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Large-scale occupancy surveys in East Antarctica discover new Adélie penguin breeding sites and reveal an expanding breeding distribution

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Abstract: Knowledge of spatial distribution is fundamental to ecological studies and crucial for conservation and management of species and biodiversity, but detailed, large-scale spatial data are lacking for most taxa. Although the Adélie penguin is one of the most intensively studied Antarctic vertebrates, spatial data that could aid in ecological study and conservation management are incomplete. We undertook a large-scale survey of the current breeding distribution of Adélie penguins along 3800 km of the East Antarctic coastline. The survey increased the number of known breeding locations by 50% and revealed that the breeding distribution has expanded in some parts of the survey region over the past two to three decades. The expanding breeding distribution may reflect underlying population dynamics of sustained growth and resultant density dependent effect on dispersal and movement from established breeding sites to new sites. The comprehensive, large-scale distribution data from this study will form a baseline for assessing any future changes in Adélie penguin breeding distribution, provide data for developing spatial models for predicting future changes in breeding distribution under plausible scenarios of environmental change, and contribute to the development of metapopulation models by providing estimates of local colonization and extinction probabilities under specific conditions of metapopulation change.

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Introduction

Knowledge of spatial distribution is fundamental to ecological studies (Krebs 1972) and crucial for conservation and management of species and biodiversity (Pearce & Boyce 2006). Common applications of spatial data in ecology and conservation include understanding species' realized niches and related ecological drivers and requirements, identifying important sites for protection, predicting sites at risk from alien or invasive species, predicting unknown populations, and predicting future distributional change in response to a changing environment (Manel *et al*. 2001, Peterson 2006). Despite the need for such information, detailed spatial data are lacking for most taxa, particularly at large scales (Tsoar *et al*. 2007).

The Adélie penguin (*Pygoscelis adeliae* (Hombron & Jacquinot)) is an abundant, colonial-breeding seabird with a circumpolar distribution, breeding on ice-free continental land and offshore islands around the Antarctic continent (Ainley 2002). Although the Adélie penguin is one of the most intensively studied Antarctic vertebrates, spatial data that could aid in ecological study and conservation management are incomplete. While data on Adélie penguin breeding distribution are thought to be reasonably complete for the Antarctic Peninsula in West Antarctica where most Antarctic research has been focussed, research effort along the extensive coastline of East Antarctica has been more dispersed and knowledge of breeding distribution is uncertain along large sections of this coastline (Barbraud *et al*. 1999, Southwell *et al*. 2009). Foraging and at-sea distribution data are also limited because logistical difficulties and equipment expense have restricted tracking studies, particularly during winter.

To improve the basis for ecological understanding and species' conservation management in East Antarctica, we are investigating large-scale breeding and foraging distribution for a range of Antarctic seabirds, including the Adélie penguin. In this paper we report on large-scale surveys to map the current breeding distribution of Adélie penguins along the East Antarctic coastline. Results for two small sections of this coast have been reported in Low *et al*. (2007) and Wilson *et al*. (2009). This paper extends beyond these sections to cover survey efforts along 3800 km of coastline. We also review historical observations of Adélie penguin breeding distribution and assess whether any changes in distribution have occurred in recent decades in those regions where historical observations are accurately described and overlap with our observations.

Methods

We surveyed approximately one fifth of the Antarctic coastline between 59.4 and 136.0°E (Fig. 1). The search

