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RESEARCH PAPER

Penguins from space: faecal stains reveal the location of emperor penguin colonies

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ABSTRACT

Aim To map and assess the breeding distribution of emperor penguins (*Aptenodytes forsteri*) using remote sensing.

Location Pan-Antarctic.

Methods Using Landsat ETM satellite images downloaded from the Landsat Image Mosaic of Antarctica (LIMA), we detect faecal staining of ice by emperor penguins associated with their colony locations. Emperor penguins breed on sea ice, and their colonies exist *in situ* between May and December each year. Faecal staining at these colony locations shows on Landsat imagery as brown patches, the only staining of this colour on sea ice. This staining can therefore be used as an analogue for colony locations. The whole continental coastline has been analysed, and each possible signal has been identified visually and checked by spectral analysis. In areas where LIMA data are unsuitable, freely available Landsat imagery has been supplemented.

Results We have identified colony locations of emperor penguins at a total of 38 sites. Of these, 10 are new locations, and six previously known colony locations have been repositioned (by over 10 km) due to poor geographical information in old records. Six colony locations, all from old or unconfirmed records, were not found or have disappeared.

Main conclusions We present a new pan-Antarctic species distribution of emperor penguins mapped from space. In one synoptic survey we locate extant emperor penguin colonies, a species previously poorly mapped due to its unique breeding habits, and provide a vital geographical resource for future studies of an iconic species believed to be vulnerable to future climate change.

Keywords
Antarctica, *Aptenodytes forsteri*, climate change, distribution, emperor penguins, penguin distribution, remote sensing, satellite imagery.

INTRODUCTION

Detailed information on the location of emperor penguin (*Aptenodytes forsteri*) colonies is the first prerequisite for understanding total breeding population size and population trajectory. As several recent studies (Barbraud & Weimerskirch, 2001; Jenouvrier *et al*., 2005; Barber-Meyer *et al*., 2008; Jenouvrier *et al*., 2009) have highlighted, the susceptibility of emperor penguins to changes in sea ice distribution suggests that climate change is likely to impact on their breeding success and colony viability. An accurate assessment of the total population is therefore essential in order to assess the vulnerability of the species to future climate change. Our knowledge of the location and status of breeding colonies is limited, and these concerns have led to the suggestion that the species be reclassified by the IUCN from 'of least concern' to 'data deficient' (Wienecke, 2009).

Emperor penguins breed in Antarctica almost exclusively on sea ice. This causes logistical problems in accessing breeding locations. In most cases, the sea ice on which they breed breaks up in the summer months after the young have fledged (Williams, 1995). Therefore, manual counts must be carried out

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in the late winter or early spring when access is very difficult. As a result, only a very few of the known colonies are monitored on an annual basis. Locating new emperor penguin colonies has also proved to be difficult; their colonies on sea ice are invisible from sea level unless the observer is within a few kilometres (due to the curvature of the earth), and as sea ice is universal around the coast of Antarctica, the search cannot be limited to the few rocky outcrops on the coast that other seabird species frequent.

Previous syntheses of colony locations and numbers are limited. In 1993, Woehler (1993), expanding upon a previous syntheses (Wilson, 1983), gave a total of 36 breeding colonies and estimated a minimum total breeding population of 195,400 pairs, although he considered that reliable data were only available to support estimates of around 153,000 pairs. Many of these counts were from old records (pre-1970) and it is uncertain whether all colonies still exist, or whether their locations were reliably recorded. This uncertainty has been highlighted in a recent report (Wienecke, in press) of colonies in the Australian Antarctic Territory, where several sightings used in population estimates by Wilson and Woehler have been questioned. Four new colonies (Melick & Bremmers, 1995; Todd *et al.*, 2004; Lea & Soper, 2005) have been recorded since 1993, giving a total of 32 confirmed breeding sites and 15 unconfirmed.

This study detects the precise location of emperor penguin colonies in Antarctica by identifying the faecal stains produced on the sea ice by birds at each colony and visible on satellite remote sensing imagery. Sea ice, unlike glacial ice or ice shelves, forms from frozen seawater and is therefore uniform and free from impurities. The spectral reflectance of sea ice is always pure white or, in shadow or melt-pool areas, slightly blue. The only exception to this is where faeces from large groups of penguins stain the surrounding area light brown. This staining is visible from Landsat ETM imagery downloaded from the Landsat Image Mosaic of Antarctica (LIMA), a new pan-Antarctic resource published in 2007 (Bindschadler *et al.*, 2008; http://lima.usgs.gov/). Satellite imagery and remote sensing techniques have been used before to assess colony size (Barber-Meyer *et al.*, 2007) but until now no studies have used satellite imagery to locate the positions of both known and previously undetected penguin colonies around all of the Antarctic continent. This paper details the first synoptic pan-Antarctic assessment of the colony distribution of emperor penguins by satellite imagery.

