso	140.21	-66.57	01/10/2009	8522	2956	poor	2368	176	Standing in perched/roost band
Willy Glacier	146.2	-66.82	11/11/2009	3122	4191	poor	Unrecorded		Standing small and difficult to count
Deer Bay	158.49	-65.33	11/10/2009	1870	1762	good	Unrecorded		
Cape Washington	163.27	-74.24	10/10/2009	12463	17648	good	14822	176	176
Beaufort Island	167.52	-75.93	12/10/2009	1769	1641	poor	1312	176	176
Faraday Island	168.42	-76.18	12/10/2009	8143	7941	good	2460	176	176
Cape Crozier	169.23	-77.46	11/10/2009	525	553	good	437	176	176
Chickman Island	169.81	-77.26	10/10/2009	27174	28298	fair	31412	176	176
Cape Regan	170.29	-71.89	10/10/2009	10196	9026	fair	7207	176	176
									Some standing in perched/roost band, results may be overestimate
<b>Total</b>							<b>238679</b>		

Table 1 presents the location and best available estimate (BE) for each emperor penguin colony in the survey. The table also gives the image quality and the most recently published count for the colonies that have been previously counted with corresponding references. doi:10.1371/journal.pone.0033751.t001

**Table 1. Emperor penguin population survey 2009 results.**  
<https://doi.org/10.1371/journal.pone.0033751.t001>

Here we present the first synoptic survey of the entire population of a single species (breeding in a single year) using satellite remote sensing. Emperor penguins are particularly suitable for such a project because they breed at a relatively small number of sites and they breed mainly on sea ice where they have high contrast with their surrounding environment, making them easier to count in remote sensing imagery. Furthermore, our current knowledge of their global breeding population is limited. Finally, their predicted future decline due to climate change means that accurate current population assessments are needed to model their population dynamics.

Using Very High Resolution (VHR) satellite imagery we set out to:

1. Complete the survey initiated by the use of Landsat imagery [4] so that the entire Antarctic coastline has been surveyed by remote sensing for emperor penguin colonies.
2. Assess the population at every breeding emperor penguin colony.
3. Present a single breeding population figure from one synoptic count.

**Materials and Methods**

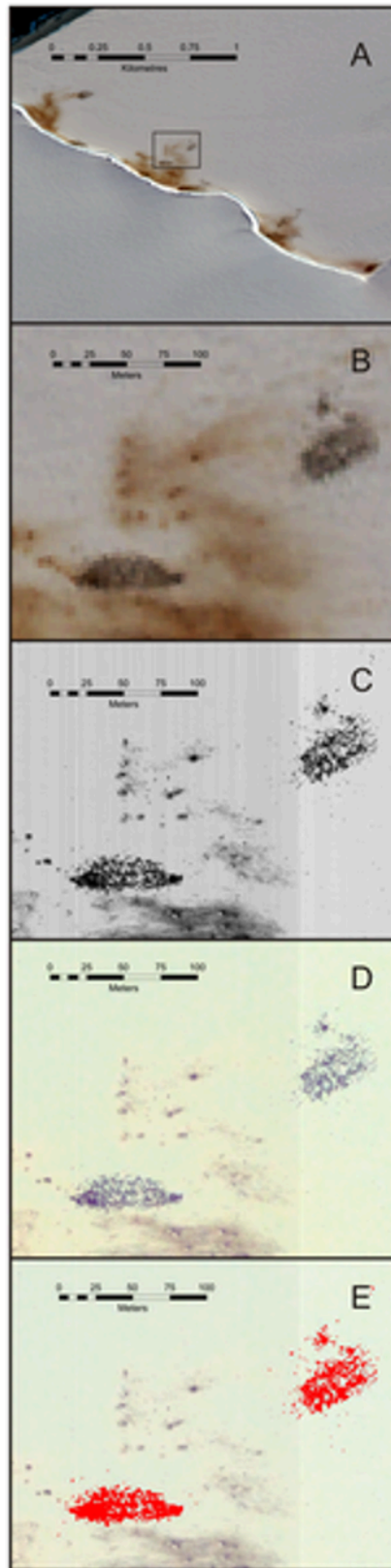
#### Data acquisition

To assess whether a penguin colony could be detected on an image and whether the image could be analysed, we examined un-georeferenced quick-looks from the QuickBird, WorldView-2 and Ikonos satellites. These quick-looks have a nominal resolution of ~10 m, and therefore show greater detail than corresponding Landsat ETM images (see <http://browse.digitalglobe.com/imagefinder/main.jsp> for examples). Where evidence of emperor penguins was found, VHR satellites were tasked to collect images at these locations between September and December 2009, focussing on where colonies were previously thought to exist [11], [12]. The whole Antarctic coastline was assessed during the emperor penguin breeding season. Specific focus was given to sites where new colonies had been identified [15], [17], [18], [19], [20], and sites where there were unconfirmed sightings [11], [12], as well as locations where the previous Landsat survey had failed to acquire usable imagery of previously known sites [15].