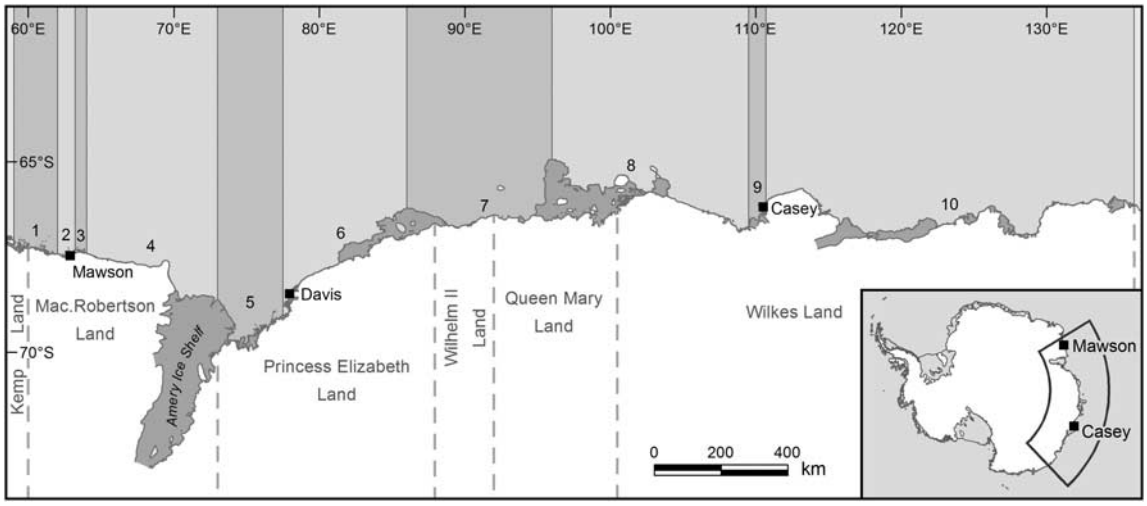

Fig. 1. Map of the survey region. Sub-regions from west to east are: 1. Stefansson Bay to Low Tongue, Kemp and Mac. Robertson Land coasts. 2. Holme Bay, Mac. Robertson Land coast. 3. Robinson Group, Mac. Robertson Land coast. 4. Austskjera to Amery Ice Shelf, Mac. Robertson Land coast. 5. Amery Ice Shelf to Ranvik Glacier, Princess Elizabeth Land coast. 6. Ranvik Glacier to West Ice Shelf, Princess Elizabeth Land coast. 7. West Ice Shelf to Shackleton Ice Shelf, Wilhelm II and Queen Mary Land coasts. 8. Shackleton Ice Shelf to ANZAC Glacier, Queen Mary and Wilkes Land coasts. 9. ANZAC Glacier to Cape Folger, Wilkes Land coast. 10. Cape Folger to Pourquoi Pas? Glacier, Wilkes Land coast. The number of breeding sites in each sub-region is shown in Table I.

effort extended along 3800 km of coastline and included islands up to 100 km north from the continental coast. We divided the survey region into 10 sub-regions to match the scale of earlier surveys and to facilitate comparison and discussion of results. To guide search effort over this large area, and to compare our observations to distribution data from previous surveys, we used the database and maps of potential Adélie penguin breeding sites developed by Southwell *et al*. (2009) for a gap analysis of previous search effort. The scale of the maps allowed an observer on the ground or in an aircraft to identify individual islands by referring to their shape, size, configuration and location. Potential breeding sites were defined as discrete ice-free islands and continental rock features with area $> 1000\,m^2$ and within 1 km of the ocean. This simple definition, which is based on two physical criteria, does not aggregate islands and rock outcrops under a biological interpretation in the way that Ainley's (2002) definition of Adélie penguin

Table I. Details of search effort and breeding sites by sub-region. Potential breeding sites were identified and mapped using a coarse-scale, qualitative model of Adélie penguin breeding habitat in a GIS and were used to guide the search effort. Occupied breeding sites are those potential sites that were observed to have breeding populations in this survey. Newly reported breeding sites are those that have not been previously reported as occupied in search effort from earlier decades (because they were either previously searched and found to be unoccupied, or not previously searched) but were occupied in these surveys. Newly established sites are those newly reported sites that have evidence of being searched in previous surveys and were not reported to be occupied, but were occupied in this survey. Abandoned sites are those that have been reported as occupied in previous surveys but were unoccupied in this survey. "-" indicates that accurate identification of newly reported, newly established or abandoned sites was not possible because the description of sites previously reported in the literature was too imprecise.

Sub-region	Longitudinal range	Time of search	Search method	Number of potential sites	Number of occupied sites	Number of newly reported sites	Number of newly established sites	Number of abandoned sites
1	59.4°E–62.0°E	Mar 2008, Nov 2008	Helicopter[c], ground	458	6[a]	2[a]	-	-
2	62.0°E–63.2°E	Nov 2005, Nov 2007	Ground	290	22	1	1	0
3	63.2°E–64.0°E	Nov 2005	Ground	94	30[b]	29[b]	-	-
4	64.0°E–73.0°E	Dec 2010	Fixed wing aircraft	2	2	0	0	0
5	73.0°E–77.5°E	Nov 2009	Helicopter[c]	422	16	-	-	-
6	77.5°E–86.0°E	Nov 2008	Helicopter[c]	775	44	7	7	0
7	86.0°E–96.0°E	Jan 2011	Fixed wing aircraft[d]	11	7	1	-	-
8	96.0°E–109.5°E	Dec 2009, Jan 2011	Fixed wing aircraft[d]	26	6	4	-	-
9	109.5°E–110.7°E	Dec 2009, Jan 2011	Fixed wing aircraft[d]	222	14	0	0	0
10	110.7°E–136.0°E	Jan 2012	Fixed wing aircraft[e]	7	6	-	-	-