MATERIALS AND METHODS

We identified faecal stains from emperor penguin colonies visually using Landsat ETM imagery, confirmed them by spectral analysis and, where possible double-checked them using additional imagery. In the spectral analysis, raw data from Landsat imagery downloaded from the LIMA website was used. Visible blue light from Landsat imagery (band 1) was subtracted from visible red light (band 3). Any values left above zero on sea ice are either single noise pixels or emperor colonies. The only exception to this are unidentified rocky islets which have much darker signals with sharp edges, as opposed to the penguin colonies that have lighter signals with soft edges.

Figure 1 shows three examples of the dataset used in the location of the colony near the UK Halley Research Station, Brunt Ice Shelf, Coats Land. Figure 1(a) shows the data viewed online from the LIMA mosaic (note that the online view has poor colour balance). Figure 1(b) shows data downloaded from the LIMA website and viewed in GIS software. Using these data, the brown faecal staining of the colony is clearly visible. Figure 1(c) shows spectral analysis identifying areas where the red band has a higher value than the blue band; the resulting positive area is shown in red. It can be seen that both the downloaded imagery and the spectral analysis clearly delineate a colony that was subsequently identified as the Windy Creek emperor colony by overwintering personnel from the UK Halley Research Station.

The imagery from LIMA has a resolution of 15 m (a composite of 28.5 m colour imagery enhanced with 15 m panchromatic bands) and the underlying Landsat imagery has colour resolution of 28.5 m. This is sufficiently detailed to show all but the smallest (< 50 m wide) or highly fragmented colonies. The LIMA is a seamless, cloud-free mosaic of Landsat ETM scenes all acquired between 1999 and 2004, and covers the whole of the

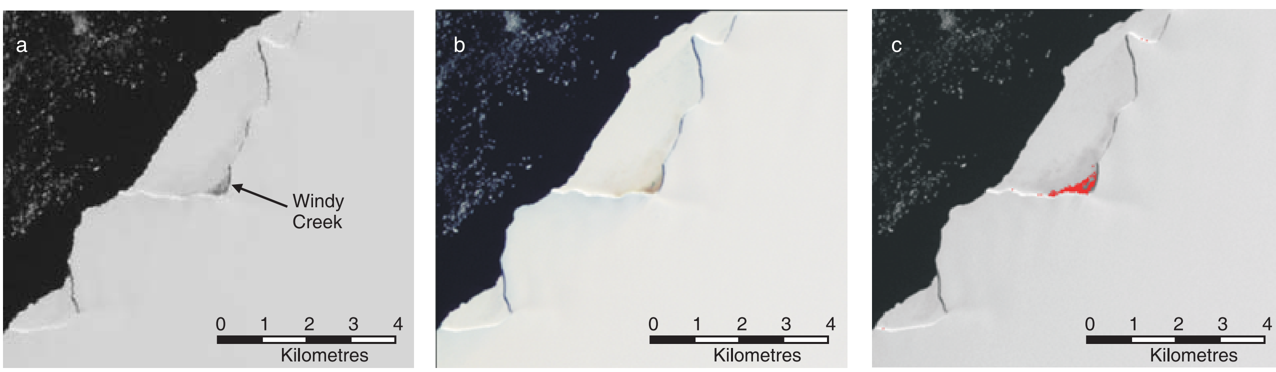

Figure 1 Comparison of data types: (a) screenshot of online Landsat Image Mosaic of Antarctica (LIMA); (b) Landsat ETM tile, downloaded from the LIMA website – note brown staining at the colony location; (c) spectral analysis red minus blue band, positive values shown in red, picking out the exact area of the colony.

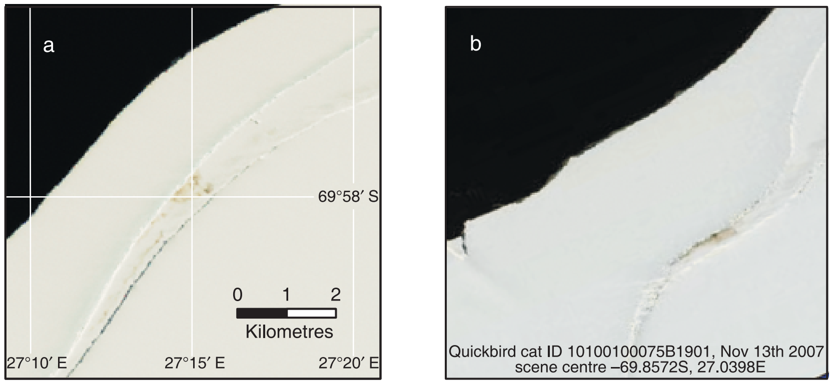

Figure 2 Comparison of data types: (a) Landsat Image Mosaic of Antarctica (LIMA) imagery of a newly found colony on Princess Ragnhild Coast; (b) screenshot of the corresponding area from the online 'quick-look' of imagery from the Quickbird satellite.

continent (details of compilation and mosaicking are available in Bindschadler *et al.*, 2008). LIMA imagery was viewed around the coastline of the whole continent to find possible signals of emperor penguins; where possible signals occur individual Landsat scenes from the mosaic were downloaded and the raw data used to confirm possible colony locations.