Using this method, 51 possible sites were identified (46 from [Table 1](#) and a number of other possible sites that eventually proved negative). Full resolution images for these sites were then uploaded and assessed to confirm whether an emperor penguin colony was present. All except one of these images were taken in the 2009 breeding season between late September and early December. The one exception was a newly found colony on the Rupert Coast (75.38°S latitude, 143.3°E Longitude), which was discovered too late in the season to acquire usable imagery. In this case imagery from the 2008 breeding season was used. Of the other 43 colony sites counted in this survey, 41 were assessed during a 54 day window between early October and late November (see [Table 1](#)). Thus, all known, or suspected breeding sites located on the fast-ice have now been examined for the presence of emperor penguin colonies.

#### Analysis

QuickBird imagery has a resolution of 61 cm (at nadir) in the panchromatic band and 2.44 m resolution in the four multispectral bands (blue, green, red, and infrared). Emperor penguins show as single or multiple pixels in the panchromatic band. Where penguins are dispersed, individuals can be identified and counted. However, in the majority of cases penguins group into close clusters and their shadows overlap, meaning that individuals cannot be differentiated and a different approach is needed. [Figure 1](#) shows an example of the high resolution imagery used in our analyses.



**Figure 1. Example of imagery used in analysis.**

A: Multispectral QuickBird image of the emperor penguin colony at Windy Creek, Halley Bay, Antarctica. Black box indicates the area of images B–E below. B: Detail of multispectral image showing area of penguins as black/grey pixels and guano in brown. Although there is good differentiation between penguins and guano the coarse resolution of the multispectral image (2.54 m cell size) means that individual penguins cannot be identified and limits the usefulness of the image. C: Detail of the

panchromatic band of the corresponding QuickBird image. The higher resolution (61 cm) gives better detail of the penguin area, but many of the penguin pixels have the same value as the areas of guano and therefore are difficult to separate using a classification index. D: Detail of the corresponding pansharpened QuickBird image. A histogram stretch has been used to maximize the difference between penguins and guano. Using this method the image retains the detail of the panchromatic image while keeping the colour differentiation of the multispectral image. E: Results from the supervised classification analysis of the pansharpened QuickBird image with the area classified as penguins shown in red.  
<https://doi.org/10.1371/journal.pone.0033751.g001>

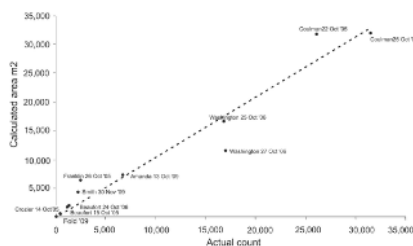
We used a multivariate supervised classification implemented in ArcGis™ v9.3 (ESRI®, 1999–2006) on QuickBird satellite images to assess the numbers of penguins at each colony. In previous work using this approach on the panchromatic band of VHR imagery, large errors were evident between estimated and actual counts [16], [21]. This was partially due to the problems of differentiating between penguins, shadows and guano (for an expanded discussion see Barber-Mayer et al [16]). For example, Barber-Mayer et al [16] encountered difficulties at the Cape Washington colony where the emperor penguins remained in large clusters in or around guano stained areas. Here an absolute deviation of 128% between the known and predicted count was found in 2005. This large deviation was attributed to the problem of differentiating guano from penguins in the panchromatic image bands. We have therefore modified the previous methods used by Barber-Mayer et al [16] by pansharpening the imagery (using an intensity/hue/saturation method). This results in a four band 61 cm resolution image that allows for much greater differentiation between guano, shadows and penguins. This process was carried out on the eight images from 2005 and 2006 that were used by Barber-Mayer et al [16]. These images were compared to aerial photographs taken simultaneously with the satellite imagery where adults were counted. A further three colonies (also adults only) were also counted. The three new counts were determined from vertical aerial (Smith Peninsula) or ground based photography (Amanda Bay and Fold Glacier) in the corresponding month as the satellite images from 2009.

Our processing routines may be summarised as follows. Each image was clipped to an area of interest and features within the image were classified into a number of classes. The number of classes depended upon each individual image and ranged between two and six, but most commonly four classes were used. The image classes used were: penguin, snow, shadow, guano, sometimes lighter snow and lighter penguins in areas of more contrast. In areas of different lighting conditions or where image banding (strips of different contrast on the image) occurred the colony was cropped into separate areas and multiple classifications conducted. The supervised classification process depends upon human interpretation to differentiate whether a pixel area is penguins or not. In some images, especially those with deep guano staining, this interpretation was more difficult and results will be less reliable in these areas (see Table 1 for details of each image). The method is iterative and usually several attempts were required before a good match between observed penguins and classified penguin area was obtained. When the area represented by penguins was determined, we converted the “penguin area raster” to a vector polygon within a GIS and reprojected the vector file to an equal-area projection. We then derived the true ground area represented by penguins at each colony by using the robust regression equation that was derived.

This approach (supervised classification) was then applied to all images of colonies obtained in 2009. The statistics from the robust regression were used to convert the area of penguins to population numbers for each site. The overall population figure includes counts from 16 previously uncounted colony sites.

#### Statistical procedure

The relationship between the colony area (total of all birds) and the number of adult birds present at a colony was estimated using robust linear regression (see Figure 2) with data from a sample of colonies for which both satellite area estimates were available and direct counts. Robust regression was used as this minimises the influence of outliers in the response variable, explanatory variable, or both. The model estimated a slope coefficient with SE (0.0464) but no intercept: this is in keeping with the truism that zero birds will occupy zero area. This was confirmed using a regression model excluding the intercept as this resulted in a negligible increase in variance. This model was fitted using the rlm function from the MASS library in R (R 2.8.0).



