Discovering and Monitoring Antarctic Wildlife Populations by Remote Sensing

Submission for the award of PhD by Published Work

In the field of Ecology and Remote Sensing

From the Open University

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British Antarctic Survey (Affiliated Research Centre)

2016

Acknowledgements

I would like to extend my thanks and appreciation to many individuals who have helped, supported and contributed to my science over the last decade.

Firstly I would like to acknowledge my supervisors Phil Trathan and Phil Wheeler. Phil Trathan has supported my efforts to take a more scientific direction in my career over the past eight years and has helped and encouraged me to work on penguins and higher predators. His knowledge of the science, politics and scientific community has been vital in researching and publishing in the field. Thanks too to Phil Wheeler for the helpful and knowledgeable advice (often at short notice) in putting together this thesis.

I am also extremely grateful to my line management, especially Adrian Fox who has allowed me to chart a path into research away from the pure mapping role that I was originally employed for. Hopefully the success that the research has engendered for British Antarctic Survey has validated the approach. I would also like to mention John Shears, whose initial support and enthusiasm on the first penguin mapping paper facilitated the initial breakthrough. Also my other co-workers within the Mapping And Geographic Information Centre at British Antarctic Survey.

I am appreciative of the work and support of my co-authors, far too many to list individually, but particularly to Michelle LaRue, Jerry Kooyman, Barbara Wienecke, Richard Phillips and Paul Morin.

Special mention goes to my old MSc supervisor Prof David Smith who fanned the flames of an inquisitive mind and has encouraged my research, he has been a stalwart friend and supporter over the last decade.

Finally and by no means least, thank you to my wife Ellie, who supported my career change into research back in 2000 and has always been there for advice and help whenever they were needed.

Contents

Cover letter

To the supervisors, reviewers and Open University,

Please find enclosed a selection of peer-reviewed published papers which I am submitting for consideration for the degree of Doctor of Philosophy by Published Work. This selection of papers constitutes a unified group of work on the theme of Discovering and Monitoring Antarctic Wildlife Populations by Remote Sensing. This is a recent field of study and one in which I have been fortunate enough to make a significant contribution.

The study of Antarctic wildlife is often logistically difficult; extreme weather conditions, poor transport links and the size of the continent make fieldwork challenging, expensive, and, in some cases, dangerous. Many regions of the continent are remote and distant from regularly visited research stations, so are still poorly explored. Previous wildlife monitoring studies have tended to be based close to scientific research stations, the distribution of which is uneven and clustered into a limited number of bio-geographic regions, which has left us with a biased and relatively poor knowledge of the population and distribution of many species of Antarctic vertebrates. The use of satellite remote sensing which can be low cost, frequent, and ubiquitous has allowed me to study wildlife in remote sites and to upscale existing point datasets into regional estimates.

There is a pressing need for better information on Antarctic wildlife populations, this originates from two factors: the impacts of regional climate change on Southern Ocean predator populations; and, the impacts of commercial fishing for Antarctic krill (*Euphausia superba*) on krill-eating predators. Recent increases in krill harvesting mean that we urgently require better estimates of krill-eating vertebrate population sizes allowing better estimates of krill consumption rates. We also need better estimates of predator distribution and estimates of their population trajectories to enable sustainable harvesting, including the spatial management of fisheries.

Generating estimates of vertebrate populations in the Antarctic by remote-sensing methods is made easier by the lack of vegetation and absence of terrestrial mammalian predators, meaning that seabirds and seals have no need to hide to the degree often found in other systems, burrow or camouflage their breeding sites. Many species therefore have a high visible contrast with their surrounding environment and often breed colonially in large groups, which, along with the lack of obscuring vegetation, makes them more easily visible by remote sensing. These characteristics mean that seabirds and seals in the Antarctic are potentially more-simple to count than in any other region of the globe.

The urgent requirement to quantify wildlife populations and the high visibility of those populations to satellites, make Antarctic wildlife ideal candidates for census by remote sensing.

The scientific field of wildlife and conservation remote sensing is expanding rapidly. When I started my work the number of papers using satellite imagery to map or estimate the abundance of Antarctic wildlife was limited, with one paper on emperor penguins and two papers on Adélie penguins which dated back to the 1980's. These papers were methodological papers studying a limited number of colonies and none of the techniques were deemed robust enough to provide realistic population data at the time of publication. Likewise the use of Very High spatial Resolution (VHR) imagery for census work was almost unknown. The papers introduced here developed new techniques that are accurate enough for robust population estimates using medium and VHR imagery. Critically, as well as developing those techniques the work also applied them to broad areas; in the case of emperor penguins enabling continent-wide population assessment of wildlife by direct observation for the first time. Today the techniques and principles laid out in the papers below have been applied to many other species co-driven in-part by the ever-higher resolution of satellite imagery; which allows new species to be monitored as greater resolution becomes available.

My expertise is in the application of remote sensing techniques and the construction of image-processing algorithms to answer ecological questions about abundance and population change. This, coupled with ecological knowledge from my co-authors, has meant that I have been able to make a significant contribution to the field, which has, and will in future, enable more robust estimates of resilience to climate change and enable more accurate assessment of harvesting quotas for ecosystem-based management of Southern Ocean fisheries. Having now published a number of signature papers in the field I feel that I am in an excellent position to drive forward the science to new species and subjects in and beyond Antarctica.

The theme of wildlife remote sensing runs through all of the seven submitted articles introduced here, these papers provide a small selection of the 48 refereed published papers of which I have lead-authored (14) or co-authored (34).

Direct Satellite Remote Sensing of Wildlife

1. Introduction

1.1 Satellite remote sensing overview

Over the past four decades Satellite Remote Sensing (SRS) data have been used to effectively assess some of the greatest challenges to biodiversity; the threat of climate change, habitat loss, overexploitation and the effects of invasive species (Horning 2010). Satellites collect data on many physical characteristics of the environmental that can be used to inform stakeholders of land use, environmental change and habitat (Lillesand *et al.* 2008). The data collected by these satellite platforms offers repeatable, standardized information in a cost effective manner, which, subject to cloud cover and tasking limitations, can be gathered over large areas, anywhere, regardless of remoteness, accessibility or geopolitical boundaries. Many satellites provide long and comprehensive time series of these data that can be used to effectively monitor environmental change and SRS methods have become widely used across a variety of applications and spatial and temporal scales ranging from crops assessment to measuring deforestation. One of the most commonly used methods is by categorizing the red edge of vegetation (Tucker 1980) (and of plankton in the sea (Platt 1986)), which can generate simple effective indices that categorize vegetation or vegetation assemblages. On land, vegetation has been mapped effectively by satellite since the beginning of the Landsat era over four decades ago, whilst in the marine environment, platforms such as SeaWiFs and MODIS have been collecting ocean colour data since the late 1970s. Other physical characteristics such as winds, currents, elevation, temperature, and rainfall data are routinely collected by satellite and can be used to help determine an area's biological diversity (Turner *et al.* 2003,Turner 2014, Pettorelli *et al.* 2014). A review of the uses of remote sensing for monitoring biodiversity in 2007 (Leyequien *et al.* 2007) divided the use into five categories; habitat suitability, photosynthetic productivity, multi-temporal patterns, structural properties of habitat and forage quality, but there was no mention of the direct observation of biodiversity using SRS.

Until recently the spatial resolution of satellite data has not been fine enough to discern individual animals on the ground, so direct observation has not been possible (Turner et al. 2003). This has meant that remotely sensed measurement of biodiversity and abundance has been indirect; calculations are based on estimating available habitat rather than directly counting the animals themselves. But the rapid advancement of sensor technology has improved resolution to a degree that direct observation is now possible for many larger bodied species.

The aim of this review is therefore to chart the development of direct satellite remote sensing of wildlife and to discuss its use, advantages and disadvantages, and future direction.

1.2 Why count?

Direct estimates of wildlife abundance are urgently needed for a variety of reasons including:

A) **Species status assessments**: Assessing population size and monitoring change is a fundamental component of conservation status assessments, such as those of the IUCN red list (IUCN 2015). It is particularly challenging for large, widely distributed species. SRS may facilitate better status assessments for these species.

B) **Identifying important wildlife sites:** The distribution of populations across landscapes is heterogeneous. Identifying sites which are of particular importance to populations of wide-ranging target species from the ground is problematic. SRS gives the potential of long-term assessments of sites of principal importance to target species. Important wildlife areas need to be identified in order to best preserve vulnerable species and areas of high biodiversity (Mittermeier et al. 1998). These areas can then be given extra protection, designated as protected areas and conservation and monitoring efforts can be concentrated on them . For examples see Birdlife International's Important Bird Areas (Harris et al. 2011), or WWF's RaCeR project (Christie &Sommerkorn 2012). Additionally, for those species that migrate, knowledge of breeding, migration routes and life histories are important as threats may often occur outside protected areas (Hall et al. 2009, Alerstam and Lindström 1990). This is especially true of birds and marine life that conduct long migrations and many species' routes and breeding grounds are unknown. Many ecological processes occur at scales beyond which it is possible to study from the Earth's surface. SRS provides an opportunity to do this and in the process facilitate sustainable management of natural resources. For example the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR, https://www.ccamlr.org/) in the Southern Ocean uses higher trophic level indicator species to monitor ecosystem health in order to set fishing quotas within sustainable limits. To do this accurate abundance estimates and an understanding of ecosystem dynamics is required. CCAMLR is beginning to use SRS to fulfil this requirement.

C) **Assessing large-scale responses to anthropogenic activity, including climate change:** Human impact on wildlife is increasing (Vitousek *et al.* 1997, Halpern *et al.* 2008, Wackernagel & Rees 1998). Increasing human population and standard of living leaves less space and resources for biodiversity. Habitat loss, pollution, overexploitation of natural resources and ecosystem services, introduction of alien species, and the unbalancing of ecosystems threaten many species and communities (Trathan *et al.* 2011). Monitoring both the threat and the resultant change, at environmental and species level, is urgently required and satellite observations can play a crucial part in this. Although at local scales this impact is well studied, the global nature of human impacts, including in areas remote from human access, require tools for scales from regional to global (Vitousek *et al.* 1997). The effects of climate change are a case in point. Understanding the effects of climate change on biodiversity will be dependent on an ability to study species' responses at very large spatial and relatively long temporal scales.

1.3 Traditional methods

The need for direct abundance measurements has traditionally been met by high spatial resolution surveys that are either ground-based, ship-based or flown from aircraft. Each of these techniques has advantages and limitations; ground surveys can be accurate over small areas but are impractical for larger studies and have inherent scaling errors. They are often limited to areas that are logistically easy to reach, which in turn can lead to bias. Ship surveys, attempting to estimate pelagic or surface sea life abundance, are often expensive, of limited accuracy and subject to the same scaling errors. Aerial surveys are widely used, both for terrestrial and marine targets, but these can also be expensive to conduct over large areas and contain a degree of risk: in recent years there have been at least 13 fatalities in air crashes during cetacean surveys (Vicky Rowntree pers. comms.). Aerial surveys are limited by the availability of planes and airstrips; some remote locations are beyond the range of most light aircraft. In some cases where abundance estimates are required over very large areas, fine scale aerial survey has been combined with habitat models to upscale to population level (e.g.Klien & Kuzyakin 1982), in a few cases very large surveys over many thousands of square kilometres have been completed. One such example is the recent South Gobi aerial census which surveyed 150,000 km^2 of desert by small aircraft in 2013 (see http://southgobi2013.countingstuff.org/census-zone/). Direct aerial survey has been most common for ungulates, and cetaceans, although other taxa such as seabirds (especially for impact assessment of offshore wind farms), elephants and larger feline species have been targeted.

In polar environments the remote and inaccessible nature of the environment has meant that the use of aerial survey has been extensive if infrequent. Such surveys have been conducted on a number of species including pygoscelis penguins (Stonehouse 1969, Woehler 1993, Southwell & Emmerson 2013) emperor penguins (*Aptenodytes forsteri*) (Hempel & Stonehouse 1987, Kooyman & Mullins 1990), seabirds (Buckland *et al.* 2012), elephant seals (*Mirounga leonina*) (Campagna *et al.* 1992), ice seals (Ackley *et al.* 2006), walrus (*Odobenus rosmarus*) (Estes & Gilbert 1978, Gilbert 1989), polar bears (*Ursus* *maritimus*) (Evans *et al.* 2003, Monnett *et al.* 2006, Wiig & Derocher 1999) and reindeer (*Rangifer tarandus*) (Nellemann *et al.* 2001, Vistnes *et al.* 2008, Klein & Kuzyakin 1982).

Aerial survey is also common in marine environments, especially for whales and other large mammals. It is the most common survey technique in the USA for Marine Mammal Stock Assessment reports (Eberhardt *et al.* 1979), which have to be completed each year for each species in each state. Cetacean survey presents a number of additional problems in estimating total abundance as animals underwater are often indistinct in imagery, only spending a short percentage of their time near the surface and so only a subset of the population will be seen at any time.

The techniques and spatial resolution of aerial census vary depending upon target species and survey requirements, some surveys are photographic, whilst others rely on manual counters recording their observations. Over time these survey techniques have been refined and standardized so that for some taxa, such as cetaceans (Garner *et al.* 1998) and seabirds (Camphuysen *et al.* 2004) there are comprehensive guidelines.

2. The history of Direct Observation of wildlife by satellite imagery

The first applications of direct observation from satellites to monitor wildlife started in the 1980's, but its use has accelerated markedly in the last four years. This acceleration has been facilitated by the increasing spatial resolution of satellite sensors and accessibility to cheap or free imagery, such as the Landsat archive, that became open access in 2008. A timeline highlighting scientific publications using the method is shown in figure 1.

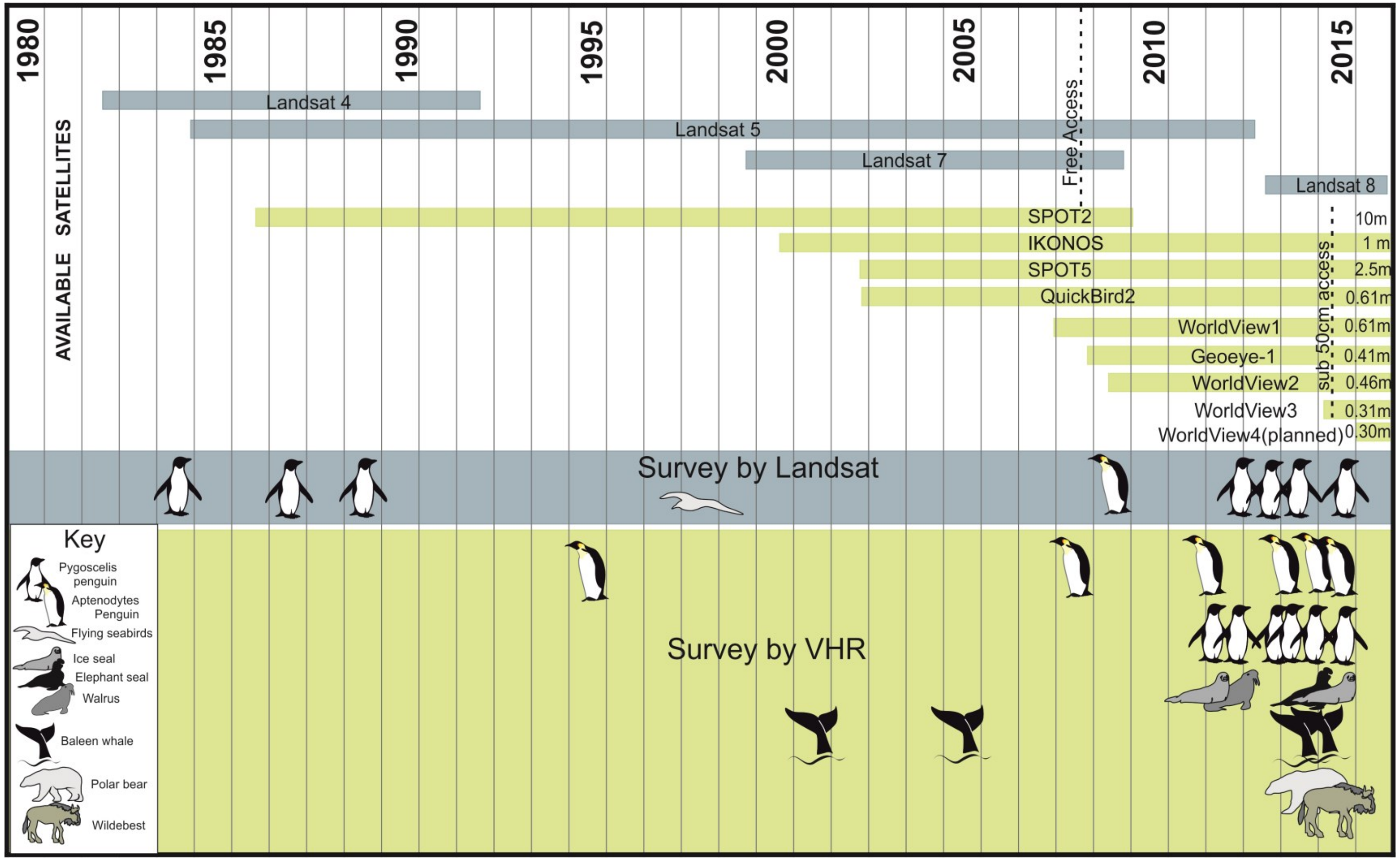

Fig. 1 The number of scientific papers and published reports on the direct and semi-direct remote sensing of wildlife by satellite (identified in Google Scholar, Web of Science and from cross referencing literature citations), each icon represents one paper. This timeline displays both the rapid rise in the number of publications in the last four years and the diversification of techniques to other species. This acceleration has been facilitated by the increasing spatial resolution of VHR imagery and open access to Landsat data.

2.1 Monitoring penguins by satellite remote sensing

2.1.1 Semi-direct observation of penguins from Landsat

Horning (2010) reviewed approaches to monitoring biodiversity abundance by satellite and divided the field into direct and indirect observation. Indirect observation tends to rely on identifying suitable habitat and from that extrapolating population (Leyequien *et al.* 2007), whilst direct observation counts the animals themselves. There is however a third alternative distinction, not differentiated in previous work; that of identifying the presence of animals by indications of how they alter their surrounding environment. By identifying these tell-tale signals in satellite imagery, presence and sometimes abundance information can be gained. These methods are neither truly direct, as they do not target the biota themselves, nor indirect *sensu* Horning (2010). Here I use the term *semi-direct* to refer to them.

Several novel techniques have been used to detect the presence of wildlife in remotely sensed images without directly measuring the animals themselves. Seabird colonies have been the primary target, as large congregations of densely packed birds alter the surrounding environment in a number of ways. The first successful attempt to utilize remote sensing in this way was in the 1980s when it was discovered that penguin guano could be identified in Landsat imagery (Schwaller et al 1984, 1987, 1989). These studies showed that Adélie penguin (*Pygoscelis adeliae*) guano had an unusual spectral signature in the short wave infra-red and this signal could be isolated from the surrounding environment in Landsat imagery. Analysis of three colonies in the Ross Sea area suggested that penguin colonies could be automatically identified using this technique and, as there was a good statistical match between the area of the staining and historical population counts, abundance estimates could be calculated from the imagery. Two factors however limited the usefulness of Schwaller's initial technique; firstly the cost of Landsat imagery in the mid-1980s was very high (~$500 per scene), and secondly penguin ecologists knew that the whole guano-covered area of a rookery was not a good indicator of the colony size, for although this area did not change, the number of penguins within it each year could vary considerably on an annual basis (Woehler & Riddle 1998).

Other indicators of large seabird colonies were also developed using Landsat imagery. In the Arctic where seabirds tend to be cliff dwelling, the guano signal was a less useful indicator of presence, as most birds defecated before returning to the nest and a downwards looking satellite would not be suitable for looking at cliffs. Here the signal used to indicate seabird presence was an increase in vegetation below the cliffs (Williams & Dowdeswell 1998). The study analysed Landsat 5 TM images of Franz Joseph Land in the Russian High Arctic and identified colonies of a number of seabird species. They used the locations of 100 known bird colonies, finding 96 of them from the increased vegetation signal and identifying another 300 probable sites.

In 2009 a continental scale study of emperor penguins was published using SRS (Fretwell &Trathan 2009). This work identified colony locations by finding the red/brown guano stain of emperor penguin colonies on sea ice using Landsat ETM+ imagery. Previous estimates of the number and location of colonies for this species had been very poor (Woehler 1993, Wienecke 2010) and this study was the first to comprehensively map emperor distribution and the first continental scale study of its kind for any species. Ten new colony locations were identified (bringing the total to 38 known sites) and many other site coordinates were refined. The study was aided by NASA making the archive of Landsat imagery freely available in 2008 (Fig 1) and paved the way for further continental scale studies of penguins by SRS.

Freely available Landsat imagery was utilized to map the locations of Adélie penguins in 2013 (Schwaller *et al.* 2013) around all of continental Antarctica other than the Antarctic Peninsula region. This survey used ground-truthing from new aerial surveys in East Antarctica (Southwell *et al.* 2013, Southwell & Emmerson 2013). Like the emperor penguin survey, many new colonies were found and further assessment between the size of the guano staining and population numbers showed that the estimated population of Adélies in several regions, such as the Amundsen Sea sector had been seriously underestimated.

Parallel to this work, scientists funded by the German Environment Ministry were also assessing the possibility of using satellite imagery to assess pygoscelis penguins (Mustafa *et al.* 2012). A detailed internal report was published which trialled a number of resources, including Landsat 7, VHR imagery, and tested the applicability of Radar imagery to detect colonies. The group tested manual interpretation and several automated techniques for defining the area of guano staining at six sites around the continent. Their conclusions suggested that Landsat data were successful at finding and delineating larger pygoscelis colonies, but higher spatial resolution imagery would be needed if the aim was to identify changes in the area of guano, or to identify smaller colonies.

The Schwaller *et al.* (2013) survey had omitted the Antarctic Peninsula as this region is generally more vegetated and several other penguin species and a greater diversity of flying seabirds coexist with Adélies making the ground-truthing from East Antarctica unrepresentative. In 2014 a publication compared the spectral signature of guano samples taken from Adélie penguin colonies against a library of geological and vegetation spectra and found that the signature was unique (Fretwell *et al.* 2014). Using a single Landsat 7 ETM+ scene in a well surveyed area around Marguerite Bay that contained a number of known Adélie colonies these authors used a target finding algorithm to identify areas of guano. The results highlighted the fact that the guano signal was easily differentiated from vegetation, but that the method identified not only the Adélie penguin colonies but also a number of other seabird colony locations including Antarctic fulmars (*Fulmarus glacialoides*) and Antarctic shags (*Phalacrocorax atriceps*). It also picked out a location that was a known moulting site for Adélies. They concluded that a spectral signature from Landsat data could be used very successfully to find guano, however, it should not be assumed that the guano belonged to Adélie, or other penguins or even that it was associated with a currently occupied breeding site. There remains a need for further work on the guano spectra or other methods to enable differentiation between species.

2.2.2 Very High Resolution satellite studies of penguins

The first use of higher spatial resolution imagery for penguin study was by Guinet *et al.* (1995) studying king penguins (*Aptenodytes patagonicus*) on Ile aux Cochons in the Crozet Archipelago (Guinet *et al.* 1995). A single panchromatic SPOT image at 10m spatial resolution was used to identify and map a large king penguin colony. The identified area was compared to the area surveyed previously by ground based methods and a 56% increase in area was documented. The particular colony surveyed was very large (the world's largest king penguin colony with ~700,000 birds), but the authors noted that with the planned increase in spatial resolution that the technique of satellite survey would be a useful future methodology for other, smaller colonies.

By the early 2000s the emphasis had moved to emperor penguins. Kooyman's team at Scripps Research Institute led the way in using Digital Globe VHR imagery (Sanchez & Kooyman 2004, Barber-Meyer *et al.* 2008). Unlike the Landsat imagery, the VHR data had enough spatial resolution to differentiate between guano and the birds themselves, although in areas of heavy staining, or locations where the colony stayed in the same spot over the whole season this became more difficult. Like the king penguin work this study primarily used the higher spatial resolution panchromatic data, although in this case a supervised classification technique was used to automatically find the area of penguins. Results for the initial study were mixed, the use of the panchromatic band in the classification led to problems differentiating penguins from shadow and heavy guano staining, leading the authors to restrict their population classification to only two groups: <3,000 birds and >5,000 birds.

One of the drawbacks of using VHR imagery is that it is not ubiquitous, but needs to be tasked, and the relatively high cost and large data volumes make whole continent surveys difficult. However the 2009 Landsat survey that highlighted the location and distribution of emperor colonies (Fretwell and Trathan 2009) heralded the possibility of using the coarser, but ubiquitous Landsat data to find colonies, and once found, using the VHR data to count them. The problem was that the method of using just the panchromatic band did not return precise enough results to give good population data. This problem was addressed by pansharpening the data and doing the same classification used by Barber-Meyer *et al.* (2008) on the higher spatial resolution pansharpened colour imagery. This method gave much better results and, in most cases where the image quality was good, returned plausibly accurate results. In a landmark paper in 2012 scientists from the UK, USA and Australia published a global population estimate for emperor penguins based of remote sensing (Fretwell *et al.* 2012). Satellite data were analysed for every breeding location of emperor penguins around the continent. The VHR satellite data, a mixture of Worldview2 and Quickbird imagery, were taken within a two month window of a single breeding season. This work was believed to be the first census of a whole species from space. Semi-synoptic ground truthing from 11 aerial and ground counts were used to assess the density of penguin huddles, the work continued the discovery of new colonies that started with the Landsat work, now using a mixture of new Landsat imagery and the "quicklooks" provided by the commercial satellite provider DigitalGlobe. The result was the discovery of four new colonies and the confirmation of several previously suspected sites, bringing the total number of known breeding locations analysed to 46. The population estimate raised the estimate of breeding pairs from 135,000-175,000 to ~238,000 pairs which the authors estimated translated to a total breeding population of 595,000 birds, approximately double the previous estimate.

The finding of so many new colonies in unsurveyed and unexpected locations, and being able to access imagery on a yearly basis has also given rise to several new findings about the behaviour of emperors, such as colony movement (LaRue *et al.* 2014), re-establishment of colonies and breeding on ice-shelves (Ancel *et al.* 2014, Fretwell *et al.* 2014). Some such behaviours had been suggested (Trathan *et al.* 2011) but others were new.

Study of how VHR imagery could improve knowledge for other penguin species was being conducted in parallel with the remote sensing work on emperors. The higher spatial resolution of various VHR satellite sensors was being trialled to assess how it could improve pygoscelis penguin assessment and whether it could alleviate some of the problems associated with the coarser pixels of the Landsat imagery. The first two papers using VHR imagery to look at the guano stained areas of pygoscelis penguins were published in 2012 (Naveen & Lynch 2012, Lynch *et al.* 2012). Both papers used the visible wavelengths of the imagery, and especially the higher spatial resolution of the panchromatic band. The first of these studies looked at the large chinstrap (*Pygoscelis antarctica*) colonies at Deception Island in the South Shetland Islands. The second paper concentrated on the Adélie penguins of Paulet Island on the Eastern Side of the Peninsula. Both papers employed a simple methodology of manually digitizing around the darker guano stained area in the high spatial resolution imagery and applying a density estimate to the areas of penguins to estimate numbers. The advantage of the higher spatial resolution imagery was that unlike the Landsat data, in the VHR imagery the sub-colony areas could be identified, which helped refine the accuracy of the method. Earlier work had already noted that the total guano covered area was a poor indicator of population, as the number of penguins within the colony varied annually but the area of the overall colony stayed the same. However, the sub-colonies inside each penguin rookery had more consistent densities (Woehler and Riddle 1998) and this could be used effectively to estimate populations with some accuracy by measuring the areas of the sub colonies and applying a density estimate. So the ability to pick out just the sub colony area of breeding penguins, rather than the whole guano stained area made population estimates much more robust than the earlier Landsat work. This method of using panchromatic VHR data and manually digitizing colony outlines was used subsequently in estimating the population of the Adélie penguin colony on Beaufort Island in the Ross Sea (LaRue *et al.* 2013).

The problem of automating a procedure to reduce the effort required for manual digitization was addressed by LaRue et al. (2014) who applied the classification techniques used successfully on emperor penguins to Adélie penguin rookeries. The result found that satellite estimates from automated classification were highly correlated with the manually digitized polygons, but that although there was a strong correlation between guano area and Adélie penguin abundance, residual variability in the nesting density still produced relatively wide prediction intervals.

A second paper published almost concurrently with the LaRue et al. (2014) study also used a supervised maximum classification likelihood analysis on VHR imagery to demark the extent of Adélie penguin sub colonies (Waluda et al. 2014). Interestingly the site chosen on Signy Island had a mixture of chinstrap and Adélie penguins. Previous field records had shown that when penguin chicks hatch the guano changed colour to a deep red hue. The exact reason for this change was unknown, but it was realised that it could be used to differentiate species as Adélie chicks hatched well before other species. Careful timing of satellite image acquisition just after Adélie chicks hatched displayed their locations with a deep pink guano colouration, but the chinstrap chicks were still incubating and had much paler guano staining. This enabled differentiation between species in the automated supervised classification of the VHR imagery.

Using the results of the LaRue methodology and the new distribution data from the Schwaller *et al.* (2013) paper a full-continental population estimate was conduction in late 2014 (Lynch & LaRue 2015). A mixed methodology of field census, supervised classification and manual digitization was employed to estimate breeding populations. The final Adélie penguin estimate suggested that the population was 53% larger than previous estimates; a likely conclusion as 41 of the 251 known colonies were previously unsurveyed and did not feature in existing population estimates. The paper also commented on the possible expansion of the species into new breeding areas and the local extinction at other breeding sites. Like previous papers, this work highlights the utility of using commercial VHR imagery to estimate abundance of penguins and seabirds in remote areas.

Although the whole population of Adélie penguins has now been counted a number of questions remain. The most pressing of which is how the guano signal changes over time. We know from field evidence that the colour varies considerably throughout the season and this may have an effect on the manual or automated classification of penguin sub-colonies. Furthermore detailed phenological knowledge linked to changes in guano may aid efforts to rigorously differentiate between penguin species and between penguins and other species of colonial nesting seabird. Fieldwork and analysis is currently underway to assess this question by scientists at British Antarctic Survey and the University of Cambridge.

2.2 Monitoring Mammals by Satellite Remote Sensing

2.2.1 Marine Mammals: Whales

The first attempt to utilize SRS data to directly observe mammals was in an attempt to identify whales (Abileah 2001). Marine mammal populations are routinely studied by aerial survey and large numbers of survey flights are conducted for conservation, tourism, and environmental impact assessments. Over several decades formal methods have been developed to standardize survey protocols (Eberhardt *et al.* 1979, Garner *et al.* 1999). The ability to study marine mammals by satellite could potentially be a transformative technology and supplement or replace the need for costly, and sometimes dangerous, aerial or boat surveys. The first High Resolution (HR) satellite images to be commercially available were the IKONOS-2 satellite launched in 1999 and in 2001 Abileah (2001) reviewed the prospect of using this and other VHR imagery to look for whales, discussing the spatial and radiometric resolution of various sensors available at the time and theorizing on what might be possible and what signal-to-noise ratios might be returned. It also looked into the potential reflectivity of different whale species that might be captured by the satellites. A second paper (Abileah 2005) took this theoretical work forward into a project that used IKONOS-2 imagery to try to identify both simulated targets and actual humpback whales. The study used one IKONOS-2 image which has a panchromatic resolution of 1 m and a multispectral resolution of 4 m over Maui, Hawaii. The paper set forward a methodology for finding whales in imagery and also theorized about the probable reflectance signal that a whale would return. The results were promising, with several potential sightings of humpbacks (*Megaptera novaeangliae*) in the Maui image, but the pixels returned were difficult to identify as whales. Importantly the work discussed the effect of ocean clutter (waves, swell, whitecaps) on the method and proposed ways of filtering ocean clutter from the imagery. The recommendations looked to the increased spatial and radiometric resolution of forthcoming satellites (such as Quickbird2) and the need for better radiometric resolution and better contrast in dark areas such as the ocean (lowering the sensor quantization level).

Although a number of new, higher spatial resolution satellites were launched in the following years it was not until 2013 that a further paper looked into utilizing this new technology (Fretwell *et al.* 2014). This study again took a single VHR image to establish if whales could be identified and possibly counted from it. In this case the imagery used was a 50 cm resolution WorldView2 (WV2) image (50cm panchromatic, 2m multispectral) and the target species was the southern right whale (*Eubalaena australis*). This species is a favourable target in comparison to other species for several reasons: it has areas of callosities on its head which act as bright targets in the water column, it breeds in calm locations in high densities and the females spend most of the breeding period near the surface of the ocean. Additionally the WV2 data collected light in a "far blue" wavelength that theoretically would penetrate the water column further than visible light. The location targeted in the study was Golfo Nuevo near Peninsula Valdes in Argentina, the largest known breeding agglomeration of southern right whales. A pragmatic approach to minimizing ocean clutter was taken – searching and acquiring an image with the calmest possible sea conditions. The study was successful; whale shapes were clearly identified in the imagery and 55 probable whales and 23 other possible whales were manually identified giving a density similar to that recorded in aerial survey.

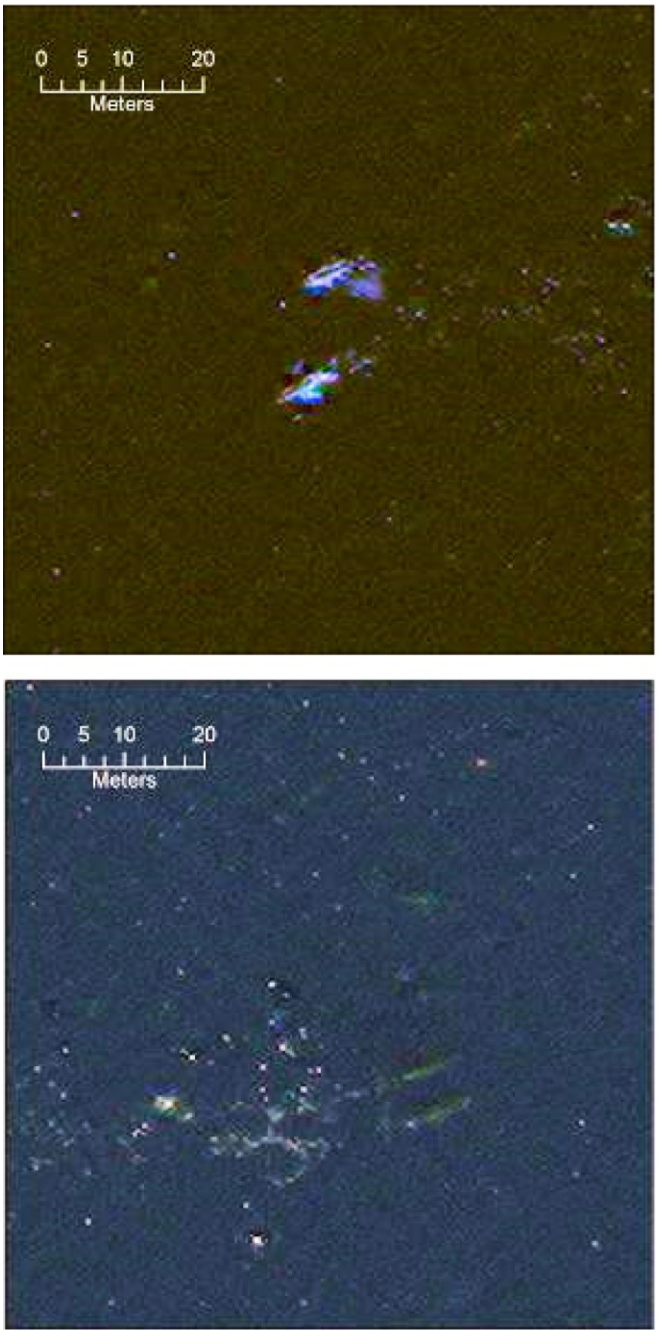

Figure 2: two pairs of humpback whales off the coast of Maui, Hawaii using pansharpened WV3 imagery (Imagery curtsy of Digital Globe Foundation) with a resolution of 31cm. The top figure shows whales breaking the surface, characterized by bright pixels, while the lower image indicated whales beneath the surface, which are shown by darker, less blue objects

The study also trialled and developed algorithms to automatically detect whale-like objects and found that these methods were comparable to the results from manually digitized whales. However the automated analysis highlighted possible confounding factors leading to the recommendation that, over large areas, a semi-automated method should be employed with the returns from the automated analysis checked manually before being classed as a whale.

The launch of the WV3 satellite with a spatial resolution of 31cm should add impetus to this field. Initial tests show that humpbacks can been identified with some confidence with the improved spatial resolution (figure 2)

2.2.2 Marine Mammals: Seals

Like whales most previous seal surveys have usually been conducted by aerial survey (e.g. Erickson *et al.* 1971, Kumar & Johnson 2014 – for exceptions see Southwell *et al.* 2004), and like the whale surveys the amount of coverage needed, remote nature and extreme environment means that these surveys are expensive and occur infrequently. This is especially problematic for ice-seals which breed on the sea ice rather than on land, as the winter extent of sea ice around Antarctica approximately doubles the size of the continent each year, so the breeding habitat for ice seals is very large. The sea ice environment is also dynamic, with the extent and character of the annually changing ice making survey design for multi-year monitoring challenging. These problems result in large uncertainties on the abundance and distribution of ice seals (Ackley *et al.* 2006, Southwell *et al.* 2012).

Several species of land breeding and ice breeding seals have been targeted by direct remote sensing: in Antarctica the Southern elephant seal (*Mirounga leonina*) and the Weddell seal (*Leptonychotes weddellii)*, and the walrus in the Arctic. A number of projects are currently underway to use the technology more widely on other species. The single publication on elephant seals used VHR Geo-Eye-1 satellite (resolution panchromatic 0.5 m, multispectral 1.65 m) on the Isthmus beaches of Macquarie Island in the Southern Ocean (McMahon *et al.* 2014). Elephant seals in the satellite data were counted manually and the counts compared to coincident ground counts. The two counts were comparable, with the satellite count around 11% lower than the ground count, but within the confidence limits of the survey. To improve the methodology the authors suggested a number of methods including counting duplicate images on the same day and on different days and further work to improve contrast within the images (the platform for counting seals in this study was Google Earth and therefore the ability to manipulate the imagery was limited).

In the Arctic the use of satellite imagery to count walrus populations was assessed by the WWF (Boltunov *et al.* 2012). Ice seals in the Arctic are particularly threatened due to the impact of sea ice loss through climate change and the growing commercialization and exploitation of the region for natural resources. The survey chose four locations on the western Arctic coast of Russia and used EROS-B imagery with a panchromatic spatial resolution of 0.7 m to search for walrus. Animals were obvious in the imagery and were counted manually. The test study highlighted the utility of using satellite imagery for this type of survey.

Weddell seals were counted in Erebus Bay, a well-studied location in the Ross Sea (LaRue *et al.* 2011). Weddell seals are smaller than elephant seals, but once hauled out of the ice have a high contrast with their surrounding environment making them easy targets for satellite or aerial survey (unlike in the Arctic where breeding ice seals are concealed in ice dens to avoid predation from polar bears). Five images from the Worldview1 (panchromatic resolution 0.6 m) and Quickbird2 (panchromatic resolution 0.6 m, multispectral resolution 2.4 m) satellite were analysed. Ground counts are conducted in Erebus bay multiple times each year, so this well-studied population was an ideal test site for the comparison. The five images used were each from different years and the correlation between ground counts and satellite counts varied considerably between each image highlighting the problem of synoptic ground-truthing of satellite imagery. Satellite counts were conducted manually and tended to underestimate the number of seals in comparison with ground counts. The underestimation of satellite count to ground count was reasonably consistent in a geographical and temporal context. The overall conclusion of the paper was that satellite data will prove a vital tool in Weddell seal population assessment in future.

The satellite methodology developed by LaRue *et al.* (2011) has since been used in a larger scale study to identify a population decrease of Weddell seals along the Victoria Land coast in the Ross Sea (Ainley *et al.* 2015). The study up-scaled the geographical area to that of the whole eastern side of the Ross Sea and compared recent satellite counts to historical counts going back to the

1960s. The results of the analysis showed that several locations had apparently suffered from dramatic declines in seal numbers, more than the variability that could be attributed to the accuracy of the satellite counts or natural yearly variability. The study has shown the utility of satellite survey for this type of data and recommended further monitoring using this technology.

2.2.3 Terrestrial mammals

Whist colonial nesting seabird studies have been at the forefront of SRS to estimate abundance, studies on terrestrial mammals have been slow to take up the potential, possibly due to their dispersed distributions. In the Arctic a single study on detecting polar bears was published in 2014 (Stapleton *et al.* 2014). In most circumstances polar bears would be difficult to detect against a white icy background. This study circumvented that problem by studying a population that spent the summer on the ice-free Rowley Island in Nunavut. In these cases the white coats of the bears gave high contrast with the surrounding environment, which is usually much darker rock, soil or vegetation. Quickbird2 data at 50cm spatial resolution was initially analysed and the bears in the imagery were counted manually by two observers. Results between the population estimated modelled from ground survey and the satellite counts were comparable to the satellite count showing 94 bears and the modelled ground estimate suggesting 102 bears.

To-date almost all SRS studies of wildlife have been based in polar locations (LaRue & Knight 2014), often in the Antarctic where the lack of large terrestrial predators negates the need for camouflage and animals often group together in the open in large numbers. The first terrestrial non-polar study was published in late 2014 and assessed the possibility of identifying large mammals in East African savannah environments by satellite (Yang *et al.* 2015). A GeoEye-1 image of part of the Maasai Mara National Reserve in Kenya was used. The authors developed a hybrid classification method that utilized both object based and pixel based routines to automate the detection and classification of large mammals in the park. One of the main advantages of using satellites noted by the study was the lack of disturbance which when using other ground or aerial methods may affect the survey results. The automated methods were tested on adult wildebeest

(*Connochaetes sp.)* and adult zebras (*Equus sp.)*. A sample of the image was manually counted and this was compared to the automated analysis.

3. Discussion

3.1 Advantages and disadvantages of remote sensing of wildlife

There are a range of advantages that SRS has over more traditional types of survey, but it also has numerous constraints including financial and logistical constrains and technical considerations.

3.1.1 Financial

For many species the ability to scale up to regional estimates or address long term monitoring studies is cost dependent. Satellite imagery is, in many cases, cheaper than traditional survey methods, but not always; tasked WV3 imagery at full commercial rates and full spatial resolution with all spectral bands can be over $100 per square kilometre, a price which compares poorly with aerial survey costs. The pricing structure for Digital Globe VHR imagery is complex and the actual full price is dependent upon many factors including; priority level, tasked or untasked, number of bands required, level of processing required, where in the world the image is from and the type of institution buying the imagery. Buying archival imagery reduces the cost considerably, but in many cases new surveys will need newly tasked imagery. Overall the pricing of tasked VHR imagery is comparable with aerial survey. A recent comparison with one environmental survey company quoted prices in the range of $22-26 per square kilometre at 50 cm and 30 cm resolution for aerial survey, plus a fixed amount for the cost of aircraft transit to the survey site. Satellite imagery cost from Digital Globe at the same time were between $10.80 to $69.60 depending upon the type of institution purchasing, the resolution required and the geographical area. The satellite provider discounts heavily for non-commercial use with educational establishments receiving a 30% discount and NGOs such as conservation charities receiving a 50 % discount. Thus a conservation charity tasking 30 cm 4 band WV3 imagery would pay \$26 - \$35 per km^2 depending upon the geographic location of the area of interest. Furthermore there are no other costs involved. Analysis effort for satellite imagery also tends to be less; the analysis for aerial transect sampling can be expensive and requires model inputs to compensate for the partial coverage, whereas the wider, often total coverage of satellite imagery negates the need for such models. So for conservation bodies in most cases satellite imagery will prove cheaper than aerial survey. Other satellite providers of VHR imagery such as SPOT data from Airbus have comparable pricing.