A disadvantage of this dataset is that imagery was acquired at different times of the year. The breeding colonies of emperor penguins are highly seasonal, and their size, shape and existence vary in different months. Colonies begin to form in the austral autumn so that incubation occurs over the austral winter (Williams, 1995) after the formation of sea ice. Chicks hatch in spring and usually fledge in December. The colonies generally disperse in late December or January as the sea ice breaks up and melts, although the exact timing is dependent upon latitude and local weather and sea ice conditions. In some cases, colonies are located upon semi-permanent fast ice that remains all year (often retaining some faecal signal), but in others the sea ice upon which the colony is situated breaks up in mid to late summer leaving no evidence of the penguins' previous presence. Therefore some of the images in the LIMA mosaic are unsuitable for the purpose of colony identification. Furthermore, it should also be noted that the location and timing of moulting in juvenile emperor penguins and subadult and non-breeding birds is as yet poorly understood. Consequently, groups of moulting birds could appear at locations and during time periods outside those used by breeding birds. Colonies that exist on land are also not distinguishable on satellite images. Two known colonies are located on land (Dion Islands and Taylor Glacier), and if other unknown colonies also exist on land this methodology will not identify them.

Only limited information is available on the acquisition dates of the underlying Landsat scenes that make up the LIMA, and so a quantitative assessment of the percentage of the continental coastline covered by suitable LIMA imagery is difficult. Best estimates from the LIMA website and from ice conditions around the coastline suggest that approximately 70–80% of LIMA imagery is suitable for colony detection. With this in mind, approximately 30 different Landsat scenes additional to LIMA and several ASTER satellite images (with similar band combinations to Landsat) have been examined where the LIMA is not suitable. These extra images are either from the archives of British Antarctic Survey or have been downloaded from the USGS website at http://glovis.usgs.gov/, and account for over 10% of the Antarctic coastline. Another resource used were the freely downloadable 'quick-looks' from the Quickbird sensor (http://www.digitalglobe.com/). Although these quick-looks are of poorer resolution than Landsat, they give an indication of possible colony sites in areas where the LIMA mosaic is unsuitable and so have helped to find new colony locations even in areas where other imagery is too late in the season. Figure 2 shows a comparison of Landsat and Quickbird quick-look imagery of a newly discovered colony on the Princess Ragnhild Coast. This Quickbird imagery has been checked over an area of *c.* 5% of the continent's coastline. We estimate that using imagery from LIMA Landsats, Landsats from USGS and Quickbird quick-looks, a total of around 85–95% of the coastline of Antarctica has been surveyed with suitable satellite imagery. Where new colonies have been found, extra imagery has been acquired from the above sources to double-check the existence of the colony signal (see Table 1).

Although some estimation of colony size can be made, the mobility and variable nature of the spatial extent of colonies throughout the year means that the imagery is not suitable for making an accurate assessment of the numbers of birds at each site. Hence, this study concentrates on the number and location of colonies; other techniques are necessary to provide accurate counts within these colonies. It should be noted that some of the new colonies found in this study that have been located from imagery acquired after November and need to be checked to ensure that they are breeding areas and not moulting sites only.

RESULTS

We have located 10 entirely new sites that we consider (given the timing of the images and the strength of the corresponding faecal staining) are most likely to be the sites of breeding colonies. We have also relocated or corrected the positions for six other breeding sites and have confirmed the positions of 17 previously known breeding sites. Five further known sites with recent counts or reports are thought to be still extant, but were not found on the imagery due to the late season of the corresponding

Table 1 Details of previously confirmed breeding colonies, previous unconfirmed colony sightings and new colonies found in this study. NA, not applicable; ALE, Antarctic Logistics and Expeditions.