**Figure 2. Regression plot based on the eleven ground truthing sites.**

The slope of the regression was 0.933 (SE=0.046). Ground truth sites: Co6. Coulman Island 2006, Co5. Coulman Island 2005, Wa6. Cape Washington 2006, Wa5. Cape Washington 2005, Am. Amanda Bay 2009, Sm. Smith Peninsula 2009, Fr. Franklin Island 2005, Be6. Beaufort Island 2006, Be5. Beaufort Island 2005, Cr. Cape Crozier 2005.

<https://doi.org/10.1371/journal.pone.0033751.g002>

Population size estimates and confidence intervals around these were estimated for each colony using a Monte Carlo procedure. Simulated slope values were selected randomly from a normal distribution defined by a slope coefficient (0.933), the residual standard error (1851), residual degrees of freedom (10) and unscaled variance-covariance matrix of fixed effects (3.915766e-10) using the mvnorm function in the R base package [22].

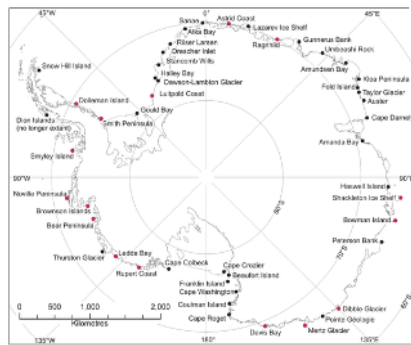
A slope value was generated for each colony and multiplied by its area to produce a population estimate for each, and these were summed to produce a global breeding population estimate. This was repeated 10,000 times, and the mean, 2.5 and 97.5 percentiles were calculated to represent the lower 95% and upper 95% confidence intervals (respectively) of the number of birds present at each colony, and globally.

## Results

We estimated a total population size of 238,079 adults present in all colonies in 2009, with 95% confidence intervals of 217,336 and 258,788 (see [Table 1](#)). We confirm the existence of 37 of the 38 colonies found in the previous Landsat study [15]. Our new survey also detected four new colonies (Brownson Islands, Dolleman Island, Dibble Glacier and Rupert Coast), and three previously suspected colonies [14] (Shackleton Ice Shelf, Bowman Island and Lazarev Ice Shelf). Two colonies remain uncounted; at Ledda Bay previous Landsat imagery from 1999 had identified a small colony, but in subsequent years early break up of fast-ice in the area has meant that no colony was present when there was coincident high resolution satellite imagery. The second location at Peterson Bank [18] was identified by air and ground survey in 1994. The corresponding QuickBird image in the 2009 breeding season was taken on 24 November and at this site the fast-ice had already retreated to the edge of the site and the majority of the colony had already departed. This colony probably still exists, but may have been unsuccessful in breeding in 2009. As earlier imagery of the area does not exist it is impossible to add an accurate estimate of numbers from this colony to our survey.

This makes a total of 46 colony locations around the coast of Antarctica. Note that the Dion Island colony is no longer believed to be occupied [8] and is not included (see [figure S1](#) for distribution of population).

As previous population estimates did not take account of 16 of the 46 colonies (see [Figure 3](#)), and many previous counts were of poor quality and widely separated in time [11], [12], [23] these historical estimates cannot be considered representative of the total breeding population of emperor penguins (previous counts are given for comparison in [Table 1](#)). Our new global estimate may plausibly be used for calculation of future global population trends.



**Figure 3. Distribution of emperor penguin colonies in Antarctica, see [Table 1](#) for details of each colony.**

Red dots refer to those colonies with no previous population estimates.

<https://doi.org/10.1371/journal.pone.0033751.g003>

## Discussion

### Colony Detection

To determine whether any other unknown colonies have been missed is difficult; the variability in Antarctic sea-ice conditions means that in some locations sea-ice may have broken up early removing any evidence of a colony (as in the case of Ledda Bay). Also, image quality and cloud cover may make identification from ~10 m imagery difficult. Finally, smaller colonies with less than 200 individuals may exist but these are more difficult to identify using imagery at this resolution. We believe that the number of small colonies will be limited as small groups are less likely to be able to huddle effectively during incubation [24]. Although a minimum effective huddle size has not yet been established, this limitation must exist, and penguins that cannot huddle effectively may suffer greater energy demands and thus greater weight loss and higher adult male mortality during the winter fast. The biological disadvantages of small colonies suggest that their number should be limited [32], [33], and although there may be a number of small colonies missing from this survey their contribution to the overall total population size is expected to be small. Any associated error on our overall population estimate should be minimal and probably within the confidence limits of our current global population estimate.