One potential rival is the expanding use of Unmanned Aerial Vehicle (UAV) surveys. The use of small UAVs for small area survey is becoming increasingly common and can be considerably cheaper than VHR satellite survey, with the purchase price of a drone and camera often being less than a single satellite image. However the limited range and local regulations, such as not flying beyond line of sight, restrict the use of this technology for larger surveys. Long-range fixed wing UAVs have the potential to provide an alternative to satellite survey (Hodgson *et al.* 2013), but at present few commercial companies provide this technology and where it exists it can be prohibitively expensive (Amanda Hodgson pers comms.).

Medium spatial resolution imagery on the other hand is freely available. The quality and temporal return rate of Landsat sensors makes them extremely useful for semi-direct applications. Recently data from Sentinel2 and 2a have come on-stream and promise the free availability and spectral bands of Landsat but at higher 10m spatial resolution. This is a resource that may be important for further guano searching efforts both in Antarctica and other regions.

3.1.2 Logistical

One of the great advantages of satellites is that they can potentially image any part of the world on any day of the year and even acquire multiple images of the same area in the same day. The orbital parameters of each satellite varies; the revisit rate of the nadir-pointing Landsat8 sensor is sixteen days, however most VHR satellites are non-nadir pointing and have the ability to direct their sensors to geographical regions not directly beneath them, meaning that repeat acquisitions for a single sensor can be less than one day. With a constellation of VHR satellites the ability to target specific areas becomes much greater. However, practice and experience shows that the chance of getting VHR imagery on a specific day are very low. This is partially due to cloud cover, but the chances of the satellite taking imagery also depends upon the priority tasking of the satellite and the orbital parameters. Trying to match satellite survey with ground truthing often proves difficult and in practice even at the highest level of priority tasking (for which satellite providers charge a premium) there is no guarantee of acquiring imagery at the right time. Several potential studies have been cancelled due to lack of satellite acquisition to match ground-truthing surveys. Conversely, projects where there is a wide temporal window to take imagery, in areas that are often cloud free and where there is a lack of competing interest from other potential satellite users have a much greater chance of success.

Cloud cover is an obvious confounding issue, especially in tropical or maritime climates. Some areas are almost always cloud covered; in thirty years of Landsat data collection over South Georgia there has never been a single totally cloud free image of the island. Alternative methods can be employed such as piece-meal collection of smaller tiles, but this has implications for survey design. VHR satellites tend to take imagery around 11 am local time (pers comms. Digital Globe inc.), in a compromise between high sun angle and low atmospheric moisture content. Off-nadir acquisition does give some flexibility to this system, but this must be balanced against the potential issues of using heavily off-nadir images for classification. Overall cloud is often a major issue especially in surveys where multiple images or multiple imaging times are required.

3.1.3 Technical

Many of the preliminary studies on the direct observation of wildlife have identified and counted animals manually in the imagery. However the tendency to use satellite to “scale-up” to regional studies and the ever-increasing spatial resolution of those images mean that searching large areas at pixel level can be very labour intensive. A survey area of 1000 km2 similar to the recent IFAW

Blue whale survey (Section 3.1) would result in over 10 billion panchromatic pixels in a WV3 image. Several authors have noted the need for automated or semi-automated approaches to minimize the user time spent in counting such imagery. There have been a number of attempts and approaches to this problem. Studies trying to discriminate area features such as guano have concentrated on pixel based algorithms using bivariate plots (Schwaller *et al.* 1984), supervised classifications (Barber-Meyer *et al.* 2008, Fretwell &Trathan 2009, LaRue *et al.* 2014) and spectral angle mapper (Fretwell *et al.* 2014). Whilst those using VHR imagery to identify individual animals have developed a variety of techniques including rule based (Fretwell *et al.* 2014) and hybrid (pixel based and object based) (Yang *et al.* 2015) algorithms to try to find and count individuals, some current studies are using a combination of rule based algorithms mixed with habitat analysis to help refine potential search areas for the analysis (Fretwell & Phillips in prep). What is clear is that although some methods are transferable between species, overall the different shape, size, colour, behaviour and phenology of each species leads to unique challenges that often need unique remote sensing solutions. In many cases, such as the problem of detecting whales and other animals whose shape in the imagery is variable, semi-automated routines where the computer picks out potential targets that are then confirmed manually, will probably be more useful that fully automated routines. For other species, such as albatross whose profile is more consistent, a more automated system could be employed. The development, testing and implementation of these automated and semi-automated routines will be one of the challenges over the next decade.

One of the characteristics of satellite imagery is the instantaneous nature (in reality semi-instantaneous due to the push-broom nature of most sensors) of data collection over large areas. This can be both an advantage and disadvantage for estimating abundance. For species such as whales or ice seals that only spend a percentage of their time at the surface availability bias must be considered and it is likely that these will be different to the availability bias from other more mature survey techniques. Potentially a whale swimming a few metres under the surface could be seen by satellite that could not be seen by a passing ship, or possibly even by aerial survey, but both plane and ship based observers have the opportunity to see the whale surfacing over a prolonged period of time (which also runs the risk of double counting), where a satellite does not. Ground truthing to test the ability of satellites to see animals is essential, but it is often difficult to match the timings of surveys to correspond (see previous section). One option may be to combine satellite surveys closely with occupancy models, especially with species such as whales and ice-seals where imperfect detection is a problem (MacKenzie *et al.* 2002, Karanth *et al.* 2011). In essence we have a lot still to learn about the detection probability and availability bias for almost all the species studied by remote sensing. Converting these snapshot estimates to a full population estimate is a complex task with many factors to consider, especially if the survey is taken at non-optimal times such as with emperor penguin surveys (Fretwell *et al.* 2012). One option is to take multiple images over the course of the season or even over the same day. This will refine estimates and help estimate detection and availability, particularly if linked to synoptic ground truthing, but multiple imagery would be expensive over large areas. Potentially small areas could be assessed for variability and extrapolated to the larger dataset.

3.2 Future Directions

With the ever-increasing spatial resolution of satellite sensors and the greater availability of data there is the prospect of a rapid acceleration in the subject field. At the time of writing further studies on baleen whales, penguins, Antarctic seabirds, albatross, flamingo and seals are known to be ongoing. The availability of WorldView3 data with a 31 cm spatial resolution, increases the number of pixels per m^2 from 4 to 10.4, effectively increasing satellite resolution by a factor of 2.6. This increase in spatial resolution will cross a number of thresholds making new, previously untried species detectable by SRS. There will always be types of animals and habitat that are unsuitable, but the need for abundance and

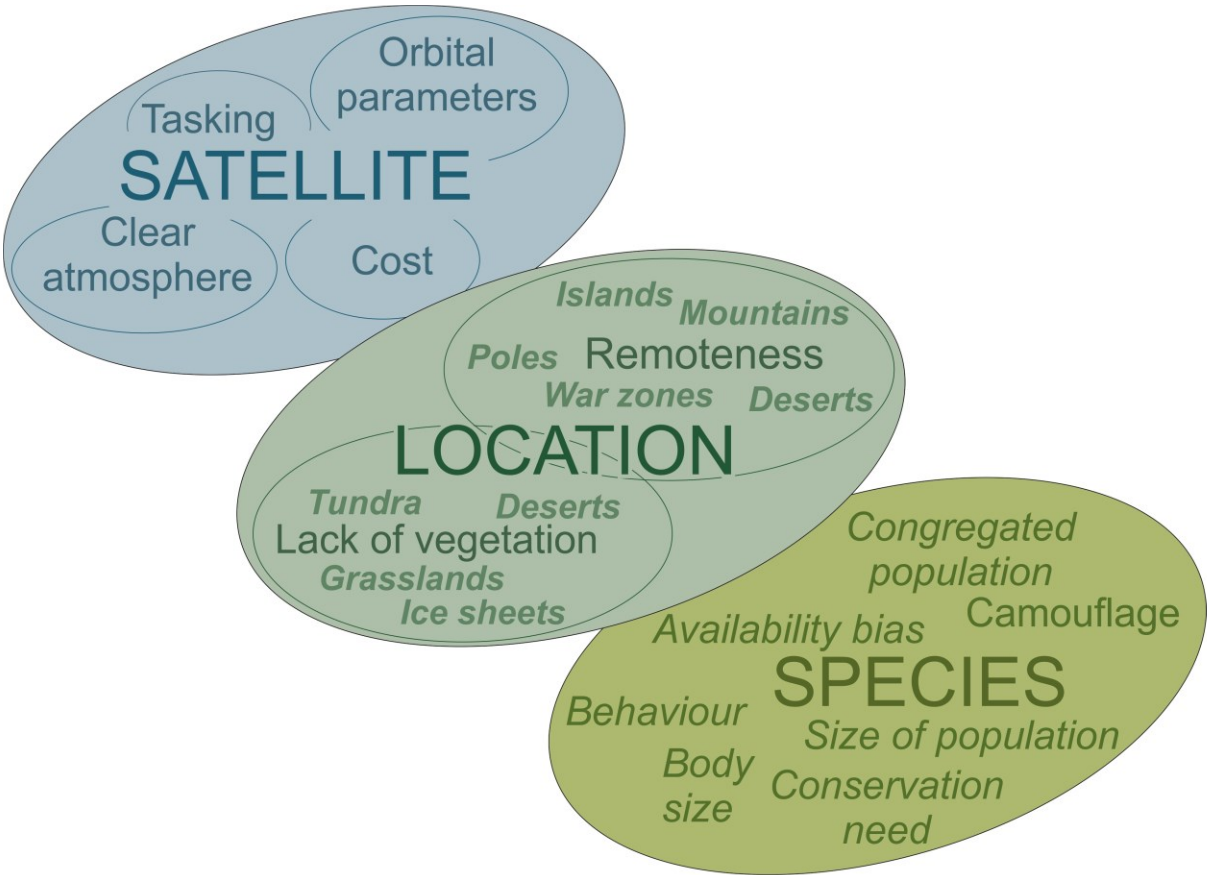

Figure 3. Infogram of some of the constraints and considerations needed when assessing which species and projects are suitable for direct observation from satellite, grouped into three types; satellite considerations, locational constrains and species considerations.

monitoring of many species might be met by satellite imagery. Below I discuss some of the criteria, factors and relative advantages of the technology.

Like much remote sensing that uses visible wavelengths the availability of satellite imagery will be biased toward certain areas. Cloud cover and atmospheric moisture is a problem in areas where persistent cloud or mist render most images unusable. These areas will tend to be maritime, such as the Southern Ocean islands, or tropical rainforest where high cloud and persistent mist are a problem.

The second consideration is the location; SRS studies will be more beneficial in remote areas, or areas that are difficult to access where aerial or ground survey options are limited, these will include remote islands, deserts, the poles, mountainous areas and war zones or areas of political unrest. Vegetation is an obvious confounding factor and it is unlikely that direct survey will be suitable in forested areas. Regions with low or sparse vegetation, such as deserts, grasslands and tundra are better targets.

The final and possibly the most important considerations are those based on the animals themselves. The size of the animal is of primary importance in direct observation, depending upon the current and future spatial resolution of satellite sensors. But size is of little consequence if the animal spends little time visible to the satellite (availability bias), non-surfacing marine species, forest dwellers, burrowers, cliff dwelling and nocturnal species are unlikely to be addressed using existing technology. Trials on blue whales using VHR imagery over 1000 km^2 of sea have not conclusively identified whales, showing that even the largest animals may be unsuitable for satellite survey if they do not spend a large enough percentage of time at the sea surface (unpublished IFAW report courtesy of Russell Leaper). As well as size and availability the contrast of the animal with the surrounding environment is important; camouflaged animals will be more difficult to identify, although the use of different spectral information, multiple imagery or low sun angles could help in some cases. The size and the aggregation of population is another factor. Colonial nesting seabirds such as penguins are especially suited, as groups rather than individuals are more easily located and congregated populations mean fewer images need to be analysed. For example emperor penguins exist in hundreds of thousands but they only breed at ~50 sites, so the whole population can be captured in ~50 images. Larger, and more dispersed populations that are difficult to assess by aerial or ground techniques (such as ice seals), may also be suitable although this has to be offset against the cost of large area satellite surveys. Behaviour such as migration, length of breeding season and movement may also impact upon the suitability of the species.

Finally the conservation need of the species must be taken into account as priority should be given to those species with the most pressing conservation need, or those not already successfully counted by more traditional methodologies.

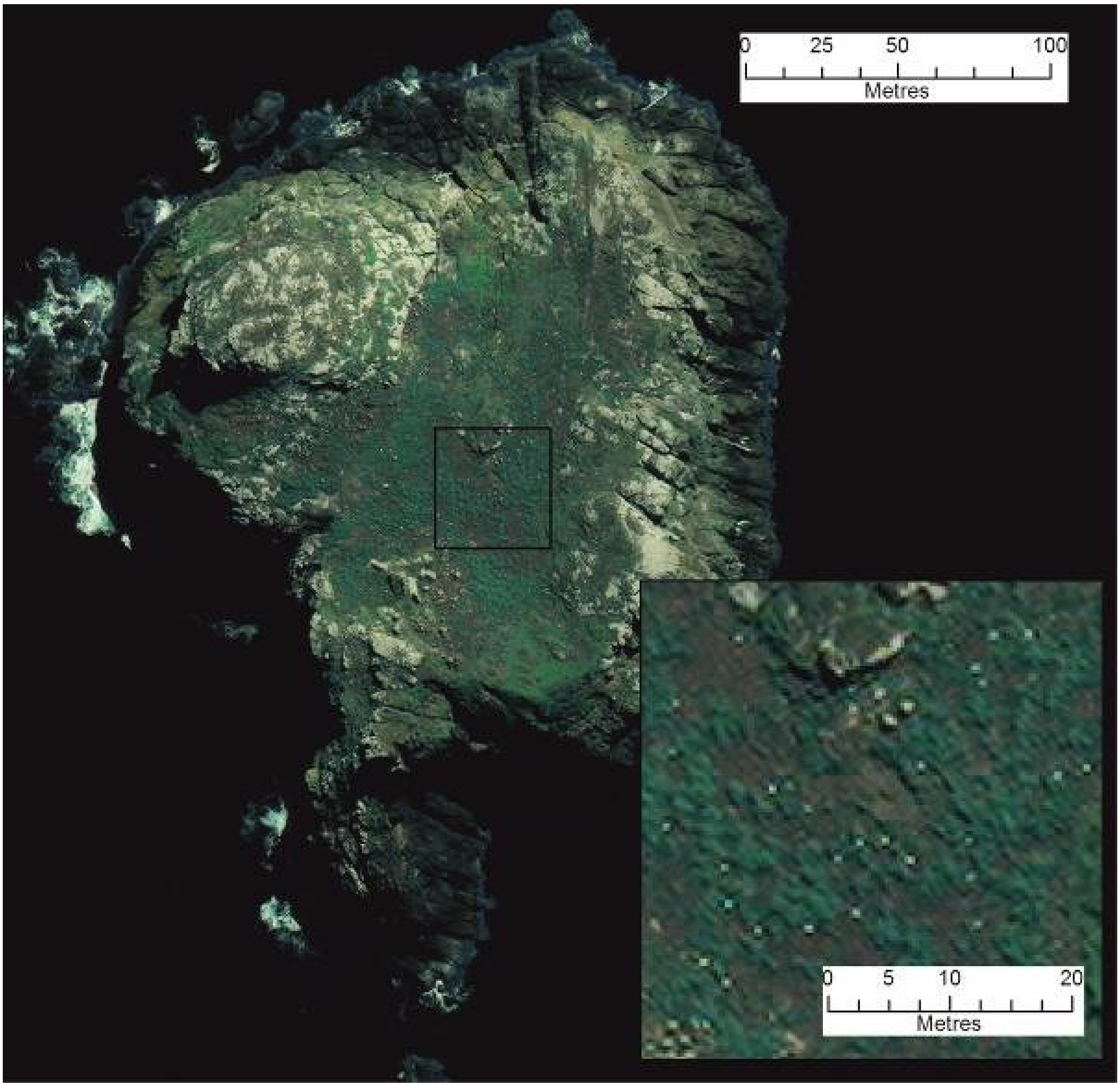

Figure 4. WorldView 3 satellite image of a known Royal Albatross breeding colony on Little Sister Island in the Chatham Islands. The white dots in the inset are assumed to be nesting albatross. This is an example of promising ongoing and future work using direct observation from SRS.

Considering the above constraints and considerations several likely future candidate taxa for SRS spring to mind. Some are species whose abundance has been previously or partially assessed by aerial survey, for example, large ungulates such as reindeer, wild camels or rhino, and other

African grassland species like elephants. Effort to test the applicability of SRS on other types of seals and whales are ongoing, and there are already studies underway on species of large seabirds such as petrels and albatross (see figure 4). Other colonial nesting birds such as flamingo would also be possible.

3.3 Conclusion

The use of satellite imagery to elucidate animal numbers by direct or semi-direct remote sensing was first suggested in the 1980s but it has not been until the era of very high spatial resolution satellites, particularly in the last five years that the technology has been applied successfully. Satellite imagery has a number of key advantages over other survey techniques, primarily the availability of the imagery over remote areas and the ability of satellites to collect data over large regions. This has led to satellite data being used to "scale-up" more detailed ground or aerial surveys to regional studies.

Many of the larger and more successful surveys undertaken so far have concentrated on Antarctic species, especially penguins where whole populations of two species have been counted by satellite. In other areas of the globe animal behaviour, camouflage, and concealing vegetation often make visibility of wildlife more difficult. The increasing availability of ever more powerful sensors such as the WorldView3 satellite will allow the application of these satellite techniques to many other species over the coming decades and could solve some of the problems of visibility that have so far restricted the use of the technology. Many challenges remain; how to understand the data and how to automate/process the large quantities of imagery data are major problems that need to be addressed. Additionally the cost of the satellite data and the transfer of knowledge and techniques from the remote sensing community to the conservation community will be key factors if satellite technology and techniques are to be more widely used to find, count and monitor wildlife successfully.

References

Abileah, R. 2001. The Use Of High–Resolution Space Imagery to Census Marine Mammals, MTS/IEEE Oceans 2001 Conference, Hilton Hawaiian Village, Honolulu, Hawaii, November 5-8, http,//www.abileah.com/DigitalOcean/Publications/Abileah%202001%20Use%20of%20High%20Resolution%20Space%20Imagery%20to%20Monitor%20the%20Abundance%20%20Distribution.pdf

Abileah, R. 2005. Marine mammal census using space satellite imagery 2005. *U.S. Navy Journal of Underwater Acoustics*, Volume 52, 3.

Ackley, S. Bengtson, J. Bester, M.N. Blix, A.S. Bornemann, H. et al. 2006. *The International Antarctic Pack Ice Seals APIS. Program. Multi-disciplinary Research into the Ecology and Behaviour of Antarctic Pack Ice Seals. Summary Update*, The Expert Group on Seals, Scientific Committee on Antarctic Research.

Alerstam, T. & Lindström, Å. 1990. *Optimal bird migration, the relative importance of time, energy, and safety*. In Bird migration, pp. 331-351. Springer Berlin Heidelberg.

Ancel, A., Cristofari, R., Fretwell, P.T., Trathan P.N., Wienecke, B., et al.   2014. Emperors in Hiding, When Ice-Breakers and Satellites Complement Each Other in Antarctic Exploration. *PloS one* 9, e100404.

Ainley, D.G., Larue, M.A., Stirling, I., Stammerjohn, S., Siniff, D.B. 2015. An apparent population decrease, or change in distribution, of Weddell seals along the Victoria Land coast. *Marine Mammal Science* 31, 1338-1361.

Barber-Meyer, S.M., Kooyman, G.L., Ponganis, P.J. 2008. Trends in western Ross Sea emperor penguin chick abundances and their relationships to climate. *Antarctic Science* 20, 3-11.

Boltunov, A., Evtushenko, N., Knijnikov, A., Puhova, M. & Semen-ova, V. 2012. *Space technology for the marine mammal research and conservation in the Arctic, results of the pilot project to develop methods of finding walruses on satellite images.* WWF, Russia.

Buckland, S.T., Burt, M.L., Rexstad, E.A., Mellor, M., Williams, A.E., et al. 2012. Aerial surveys of seabirds, the advent of digital methods. *Journal of Applied Ecology* 49, 960-967.

Campagna, C., Leboeuf, B.J., Lewis, M., Bisioli, C. 1992. Equal Investment in Male and Female Offspring in Southern Elephant Seals. *Journal of Zoology* 226, 551-561.

Camphuysen, K. J., Fox, A.D., Leopold, M.F., & Petersen, I.K. 2004. Towards standardised seabirds at sea census techniques in connection with environmental impact assessments for offshore wind farms in the U.K., a comparison of ship and aerial sampling methods for marine birds, and their applicability to offshore wind farm assessments, NIOZ report to COWRIE BAM – 02-2002. Texel, 37pp.

Christie, P. & Sommerkorn, M. 2012. RaCeR, Rapid assessment of Circum-arctic ecosystem Resilience, 2nd ed. ottawa, Canada, WWf Global arctic programme. 72 pp

Eberhardt, L.L., Chapman, D.G., Gilbert, J.R. 1979. Review of Marine Mammal Census Methods. *Wildlife Monographs*, 6-46.

Erickson, A.W., Hofman, R.J. Oehlensc, R.J. Otis, J. Kuehn, D. 1971. Seal Population Studies in Ross Sea. *Antarctic Journal of the United States* 6.

Estes, J.A. & Gilbert. J.R. 1978. Evaluation of an aerial survey of Pacific walruses Odobenus rosmarus divergens. *Journal of the Fisheries Research Board of Canada* 35, 1130-1140.

Evans, T. J., Fischbach, A. S., Schliebe, S., Manly, B., Kalxdorff, S. B. & York, G. S. 2003. Polar bear aerial survey in the eastern Chukchi Sea, A pilot study. *Arctic* 56, 4,356-366.

Fretwell, P.T. & Trathan, P.N. 2009. Penguins from space, faecal stains reveal the location of emperor penguin colonies. *Global Ecology and Biogeography* 18, 543-552.

Fretwell, P.T., LaRue, M.A., Morin, P., Kooyman, G.L., Wienecke, B., et al. 2012. An emperor penguin population estimate, the first global, synoptic survey of a species from space. *PloS one* 7, e33751.

Fretwell, P.T,. Trathan, P.N., Wienecke, B., Kooyman, G.L. 2014. Emperor penguins breeding on iceshelves. *PloS one* 9, e85285.

Fretwell, P., Phillips, R., Brooke, MdL., Fleming, A., McArthur, A. 2015. Using the unique spectral signature of guano to identify unknown seabird colonies. *Remote Sensing of Environment* 156, 448-456.

Fretwell, P.T., Staniland, I.J., Forcada, J. 2014. Whales from space, counting southern right whales by satellite. *PloS one* 9, e88655.

Garner, G.W., Amstrup, S.C., Laake, J.L., Manly, B.F.J., McDonald, L.L., Robertson, D.G. 1998. Marine Mammal Survey and Assessment methods. *Proceedings of the symposium on surveys, status & trends of marine mammal populations*, Seattle/Washington/USA/ 25-27 February 1998

Gilbert, J.R. 1989. Aerial Census of Pacific Walruses in the Chukchi Sea, 1985. *Marine Mammal Science* 5, 17-28.

Guinet, C., Jouventin P, Malacamp J 1995. Satellite Remote-Sensing in Monitoring Change of Seabirds - Use of Spot Image in King Penguin Population Increase at Ile-Aux-Cochons, Crozet Archipelago. *Polar biology* 15, 511-515.

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J.F. et al. 2008. A global map of human impact on marine ecosystems. *Science* 319, 5865, 948-952.

Harris, C.M., Carr, R., Lorenz, K. & Jones, S. 2011. *Important Bird Areas in Antarctica, Antarctic Peninsula, South Shetland Is lands, South Orkney Islands – Final Report.* Prepared for BirdLife International and the Polar Regions Unit of the UK Foreign & Commonwealth Office. Environmental Research & Assessment Ltd. Cambridge.

Hempel, G. & Stonehouse, R.J. 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.

Hodgson, A., Kelly, N., Peel, D. 2013. Unmanned Aerial Vehicles (UAVs) for Surveying Marine Fauna: A Dugong Case Study. *PLoS ONE* 8(11): e79556. doi:10.1371/journal.pone.0079556

Horning, N. 2010. *Remote sensing for ecology and conservation, a handbook of techniques.* Oxford, New york, Oxford University Press. 26, 467 pp.

IUCN 2015. The IUCN Red List of Threatened Species. Version 2015-3. ttp,//www.iucnredlist.org>. Downloaded on 9 September 2015.

Karanth, K.U., Gopalaswamy, A.M., Kumar, N.S., Vaidyanathan, S., Nichols, J.D., et al. 2011. Monitoring carnivore populations at the landscape scale, occupancy modelling of tigers from sign surveys. *Journal of Applied Ecology* 48, 1048-1056.

Klein, D.R., Kuzyakin, V. 1982. Distribution and Status of Wild Reindeer in the Soviet-Union. *Journal of Wildlife Management* 46, 728-733.

Kooyman, G. L. & Mullins, J. 1990. *Ross Sea emperor penguin breeding populations estimated by aerial photography.* In, Kerry, K. R. and Hempel, G. eds. Antarctic ecosystems, ecological change and conservation. Springer, pp. 169 – 176.

Kumar, R.S., Johnson, J.A. 2014. Aerial surveys for pack-ice seals along the Ingrid Christensen and Princess Astrid Coasts, East Antarctica. *Journal of Threatened Taxa*, 6, 9. DOI, http,//dx.doi.org/10.11609/JoTT.o3817.6230-8

LaRue, M.A., Kooyman, G., Lynch, H.J., Fretwell, P. 2014. Emigration in emperor penguins, implications for interpretation of long-term studies. *Ecography.* DOI: 10.1111/ecog.00990.

LaRue, M.A., Ainley, D.G., Swanson, M., Dugger, K.M., Lyver, P.O., et al. 2013. Climate Change Winners, Receding Ice Fields Facilitate Colony Expansion and Altered Dynamics in an Adélie Penguin Metapopulation. *PloS one* 8, 4, e60568.

LaRue, M.A., Lynch, H.J., Lyver, P.O.B., Barton, K., Ainley, D.G., et al. 2014. A method for estimating colony sizes of Ad,lie penguins using remote sensing imagery. *Polar biology* 37, 507-517.

LaRue, M.A., Rotella, J.J., Garrott, R.A., Siniff, D.B.. Ainley, D.G. et al. "Satellite imagery can be used to detect variation in abundance of Weddell seals Leptonychotes weddellii. in Erebus Bay, Antarctica." *Polar Biology* 34, 11, 2011., 1727-1737

Larue, M.A., & Knight, J. 2014. Applications of Very High-Resolution Imagery in the Study and Conservation of Large Predators in the Southern Ocean. *Conservation Biology* 28, 1731-1735.

Lynch. H.J., White, R., Black, A.D., Naveen, R. 2012. Detection, differentiation, and abundance estimation of penguin species by high-resolution satellite imagery. *Polar biology* 35, 963-968.

Lynch, H.J., LaRue, M.A. 2015. First global census of the Adélie Penguin vol 131, pg 457, 2014. *Auk* 132, 562-562.

Leyequien, E., Verrelst, J., Slot, M., Schaepman-Strub, G., Heitkonig, I.M.A., et al. 2007. Capturing the fugitive, Applying remote sensing to terrestrial animal distribution and diversity *International Journal of Applied Earth Observation and Geoinformation* 9, 224-224.

Lillesand, T.M., Kiefer, R.W., Chipman, J.W. 2008. *Remote sensing and image interpretation.* Hoboken, NJ, John Wiley & Sons. 12, 756-776 pp

Lindeman, R.L. 1942. The trophic-dynamic aspect of ecology. *Ecology* 23, 4, 399-417.

MacKenzie, D.I., Nichols, J.D., Lachman, G.B., Droege, S., Royle, J.A., et al. 2002. Estimating site occupancy rates when detection probabilities are less than one. *Ecology* 83, 2248-2255.

McMahon, C.R., Howe, H., van den Hoff, J., Alderman, R., Brolsma. H., et al. 2014. Satellites, the All-Seeing Eyes in the Sky, Counting Elephant Seals from Space. *PloS one* 9, 3, e92613. doi:10.1371/journal.pone.0092613.

Mittermeier, R. A., Myers, N., Thomsen, J. B., Da Fonseca, G. A. B., & Olivieri, S. 1998. Biodiversity Hotspots and Major Tropical Wilderness Areas, Approaches to Setting Conservation Priorities. *Conservation Biology*, 12, 516–520. doi, 10.1046/j.1523-1739.1998.012003516.x

Monnett, C., & Gleason, J.S. 2006. Observations of mortality associated with extended open-water swimming by polar bears in the Alaskan Beaufort Sea. *Polar Biology* 29.8 681-687.

Mougin, J.L., 1966. Observations e cologiques a la colonie de manchots empereurs de Pointe Gelologie Terre Adélie. en 1964. *Oiseau Rev Fr Ornithol* 36, 3–4.166–226

Mustafa, O., Pfeifer, C., Hans-Ulrich, P., Kopp, M., Metzig, R. 2012. Pilot study on monitoring climate induced changes in penguin colonies in the Antarctic using satellite images N.C.a.N.S. German Federal Ministry of the Environment Ed.

Naveen, R., Lynch, H. J., Forrest, S., Mueller, T., & Polito, M. 2012. First, complete site-wide penguin survey at Deception Island, Antarctica reveals massive declines consistent with climate change. *Polar Biology* 35 12 1879-1888.

Nellemann, C., Vistnes, I., Jordhoy, P., Strand, O. 2001. Winter distribution of wild reindeer in relation to power lines, roads and resorts. *Biological Conservation* 101, 351-360.

Pettorelli, N., Safi, K., Turner, W. 2014. Satellite remote sensing, biodiversity research and conservation of the future. *Philosophical Transactions of the Royal Society B-Biological Sciences* 369.

Pimm, S.L. Food webs. Springer, Netherlands, 1982.

Platt, T. 1986. Primary Production of the Ocean Water Column as a Function of Surface Light-Intensity - Algorithms for Remote-Sensing. *Deep-Sea Research Part a-Oceanographic Research Papers* 33, 149-163.

Sanchez, R.D. & Kooyman, G.L. 2004. Advanced systems data for mapping Emperor Penguin habitats in antarctica, U.S. Geological Survey Open-File Report 2004–1379, 8 p. available only online at http,//pubs.usgs.gov/of/2004/1379/.

Hall, S., Kauffman, M.J., Nielson, R.M. & Horne. J.S. 2009. Identifying and prioritizing ungulate migration routes for landscape-level conservation. *Ecological Applications* 19, 8, 2016-2025.

Schwaller, M.R., Benninghoff, W.S., Olson C.E. 1984. Prospects for satellite remote-sensing of Adélie penguin rookeries. *International Journal of Remote Sensing* 5. 849–853

Schwaller, M. R., Olson, C. E., Jr. Benninghoff, W. S., & Whenes, K. M. 1987. Preliminary report on satellite remote sensing of Adélie penguin rookeries, Antarct. 1. U.S. 21,205-206.

Schwaller, M.R., Olson, C.E., Ma, Z.Q., Zhu, Z.L., Dahmer, P. 1989. A remote-sensing analysis of Adélie penguin rookeries. *Remote Sensing of Environment*, 28, 199–206

Schwaller, M.R., Southwell, C.J., Emmerson, L.M. 2013. Continental-scale mapping of Adélie penguin colonies from Landsat imagery. *Remote Sensing of Environment* 139, 353-364.

Southwell, C., McKinlay, J., Low, M., Wilson, D., Newbery, K., et al. 2013. New methods and technologies for regional-scale abundance estimation of land-breeding marine animals, application to Adélie penguin populations in East Antarctica. *Polar biology* 36, 843-856.

Southwell, C.J. & Emmerson, L.M. 2013. New counts of Adélie penguin populations at Scullin and Murray monoliths, Mac. Robertson Land, East Antarctica. *Antarctic Science* 25, 381-384.

Southwell, C. & Emmerson, L. 2013. Large-scale occupancy surveys in East Antarctica discover new Adélie penguin breeding sites and reveal an expanding breeding distribution. *Antarctic Science* 25, 531-535.

Southwell, C., de la Mare, B., Borchers, D., Burt, L. 2004. Shipboard line transect surveys of crabeater seal abundance in the pack-ice off east Antarctica, Evaluation of assumptions. *Marine Mammal Science* 20, 602-620.

Southwell, C. J., Bengtson, M., Bester, A., Schytte-Blix, H., Bornemann, P., at al. 2012. Southern Ocean ice-breeding seals. *CCAMLR Science* 19, 1–49

Stapleton, S., LaRue, M.A, Lecomte, N., Atkinson, S., Garshelis, D., et al. 2014. Polar Bears from Space, Assessing Satellite Imagery as a Tool to Track Arctic Wildlife. *PloS one* 9, 7, e101513. doi:10.1371/journal.pone.0101513

Stonehouse, B. 1969. Air census of two colonies of Adélie penguins Pygoscelis adeliae. in Ross Dependency, Antarctica. *Polar Record* 14, 91, 471-475.

Trathan P.N., Fretwell, P.T., 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

Tucker, C.J. 1980. Remote-Sensing of Leaf Water-Content in the near-Infrared. *Remote Sensing of Environment* 10, 23-32.

Turner, W. 2014. Sensing biodiversity. *Science* 346, 301-302.

Turner, W., Spector, S., Gardiner, N., Fladeland, M., Sterling, E., et al. 2003. Remote sensing for biodiversity science and conservation. *Trends in Ecology & Evolution* 18, 306-314.

Vistnes, I.I., Nellemann, C., Jordhøy, P. & Støen, O.G. 2008. Summer distribution of wild reindeer in relation to human activity and insect stress. *Polar Biology*, 31, 11, 1307-1317.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M. 1997. Human domination of Earth's ecosystems. *Science* 277, 5325,494-499.

Wackernagel, M., & Rees, W. 1998. *Our ecological footprint, reducing human impact on the earth.* No. 9. New Society Publishers.

Waluda, C.M., Dunn, M.J., Curtis, M.L., Fretwell, P.T. 2014. Assessing penguin colony size and distribution using digital mapping and satellite remote sensing. *Polar biology* 37, 1849-1855.

Wienecke, B. 2010. The history of the discovery of emperor penguin colonies, 1902–2004 *Polar Record* 46, 271–276.

Wiig, O., Derocher, A.E. 1999. Application of aerial survey methods to polar bears in the Barents Sea. Marine Mammal Survey and Assessment Methods, 27-36.

Williams, M. & J.A. Dowdeswell. 1998. Mapping seabird nesting habitats in Franz Josef Land, Russian high Arctic, using digital Landsat Thematic Mapper imagery. *Polar Research* 17, 15-31.

Woehler, E.J. 1993. *The distribution and abundance of Antarctic and Subantarctic penguins.* Scientific Committee on Antarctic Research, Cambridge.

Woehler, E.J. & Riddle, M.J. 1998. Spatial relationships of Adélie penguin colonies, Implications for assessing population changes from remote imagery Antarctic Science, 10, 449–454.

Yang, Z., Wang, T., Skidmore, A., de Leeuw, J., Said, M., Freer, J. 2015. Spotting East African Mammals in Open Savannah from Space. PLoS one DOI, 10.1371/journal.pone.0115989

Papers to be considered:

1) Detecting and mapping vegetation distribution on the Antarctic Peninsula from remote sensing data (2011)

Although this paper was published sometime after my first penguin paper, my first scientific work on remote sensing was using Landsat data to map Antarctic vegetation. I therefore include this paper as an introduction to later work on wildlife as it uses Landsat data in a similar way.

Whilst mapping parts of the Antarctic Peninsula I noticed that I could clearly see the "red edge" of vegetation in the near-infra-red band of Landsat ETM+ images. At the time, although remote sensing for vegetation mapping and monitoring was well established in other regions, no remote sensing studies of Antarctic vegetation existed. The sparse nature of Antarctic vegetation, combined with the low verdancy of the typical mosses and lichens that comprise assemblages on the continent make vegetation impossible to differentiate using coarser satellite sensors (MODIS, AVHRR etc.). However, useful results are obtainable with higher spatial resolution platforms such as Landsat, especially with targeted acquisitions. I instigated a project over an area in Marguerite Bay to test NDVI values in Landsat ETM+ against ground-truthing data collected opportunistically in the field by BAS colleagues. The results were very promising, and showed that vegetation could be differentiated from the surrounding rock even at very low NDVI values.

I then analysed Landsat imagery covering much of the northern Antarctic Peninsula to map the distribution and intensity of vegetation. This was the first time satellite imagery had been used to map vegetation and provided a method to quantify vegetation verdancy in the region. I gave a paper about this work at the 2008 RSPSoc symposium and won the inaugural President's Prize for best presentation. The work introduced me to the science of applied remote sensing in Antarctica and the background to this study influenced my later papers. Due to my ongoing penguin work this paper was published in 2011 in *Polar Biology* (impact factor 2.071); it has now been cited 25 times. The method has since been used in the 2014 WWF RACER (Rapid Assessment of Circum-

Arctic Ecosystem Resilience) study to highlight regions of ecological resilience (given as a working paper at the Antarctic Treaty Consultative Meeting (ATCM) 2014).

My vegetation analysis was important because it shows that even low density and intensity vegetation can be distinguished from rock and guano allowing us to map vegetation in remote areas and over large regional scales and define baselines to assess future assessment of change.

2) Penguins from space: faecal stains reveal the location of emperor penguin colonies (2009)

This can be considered a breakthrough paper in many respects. It had a similar genesis to the vegetation work – whilst using Landsat imagery for mapping I realised I could see red/brown staining on the sea ice. Following discussions with BAS ecologists and after checking published literature; I showed that the stains matched with the location of some known emperor penguin colonies: we were seeing the guano deposits left by the penguins. Emperor penguins are notoriously difficult to find and study by traditional field-study means; they breed on fast sea ice, in the extreme climate conditions of the Antarctic winter. By the summer, when scientists arrive, most of the emperors will have left their breeding sites and the sea ice will often have melted leaving no trace of the colony. A quote from the eminent Australian penguin expert Barbara Wienecke in 2009 before our work was published sums up the situation *"As we have no firm understanding of the number of existing breeding colonies, we cannot estimate the size or trends of the global population of emperor penguins"*. This was a problem, as the species' reliance on sea ice suggested that the species would face rapid reduction in population if current predictions of future climatic warming in Antarctica were true.

In October 2008, in conjunction with BAS ecologist Phil Trathan who supplied the biological knowledge of the species to help inform the study, I started a project to download Landsat images from the Landsat Image Mosaic of Antarctica (LIMA) of as much of the Antarctic coastlines as I could to visually and automatically identify these brown stains. However, in November 2008 NASA made the whole Landsat archive freely downloadable, so we were able to cover around 85 % of the Antarctic coastline using suitable imagery. This was the first continental scale survey of wildlife in this way. We found ten new colony locations, raising the number of known colonies from 28 to 38, confirmed many others and re-drew the distribution map for the species.

The paper, published in *Global Ecology and Biogeography* (impact factor 7.242), won many plaudits: it was awarded Faculty1000 status for the best biological papers; there were parliamentary questions Prime Minister's Questions about Britain's work on emperor penguins; it led to funds from the British Antarctic Territories fund to do more research; it was included, along with LIMA, as one of the top ten scientific achievements of the 40-year NASA Global Landsat mission and, several Antarctic Treaty Consultative Meeting papers were generated as a result of the papers findings. The paper has been cited 66 times in the last 5 years. Crucially the paper identified the locations of colonies so that further work could be done on them.

3) An emperor penguin population estimate: the first global, synoptic survey of a species from space (2012)

Once I had identified the majority of emperor colony locations I took advantage of an opportunity to count these colonies using high spatial resolution satellite imagery and so provide a global population estimate for the species. Jerry Kooyman, an eminent USA penguin biologist, had already started this work, but his results were only partially successful. I realised that by pan-sharpening the imagery we would improve on his results. In 2009 I tasked the image provider Digital Globe to take imagery of every known and suspected penguin colony location and to cover the areas not already imaged in our Landsat survey. I created and tested an improved classification method to improve emperor classification routines from the VHR imagery. Myself and workers from the US Polar Geospatial Center in Minneapolis then classified the images and collated the results. I gathered a group of emperor experts to help write the paper. In 2012 we published the census; the first synoptic survey of any species by satellite. We found six new colonies and produced a population estimate of 595,000 birds, almost twice the previous population estimate. The survey provided a rigorous method, using a consistent methodology from a single breeding season to calculate the numbers. Doubling the population estimate of such an iconic animal attracted attention from the media, scientists and policy makers. It also provided the impetus to attempt continent wide surveys of other species in the same way (similar Adélie penguin estimates have been published this year). The paper, published in PLoS One (impact factor 3.534) has been cited 99 times in the three years since publication. This, along with my previous emperor penguin work, led to a Scientific Committee on Antarctic Research (SCAR) Special Interest Group on Penguin Remote Sensing being set up, with its first meeting in summer 2013 on which I have been a leading participant. The new population estimate was instrumental in changing the status of the species in the IUCN Red List from "least concern" to "near threatened"

4) Emperor Penguins Breeding on Iceshelves (2014)

I have continued to monitor emperor penguins, and every year the satellite imagery provider, Digital Globe, has been tasked with collecting imagery over the colony areas in the expectation of a monitoring study when a sufficiently long time series has been acquired. Some of the images collected for this future analysis contained surprising information; several colonies were located, not on the sea ice as previously recognised, but on ice-shelves. By looking back at the archive of imagery and comparing results with sea ice data collected by synthetic aperture radar satellites I was able to show that, in at least one case, the colony moved onto the ice shelf when the sea ice formed late in the austral autumn – too late to be a stable platform when the emperors turned up at the breeding site. Some of the four colonies that displayed this behaviour bred on the ice-shelves every year, whilst others only did so when the ice conditions dictated. I published a paper in *PLoS One* (impact factor 3.534) highlighting and discussing this unusual behaviour with several of the scientists who were involved in my previous census work. Although only published in 2014 the paper had been cited 17 times. The paper has major implications for modelling the interactions of climate change with the ecological and demographic characteristics of emperor penguins, especially in relation to potential population change.