Location	Reference	Date discovered	Breeding status	Found in imagery	Image type	Landsat image date (day/month/year)	New longitude	New latitude	Notes
Previously confirmed breeding colonies									
Amundsen Bay	Kato & Ichikawa (1999)	1999	Confirmed	Yes	LIMA	26/11/2002	50.81500	–66.76700	New signal found on lake 10 km south of previous report, needs confirmation
Cape Crozier	Wilson (1983)	1983	Confirmed	No	NA	25/12/1999			No, numbers too small
Sanae	Woehler (1993)	1979	Confirmed	Yes	Landsat	No date on image	–1.37569	–70.05065	Relocated 47 km, weak signal – small colony needs confirmation
Beaufort Island	Wilson (1983)	1983	Confirmed	Yes	Landsat	27/12/2001	166.951	–76.933	Not on LIMA but strong signal on downloaded Landsat
Umbeashi Rock	Wienecke (2009)	1990	Confirmed	No	NA	22/11/2002			No colony found – too small
Fold Island	Wienecke (2009)	1985	Confirmed	No	NA	02/10/2001			No, image too late – or colony too small
Pointe Géologie	Wilson (1983)	1987	Confirmed	Yes	Landsat	26/11/2002	140.01487	–66.66645	Medium sized colony amongst islands
Taylor Glacier	Wienecke (2009)	1988	Confirmed	No	NA	10/02/2001			Image too late – nest on rocky island, detection unlikely
Stancomb Wills	Hempel & Stonehouse (1987)	1986	Confirmed	Yes	ASTER	04/01/2001	–23.02404	–74.15627	Found on ASTER only, much smaller colony
Cape Roget	Wilson (1983)	1983	Confirmed	Yes	Landsat	04/12/2002	170.55849	–71.97863	Strong signal
Kloa Point	Wienecke (2009)	1985	Confirmed	Yes	Landsat	02/10/2001	57.29533	–66.64187	Weak signal from late season image
Franklin Island	Wilson (1983)	1983	Confirmed	Yes	Landsat	19/12/2008	168.40	–76.18	Not covered by LIMA, but visible on downloaded Landsat and Quickbird quick-looks
Cape Darnley	Wilson (1983)	1961	Confirmed	Yes	Landsat	28/11/2002	69.70371	–67.88468	Yes medium colony
Riiser Larsen	Hempel & Stonehouse (1987)	1986	Confirmed	Yes	Landsat	19/12/2001	–15.131	–72.136	Not on LIMA Landsat, but clearly visible site identified 65 km east on freely downloaded Landsat
Drescher Inlet	Hempel & Stonehouse (1987)	1986	Confirmed	Yes	Landsat		–19.11876	–72.86421	Small signal, no date on imagery, needs confirmation
Riiser Larsen Peninsula	Wilson (1983)	1990	Confirmed	Yes	Landsat	15/11/2001	34.39143	–68.78253	Medium colony relocated 12 km
Gould Bay	Wilson (1983)	1952	Confirmed	Yes	Landsat	06/01/2000	–47.31769	–77.74430	Relocated 39 km, confirmed by ALE
Atka Bay	Hempel & Stonehouse (1987)	1986	Confirmed	Yes	LIMA		–8.13224	–70.62046	Strong signal, relocated 35 km
Amanda Bay	Wienecke (2009)	1987	Confirmed	Yes	Landsat	18/01/2001	76.83300	–69.26800	Not on LIMA, but located on free Landsat
Auster	Wienecke (2009)	1988	Confirmed	No	NA	20/01/2001			Image too late
Dawson Lambton	Hempel & Stonehouse (1987)	1986	Confirmed	Yes	LIMA	06/01/2000	–26.55824	–76.00584	Fragment of former colony on edge of Brunt Ice Shelf
Halley Bay	Wilson (1983)	1987	Confirmed	Yes	Landsat	06/01/2000	–27.20005	–75.52470	Strong signal
Haswell Island	Wienecke (2009)	1970	Confirmed	Yes	Quickbird	06/12/2002	93.01116	–66.53096	Very weak signal, better signal from Quickbird quick-looks
Cape Washington	Wilson (1983)	1986	Confirmed	Yes	Landsat	04/12/2002	165.37983	–74.64530	Strong signal

Table 1 *Continued*

Location	Reference	Date discovered	Breeding status	Found in imagery	Image type	Landsat image date (day/month/year)	New longitude	New latitude	Notes
Coulman Island	Wilson (1983)	1983	Confirmed	Yes	Landsat	04/12/2002	169.63851	−73.33625	Large if dispersed signal
Edward VII Peninsula	Lea & Soper (2005)	2005	Confirmed	Yes	LIMA	15/11/2001	−157.73661	−77.12781	Confirmation of previous, large colony found on images
Peterson Bank	Melick & Bremmers (1995)	1995	Confirmed	No	NA	29/11/2001			Several suitable images studied – no sign of recent colony
Thurston Glacier	Lea & Soper (2005)	2004	Confirmed	Yes	Landsat	17/12/1999	−125.69563	−73.41285	Two small signals, confirming recent find
Snow Hill Island	Todd *et al.* (2004)	2004	Confirmed	Yes	ASTER	08/01/2001	−57.46007	−64.52332	Not found on LIMA, but found on corresponding ASTER imagery
West Ice Shelf	Wienecke (2009)	1997	Confirmed	No	Landsat	18/01/2001			LIMA image late, not found on free Landsat or Quickbird quick-looks
Bowman Island	Wienecke (2009)	1960	Confirmed	No	NA	06/02/2000			No colony found, old record, late imagery, therefore may still exist
Lazarev Sea	Woehler (1993)	Not given	Confirmed	No	NA	18/11/2002			Original colony never found; new colony 107 km E this study
Previously abandoned or unconfirmed breeding colonies									
Inaccessible Island	Wilson (1983)	1973	Non-breeding site	No	NA	25/12/1999			Colony no longer extant in record
Dion Islands	Wilson (1983)	1978	Abandoned	No	NA				Colony no longer extant in recent aerial photography
Jason Peninsula	Larsen (1893) in Todd *et al.* (2004)	1893	Unconfirmed	No	NA	22/11/2001			Colony thought to have relocated to Snow Hill Island
Norsel Bay	Woehler (1993)	Not given	Unconfirmed	No	NA				Not found – breeding colony never confirmed
Ongul Island	Wilson (1983)	Not given	Unconfirmed	No	Landsat	24/01/2001			Possible signal amongst rocks very weak, could be erroneous
Casey Bay	Wienecke (2009)	1961	Unconfirmed	No	NA	12/01/2002			No colony found, no recent reports
Ninnis Glacier	Wienecke (2009)	1959	Unconfirmed	No	Landsat	12/02/2002			Not found but new colony at Merzt Glacier
Yule Bay	Woehler (1993)	1982	Unconfirmed	No	NA	01/01/2003			No clear signal, no estimate of colony numbers in record, possibly a moulting site
Wilson Hills	Wienecke (2009)	1959	Unconfirmed	No	NA	12/01/2002			Several birds sighted, colony not found, could be from Davies Bay colony found in this study
Sandefjord Bay	Wienecke (2009)	1968	Unconfirmed	No	Landsat	06/01/2003	73.72085	−69.73158	Possible very weak signal, if so very small, not visible on three other images, needs confirmation
Karelin Bay	Wienecke (2009)	1958	Unconfirmed	No	NA	19/01/2003			Not found, old record of small colony, not found
Gaussberg	Wienecke (2009)	1960	Unconfirmed	No	NA	18/11/2002			Not found, LIMA over-exposed, but no sign on Quickbird quick-looks
Lazarev Ice Shelf	Wilson (1983)	Not given	Unconfirmed	No	NA	19/11/2001			No, dubious location, possibly Lazarev Sea colony
Shackleton Ice Shelf	Wienecke (2009)	1960	Unconfirmed	No	NA	17/12/2002			No colony found, old record