### Accuracy and uncertainty

Our results provide a new approach for assessing emperor penguin population numbers, though we believe some issues still need to be resolved. With future developments in ultra high resolution imagery, some of these issues will be naturally resolved. With existing capability, residual uncertainty derives from a number of sources, summarized in [Table 2](#). These can be divided into (A) methodological error and (B) natural variability. Methodological errors can be divided into four types and are discussed below:

Procedure	Result	Source of variability	Variability	Notes and suggestions for future work
1. Supervised classification	Area of pixels at each colony	Interpretation error of pixels (misclassification of pixels) due to complex geometry or low contrast in some colonies or to low accuracy of supervised classification (e.g. due to heavy guano staining or to complex geometry)	Area (5% with best imagery, but progressively worse with poorer imagery). Can be as high as 15% with low quality imagery.	Depends on the quality of the imagery. We suggest that future surveys should use high quality imagery with heavy guano staining.
2. Chick/adult area assumption	Area of adults at each colony	Chick/adult ratio error: we assume the number of adults is equal to the number of chicks. The ratio of chicks to adults is equal to the ratio of pixels to pixels in the same proportion, when there are enough pixels to be verified.	Unknown at this stage, but we assume that the ratio is 1:1. Images from other regions suggest that the ratio is not 1:1 and that the assumption is likely to be wrong.	We suggest further work is needed to determine the ratio of chicks to adults. It is not clear that the ratio is 1:1 and that the assumption is likely to be wrong.
3. Ground truthing	Location of adult and chick pixels	Human error in the location of pixels. Human error in the location of pixels. Human error in the location of pixels.	Depends on the quality of the imagery. Human error in the location of pixels. Human error in the location of pixels.	Low level of error (about 1% of total pixels) is expected. Human error in the location of pixels. Human error in the location of pixels.
4. Statistical analysis	Estimate of adult area at each colony	Statistical error: variance of the estimate. Variance of the estimate. Variance of the estimate.	15% based on Monte Carlo analysis.	More ground truthing over the entire area is required to improve the statistical procedure.
5. Seasonal extrapolation	Area of pixels at each colony	Extrapolation error: we assume that the area of pixels is constant over time. Extrapolation error: we assume that the area of pixels is constant over time.	None (we use a single image for each colony).	Does there evidence other counts or seasonal variability would be useful? Seasonal variability in adult and chick numbers.
6. Yearly population estimate	Population estimate for 2019	Conversion error: we assume that the area of pixels is constant over time. Conversion error: we assume that the area of pixels is constant over time.	None (we use a single image for each colony).	Further investigation is needed. Ground truthing over the entire area is required.
7. Inter-annual variability	Area of pixels at each colony	Inter-annual variability: we assume that the area of pixels is constant over time. Inter-annual variability: we assume that the area of pixels is constant over time.	None (we use a single image for each colony).	Number of colonies over which to extrapolate is a major population estimate.

The column headers of the table are: Accuracy and uncertainty in the Discussion for further details of each area. doi:10.1371/journal.pone.0033751.t002

**Table 2. Sources of error.**  
<https://doi.org/10.1371/journal.pone.0033751.t002>

A.1. Supervised classification procedure: Based upon the difficulty in differentiating penguins from guano or shadow, and from differing densities of penguins in clusters classed as penguin. This error source is compounded by manual interpretation inherent in the supervised classification procedure. To test the variability between operators when classifying pixels, four sites were classified by three different people. Results showed that the CV% around population estimates for individual colonies is low for colonies where there is good imagery (2.5 CV%), but becomes progressively worse with increasingly poor imagery. The quality of imagery is dependent upon contrast levels, whether the penguins are in shadow and if there is heavy guano staining. Errors in images with heavy guano staining such as from multispectral imagery at Haswell Island (original estimate of 50 CV%) can be large and almost certainly resulted in an over-estimate of penguin numbers at this site. Images such as this were the exception though; most colonies (24 out of 42 sites analysed) had very good imagery. (In the case of the Haswell Island image, the bad quality of the original multispectral image forced us to acquire an additional panchromatic image from earlier in the season in late August upon which our estimate for this colony is calculated). Based on a classification of each image by the user operator, image quality was classified into three quality groups, with each being assigned a corresponding level of variability; Table 3 shows the corresponding image classifications: good (2.5 CV%), reasonable (7.5 CV%) poor (15 CV%). To estimate the CV% of the total survey each pixel classed as penguin was attributed with a reliability estimate based upon these classes (see Table 3). The average CV% due to the image quality for all the pixels in the whole survey was calculated using this combined value, giving a value of 5.59CV%. Future surveys should attempt to acquire imagery with the minimum of guano staining to minimize operator error.