5) Using the unique spectral signature of guano to identify unknown seabird colonies

This paper explores the spectral signature of guano, testing lab spectra from penguin guano against a number of spectral libraries to show that the spectral profile of guano is unique. We then use spectral target-matching techniques from pixels of known penguin colonies to detect other pixels with similar spectra in a single Antarctic Landsat scene. The technique is very successful and finds all known penguin colonies and all known large seabird colonies in the area, it also identifies a number of potential unknown sites. We make the case that these methods, using remote sensing techniques to find seabirds, could be transferred to many other areas outside Antarctica, indeed we are already using the technique in a number of other projects. This paper has only just been published in Remote Sensing of Environment, 5 year impact factor 6.07, at the time of writing (January 2015). This paper was instigated by a question from one of the co-authors to me and on this paper I contributed all project development, analysis and writing.

The Future

I have several new innovative and important projects at various stages of completion these include:

1. SCAR Antarctic Pack Ice Seal Census II. This project, in collaboration with UK, Australian and US partners will use VHR satellite data and thermal data from UAVs to automate the counting of pack ice seals. It has already received grant funding from the Australian Research Council and a further bid is currently in progress.
2. UK Overseas Territories seabird census. Building on the VHR and guano work I propose to bid for Darwin funds to find and count seabird colonies in UK Overseas Territories, a joint project with RSPB. This has started with a small grant to count Northern royal albatross using VHR imagery on the Chatham Islands. A paper on counting wandering albatross, on which I am lead author, is about to be submitted.

3. Whale remote sensing. I have a variety of follow-on projects from our satellite whale work concentrating on right whales, Fin whales and humpbacks. This involved collaborating with the EU Ecopotential project to count Fin whales in the Mediterranean and a NERC Doctoral Training Partnership project with Cambridge University to recruit a new PhD student to study whales from space.

A number of other projects on seabirds, penguins, seals and whales both in Antarctica and other areas of the globe are under discussion with a range of organizations which underlines that there is great potential to transfer the use of direct and semi-direct observation to many other species. As with all technology, VHR satellite imagery will become cheaper over time and already new sensors such as WorldView4 are nearing launch which will alleviate some of the problems with over demand. There is pressure on the satellite industry from national bodies such as NASA and ESA to make imagery for "public good" such as non-profit conservation work freely available, as is already the case with disaster-relief imagery. If cheaper 30 cm spatial resolution imagery becomes available then many species of large birds, especially those which are rare, difficult to survey or endangered such as certain species of geese, bustards, pelicans, albatross, flamingos and frigate birds can be counted by SRS. Large mammals are also a possibility; African ungulates have already been successfully counted using 50cm imagery so higher spatial resolution would improve detection rates and increase the number of species possible. Wildebeest, zebra, elephant, rhino, giraffe and buffalo would all be possible and, with the use of automated change detection, it may also be possible to detect smaller animals such as important predator species and more camouflaged species. The ability of timed acquisition to target low sun angles which give long shadows for ease of detection and "tell-tale" profile-shapes from downward point sensors would also be advantageous.

Offshore it may be possible to target many species of whales, especially those breeding in calmer waters; right whale, humpback whales, grey whales and beluga whales are species that have this trait. I am already investigating the possibility of finding large dolphin pods by detecting the common characteristic splash patterns left by large number of jumping dolphins. Dugongs have already been surveyed using long range UAVs, these, and several species of manatee, that are often found at the surface in calm waters would also be good targets.

Animals in difficult to survey regions such as deserts or mountains would suit these techniques; wolves in mountainous regions could be targeted in winter snow by change detection methods, while camel, oryx, ibex, the Mongolian wild ass, the Saharan cheetah and several other endangered desert-dwellers could be targeted by change and shadow-detection from VHR satellite imagery over large areas. These desert and mountain species often range over wide territories, so the broad coverage of satellite data are advantageous.

Conclusion

Here I present five peer reviewed scientific papers on which I have been first author that have uniform thread or remote sensing wildlife in Antarctica. The first paper, identifying vegetation, is included as an introduction, and as an insight into my own development in the subject area. The overall aim of my work has been to develop and apply new satellite remote sensing methods to answer critical questions on the distribution and abundance of Antarctic wildlife. The five papers display a distinct progression, becoming more technical as my own knowledge and remote sensing skill-set has increased. I have utilized these remote sensing techniques on a number of other papers and projects that are not included within this thesis. These include identifying whales using VHR imagery, correlating Antarctic sea ice loss with the decline of an emperor penguin colony, classifying pygoscelis penguins by satellite on the South Orkney Islands and two other papers discussing the distribution of emperor penguins found by satellite. Two of these papers, “First recorded loss of an emperor penguin colony in the recent period of Antarctic regional warming: implications for other colonies” and “Whales from space: counting southern right whales by satellite” are included as appendices at the end of this manuscript, the others are highlighted within the full list of publish papers below.

The five papers included in this thesis have had a considerable impact on the fields of Antarctic remote sensing, especially for penguin studies where remote sensing is now considered an essential tool. Our knowledge of emperor penguins; their distribution, population and behaviour, has changed markedly with, and since, the publication of these papers. I hope that future efforts using remote sensing can also address the question of emperors' response to climate change and how their populations will change as Antarctica warms.

Overall, the advances I have made in using remote sensing to identify, count and monitor Antarctic Wildlife have had a significant impact in the field of conservation remote sensing. Understanding Antarctic populations and detecting changes is of growing importance as climate change is predicted to impact on many Antarctic species in the coming decades. Additionally, the need for predator population estimates to manage fisheries and ecosystem resources in the southern ocean means that the need for accurate predator population assessment in and around Antarctica is vitally important. My work on remote sensing of wildlife facilitates these requirements.

Peter Fretwell, February, 2016

Full list of published papers:

Ancel, André, Robin Cristofari, Peter T Fretwell, Phil N Trathan, Barbara Wienecke, Matthieu Boureau, Jennifer Morinay, et al. "Emperors in Hiding: When Ice-Breakers and Satellites Complement Each Other in Antarctic Exploration." PloS one 9, no. 6 (2014): e100404.

Atkinson, A, V Siegel, EA Pakhomov, P Rothery, V Loeb, RM Ross, LB Quetin, et al. "Oceanic Circumpolar Habitats of Antarctic Krill." Mar Ecol Prog Ser 362, no. 1 (2008): 23.

Barnes, David KA, Martin Anthony Collins, P Brickle, Peter Fretwell, Huw J Griffiths, David Herbert, Oliver T Hogg, and Chester J Sands. "The Need to Implement the Convention on Biological Diversity at the High Latitude Site, South Georgia." Antarctic Science 23, no. 04 (2011): 323-31.

Belchier, M, and P Fretwell. "Revised Estimates of the Area of the South Georgia and Shag Rocks Shelf (Ccamlr Subarea 48.3)." CCAMLR Science 16 (2009): 167-75.

Black, Martin, Andrew Fleming, Teal Riley, Graham Ferrier, Peter Fretwell, John McFee, Stephen Achal, and Alejandra Umana Diaz. "On the Atmospheric Correction of Antarctic Airborne Hyperspectral Data." Remote Sensing 6, no. 5 (2014): 4498-514.

Martin Black, Teal R. Riley, Graham Ferrier, Andrew H. Fleming, Peter T. Fretwell

"Automated lithological mapping using airborne hyperspectral thermal infrared data: A case study from Anchorage Island, Antarctica" Remote Sensing of Environment, Volume 176, (2016), 225-241

Casanovas, Paula; Black, Martin; Fretwell, Peter; Convey, Peter "Mapping lichen distribution on the Antarctic Peninsula using remote sensing, lichen spectra and photographic documentation by citizen scientists" Polar Research, 34, (2015), 25633, http://dx.doi.org/10.3402/polar.v34.25633

Cooper, A Paul R, and Peter Fretwell. "A Placename Geography for Antarctica." Bulletin of the Society of Cartographers 37, no. 2 (2003): 53-55.

Dawson, Alastair G, Shaun Hampton, Peter Fretwell, Stephan Harrison, and Peter Greengrass. "Defining the Centre of Glacio-Isostatic Uplift of the Last Scottish Ice-Sheet: The Parallel Roads of Glen Roy, Scottish Highlands." Journal of Quaternary Science 17, no. 5-6 (2002): 527-33.

Downie, Roderick H, and Peter T Fretwell. "Antarctic Peninsula." (2007).

Fretwell, P, IR Peterson, and DE Smith. "The Use of Gaussian Trend Surfaces for Modelling Glacio-Isostatic Crustal Rebound." Scottish Journal of Geology 40, no. 2 (2004): 175-79.

Fretwell, PT, RA Phillips, M de L Brooke, AH Fleming, and A McArthur. "Using the Unique Spectral Signature of Guano to Identify Unknown Seabird Colonies." Remote Sensing of Environment 156 (2015): 448-56.

Fretwell, P, Hamish D Pritchard, David G Vaughan, JL Bamber, NE Barrand, R Bell, C Bianchi, RG Bingham, DD Blankenship, G Casassa, G Catania, D Callens, H Conway, AJ Cook, HFJ Corr, Detlef Damaske, V Damm, F Ferraccioli, René Forsberg, S Fujita, Y Gim, P Gogineni, JA Griggs, RCA Hindmarsh, Per Holmlund, JW Holt, RW Jacobel, A Jenkins, W Jokat, T Jordan, EC King, J Kohler, W Krabill, M Riger-Kusk, KA Langley, G Leitchenkov, C Leuschen, BP Luyendyk, K Matsuoka, J Mouginot, FO Nitsche, Y Nogi, OA Nost, SV Popov, E Rignot, DM Rippin, A Rivera, Jason Roberts, N Ross, MJ Siegert, AM Smith, D Steinhage, M Studinger, B Sun, BK Tinto, BC Welch, D Wilson, DA Young, C Xiangbin, A Zirizzotti "Bedmap2: Improved Ice Bed, Surface and Thickness Datasets for Antarctica." The Cryosphere 7, no. 1 (2013): 375-93.

Fretwell, Peter, Norman Ratcliffe, and Phil Trathan. "A Global Estimate of Emperor Penguin Population Size." (2012).

Fretwell, PT, DE Smith, and S Harrison. "The Last Glacial Maximum British–Irish Ice Sheet: A Reconstruction Using Digital Terrain Mapping." Journal of Quaternary Science 23, no. 3 (2008): 241-48.

Fretwell, PT, AJ Tate, TJ Deen, and Mark Belchier. "Compilation of a New Bathymetric Dataset of South Georgia." Antarctic Science 21, no. 02 (2009): 171-74.

Fretwell, Peter T, Peter Convey, Andrew H Fleming, Helen J Peat, and Kevin A Hughes. "Detecting and Mapping Vegetation Distribution on the Antarctic Peninsula from Remote Sensing Data." Polar biology 34, no. 2 (2011): 273-81.

Fretwell, Peter Thomas, DA Hodgson, EP Watcham, MJ Bentley, and SJ Roberts. "Holocene Isostatic Uplift of the South Shetland Islands, Antarctic Peninsula, Modelled from Raised Beaches." Quaternary Science Reviews 29, no. 15 (2010): 1880-93.

Fretwell, Peter T, Michelle A LaRue, Paul Morin, Gerald L Kooyman, Barbara Wienecke, Norman Ratcliffe, Adrian J Fox, et al. "Correction: An Emperor Penguin Population Estimate: The First Global, Synoptic Survey of a Species from Space." PloS one 7, no. 4 (2012).

Fretwell, Peter T, Iain J Staniland, and Jaume Forcada. "Whales from Space: Counting Southern Right Whales by Satellite." PloS one 9, no. 2 (2014): e88655.

Fretwell, Peter T, and Philip N Trathan. "Penguins from Space: Faecal Stains Reveal the Location of Emperor Penguin Colonies." Global Ecology and Biogeography 18, no. 5 (2009): 543-52.

Fretwell, Peter T, Phil N Trathan, Barbara Wienecke, and Gerald L Kooyman. "Emperor Penguins Breeding on Iceshelves." PloS one 9, no. 1 (2014): e85285.

Fretwell, Peter T "Cryosphere: Entry beneath Ice" Nature Geoscience 8 (4), (2015): 253-254

Graham, Alastair GC, Peter T Fretwell, Robert D Larter, Dominic A Hodgson, Christian K Wilson, Alex J Tate, and Peter Morris. "A New Bathymetric Compilation Highlighting Extensive Paleo–Ice Sheet Drainage on the Continental Shelf, South Georgia, Sub-Antarctica." Geochemistry, Geophysics, Geosystems 9, no. 7 (2008).

Grant, SM, SL Hill, and PT Fretwell. "Spatial Distribution of Management Measures, Antarctic Krill Catch and Southern Ocean Bioregions: Implications for Conservation Planning." CCAMLR Science 20 (2013): 1-19.

Haselwimmer, Christian, and Peter Fretwell. "Field Reflectance Spectroscopy of Sparse Vegetation Cover on the Antarctic Peninsula." Paper presented at the Hyperspectral Image and Signal Processing: Evolution in Remote Sensing, 2009. WHISPERS'09. First Workshop on, 2009.

Hodgson, Dominic A, Michael J Bentley, Christoph Schnabel, Andreas Cziferszky, Peter Fretwell, Peter Convey, and Sheng Xu. "Glacial Geomorphology and Cosmogenic 10be and 26al Exposure Ages in the Northern Dufek Massif, Weddell Sea Embayment, Antarctica." Antarctic Science 24, no. 04 (2012): 377-94.

Hoffman, Joseph I, Andy Clarke, Melody S Clark, Peter Fretwell, and Lloyd S Peck. "Unexpected Fine-Scale Population Structure in a Broadcast-Spawning Antarctic Marine Mollusc." PloS one 7, no. 3 (2012): e32415.

Hughes, Kevin A, Peter Fretwell, Joanna Rae, Keith Holmes, and Andrew Fleming. "Untouched Antarctica: Mapping a Finite and Diminishing Environmental Resource." Antarctic Science 23, no. 06 (2011): 537-48.

LaRue, Michelle A, Gerald Kooyman, Heather J Lynch, and Peter Fretwell. "Emigration in Emperor Penguins: Implications for Interpretation of Long-Term Studies." Ecography (2014).

Martin, AR, S Poncet, Christophe Barbraud, E Foster, P Fretwell, and P Rothery. "The White-Chinned Petrel (Procellaria Aequinoctialis) on South Georgia: Population Size, Distribution and Global Significance." Polar biology 32, no. 4 (2009): 655-61.

Leat, P.T., Fretwell, P.T., Tate, A.J., Larter, R.D., Martin, T.J., Smellie, J.L., Jokat, W., Bohrmann, G."Bathymetry and Geological Setting of the South Sandwich Islands Volcanic Arc" Antarctic Science, (accepted manuscript in press February 2016)

Murphy, EJ, EE Hofmann, JL Watkins, NM Johnston, A Pinones, T Ballerini, SL Hill, SL Hill, PN Trathan, GA Tarling, RA Cavanagh, EF Young, SE Thorpe, P Fretwell "Comparison of the Structure and Function of Southern Ocean Regional Ecosystems: The Antarctic Peninsula and South Georgia." Journal of Marine Systems 109 (2013): 22-42.

Newsham, Kevin K.; Hopkins, David W.; Carvalhais, Lilia C.; Fretwell, Peter T.; Rushton, Steven P.; O'Donnell, Anthony G.; Dennis, Paul G.. “Relationship between soil fungal diversity and temperature in the maritime Antarctic.” *Nature Climate Change.* 10.1038/nclimate2806 (2015)

Rose, Kathryn C, Fausto Ferraccioli, Stewart SR Jamieson, Robin E Bell, Hugh Corr, Timothy T Creyts, David Braaten, et al. "Early East Antarctic Ice Sheet Growth Recorded in the Landscape of the Gamburtsev Subglacial Mountains." Earth and Planetary Science Letters 375 (2013): 1-12.

Smellie, JL, WC McIntosh, R Esser, and P Fretwell. "The Cape Purvis Volcano, Dundee Island (Northern Antarctic Peninsula): Late Pleistocene Age, Eruptive Processes and Implications for a Glacial Palaeoenvironment." Antarctic Science 18, no. 03 (2006): 399-408.

Smith, DE, RA Cullingford, TM Mighall, JT Jordan, and PT Fretwell. "Holocene Relative Sea Level Changes in a Glacio-Isostatic Area: New Data from South-West Scotland, United Kingdom." Marine geology 242, no. 1 (2007): 5-26.

Smith, DE, N Hunt, CR Firth, JT Jordan, PT Fretwell, M Harman, J Murdy, JD Orford, and NG Burnside. "Patterns of Holocene Relative Sea Level Change in the North of Britain and Ireland." Quaternary Science Reviews 54 (2012): 58-76.

Smith, DE, S Shi, RA Cullingford, AG Dawson, S Dawson, CR Firth, IDL Foster, et al. "The Holocene Storegga Slide Tsunami in the United Kingdom." Quaternary Science Reviews 24, no. 3 (2005): 2291-322.

Smith, DE, S Shi, RA Cullingford, Alastair G Dawson, S Dawson, CR Firth, Ian DL Foster, et al. "The Holocene Storegga Slide Tsunami in the United Kingdom." Quaternary Science Reviews 23, no. 23 (2004): 2291-321.

Smith, David E, Peter T Fretwell, Robin A Cullingford, and Callum R Firth. "Towards Improved Empirical Isobase Models of Holocene Land Uplift for Mainland Scotland, Uk." Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 364, no. 1841 (2006): 949-72.

Tarling, Geraint A, Natalie S Ensor, Torsten Fregin, William P Goodall-Copestake, and Peter Fretwell. "1 an Introduction to the Biology of Northern Krill (Meganyctiphanes Norvegica Sars)." Advances in marine biology 57 (2010): 1.

Trathan, Philip N, Peter T Fretwell, and Bernard Stonehouse. "First Recorded Loss of an Emperor Penguin Colony in the Recent Period of Antarctic Regional Warming: Implications for Other Colonies." PloS one 6, no. 2 (2011): e14738.

Vaughan, David G, David KA Barnes, Peter T Fretwell, and Robert G Bingham. "Potential Seaways across West Antarctica." Geochemistry, Geophysics, Geosystems 12, no. 10 (2011).

Wakefield, Ewan D, Richard A Phillips, and Mark Belchier. "Foraging Black-Browed Albatrosses Target Waters Overlaying Moraine Banks-a Consequence of Upward Benthic-Pelagic Coupling?". Antarctic Science 24, no. 03 (2012): 269-80.

Waluda, Claire M, Michael J Dunn, Michael L Curtis, and Peter T Fretwell. "Assessing Penguin Colony Size and Distribution Using Digital Mapping and Satellite Remote Sensing." Polar biology 37, no. 12 (2014): 1849-55.

Watcham, EP, MJ Bentley, DA Hodgson, SJ Roberts, PT Fretwell, JM Lloyd, RD Larter, et al. "A New Holocene Relative Sea Level Curve for the South Shetland Islands, Antarctica." Quaternary Science Reviews 30, no. 21 (2011): 3152-70.

Polar Biol (2011) 34:273–281
DOI 10.1007/s00300-010-0880-2

ORIGINAL PAPER

Detecting and mapping vegetation distribution on the Antarctic Peninsula from remote sensing data

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Received: 20 March 2009 / Revised: 20 July 2010 / Accepted: 9 September 2010 / Published online: 10 October 2010

Abstract We present the first regional map of vegetation of anywhere on the Antarctic continent based on remote sensing (RS) data. We have used a normalized difference vegetation index (NDVI) for the examination of Landsat ETM data on the Antarctic Peninsula. The results show that 44.6 km^2 (0.086%) of the study area (74,468 km^2) is classed with a probability of vegetation of over 50%. The NDVI analysis is ground-truthed against vegetation surveys in Ryder Bay on the Antarctic Peninsula, and the results have been corrected for several factors influencing low NDVI readings in this environment. This methodology has been applied to 13 Landsat scenes covering Graham Land in the Northern part of the Antarctic Peninsula to examine the distribution of vegetation in the region. The Antarctic Peninsula region is important, as it has shown rapid warming of over 3°C during the past 50 years, and predictions indicate accelerated future warming. A baseline survey of the amount and distribution of vegetation is required against which to monitor future change. The results give a comprehensive coverage and allow us to present the first remote sensing-based vegetation map in Antarctica. However, initial results point to the need for further investigation of apparent errors resulting from geology on bare ground.

Keywords Remote sensing · Vegetation mapping · Climate change · Regional warming · *Deschampsia antarctica* · NDVI · Antarctica

Introduction

The Antarctic Peninsula region has shown rapid warming in recent decades, station records show that mean temperature has warmed by 3.7°C (century)$^{-1}$ (Vaughan et al. 2003). Predictions of change in the next 50 years include a more than doubling the days when melt can occur in the region (Vaughan 2006). This climatic change has led, and will continue to lead, to higher summer-growing season temperatures and an increase in the amount of available water, thereby relaxing two of the abiotic constraints on biological activity, along with an increase in the duration of the active or growing season (Convey 2003, 2006; but see also discussion on possible adverse effects in some circumstances in the latter review). The warming has also led to thinning (Pritchard and Vaugan 2007) and recession in local ice-caps and glaciers (Cook et al. 2005), exposing new bare ground for colonization by terrestrial biota (Convey and Smith 2006).

Predictions of changes in vegetation due to these changing environmental conditions were first put forward in the 1980s and early 1990s (Roberts 1989; Smith and Steenkamp 1990; Voytek 1990; Kennedy 1995). The two most consistently proposed predictions are of positive responses in indigenous species, through the general relaxation of current environmental constraints, and of colonization and establishment by exotic species, through the lowering of environmental barriers coupled with anthropogenic assistance in dispersal (Convey 2003, 2006; Frenot et al. 2005). Experiments and observations from the region

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Herbarium specimens and details of Antarctic collections can be found at: http://www.antarctica.ac.uk/bas_research/data/information_about_collections.php

Landsat 7 user handbook: http://landsathandbook.gsfc.nasa.gov/handbook.html

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generally confirm these predictions, describing colonization of newly exposed ground, and the expansion of populations of flowering plants in the recent past (Fowbert and Smith 1994; Smith 1994; Convey and Smith 2006). Future predictions suggest ongoing change and, in the longer term, that increased competition may lead to the loss of some indigenous species (Convey 1996).

Based on the exceptional rates of physical environmental change experienced over recent decades in parts of Antarctica and the simplicity and implied sensitivity of indigenous polar terrestrial ecosystems (e.g. Callaghan and Jonasson 1995; Freckman and Virginia 1997), the Antarctic Peninsula region has been highlighted as a globally important barometer for identifying the consequences of climate change (Convey et al. 2003). To monitor and assess future changes of Antarctic Peninsula vegetation, a robust quantitative baseline assessment of vegetation for the region is required. At present, no such assessment exists.

An overview of the vegetation of the Antarctic Peninsula region is provided by Smith (1996) and of Antarctic botanical records and general biogeographical patterns by Peat et al. (2007). The Antarctic Peninsula region is one of the most biodiverse terrestrial regions in the Antarctic but, detailed studies are limited to a few small areas, generally in the vicinity of established research stations (Chown and Convey 2007). Many ice-free areas are very sparsely vegetated, but in favourable locations such as sheltered north-facing slopes, closed stands of mosses and/or Antarctic hair grass (*Deschampsia Antarctica*) (one of only two flowering plants in Antarctica) covering 10s or occasionally 100s of square metres may be found.

Current knowledge on the distribution of the vegetation can be best determined from herbarium specimens. The British Antarctic Survey (BAS) Antarctic Plant Database, a database of Antarctic and sub-Antarctic herbarium specimens, contains 128,00 records of specimens from the Antarctic Peninsula region—4,700 moss specimens, 7,200 lichen specimens, with liverworts, flowering plants, fungi and algae forming the remainder. These records show that the majority of the vegetation is found at low altitudes on the western side of the Peninsula, particularly on its offshore islands, with much less vegetation on the colder, more heavily glaciated eastern side, and virtually none at altitude along the mountainous spine of the Peninsula. However, while collections have been made by over 200 collectors in the last 110 years, there remain many locations in this region, particularly those lacking safe landing sites from the sea, which have never been visited. Furthermore, many visits are likely to have been brief (typically, a few hours), and the majority of sites have not been visited by a botanist. Thus, the quality of data available and its geographic coverage remain extremely variable and patchy (Chown and Convey 2007). Even within the few areas where comprehensive collections of specimens have been made, there is generally very little quantitative information available on the detailed distribution and abundance of the vegetation.

The extent of the Antarctica Peninsula region (~420,000 km^2—twice that of Great Britain) and its remote, inaccessible and rugged nature means that ground-based survey methods are of limited utility. Therefore, satellite remote sensing (RS) methods that have regional and consistently repeatable coverage are the only practical means of mapping, monitoring and analysing vegetation distributions. This is especially true of the eastern side of the Antarctic Peninsula, an area experiencing rapid environmental change since the break-up of the Prince Gustav and Larsen Ice Shelves. In this study, we use normalized difference vegetation index (NDVI) to identify areas of vegetation; this index is based on the ratio of reflectance of visible red to near-infrared light.

Previous polar NDVI studies have used NOAA AVHRR data to analyse vegetation and phytomass over large-scale areas in the Arctic (Raynolds et al. 2006; Verbyla 2008). In these studies, data were intergrated into a 1.1 × 1.1 km grid—a cell size too coarse to analyse Antarctic Peninsula (AP) vegetation. Due to its patchy and sparse nature, almost all of the areas on the Antarctic Peninsula would show as un-vegetated using this method.

Attempts at vegetation analysis by RS in Antarctica have been extremely limited to date. Underlying this lack of application is the simple fact that the sparse and patchy nature of the typical Antarctic 'fellfield' vegetation that consists of fragmented growth of cryptogamic vegetation (mosses and lichens) interspersed with bare ground and rock (Smith 1984; Block et al. 2009).Orbiting RS satellite platforms with large pixel sizes (10s–100s m) cannot differentiate smaller or sparsely distributed vegetation. This problem is exacerbated by much of the vegetation consisting of lichens, whose symbiotic nature and structural morphology shield the chlorophyll contained in their algal cells, thus reducing the possibility of identification through RS. Nevertheless, spectral analysis of mosses and algae (Dana et al. 1994; Lovelock and Robinson 2002) shows the potential viability of identifying a variety of Antarctic vegetation types by their spectral reflectance. These studies utilized hand-held spectrometers, rather than satellite RS, but demonstrate that detection of these vegetation types using satellite RS is theoretically possible. In this study, we test and refine the application of RS, especially NDVI, in order to provide a new and more comprehensive baseline description of the extent of terrestrial vegetation on the Antarctic Peninsula. By comparing ground truthing and RS data in a test area, we derive likelihood thresholds for vegetation in the region, these thresholds are then used to map the distribution of vegetation across a wider study area.

Methods

Image-processing techniques using Landsat satellite imagery have been proven able to map the distribution of vegetation of temperate and tropical regions, typically consisting of higher plant types, but previous studies have not attempted to apply this index to the typical cryptogam-dominated or fellfield-type habitats of the Antarctic. These techniques rely on the different spectral response of vegetation to solar radiation at different parts of the electromagnetic (EM) spectrum, where absorbency by chlorophyll and the cellular structure of leaves results in low reflectance in the visible red wavelength and relatively high reflectance in the infrared wavelength (Billings and Morris 1951; Knipling 1970). The normalised difference vegetation index (NDVI) is based on a ratio of visible red light and near infrared; it can be written as NDVI = [(NIR − RED)/NIR + RED)] (Gates 1980) and is a commonly used index, giving values varying between −1.0 and +1.0. Values near +1 indicate pixels with very high chlorophyll content, those at zero or negative numbers indicate bare rock, snow or water. As it is based on a ratio of image bands, it has the effect of normalizing the effect of changing illumination, surface slope, aspect and other factors.

We converted the Landsat ETM + DN values to surface reflectance values (Lillesand and Keifer 1994, p. 14) using the SRFI.sml script (http://www.microimages.com/sml/SRFI.sml) and the TNTMips image-processing software. This corrects for varying illumination, it does not correct for atmospheric conditions, but the low atmospheric temperatures in Antarctica (rarely above +5°C) result in little atmospheric moisture without cloud formation. Using surface reflectance values is especially important when deriving accurate band ratio indices from multiple dates and locations. In this study, we used NDVI simply to detect the presence of vegetation, whereas its use in more quantitative assessments of biomass is more complex and needs to consider many other factors.

Remote sensing

We used the standard NDVI index to determine whether Antarctic terrestrial vegetation can be reliably detected using multispectral satellite imagery. Landsat ETM data were used exclusively for this analysis, thus giving a consistent dataset. The pixel size of these data in the multispectral bands is 30 m × 30 m. Even at this resolution, the sparse and variable nature of the typical Antarctic vegetation gives rise to several unique challenges. Calculation of the NDVI values used ESRI ArcGIS software. Initially, one Landsat ETM scene (scene path 220, row 107 acquired 19 February 2001) was used for ground truthing and to assess vegetation thresholds before expanding the methodology to other areas. NDVI values derived from the test scene were plotted against a detailed map of the area (British Antarctic Survey 2006). This map is photogrametrically compiled aerial photography and horizontally accurate to within 5 m. The Landsat scene was georeferenced using orbital parameters and was found to be ~50 m offset from the more detailed map data, so the scene was re-referenced using the detailed map coastline, making the data accurate to within 5 m. This process also enabled accurate positioning of GPS-collected ground-truth data.

Ground truthing

Two islands in Ryder Bay, Léonie Island and Anchorage Island, which have a well-studied terrestrial biology (e.g. Convey and Smith 1997; Bokhorst et al. 2007) and for which high-definition mapping is available, were chosen as appropriate locations to provide ground truthing for the NDVI values (Fig. 1). Léonie Island is a steep mountainous island, reaching 500 m in height and is ice-free on the North side. It has distinct patches of vegetation including the flowering plants, *Deschampsia antarctica* and *Colobanthus quitensis*, and a variety of bryophyte species (34 moss species and 3 liverwort species) have been recorded from the island. These vegetation patches occur on cliff terraces, mainly at altitudes of less than 100 m. Anchorage Island, in contrast, has a maximum altitude of 54 m and is largely unvegetated at altitudes of less than 20 m and lichen-covered at higher altitudes. It has much less-developed vegetation, consisting of small bryophyte-dominated patches

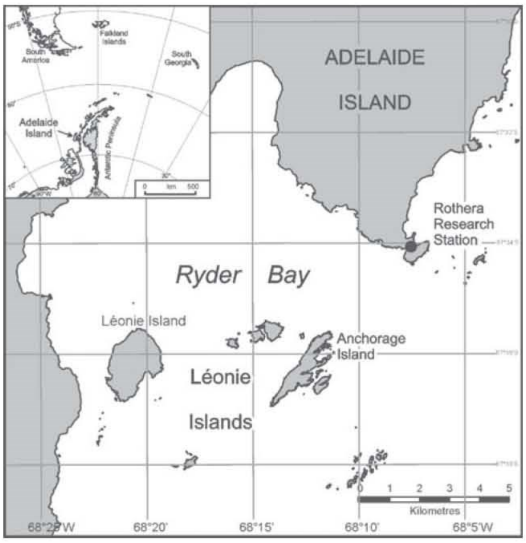

Fig. 1 Location map of ground-truthing area

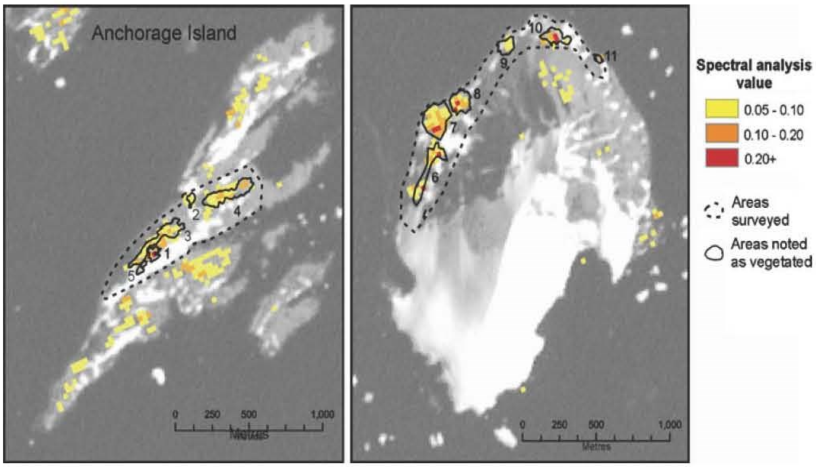

Fig. 2 Areas of vegetation on Anchorage and Léonie Island assess by ground truthing in comparison with NDVI values computed form Landsat imagery. *Dotted line* indicates area of ground survey, *solid line* indicates the areas assessed as vegetation on the ground survey. *Coloured pixels* refer to NDVI figures from the Landsat imagery. Numbers relate to areas in Table 1

(only 14 moss species and one liverwort species have been recorded), and very few grass (*Deschampsia antarctica*)-dominated patches. Most rock outcrops are lichen-covered, predominantly consisting of *Usnea* and *Umbilicaria* spp.

A hand-held Garmin GPS was used to provide ground truthing by walking round discrete patches of vegetation and saving the recorded track. Léonie Island was visited on 9 February 2007 when the ice-free part of the island was examined thoroughly and all large patches of continuous vegetation were mapped, with the exception of a few small patches (less than 10 m^2) located at high altitudes and difficult to access. One large discrete patch on particularly steep cliffs was difficult to access, and only the top edge of the patch was mapped and a visual estimate made of its extent (patch six and seven shown in Fig. 2). While there is a 6-year temporal difference between the vegetation ratios given by the remotely sensed data (2001) and this ground survey, vegetation on the Antarctic Peninsula is very slow growing (Smith 1996), and we consider that this will be a minor confounding influence on the data obtained and must be consider as a small but unquantifiable possible source of error in the larger study.

Anchorage Island was visited on 10 and 13 February 2007. Here, to enable the NDVI values of moss- and lichen-dominated areas to be compared, two discrete patches of moss vegetation and two patches of lichen vegetation were mapped. The second of the lichen tracks included a small, distinct area dominated by grass, but no areas dominated by moss. Finally, an area of algal vegetation on one of the island's beaches was mapped to assess whether the remote sensing data was likely to be sensitive to marine algal vegetation.

We compared the vegetation boundaries from this ground truthing with the NDVI values from the Landsat data by overlaying the two datasets onto the detailed map of the area (Fig. 2).

Results from ground truthing

Figure 3 shows the percentage of image pixels with each NDVI value that fall inside the vegetated polygon boundaries collected from the ground-truthing survey. The polygons noted as vegetated all contained variable amounts of moss or lichen. In this study, no assessment was made of percentage cover of the vegetation patches, and therefore we cannot quantify the density of vegetation within each pixel. The NDVI statistics in the ground-truthing area have been used to assess the likelihood of NDVI values from other areas identifying vegetation.

Only 28% of the pixels with NDVI values between 0.00 and 0.05 were within vegetated areas, this low value is

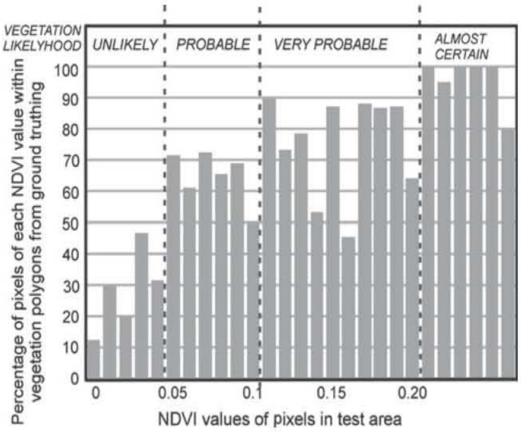

Fig. 3 Percentage of pixels falling within the area assessed as vegetated by ground truthing, in relation to their NDVI values. Each value along the *x* axis relates to a specific NDVI value, the *y* axis relates to the percentage of these values within areas classed as vegetation in the ground truthing. The data have been divided into four classes: below 0.05 NDVI is unlikely to be vegetated, between 0.05 and 0.1 is classed as probably vegetated, between 0.1 and 0.2 is classed as very probable and over 0.2 is classed as almost certain

considered to indicate either an absence of vegetation or extremely sparse coverage of vegetation. Conversely, over 50% of all pixels (with the exception of one value at 0.16 NDVI) with over 0.05 NDVI are within areas identified as vegetated. This percentage rises with higher NDVI, indicating higher probability of vegetation and/or higher cover within each pixel. Between 0.05 and 0.10 NDVI, 50–72% of pixels fall into vegetated areas. Between 0.1 and 0.2 NDVI, a mean of 87.3% of pixels are within vegetated areas, and with NDVI values above 0.2 the average rises to 95.9%.

In line with this reasoning, the dataset has been divided into four classes; NDVI values of less than 0.05 are considered unlikely to be vegetated. Above NDVI 0.05 is considered probably vegetated, above 0.1 is very probable and above 0.2 is classed as almost certain.

The variability of percentages of pixels within classes is due mainly to two causes. Firstly that of mixed pixels, and secondly due to the amount, type or amount of chlorophyll in that pixel.

Mixed pixels are a particular problem in the ground-truthing area (see Lillesand et al. 2004 for a futher discussion of mixed pixels). In the small test areas used in this study (two test areas totalling 0.7 km^2), with the small patches of vegetation sampled (21 areas of vegetation with a mean area of 0.009 km^2), it is inevitable that some of the Landsat pixels fall on either side of the edges of the ground-truthing polygons. Due to the small area of ground survey, several of the NDVI classes have a limited number of pixels in them; therefore, any single mixed pixels in these classes can give a bias to the percentage of pixels in that class. It would be advisable to use larger patches of vegetation, but the nature of vegetation at this latitude means that large areas of continuous vegetation cover are very rare and so preclude this option. The problem of mixed pixels may be exacerbated by small changes in vegetation between the collection of the ground-truthing data in 2007 and the acquisition of the imagery in 2001. Although vegetation changes in the Antarctic Peninsula are slow (Smith 1996), only small changes would be needed to create a noticeable number of mixed pixels in small test areas such as those used.

The second cause is whether higher NDVI values indicate greater coverage of vegetation or differing vegetation type. This problem is discussed in more detail later in this study. However, for the purposes of ground truthing, larger NDVI figures in this study are considered statistically more likely to be vegetation rather than noise or background readings from rock or soil.

Figure 2 shows satellite images of the two test areas indicating the areas of ground, superimposed upon this are the NDVI readings of each pixel from the landsat. These pixels are coloured depending upon the NDVI reading: 0.05–0.1 NDVI for probable vegetation, 0.1–0.2 for very probable and over 0.2 for almost certain. The maximum NDVI value for any cell in the survey area was 0.27 in area 11 on Léonie Island. All areas of high NDVI readings in the test area corresponded with areas identified as vegetation during the ground-truthing survey, although some overlap around the edges of vegetation polygons occurred.

Extending the study area

Having identified threshold levels for the NDVI of vegetation from the ground survey, the analysis was extended to cover a wider area. Thirteen Landsat ETM scenes acquired for the LIMA mosaic were chosen, covering the northern part of the Antarctic Peninsula (Graham Land). The three thresholds identified from the test area in Ryder Bay were then used to identify the distribution of sparse, medium and dense vegetation over this area.

Data quality control and possible confounding factors

It was apparent that a number of the selected scenes were widely saturated in band 3 and therefore unsuitable for use in the analysis since they did not indicate the real difference between band 4 and band 3. This caused widespread high NDVI values that were obviously false since they corresponded with snow and ice surfaces. Those scenes suffering from saturation all have high sun elevation angles (>34°), compared to the remaining useable images (<27°) and had low gain settings in band 4 (see Fig. 4, Table 2 for details). These unused scenes accounted for 20.2% of the rock outcrop in the study area. For comparability, only Landsat ETM + scenes with high gain settings in the first four bands were used in the final analysis.

Inspection of NDVI values obtained from the Landsat image of Ryder Bay identified some anomalous positive values that necessitated correction before the method could be applied to a wider area. High NDVI values at the edges of icebergs showed as anomalies. The values were almost exclusively single pixels that were associated with highly contrasted edges or boundaries (i.e. when passing from a very light to a very dark signal), when low positive NDVI values were returned, which were comparable to the readings obtained from vegetation. This was a frequent occurrence at the boundary between bright snow and shadow or at the edge of floating icebergs. We believe these anomalies result from differences in pixel values across sharp boundaries caused by the necessary resampling to a common grid due to band offsets in the ETM + instrument (Landsat 7 science user hand-book, see notes). Conversion from DN values to spectral reflectance values corrected for many of these anomalies in the data, with the remaining anomalous pixels confined to a small number at the edge of icebergs, a sea mask was used to remove these pixels.