[a]From Wilson *et al*. (2009), [b]From Low *et al*. (2007), [c]Squirrel AS350BA, [d]CASA 212, [e]DC3 T (Basler).

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Table II. Details of breeding sites that have not been reported in search effort from earlier decades.

Sub-region	Latitude	Longitude	Name
1	*	*	*
2	67.59945	62.48048	Un-named island
3	**	**	**
4	No newly reported sites		
5	-	-	-
6	68.76703	77.75058	Un-named island
	68.90116	77.73602	Un-named island
	68.44018	78.20990	Un-named island
	68.60779	77.85683	Un-named island
	68.61500	77.86149	Un-named island
	68.65759	77.85620	Un-named island
	68.66403	77.85415	Un-named island
7	66.54590	92.54855	Adams Island
8	66.45877	107.15648	Merritt Island
	66.63523	108.21270	Cape Nutt
	66.82996	108.64329	Mallory Point
	66.88028	109.12756	Ivanoff Head
9	No unreported sites		
10	-	-	-

*Two newly reported sites described in Wilson *et al*. (2009).
**29 newly reported sites described in Low *et al*. (2007).
- = identification of newly reported sites not possible because description of previously reported sites was too imprecise.

colonies does, where breeding populations at closely adjacent islands (potential breeding sites) may be considered a single colony. The database and maps covered 2307 potential breeding sites in the survey region. All but four of the sites were searched over seven summer seasons from 2005/06–2011/12. The four unsearched sites were located off the Kemp Land coast at the extreme western end of the survey region (Wilson *et al*. 2009). Observers searched from the air or the ground according to available logistical support and at a time of year when penguins were present at their breeding sites (Table I). Aerial surveys were conducted from helicopters (Squirrel AS350BA) and fixed wing aircraft (CASA 212 and DC3 T Basler) at 750 m altitude and observations were made directly by eye or from photographs.

Results and discussion

We found Adélie penguins breeding at 149 of the 2303 potential sites that were searched along the 3800 km length of coastline. Two large areas of discrete continental rock (Long Peninsula in Vestfold Hills and Clark Peninsula in the Windmill Islands) have breeding populations that have previously been considered as six colonies because they are separated from each other by a distance of several kilometres (Rookery Lake, Albino Rookery, Organic Lake and Northern Rookery (unofficial name) at Long Peninsula (Whitehead & Johnstone 1990), and Whitney Point and Blakeney Point at Clark Peninsula (Woehler *et al*. 1989b)). In keeping with this reporting convention, we present them here as six separate breeding sites even though they occurred on only two rock features, hence the total number of breeding sites in Table I is 153. Forty-four of the 153 breeding sites have not been reported in publications of previous search efforts from earlier decades. The locations of 31 of these 44 newly reported sites were identified in recent publications by Low *et al*. (2007) and Wilson *et al*. (2009), which presented initial results from restricted sections of the larger search effort. Locations of an additional 13 newly reported sites are presented in Table II.

The documentation of search effort in previous surveys from earlier decades was complete and precise enough to assess change in breeding distribution for four of the ten sub-regions (Table I). Breeding distributions at Holme Bay and between the Ranvik Glacier and the West Ice Shelf (sub-regions 2 and 6, Fig. 1) have expanded from 58 to 66 breeding sites (eight newly established sites, no abandoned sites, Table I) since they were last surveyed by Woehler *et al*. (1989a) and Whitehead & Johnstone (1990) respectively in the early 1980s. In contrast, breeding distributions between Austskjera and the Amery Ice Shelf (sub-region 4), documented in Alonso *et al*. (1987) and Falla (1937), and between the ANZAC Glacier and Cape Folger (sub-region 9), reported in Orton (1963) and Woehler *et al*. (1991), are identical to our survey and indicate no change in the number (16) or location of breeding sites over the past several decades (Table I).