Table 1 *Continued*

Location	Reference	Date discovered	Breeding status	Found in imagery	Image type	Landsat image date (day/month/year)	New longitude	New latitude	Notes
Pingvin Island	Wienecke (2009)	1960	Unconfirmed	No	NA				No, thought to be spurious island, more recent sightings not found
New sites									
Luitpold Coast	This study	2009	New	Yes	Landsat	04/12/2002	−33.65229	−77.26934	Two medium sized groups, confirmed by ALE visit
Smith Peninsula	This study	2009	New	Yes	Landsat	Date not available	−60.84934	−74.37611	Medium sized colony, also on Quickbird quick-looks
Smyley Island	This study	2009	New	Yes	Landsat	19/11/2002	−78.84305	−72.30711	Two medium sized colonies
Bear Peninsula	This study	2009	New	Yes	Landsat	16/01/2001	−110.17133	−74.37410	On Landsat, but not on LIMA, also on Quickbird quick-looks
Ledda Bay	This study	2009	New	Yes	Landsat	15/12/1999	−131.56803	−74.36452	Small colony, needs confirmation
Mertz Glacier Tongue	This study	2009	New	Yes	Landsat	21/11/2002	146.45134	−66.92560	Large colony, may have relocated from Ninnis Glacier
Ragnhild Coast	This study	2009	New	Yes	Landsat	27/11/2001	27.24713	−69.96615	Strong signal in ice creek (see Figure 2)
Princess Astrid Coast	This study	2009	New	Yes	Landsat	18/11/2002	8.30705	−69.93813	Strong signal in ice creek, not yet confirmed
Noville Peninsula	This study	2009	New	Yes	Quickbird	23/12/2008	−98.45400	−71.76700	Found using Quickbird quick-looks confirmed with free Landsat
Davies Bay	This study	2009	New	Yes	Landsat	12/01/2002	158.40966	−69.32825	LIMA signal small, image late, needs confirmation