Name	Regression uncertainty				Image uncertainty		Total CV
	Area	RPE	SEI	SEI	%CV	Image Quality	
Adelie Island	1242	1140	1140	1212	8.0	good	10.1
Adelie Coast	1485	1330	1413	1481	8.79	good	11.1
Adelie Bay	0	0	0	0	0.02	NA	7.0
Adelie Glacier	2295	2095	2295	2400	8.70	good	10.1
Beer Peninsula	10168	9027	9025	10170	8.7	good	11.1
Bonaparte Islands	4140	3720	3740	4236	8.58	good	10.1
Bonaparte Peninsula	1022	1008	1016	1076	8.70	good	11.1
Brady	4646	4660	5027	4664	8.88	good	11.1
Brady	4307	4020	3920	4366	8.66	good	11.1
Brady	1290	1000	1000	1100	8.47	good	11.1
Brady	1231	1054	1054	1100	8.7	good	11.1
Brady	8816	8240	7910	8911	8.69	good	11.1
Brady	4960	4960	4960	4960	8.62	good	11.1
Brady	2798	2797	2870	2838	8.81	good	11.1
Brady	2427	2319	2380	2484	8.59	good	11.1
Brady	3486	3400	3480	3612	8.67	good	11.1
Brady	2469	2300	2300	2362	8.6	NA	7.0
Brady	4294	4010	3910	4312	8.66	NA	7.0
Brady	10210	9027	9027	10470	8.68	good	11.1
Brady	3420	3390	3390	3460	8.71	good	11.1
Brady	1427	1300	1300	1407	8.70	good	11.1
Brady	881	820	790	862	8.74	NA	7.0
Brady	752	670	670	741	8.62	good	11.1
Brady	1660	1620	1620	1660	8.67	good	11.1
Brady	156	146	133	156	8.7	good	11.1
Brady	90	80	80	90	8.67	good	11.1
Brady	1020	1000	1000	1010	8.7	good	11.1
Brady	128	118	104	121	8.67	good	11.1
Brady	100	100	100	100	8.6	NA	7.0
Brady	2640	2600	2600	2640	8.65	good	11.1
Brady	1710	1680	1680	1760	8.70	good	11.1
Brady	7710	6810	6810	7410	8.76	good	11.1
Brady	1460	1300	1300	1410	8.80	good	11.1
Brady	4637	4637	4637	4637	8.68	good	11.1
Brady	1030	1000	1000	1030	8.79	good	11.1
Brady	0	0	0	0	0.02	NA	7.0
Brady	1337	1240	1240	1337	8.66	NA	7.0
Brady	2030	2000	2000	2070	8.7	good	11.1
Brady	1120	1000	1000	1120	8.70	good	11.1
Brady	1870	1740	1740	1870	8.79	good	11.1
Brady	1000	1000	1000	1000	8.69	good	11.1
Brady	1260	1160	1160	1260	8.67	good	11.1
Brady	810	780	780	810	8.66	good	11.1
Brady	200	180	180	200	8.67	good	11.1
Brady	2714	2570	2570	2760	8.64	NA	7.0
Brady	1000	1000	1000	1000	8.6	NA	7.0
Brady	20300	18000	18000	20300	7.79	3.99%	14213.8

Table 3 gives details of the advanced statistical uncertainties associated with each colony. This is based on the robust regression analysis and the image quality of each pixel. The uncertainty from the robust regression is estimated using Monte Carlo analysis (see Methods) procedure across the main area. The uncertainty from the image quality is estimated using multiple analysis of image of differing quality from the same site from between the four classes of image quality (see Methods) in the Discussion section. doi:10.1371/journal.pone.0033751.t003

**Table 3. Uncertainty estimates.**  
<https://doi.org/10.1371/journal.pone.0033751.t003>

A.2. Chick versus adult assumption: Most of our images (39 of 42 sites analysed) were taken over a 54 day window in the chick rearing season. At this time there is a mixture of adults and chicks at the site. Chick mortality during this period is low [3]. At the start of the period of our image acquisition there will be one adult per chick [31], at this time chicks are small or hidden and make up very little of the area classified as “penguin” in our supervised classification analysis. Later in the season chicks have emerged from under the feet of adults and are larger. At this stage they make up more of the pixels classified as “penguin” in our analysis.

Conversely, the ratio of adults to chicks has diminished as more adults have left the colony to forage at sea. We make the assumption that in the 54 day window of image acquisition the ratio of pixels showing as penguin in the satellite imagery remains approximately constant to the number of adult pairs: i.e. That the area of larger chicks and fewer adults seen late in the season (November) is equal to the area with more adults seen by the satellite earlier in the season (October). This assumption needs to be tested, but at present not enough ground truthing concurrent with satellite imagery is available across the period to test how this affects the accuracy of our estimate.

**A.3. Ground truthing estimates:** Our regression analysis is based on the assumption of accurate ground truthing. In reality, ground truthing from ground counts or aerial photography also has inherent errors. Two sources of ground truthing have been used; aerial photography and ground counts. Estimations of variability in aerial photography counts indicate errors of  $\pm 10\%$ . This tends to be independent of colony size. With ground counts there is variability in both operator estimate and scaling errors.

**A.4. Statistical analysis errors:** conversion of the pixels to penguins relies on a regression between area identified as penguin and the number of adults from ground truthing. Enough good ground truthing, concurrent with satellite imagery must be available to make this regression accurate. The low Standard Error (0.0464) of the robust regression line in our study suggests that the relationship between area of penguins and the number of adults is consistent, and that other inherent errors (see 1 to 3 above) are small. Confidence in the levels of reliability is high for the population estimates for individual colonies, with confidence limits of  $\sim 8.7\%$ . Methodological errors will reduce in the future with the advent of even higher resolution imagery and additional ground truthing.

**B. Natural variability:** We make the assumption that at the time that the satellite imagery was taken, half of the adult breeding population would be present at the colony [31]; that is, our figure potentially represents the number of breeding pairs. Our initial estimate of 238,079 can therefore be considered to represent a count of breeding pairs that have successfully hatched a chick and raised it until at least October. Converting this figure to an overall population estimate brings further sources of variability. Uncertainty associated with naturally occurring fluctuations in penguin numbers stem from both seasonal and daily variation in the numbers of adults and chicks.