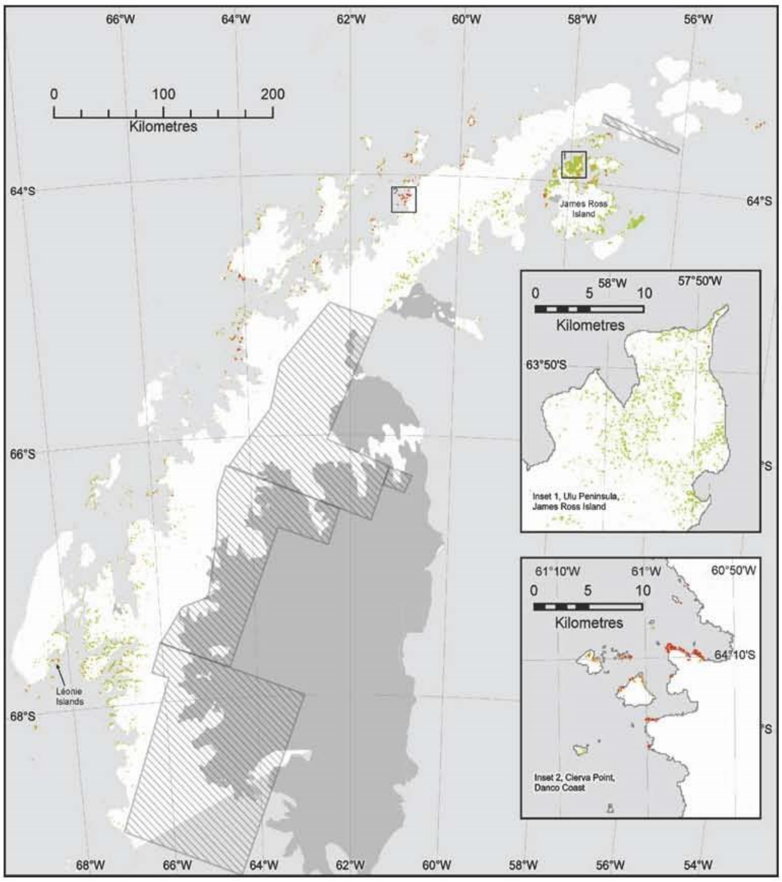

Fig. 4 Vegetated areas in Graham Land calculated using the three NDVI thresholds: *Green* denotes areas of probable vegetation but sparse coverage, orange equates to very probable and moderate coverage, and *red* is almost certain vegetation with dense coverage. Hatching indicates areas where available imagery was unsuitable. Some exaggeration of the size of each area of vegetation has been necessary to display the distribution at this scale. To show this, two inset maps have been included that display examples of the dataset in more detail. *Inset 1* shows Ulu Peninsula on James Ross Island, a large area of rock outcrop that has many low NDVI values that are widely spaced over a large area with a low density. *Inset 2* shows an area of the Danco Coast, around Cierva Point. This has fewer vegetated pixels, but these are of higher NDVI values and are concentrated in a few geographic locations showing a dense coverage of vegetation in each of these areas

Table 1 Vegetation patches in the two ground study sites (see Fig. 2 for the location of each area) noting the main vegetation type in each patch and the mean NDVI value of the Landsat pixels falling within the ground-truthed area

Area	Description	Type of vegetation	Analysis value
Anchorage Island			
1	Main vegetation site	Umbilicaria, other lichens, some Deschampsia	0.167
2	Green algal patch	Seasonal algal patch includes small moss patch	0.036
3	Large Lichen patch	Usnea and Umbilicaria	0.076
4	Lichen-dominated patch	Usnea and Umbilicaria	0.085
5	Moss patch	Mix of mosses some Usnea and other lichens	0.073
		area not classed as vegetated	0.013
Léonie Island			
6	Dense vegetation	Mosses and grass	0.075
7	Cliff patches	A variety of vegetation on steep cliffs	0.091
8	Mosses and grass	Mixed species of mosses and grasses	0.083
9	Scattered vegetation	Scattered patches of mosses and grasses	0.052
10	Patch under cliff	Scattered moss, grass and Colobanthus	0.132
11	Small patch	Small patch of moss and grass	0.225
		area not classed as vegetated	−0.021

Table 2 List of Landsat ETM scenes used in the analysis, showing details of date, sun angle, gain settings and whether the image was used in the final analysis

Name	Path	Row	Acquisition	Area	Sun elevation	Sun azimuth	Gain	Used?
Rast1	218	105	21022001	Brabant	25.9556293	56.9352684	LLLHHH	Y
Rast2	216	105	21022000	JRI	26.425	56.455	LLLHHH	Y
Rast3	215	104	29012000	Joinville1	34.3648682	59.2096252	LLLLHH	N
Rast4	214	104	23022000	Joinville2	26.9239998	55.6045189	LLLHH?	Y
Rast5	218	106	21022001	Graham	24.8118801	57.54879	LLLHH?	Y
Rast6	218	107	21022001	Foyn	23.6615868	58.3155327	LLLHH?	Y
Rast7	220	107	19022001	Ryder Bay	24.318	58.636	LLLHHH	Y
Rast8	220	108	19022001	Marguerite	23.1671028	59.5604057	LLLHH?	Y
Rast9	216	106	21022000	LarsenB	25.2738857	57.0637932	LLLHH?	Y
Rast10	217	106	18122002	Jason	38.1356621	59.4295082	LLLLHH	N
Rast11	218	108	25122002	Fallieres	35.5995369	61.4479256	LLLLH?	N
Rast12	216	107	22112001	LarsenC	34.9315338	55.6270294	LLLLHH	N
Rast13	217	104	26112000	Bransfield	39.3245354	54.5703354	LLLLH?	N
Rast14	216	104	22112001	Trinity	38.4743614	54.3640976	LLLLH?	N

NDVI readings can be erroneous because of soil type (Huete 1988). This is especially problematic in soils with high organic content where, for instance, NDVI readings can increase in areas of peaty soils (Rondeaux et al. 1996). In the study area and in Antarctica in general, the vast majority of soils are minerogenic, with very little organic matter, and initial results from the ground-truthing study generated no evidence of this effect. However, certain rock types were found to return NDVI ratios of up to 0.15, which is within the range of values given by sparse vegetation. Although no bare ground in the test area in Ryder Bay could be attributed to this phenomenon, elsewhere on the Antarctic Peninsula, in particular on James Ross Island and around the Prince Gustav Channel, large areas of bare ground returned ratios of over 0.10. All large areas returning these figures are of one rock type; olivine-rich sub-aerial palagonite-tuffs (Middle to Upper Miocene, James Ross Island Volcanic Group). This lithology is well mapped on James Ross Island (British Antarctic Survey 1996), allowing identification of potentially unreliable components of datasets obtained from locations where these rocks occur.

A method was developed to identify this lithology based on its spectral profile. It allowed accurate masking of the anomalous NDVI signal. Areas mapped as consisting of the rock type concerned were found to generate low readings in the visible green wavelengths (band 2) in relation to band 3 or band 4. In contrast, vegetation tends to have high reflectance in band 2, in comparison with band 3, although occasionally the values are comparable. All pixels where values from band 2 were over ten per cent lower than band 3 were masked, thus removing the NDVI signal from the palagonite-tuffs. This simple and effective technique proved to be the most effective at masking this lithology from a range of methods tested.

Results from the regional analysis

The total study area covers 74,468 km^2, of which 51,755 km^2 is covered by usable imagery. Within this, there is a total of 3,320 km^2 of ice-free ground. Data from our NDVI analyses indicate that 44.6 km^2 of this ground has an NDVI of over 0.05 and is classed as probably vegetated, equating to 1.34% of the available ice-free ground or 0.086% of the total area with usable imagery. In the second class with values over 0.1 NDVI and area of 8.516 km^2 is classed as very probably vegetated, and in the third class with values over 0.2 NDVI an area of 2.44 km^2 is classed as almost certain vegetation. The distribution of vegetation identified using RS within this area is shown in Fig. 4, indicates areas of low, medium and higher NDVI readings. Figure four also includes two insets that show local areas in more detail. The first of Ulu Peninsula on James Ross Island shows an extensive area of rock outcrop with a well distributed, but low density of sparse vegetation. The second inset shows Cieva Point on the Danco Coast where the limited rock outcrop has a much greater density of vegetation with higher NDVI values. The dataset includes many previously unknown vegetated areas and illustrates patterns of vegetation. Many of the more vegetated areas correlate with the areas of greatest rock outcrop, such as James Ross Island in the north east of the AP. Most of the areas on the west coast of the Antarctic Peninsula are restricted to smaller coastal outcrops and offshore islands. The southern part of the east coast remains unknown due to the gain settings of the Landsat imagery in this area.

Discussion

The correlation of ground-truthing and remote sensing data in the test area has allowed us to identify vegetation on the AP within a range of confidence thresholds. These confidence thresholds have been applied to data at the regional scale. The acquisition of complete coverage of Landsat ETM scenes for use in the Landsat Image Mosaic of Antarctica (LIMA), with a cell size of 30 m × 30 m, allows for detailed investigation and quantification of vegetation across large areas of the AP. These scenes have been collected from a limited time window (2000–2004) and so provide a snapshot of the environment at the start of the twenty-first century. We have demonstrated that the analytical methodology developed in this study provides, for the first time, a means of identifying vegetation on the Antarctic Peninsula from remote sensing. No remotely sensed vegetation studies of the Antarctic have previously been attempted, while approaches used in areas of the Arctic (Raynolds et al. 2006) would not be appropriate for this region due to the coarse nature of the RS data used in those studies. The work described in this paper complements and considerably extends data currently available from herbarium records and databases, and provides a benchmark baseline assessment of vegetation distribution that is clearly far beyond that achievable through the very limited operational resources available to workers on the ground in this region.

This study is a 'proof of principle', of large-scale vegetation mapping, testing the use of NDVI data for areas that are not typified by continuous vegetation cover dominated by higher plants. Our analysis was complicated by both the low NDVI values returned by the cryptogam-dominated vegetation and its sparse and patchy nature. With a Landsat cell size of 30 × 30 m, each pixel often includes several types or areas of vegetation, plus varying amounts of rock and snow. Thus, it is currently not possible to discriminate whether any specific low value relates to partial coverage of chlorophyll-rich plants that, if continuous, would give higher readings (i.e. mosses or grass) or lower-order plants with continuous coverage (lichen or algae) or if the pixel includes a significant area of vegetation-free ground. Such matters can only be resolved by further targeted and more detailed ground survey work and higher-resolution imagery which, while practicable at small individual locations, obviously cannot then be extended to cover the spatial scale required for the entire Antarctic Peninsula. Integration of more detailed ground survey and RS data (from multispectral high-resolution commercial imagery), combined with the use of other RS techniques such as spectral unmixing and supervised image classification have the potential to provide better information on sub-pixel vegetation cover and the contribution of different Antarctic terrestrial vegetation types (higher plants, mosses, lichens, algae). If this potential can be realized, it would provide an important new means of monitoring not only vegetation community extent but also compositional change in this region.

Having confirmed the applicability of our methodology using ground-truthing studies in Ryder Bay, we were then able to extend the approach to separate Landsat images covering other parts of the Antarctic Peninsula region. Using this methodology, all Landsat scenes showed evidence of vegetation, and in many cases identified areas of vegetation previously unknown on the Peninsula. There is clearly a requirement for much wider scale baseline data describing vegetation distribution within this region than is currently available. The approach used in this study provides a means of remotely identifying areas of vegetation and is the first attempt at a quantitative assessment of vegetation coverage across the region, giving a potential baseline for future monitoring and assessment of change. However, further work on potentially anomalous values caused by geology, further ground truthing and the use of other RS data are recommended to refine the values given in this paper.

Acknowledgments The authors would like to thank Anna Nelson British Antarctic Survey, for information on the geology of James Ross Island.

References

Billings WD, Morris RJ (1951) Reflection of visible and infrared radiation from leaves of different ecological groups. Ecology 38:327–331

Block W, Smith RIL, Kennedy AD (2009) Strategies of survival and resource exploitation in the Antarctic fellfield ecosystem. Biol Rev 84:449–484

Bokhorst S, Huiskes A, Convey P, Aerts R (2007) The effect of environmental change on vascular plant and cryptogam communities along a latitudinal gradient from the Falkland Islands to the Maritime Antarctic. BMC Ecol 7:15. doi:101186/1472-6785-7-15

British Antarctic Survey (1996) Scientific Reports No 54. The James Ross Island Volcanic Group of North East Graham Land. PHH Nelson

British Antarctic Survey (2006) Ryder Bay 1:25 000 scale map BAS 25 series, sheet 3 Cambridge, UK

Callaghan TV, Jonasson S (1995) Arctic terrestrial ecosystems and environmental change. Philos Trans R Soc Lond A 352:259–276

Chown SL, Convey P (2007) Spatial and temporal variability across life's hierarchies in the terrestrial Antarctic. Philos Trans R Soc Lond B 362:2307–2331

Cook AJ, Fox AJ, Vaughan DG, Ferrigno JG (2005) Retreating glacier fronts on the Antarctic Peninsula over the past half-century. Science 308(5721):541–544. doi:10.1126/science.1104235

Convey P (1996) The influence of environmental characteristics on life histories of Antarctic terrestrial biota. Biol Rev 71:191–225

Convey P (2003) Maritime Antarctic Climate change: signals from terrestrial biology. In: Domack E, Burnett A, Leventer A, Convey P, Kirby M, Bindschadler R (eds) Antarctic Peninsula climate variability: historical and palaeo-environmental perspectives. Antarctic research series vol 79. American Geophysical Union, Washington DC, pp 145–158

Convey P (2006) Antarctic climate change and its influences on terrestrial ecosystems. In: Bergstrom DM, Convey P, Huiskes AHL (eds) Trends in Antarctic terrestrial and limnetic ecosystems: Antarctica as a global indicator. Springer, Dordrecht, pp 253–272

Convey P, Smith RIL (1997) The terrestrial arthropod fauna and its habitats in northern Marguerite Bay and Alexander Island, maritime Antarctic. Antarct Sci 9:12–26

Convey P, Smith RIL (2006) Responses of Antarctic ecosystems to climate change. Plant Ecol 182:1–10

Convey P, Scott D, Fraser WR (2003) Biophysical and habitat changes in response to climate alteration in the Arctic and Antarctic. In: Lovejoy TE, Hannah L (eds) Climate change and biodiversity: synergistic impacts. Conservation International, Center for Applied Biodiversity Science. Adv Appl Biodivers Sci 4:79–84

Dana GL, Tate CM, Dewey SL (1994) McMurdo LTER: using narrow band spectroradiometry to assess algal and moss communities in a dry valley stream Antarctic. J USA 29:232–234

Fowbert JA, Smith RIL (1994) Rapid population increase in native vascular plants in the Argentine Islands, Antarctic Peninsula. Arct Alp Res 26:290–296

Freckman DW, Virginia RA (1997) Low-diversity Antarctic soil nematode communities: distribution and response to disturbance. Ecology 78:363–369

Frenot Y, Chown SL, Whinam J, Selkirk P, Convey P, Skotnicki M, Bergstrom D (2005) Biological invasions in the Antarctic: extent, impacts and implications. Biol Rev 80:45–72

Gates DM (1980) Biophysical ecology. Springer, New York 611 p

Huete AR (1988) A soil-adjusted vegetation index (SAVI). Remote Sens Environ 25(3):295–309

Kennedy AD (1995) Antarctic terrestrial ecosystem response to global environmental change. Annu Rev Ecol Syst 26:693–704

Knipling EB (1970) Physical and physiological basis for the reflectance in visible and near-infrared radiation from vegetation. Remote Sens Environ 1(70):155–159

Lillesand TMR, Keifer W (1994) Remote sensing and image interpretation, 3rd edn. Wiley, Hoboken 750 pp

Lillesand T, Kiefer R, Chipman J (2004) Remote sensing and image interpretation, 5th edn. Wiley, Hoboken, NJ, p 763

Lovelock CE, Robinson SA (2002) Surface reflectance properties of Antarctic moss and their relationship to plant species, pigment composition and photosynthetic function. Plant Cell Environ 25:1239–1250

Parnikoza I, Convey P, Dykyy I, TrakhimetsV, Milinevsky G, Tyschenko O, Inozemtseva D, Kozeretska I (2009) Current status of the Antarctic herb tundra formation in the central Argentine Islands. Glob Chang Biol 15:1685–1693

Peat HJ, Clarke A, Convey P (2007) Diversity and biogeography of the Antarctic flora. J Biogeogr 34:132–146

Pritchard HD, Vaugan DG (2007) Widespread acceleration of tidewater glaciers on the Antarctic Peninsula. J Geophys Res 112:F3 F03S29

Raynolds MK, Walker DA, Maier HA (2006) NDVI patterns and phytomass distributions in the circumpolar Arctic. Remote Sens Environ 102:271–281

Rondeaux G, Steven M, Baret F (1996) Optimization of soil adjusted vegetation indicies. Remote Sens Environ 55:95–107

Smith RIL (1984) Terrestrial biology of the Antarctic and sub-Antarctic. In: Laws RM (ed) Antarctic ecology. Academic Press, London, pp 61–162

Smith RIL (1994) Vascular plants as bioindicators of regional warming in Antarctica. Oecologia 99:322–328

Smith RIL (1996) Terrestrial and freshwater biotic components of the western Antarctic Peninsula. Antarct Res Ser 70:15–59

Smith VR, Steenkamp M (1990) Climate change and its ecological implications at a sub-Antarctic Island. Oecologia 85:14–24

Vaughan DG (2006) Recent trends in melting conditions on the Antarctic Peninsula and their implications of ice-sheet mass balance and sea level Arctic. Antarct Alp Res 38(1):147–152

Vaughan DG, Marshall GJ, Connelly WM, Parkinson C, Mulvaney R, Hodgson DA, King JC, Pudsey CJ, Turner J (2003) Recent rapid regional climate warming on the Antarctic Peninsula. Clim Chang 60:243–274

Verbyla D (2008) The greening and browning of Alaska based on 1982–2003 satellite data. doi:10.1111/j1466-8238200800396x

Voytek MA (1990) Addressing the biological effects of decreased ozone on the Antarctic Environment. Ambio 19:52–61

Global Ecology and Biogeography, (*Global Ecol. Biogeogr.*) (2009) **18**, 543–552

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.

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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

DOI: 10.1111/j.1466-8238.2009.00467.x
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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

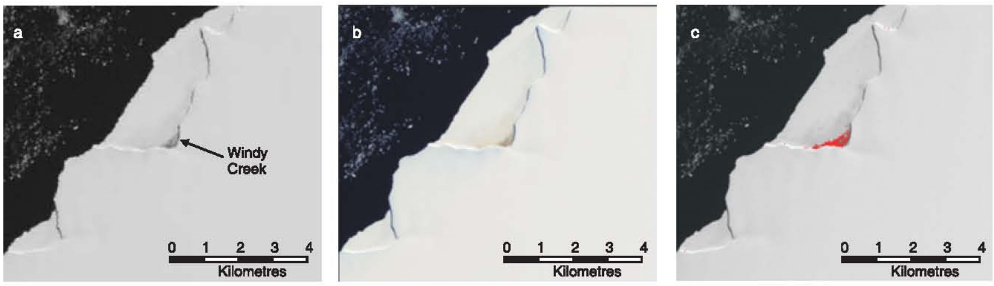

Figure 1 Comparison of data types: (a) screenshot of online Landsat Image Mosaic of Antarctica (LIMA); (b) Landsat ETM tile, downloaded from the LIMA website – note brown staining at the colony location; (c) spectral analysis red minus blue band, positive values shown in red, picking out the exact area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

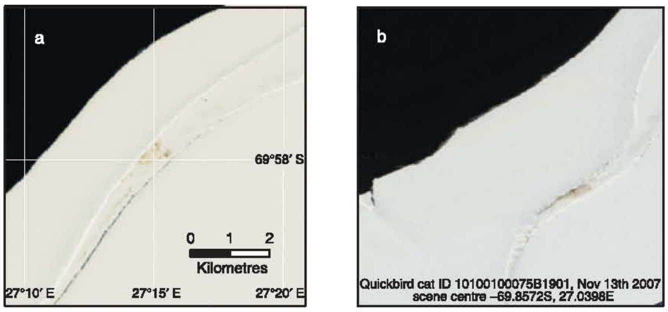

Figure 2 Comparison of data types: (a) Landsat Image Mosaic of Antarctica (LIMA) imagery of a newly found colony on Princess Ragnhild Coast; (b) screenshot of the corresponding area from the online 'quick-look' of imagery from the Quickbird satellite.

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 *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

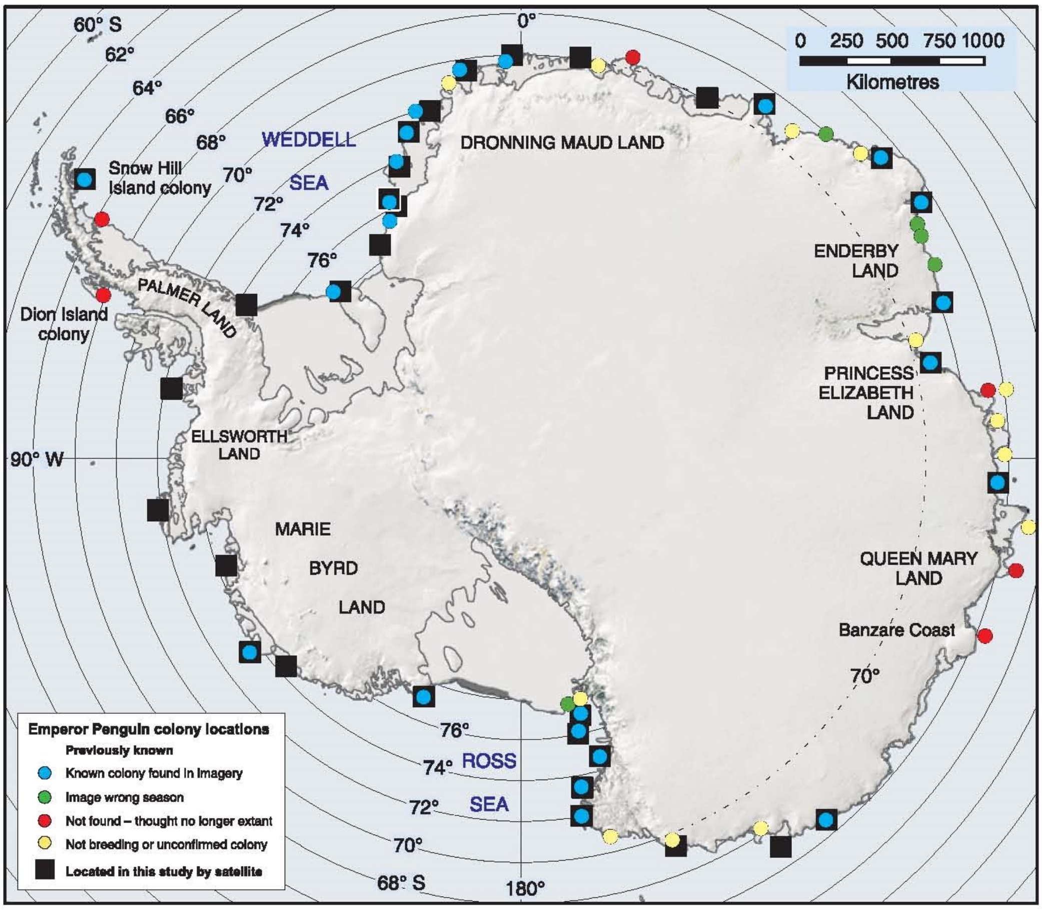

Figure 3 Distribution of emperor penguins found in this study versus previously recorded breeding sites. Black squares show locations found in this study. Other coloured dots relate to previously known sites: blue are those that have been located by satellite in the correct position, green dots are those 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 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.

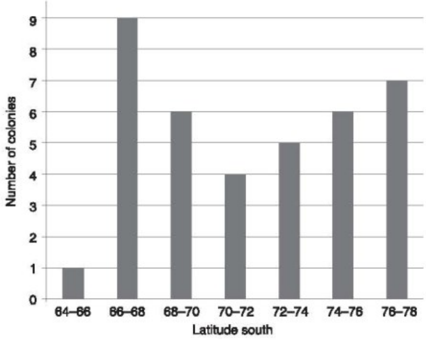

Figure 4 Distribution of emperor penguin colonies by latitude. Ainley *et al*. (2007) state that colonies north of 70° latitude will be at risk if global temperatures rise by 2 °C, equating to 16 colonies in this study.

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

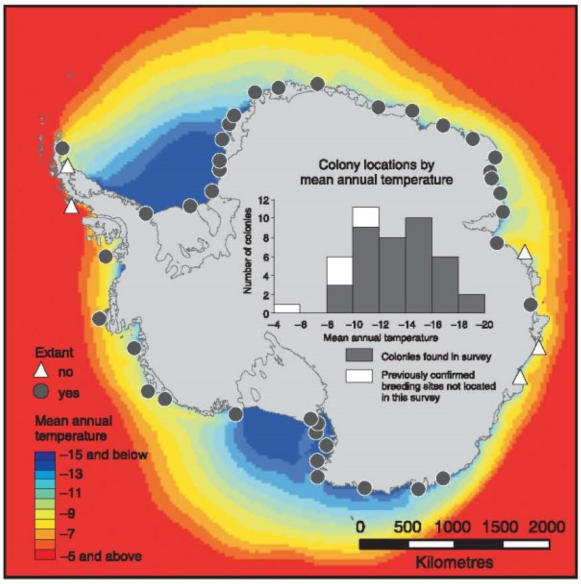

Figure 5 Extant and no longer extant colonies in relation to mean annual air temperature. We find 38 extant breeding colonies; six previously recorded breeding colonies are no longer extant. Further work is needed to assess why other colonies have been lost; however, three of the lost colonies in East 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.

ACKNOWLEDGEMENTS

We would like to thank J. Shears, A. Clarke, J. Turner and A. Fox for their input and advice, A. Fleming for providing satellite data and G. Marshall for constructing the Antarctic temperature model.

REFERENCES

Ainley, D., Russell, J. & Jenouvrier, S. (2007) *The fate of Antarctic penguins when Earth's tropospheric temperature reaches 2 °C above pre-industrial levels*. World Wildlife Fund report, http://assets.panda.org/downloads/wwf_climate_penguins_final_1.pdf.

Barber-Meyer, S.M., Kooyman, G.L. & Ponganis, P.J. (2007) Estimating the relative abundance of emperor penguins at inaccessible colonies using satellite imagery. *Polar Biology*, **30**, 1565–1570.

Barber-Meyer, S.M., Kooyman, G.L. & Ponganis, P.J. (2008) Trends in western Ross Sea emperor penguin chick abundances and their relationship with climte. *Antarctic Science*, **20**, 3–11.

Barbraud, C. & Weimerskirch, H. (2001) Emperor penguins and climate change. *Nature*, **411**, 183–186.

Bindschadler, R., Vornberger, P., Fleming, A., Fox, A. Mullins, J. Binnie, D. Paulsen, S.J., Granneman, B. & Gorodetzky, D. (2008) The Landsat image mosaic of Antarctica. *Remote Sensing of the Environment*, **112**, 4214–4226.

European Centre for Medium Range Weather Forecasts (2007) ECMWF era-40 model. http.ecmf.int/.

Gillett, N.P., Stone, D.I., Stott, P.A. Nozawa, T., Karpechko, A.Y., Hegerl, G.C., Wehner, M.F. & Jones, P.D. (2008) Attribution of polar warming to human influence. (2008) *Nature Geoscience*, **1**, 750–754.

Hempel, G. & Stonehouse, R.J. (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.

Jenouvrier, S., Barbraud, C. & Weimerskirch, H. (2005) Long-term contrasted responses to climate of two Antarctic Seabird species. *Ecology*, **86**, 2889–2903.

Jenouvrier, S., Caswell, H., Barbraud, C., Holland, M., Stroeve, J. & Weimerskirch, H. (2009) Demographic models and IPCC climate projections predict the decline of an emperor penguin population. *Proceedings of the National Academy of Sciences USA*, **106**, 1844–1847.

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.

Kato, A., Watanabe, K. & Naito, Y. (2004) Population changes of Adélie and emperor penguins along the Prince Olav Coast and on the Riiser-Larsen Peninsula. *Polar Bioscience*, **17**, 117–122.

Lea, M. & Soper, T. (2005) Discovery of the first emperor penguin *Aptenodytes forsteri* colony in Marie Byrd Land, Antarctica. *Marine Ornithology*, **33**, 59–60.

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.

Todd, F.S., Adie, S. & Splettstoesser, J.F. (2004) First ground visit to the emperor penguin *Aptenodytes forsteri* colony at Snow Hill Island, Weddell Sea, Antarctica. *Marine Ornithology*, **32**, 193–194.

Turner, J, Colwell, S.R., Marshall, G.J., Lachlan-Cope, T.A., Carleton, A.M., Jones, P.D., Lagun, V., Reid, P.A. & Iagovkina, S. (2005) Antarctic climate change during the last 50 years. *International Journal of Climatology*, **25**, 279–294.

Vaughan, D.G., Marshall, G.J., Connolley, W.M., Parkinson, C., Mulvaney, R., Hodgson, D.A., King, J.C., Pudsey, C.J. & Turner, J. (2003) Recent rapid climate warming on the Antarctic Peninsula. *Climate Change*, **60**, 243–274.

Wienecke, B. (2009) Emperor penguin colonies in the Australian Antarctic Territory: how many are there? *Polar Record*, doi: 10.1017/sDD32247409008341.

Williams, T.D. (1995) *The penguins*. Oxford University Press, Oxford.

Wilson, G.J. (1983) *Distribution and abundance of Antarctic and sub-Antarctic penguins: a synthesis of current knowledge*. Scientific Committee on Antarctic Research, Cambridge.

Woehler, E.J. (1993) *The distribution and abundance of Antarctic and Subantarctic penguins*. Scientific Committee on Antarctic Research, Cambridge.

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Editor: Jeremy Kerr

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

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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, et al. (2012) An Emperor Penguin Population Estimate: The First Global, Synoptic Survey of a Species from Space. PLoS ONE 7(4): e33751. doi: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

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.

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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

Table 1. Emperor penguin population survey 2009 results.

Name	long	lat	image date	area (m^2)	BE	image notes	PLC	source	notes
Cape Colbeck, Edward VII Peninsula	−157.7	−77.14	13/10/2009	12262	11438	good	6358	[16]	
Rupert Coast	−143.3	−75.38	20/10/2008	1660	1550	good	Uncounted		
Ledda Bay	not found		27/10/2009	0	0	NA	Uncounted		Sea ice gone before image taken
Thuston Glacier, Mt Siple	−125.621	−73.5	17/10/2009	3205	2989	good	2500	[11] chick estimate	Previous count very late in the season
Bear Peninsula	−110.25	−74.35	18/11/2009	10144	9457	good	Uncounted		
Brownson Islands	−103.64	−74.35	18/11/2009	6140	5732	poor	Uncounted		Heavy guano
Noville Peninsula	−98.45	−71.77	17/11/2009	3822	3568	poor	Uncounted		Heavy guano
Smyley	−78.83	−72.3	12/11/2009	6496	6061	good	Uncounted		
Smith	−60.83	−74.37	30/10/2009	4307	4018	good	Uncounted		
Dolleman	−60.43	−70.61	04/10/2009	1737	1620	good	Uncounted		Small part of colony missing in image
Snowhill	−57.44	−64.52	26/10/2009	2321	2164	poor	3885	[19]	
Gould	−47.68	−77.71	14/10/2009	8833	8242	good	7500	[34]	
Luitpold	−33.6	−77077	12/11/2009	6969	6498	good	Uncounted		
Dawson	∼−26.67	∼−76.02	13/10/2009	2784	2597	good	11700	Asplin -unpublished BAS report 1986	
Halley	−27.43	−75.54	27/10/2009	24127	22510	good	14300	Asplin -unpublished BAS report 1987	
Stancomb	−23.09	−74.12	21/10/2009	5849	5455	fair	3000	Asplin –unpublished BAS report 1986	Small amount of smearing
Drescher	−19.34	−72.83	04/10/2009	2469	2305	fair	6600	[35]	No guano, analysis on panchromatic band only
Riiser	−15.11	−72.12	27/10/2009	4304	4013	fair	5900	[35]	High cloud- cover
Atka	−8.13	−70.61	08/09/2009	10355	9657	good	8000	[35]	
Sanae	−1.42	−70	28/10/2009	3423	3193	good	113	[36]	
Astrid	8.31	−69.95	28/11/2009	1467	1368	poor	Uncounted		Late image, colony already dispersed
Lazarev	15.55	−69.75	11/10/2009	881	821	fair	4500	[37]	
Ragnhild	27.15	−69.9	10/10/2009	7362	6870	good	Uncounted		
Gunnerus	34.38	−68.75	31/10/2009	4989	4652	fair	7000	[28]	
Umbeashi	43.01	−68.05	14/10/2009	156	146	good	225	[28]	
Amundsen Bay	50.55	−66.78	20/10/2009	94	88	poor	250	[39]	Small, difficult to assess
Kloa Point	57.28	−66.64	13/11/2009	3521	3283	good	4500	[38]	
Fold Island	59.32	−67.32	14/10/2009	228	213	good	348	[38]	
Taylor Glacier	60.88	−67.45	21/10/2009	556	519	fair	2900	[11]	Some smearing over colony
Auster	63.98	−67.39	25/10/2009	8422	7855	poor	11000	[11]	
Cape Darnley	69.7	−67.88	15/10/2009	3713	3465	good	5000	[40]	
Amanda Bay	76.83	−69.27	13/10/2009	7315	6831	good	9000	[38]	
Haswell Island	93.01	−66.52	27/08/2009	3482	3247	poor	17000		Multispectral image bad, reanalysed with panchromatic image
Shackleton Ice Shelf	96.02	−64.86	10/10/2009	6937	6471	good	Uncounted		
Bowman Island	103.07	−65.16	26/10/2009	1724	1609	good	Uncounted		Good image
Peterson Bank	110.23	−65.92	24/11/2009	0	0	NA	1000	[18]	Late image, colony dispersed
Dibble Glacier	134.79	−66.01	12/10/2009	13377	12476	fair	Uncounted		Analysis of panchromatic only
Point Geologie	140.01	−66.67	01/10/2009	2632	2456	poor	2300	[11]	Streaking in panchromatic band

Table 1. Cont.

Name	long	lat	image date	area (m^2)	BE	image notes	PLC	source	notes
Mertz Glacier	146.62	−66.892	17/11/2009	5122	4781	poor	Uncounted		Huddles small and difficult to assess
Davis Bay	158.49	−69.35	11/10/2009	1870	1745	good	Uncounted		
Cape Washington	165.37	−74.64	16/10/2009	12663	11808	good	16822	[16]adults	Good image, lots of guano, may be underestimate
Beaufort Island	167.02	−76.93	12/10/2009	1758	1641	poor	1312	[16] adults	colony in shadow, difficult to differentiate
Franklin Island	168.43	−76.18	13/10/2009	8101	7561	good	2460	[16]adults	probable over-estimate
Cape Crozier	169.32	−77.46	11/10/2009	325	303	good	437	[16]adults	Small colony, image OK.
Coulman Island	~169.61	~−73.35	16/10/2009	27114	25298	fair	31432	[16]adults	Streaking in panchromatic band
Cape Roget	170.59	−71.99	16/10/2009	10186	9505	fair	7207	[3] chicks counted1996	Some streaking in panchromatic band; results may be overestimate
			Total	**238079**					

Table 1 presents the locations and best population 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

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].

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.

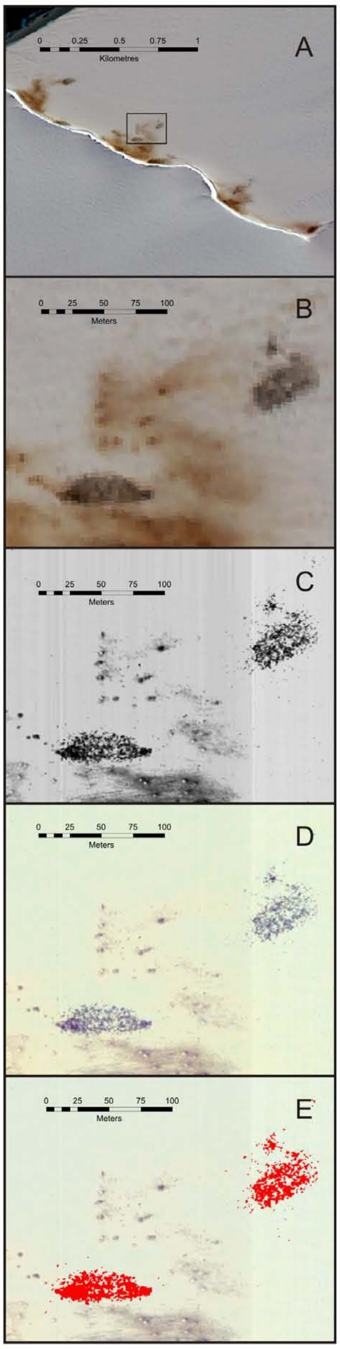

Figure 1. Example of imagery used in analysis. A: Multispectral QuickBird image of the emperor penguin colony at Windy Creek, Halley Bay, Antarctica. Black box indicates the area of images B–E below. B: Detail of multispectral image showing area of penguins as black/grey pixels and guano in brown. Although 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.
doi:10.1371/journal.pone.0033751.g001

We used a multivariate supervised classification implemented in ArcGis$^{\mathrm{TM}}$ 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-Meyer 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).

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 mvrnorm 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

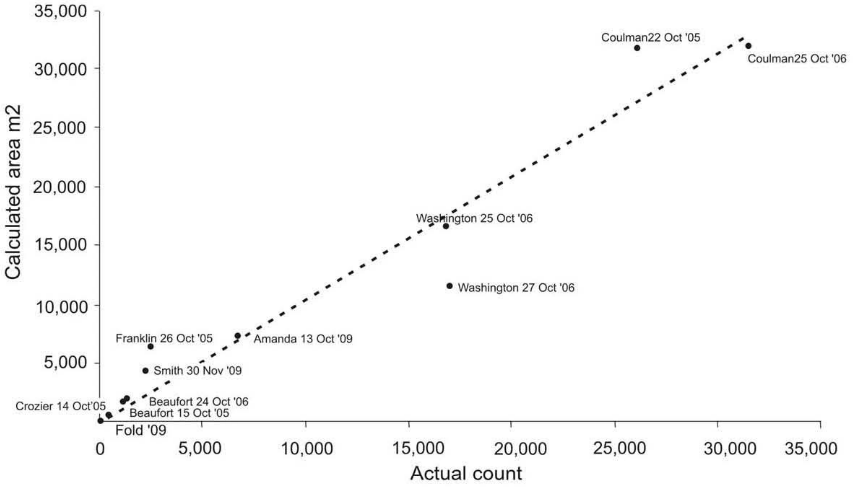

Figure 2. Regression plot based on the eleven ground truthing sites. The slope of the regression was 0.933 (SE = 0.046). Ground truth sites: Co6. Coulman Island 2006, Co5. Coulman Island 2005, Wa6. Cape Washington 2006, Wa5. Cape Washington 2005, Am. Amanda Bay 2009, Sm. Smith Peninsula 2009, Fr. Franklin Island 2005, Be6. Beaufort Island 2006, Be5. Beaufort Island 2005, Cr. Cape Crozier 2005.
doi:10.1371/journal.pone.0033751.g002

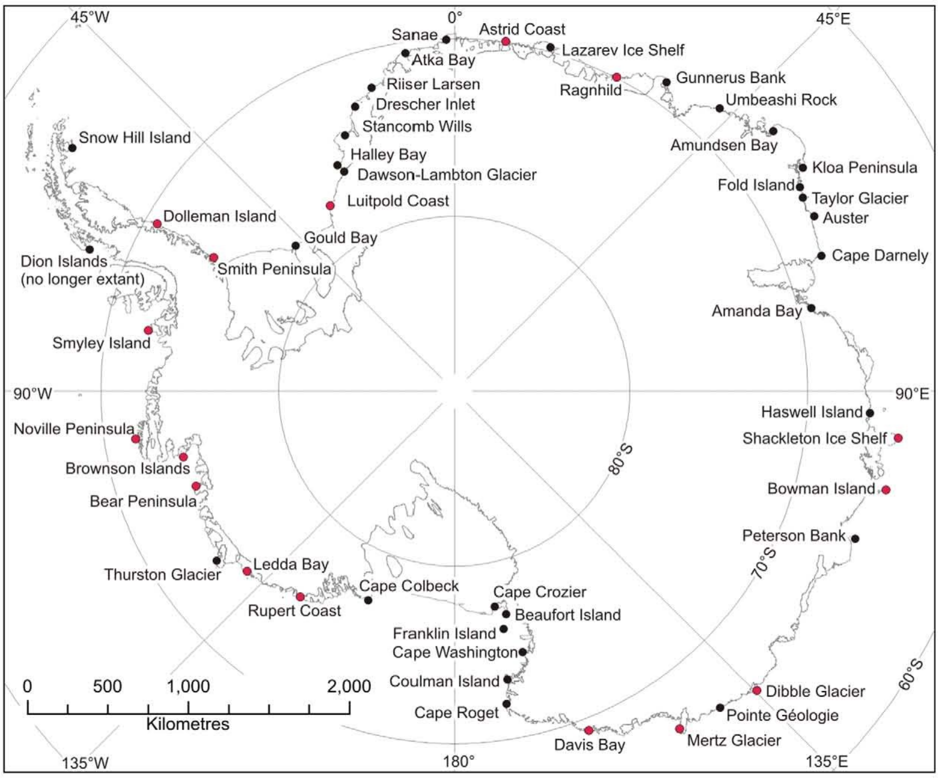

Figure 3. Distribution of emperor penguin colonies in Antarctica, see Table 1 for details of each colony. Red dots refer to those colonies with no previous population estimates.
doi:10.1371/journal.pone.0033751.g003

given for comparison in Table 1). Our new global estimate may plausibly be used for calculation of future global population trends.

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:

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

Table 2. Sources of error.

	Procedure	Result	Source of variability	Variability	Notes and suggestions for future work
1	Supervised classification	Area of penguins at each colony	Interpretation error: manual interpretation of which pixels constitute penguins as opposed to snow, guano or shadow. Variability here stems from being able to accurately determine penguins in the image, and repeatability between operators.	Less than 10% with most imagery but progressively worse with poorer imagery. Can be as much as 50% out in worst cases.	Depends upon the quality of the imagery. We suggest that future satellite acquisitions should avoid images with heavy guano staining.
2	Chick/adult area assumption	Area of adults at each colony	Chick adult ratio error: we make the assumption that the ratio of pixels showing as penguin in the satellite imagery remains 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 of adults seen by the satellite earlier in the season (September, when chick are virtually invisible to the satellite).	Unknown at this stage, but the high correlation in good imagery from robust regression analysis confirms that the assumption is broadly true.	We suggest further work is needed to assess the variability. At present there is not enough ground truthing linked to satellite imagery over the period when the imagery is acquired.
3	Ground truthing estimates	Number of adults at selected colonies	From ground counts a mixture of error sources, mainly the error associated with counting an areas and scaling up to the whole colony. In aerial counts there can be variability in the manual interpretation of how many penguins (especially chicks) are on an image.	Approximate variability of ground truthing is around 10% using aerial photography, but can be higher for ground counts especially at larger colony sites	Low level vertical aerial photography is recommended to minimize ground truthing errors.
4	Statistical analysis	Estimated of adults at each colony at time of image	Statistical error: 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.	1.75% based on Monte-Carlo analysis	More ground truthing over the entire season is recommended to improve the statistical procedure.
5	Seasonal assumption	Autumn population estimate	errors in the ground truthing and fluctuations between the dates of the ground truthing and satellite imagery	How this varies on a daily or weekly basis is at present unknown	Data from colonies where counts on seasonal variability would be useful. Especially if data exists on daily and weekly fluctuations in adult and chick numbers.
6	yearly population estimate	population estimate for 2009	Conversion between spring population and total population. Literature suggests that only 10% of birds are non- breeders	No variability estimate in literature	Further investigation required. Ground data from long term monitoring sites needed.
7	Inter-annual variability	Mean population estimate	Inter-annual changes at each emperor colony	Different estimates between colonies. Possibly size dependent (see text)	Monitor all colonies over multiple years by satellite to assess population change

The various sources of error; see section on Accuracy and uncertainty in the Discussion for further details of each area.

doi:10.1371/journal.pone.0033751.t002

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.

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

Table 3. Uncertainty estimates.