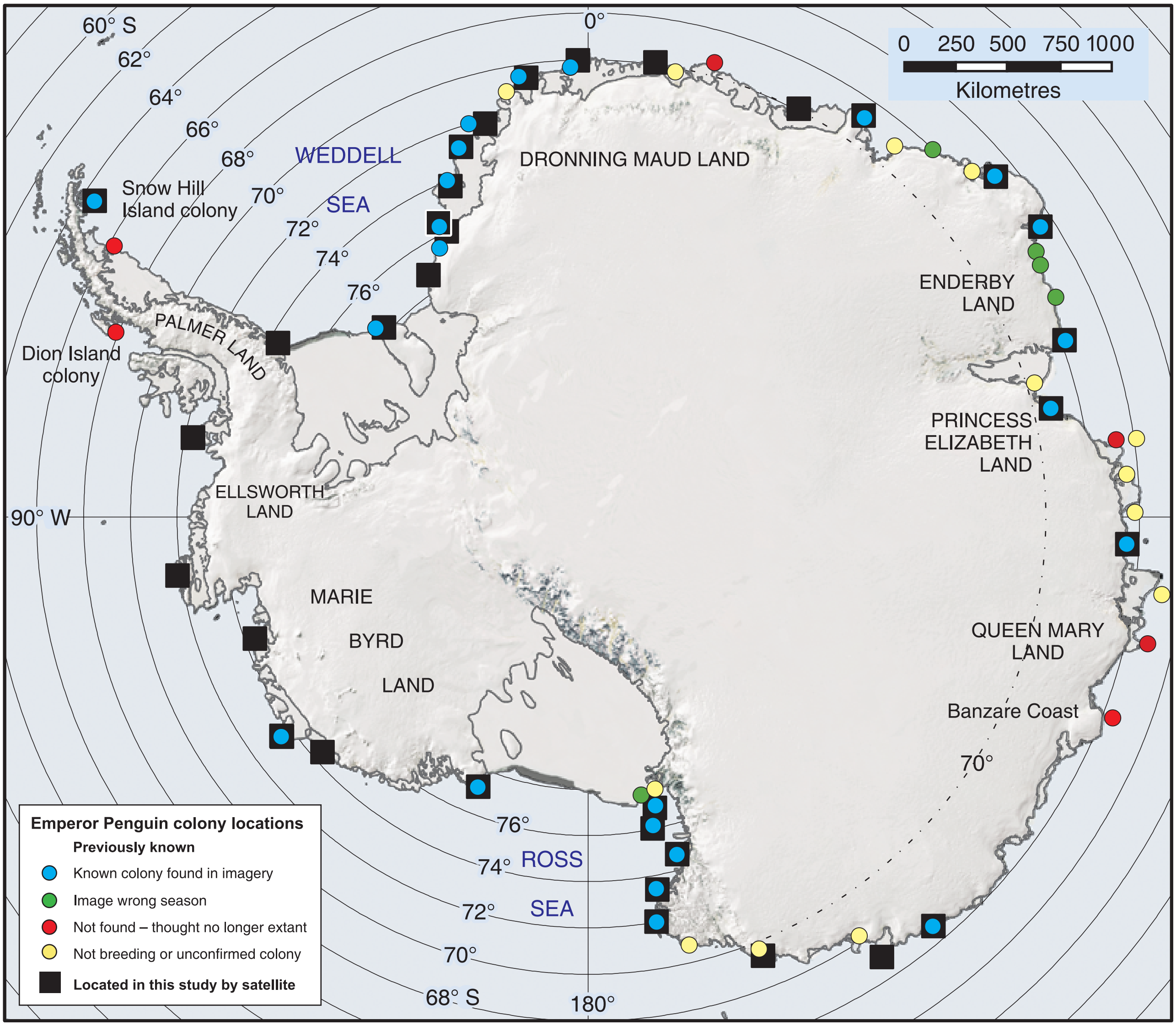

Figure 3 Distribution of emperor penguins found in this study versus previously recorded breeding sites. Black squares show locations found in this study. Other coloured dots relate to previously known sites: blue are those that have been located by satellite in the correct position, green dots are those that have not been identified due to the imagery being too late in the season; yellow dots are records of sightings but no breeding colony; red dots are those colonies that have not been found and are believed to no longer be extant.

images or the colony being too small to be visible. The remaining six confirmed records (all of which are either small colonies or from old reports) must be considered to be either no longer extant or located incorrectly. This brings the total number of know colonies though to be extant in this study to 38. The 10 new colonies therefore represent 26% of the total number of emperor penguin breeding sites. Figure 3 shows the new distribution of breeding colonies in Antarctica. Details of each colony are given in Table 1.

DISCUSSION

The verification of potentially new, relocated and existing emperor penguin colonies identified in this study has been performed in a number of ways. Although published coordinates for existing colonies are sometimes inexact or out of date, detailed locations of known colonies can often be found in published research papers or research station reports. In many cases the signals derived from satellites match to within a few hundred metres of recently published coordinates of known colonies. However, some colony locations will vary from year to year depending upon weather and local sea ice conditions. Of the known breeding colonies that were not identified in satellite imagery, only four of the regularly visited colonies were not found: Auster, Fold Island, Taylor Glacier and Cape Crozier colonies. Of these, Auster and Fold Island had imagery from too late in the season, the Taylor Glacier colony is located on rock and the Cape Crozier colony has fewer than 100 pairs and so is probably too small to be identified by this method. The fact that

23 other known breeding sites have been located by satellite imagery provides confidence in the methodology, and confidence that environmental factors such as blowing snow, rain or wind do not render the faecal stains unidentifiable.

New colonies have been double-checked by examining additional remote sensing data, either freely available Landsat imagery from other years or Quickbird 'quick-looks'; Table 1 displays secondary sources. However, it is recommended that further investigation is needed for each new colony in order to assess size and permanence. It is believed that some undiscovered colonies may still remain in the few areas where satellite image data are currently unsuitable. One new and one of the relocated colonies in this study have been visited; one new colony identified on the Luitpold Coast (33.6522° W, 77.2693° S), and one relocated colony on the Ronne Ice Shelf, were visited in 2007 by Antarctic Logistics and Expeditions and the location confirmed to within 500 m of the new locations shown on the LIMA mosaic (David Roots, personal communications).