Our count only includes adult birds at the breeding site. Numbers of adults vary less on an inter-annual basis than that of chicks and are therefore a more accurate metric of population size [33]. Previously published work suggests that total chick mortality can be as high as 90% [25], [33] especially where storm events result in total breeding failure [26] (total chick loss would result in the early dispersal of the colony, and this is a possible reason why the Peterson Bank colony did not exist at the time of imaging in late November). Our estimate does not include juveniles or non-breeding adults not present at the colony, or birds that have attempted to breed (present in May or June at the colony site) and have since departed. The percentage of birds remaining at the colony site after egg loss (egg loss is estimated to be approximately 20% of eggs laid with a SD of 6.4% [33]) is low; typically less than 1%. Egg loss variability is one of several sources of potential error that must be included when converting a figure of adults at the colony site in October/November to a total population figure.

A better metric of population size would be a count of all colonies in June, when one male per breeding couple is at the colony site [33], all but five of our colony locations are south of the Antarctic circle and would be in 24 hour darkness at this time, so remote sensing with visible wavelengths of light at these colonies will be impossible. Even in the more northerly colonies at midwinter it is not feasible to use optical satellite imagery as the small time window, long shadows and low light levels result in a very limited number of very poor images, rendering accurate analysis impractical. The earliest possibility of gathering data from the most southerly emperor penguin colony (Gould Bay) is in late September or early October, so any continent wide survey that uses a consistent remote sensing methodology using visible wavelengths has to be after this date. Further ground truthing work to assess the number and variability of adults present in October/November compared to the actual breeding population present in June would aid our estimate.

#### Numbers and interpretation

Mature emperor penguins breed almost every year [27]. The proportion of the breeding population each year has been estimated at 80% of the total population [26]. Using these estimates our October breeding population estimate therefore may represent a global population of around  $595,000 \pm 81,753$  individual birds, pre-breeding, i.e. before chicks of the year have hatched. The error figure is the sum of the regression error and potential variability associated with image quality, plus SD of egg loss variability, the variability of chick mortality between hatching and image acquisition is not included as this potential error source is presently unknown. However, it must be noted that our breeding estimate stems from for only one year (2009). Inter-annual population fluctuations at individual colonies can be as high as 30%, and changes of 10% or more per year are typical [3], [26], [28]. Recent population work gives the standard deviation of breeding adults at two well documented colonies; at Pointe Géologie over a fifty year period of CV 33.2%, and Haswell Island over a similar, but less well sampled, period as CV 22.4%. This magnitude of annual change should be identified by using the methods suggested in this paper and could be used in future to detect population trends. In the past, such variability was linked to a number of factors, which have been discussed in detail elsewhere [2], [8], [27], [29]. There is some indication that these factors are not independent, but act on the population as a whole [33]. Relationships with sea-ice variability, the Southern Annular Mode and prey and predator abundance all have the potential to modulate the annual breeding population. Therefore, to disentangle global, regional, or colony population trajectories associated with climate change from other influences will require long term ecological research. Such research is now becoming urgent as regional climate change is already impacting upon areas of West Antarctica and the Antarctic Peninsula [30] and colonies in this region may already be affected by the consequent loss of sea ice [8].

#### Ecological implications

Current predictions [5], [6] suggest that trends in sea ice extent will alter in the second half of this century and that the annual average sea ice extent will diminish by 33%; most of this retreat is expected to occur in winter and spring [5], [6], with attendant risks for emperor penguins. Ainley et al [2] suggest that in the coming decades all colony sites located north of 70° South will become unviable for emperors. Ainley et al [2] equated this to approximately 40% of the world population. Our updated figures



suggest that actually 34.8% of the total population breeds north of 70° South and is vulnerable to reductions in sea ice. However, an important consideration discussed in Trathan et al [8], is that warming is currently regional, and that a simple latitudinal gradient in the loss of sea ice is unlikely. Currently the loss of sea ice has been greatest from the West Antarctic Peninsula region. However, should the ozone hole indeed recover in the middle of this century, warming in East Antarctica is predicted to increase significantly [5], [6]. The ability to monitor populations using remotely-sensed data during consecutive breeding seasons and on a regional or global basis is a cost effective use of resources, particularly in comparison with aerial survey or ground counts. Such methods will therefore lead to a greater understanding of emperor penguins' current and future continued existence in areas affected by environmental change.

Understanding the causes of penguin decline will however require additional effort. Currently some of the important ecological factors needed to understand population change are not recorded on a regular or systematic basis. For example, fast ice provides a critical habitat for emperor penguins, yet this remains difficult to distinguish from pack ice at a regional and global scale. Developing new and appropriate remote sensing indices of pertinent environmental factors is therefore important, if we are to do more than simply measure population change.