		Regression uncertainty				Image uncertainty		
Name	**Area**	**BPE**	**UCI**	**LCI**	**%CV**	**Image Quality**	**%CV**	**Total CV**
Cape Colbeck	12262	11438	10409	12442	8.89	good	2.5	306.6
Rupert Coast	1660	1550	1413	1685	8.78	good	2.5	41.5
Ledda Bay	0	0	0	0	8.62	NA	7.5	
Thurston Glacier	3205	2989	2725	3250	8.78	good	2.5	80.1
Bear Peninsula	10144	9457	8625	10270	8.7	good	2.5	253.6
Brownson Islands	6140	5732	5243	6226	8.58	poor	15	921.0
Noville Peninsula	3822	3568	3254	3876	8.71	poor	15	573.3
Smyley	6496	6061	5527	6604	8.88	good	2.5	162.4
Smith	4307	4018	3670	4366	8.66	good	2.5	107.7
Dolleman	1737	1620	1477	1764	8.87	good	2.5	43.4
Snowhill	2321	2164	1974	2351	8.7	poor	15	348.2
Gould	8833	8242	7519	8951	8.69	good	2.5	220.8
Luitpold	6969	6498	5944	7064	8.62	good	2.5	174.2
Dawson	2784	2597	2370	2828	8.81	good	2.5	69.6
Halley	24127	22510	20583	24444	8.58	good	2.5	603.2
Stancomb	5849	5455	4982	5922	8.61	fair	7.5	438.7
Drescher	2469	2305	2106	2502	8.6	fair	7.5	185.2
Riiser	4304	4013	3659	4372	8.88	fair	7.5	322.8
Atka	10355	9657	8807	10479	8.66	good	2.5	258.9
Sanae	3423	3193	2913	3469	8.71	good	2.5	85.6
Astrid	1467	1368	1249	1487	8.71	poor	15	220.1
Lazarev	881	821	748	892	8.74	fair	7.5	66.1
Ragnhild	7362	6870	6277	7461	8.62	good	2.5	184.1
Gunnerus	4989	4652	4237	5054	8.77	fair	7.5	374.2
Umbeashi	156	146	133	158	8.7	good	2.5	3.9
Amundsen Bay	94	88	80	95	8.67	poor	15	14.1
Kloa Point	3521	3283	2994	3565	8.7	good	2.5	88.0
Fold Island	228	213	194	232	8.87	good	2.5	5.7
Taylor Glacier	556	519	474	563	8.6	fair	7.5	41.7
Auster	8422	7855	7168	8556	8.83	poor	15	1263.3
Cape Darnley	3713	3465	3162	3766	8.72	good	2.5	92.8
Amanda Bay	7315	6831	6228	7425	8.76	good	2.5	182.9
Haswell Island	3482	3247	2958	3537	8.91	poor	15	522.3
Shackleton Ice Shelf	6937	6471	5918	7041	8.68	good	2.5	173.4
Bowman Island	1724	1609	1467	1748	8.74	good	2.5	43.1
Peterson Bank	0	0	0	0		NA		
Dibble Glacier	13377	12476	11376	13587	8.86	fair	7.5	1003.3
Point Geologie	2632	2456	2242	2670	8.7	poor	15	394.8
Mertz Glacier	5122	4781	4370	5208	8.77	poor	15	768.3
Davis Bay	1870	1745	1589	1895	8.79	good	2.5	46.8
Cape Washington	12663	11808	10790	12843	8.69	good	2.5	316.6
Beaufort Island	1758	1641	1497	1781	8.67	poor	15	263.7
Franklin Island	8101	7561	6900	8212	8.68	good	2.5	202.5
Cape Crozier	325	303	276	330	8.91	good	2.5	8.1
Coulman Island	27114	25298	23116	27486	8.64	fair	7.5	2033.6

Table 3. Cont.

		Regression uncertainty				Image uncertainty		
Name	**Area**	**BPE**	**UCI**	**LCI**	**%CV**	**Image Quality**	**%CV**	**Total CV**
Cape Roget	10186	9505	8694	10331	8.61	fair	7.5	764.0
	255202	**238079**	**217336**	**258788**	**1.75**		**5.59%**	**14273.8**

Table 3 gives details of the estimated statistical uncertainties associated with each colony. This is based on the robust regression analysis and the image quality of each VHR image. The uncertainty from the robust regression is estimated using Monte Carlo analysis (see Statistical Procedure section of the main text). The uncertainty based upon the image quality has been estimated using multiple analyses of images of differing quality. From this the survey has been broken into four classes as discussed in the Accuracy and uncertainty in the Discussion section.

doi:10.1371/journal.pone.0033751.t003

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 +/−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 ~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±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 simple 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.
(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.
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.
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.
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: doi:101029/2007JC004269.
5. Turner J, Bindschadler RA, Convey P, Di Prisco G (2009) Antarctic Climate Change and the Environment. Cambridge; SCAR UK 526p.
6. Bracegirdle TJ, Connolley WM, Turner J (2008) J Antarctic climate change over the Twenty First Century J Geophys Res 113; D03103: doi:101029/2007JD008933.
7. Forcada J, Trathan PN (2009) Penguin responses to climate change in the Southern Ocean Glob Chaahnge Biol 15: 1618 1630. doi: 101111/j1365-2486200901909x.
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: doi:101371/journal-pone0014738.
9. Massom RA, Stammerjohn SE (2010) Antarctic sea ice change and variability Physical and ecological implications Polar Science 4; 149 186.
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.
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.
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.
14. Wienecke B (2009) Emperor penguin colonies in the Australian Antarctic Territory: how many are there? Polar Record 45; 309 312.
15. Fretwell PT, Trathan PN (2009) Penguins from space: faecal stains reveal the location of emperor penguin colonies Glob Ecol Biogeogr 18; 543 552.
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.
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.
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.

19. Todd FS, Adie S, Splettstoesser JF (2004) First ground visit to the emperor penguin Aptenodytes forsteri colony at Snow Hill Island, Weddell Sea, Antarctica. Marine Ornithology 32; 193 194.
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.
21. Sanchez RD, Kooyman GL (2004) Advanced systems data for mapping emperor penguin habitats in Antarctica USGS Open-File Report 2004-1379 8p.
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.
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.
25. Yeats GW (1975) Microclimate, climate and breeding success in Antarctic penguins. In: 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.
27. Jenouvrier S, Barbraud C, Weimerskirch H (2005) Long term contrasted responses to climate of two Antarctic Seabird species. Ecology 86; 2889 2903.
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.
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.
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.
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.
33. Barbraud C, Gavrilo 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.
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.
36. Condy PR (1979) Observations on penguins in the King Haakon VII Sea, Antarctica. South African Journal for Antarctic Research 9: 29 32.
37. Ledenev VG (1965) New emperor penguin colony. Soviet Antarctic Expedition Information Bulletin (English) 3: 107 109.
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.
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.
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.

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Emperor Penguins Breeding on Iceshelves

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Abstract

We describe a new breeding behaviour discovered in emperor penguins; utilizing satellite and aerial-survey observations four emperor penguin breeding colonies have been recorded as existing on ice-shelves. Emperors have previously been considered as a sea-ice obligate species, with 44 of the 46 colonies located on sea-ice (the other two small colonies are on land). Of the colonies found on ice-shelves, two are newly discovered, and these have been recorded on shelves every season that they have been observed, the other two have been recorded both on ice-shelves and sea-ice in different breeding seasons. We conduct two analyses; the first using synthetic aperture radar data to assess why the largest of the four colonies, for which we have most data, locates sometimes on the shelf and sometimes on the sea-ice, and find that in years where the sea-ice forms late, the colony relocates onto the ice-shelf. The second analysis uses a number of environmental variables to test the habitat marginality of all emperor penguin breeding sites. We find that three of the four colonies reported in this study are in the most northerly, warmest conditions where sea-ice is often sub-optimal. The emperor penguin's reliance on sea-ice as a breeding platform coupled with recent concerns over changed sea-ice patterns consequent on regional warming, has led to their designation as "near threatened" in the IUCN red list. Current climate models predict that future loss of sea-ice around the Antarctic coastline will negatively impact emperor numbers; recent estimates suggest a halving of the population by 2052. The discovery of this new breeding behaviour at marginal sites could mitigate some of the consequences of sea-ice loss; potential benefits and whether these are permanent or temporary need to be considered and understood before further attempts are made to predict the population trajectory of this iconic species.

Citation: Fretwell PT, Trathan PN, Wienecke B, Kooyman GL (2014) Emperor Penguins Breeding on Iceshelves. PLoS ONE 9(1): e85285. doi:10.1371/journal.pone.0085285

Editor: Antoni Margalida, University of Lleida, Spain

Received June 27, 2013; **Accepted** December 4, 2013; **Published** January 8, 2014

Funding: Funding for this study came internally from BAS-NERC ecosystems programme. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. No current external funding sources for this study.

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

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Introduction

Recent studies suggest that emperor penguin populations will decline in future decades due to climate change [1–6]. Current projections suggest that the world population will halve before 2052[3] with more northerly colonies, above 70°S being lost entirely [6]. This has led the IUCN to re-list the species from "Least Threatened" to "Near Concern" [7]. The primary reason cited for this predicted decline is the species' reliance on sea-ice, a habitat that is expected to decrease in future years [8,9]. Sea ice is important to the species in two ways; firstly as a breeding platform and secondly as a foraging environment. A decrease in sea-ice distribution will negatively impact food webs [10], reducing numbers of Krill (*Euphausia superb), and the higher trophic levels which feed on Krill such as glacial squid* (*Pleuragramma antarcticum*); two species which compose the majority of the emperors diet [11]. A decrease in food availability may negatively affect survival, breeding success, recruitment and therefore population size.

As a breeding platform, stable or "fast" sea-ice is required which forms when the emperors arrive at their breeding locations (usually in April) and remains unbroken until the chick fledge (usually in December). If the sea-ice breaks up too early in the season it will result in high chick mortality [1–6], multiple years of poor sea-ice will lead to poor breeding success, population decline and eventual extinction of a colony [12]. The emperor penguin is a sea-ice obligate, the species is too clumsy to climb onto ice shelves and needs ice of a low freeboard to exit the ocean [2]. Of the 46 colonies presently known 44 breed on fast-sea- ice [13] (stable sea-ice attached to the coast). Of the two remaining colonies, one is recorded as breeding on rock and one on a frozen lake, both of these colonies are small, one having a recorded population of 2900 pairs and the other 250 pairs [13] (the mean colony size is approximately 5500 pairs).

In recent years satellite observations have improved our knowledge of the emperor penguins breeding distribution [14] and population [13]. Here we report on newly discovered breeding behaviour in emperor penguins seen from satellite and aerial surveys. Four emperor colonies have been observed breeding on ice-shelves not sea-ice The first, discovered in 2009[15]on the West Ice Shelf at the edge of Barrier Bay was a small colony of that could have been judged an anomaly or a break off group from the larger West Ice shelf colony located ~110 km to the north. However, since the discovery of the colonies on the West Ice Shelf, three other, large colonies, have been found that are either permanently, or annually located on ice shelves rather than on sea-ice.

Whereas sea-ice is frozen sea-water, ice-shelves are floating glacial ice that has flowed from the land into the sea; where the base of such glaciers breaks hydrostatic equilibrium, the ice-foot detaches from the ground bed and the glacial ice floats. When a single glacier feeds into the sea a glacier tongue is formed, but around the Antarctic coastline it is more common for ice from several glaciers or ice-streams to merge to form an ice-shelf. At their terminus ice-shelves can form ice cliffs, in some place over 60 metres high, although a few tens of metres is more common. Ice creeks often indent the cliff face giving a potential route up onto the ice-shelf itself, or where ice shelves are ablating the ice cliff may be less steep. As sea-ice forms, local weather conditions mean it can be highly variable in extent and duration, and therefore highly susceptible to regional climate change [8]. Ice-shelves are less dynamic, and are less susceptible to weather patterns and storm events, although cyclical calving events could pose a threat to organisms located near the ice-cliff edge and over longer time periods ice-shelves can collapse catastrophically such as the well documented break-up of the Larsen B Ice Shelf in 2002[16].

It is at present unclear whether this behaviour of breeding on ice shelves is a new phenomenon associated with recent climate change, or one that has always existed but has not yet been documented. Models of how animals adapt to climatic change exist [17] and we examine how this phenotype plasticity fits into those theories (see discussion).

That emperor penguins can move their breeding site depending upon ice conditions to a more stable location, including onto the top of the ice-shelf itself, means new factors should be incorporated into modelled population trajectories for this species. Whether such factors will provide temporary or permanent relief from the impacts of climate change remains uncertain.

The fact that emperors exhibit a previously unknown breeding behaviour, intimates that other less-well known species may also have similar unknown adaptive behaviours that may also offer temporary or permanent relief to the challenges of climate change.

Materials and Methods

Observations

The first emperor colony found on an ice shelf was the Barrier Bay colony, 67.22°S, 81.93°E discovered in December 2009 [14]. Some 295 chicks and a small number of adults were seen. The group was located near the edge of the ice cliff of the West Ice Shelf. The birds had accessed the ice shelf via an ice gully approximately 5km to the southeast. The colony has been observed in three subsequent years in the same position. The presence of chicks at Barrier Bay confirms that this is a breeding location rather than a temporary site (Figure 1).

The second colony identified on the top of an ice shelf is the Shackleton Ice Shelf colony. This colony was first located in 2008 [14] at 64.86°S, 96.02°E. The December 2008 position, found by Landsat imagery and later confirmed by Very High Resolution (VHR) satellite imagery (November 2009), was on sea-ice. The colony comprised approximately 6,470 pairs [13]; satellite observations confirmed that the breeding location remained constant in 2008, 2009 and 2010. However, in 2011 it appeared 15km to the south (64.98°S, 96.06°E) of its original location and on top of the ice shelf. The access route to the top of the shelf was a gulley 3.4 km to the east. In 2012, the breeding location was the same as in 2011 (Figure 2).

The third breeding location on top of an ice shelf is near the Jason Peninsula, at the northern limit of the Larsen C Ice Shelf. In 1893, the explorer and sealer Carl Anton Larsen was the first to visit this area [18,19]. He reported on 4 December 1893 that "The kongepenguinerne (king penguin) are very numerous in those (ice) fjords" (ice creeks are a favoured breeding location of emperor penguin colonies). When recording this, his ship was located on the northern side of what became known as the Larsen C Ice Shelf (noon position of 67.00°S, 60°.00W). At the time of this discovery little was known about emperor penguins and they were often confused with the similar, but smaller king penguin (*A. patagonicus*), a species which Larsen would have been familiar with from his sealing trips to South Georgia. It is likely that Larsen's sighting late in the breeding season indicated a colony in the vicinity. Although exhaustive satellite searches of the sea-ice in the area during previous studies [14,15] were conducted, no colony was found.

However, in 2012, a further satellite survey for emperor colonies was conducted along the edge of the Larsen C Ice Shelf. A medium sized colony was discovered on top of the shelf (at 66.08°S, 60.65°W). An aerial survey of the colony was undertaken

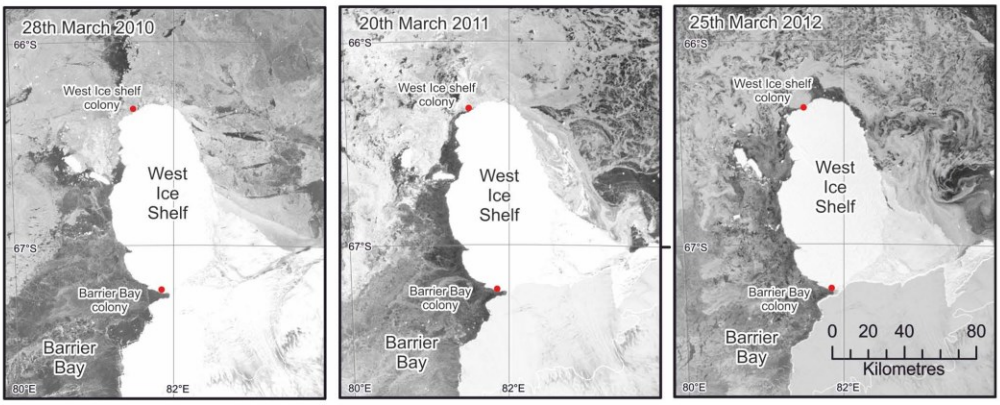

Figure 1. Envisat images showing the sea-ice conditions in late March around the West Ice shelf where two emperor colonies are located (equivalent imagery for 2009 is not available). Darker areas denote poor sea-ice, grey shows thicker sea-ice and white indicates ice shelf. Note that the Barrier Bay colony has a permanent polynya while the West Ice shelf colony located on the sea-ice has thicker sea-ice at this time of year when the birds would be arriving in the area to breed (images courtesy of Polarview – www.polarview.aq).
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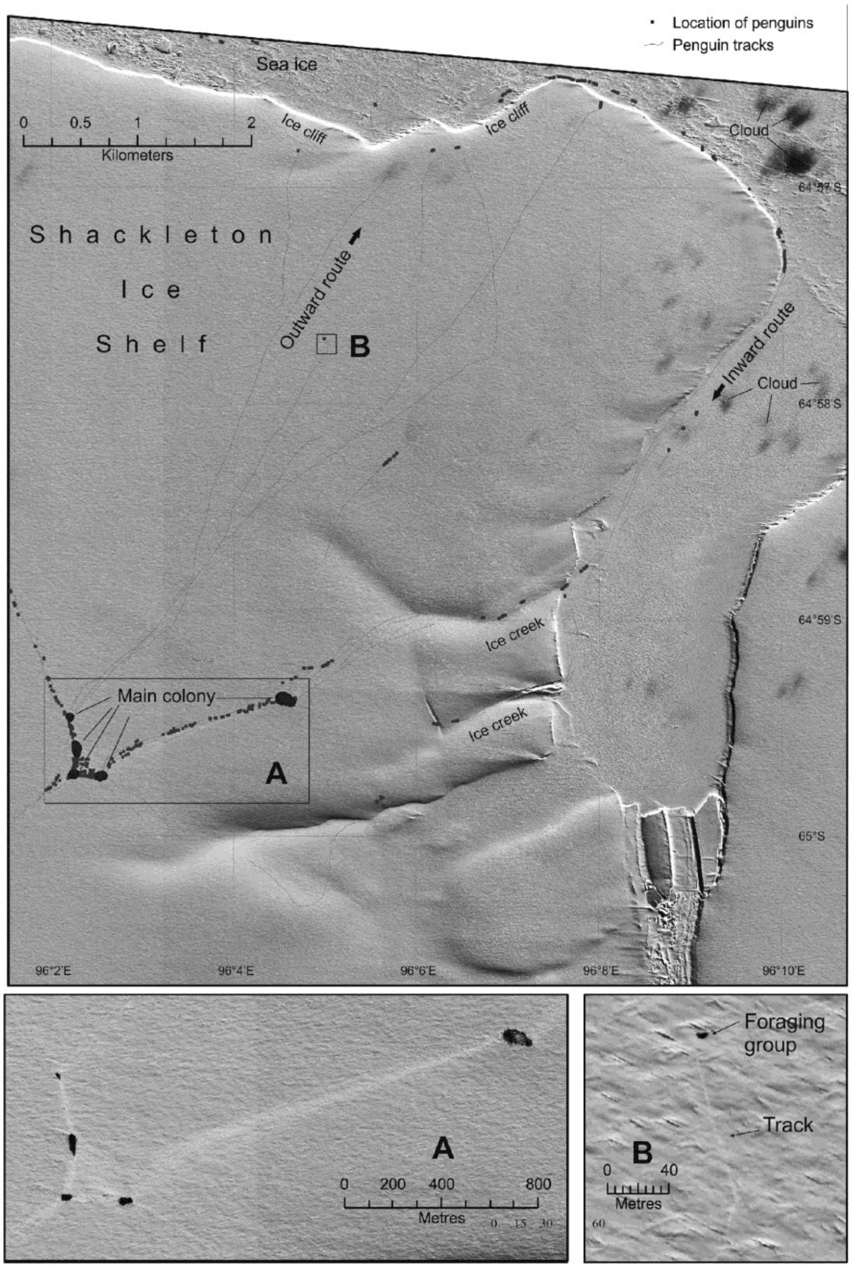

Figure 2. Shackleton Ice Shelf very high resolution satellite image. WorldView2 image (15 September 2012) showing the location of the Shackleton Ice shelf colony in 2012 in context with the ice edge. On this image the four main sub-colonies are clearly visible on top of the Shackleton

Ice Shelf around 5 km from the ice cliffs that form the edge of the ice shelf. The image data also clearly shows groups of penguins on their way to and from the ice edge, and the tracks they leave behind them. By marking these trails it is possible to assess where each group has come from and which direction it is heading. Interestingly at this site, the outgoing forages use a different route to the incoming penguins; on the way out they negotiate a large ice cliff. ICESAT data from the area suggest that the top of the ice sheet is 32–34 m high, the image shows no slope down to the cliff so the drop may be considerable (although there is evidence of large snowdrifts abutting the cliff). The incoming parties cannot negotiate the cliff and so take a 5 km longer route around the edge of the ice shelf until they can access the gentle slopes afforded by a number of ice creeks to the east of the colony. How the emperor penguins get down the ice cliff is, at present, unclear.
doi:10.1371/journal.pone.0085285.g002

in early December 2012 (Figure 3) revealing that the colony comprised around 3,800 adult birds. Archival satellite imagery shows that it has been located on the ice shelf since at least 2008, the earliest imagery available for the area. The Antarctic Peninsula is one of the fastest warming regions [20] and has suffered significant ice shelf loss [21]. The sea-ice regime here has also been affected by climatic forcing and the birds may have moved from the sea-ice creeks to the top of the ice shelf. Exactly how the birds access the shelf is unclear but it appears that they climb the low ice cliff (Figure 4). King penguins climb up dry glaciers in warm weather to stay cool; perhaps the less agile emperor is also able to climb slopes, particularly where ice shelves weather and ablate the steepness of the shelf face.

Finally, a colony was sighted on top of an ice shelf at the Ruppert Coast colony. This colony was only discovered in 2010 when it was located on the sea-ice under the ice cliffs of the Nickerson Ice Shelf at 75.38°S, 143.35°W. Satellite imagery shows that in 2008, 2011 and 2010 (no images from 2009 are available) the colony was located on the sea-ice at 75.38°S, 143.28°W, but in 2012 (17/10/2012) it had moved onto the edge of the ice shelf above the ice cliff (Figure 5). At present no information is available to suggest why the colony moved onto the shelf in this year.

Analyses

To assess why the colony location had moved from sea-ice to ice-shelf ENVISAT synthetic aperture radar imagery of sea-ice concentration was acquired of the Shackleton Ice shelf colony (for which the most data existed) several times over the course of the breeding season. The imagery from March, when adults start to return to their breeding location [22], shows that in 2008, 2009 and 2010 the sea-ice concentration at the initial site was dense and was sufficiently stable for the penguins to access the location (Figure 6). But in 2011 and 2012, the sea-ice did not form until early- to mid-April. The birds therefore chose a site on top of the ice shelf in years when sea-ice formed late. The birds show remarkable fidelity to the site, changing their breeding platform in preference to changing the breeding location when April sea-ice conditions become unsuitable.

To test whether the presence of colonies that have been found on ice-shelves was linked to environmental conditions, three

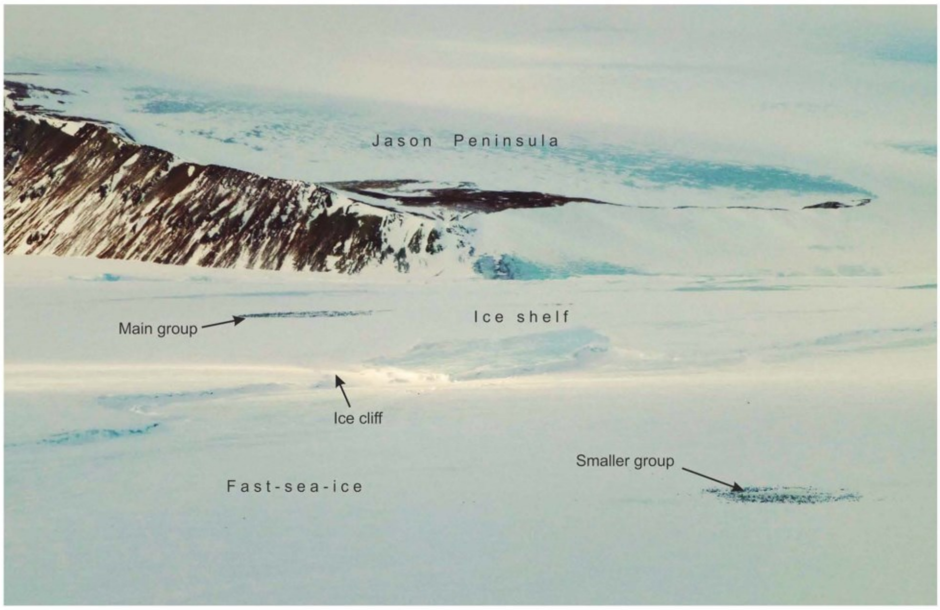

Figure 3. Emperor penguins on the edge of the Larsen Ice Shelf near the Jason Peninsula late in the breeding season. The larger group is on the ice-shelf, the smaller group has moved onto the fast-ice; earlier in the season data from QuickBird1 satellite imagery shows that the whole colony was located on the ice-shelf. Note the ice cliff which is probably an insurmountable barrier to the adult emperor penguins. No evident route to the colony was determined from the images. (Photo Ian Potten).
doi:10.1371/journal.pone.0085285.g003

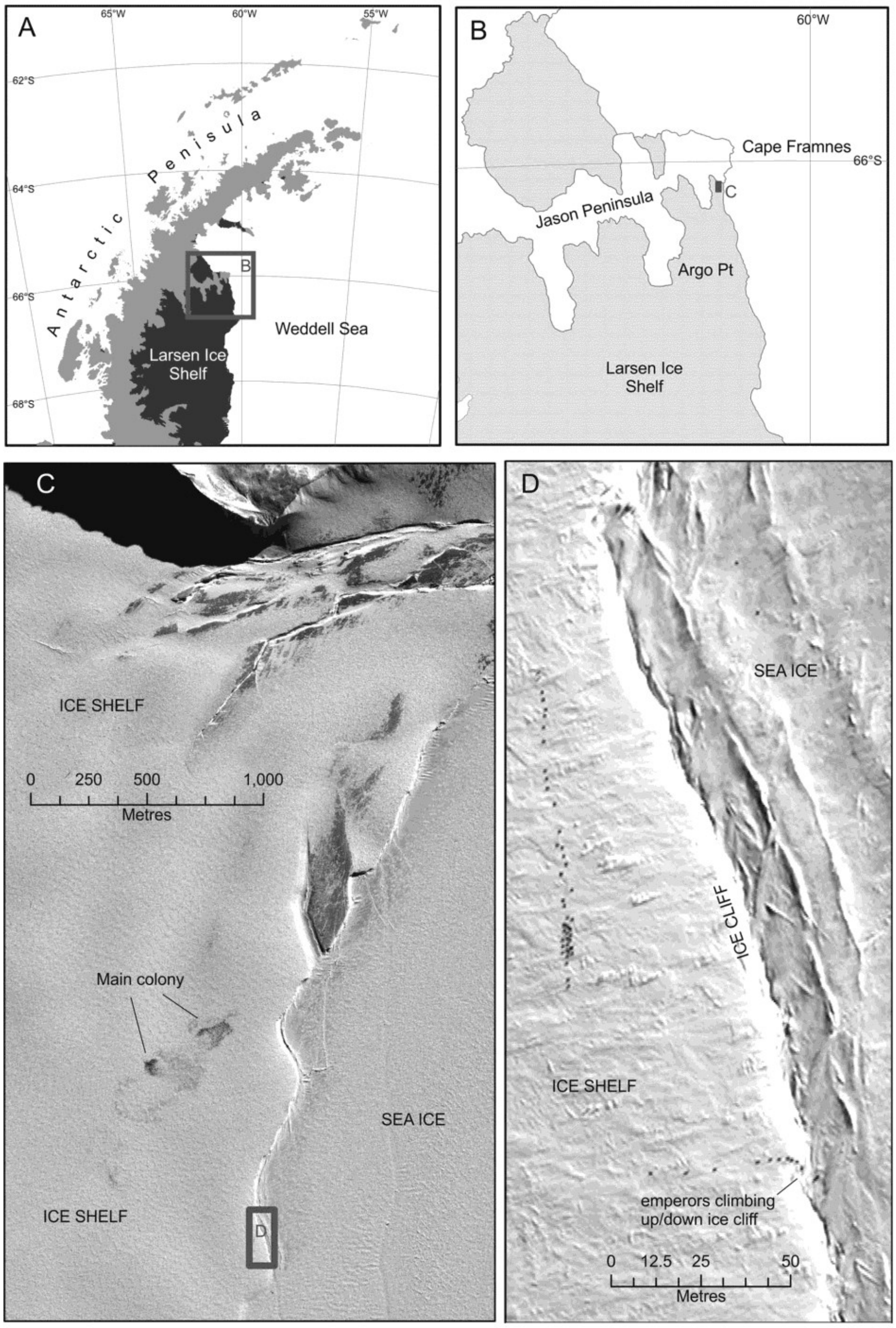
A
65°W
60°W
55°W
62°S
64°S
66°S
68°S
Antarctic Penisula
B
Weddell Sea
Larsen Ice Shelf
B
60°W
Cape Framnes
66°S
C
Jason Peninsula
Argo Pt
Larsen Ice Shelf
C
ICE SHELF
0 250 500 1,000
Metres
Main colony
SEA ICE
ICE SHELF
D
D
SEA ICE
ICE CLIFF
ICE SHELF
emperors climbing up/down ice cliff
0 12.5 25 50
Metres

Figure 4. A and B; maps showing location of the Jason Peninsula colony. C: Quickbird1 image (12 Sept 2012) showing the main Jason Peninsula emperor penguin colony in relation to the ice-shelf and sea ice edge. D: Emperor penguins (small black dots) on their way to or from the breeding colony onto of the sea-ice. They have to climb up or down a small ice cliff, which shows up as white in this image. To the left of this cliff is ice shelf, while the ridged area to the right is fast-ice. In this image emperors can be seen on the ice shelf (a long line in upper left and parallel to the cliff face) and the cliff (shorter linear group at middle bottom and perpendicular to the cliff face). The height of this ice cliff is presently unknown but based on the size of the penguins in the image it may be only a few metres high.
doi:10.1371/journal.pone.0085285.g004

environmental variables were assessed at the four sites and compared with values for other emperor penguin colony locations (Figure 7). Autumn (March/April) sea-ice concentration was modelled using synthetic aperture radio imagery from the Polarview website (http://www.polarview.aq/), mean temperature was assessed using the RACMO region climate model [23] and latitude using the recent calculation of the circumpolar emperor penguin population [13].

Results and Discussion

Of the four colonies described here, the three that have been found breeding on ice shelves in multiple years could be described as located in marginal conditions. The Shackleton Ice Shelf and Barrier Bay sites have the lowest mean autumn sea-ice concentrations of any colonies and both these and the Larsen ice-shelf colony are in the most northerly part of the emperors range and have higher-than-average mean-temperature regimes. Three other colonies have mean annual temperatures higher than the Larsen colony; Smyley Island, Bowman Island and Snow Hill Island. On Smyley Island in 2009 the colony was observed by QuickBird satellite imagery breeding on top of an iceberg (QuickBird catalogue number 101001000A9A8B00 November 12th 2009), a possible response to poor sea-ice earlier in the season. A similar behaviour has been observed at the Mertz Glacier colony which is also located in an area that has a high mean temperature (André Ancel pers coms.). This behaviour at these other colonies suggests that breeding on ice-shelves is only one of several possible adaptations that could be employed by emperor penguins when sea-ice conditions are poor; others include moving onto land (for example Dion Islands). Of the other warmer sites the Snow Hill Island colony has not only the warmest mean temperature but is also is the highest latitude, although it has a reasonable high mean sea-ice concentration. Bowman Island has the third highest mean temperature and the fourth lowest sea-ice concentration. These two must be considered some of the most marginal and potentially vulnerable of emperor breeding locations as neither colony has the option of moving onto floating ice-shelves as there are none in the nearby locality and neither has it shown evidence of breeding on icebergs.

The Ruppert Coast colony that has been found located on the edge of an ice shelf in one year is neither in a warm or poor sea-ice location; as yet we have no explanation of why this colony moved to a more elevated location.

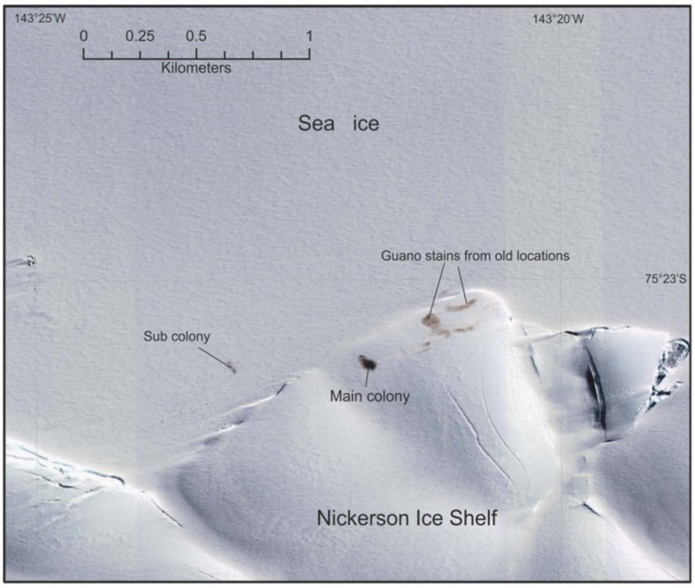

Figure 5. QuickBird 2 very high resolution satellite image of the Ruppert Coast emperor penguin colony(17 October 2012) including part of the Ruppert Coast and Nickerson Ice Shelf, it clearly shows the emperor penguin colony located on the higher ice shelf. Access to the main colony seems to be by a shallow ice ramp north and west of the present location. Brown guano stains mark the previous colony site approximately half a kilometres northeast, and to the west, on the sea-ice is a smaller subgroup of penguins.
doi:10.1371/journal.pone.0085285.g005

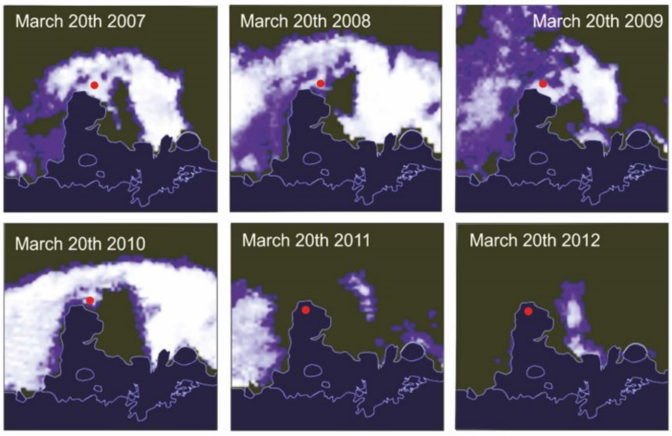

Figure 6. Sea-ice concentration around the Shackleton Ice Shelf for the time period 2007 to 2012, each from the 20th of March. White shading denotes thick sea-ice; blue, thinner sea-ice; black, open water. The red dot shows the location of the breeding colony identified from QuickBird VHR imagery (images courtesy of Polarview/University of Bremen).
doi:10.1371/journal.pone.0085285.g006

Only a relatively small number of emperor colonies have been studied across Antarctica [1,12,22,24], with the longest study based at Pointe Géologie, which has been continually monitored since the 1950s [1,4,5,24]. The behaviour of breeding on ice-shelves, as reported here, has only been reported once at a small colony in East Antarctica [15]. That this behaviour is not the exception but is apparently more common among emperor penguins is a surprising result. The reasons why this behaviour

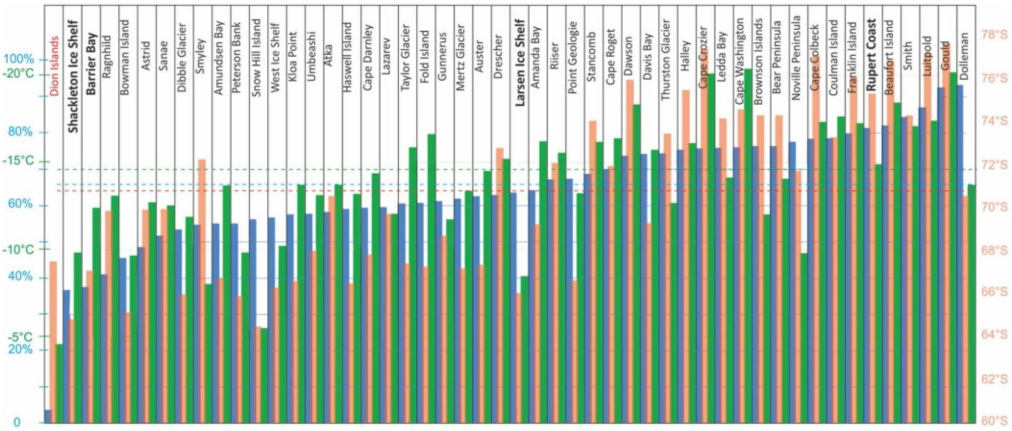

Figure 7. Marginality. Histogram of three parameters at emperor penguin breeding colonies: blue bars represent mean March/April sea-ice concentration, red bars are latitude and green are mean temperature. Colonies are ranked from left to right with lowest sea-ice concentrations to the left. The four colonies mentioned in this paper are named in bold. Dashed lines in blue, red and green denote the mean of the three parameters for all colonies. Shackleton Ice shelf and Barrier Bay colonies are in locations that have the lowest mean autumn sea-ice concentrations. The Larsen ice shelf colony has slightly lower than average sea-ice concentrations, but its latitude and mean annual temperature are well above average. The colony on the far left, Dion Islands, marked in red is believed to have declined and ceased to exist following recent climate change (temperature rise and sea-ice loss) on the Antarctic Peninsula. This previously occupied site is included to give an indication of the current breeding limits. These parameters give no indication of why the Ruppert Coast colony, found breeding on the ice shelf in only one year, relocated onto this ice shelf in 2012. Mean sea-ice concentration (blue) is recorded as a percentage for March/April when emperors prospect and recruit at breeding sites. The figures are calculated using synthetic aperture radar measurements for all dates in these two months for the years 1998–2007. Latitude (red) is the latitude of the colony location from Fretwell et al. 2012 and Wieneke 2012, with the addition of the newly found Larsen Ice Shelf colony described in this paper. Mean temperature is based on a yearly mean for 2000–2004 based on the RACMO climate model.
doi:10.1371/journal.pone.0085285.g007

has not been recorded before are unclear, possible explanations include:

1. The phenomenon may be recent phenotypic plasticity as regional climate change affects parts of the Antarctic coastline.
2. Most previous study-sites are not located at ice-shelf breeding colonies where this behaviour is exhibited.
3. There have been no large scale systematic searches for emperors on ice shelves (although many flights and surveys have overflown iceshelves).

Visser [17] has proposed a number of possible adaptations to climate change in birds, including phenotype plasticity, which includes changes in breeding behaviour. One special case of phenotype plasticity noted in the work is that of "learning" where animals can adapt to climate change if they learn from their experiences. Whether the adaptation of emperor penguins breeding on ice-shelves is learnt, or inherited behaviour is at present unclear; the Larsen and Barrier Bay colonies seem to be permanently located on the shelf, but the Shackleton colony moves there only when sea-ice conditions in April dictate. One aspect of Visser's work that must be considered is that it concentrates on individual nesting birds rather than colonial species. Colonial species, especially emperor penguins, seem to move en-mass to new locations, although how this decision is made is unclear. The previous work may not therefore prove an ideal model for assessing how colonial nesting sea-birds may adapt to climate change.

The ability of emperor penguins to change their breeding platform when fast ice conditions deteriorate may be an important adaptation that could help the species survive in a warming environment. Although regional warming has led to loss of ice-shelves around the Antarctic Peninsula [21] ice-shelves are less sensitive to a warming environment and react to warming on slower timescales than sea-ice, the extent, stability and seasonality of which can change rapidly with warming temperatures as already seen in the Arctic [25,26,27,28] and in the west Antarctic Peninsula [8].

For emperor penguins, the loss of the sea-ice as a breeding platform is not the only consequence of a warming environment. Factors, such as changes to food webs [10,29] and increased predation and competition [12] will also affect breeding success survival rates and other demographic parameters in areas that experience regional warming. Additionally, there are several negative factors that could potentially result from breeding on ice shelves, including the lack of shelter and exposure to katabatic winds, lack of fresh snow in areas where increased wind speeds scour the surface and a risk from calving ice fronts. How great these risks are and how much of an advantage or disadvantage breeding on ice-shelves proves to be for this species has yet to be quantified. This new discovery also leads to a number of other potential behavioural questions. For example: How do emperors access the ice shelves? Does the breeding cycle differ in locations such as at the Larsen colony where breeding on ice-shelves has become the norm? What is the energetic cost of scaling the ice-front? Such questions will be important future topics of research.

Currently, sea-ice conditions and their predicted decline are one of the key inputs into models that suggest large decreases in emperor penguin numbers. Therefore, the suitability of ice-shelves versus sea-ice as a breeding platform for emperors urgently needs quantifying. Future research efforts need to assess which colonies could potentially move to ice-shelves and whether this newly described behaviour is a temporary or partial solution for coping with future climate change. Emperors are often portrayed as a barometer for the ecosystem, that is, a "canary in the coalmine" for species more difficult to study. This previously unknown and surprising behaviour recorded in such an iconic animal suggests that other species may also be capable of unpredicted or unknown behavioural adaptations that may also increase their survival in a future warming world.

Author Contributions

Conceived and designed the experiments: PTF PNT BW GLK. Performed the experiments: PTF. Analyzed the data: PTF BW. Contributed reagents/materials/analysis tools: PTF. Wrote the paper: PTF PNT BW GLK.

References

1. Barbraud C, Weimerskirch H (2001) Emperor penguins and climate change. Nature 411, 183 186.
2. Ainley DG, Clarke ED, Arrigo K, Fraser WR, Kato A, et al. (2005) Decadalscale changes in the climate and biota of the Pacific sector of the Southern Ocean, 1950s to the 1990s. Ant Sci 17; 171 182.
3. Ainley D, Russell J, Jenouvrier S, Woehler E, Lyver P, et al. (2010) Antarctic penguin response to habitat change as Earth's troposphere reaches 2uC above preindustrial levels Ecol Monogr 80; 49 66.
4. Jenouvrier S, Barbraud C, Weimerskirch H (2005) Long term contrasted responses to climate of two Antarctic Seabird species. Ecology 86; 2889 2903.
5. 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.
6. Massom RA, Stammerjohn SE (2010) Antarctic sea ice change and variability Physical and ecological implications Polar Science 4; 149 186.IUCN. IUCN Red list of threatened species. Version 2012 2. Available: www.iucnredlist.org. Downloaded on 5 May 2013.
7. IUCN. IUCN Red list of threatened species. Version 2012 2. Available: www.iucnredlist.org. Downloaded on 5 May 2013.
8. 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 Nin~o Southern Oscillation and Southern Annular Mode variability. J Geophys Res 113, C03S90: doi:101029/2007JC004269.
9. Turner J, Bindschadler RA, Convey P, Di Prisco G (2009) Antarctic Climate Change and the Environment. Cambridge; SCAR UK 526p.
10. Forcada J, Trathan PN (2009) Penguin responses to climate change in the Southern Ocean Glob Change Biol 15: 1618 1630. doi: 101111/j1365-2486200901909x.
11. Klages N (1989) Food and Feeding Ecology of Emperor Penguins in the Eastern Weddell Sea. Polar Biol. 9, 385 390.
12. 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: doi:101371/journal-pone0014738.
13. Fretwell P T, LaRue MA, Morin Pl, Kooyman GL, Wienecke B, et al. (2012) An Emperor Penguin population estimate: The first global, synoptic survey of a species from space. Plos One, 7 (4). 11,pp.0.1371/journal.pone.0033751.
14. Fretwell PT, Trathan PN (2009) Penguins from space: faecal stains reveal the location of emperor penguin colonies. Glob. Ecol. Biogeogr. 18, 543 552.
15. Wienecke B (2012) Emperor penguins at the West Ice Shelf. Polar Biol. 35, 1289 1296.
16. Rack W, Rott H (2004) Pattern of retreat and disintegration of the Larsen B ice shelf, Antarctic Peninsula. Annals of Glaciology, 39 505 510.
17. Visser ME (2008) Keeping up with a warming world: assessing the rate of adaptation to climate change. PRSB 275, 649 659.
18. Wienecke B (2010) The history of the discovery of emperor penguin colonies, 1902 2004 Polar Rec. 46, 271 276.
19. Larsen CA (1894) The voyage of the "Jason" to Antarctic regions. Geogr. J. 4,333 344.
20. Morris EM, Vaughan DG (2003) in *Antarctic Peninsula Climate Variability: Historical and Paleoenvironmental Perspectives*, (ed. Domack, E. et al. Antarct. Res. Ser., 79 61 68 (AGU, Washington, D. C., doi:10.1029/AR079p0061. 2003).
21. Cook AJ, Vaughan DG (2010) Overview of areal changes of the ice shelves on the Antarctic Peninsula over the past 50 years. The Cryosphere 4, 77 98 doi:10.5194/tc-4-77-2010.
22. Kooyman G (1993) Breeding habitats of emperor penguins in the western Ross Sea. Antarct. Sci. 5, 743 148.
23. Van Lipzig NP, Van Meijgaard E, Oerlemans J (2002) The spatial and temporal variability of the surface mass balance in Antarctica: results from a regional atmospheric climate model. Int J. Climatol. 22, 1197 1217.