Woehler (1993) suggested that colonies exist in three main areas: Weddell Sea to Dronning Maud Land, Enderby and Princess Elizabeth Land, and the Ross Sea. We suggest that the distribution is far wider, with new colonies found in Marie Byrd Land, Palmer Land and Ellsworth Land. The overall distribution of colonies is much more even around the coast of the continent. The only unfavourable habitat is where the coast consists of precipitous, continuously calving ice shelves (e.g. the Banzare Coast area).

This new pan-continental dataset of colony locations gives, for the first time, the chance to assess an accurate emperor penguin breeding distribution against environmental factors such as latitude and temperature. Several studies have asserted that there is a link between emperor penguin breeding success and sea ice conditions (Barbraud & Weimerskirch, 2001; Jenouvrier *et al.*, 2005, 2009; Barber-Meyer *et al.*, 2008). Predictions that sea ice conditions in Antarctica will change with climate change, suggest that some breeding colonies are at risk. A recent study by Ainley *et al.* (2007) (http://assets.panda.org/downloads/wwf_climate_penguins_final_1.pdf) has shown colonies north of 70° S may be unviable with a global temperature increase of 2 °C due to climate change. Figure 4 displays the latitudinal distribution of emperor penguin colonies from the current study. Sixteen breeding colonies (42%) are located north of 70° S and consequently would be classed as vulnerable under the assessment of Ainley *et al.* (2007).

Though emperor penguins are potentially vulnerable to the effects of climate change, either directly through the loss of sea ice breeding habitat or indirectly through consequential changes to the food web upon which they rely, it is currently not feasible to make an assessment of the total population trajectory.

Some colonies appear to be more vulnerable than others, particularly those in more northerly latitudes. The colonies at Snow Hill Island (64°25′ S, 57°15′ W) and on the Dion Islands (67°52′ S, 68°43′ W) are potentially the most vulnerable, being located in an area where rapid regional warming is known to be happening (Vaughan *et al.*, 2003). However, these colonies are very rarely visited and historical estimates of the breeding population are questionable. Suggestions that the Snow Hill colony

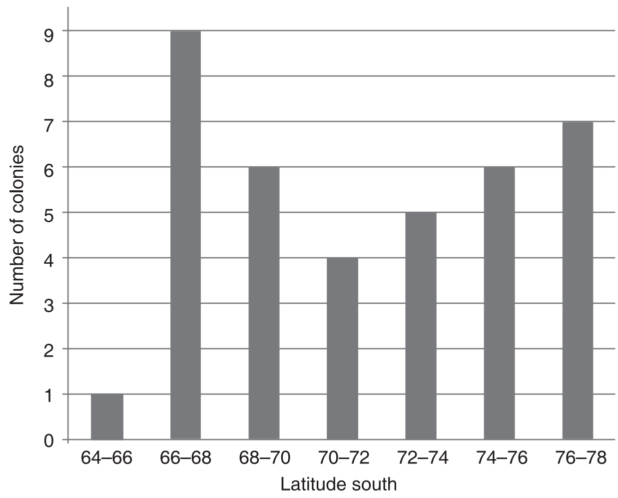

Figure 4 Distribution of emperor penguin colonies by latitude. Ainley *et al.* (2007) state that colonies north of 70° latitude will be at risk if global temperatures rise by 2 °C, equating to 16 colonies in this study.

has relocated from a previous location near Jason Peninsula (Todd *et al.*, 2004) before the break-up of the Larsen B ice shelf remain plausible, but need further confirmation. Aerial photography of the Dion Island site from 1998 and 2005 suggests that the colony has only a few birds (< 20) remaining and it was therefore classed as no longer extant for the purposes of this study. However, long-lived birds such as emperor penguins occasionally suffer poor breeding seasons. Long-term studies (in association with reliable environmental information) are therefore the only means to establish whether population trajectories are actually related to regional climate change.

In Fig. 5 we plot the locations of extant colonies and those no longer extant or abandoned onto a mean annual temperature grid of Antarctica (European Centre for Medium Range Weather Forecast, 2007; http://www.ecmwf.int/). Two of the lost colonies are on the Antarctic Peninsula, one in Dronning Maud Land and three in the Australian Antarctic Territory. The group of three lost colonies between Princess Elizabeth Land and Queen Mary Land are in an area where the mean temperature is close to that of the northern Antarctic Peninsula (between −8 °C and −10 °C mean annual temperature in 2007), and it is feasible that this area is near the limit of viability of sea ice conditions suitable for emperor penguin colonies. Although recent work (Gillett *et al.*, 2008) shows that overall Antarctic temperature records display a warming trend linked to human influence, climate records from this area (Turner *et al.*, 2005) suggest a slight cooling rather than warming of the local environment. Average wind speeds, another factor sited as critical to breeding colony success (Jenouvrier *et al.*, 2005; Ainley *et al.*, 2007), are stable or decreasing in the area, so the reason for the loss of these colonies is currently unknown. Accurate models of future regional climate change are essential to assess the future viability of colonies in warmer areas. Previous work from the few colony locations regularly monitored (Barbraud & Weimerskirch, 2001; Kato *et al.*, 2004; Barber-Meyer