#### Expanding the methodology

Emperor penguins are suited to census by remote sensing for reasons mentioned above. Indeed, the results of this survey increase our knowledge of this species' population and distribution and provide a technique for long term monitoring. Though emperor penguins provide a particularly valuable model species, the techniques developed in this study may be applicable to a number of other animals. For example, some species of large herbivores with known migration patterns, especially those that are threatened by habitat degradation, climate change or human impact, may also benefit from the use of our methods. Many species are currently monitored by aerial survey, such methods are proportionally more expensive than satellite survey and have the potential to cause disturbance. The techniques used in this study, or similar techniques may therefore be appropriate for use with these species. The factors that make emperor penguins such a good model are useful criteria in assessing the suitability of other species for similar survey.

#### Supporting Information

##### Figure S1.

**Emperor penguin colonies 2009.** Size of circle relates to estimated number of pairs in each colony.

<https://doi.org/10.1371/journal.pone.0033751.s001>

(EPS)

#### Acknowledgments

We would like to thank Jaume Forcada for his advice on statistical modelling. Imagery for the US Analysis provided through the National Science Foundation. We would also like to acknowledge DigitalGlobe, Inc. and GeoEye, Inc. for their continued support of this work.

#### Author Contributions

Conceived and designed the experiments: PF NR GK CP AHF. Performed the experiments: PF ML CP. Analyzed the data: PF ML GK AJF. Contributed reagents/materials/analysis tools: PF ML PM CP. Wrote the paper: PF PT GK BW ML PM. Provided data: PM AHF GK BW.

#### References

1. Jenouvrier S, Caswell H, Barbraud C, Holland M, Stroeve J, et al. (2009) Demographic models and IPCC climate projections predict the decline of an emperor penguin population. *Proceedings on Natl Acad Sci U S A* 106; 1844–1847:  
[View Article](#) • [Google Scholar](#)
2. Ainley D, Russell J, Jenouvrier S, Woehler E, Lyver P, et al. (2010) Antarctic penguin response to habitat change as Earth's troposphere reaches 2°C above preindustrial levels *Ecol Monogr* 80; 49–66:  
[View Article](#) • [Google Scholar](#)
3. Barber-Meyer SM, Kooyman GL, Ponganis PJ (2008) Trends in western Ross Sea emperor penguin chick abundances and their relationship with climate *Ant Sci*, 20; 3–11:  
[View Article](#) • [Google Scholar](#)
4. Stammerjohn SE, Martinson DG, Smith RC, Yuan X, Rind D (2008) Trends in Antarctic annual sea ice retreat and advance and their relation to El Niño–Southern Oscillation and Southern Annular Mode variability. *J Geophys Res* 113, C03S90:  
[View Article](#) • [Google Scholar](#)
5. Turner J, Bindschadler RA, Convey P, Di Prisco G (2009) *Antarctic Climate Change and the Environment*. Cambridge; SCAR UK 526p:  
[View Article](#) • [Google Scholar](#)
6. Bracegirdle TJ, Connolley WM, Turner J (2008) J Antarctic climate change over the Twenty First Century *J Geophys Res* 113; D03103:  
[View Article](#) • [Google Scholar](#)
7. Forcada J, Trathan PN (2009) Penguin responses to climate change in the Southern Ocean *Glob Chaahnge Biol* 15: 1618–1630.

[View Article](#) • [Google Scholar](#)

8. Trathan PN, Fretwell PT, Stonehouse B (2011) First Recorded Loss of an Emperor Penguin Colony in the Recent Period of Antarctic Regional Warming: Implications for Other Colonies PLoS ONE 6; e14738:  
[View Article](#) • [Google Scholar](#)
9. Massom RA, Stammerjohn SE (2010) Antarctic sea ice change and variability – Physical and ecological implications Polar Science 4; 149–186:  
[View Article](#) • [Google Scholar](#)
10. Ainley D, Ballard D, Blight LK, Ackley S, Emslie SD, et al. (2010) Impacts of cetaceans on the structure of Southern Ocean food webs. Mar Mammal Sci 26(2); 482–498:  
[View Article](#) • [Google Scholar](#)
11. Woehler EJ (1993) The distribution and abundance of Antarctic and Subantarctic penguins. Cambridge; SCAR UK.
12. Wienecke B (2010) The history of the discovery of emperor penguin colonies, 1902–2004 Polar Record 46; 271–276:  
[View Article](#) • [Google Scholar](#)
13. Martinez I (1992) Emperor penguin In Handbook of the Birds of the World Vol 1, eds del Hoyo J, Eliot A, Sargatal J, Barcelona; Lynx Edicions, 155p:  
[View Article](#) • [Google Scholar](#)
14. Wienecke B (2009) Emperor penguin colonies in the Australian Antarctic Territory: how many are there? Polar Record 45; 309–312:  
[View Article](#) • [Google Scholar](#)
15. Fretwell PT, Trathan PN (2009) Penguins from space: faecal stains reveal the location of emperor penguin colonies Glob Ecol Biogeogr 18; 543–552:  
[View Article](#) • [Google Scholar](#)
16. Barber-Meyer SM, Kooyman GL, Ponganis PJ (2007) Estimating the relative abundance of emperor penguins at inaccessible colonies using satellite imagery. Polar Biology 30; 1565–1570:  
[View Article](#) • [Google Scholar](#)
17. Lea M, Soper T (2005) Discovery of the first emperor penguin *Aptenodytes forsteri* colony in Marie Byrd Land Antarctica. Marine Ornithology 33; 59–60:  
[View Article](#) • [Google Scholar](#)
18. Melick D, Bremmers W (1995) A recently discovered breeding colony of emperor penguins (*Aptenodytes forsteri*) on the Budd Coast, East Antarctica. Polar Record 31; 426–427:  
[View Article](#) • [Google Scholar](#)
19. Todd FS, Adie S, Spletstoesser JF (2004) First ground visit to the emperor penguin *Aptenodytes forsteri* colony at Snow Hill Island, Weddell Sea, Antarctica. Marine Ornithology 32; 193–194:  
[View Article](#) • [Google Scholar](#)
20. Kato A, Ichikawa H (1999) Breeding status of Adélie and emperor penguins in the Mt Riiser-Larsen area, Amundsen Bay. Polar Bioscience 12; 36–39:  
[View Article](#) • [Google Scholar](#)
21. Sanchez RD, Kooyman GL (2004) Advanced systems data for mapping emperor penguin habitats in Antarctica USGS Open-File Report 2004-1379 8p:  
[View Article](#) • [Google Scholar](#)
22. Gelman A, Hill J (2007) Data analysis using regression and multilevel/hierarchical models Cambridge; Cambridge University Press, UK.
23. Weinecke B (2011) Review of historical population information of emperor penguins. Polar Biol 34; 153–167:  
[View Article](#) • [Google Scholar](#)
24. Gilberta C, Robertson G, Maho Y, Naito Y, Ancel A (2006) Huddling behavior in emperor penguins: Dynamics of huddling. Physiology & Behavior 88; 479–488:  
[View Article](#) • [Google Scholar](#)
25. Yeats GW (1975) Microclimate, climate and breeding success in Antarctic penguins. The Biology of penguins, ed Stonehouse London, Basingstoke: B Macmillan Press 397–409 pp.
26. Barbraud C, Weimerskirch H (2001) Emperor penguins and climate change. Nature 411; 183–186:  
[View Article](#) • [Google Scholar](#)
27. Jenouvrier S, Barbraud C, Weimerskirch H (2005) Long term contrasted responses to climate of two Antarctic Seabird species. Ecology 86; 2889–2903:

[View Article](#) • [Google Scholar](#)

28. Kato A, Watanabe K, Naito Y (2004) Population changes of Adelie and emperor penguins along the Prince Olav Coast and on the Riiser-Larsen Peninsula. *Polar Bioscience* 17; 117–122:  
[View Article](#) • [Google Scholar](#)
29. Ainley DG, Clarke ED, Arrigo K, Fraser , WR , Kato A, et al. (2005) Decadal-scale changes in the climate and biota of the Pacific sector of the Southern Ocean, 1950s to the 1990s. *Ant Sci* 17; 171–182:  
[View Article](#) • [Google Scholar](#)
30. Vaughan DG, Marshall GJ, Connolley WM, Parkinson C, Mulvaney R, et al. (2003) Recent rapid climate warming on the Antarctic Peninsula. *Climate Change*, 60; 243–274:  
[View Article](#) • [Google Scholar](#)
31. Williams TD (1995) *The penguins*. Oxford: Oxford University Press.
32. Jouventin P (1975) Mortality parameters in emperor penguins *Aptenodytes forsteri*. In Stonehouse B. ed. *The biology of penguins*. London: Macmillan, 435–446:  
[View Article](#) • [Google Scholar](#)
33. Barbraud C, Gavriilo M, Mizin Y, Weimerskirch H (2011) Comparison of emperor penguin declines between Pointe Ge'ologie and Haswell Island over the past 50 years. *Ant Sci* 23;5 461–468:  
[View Article](#) • [Google Scholar](#)
34. Luna Perez JC (1963) *Visita a la roqueria de pingüines emperador de bahia austral (mar de Weddell)*, Instituto Antártico Argentino, 70: 19 pages.
35. Hempel G, Stonehouse RJ (1987) The winter expedition of research vessel 'Polarstern' to the Antarctic (ANT 5,1–3). Aerial counts of penguins seals and whales in the eastern Weddell Sea. *Berichte zur Polarforschung*, 39; 227–230:  
[View Article](#) • [Google Scholar](#)
36. Condy PR (1979) Observations on penguins in the King Haakon VII Sea, Antarctica. *South African Journal for Antarctic Research* 9: 29–32.  
[View Article](#) • [Google Scholar](#)
37. Ledenev VG (1965) New emperor penguin colony. *Soviet Antarctic Expedition Information Bulletin (English)* 3: 107–109.  
[View Article](#) • [Google Scholar](#)
38. Woehler EJ, Johnstone GW (1991) Status and conservation of seabirds of the Australian Antarctic Territory. *Seabird: status and conservation*. ICBP Technical Publication, 11; 279–308:  
[View Article](#) • [Google Scholar](#)
39. Kato A, Ichikawa H (1999) Breeding status of Adélie and emperor penguins in the Mt Riiser-Larsen area, Amundsen Bay. *Pol BioScience* 12: 36–39.  
[View Article](#) • [Google Scholar](#)
40. Horne RSC (1983) The distribution of breeding colonies on the Australian Antarctic Territory, Heard Island McDonald Island and Macquarie Island. *ANARE Research Notes* 9: 8–13.  
[View Article](#) • [Google Scholar](#)