24. Barbraud C, Gavrilo M, Mizin Y, Weimerskirch H (2011) Comparison of emperor penguin declines between Pointe Géologie and Haswell Island over the past 50 years. Antarc. Sci. 23, 461 468.
25. Serrezer MC, Holland MM, Stroeve J (2007) Perspectives on the Arctic's Shrinking Sea-Ice Cover. Science 315 5818.
26. Comiso JC, Parkinson CL, Gersten R, Stock L (2008) Accelerated decline in the Arctic sea ice cover, Geophys. Res. Lett., 35.
27. Sime LC, Wolff EW, Oliver KIC, Tindall JC (2009) Evidence for warmer interglacials in East Antarctic ice cores. Nature 462, 342 345.
28. EPICA Community Members (2004). Eight glacial cycles from an Antarctic ice core. Nature 429, 623 628.
29. Barbraud C, Rolland V, Jenouvrier S, Nevoux M, Delord K, et al. (2012) Effects of climate change and fisheries bycatch on Southern Ocean seabirds: a review. Mar. Ecol. Prog. Ser. 454, 285 307.

Valdés, Argentina. Journal of Cetacean Research and Management (special issue) 2: 125 132.

11. Best PB, Brandao A, Butterworth DS (2005) Updated estimates of demographic parameters for southern right whales. Paper SC/57/BRG2 presented to the Scientific Committee of the International Whaling Commission, [Available at the International Whaling Commission Office, http://iwc.int/home. Accessed June 2013].
12. Cooke JG, Rowntree VJ (2003) Analysis of inter-annual variation in reproductive success of South Atlantic right whales (*Eubalaena australis*) from photo-identifications of calving females observed off Península Valdés, Argentina, during 1971 2000. Unpublished paper SC/55/O presented to the IWC Scientific Committee, Berlin, June 2003, [Available at the International Whaling Commission Office, http://iwc.int/home. Accessed June 2013].
13. Sironi M, Rowntree VJ, Di Martino M, Chirife A, Bandieri L, et al. (2012) Southern right whale mortalities at Península Valdés, Argentina: updated information for 2010 2011. Journal of Cetacean Research and management. (unpublished document SC/64/BRG12, [Available at the International Whaling Commission Office, http://iwc.int/home. Accessed June 2013].
14. Eberhardt LL, Chapman DG, Gilbert JR (1979) A review of marine mammal census methods. Wildlife Monographs Bo. 63: 3 46.
15. Vermeulen E, Cammareri A (2012) Abundance estimates of southern right whales (Eubalaena australis) in Bahía San Antonio, Patagonia, Argentina. Unpublished paper SC/64/BRG20, available at the International Whaling Commission Secretariat (secretariat@iwcoffice.org. Accessed June 2013).
16. Reilly S, Hedley S, Borberg J, Hewitt R, Thiele D, et al. (2004) Biomass and energy transfer to baleen whales in the South Atlantic sector of the Southern ocean. Deep Sea research II 51: 1397 1409.
17. Abileah R (2002) Marine mammal census using space satellite imagery. U.S. Navy Journal of Underwater Acoustics 52 (3) July 2002.
18. Fretwell PT, Trathan PN (2009) Penguins from space: faecal stains reveal the location of emperor penguin colonies Glob Ecol Biogeogr 18: 543 552.
19. Fretwell PT, LaRue MA, Morin P, Kooyman GL, Wienecke B, et al. (2012) An Emperor Penguin population estimate: The first global, synoptic survey of a species from space. Plos One, 7 (4). 11, pp. 10.1371/journal.pone.0033751.
20. LaRue MA, Rotella JJ, Siniff DB, Garrott RA, Stauffer GE, et al. (2011). Satellite imagery can be used to detect variation in abundance of Weddell seals (*Leptonychotes weddellii*) in Erebus Bay, Antarctica. Polar Biology 34: 1727 1737.Appendix 1.
21. Payne R (1986) Long term behavioral studies of the southern right whale (*Eubalaena australis*). Reports of the International Whaling Commission (Special issue) 10: 161 167.
22. International Whaling Commission (2001) Report of the workshop on the comprehensive assessment of right whales: a worldwide comparison. Journal of Cetacean Research and Management (special issue) 2: 1 60.
23. Lee KR, Olsen RC, Kruse FA (2012) Using multi-angle WorldView-2 imagery to determine ocean depth near the island of Oahu, Hawaii, Proc. SPIE 8390, Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery XVIII, 83901I.
24. Bastida R, Rodriguez D (2012) Marine Mammals - Patagonia & Antarctica. 208 pp. Zagier & Urruty Publications, Buenos Aires, Argentina.
25. Patra S, Ghosha S, Ghoshb A (2011) Histogram thresholding for unsupervised change detection of remote sensing images. International Journal of Remote Sensing. 32 (21): 6071 6089. DOI: 10.1080/01431161.2010.507793.
26. Ferrari GM, Hoepffner N, Mingazzini M (1996) Optical properties of the water in a deltaic environment: prospective tool to analyze satellite data in turbid waters, Rem. Sens. Environ., 58: 69 80.
27. Pohl C, Van Genderen JL (1998): Review article Multisensor image fusion in remote sensing: Concepts, methods and applications, International Journal of Remote Sensing, 19 (5): 823 854.
28. Benz UC, Hofmann P, Willhauck G, Lingenfelder I, Heynen M (2004) Multi-resolution, object-oriented fuzzy analysis of remote sensing data for GIS-ready information ISPRS Journal of Photogrammetry & Remote Sensing 58: 239 258.
29. International Whaling Commission (2010) Report of the Southern Right Whale Die-Off Workshop 15-18 March 2010, Centro Nacional Patagónico, Puerto Madryn, Argentina. IWC Document SC/62/Rep 1. 46pp., [Available at the International Whaling Commission Office, http://iwc.int/home. Accessed June 2013].

Remote Sensing of Environment 156 (2015) 448–456

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Using the unique spectral signature of guano to identify unknown seabird colonies

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ARTICLE INFO

Article history:
Received 19 March 2014
Received in revised form 8 October 2014
Accepted 14 October 2014
Available online 4 November 2014

Keywords:
Seabirds
Penguins
Distribution
Guano
Remote sensing

ABSTRACT

Despite the threats faced by seabirds in both terrestrial and marine habitats, even basic knowledge of the locations of colonies, population sizes and trends is lacking for many remote areas of the world. Recent studies have shown that the guano of Adélie penguins can be identified from Landsat Enhanced Thematic Mapper (ETM) imagery and used to map colonies on coasts around continental Antarctica. Our study highlights a new technique based on the unique spectral signature of guano that can be used to discriminate seabird colonies from background geology and vegetation in a wider range of natural environments, including the vegetated and zoologically-diverse region of the Antarctic Peninsula; moreover, the method was effective for all densely colonial, surface-nesting seabirds. Using Landsat ETM imagery, we correctly identified all known seabird colonies of over 50 pairs in the area of Marguerite Bay. Almost all other areas with a similar spectral signature that were outside known breeding areas were single pixels that were readily distinguishable from genuine colonies. If these were excluded, only 4.1% of pixels appeared to represent unknown breeding or roosting sites, and warrant further investigation. The spatial extent of the guano provided a general guide to the number of individuals present, but further work would be required to determine the accuracy of this method for estimating population size. Spectral profiles of guano collected by satellite and hand-held spectrometers were compared with available data in spectral libraries and did not match with any known geological profile. There may also be potential for discriminating colonies of different species that differ in phenology and show seasonal changes in diet by the carefully-timed acquisition of suitable satellite imagery. We conclude that the remotely-sensed guano signature is a good indicator of the location of seabird breeding or roosting sites, with potentially wide application to other areas of the world.

1. Introduction

According to the Red List index compiled by the World Conservation Union (IUCN), the conservation status of seabirds has deteriorated more rapidly than any other species group since 1988, with 28% of species currently listed as Threatened, of which 5% are considered to be Critically Endangered (Croxall et al., 2012). Well-documented threats include competition and bycatch in commercial fisheries, pollution, and predation and habitat destruction by invasive species at breeding sites (Croxall et al., 2012; Lewison et al., 2012). Impacts of global climate change are increasing, including the problem of rising sea levels and greater frequency of storm events causing inundation of breeding colonies on low-lying islands (IPCC 2007), and changes in oceanography that will have knock-on effects on prey distribution and abundance (Baker, Littnan, & Johnston, 2006; Barbraud et al., 2012). Despite the need for an improved understanding of demography and ecology in order to manage and mitigate these processes, in more remote areas of the world even basic knowledge of breeding site locations, population sizes and trends of many seabird species is sparse (Brooke, 2001). This includes Antarctica where projected changes in sea ice extent and duration are predicted to have major impacts on food webs (Ainley et al., 2010; Barbraud et al., 2011), potentially exacerbated by an increase in fisheries for Antarctic krill *Euphausia superba*, which is a key prey for many seabirds, including penguins and petrels (Watters, Hill, Hinke, Matthews, & Reid, 2013). One example of the paucity of knowledge of Antarctic seabirds is the Antarctic petrel *Thalassoica antarctica*, a bird that forages in the Southern Ocean on crustaceans (including krill), fish and squid, and breeds on remote nunataks, mountain ranges and the steep slopes of coastal Antarctic islands (Arnould & Whitehead, 1991; Lorentsen, Klages, & Rov, 1998). Ship-based estimates of abundance suggest a global population of 10 to 20 million birds, perhaps representing 4–7 million breeding birds and an at least equal number of non-breeders and immatures (Brooke, 2004). However the breeding locations of only around 500,000 pairs (i.e. 1 million breeders) are known (van Franeker, Gavrilo, Mehlum, Veit, & Woehler, 1999), probably under a quarter of the estimated total.

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http://dx.doi.org/10.1016/j.rse.2014.10.011

Recent analysis has shown the utility of satellite remote-sensing for studying seabirds in inaccessible regions. The identification of emperor penguin *Aptenodytes forsteri* breeding sites using freely-available, medium-resolution imagery has demonstrated our ability to search very extensive areas to locate colonies (Fretwell & Trathan, 2009; Schwaller, Southwell, & Emmerson, 2013). Once these sites are known, higher-resolution satellite platforms or aerial photography can be used to estimate the population size of particular species, e.g., emperor, Adélie *Pygoscelis adeliae* and chinstrap penguins *Pygoscelis antarcticus* using Very High Resolution (VHR) satellites (Fretwell et al., 2012; LaRue et al., 2014; Naveen, Lynch, Forrest, Mueller, & Polito, 2012), masked boobies *Sula dactylatra* in satellite imagery from Google Earth (Hughes, Martin, & Reynolds, 2011), and lesser flamingos *Phoeniconaias minor* using aerial photography (Groom, Petersen, Anderson, & Fox, 2011). The most appropriate methodology depends on a number of factors, including breeding habitat. Emperor penguins breed on sea ice, which makes their colonies relatively easy to find; in medium resolution imagery, the guano is clearly identifiable in the visible wavelengths as a reddish brown stain against the homogeneous white background of the sea ice. Nothing else on the sea ice has this chromatic signal and therefore emperor penguin colonies can be identified visually in manual searches, or by automated analysis (Fretwell & Trathan, 2009).

The emperor penguin is the only seabird that breeds on sea ice, and so the identification of breeding or nonbreeding aggregations of other species on rocky substrates in the Antarctic requires a different approach. Early work on the spectral signature of guano of Adélie penguins showed that colonies in the Ross Sea region could be differentiated using bivariate plots from surrounding snow and certain rock types (basalt and tuffs) in medium resolution Landsat Thematic Mapper (TM) imagery (Schwaller, Benninghoff, & Olson, 1984; Schwaller, Olson, Zhenqui, Zhiliang, & Dahmer, 1989). An improved approach using Landsat Enhanced Thematic Mapper (ETM) was used subsequently to assess the breeding distribution of Adélie penguins around the entire Antarctic coastline with the exception of the Antarctic Peninsula region (Schwaller et al., 2013). The analysis involved algorithms that distinguished Adélie penguin guano from bare rock and snow. Using ground-truthing from East Antarctica, this successfully determined the location of Adélie penguins with errors of commission in the order of 1% or less, and errors of omission of around 3–4% (by population). One of the problems noted in that study was the positive bias towards classifying colonies of other seabird species as Adélie penguin. This was one of the factors that deterred the authors from applying the method to the Antarctic Peninsula region, where the ornithological landscape is more diverse than East or West Antarctica. Other reasons were that all the ground truthing was carried out in East Antarctica; colonies of Adélie penguins around the Peninsula tend to be smaller and often include other penguin species; the climatic regime differs, and; the peninsula region is more vegetated than the more southerly coasts of West and East Antarctica.

Our aim was to develop a remote-sensing methodology using easily accessible "off the shelf" image processing software and methods that could be used to map seabird colonies in environments that are more complex and diverse than those in East and West Antarctica. We were particularly interested in finding an approach that could be used to detect colonies of flying seabirds, in which nests are often more dispersed than those of penguins, and which could reliably differentiate guano from vegetation. Our expectation was that an approach that worked in the Antarctic Peninsula region might be transferable to temperate or tropical environments where remoteness or lack of resources similarly limits knowledge of the breeding distributions and abundance of seabirds.

2. Methodology

2.1. Acquiring test spectra

To compare the spectral profiles, we measured the reflectance factors of frozen and thawed Adélie penguin guano samples, collected from Cone Island on the Antarctic Peninsula, under laboratory conditions using an ASD FS3 full wavelength (400 nm to 2500 nm) spectroradiometer. Two frozen pieces of guano were chosen for sampling. Each was measured multiple times; five measurements were taken from different aspects of the guano piece following rotation each time by c. 40°, and this procedure was repeated five times to give an average profile. The frozen guano was then left at room temperature and the procedure was repeated with the thawed sample. These data were subsequently converted to a Landsat-equivalent profile of 6 spectral bands using the satellite optical sensor band filter functions available from the Natural Environment Research Council Field Spectroscopy Facility (NERC FSF) website (http://fsf.nerc.ac.uk/user_group/user_group.shtml >) and processed using the FSF Matlab Toolbox, available from the same source. We compared the raw and Landsat-equivalent profiles to published geological spectral libraries from USGS (Clark et al., 2007), and almost 2000 unpublished archival spectra profiles of Antarctic (mostly rock samples but with some Antarctic vegetation samples) held locally at British Antarctic Survey mostly collected around the test site, and samples from other regions collected by the British Geological survey. The technique for collecting field samples is described in the published literature (Haselwimmer & Fretwell, 2009). Profiles were compared using the ENVI routine Spectral Analyst, which uses Binary Encoding, Spectral Angler Mapper and Spectral Feature Fitting to rank the match of a sample spectrum to an existing spectral library.

2.2. Landsat analysis

A single Landsat scene (ID 220108000105050) of Marguerite Bay (68°30′W, 68°30′S) at the Antarctic Peninsula was used in our initial analysis. Landsat data consist of a number of bands that cover the electromagnetic spectrum from visible wavelengths to thermal infra-red (Landsat 7 Science Data Users Handbook). We used bands 1–5 and band 7 which comprise data between 450 and 2350 nm. The advantages of using Landsat images are that they are freely available, each image covers a large footprint (typical scene width of ~180 km), and there is a comprehensive archive of Landsat TM and Enhanced Thematic Mapper (ETM) images from 1984 and 1993, respectively, to the present that cover all continental land masses. This large archive ensures that there is an available cloud-free scene of most locations at the time of year when the extent of the guano in bird colonies is likely to be high (see Section 4 Discussion).

There is information available on the location and size of Adélie penguin colonies in the area of Marguerite Bay (Harris, Carr, Lorenz, & Jones, 2011, British Antarctic Survey unpublished data). In addition, this area is close to the British Antarctic Survey (BAS) research station at Rothera Point, and the BAS archives hold records of counts of Antarctic shags *Phalacrocorax bransfieldensis*, snow petrels *Pagodroma nivea nivea*, southern giant petrels *Macronectes giganteus*, skuas (south polar skua *Stercorarius maccormicki* and brown skua *Stercorarius antarcticus)* and southern fulmar *Fulmarus glacialoides* (Fig. 1 and Tables 1 and S1). As well as information on bird colonies, the geology of the area is better mapped than many parts of Antarctica (Riley, Flowerdew, & Haselwimmer, 2011).

The Landsat image was changed from raw digital numbers (DN) to reflectance using ERDAS Imagine software. No aerosol model was used as the Antarctic atmosphere is considered cold and clean with minimum aerosol levels (Bindschadler et al., 2008). A number of classification methods were tested for the ability to discriminate areas of guano. Of these, Spectral Angle Mapper in ENVI image processing software (Exelis Visual Information Solutions) provided the best results. Spectral Angle Mapper uses the shape of the spectral profile from a number of training pixels that are manually identified by the user. We used a training sample of 44 and 88 pixels of guano from Adélie penguin colonies at Cone Island (69°09′25″W, 67°40′38″S) and Lagotellier Island (67°22′52″W, 67°53′22″S). Spectral Angle Mapper (SAM target finder with BANDMAX in ENVI software) was then applied to produce a "similarity

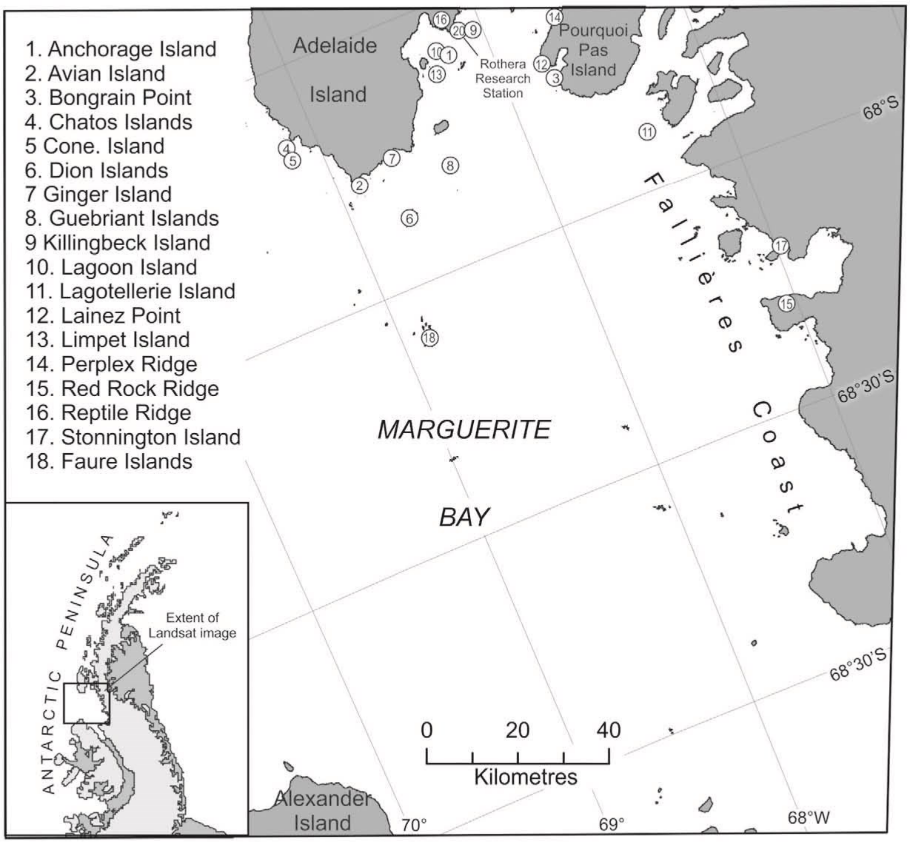


Fig. 1. Known seabird colonies in Marguerite Bay within the coverage of Landsat path 220 row 108 date 19/02/2001. Colony sizes are given in Table 1.

Table 1

Population sizes (number of pairs) in known seabird colonies in the Marguerite Bay area compiled from various sources (see references in main text). + = present, ++ = abundant. Further details are supplied in Supplementary Table S1 (the abbreviation PQP refers to Pourquoi Pas Island).

	Skuas	Dominican gull	Ant. shag	Snow petrel	Adelie penguin	Sthn. fulmar	Sthn. giant petrel
Anchorage	100 s						
Avian Island	200	60	670		77,515		250
Bongrain Pt, PQP					700		
Chatos					100		
Cone Island			55		2790		
Dion Islands	22	2	500		700		
Ginger Island			275		3000		
Guebriant	35		Colony				
Killingbeck		3	30				
Lagoon Island	200		58				
Lagotellerie Island			++		1700		
Lainez Point, PQP							76
Limpet Island	8						
Mikkelsen Island	Present						
Perplex Ridge, PQP						Many 1000s	
Red Rock Ridge					12,400		
Reptile Ridge				200			
Rothera Point	18–25	40					
Stonington Island	+		135				

ratio", which is the ratio of the nearness of the spectral profile of each individual pixel in the Landsat image to these sample pixels. The SAM algorithm requires the user to set a maximum angle which the programme applies to the spectra of each pixel to match the profile in n-dimensional space. The software then rejects pixels which do not conform to the required angle. Using trial and error, the best results for our image were using an angle of 0.05%. The resulting output contained some noise in the marine areas of the image. An initial marine mask was applied, based on the threshold of the near-infra-red (band 4) image of the corresponding Landsat scene, and the coastline from the best available digital data (SCAR ADD 6). (http://http://www.add.scar.org/) As the coastline is often poorly mapped in this area, we applied a buffer of 1 km to ensure that all land pixels were included. The resulting grid can be viewed as a ratio of the similarities of each pixel to the training dataset, and could be further refined to give the best results. Therefore two further analyses were performed. The first eliminated the least similar third of the resulting pixels (analysis 1); the second did likewise, but also eliminated single pixels (analysis 2).

Table 2
Estimates of the total number of birds from ground surveys in comparison with guano area estimates from the two Spectral Angler Mapper analyses. Analysis 1 includes single pixels, analysis 2 does not. The Faure Island colony was discovered in this study.

Location	Ground counts (estimated total breeding pairs, all species)	Analysis 1 (m^2)	Analysis 2 (m^2)
Anchorage	100	1800	1800
Avian Island	78,445	130,500	108,000
Bongrain Pt, PQP	700	9900	2700
Chatos	100	900	0
Cone Island	2845	21,600	10,800
Dion Islands	1224	14,400	5400
Ginger Island	3275	2700	2700
Guebriant	35	6300	1800
Killingbeck	30	0	0
Lagoon Island	258	4500	3600
Lagotellerie Island	1700	14,400	10,800
Lainez Point, PQP	80	1800	0
Limpet Island	8	900	0
Perplex Ridge, PQP	4000	28,800	3600
Red Rock Ridge	1200	3600	1800
Rothera Point	64	0	0
Reptile Ridge	200	5400	2700
Stonington Island	135	0	0
Faure Islands	Unknown	22,500	3600
Area of known colonies (m^2)		270,000	159,300
Area of a returns from the analysis		362,700	162,900
% of area accounted for by known colonies		74.4	98.1

2.3. Vegetation discrimination

One of the possible confounding factors that may limit the ability of satellite imagery to discriminate guano on the Antarctic Peninsula is the presence of vegetation (Schwaller et al., 2013). We used the atmospherically corrected Landsat imagery to test whether the results from the SAM analysis were sensitive to the presence of vegetation. Landsat imagery has been used to detect vegetation on the Antarctic Peninsula by NDVI analysis (Fretwell, Convey, Fleming, Peat, & Hughes, 2011) and we used this methodology to identify vegetation in the test area. We then calculated the number of rock polygons from the Antarctic Digital Database that had vegetation and compared this to the number of polygons that contained guano. The earlier vegetation work classified the NDVI results into three types; probably vegetation, very probably vegetation, and almost certain vegetation, depending upon the NDVI value of each pixel. We assessed the spatial correlation of guano pixels derived from the SAM analysis against these three classes.

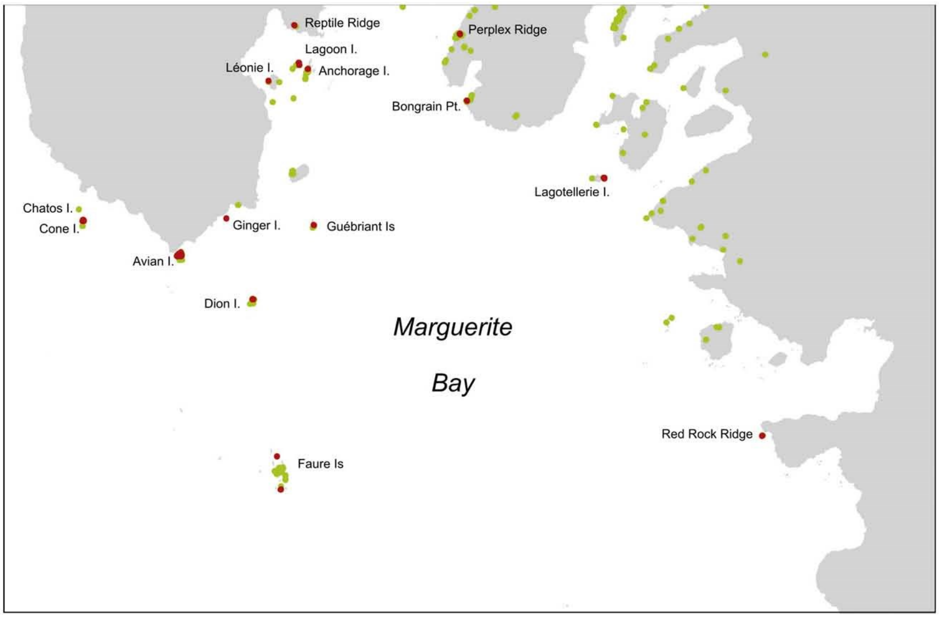


Fig. 2. Results of the Spectral Angle Mapper analysis. Green pixels — results from analysis 1 which included single pixels. Red dots — results from analysis 2 where only multiple pixels were returned.

3. Results

3.1. Comparison of spectral results with archival data

From the original ~42 million pixels (on-the-ground resolution of 30 × 30 m) contained within the Landsat scene, the SAM analysis identified 309 pixels in analysis 1, and 177 pixels in analysis 2 that matched the training data from the Adélie penguin colony at Cone Island. Of these pixels, 74.4% and 98.1%, respectively, were at, or near, known seabird colonies (Fig. 2 and Table 2). Analysis 1, which included single pixels, highlighted almost all known bird colonies with the exception of the three small colonies (<150 birds) at Killingbeck Island and Stonington Island. However, 91 pixels (29.5%), particularly single pixels, were in areas where there are no known bird colonies. It is unknown what proportion of these pixels represent small colonies of breeding birds, or roosting sites. As the majority of the single pixels had a low similarity ratio, it seems likely that most are false positives rather than genuine colony locations. It is important to note that several of the smaller colonies with <100 known breeding pairs were clearly identified in the analyses. Analysis 2, which excluded single pixels, identified 177 pixels that matched the training data; around half the number of analysis 1. This successfully identified all eight known seabird colonies that held >100 pairs in the area of the image, in addition to two locations where the number of birds was either unknown (Faure Islands) or small (Guébriant Island). It is questionable, however, if the pixels on Anchorage and Lagoon islands reflect the location of guano associated with penguin colonies. On Anchorage Island, in the Leonie Island group, there were 18 pixels identified in analysis 1 and four in analysis 2. As these pixels are dispersed and there are no breeding colonies of penguins, they would appear to reflect areas of guano associated with the several hundred skuas that nest on the islands. Although skuas breed at low density, substantial numbers of birds (presumably nonbreeders and failed breeders) congregate around ponds and other sites, some associated with seal wallows on the island (P. Geissler pers. coms.). Three of the four single pixels from analysis 2 on these islands are in such areas where skuas are known to congregate.

3.2. Examination of outliers

Analysis 2 returned only 8 pixels (4.5%) outside known colony locations. These pixels were in four separate groups located in three different areas; Léonie Island, the Faure Islands, and an un-named ridge

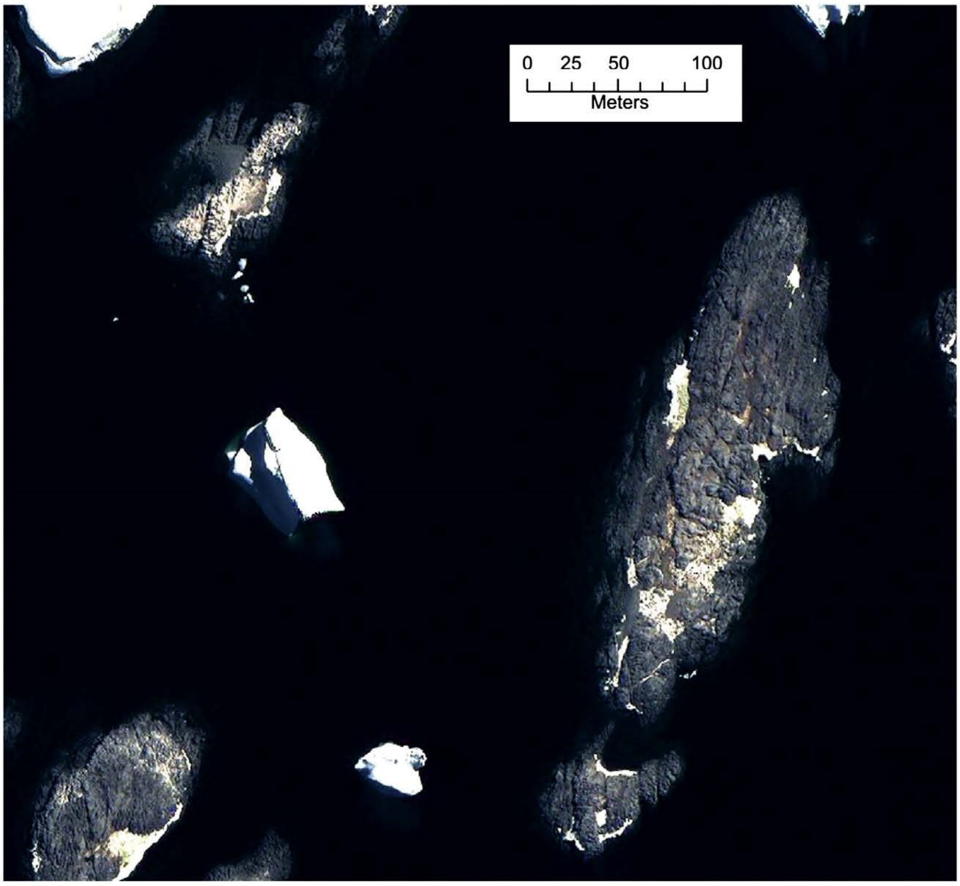


Fig. 3. Quickbird VHR imagery from the 31st of January 2010 of three islands in the Faure archipelago. Pink areas indicate guano stains. Our analysis highlighted that this island group potentially holds major seabird colonies.

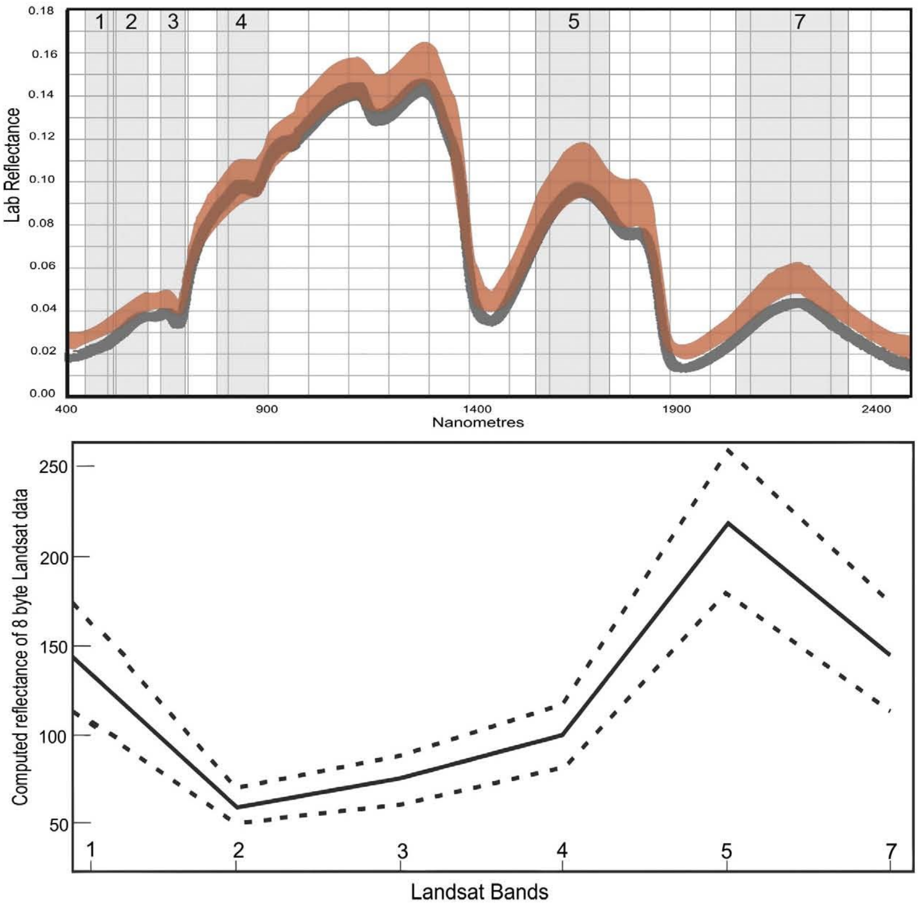
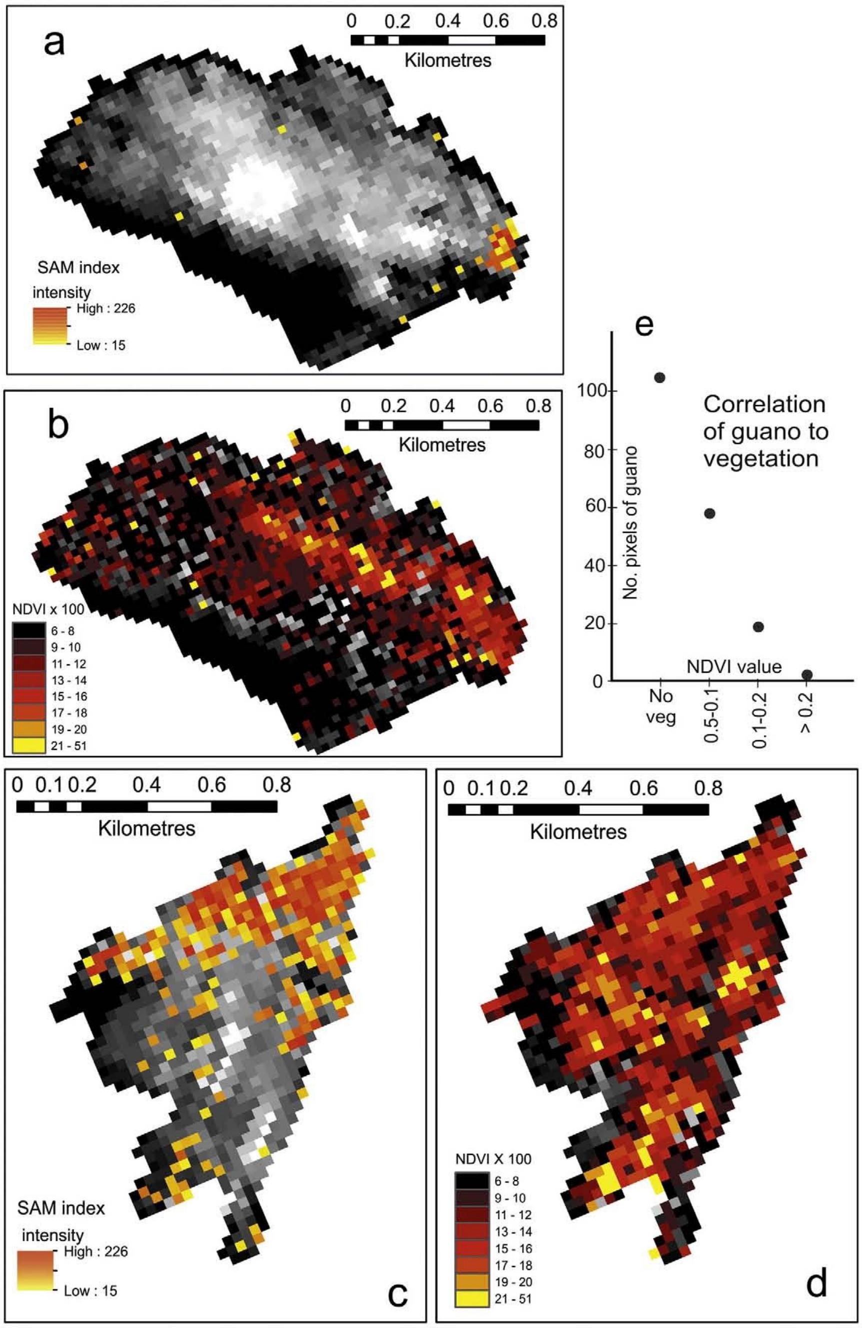


Fig. 4. Above: Laboratory derived spectral profile of Adélie penguin guano. The two lines – pink and grey – denote the two sample pieces. Variation indicated by the line width denotes the range of the 20 scans from various angles of each piece. The light grey vertical lines denote the Landsat band widths for reference. Below: Spectral profile of guano from the training sample at Cone Island convolved to Landsat bandwidths. Black line denotes mean value of 44 pixels across the 6 Landsat bands; dashed lines indicate +/−1 SD.

south of McMorrin Glacier. On the Faure Islands, analysis 1 returned 25 pixels and analysis 2 returned 4 pixels. With this in mind, a small QuickBird VHR satellite image of the area was obtained from the 31st of January 2010 (QuickBird2 catalogue number 101001000B06C800). This imagery has a resolution of 2.4 m in the multispectral bands and 0.64 m in the panchromatic. Fig. 3 shows an example of part of this image. A faint pink colouration can be identified on three of the islands, which is suggestive of guano. To determine whether this reflected the presence of seabirds, a survey flight was undertaken in early December 2012 (during the incubation period of Adélie penguins). Although there was no sign of any breeding birds in the archipelago on that date, reports from scientists who frequently visit the area suggest that this is a major roosting site for Adélie penguins in winter (Bill Fraser pers. coms.). Including the Faure Islands, the percentage of pixels in our analysis that are explained by known colonies or roosting sites are 76.7 and 98.1% in analysis 1 and 2 respectively. Overall, a linear regression relating the area of guano identified from the satellite image to the number of breeding pairs of seabirds has an r^2 value of 0.9505 if all colonies are included, and 0.5899 without an obvious influential outlier, which was the single large colony on Avian Island. This lower r^2 value may be due partly to the differing nesting densities of each species.

3.3. Comparison with spectral libraries

We tested the spectral profile of the guano pixels used as a training sample (from Cone Island and Lagotellerie) against the profiles of guano sampled in the lab and published spectral libraries (Fig. 4). These profiles show that guano has a high reflectance in band 5 in relation to the other bands, in contrast with most types of geology, vegetation or other substrates. Initial comparison with other profiles in spectral libraries suggests that although a number of geologies have high reflectance in band 5 (e.g. hydrothermally altered clays such as illite and kaolinite), no other known profile of the several thousand spectra from different types of geology and vegetation matched the spectral signature of guano.


a
0 0.2 0.4 0.6 0.8
Kilometres
SAM index
intensity
High : 226
Low : 15
b
0 0.2 0.4 0.6 0.8
Kilometres
NDVI x 100
6 - 8
9 - 10
11 - 12
13 - 14
15 - 16
17 - 18
19 - 20
21 - 51
e
Correlation of guano to vegetation
No. pixels of guano
100
80
60
40
20
0
NDVI value
No veg
0.5-0.1
0.1-0.2
> 0.2
0 0.1 0.2 0.4 0.6 0.8
Kilometres
SAM index
intensity
High : 226
Low : 15
c
0 0.1 0.2 0.4 0.6 0.8
Kilometres
NDVI X 100
6 - 8
9 - 10
11 - 12
13 - 14
15 - 16
17 - 18
19 - 20
21 - 51
d

3.4. Differentiating from vegetation

The identification of pixels from the SAM was independent of the presence of vegetation. The test area contained 169 rock polygons with vegetation from the NDVI analysis, whereas only 35 rock polygons contained guano. All rocky areas that had guano also had vegetation. Of the 177 pixels returned as guano in analysis 2, 57% did not correspond directly with vegetation polygons. Of those that did, 84.8% (36.2% of all guano) were in the lowest vegetation class, with NDVI values of between 0.05 and 0.10, 12.6% pixels (5.4% of all guano) were in the second class, termed "very probably vegetated" with NDVI between 0.10 and 0.20, and only 2.6% (1.1% of all guano) were in the "almost certain vegetation" class, with an NDVI > 0.2. Fig. 5 shows examples of the correlation from two of the larger penguin colonies in the area: Fig. 5a shows guano results from the SAM analysis of Lagotellerie Island. The intensity represents spectral match to the guano training data given by the SAM analysis and can be seen as an indication of the amount of guano. Fig. 5b shows the corresponding NDVI results that indicate the presence of vegetation. Fig. 5c and b represents the corresponding analysis of guano and vegetation on Avian Island. In line with the overall results on both islands, the majority of guano pixels tend to be in areas of low or possible vegetation, and not in the areas of highest vegetation.

4. Discussion

4.1. Overview of results

Our results show a close match between the location of known seabird breeding colonies or, in a few cases, probable roosting aggregations, and the pixels highlighted by the SAM analysis. In the more restricted analysis with a higher threshold for inclusion, all colonies with > 150 breeding pairs were identified; only a few of the smaller colonies were omitted, and there were very few errors of commission (false positives). The two colonies that were not identified in our analysis were both of Antarctic shags. This species feed predominantly on fish rather than krill and it may be that the different diet affects the spectral profile of the guano. Further work is needed to clarify whether bird with a predominantly fish diet such as Antarctic shags has guano with spectra as unique as those ones used in this study. It is also probable that surface-nesting birds that breed at low densities (e.g. terns), and burrow- or crevice-nesting species (e.g. petrels) are less suited to this type of analysis.