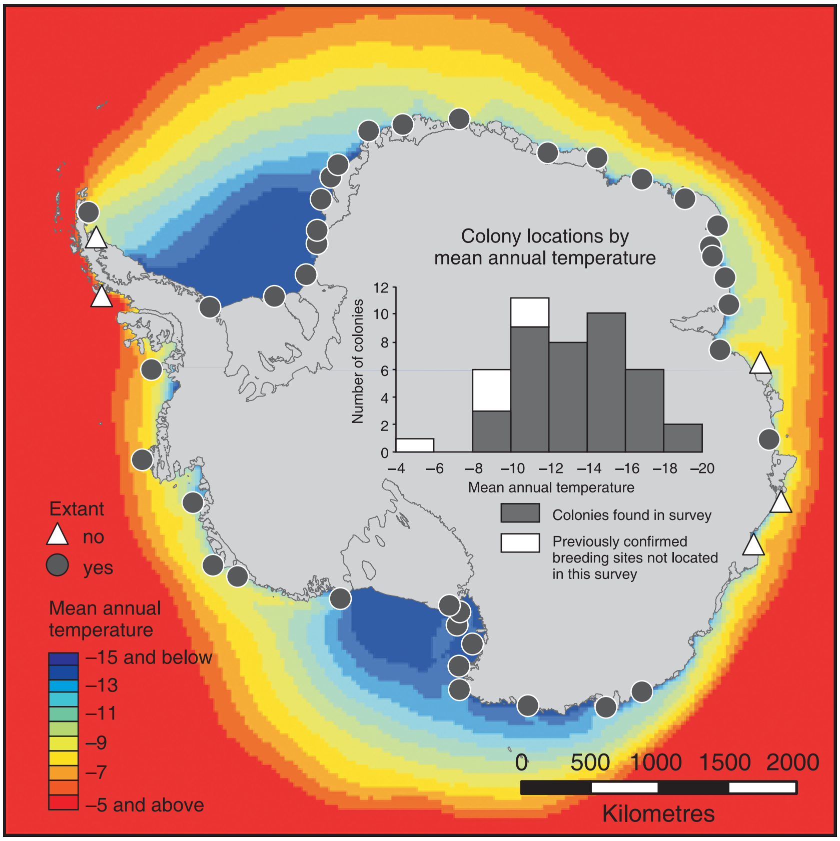

Figure 5 Extant and no longer extant colonies in relation to mean annual air temperature. We find 38 extant breeding colonies; six previously recorded breeding colonies are no longer extant. Further work is needed to assess why other colonies have been lost; however, three of the lost colonies in East Antarctica are in an area where the annual mean temperature is similar to that of the Antarctic Peninsula, indicating that these colonies are near the limit of viable sea ice needed for breeding and so are more at risk from environmental changes.

et al., 2008) indicates a mixed picture of breeding success. In the Western Ross Sea, sea ice is reported to be increasing slightly, and here colony sizes are stable or increasing (Barbraud & Weimerskirch, 2001). At Pointe Géologie in Terre Adélie, current populations are stable. While the two colonies in Lützow-Holm Bay have decreased in recent years, they are still at or above the levels from the early 1980s (Kato *et al.*, 2004). All of these long-term monitored colonies are located in areas with colder mean temperatures than the lost colonies between Princess Elizabeth Land and Queen Mary Land, or those on the Antarctic Peninsula, and are therefore not currently at risk of environmental conditions that will make sea ice unfavourable for emperor penguin colonies. However, recent studies of the affect of predicted climate change on the Antarctic sea ice indicate a dramatic decline in the number of emperor penguins in Terre Adélie by 2100 (Jenouvrier *et al.*, 2009).

Hence, key to disentangling the potential effects of climate change on emperor penguins is an accurate assessment of population trajectory, taken at regular intervals. The current study helps bring this closer by providing a pan-Antarctic assessment of emperor penguin distribution. Future studies are required to assess population trajectory within the sites identified in this study.

CONCLUSION

This study presents the first satellite-based survey of a vertebrate that captures almost the whole breeding distribution of the species. We estimate that 85–95% of the Antarctic coast has been surveyed using satellite imagery suitable for finding emperor penguin colonies. It is the first synthesis of emperor penguin colonies since Woehler (1993) and it is the first true synoptic pan-continental survey of any penguin species that does not rely on ship- or ground-based observations, which often have locational bias. We have detected the correct positions of 16 new or previously mislocated emperor penguin colonies, including 10 potentially entirely new colonies, representing 26% of the total number of colony sites. We also question the present existence of six colonies recorded before 1970. We believe that the total number of colonies (large enough to be seen by satellite) is 38, although it is possible that more may exist in the few areas not surveyed. The new distribution map resulting from this study gives a wider and more regular distribution of emperor penguins around the coast of the continent. These data will help future research formulate total population assessments for the species and to provide a baseline to estimate the species' vulnerability to future climate change.

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