In reviewing the circumpolar breeding distribution of Adélie penguins, Ainley (2002) considered most breeding populations were likely to be known and any undiscovered populations were likely to be small. A recent gap analysis of Adélie penguin breeding distribution in the Australian Antarctic Territory (AAT) in East Antarctica concluded that half of potential Adélie penguin breeding habitat in the AAT remained unsearched or unreported (Southwell *et al*. 2009), raising the possibility that a significant number of breeding locations, and therefore significant breeding populations, remained undetected or unreported in this region. Prior to our surveys, around 100 breeding sites had been collectively reported in the survey region through numerous separate survey efforts (Falla 1937, Law 1958, 1962, Orton 1963, Pryor 1968, Horne 1983, Alonso *et al*. 1987, Woehler *et al*. 1989a, 1989b, Whitehead & Johnstone 1990, Robertson 1991, Woehler *et al*. 1991, Melick *et al*. 1995). Our surveys increase the number of known sites by *c*. 50% and consequently raise the possibility that estimates of the breeding population may be significantly under-estimated. It is possible that many breeding sites remain undiscovered in other poorly surveyed regions of East Antarctica such as Enderby, Wilkes and George V lands (Woehler 1993, Barbraud *et al*. 1999, Southwell *et al*. 2009). These regions should be a priority for any future survey work.

Some of the newly reported breeding sites are likely to have been occupied for at least the past several decades but remained unreported because the region had not been

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searched or observations had not been published. This is certainly true for many of the 29 newly reported sites in the Robinson Group of islands (sub-region 3), because rough, unpublished maps of a portion of the region drawn by ANARE personnel in 1972/73 show a similar distribution to the present (K. Kerry, unpublished data). It is also possible that some of the newly reported breeding sites were overlooked in previous survey efforts, as incomplete detection is known to be a common problem in occupancy studies (MacKenzie *et al*. 2003). Although breeding Adélie penguins are relatively conspicuous when colonies are large, incomplete detection could have been an issue when assessing occupancy at sites from the air when populations were small. It was not possible to undertake multiple, independent searches of each potential breeding site in our surveys or previous surveys to increase detection probability as recommended by MacKenzie & Royle (2005) because of the remoteness of the region and logistical expense. However, newly reported breeding sites occurred in some regions that had been described as thoroughly searched and where the search effort was well documented and illustrated with detailed maps, and we conclude that these newly reported sites are very likely to have been colonized in the three decades since previous surveys. We did not find any previously known breeding sites to have since been abandoned, so overall the breeding distribution of Adélie penguins has expanded in these regions over the past three decades.

Although the number of newly established colonies discovered in this survey is relatively small, our finding of an expanding breeding distribution may reflect underlying population dynamics of sustained population growth and resultant density dependent effect on dispersal and movement from established breeding sites to new sites. Adélie penguin population increases over recent decades have been reported at some sites elsewhere in East Antarctica (Woehler *et al*. 1991, Jenouvrier *et al*. 2006, Kato & Ropert-Coudert 2006). Our results suggest that population growth could be more widespread than is currently accepted.

The impact of environmental change on species' distributions is expected to be a major conservation issue in the future and there is an urgency to establish adequate baselines for detecting change. Because Adélie penguins have a broad geographic breeding distribution (Ainley 2002) and physical and environmental change is occurring differentially around Antarctica (Massom & Stammerjohn 2010), future change in Adélie penguin breeding distribution is likely to vary regionally. Ainley *et al*. (2010) predicted that the number of Adélie penguin breeding colonies north of 70°S may decline by 75% when the earth's troposphere reaches 2°C above pre-industrial levels, but that breeding distribution might expand south of 73°S where concentrated pack ice diverges or disintegrating ice shelves expose coastline. The comprehensive, large-scale distribution data from this study provides a baseline against which future changes in Adélie penguin breeding distribution in the East Antarctic region can be compared, and also provides a basis for evaluating the utility of satellite technology for more cost-effective monitoring of broad-scale distribution in the future (e.g. Fretwell & Trathan (2009) for emperor penguins). The data will also provide a sound basis for developing or improving regional spatial models for predicting future changes in breeding distribution under plausible scenarios of environmental change, and contribute to the development of metapopulation models by providing data to estimate local colonization and extinction probabilities under specific conditions of metapopulation change.

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