Less than 2% of the identified pixels were unaccounted for by known seabird colonies or roosting sites. This suggests that the spectral signature of guano from our training sample is distinct from both the vegetation and geological substrates in the same areas. The less restricted test (analysis 1) highlighted many single pixels on low unglaciated islands; there is some evidence, especially on the Leonie Island group, that this may reflect the presence of skuas where they congregate in higher densities. However, the availability of ground truthing data even in this relatively well visited region of Antarctica is insufficient to verify if that is indeed the case.

The SAM analysis does not confuse guano with vegetation which, on the whole, is much more widely distributed. This is presumably because although most seabirds are found in, or around, vegetated areas, and several studies show that aerosol and runoff from seabird colonies can fertilize nearby vegetation (Myrcha & Tatur, 1991; Xie, Sun, Wang, & Liu, 2002), extensive areas of vegetation do not persist within dense colonies of nesting seabirds. Our test area in Marguerite Bay has a limited range of geological types, mostly of plutonic or volcanic origin (Riley et al., 2011), which do not reflect the complexity of geology on the Antarctic Peninsula. However, tests of the spectral profile of guano obtained in the laboratory against almost 3000 reference spectra from spectral libraries suggest that its signature is indeed unique and that guano can be discriminated from any type of background geology. The SAM algorithm is a widely-used analytical technique tailored to extract a single end-member from an image. It is not sensitive to albedo and less sensitive to changes in lighting, absolute illumination (sun angle/slope/detector off-nadir angle) or shading than many similar algorithms (Dennison, Halligan, & Roberts, 2004). It is therefore ideal for many areas of the Antarctic where digital elevation models needed to calculate absolute reflectance are inadequate. Also, unlike supervised classifications which require the input of many end-member signatures from of all surfaces in the image, the SAM analysis restricts itself to search for a single end-member, and the number of training pixels used need to reflect just this single surface type. This reduces the user input required to choose pixels, making this both a pragmatic and effective methodology.

4.2. Assessing population sizes

There was a significant correlation between the total breeding population size of all species of seabird at each site, and the area of guano indicated by the spectral analysis, although the correlation was much weaker without the statistical outlier of Avian Island. In analysis 1, the area comparison had an r^2 value of 0.951 when Avian Island was included and of 0.589 without Avian Island. In analysis 2, the respective r^2 values were 0.988 and 0.366. Three of these four regressions were significant at $p < 0.05$, and the other was borderline (0.058). Nevertheless, we would caution against using these relationships to predict the size of unknown seabird breeding colonies for various reasons. The resolution of the Landsat sensor is relatively coarse. In addition, most of the data on colony sizes in the study area were collected in surveys conducted in the 1950s to 1980s, many were rough estimates, and numbers have changed, often substantially, at the few sites that have been revisited; at Avian Island, for example, counts of Adélie penguins range from c. 36,000 pairs to 77,000 pairs (data from 1979 to 2002; ASPA management plan of Avian Island). New colonies may have become established at some sites, and some of the population estimates were from outside the breeding season. In addition, the differing nesting densities among seabird species, and the marked variation in density even within species, such as the Adélie penguin, will reduce substantially the degree of correspondence between colony or guano extent, and breeding numbers (Woehler & Riddle, 1998). Moreover, the 30 m pixel resolution of Landsat does not allow discrimination of the unoccupied areas of ground between nearby colonies (Naveen et al., 2012).

There is also extensive variation among different seabird species, and also to some extent between colonies, in diet, timing of breeding, and body size, which will affect the amount and chemistry of the guano on site, which in turn influences the spectral signature. Nor is the breeding density or nesting location constant during the season; birds fail, non-breeders arrive and depart, and in penguins, the structure changes from discrete nest sites always attended by at least one pair member during the incubation and brooding stages, to large groups of mostly-unattended chicks during crèche. We believe that the size of the guano signature in the satellite imagery, especially from medium resolution sensors, should only be considered as a general guide to the number of breeding pairs, pending further, extensive validation and quantification of the effects of the key variables affecting the relationship.

There are a number of considerations to take into account if the approach described here was to be extended to different regions and species. Atmospheric correction must be applied to Landsat data (Bindschadler et al., 2008), and the coarse resolution will only enable the location of large guano concentrations. These concentrations could

Fig. 5. Four examples of the correlation between the SAM guano analysis and NDVI vegetation analysis from two of the larger penguin colonies in the area. Fig. 5a shows guano results from the SAM analysis of Lagotellerie Island, the intensity represents spectral match to the guano training data given by the SAM analysis and can be seen as an indication of the amount of guano. Fig. 5b shows the corresponding NDVI results that indicate the presence of vegetation. Fig. 5c and d represents the corresponding analysis of guano and vegetation on Avian Island. Fig. 5e shows the strong negative correlation between the areas of guano and the NDVI results over the whole study area.

represent breeding colonies or non-breeding aggregations of a number of species depending on regional biogeography. However, higher resolution information from VHR satellites, aerial photography or ground survey could be used to confirm presence and species identity. If VHR satellite imagery or aerial photography is available, individual colony boundaries may be identified from the distinct patches of guano (Naveen et al., 2012). Careful timing of data acquisition may elucidate the species if there are differences in their timing of breeding based on colour change of guano in the period after chick hatching, but more field work will be required to assess how this affects the spectra. Thus, a combined approach of large-scale Landsat survey to find seabird colonies or roosting sites, and carefully timed higher-resolution imagery to estimate population size should be feasible, especially with the launch of superspectral VHR sensors such as WorldView3 and Sentinel-2, both planned for the next year. With such data, similar techniques could feasibly be expanded to any suitable area of the globe, including deserts and polar regions, and to other species, although further ground-truthing will clearly be required.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.rse.2014.10.011.

Acknowledgements

This study is part of the British Antarctic Survey Polar Science for Planet Earth Programme. It was funded by The Natural Environment Research Council.

The authors acknowledge and are grateful for the support and assistance provided by the NERC Field Spectroscopy Facility through the provision of training, loan of a spectroradiometer, laboratory studies and assistance in data analysis.

References

Ainley, D.G., Russell, J., Jenouvrier, S., Woehler, E., Lyver O'b, P., Fraser, W.R., et al. (2010). Antarctic penguin response to habitat change as earth's troposphere reaches 2 °C above pre-industrial levels. *Ecological Monographs*, *80*, 49–66.

Arnould, J.P.Y., & Whitehead, M.D. (1991). The diet of Antarctic petrels, cape petrels and southern fulmars rearing chicks in Prydz Bay. *Antarctic Science*, *3*, 19–27.

Baker, J.D., Littnan, C.L., & Johnston, D.W. (2006). Potential effects of sea level rise on the terrestrial habitats of endangered and endemic megafauna in the Northwestern Hawaiian Islands. *Endangered Species Research*, *2*, 21–30.

Barbraud, C., Rivalan, P., Inchaustip, P., Nevoux, M., Rolland, V., & Wiemerskirch, H. (2011). Contrasted demographic responses facing future climate change in Southern Ocean seabirds. *Journal of Animal Ecology*, *80*, 89–100.

Barbraud, C., Rolland, V., Jenouvrier, S., Nevoux, M., Delord, K., & Weimerskirch, H. (2012). Effects of climate change and fisheries bycatch on Southern Ocean seabirds: A review. *Marine Ecology Progress Series*, *454*, 285–307.

Bindschadler, R., Vornberger, P., Fleming, A.H., Fox, A.J., Mullins, J., Binnie, D., et al. (2008). The Landsat image mosaic of Antarctica. *Remote Sensing of the Environment*, *112*, 4214–4226.

Brooke, M. de L. (2001). Systematics and distribution of seabirds of the world: A review of current knowledge. In E. -A. Schreiber, & J. Berger (Eds.), *The biology of marine birds* (pp. 57–83). Boca Raton: CRC Press.

Brooke, M. (2004). *Albatrosses and petrels across the world.* Oxford, UK: Oxford University Press, 230–232.

Clark, R.N., Swayse, G.A., Wise, R., Livo, K.E., Hoefen, T.M., Kokaly, R.F., et al. (2007). *USGS spectral library, splib06a.* US geological survey, digital data series 231.

Croxall, J.P., Butchart, S.H.M., Lascelles, B., Stattersfield, A.J., Sullivan, B., Symes, A., et al. (2012). Seabird conservation status, threats and priority actions: A global assessment. *Bird Conservation International*, *22*, 1–34, http://dx.doi.org/10.1017/S0959270912000020.

Dennison, P.E., Halligan, K.Q., & Roberts, D.A. (2004). A comparison of error metrics and constraints for multiple endmember spectral mixture analysis and spectral angle mapper. *Remote Sensing of the Environment*, *93*, 359–367.

Fretwell, P.T., Convey, P., Fleming, A.H., Peat, H.J., & Hughes, K.A. (2011). Detecting and mapping vegetation on the Antarctic Peninsula from remote sensing data. *Polar Biology*, *34*, 273–281, http://dx.doi.org/10.1007/s00300-010-0880-2.

Fretwell, P.T., LaRue, M.A., Morin, P., Kooyman, G.L., 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*.

Fretwell, P.T., & Trathan, P.N. (2009). Penguins from space: Faecal stains reveal the location of emperor penguin colonies. *Global Ecology and Biogeography*, *18*, 543–552.

Groom, G., Petersen, I.K., Anderson, M.D., & Fox, A.D. (2011). Using object-based analysis of image data to count birds: Mapping of lesser flamingos at Kamfers Dam, Northern Cape, South Africa. *International Journal of Remote Sensing*, *32*(16), 4611–4639.

Harris, C.M., Carr, R., Lorenz, K., & Jones, S. (2011). *Important bird areas in Antarctica: Antarctic Peninsula, South Shetland Is lands, South Orkney Islands — Final report.* Prepared for birdlife international and the polar regions unit of the UK Foreign & Commonwealth Office. Cambridge: Environmental Research & Assessment Ltd (downloaded from: http://www.birdlife.org/datazone/userfiles/file/IBAs/AntPDFs/IBA_Antarctic_Peninsula.pdf accessed January 2014).

Haselwimmer, C., & Fretwell, P.T. (2009). Field reflectance spectroscopy of sparse vegetation cover on the Antarctic Peninsula. *1st IEEE GRSS workshop on hyperspectral image and signal processing — Evolution in remote sensing, Grenoble, France, 26–29 August 2009: WHISPERS'09* (pp. 162–165). New York: Institute of Electrical and Electronics Engineers.

Hughes, J.B., Martin, G.R., & Reynolds, J. (2011). The use of Google Earth™ satellite imagery to detect the nests of masked boobies *Sula dactylatra*. *Wildlife Biology*, *17*, 210–216, http://dx.doi.org/10.2981/10-106.

LaRue, M.A., Lynch, H.J., Lyver, P.O.B., Barton, K., Ainley, D.G., Pollard, A., et al. (2014). A method for estimating colony sizes of Adélie penguins using remote sensing imagery. *Polar Biology*, *37*, 507–517.

Lewison, R., Oro, D., Godley, B., Underhill, L., Bearhop, S., Wilson, R.P., et al. (2012). Research priorities for seabirds: Improving seabird conservation and management in the 21st century. *Endangered Species Research*, *17*, 93–121.

Lorentsen, S.H., Klages, N., & Rov, N. (1998). Diet and prey consumption of Antarctic petrels *Thalassoica antarctica* at Svarthamaren, Dronning Maud Land, and at sea outside the colony. *Polar Biology*, *19*, 414–420.

Myrcha, A., & Tatur, A. (1991). Ecological role of the current and abandoned penguin rookeries in the land environment of the maritime Antarctic. *Polish Polar Research*, *12*(1), 13–24.

Naveen, R., Lynch, H.J., Forrest, S., Mueller, T., & Polito, M. (2012). First direct, site-wide penguin survey at Deception Island, Antarctica, suggests significant declines in breeding chinstrap penguins. *Polar Biology*, *35*(12), 1879–1888.

Riley, T.R., Flowerdew, M.J., Haselwimmer, C.E. (2011) Geological map of Adelaide Island, Graham Land (1:200 000 scale). BAS GEOMAP 2 Series, sheet 2, British Antarctic Survey, Cambridge, UK.

Schwaller, M.R., Benninghoff, W.S., & Olson, C.E., Jr. (1984). Prospects for satellite remote sensing of Adélie penguin rookeries. *International Journal of Remote Sensing*, *5*, 849–853.

Schwaller, M.R., Olson, C.E., Jr., Zhenqui, M., Zhiliang, Z., & Dahmer, P. (1989). A remote sensing analysis of Adelie penguin rookeries. *Remote Sensing of the Environment*, *28*, 199–206.

Schwaller, M.R., Southwell, C.J., & Emmerson, L.M. (2013). Continental-scale mapping of Adélie penguin colonies from Landsat imagery. *Remote Sensing of the Environment*, *139*, 353–364.

van Franeker, J.A., Gavrilo, M., Mehlum, F., Veit, R.R., & Woehler, E.J. (1999). Distribution and abundance of the Antarctic Petrel. *Waterbirds*, *22*(1), 14–28.

Watters, G.M., Hill, S.L., Hinke, J.T., Matthews, J., & Reid, K. (2013). Decision-making for ecosystem-based management: Evaluating options for a krill fishery with an ecosystem dynamics model. *Ecological Applications*, *23*, 710–725.

Woehler, E.J., & Riddle, M.J. (1998). Spatial relationships of Adélie penguin colonies: Implications for assessing population changes from remote imagery. *Antarctic Science*, *10*, 449–454.

Xie, Z.Q., Sun, L.G., Wang, J.J., & Liu, B.Z. (2002). A potential source of atmospheric sulphur from penguin colony emissions. *Journal Geo-physical Research Letters*, *107*(4617), 2002, http://dx.doi.org/10.1029/2002JD002114.

Appendix 1

Glossary of remote sensing terms used in the thesis

AVHRR

Advanced Very High Resolution Radiometer. A type of satellite-borne sensor that collects data in five spectral bands targeted at measuring clouds and thermal emissions from the earth. In Antarctica these sensors are commonly used to map and measure ice shelves.

BAND

Multispectral images collect data from discrete (occasionally overlapping) parts of the electromagnetic spectrum. Earth observation satellites will have Multispectral instruments that include a number of sensors, each tasked with measuring the electromagnet radiation in one band (sometime also referred to as channels). Each band has certain characteristics including bandwidth; where on the spectrum the collection starts and ends, and profile, which denotes the pattern of collection across the bandwidth.

Digital Globe

A commercial satellite image provider with a constellation of very high resolution satellites.

ENVISAT

An ENVIromental earth observation SATellite launched by the European space agency in 2002. The satellite included a range of instruments including, most importantly for polar studies, the ASAR sensor; a C band synthetic aperture radar instrument. The satellite continued working until 2012. It was superseded by the sentinel series of satellites.

ESA

The European Space Agency

Hyperspectral

Similar to multispectral imagery but whereas a multispectral instrument collects information from 1-10 bands a hyperspectral instrument collects over 100 bands of data.

Ikonos-2

The first commercially available high resolution satellite, with spatial resolution of 1 and 4 metres per pixel on the ground.

Landsat ETM+

The Enhanced Thematic Mapper instrument on the Landsat7 launched in 1999. Called ETM plus as the original ETM instrument on Landsat 6 failed to launch. The ETM+ instrument collects data at 15m panchromatic, 30m in the 6 visible and near infrared bands and 60 thermal band. Part of the instrument failed in 2003, so although the satellite is still collecting data, heavy processing is needed to make more recently acquire data useable.

Landsat8

The most recent Landsat satellite launched in 2013, with similar spatial resolution to the ETM+ sensor, but greater radiometric resolution (in the SWIR bands) and quicker revist time - collecting almost three times as many scense as the previous Landsat7

LIMA mosaic

Landsat Image Mosaic of Antarctic. The first colour, medium resolution satellite image mosaic of Antarctic, which used pansharpened Landsat7 ETM+ images taken between 1999 and 2003.

MODIS

Moderate-resolution Image spectroradiometer. An earth observation sensor on NASA's Terra satellite launched in 2002. The instrument has 60 bands and collects data between 620 nm and 14.3 μm. It is used primarily to study large scale earth process and detect change.

Multispectral

A sensor with 1 to 10 spectral bands (see bands)

Nadir pointing

Directly downward pointing

NASA

National Aeronautics and Space Administration. The US government space agency.

NDVI

Normalized Difference Vegetation Index. A commonly used remote sensing algorithm to detect vegetation by characterizing the "red edge" quality of green leaves that reflect more light in the infrared than the red wavelengths.

Near infrared

A part of the electromagnetic spectrum between 700 and 2500nm, with wavelengths beyond that seen by the human eye. Many satellite instruments include near-infrared sensors for their ability to discriminate vegetation, geology, water and other environmental features.

Off-Nadir

A satellite sensor that does not point directly downwards.

Panchromatic

A single grayscale image or single band of data from a satellite sensor, often taken from the visible and near infra-red parts of the spectrum below 1000 nm. As part of multispectral instruments, the panchromatic band is commonly of higher spatial resolution than the colour bands.

Pixel

The individual cell of a raster image such as a digital photograph or satellite image. Each pixel can contain one or more “bands” of information

Quickbird 1

The Quickbird (later classed as Quickbird1) satellite was the first of Digital Globe’s very high resolution satellites. This panchromatic earth observation satellite was launched in 2001 and decayed in 2015. It had an on-the-ground spatial resolution of 0.61m

Quickbird2

The second Digital Globe satellite launched in 2004 it provides multispectral VHR imagery at 0.61m (panchromatic) and 2.4m (colour) spatial resolution.

Radiometric resolution

Defines the sensitivity of the instrument, how well the differences in brightness in an image band can be perceived. Each pixel will have a brightness value and depending upon the bit-depth of the image, more or less detail can be seen. Images with larger radiometric resolution will be able to differentiate subtle differences in the reflected energy emitted by the earth's surface.

SAR

Synthetic Aperture Radar. A satellite (or aerial) sensor that provides imagery through the use of pulses of radio waves. SAR is an active sensor, it does not create true images, but, depending upon polarization give different results over different materials mainly due to the texture/reflection at different wavelengths. SAR has the advantage of seeing through clouds and is therefore very useful in cloudy areas or where regular acquisition is required.

Sensor

The sensor is the individual device that collects electromagnetic energy in a remote sensing instrument. Each sensor usually collects energy between specific wavelengths. Panchromatic instruments have one senor, while multispectral or hyperspectral instruments have multiple sensors. Sensors can be passive or active, push-broom, swath or single shot and collect data from various parts of the electromagnetic spectrum.

Spatial Resolution

Also known as "Ground sample distance", this can be thought of as the size on the ground of each pixel, or the distance between the centre point of each pixel (in some cases, senors can be "over-sampled" which means that the distance between pixel centres and the size of each pixel is different, but this is not commonly the case.

Spectral Angle Mapper

An algorithm that classifies imagery by testing spectral angles between pixels in the image with reference pixels. The algorithm determines the spectral similarity between two spectra by calculating the angle between the spectra and treating them as vectors in a space with dimensionality equal to the number of bands.

Spectral library

A collection of spectral profiles, usually from lab samples, for comparison with remotely sensed imagery.

Spectral Profile

A profile plot that displays the reflectance of a property or pixel across a number of bands or bins. Profiles can be collected in the lab or from RS imagery and can be continuous or broken.

Spectral Resolution

The ability to resolve spectral features in the electromagnetic spectrum. In remote sensing this is commonly thought of as the number and width of sensor bands in an earth observation instrument – a higher number of bands relates to higher spectral resolution. The bandwidth and positioning of the bands within the electromagnetic spectrum is also of key importance.

Supervised Classification

A machine learning algorithm that uses user-input in the form of training data to group an image into classes of like pixels. Supervised classifications can be very useful in understanding imagery, but are reliant on the cognitive processing skill of the operator.

Temporal Resolution

Resolution in the time dimension. In remote sensing this common thought of as the amount of time needed to revisit or acquire imagery of a specific location.

VHR

Very High resolution: A term usually referring to satellite imagery with a spatial resolution of better than 1 metre ground sample distance for each pixel.

Wavelength

Commonly used to refer the length between wave crests or spatial period of the wave. In remote sensing it is a commonly used term referring to where a particular spectra sits on the electromagnetic spectrum.

WorldView 2

A VHR satellite part f the Digital Globe constellation, WorldView 2 (WV2) was launched in October 2009 and has eight multispectral bands with a spatial resolution of 1.84 m and a panchromatic band with a spatial resolution of 0.46. It has the ability to be pointed at none nadir locations, thus improving the temporal frequency of the data collection.

WorldView 3

At the time of writing the most recent VHR satellite in the commercial Digital Globe Constellation. WorldView 3 (WV3) has a high spatial, spectral and temporal resolution, Multispectral imagery is available at a spatial resolution of 31 cm panchromatic, 1.24 m in the eight visible and 3.7 m in the eight short-wave infrared bands. The satellite has a revisit time of less than one day and a number of additional bands are available to help calibration and for cloud mapping.

Appendix 2
Additional papers for context

Below are two related published papers where I have either been first author or had a considerable involvement. They are included in this appendix for completeness.

First recorded loss of an emperor penguin colony in the recent period of Antarctic regional warming: implications for other colonies (2011)

My previous work on emperor penguin colony distribution, in 2 highlighted that several colonies were too small to be seen using medium spatial resolution Landsat imagery. One of these was the Dion Island colony. Archival records showed that breeding numbers there were known to be in serious decline, so working with my supervisor Phil Trathan, we organised an aerial photography survey of the island. Results from the survey showed that there was no trace of emperors left at this site. I used remotely sensed sea ice data to show that the Dion Islands were in a region that had lost more sea ice than anywhere else on the continent suggesting that the colony had failed due to regional climate change. Phil and I wrote a paper along with Bernard Stonehouse, the scientist who originally found and studied the colony, which suggested that this colony was the first known example of an emperor penguin colony lost to climate change. The paper, published in *PLoS One* (impact factor 3.534) has been cited 35 times since publication in 2011.

Whales from space: counting southern right whales by satellite (2014)

My most recent paper diversifies the use of satellite remote sensing to look at cetaceans. Following my work on emperors, Very High Resolution imagery had been used on a number of other species including *Pygoscelis* penguins, Weddell (*Leptonychotes weddellii*) and elephant seals (*Mirounga leonina*). I made several previous attempts to count baleen whales using satellites, eventually with the help of BAS cetacean experts, identifying a population of Southern right whales near the Peninsula Valdes in Argentina. These whales calve and breed in high densities in clear calm sheltered coastal waters, with females spending large amounts of time at the surface, making them ideal targets for remote sensing. I acquired imagery of the area and showed that whales were not only clearly visible using satellite imagery, but that with suitable image analysis algorithms, animals could be identified automatically: I investigated a number of algorithms to established if I could successfully automate the process of whale detection, thus allowing population estimates of the whales over large expanses of open water in an efficient and cost effective manner. This paper has had a lot of scientific impact and many other whale scientists are now planning to use similar techniques to count baleen whales in other parts of the globe. Published in *PLoS One* (impact factor 3.534) it has been cited 26 times since publication in February 2014.

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PLoS one

First Recorded Loss of an Emperor Penguin Colony in the Recent Period of Antarctic Regional Warming: Implications for Other Colonies

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Abstract

In 1948, a small colony of emperor penguins *Aptenodytes forsteri* was discovered breeding on Emperor Island (67° 51′ 52″ S, 68° 42′ 20″ W), in the Dion Islands, close to the West Antarctic Peninsula (Stonehouse 1952). When discovered, the colony comprised approximately 150 breeding pairs; these numbers were maintained until 1970, after which time the colony showed a continuous decline. By 1999 there were fewer than 20 pairs, and in 2009 high-resolution aerial photography revealed no remaining trace of the colony. Here we relate the decline and loss of the Emperor Island colony to a well-documented rise in local mean annual air temperature and coincident decline in seasonal sea ice duration. The loss of this colony provides empirical support for recent studies (Barbraud & Weimerskirch 2001; Jenouvrier et al 2005, 2009; Ainley et al 2010; Barber-Meyer et al 2005) that have highlighted the vulnerability of emperor penguins to changes in sea ice duration and distribution. These studies suggest that continued climate change is likely to impact upon future breeding success and colony viability for this species. Furthermore, a recent circumpolar study by Fretwell & Trathan (2009) highlighted those Antarctic coastal regions where colonies appear most vulnerable to such changes. Here we examine which other colonies might be at risk, discussing various ecological factors, some previously unexplored, that may also contribute to future declines. The implications of this are important for future modelling work and for understanding which colonies actually are most vulnerable.

Citation: 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(2): e14738. doi:10.1371/journal.pone.0014738

Editor: Mark Briffa, University of Plymouth, United Kingdom

Received July 2, 2010; **Accepted** January 31, 2011; **Published** February 28, 2011

Funding: This work was supported in part by the BAS Ecosystem Programme and by a United Kingdom Overseas Territories Environment Programme Grant (BAT601) to PTF and PNT. 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.

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Introduction

Emperor penguins breed in coastal locations around the Antarctic with most colonies assembling on stable fixed or 'fast' ice, with just three occurring on land. All colonies show a similar breeding schedule regardless of colony location. Birds gather at traditional sites in autumn, with the development of the stable fast ice, usually from April onwards. Courtship, egg laying and incubation take place as winter proceeds, while hatching, brooding and crèche formation occur as winter abates and spring and early summer approach. Chicks are tended by both parents until fledging occurs in mid-summer, usually during November or December coincident with the breakup of stable fast ice into 'pack' (i.e. ice floes that drift with the winds and currents); however, chicks may still also be fed while taking refuge on drifting ice floes. Adults moult in late summer, during February, again usually on fast ice or on consolidated pack. Thus, emperor penguins depend upon stable fast ice for approximately eight months of the year, so late fast ice formation in winter and/or early breakup in spring can strongly reduce the chances of successful breeding at any given colony location.

Recently, changes in sea ice duration and distribution, associated with climate change, have been reported as important factors affecting emperor penguin population processes [1-6], with the main drivers of change thought to be reductions in sea ice [6]. Sea ice generally refers collectively to both fast ice and pack ice. Fast ice forms around the fronts of ice shelves, coastlines and between island archipelagos and grounded icebergs. It also forms over shoals or over shallows, and unlike pack ice, fast ice does not move with surface currents or wind [7]. At almost all locations emperor penguins use fast ice as a stable platform on which to breed [6,8,9] and since they are not agile, they are restricted to fast ice with a low free-board [4] that does not stand far above the ocean surface by more than a few tens of centimetres. Emperors may forage in polynyas, tide cracks and leads and within the pack ice so other consequences of climate change might also be important, particularly changing relationships with the sea ice community, including with their prey [4] which in most locations are fish, principally Antarctic silverfish, krill and squid [10].

Notwithstanding, conclusions about emperor penguin biology and ecology in relation to environmental change are limited by a severe lack of long-term population monitoring data and associated environmental data including, *inter alia*, data on prey species, predation and local and regionally scaled sea ice indices. Detailed demographic studies are currently only available from just one site [1-3] and population counts from only a few others. Consequently, without coherent monitoring programmes that examine demographic parameters in the context of a suite of environmental indices, inferences are necessarily limited and some conclusions may be merely correlative. Until more widespread demographic monitoring is available, previously unreported long-term time series of population counts from additional breeding sites might help increase our understanding of important ecological interactions between population processes and environmental drivers, particularly where population trajectories can be examined in the context of local environmental change.

One location where emperor penguin breeding population counts have been made but never previously published is at Emperor Island in the Dion Island group, Marguerite Bay, west of the Antarctic Peninsula. This site is one of the more northerly emperor penguin breeding locations; it was first discovered in 1948 [11], after which breeding counts were carried out on a sporadic and opportunistic basis, showing that the breeding population was relatively small, but stable. The demise of the colony from 1970 onwards was extremely rapid taking just over 30 years, comparable to the average lifespan of an individual [12] (~20 years) but less than the life span of the longest free-living emperor (~40 years). Here we argue that the most likely cause of this decline is a chronic reduction in the duration of sea ice from about 1970 onwards, associated with local atmospheric warming [6].

Though studies [1-6] have highlighted the importance of warming to the success of emperor colonies, mechanisms for exactly how such warming affects individual colonies remain unclear. In the case of the Emperor Island colony, the duration of seasonal pack ice has decreased at a rate of approximately four days per year at the colony site, one of the highest rates of loss recorded in the Antarctic in recent decades [13]. Implications are that atmospheric warming has reduced annual pack ice duration [14] and potentially stable fast ice, leaving the Emperor Island colony with reduced breeding habitat and vulnerable to ocean swell during late winter and spring storms.

At Emperor Island, emperors used to breed on the low rock and shingle isthmus at the southeast end of the island, one of only three colonies known to breed on land. This colony therefore also offers opportunities to speculate about how a range of other environmental drivers might also have affected the population decline.

Materials and Methods

In this study, we combine breeding count data from an irregularly visited emperor penguin colony with locally recorded air temperature data, locally observed fast ice duration data and remotely sensed circumpolar sea ice duration data to evaluate the impacts of changing environmental conditions on breeding population size. Information on breeding counts, local air-temperature and local fast ice conditions were obtained from unpublished Falkland Island Dependency Survey (FIDS) and British Antarctic Survey (BAS) reports archived at BAS. Circumpolar sea ice duration data were obtained from the literature [13].

Our study colony (67° 51′ 52″ S, 68° 42′ 20″ W) was located on Emperor Island in the Dion Island group, in Marguerite Bay, west of the Antarctic Peninsula (Figure 1). Emperor Island is just under 400 m by 300 m in dimension; at the north-western end it raises to 46 m whilst the eastern end is generally below 5 m. Emperors used to habitually breed on a low rock and shingle isthmus at the southeast end of the island. This colony is of historic interest as it was the fourth emperor colony to be discovered [11] and the location where the first study of breeding behaviour and early chick growth was carried out [15].

Emperor penguin population counts

The numbers of adults, eggs and chicks at Emperor Island (Table 1) have been counted at irregular intervals since the colony was first discovered. Early in the time series, counts were taken in the middle of the winter when the fast ice could bear the weight of a man or sledge. Later in the time series other methods of access were used, including access by yacht or ship. Counts of the different demographic categories were recorded or estimated and are documented in a variety of FIDS/BAS base reports and published accounts; here we compile all the known counts for the first time. The source for each count is provided in Table 1. Where a population range was recorded we have taken the upper value as illustrative; taking the lower value, or an average, would result in the same conclusions. Counts for different demographic categories depended upon the timing of each visit. At Emperor Island, emperor penguins lay their eggs within a short time window in early June, and as only a single egg is laid, the best estimate of the breeding population in any given year would be of incubating birds just after laying was complete. However, a visit at this time of year was not always possible, due to both fast ice conditions and other logistic and operational constraints. Egg and offspring mortality occur cumulatively throughout the breeding season, therefore in any given year, counts in the middle of winter will be more representative of the breeding population than counts later in the season. Counts of incubating and brooding adults and of free-standing chicks made from July onward probably underestimate the size of the colony, but at least provide valuable minimum figures. Counts in October and November during the crèche stage may be less representative. However, given the clear trajectory of the population after the 1970s, and the difficulty in accessing Emperor Island after BAS closed a number of nearby bases, we consider that these late-season counts provide additional valuable information about the demise of the colony.

Air temperature

No surface air temperature records exist for the Dion Islands (apart from records collected during the first study of breeding and early chick growth [15]), but a reliable temperature record exists from the FIDS/BAS base on Adelaide Island (67° 46′ S, 68° 55′ W; occupied 3 February 1961 to 1 March 1977) for the period from May 1962 until December 1974 (see www.antarctica.ac.uk/met/READER/surface/Adelaide.All.temperature.html; accessed on 7 October 2010). This is the geographically closest (~12 km) air temperature record to the Dion Islands for the 1960s and 1970s.

After the base at Adelaide Island was closed, a BAS base at Rothera Point (67° 34′ S, 68° 08′ W; occupied 1 February 1976 until the present date) was opened and this now provides the geographically closest (~40 km) air temperature record for the most recent decades (see www.antarctica.ac.uk/met/READER/surface/Rothera.All.temperature.html; accessed on 7 October 2010). The continuous temperature record has missing values for July and August 1999, but is analysed here from April 1977 until April 2010.

Fast ice

No *in situ* sea ice records exist for the Dion Islands, but the islands are visible in good weather from the old base on Adelaide Island. Sea ice observations were made from Adelaide Island whilst it was occupied. Sea ice conditions around the Dion Islands were recorded from 1961 until 1973. The quality of the annual record was variable between years and sea ice conditions were not always recorded at regular and frequent intervals. Thus, it is not possible to always determine when periods of fast ice occurred and when these blew out as a result of winter storm activity. However, the date of the first fast ice formation was always recorded. Similarly, the date of the last fast ice formation was also recorded,

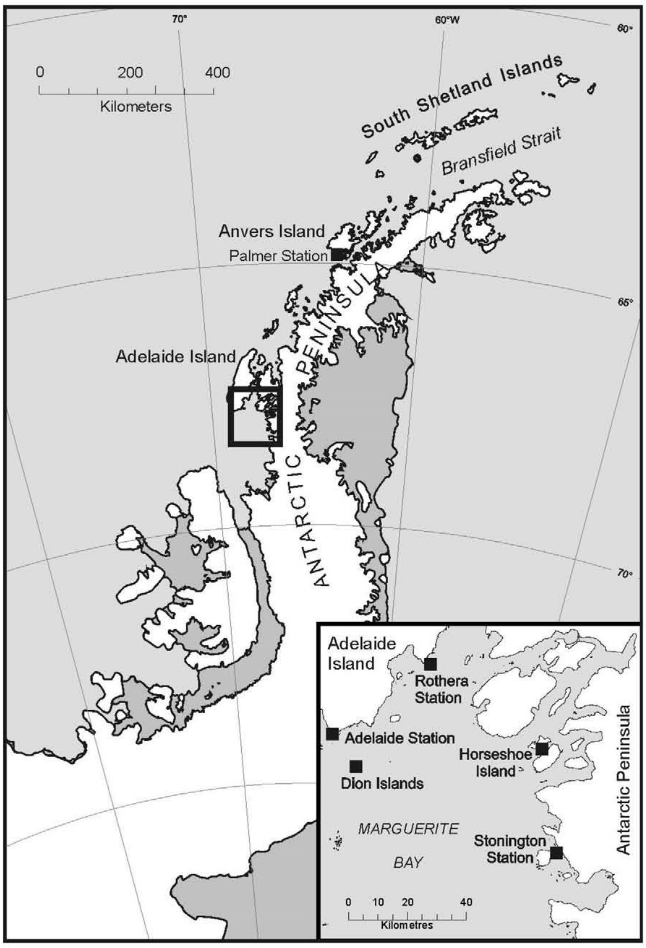

Figure 1. Map of the Antarctic Peninsula showing the study area inset.
doi:10.1371/journal.pone.0014738.g001

although we assume that the last fast ice also existed until the day before the next chronological record when the fast ice finally blew out or disintegrated into shifting pack ice.

Results

Though the breeding count data for emperor penguins at Emperor Island are irregular and often infrequent they provide an extremely valuable additional dataset for assessing emperor penguin population trajectories. The data are certainly adequate for assessing the size of the colony until 1970, and for indicating the approximate timing and rate of subsequent decline. Similarly, the data on local air temperature and local fast ice duration are intermittent and in particular do not cover the full period during which the breeding count data began to show a decline, nevertheless and in spite of these deficiencies, these data are unique and sufficient to support ecological associations in an exploratory and subjective manner.

Emperor penguin population counts

The emperor penguin colony at Emperor Island was only visited in years when fast ice was sufficient to support a transit across, it was therefore only visited in some years, and then generally only during July or August, close to the coldest part of winter. No visits were generally feasible from September onwards during either chick rearing or fledging which generally takes place during December.

Counts of the numbers of adults, eggs and chicks at Emperor Island (Table 1) were undertaken sporadically, but occurred at least twice a decade after it was discovered until the end of the

Table 1. Estimated number of emperor penguin breeding pairs on Emperor Island.

Date of visit	Number adults	Number chicks	Comment	Source reference
1948, October	NA	70		[15]
1949, 5 June–15 August	100–183	c. 150	Colony partially on sea ice	[15]
1957, 9 October	90	30 – 40	Colony on sea ice	[16]
1958, 27 July	160–170	Incubating		[17]
1963,13 August	150–200	Mostly incubating		[18]
1964, 9 July	200	Incubating		[Pers. comm. B Pimm-Smith]
1966, August	250	125		[19]
1968, 30 August	250	68		[20]
1969, 25 July	200	Incubating	Colony partially on sea ice	[21]
1970,12 August	250	Chicks on feet		[22]
1978, End of July	70–90	Incubating		[23]
1978, 3 November	85	20	Colony on sea ice	[23]
1999, 1 July	16	15 incubating		[Pers. comm. WR Fraser]
2001, 3 August	10	9 incubating		[Pers. comm. WR Fraser]
2009, 28 November	0	0		BAS aerial photography

Shaded cells indicate counts made later in the season, potentially after some egg/chick loss.

doi:10.1371/journal.pone.0014738.t001

1970s. Though colonies are known to vary inter-annually [1-3], the population at Emperor Island was relatively stable during this period (Figure 2).

After the base on Adelaide Island closed, counts were carried out less frequently, though it is during this period that the population started to show a monotonic decline (Figure 2). The decline appears to have started in the early 1970s, between 1971 and 1978.

Air temperature

In our air temperature analysis (Figure 3) we show the average monthly mean (where the percentage of raw observations are adequate to calculate an accurate average), the average annual mean (the arithmetic average of all monthly average values), and the average winter mean (the arithmetic average of June, July and August) air temperatures. Simple linear regression analyses show a significant positive trend for both the average annual and average winter temperatures at Adelaide Island and for the average annual temperatures at Rothera Point. The increases in temperatures occur from the start of each time series, consistent with the known warming trend over the last century [24,25].

Fast ice

Archived reports from the old station on Adelaide Island record the dates when fast ice formed and dispersed around the Dion

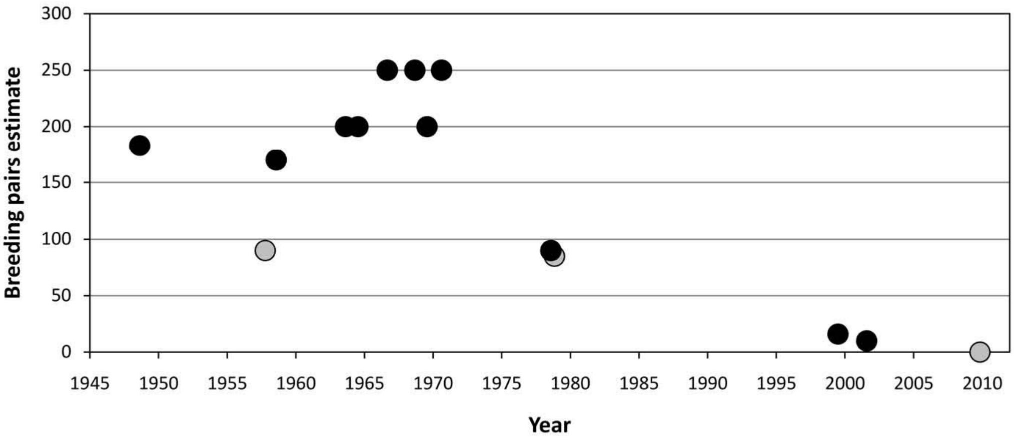

Figure 2. Estimated number of emperor penguin breeding pairs on Emperor Island. Black circles indicate counts made during winter and grey circles counts made later in the breeding season during spring, potentially after some egg/chick loss.
doi:10.1371/journal.pone.0014738.g002

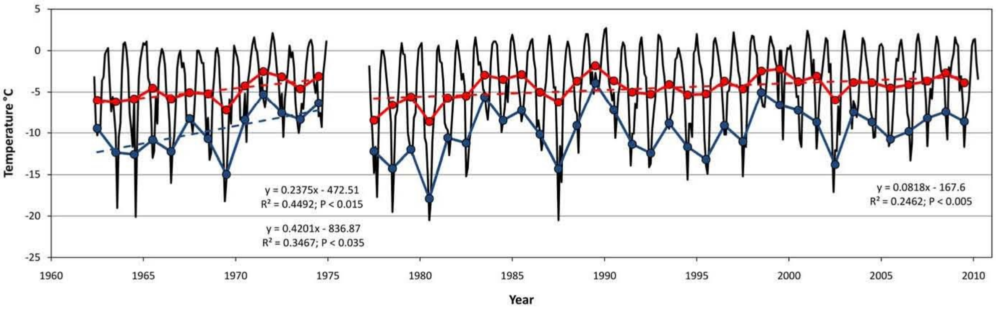

Figure 3. Variability in air temperature at Adelaide Island (May 1962 to December 1974) and at Rothera Point (April 1977 to April 2010). Thin black lines show the average monthly data; data from www.antarctica.ac.uk/met; red lines are the average annual (arithmetic average of all months) data; and blue lines average winter (arithmetic average of JJA) data. Analyses shows a significant trend in the average annual (dashed red line; F = 8.97; $P<0.015$) and average winter temperatures (dashed blue line; F = 5.84; $P<0.035$) at Adelaide Island and in the average annual temperatures (dashed red line; F = 10.13; $P<0.005$) at Rothera Point.
doi:10.1371/journal.pone.0014738.g003

Islands (Figure 4). The mean date of first fast ice formation in the area during the 1960s and early 1970s was 21 May (S.D 33.7 days), some days before the onset of egg laying and incubation in early June. The mean date of breakout was 10 November (S.D 33.0 days), at least a month before chick fledging in late December. The duration of the fast ice recorded for the Dion Island group (Figure 4) shows that the winter sea ice conditions were generally marginal for successful emperor penguin breeding and that the emperor penguin colony on Emperor Island relied upon the availability of land in most winters, even when the population size was relatively stable up until the 1970s.

Circumpolar emperor penguin site variability

The link between fast ice and pack ice is complex and detailed relationships depend upon local circumstances; however, in most situations fast ice only forms in stable conditions, with surface currents, ocean swell and wind action potentially impeding fast ice development. Therefore, changes in fast ice production would be expected to occur if altered pack ice extent and duration meant locations were subject to increased wave action. No large-scale historical datasets exist for fast ice extent or duration, though remotely sensed data do exist for seasonal sea ice. The emperor penguin breeding locations (Figure 5) of all known colonies [8] can be overlaid onto recently published sea ice duration maps [13] to examine their vulnerability. Tabulation (Table 2) of sea ice duration [13] indicates those colonies that may be currently more vulnerable to climate change effects. The colony at Emperor Island is where sea ice trends are most negative. However, the colony is not the most northerly emperor penguin breeding site, there being 9 others that occur at lower latitudes. Similarly, colony locations where sea ice trends are most positive are not the most southerly, there being a number that are further south; it is notable that those colonies where sea ice trend is most positive all occur in the Ross Sea.

Discussion

Demise of the Emperor Island colony

Emperor penguins breeding in the West Antarctic Peninsula region may be more vulnerable to climate change that colonies elsewhere on the continent. For much of the twentieth century the climate of the West Antarctic Peninsula region has warmed at an unprecedented rate [24,25]. This has been particularly rapid in recent decades [26,27]. The recent warming has been ascribed to changes in atmospheric circulation over the Southern Ocean [14,28]. The westerly winds that surround Antarctica have increased by around 15 20% since the 1970s [14,28]. These stronger winds bring northerly oceanic warm wet air into the Amundsen-Bellingshausen Sea region. These conditions have now resulted in a clear dipole in seasonal sea ice with significant positive trends in the Ross Sea and significant negative trends in the Amundsen-Bellingshausen Sea [14]. Regional warming caused by intensification of the westerly winds has reduced seasonal sea ice and even led to ice shelf collapse along the eastern edge of the Antarctic Peninsula [28,29]. Overall, 87% of the Peninsula's glaciers have retreated in recent decades [30]. At the same time surface waters are also known to have warmed [27]. Air temperatures at Rothera station, 40 km to the north of Emperor Island, have shown a very substantial warming trend [31], although the duration of the temperature record and large inter-annual variability in temperatures driven in part by the El Niño-Southern Oscillation means that this trend is not always statistically significant.

At the Dion Islands, FIDS/BAS archived reports show that in some years, fast ice only formed after emperor penguins began to lay their eggs, while fast ice usually blew out or melted before any chicks fledged. For some years the archived reports also included details of ocean swell, indicating when sea ice was limited and insufficient to dampen wave action in the area. The shingle isthmus on which the colony existed was formed by storm action and as such would be vulnerable to the significant increase in severe storm events reported for the Peninsula region [32], particularly if unprotected by sea ice during winter. Even up until 1970, the Emperor Island colony must have been a site of high risk for both incubating birds and chicks, perhaps accounting for the relatively small size of the colony. Thereafter annual hazards must have increased as pack ice became progressively less extensive and of shorter duration offering less damping to wave action.

During several visits to Emperor Island, the colony was recorded wholly or partially (June 1949, July 1969, October 1957 and November 1978) on fast ice (Table 1) and it may have existed on fast ice in other years. When restricted to land, as opposed to the surrounding fast ice, breeding habitat would be more limited, potentially reducing an individual's ability to escape

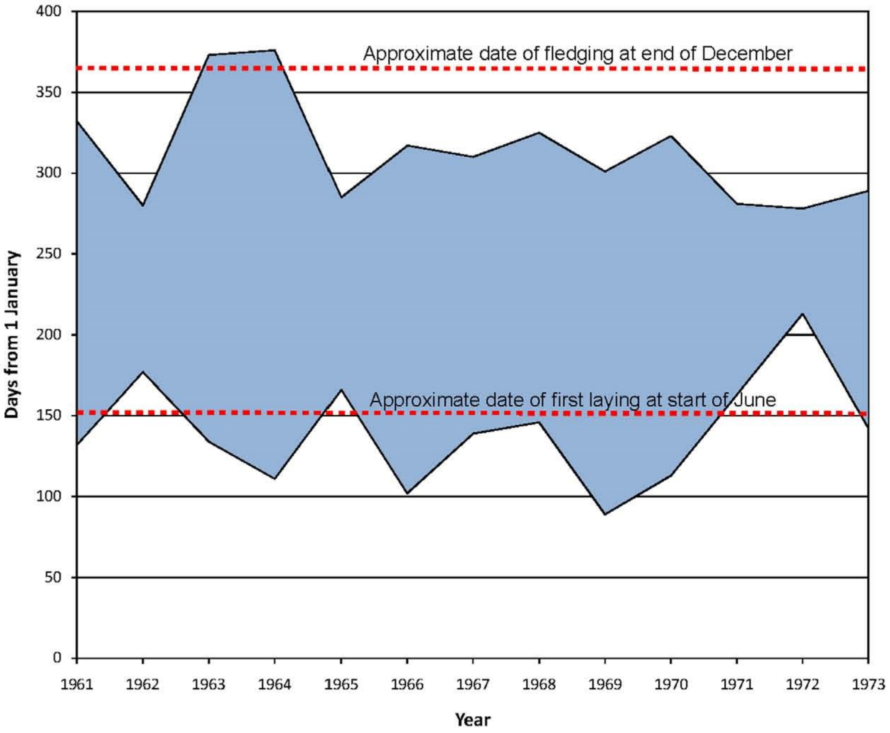

Figure 4. Inter-annual changes in the date of fast ice formation and break-up at the Dion Islands, observed from Adelaide Island, West Antarctic Peninsula; data from reports in BAS archives. The estimated dates for first egg-laying and fledging are shown.
doi:10.1371/journal.pone.0014738.g004

the worse extremes of the wind and to access fresh snow to reduce any increasing effects of dehydration [33]. This could have physiological implications for males during incubation and for chicks after hatching and prior to fledging. Such restrictions may then limit chick survival and colony size, as has been suggested previously for other small colonies at Cape Crozier, Beaufort Island and Franklin Island [33].

Warming and reduced sea ice duration may also have led to changes in a number of important trophic interactions that might have contributed to the decline of the colony. Changes in fish, krill and squid communities on which emperor penguins feed are likely to be important drivers of population change [4], especially when prey stocks are reduced locally by loss of sea ice [34], and particularly within their foraging ambit when emperors act as central-place foragers. An additional factor that has not been noted previously is the possibility of increased predation. Emperor penguins breed so far south that chicks are generally well advanced before raptorial seabirds commence breeding. However, in October 1957 giant petrels (*Macronectes giganteus*) were predatory on the group; their nearest known breeding site is at Avian Island, 12 km away. With warmer, earlier springs we speculate that giant petrels or other raptorial seabirds could be more active at some of the more northerly emperor colonies. Future monitoring at emperor colonies should therefore also include monitoring of nearby raptorial seabird species.

The number of ecological processes affected by climate change is extensive, including for processes operating at different times of year and across all life history stages. In Figure 6 we show a partial ecogram summarising some of the important potential ecological drivers of change.

The rate of climate change in the West Antarctic Peninsula region has been extremely rapid [35], almost certainly beyond levels of phenotypic plasticity exhibited by penguins over millennial timescales [36,37]. Indeed, it has been suggested [38] that the most likely response of penguins to climate change is dispersal, recognising that adaptation and in particular microevolution in penguins is a slow process, or at least, punctuated. Thus, emperor penguin population processes at Emperor Island might be expected to exhibit this same pattern; that is, that population numbers declined in response to climate change as recruitment to the colony became increasingly uncommon. Breeding habitat availability (on land) will have changed little over the past 50 years, and emperor penguins with their long lifespan might have remained site-faithful long after environmental conditions became sub-optimal. Thus, we speculate that recruits from the late 1970s may have continued to breed, in ever decreasing numbers, up until the start of this century. There is little information available about how emperors disperse and recruit, but given the vulnerability of their fast ice breeding habitat to storm action, breeding pairs may

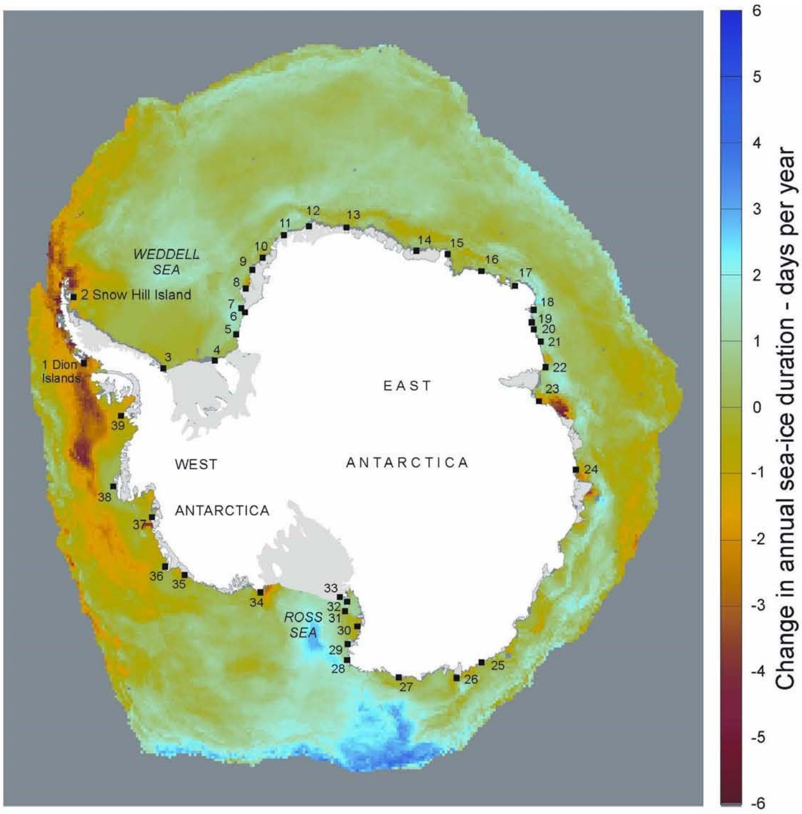

Figure 5. The spatial pattern of trend in sea ice duration change over 1979–2004 [13]. Scale shows trend in days per year. Black squares indicate the location of all known emperor penguin colonies [8]. Colony reference numbers refer to Table 2.
doi:10.1371/journal.pone.0014738.g005

move between sites and juveniles may recruit to other sites rather than to their natal colony. Each colony is thought to form within a few kilometres of its traditional location [39]; however, the instability of ice shelves and ice tongues means that emperor colonies located close to such features must periodically relocate, even if only a short distance. For example, the recent break-off of the Mertz Glacier Tongue in February 2010, means that the emperor colony located close to this features [8] must now relocate. All existing demographic studies suggest that emperors are philopatric [1-3], but with changing, though not necessarily catastrophic, conditions, recruitment of juveniles might also be to other sites. Monitoring of juvenile recruitment with respect to their choice of breeding site must now be a priority for future research.

Generic considerations

The ability of emperors to accommodate changes in patterns of climate and environmental variation is likely to be critically important [3,40]. However, understanding the altered ecological interactions driving a population's vital rates is also key. When breeding on land emperors would not have an obligate requirement for the stable substrate of fast ice, therefore it is plausible that other consequences of climate change, such as the reduced duration and extent of pack ice, might mean that altered food-web connections may be more critically important. Although the other land-based colonies, Taylor Glacier (67° 40′ S, 60° 53′ E) and Amundsen Bay (66° 46′ S, 50° 45′ E) [8], do not appear to be vulnerable to current changes in sea ice, the demise of the Emperor Island colony shows that shifting their breeding habitat to accessible low-lying land to mitigate against the loss of sea ice might not be a long term survival option for this species.

Recent studies indicate that reductions in sea ice associated with climate change will have profound consequences for emperor penguin populations [3,4]. Currently such studies do not expressly discuss projections of fast ice and rely upon projections of sea ice. Given the complex local association between protective pack ice [7] and fast ice, changes in pack ice extent and duration will potentially not only alter the character of stable breeding habitat, but also and importantly, the foodweb connections within the pack itself. Results from Emperor Island suggest that this may be vitally important.

Table 2. Emperor penguin colony locations in relation to trends in sea ice duration.

	NAME	LONGITUDE	LATITUDE	SEA-ICE TREND AT COLONY
		(decimal degrees)	(decimal degrees)	(days per annum)
1	Dion islands	−68.70	−67.87	−4
2	Snow Hill Island	−57.46	−64.52	0
3	Smith Peninsula	−60.85	−74.38	0
4	Gould Bay	−47.32	−77.74	0
5	Luitpold Coast	−33.65	−77.27	0
6	Dawson Lambton	−26.56	−76.01	0
7	Halley Bay	−27.20	−75.52	0
8	Stancomb Wills	−23.02	−74.16	0
9	Drescher Inlet	−19.12	−72.86	0
10	Kitkuven (RI ice shelf)	−15.13	−72.14	0
11	Atka Bay	−8.13	−70.62	0
12	Sanae	−1.38	−70.05	0
13	Astrid Coast	8.31	−69.94	0
14	Ragnhild Coast	27.25	−69.97	0
15	Riiser Larsen Pen(Gunn)	34.39	−68.78	0
16	Umbeashi Rock	43.12	−68.05	0
17	Amundsen Bay	50.74	−66.77	0
18	Kloa Point	57.30	−66.64	0
19	Fold Glacier	59.38	−67.33	0
20	Taylor Glacier	60.88	−67.48	0
21	Auster	64.00	−67.40	0
22	Cape Darnley	69.70	−67.88	0
23	Amanda Bay	76.88	−69.28	−1
24	Haswell Island	93.01	−66.53	−1
25	Point Geologie	140.01	−66.67	0
26	Mertz Glacier	146.45	−66.93	0
27	Davies Bay	158.41	−69.33	0
28	Cape Roget	170.56	−71.98	1
29	Coulman Island	169.64	−73.34	1
30	Cape Washington	165.38	−74.65	0
31	Beaufort Island	167.04	−76.94	0
32	Franklin Island	168.40	−76.18	1
33	Cape Crozier	169.43	−77.51	1
34	Edward VII Pen	−157.74	−77.13	0
35	Ledda Bay	−131.57	−74.36	0
36	Thurston Glacier	−125.59	−73.43	0
37	Bear Peninsula	−110.17	−74.37	0
38	Noville Peninsula	−98.49	−71.75	0
39	Smyley Island	−78.75	−72.31	0

Locations for all known colonies are taken from published analyses [8]. Sea ice trend values are also taken from recent analyses [13], with values for each colony location represented by the geographically closest pixels. Shaded values indicate colonies that are in areas of current significant sea ice loss.

doi:10.1371/journal.pone.0014738.t002

Current assessments suggest that the observed di-pole in sea ice between the Antarctic Peninsula and the Ross Sea will alter as the ozone hole heals in the second half of this century [14,28]. Contributory factors continue to be debated [41] and refined, but current predictions [14,28] suggest that trends in sea ice will alter and the annual average sea ice extent will diminish by 33%; most of this retreat will be in winter and spring [28], with attendant risks for emperors.

Of fundamental importance to future forecasts of emperor penguin colony viability will be an increased ecological understanding of how they utilise their available habitat and therefore how environmental changes will affect both their use of habitat and their behaviour. For example, the wider regional pack ice, in terms of the level of convergence/divergence, seasonality and concentration, will impact on the well-being of non-breeding birds

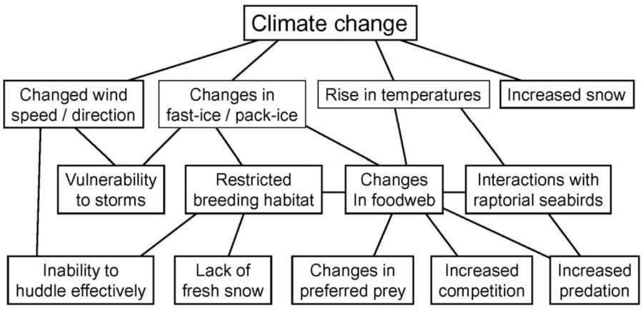

Figure 6. Partial ecogram summarising climate change effects: potential ecological drivers of change in emperor penguin populations.
doi:10.1371/journal.pone.0014738.g006

and breeding birds both during and outside the breeding season. Changes in pack ice extent and duration may affect predictable foraging grounds that are within foraging range of each breeding or moult location; similarly changes in polynya extent and persistence will almost certainly be an important factor. Also, knowledge about fast ice production is a potentially crucial factor for breeding and possibly moult. At present there are fundamental gaps in our knowledge about the types of sea ice features that emperor penguins rely upon. Similarly, current climate models do not represent most of these sea ice features to the extent required for future habitat modelling. Coupled atmosphere-ocean models are the foundation for most climate initiatives. However, the models have many problems in simulating sea ice extent, as small errors in the atmospheric circulation or oceanic conditions can give large errors in the sea ice extent and area [42]; fast ice and polynyas are even more difficult to model.

Alternative hypotheses

In this paper we have considered the demise of the emperor penguin colony on Emperor Island in relation to climate change. However, alternative plausible explanations might be used to interpret the reduction in numbers at the colony. Such alternatives are essential to consider if we are to avoid incorrectly diagnosing threats to potentially vulnerable species, or indeed individual colonies, and if we are to understand the influence of regional change on marine ecosystems [43,44]. Here we consider five alternative, but not mutually exclusive hypotheses that might have led to the demise of the colony on Emperor Island.

Firstly, increased snowfall consequent on increased warm, wet conditions may have contributed to population declines [9]. Such a situation has been reported for the West Antarctic Peninsula close to Palmer Station, Anvers Island (64° 46′ S, 64° 03′ W) [35] where increased snow precipitation has affected Adélie penguin colonies breeding on landscapes where snow accumulations are enhanced by landscape aspect and prevailing winds during spring storms; these colonies have decreased significantly faster than colonies where wind scour abates snow accumulations. However, no snowfall records exist for Emperor Island and no previous impacts of increased snowfall have been noted for emperors.

Secondly, short, but extreme weather events could also have led to the demise of the colony. Such extreme events have been reported for the West Antarctic Peninsula region [45]; they occur periodically and have impacts across a wide range of trophic levels, including for penguin populations. Further, but related to this are anomalous periods of weather that last over longer timescales. For example, between 1975 and 1980 there was a step change in the population size of the emperor penguin colony at Pointe Géologie, Dumont d'Urville, Terre Adélie (66° 40′ S, 140° 01′ E) during a prolonged abnormally warm period with reduced sea ice extent [1]. Emperor mortality rates increased when warm sea-surface temperatures occurred in the foraging area and when annual sea ice extent was reduced, and were higher for males than for females. Interestingly, the start of the colony decrease at Emperor Island began between 1971 and 1978 and coincides with that at Terre Adélie; however, there is no evidence of a close climatic relationship between Terre Adélie and the West Antarctic Peninsula region and environmental teleconnections between the two sites have not been described.

Thirdly, as the numbers of tourists visiting Antarctica have increased, concerns have been expressed about the potential disturbance caused by visitors. Disturbance may be caused by a number of activities, including by visitors approaching too close to penguin colonies [46]. Despite the diversity of species, experimental approaches and observations, there is still little general consensus about the conclusions drawn from a range of penguin disturbance studies. As a result, there is still considerable uncertainty about the magnitude and significance of tourist impacts upon breeding penguins. However, in the case of Emperor Island, tourism can be ruled out as a possible cause of colony decline. The island has been an Antarctic Specially Protected Area since 1965 (www.ats.aq/documents/recatt/Att178_e.pdf; accessed 7 October 2010) and apart from difficulties of access during the breeding season, tourism and other visits (except for purposes of specific scientific research) are not permitted.

Fourthly, the demise of the emperor colony could have been because of disease. For example, disease was implicated in a die-off of Adélie penguins in the vicinity of Mawson Station (67° 36′ S, 62° 52′ E) during 2001 [47]. Such die-offs are thought to be rare [47] and indeed no infectious pathogens were ever isolated from the Mawson event. However, such factors cannot be discounted. Unfortunately, no information is available for Emperor Island to investigate whether this was a possible cause.

Finally, marine harvesting has been shown to have important impacts on penguins; commercial fisheries have reduced the carrying capacity of the Benguela ecosystem for penguins to only 10 20% of what it was in the 1920s [48]. However, though harvesting for Antarctic krill and finfish has been underway in the Antarctic since the late 1960s, the closest reported harvesting has been distant from Emperor Island occurring some 400 km to the north close to the South Shetland Islands and in Bransfield Strait [49,50]. Thus, no harvesting has been recorded in the vicinity of the colony.

In summary, we believe that tourism (or other visits), and fishing can be discounted as causes leading to change at the emperor colony on Emperor Island. However, the other alternative hypotheses remain feasible and cannot be ruled out entirely, although on examining each hypothesis in turn we have no evidence that increased snowfall, extreme events, or disease played any part in the decline of this colony.

Conclusion

We suggest that the Emperor Island colony might be a sentinel for those other colonies in the West Antarctic recently discovered [8] and even those elsewhere in the Antarctic as regional temperatures continue to rise [28] affecting changes in sea ice dynamics, formation of predictable or persistent polynyas, snowfall, wind characteristics, extreme weather events, foodwebs, and other ecological factors important for emperor penguin population processes.

The location of this colony suggests that ecological models, even simple conceptual models such as shown in our partial ecogram (Figure 6), are important for formulating predictions about future population outcomes. Such models are always site and context specific but they are critical in the absence of adequate monitoring data that would enable rigorous empirical analysis or innovative population modelling [3]. The location of the Emperor Island colony highlights that breeding habitat is only one of the factors important in such population analyses and that other factors are also essential to consider.

Our more specific conclusions include:

1. Our study is severely limited by a lack of consistent long-term monitoring information documenting, *inter alia*, penguin breeding parameters, prey species, predation and fast ice coverage. However, the available data suggest that changing sea ice conditions (plausibly both pack ice and fast ice) have had a major impact on a colony that was already vulnerable and towards, but not at, the edge of the species geographic range.
2. The principle factors leading to the decline are now difficult to disentangle and might involve factors that operate either at the breeding colony (e.g. increased snowfall, altered wind characteristics, increased predation) and/or within the seasonal foraging ambit of the population (e.g. altered foodweb characteristics).
3. Extreme weather events may have contributed to the colony decline, but records are inadequate to determine whether this was an important factor.
4. The Emperor Island colony now apparently no longer exists and any future analysis will continue to be bound by existing (and sparse) data.
5. Given their lack of agility, emperors would be limited by terrain and elevation, nevertheless, shifting their breeding habitat to low-lying accessible land is not necessarily a long term survival option for the species.

Acknowledgments

This paper is dedicated to the party of three men, Stanley Black, David Statham and Geoffrey Stride, who left Horseshoe Island on 27 May 1958, travelling over recently-formed fast ice to the Dion Islands. A storm over the following two days caused the fast ice to break up leading to the tragic loss of all three men. Search parties from Horseshoe, Stonington and Detaille failed to find any traces of the missing men.

We thank all the FIDS and BAS people involved in the monitoring programme at Emperor Island. We are also extremely grateful to SE Stammerjohn for permission to reproduce data contained in Figure 5 and to WR Fraser, K Holmes, J Kooyman, B Pimm-Smith and E Woehler for corresponding with BS and PNT about colony visits and particularly counts in 1964, 1999 and 2001. Two referees also offered positive criticism, allowing us to greatly improve the paper.

Author Contributions

Conceived and designed the experiments: PNT PTF BS. Performed the experiments: PNT PTF BS. Analyzed the data: PNT PTF BS. Contributed reagents/materials/analysis tools: PNT PTF BS. Wrote the paper: PNT PTF BS.

References

1. Barbraud C, Weimerskirch H (2001) Emperor penguins and climate change. Nature 411: 183 186.
2. Jenouvrier S, Barbraud C, Weimerskirch H (2005) Long-term contrasted responses to climate of two Antarctic seabird species. Ecology 86: 2889 2903.
3. Jenouvrier S, Caswell H, Barbraud C, Holland M, Stoeve J, et al. (2009) Demographic models and IPCC climate projections predict the decline of an emperor penguin population. Proceedings of the National Academy of Sciences USA 106: 1844 1847.
4. 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. Ecological Monographs 80: 49 66.
5. Barber-Meyer SM, Kooyman GL, Ponganis PJ (2008) Trends in western Ross Sea emperor penguin chick abundances and their relationship with climate. Antarctic Science 20: 3 11.
6. Massom RA, Hill K, Barbraud C, Adams N, Ancel A, et al. (2009) Fast ice distribution in Adélie Land, East Antarctica: interannual variability and implications for emperor penguins *Aptenodytes forsteri*. Marine Ecology-Progress Series 374: 243 257.
7. Giles AB, Massom RA, Lytle VI (2008) Fast ice distribution in East Antarctica during 1997 and 1999 determined using RADARSAT data. Journal Geophysical Research 113: C02S14. doi:10.1029/2007JC004139.
8. Fretwell PT, Trathan PN (2009) Penguins from space: faecal stains reveal the location of emperor penguin colonies. Global Ecology & Biogeography 18: 543 552.
9. Massom RA, Stammerjohn SE (2010) Antarctic sea ice change and variability - Physical and ecological implications. Polar Science 4: 149 186.
10. Kirkwood R, Robertson G (1997) Seasonal change in the foraging ecology of emperor penguins on the Mawson Coast, Antarctica. Marine Ecology-Progress Series 156: 205 223.
11. Stonehouse B (1952) Breeding Behaviour of the Emperor Penguin. Nature 169: 760 760. doi:10.1038/169760a0.
12. Mougin J-L, Van Beveren M (1979) Structure et dynamique de la population de manchots empereur *Aptenodytes forsteri* de la colonie de l'archipel de Pointe Géologie, Terre Adélie. Compote Rendus Academie Science de Paris 289D: 157 160.
13. 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. Journal of Geophysical Research 113: C03S90. doi:10.1029/2007JC004269.
14. Turner J, Comiso JC, Marshall GJ, Lachlan-Cope TA, Bracegirdle T, et al. (2009) Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent. Geophysical Research Letters 36: L08502. doi: 10.1029/2009GL037524.
15. Stonehouse B (1953) The emperor penguin *Aptenodytes forsteri* Gray. 1. breeding behaviour and development. Falkland Islands Dependencies Survey Scientific Reports No. 6.
16. Procter N (1957) Ornithological Report, Base Y; Emperor penguin note. British Antarctic Survey Archives: AD6/2Y/1957/Q.
17. Rothera JM (1958) Sledging journey to the Dion Islets in search of the sledging party missing from Base Y. British Antarctic Survey Archives: AD6/2W/1958/K4.
18. Woolley WS (1963) Field Diary 1962-63, Adelaide Island. British Antarctic Survey Archives: G15/1/1.

19. Barlow J (1967) Biology Report, Adelaide Island 1967/68. British Antarctic Survey Archives: AD6/2T/1967/N.
20. Willey IM (1968) Adelaide Island Bird Report. British Antarctic Survey Archives: AD6/2T/1968/Q.
21. Taylor W (1969) Dion Islands Report. In: Wormold, S., Blakely, H., Taylor, W. (Contributors): Journey Report of the Rabble, Winter 1969. British Antarctic Survey Archives: AD6/2T/1969/K2.
22. Hasbrook R (1970) Base Journal for 1970, Base T. British Antarctic Survey Archives: AD6/2T/1970/B.
23. Poncet J, Poncet S (1979) Ornithological Report, Avian Island 1978-79. British Antarctic Survey Archives: AD6/2R/1978/Q.
24. Thomas ER, Dennis PF, Bracegirdle TJ, Franzke C (2009) Ice core evidence for significant 100-year regional warming on the Antarctic Peninsula. Geophysical Research Letters 36: L20704. doi:10.1029/2009GL040104.
25. Barrett BE, Nicholls KW, Murray T, Smith AM, Vaughan DG (2009) Rapid recent warming on Rutford Ice Stream, West Antarctica, from borehole thermometry. Geophysical Research Letters 36: L02708. doi:10.1029/2008GL036369.
26. 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.
27. Meredith MP, King JC (2005) Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century. Geophysical Research Letters 32: L19604. doi:10.1029/2005GL024042.
28. Turner J, Bindschadler R, Convey P, di Prisco G, Fahrbach E, et al. (2009) Antarctic Climate Change and the Environment. Cambridge: SCAR. 526 p.
29. Cook AJ, Vaughan DG (2010) Overview of areal changes of the ice shelves on the Antarctic Peninsula over the past 50 years. Cryosphere 4: 77 98.
30. Cook AJ, Fox AJ, Vaughan DG, Ferrigno JG (2005) Retreating glacier fronts on the Antarctic Peninsula over the past half century. Science 308: 541 544.
31. Vaughan DG, Marshall GJ, Connolley WM, King JC, Mulvaney R (2001) Climate change - Devil in the detail. Science 293: 1777 1779.
32. Turner J, Chenoli SN, abu Samah A, Gareth Marshall G, Phillips T, et al. (2009) Strong wind events in the Antarctic. Journal Geophysical Research 114: D18103. doi:10.1029/2008JD011642.
33. Kooyman GL (1993) Breeding habitats of emperor penguins in the western Ross Sea. Antarctic Science 5: 743 148.
34. Cheung WWL, Lam VWY, Pauly D (2008) Modelling present and climate-shifted distribution of marine fishes and invertebrates. Fisheries Centre Research Report 16: Vancouver: University of British Columbia.
35. Ducklow HW, Baker K, Martinson DG, Quetin LB, Ross RM, et al. (2007) Marine pelagic ecosystems: the West Antarctic Peninsula. Philosophical Transactions Royal Society Series B 362: 67 94. doi:10.1098/rstb.2006.1955.
36. Emslie SD, Fraser W, Smith RC, Walker W (1998) Abandoned penguin colonies and environmental change in the Palmer Station area, Anvers Island, Antarctic Peninsula. Antarctic Science 10: 257 268.
37. Smith RC, Ainley D, Baker K, Domack E, Emslie S, et al. (1999) Marine ecosystem sensitivity to climate change. BioScience 49: 393 404.
38. Forcada J, Trathan PN (2009) Penguin responses to climate change in the Southern Ocean. Global Change Biology 15: 1618 1630. doi: 10.1111/j.1365-2486.2009.01909.x.
39. Stonehouse B (1964) Emperor Penguins at Cape Crozier. Nature 203: 849 851. doi:10.1038/203849a0.
40. Forcada J, Trathan PN, Murphy EJ (2008) Life history buffering in Antarctic mammals and birds against changing patterns of climate and environmental variation. Global Change Biology 14: 2473 2488.
41. Sigmond M, Fyfe JC (2010) Has the ozone hole contributed to increased Antarctic sea ice extent? Geophysical Research Letters 37: L18502. doi:10.1029/2010GL044301.
42. Lefebvre W, Goosse H (2008) Analysis of the projected regional seaice changes in the Southern Ocean during the twenty-first century. Climate Dynamics 30: 59 76.
43. Votier SC, Bearhop S, Attrill MJ, Oro D (2008) Is climate change the most likely driver of range expansion for a critically endangered top predator in northeast Atlantic waters? Biology Letters 4: 204 205.
44. Wynn RB, Josey SA, Martin AP, Johns DG, Yesou P (2007) Climate-driven range expansion of a critically endangered top predator in northeast Atlantic waters. Biology Letters 3: 529 532.
45. Massom RA, Stammerjohn SE, Smith RC, Pook MJ, Iannuzzi RA, et al. (2006) Extreme anomalous atmospheric circulation in the West Antarctic Peninsula region in austral spring and summer 2001/02, and its profound impact on sea ice and biota. Journal Climate 19: 3544 3571.
46. Culik BM, Wilson RP (1995) Penguins disturbed by tourists. Nature 376: 301 302.
47. Kerry KR, Irvine L, Beggs A, Watts J (2009) An unusual mortality event among Adélie penguins in the vicinity of Mawson Station Antarctica. In: Kerry KR, Riddle M, eds. Health of Antarctic wildlife: A challenge for science and policy. Heidelberg: Springer. pp 107 112.
48. Crawford RJM, Underhill LG, Upfold L, Dyer BM (2007) An altered carrying capacity of the Benguela upwelling ecosystem for African penguins (*Spheniscus demersus*). ICES Journal of Marine Science 64: 570 576.
49. Everson I (1977) The living resources of the Southern Ocean. Southern Ocean Fisheries Survey Programme GLO/SO/77/1. Rome: FAO.
50. Kock K-H (1992) Antarctic fish and fisheries. Cambridge: Cambridge University Press. 359 p.

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Whales from Space: Counting Southern Right Whales by Satellite

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Abstract

We describe a method of identifying and counting whales using very high resolution satellite imagery through the example of southern right whales breeding in part of the Golfo Nuevo, Península Valdés in Argentina. Southern right whales have been extensively hunted over the last 300 years and although numbers have recovered from near extinction in the early 20th century, current populations are fragmented and are estimated at only a small fraction of pre-hunting total. Recent extreme right whale calf mortality events at Península Valdés, which constitutes the largest single population, have raised fresh concern for the future of the species. The WorldView2 satellite has a maximum 50 cm resolution and a water penetrating coastal band in the far-blue part of the spectrum that allows it to see deeper into the water column. Using an image covering 113 km^2, we identified 55 probable whales and 23 other features that are possibly whales, with a further 13 objects that are only detected by the coastal band. Comparison of a number of classification techniques, to automatically detect whale-like objects, showed that a simple thresholding technique of the panchromatic and coastal band delivered the best results. This is the first successful study using satellite imagery to count whales; a pragmatic, transferable method using this rapidly advancing technology that has major implications for future surveys of cetacean populations.

Citation: Fretwell PT, Staniland IJ, Forcada J (2014) Whales from Space: Counting Southern Right Whales by Satellite. PLoS ONE 9(2): e88655. doi:10.1371/journal.pone.0088655

Editor: Tom Gilbert, Natural History Museum of Denmark, Denmark

Received October 3, 2013; **Accepted** January 12, 2014; **Published** February 12, 2014

Funding: The authors have no support or funding to report.

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

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Introduction

"How many are there?" Is a question that is often difficult to address in ecology particularly for marine species that are generally inaccessible and cryptic. This is clearly demonstrated in whales where, despite their enormous size, robust population estimates are very difficult to obtain. The extreme size of whales means that they have a high per-capita rate of food consumption and hence a potentially massive impact on their prey populations as well as the marine ecosystem. Accurate population estimates are also essential to *inter alia* assess the recovery of depleted populations, evaluate conservation threats and also to use whales as indicators of the health of local ecosystems. Here we investigate the use of available Very High Resolution (VHR) satellite imagery to detect and count baleen whales as a proof-of-concept to augment current population studies. We target Southern right whales (*Eubalaena australis*) as a test species to evaluate; the southern right whale is an ideal subject for this work for many of the same reasons as it was an ideal whale to hunt, specifically its large size (maximum size ~ 15 m) and a tendency, in the breeding season, to bask near the surface in large aggregations around sheltered coastal waters. This is particularly true for mothers that use shallow water areas to raise their calves to the surface during their first months of life. The techniques described in this paper may also be relevant to other species of baleen whales, especially other large whales that, like the southern right, breed in calm coastal waters. Further work to test availability and perception bias of counting whales by satellite will need to be completed before the techniques described here can be used to independently assess populations, such a system would reduce the observer cost and effort and improve the accuracy of population estimates and trajectories.

Southern right whales have a circumpolar distribution in the Southern Hemisphere. The distribution in winter, at least for breeding animals, is concentrated in shallow coastal waters in the northern part of their range [1]. In summer right whales are found mainly in latitudes 40 50°S [2] but have been seen, especially in recent years, in the Antarctic as far south as 65°S [3,4] and around South Georgia [5,6].

Southern right whales were hunted extensively from the 17th through to the 20th century. The total number processed is conservatively estimated at about 155,000. The pre-whaling population was estimated at 55,000 70,000 dropping to a low of about 300 animals by the 1920s. After 1935 they were legally protected but over 3,000 more were thought to have been taken by illegal whaling in the 1960's [7].

Since the cessation of whaling several southern right whale breeding populations (Argentina/Brazil, South Africa, and Australia) have shown a strong recovery [8,9,10] but the other breeding populations are still very small. In 1997 the estimated total population size was 7,500 animals and the three main populations have continued to increase [3,11,12]. Overall the population appears to have grown strongly since the cessation of whaling but is still at <15% of even conservative historical estimates.

Of current concern is the unprecedented mortality of southern right whales on their nursery grounds at Península Valdés, Argentina, in what are the most extreme mortality events ever observed in a baleen whale [13]. Over 420 whale deaths in recent years, the majority of which were calves, suggests that this population and its ecosystem may be less healthy and robust than previously thought [13].

The traditional methods by which cetacean population abundance estimates are obtained use counts of whales along transects from platforms such as aircraft or ships, or counts from land-based vantage points [14]. These can be very labour intensive involving long hours of recording by trained researchers and, as whales range over large geographic areas, these survey methods can be costly and inefficient. Additionally, not all individual whales are present at once, and if present they are not easily detectable (so called availability and perception bias, respectively). Detection probabilities for whales are typically high for shipboard surveys, but for the study area, where surveys are typically carried out by small airplanes, they can be down to 40% [15]. In addition, there are not many precision estimates for southern right whale abundance, particularly for the study area. Typically abundance is assessed with line transect methods and for right whales from the same population in the Scotia Sea coefficients of variation are wide, ranging from 65 to 185% [16].

A previous attempt to count whales using satellite remote sensing data and had limited success [17]. Using the first generation of VHR imagery from the Ikonos satellite, with a resolution of 0.8 m in the panchromatic and 3.3 m in the colour bands, two areas were looked at: the orca pools at SeaWorld theme park in San Diego, and a section of coastal water around Maui known to have large numbers of humpback whales [17]. Although objects which were probably whales were identified in the IKONOS imagery, the lower resolution and the cluster and noise associated with waves sea-surface state meant that definitive sightings were difficult to prove. Since 2002 the spectral, spatial and temporal accuracy of high resolution satellites has improved and cost of acquiring such imagery has decreased. A number of recent studies have used VHR satellites to count animals such as penguins and seals from space [18,19,20]. The highest accuracy satellite, the Worldview2 satellite, has an on-the-ground pixel size of 50 cm in the panchromatic and 2 m in its eight colour spectral bands. One of these bands, termed the coastal band, uses the far blue part of the spectrum to penetrate the water column and is routinely used for hydrographic mapping [21].

Here we describe a method of identifying and counting southern right whales breeding in part of the Golfo Nuevo in Argentina using satellite imagery from the WorldView2 satellite count. This is an ideal location to evaluate our methods because every year, from July to November, whales concentrate in high densities to calve and mate. These enclosed bays are characterized by calm and shallow waters increasing the chances of obtaining images with optimum conditions of visibility.

Materials and Methods

We acquired a single WorldView2 satellite image of a region of the Golfo Nuevo Bay, the southern of two bays which separate Península Valdés from the mainland of Argentina (figure 1).

The location

Golfo Nuevo, the southern gulf of the Península Valdés, is a roughly circular shaped bay and between 80 – 100 km wide. The sheltered waters attract southern right whales in great numbers and, together with a similar sized bay just to the north, they hold one of the world's largest breeding aggregations of the species. This represents one of the best studied populations of southern right whales, with an ongoing programme detailing the natural history and ecology of the species [5]. From July to November (winter and early spring), much of the population is on the nursery ground at Península Valdés [21] (42°S, 64°W). In 1997, the population was estimated at 2,577 whales [22], with an annual growth rate of 6.9% per year [10]. Current estimates are unavailable and are required as whale calf mortality has increased sharply since 2005 when the population has experienced several severe mortality events, particularly in Golfo Nuevo [13].

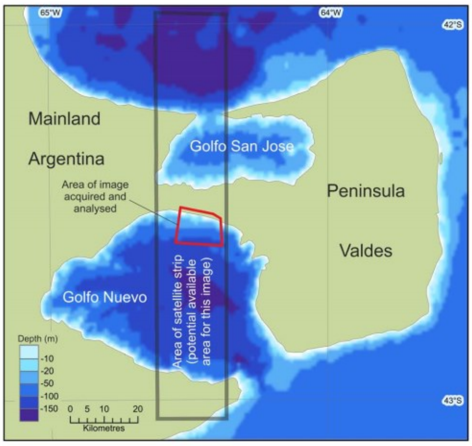

Figure 1. The area of the study and the location of places named in the text. The red box denotes the area of imagery acquired for this study. The grey area gives an indication of the possible swath width of a single satellite pass.
doi:10.1371/journal.pone.0088655.g001

The image

A section of a single WorldView2 image (Catalog ID: 103001001C8C0300) covering an area of 113 km^2 and taken on the 19th of September 2012 was purchased from the commercial provider Digital globe. The image was chosen from the Digital Globe archive for three reasons:

1. It covers the middle of the Golfo Nuevo Bay, an area with a high density of southern right whales.
2. The timing corresponds with the middle of the breeding/calf rearing season, which lasts between July and November.
3. It is cloud free with a calm sea-state.

Sea surface waves have a very strong influence on the ability to detect submarine features [17] Our previous analyses using VHR imagery in the Southern Ocean show that choppy water or sea swell refracts the sunlight making practical detection of whales almost impossible. This is especially true if attempting to construct routines to automatically identify targets. When choosing imagery from archival footage an online reduced resolution library is usually viewed. These reduced resolution "quick-looks" do not allow judgement on the sea-state, as they are too coarse to show surface waves – although whitecaps and swell lines can occasionally be seen. However several key features can indicate suitable

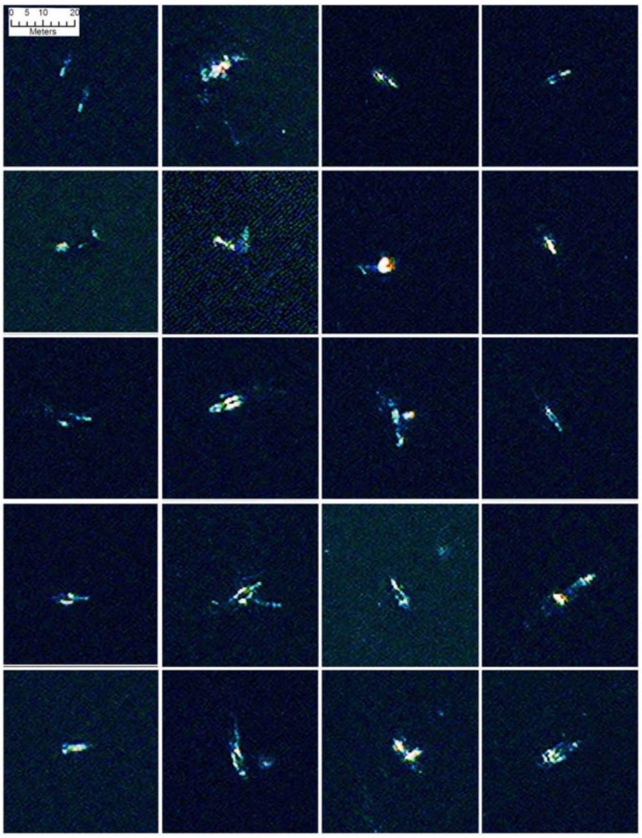

Figure 2. A selection of 20 comparable false colour image chips (bands 1-8-5) of probable whales found by the automated analysis. Several of the images could be interpreted as whale pairs, or as a mother and calf, others may be displaying behaviour such as tail slapping, rolling or blowing. On several images there is a strong return at one end of the feature which is mostly likely the calluses on the whales head. Reprinted under a CC BY license with permission from British Antarctic Survey and DigitalGlobe.
doi:10.1371/journal.pone.0088655.g002

calm conditions; these include sediment patterns and algal blooms and lack of surf at the coast.

The image acquired consists of nine bands of information; eight colour bands with an on the ground resolution of ~2 m per pixel, (Digital globe http://www.digitalglobe.com/downloads/WorldView2-DS-WV2-Web.pdf) and one panchromatic band with an on the ground resolution of 50 cm. The fifth of the eight bands is termed the coastal band and collects light of wavelengths between 400 nm and 450 nm. This far-blue or violet light penetrates deeper into the water column with less absorption and attenuation than longer wavelengths (dependent upon water clarity and turbidity). This data is routinely used by hydrographic institutions for mapping coastal bathymetry [23].

We assessed the returns of each band over a cross section of pixels through whale-like features of two types; surface features and assumed submarine features (figure 2). As can be seen in figure 3, all bands responded to surface features, with the strongest response in the panchromatic band, although this band also showed the most noise. In the submerged cross section only the coastal band (band 5) responded, no other band showed evidence of any feature. This also shows the noisy nature of the panchromatic data in an area of open water (figure 3).

Previous attempts to identify whales using IKONOS imagery show that attenuation of light through the atmosphere is weak in comparison to the two major components of image degradation; scattering from surface roughness of the sea and attenuation of light through the water column due to water turbidity [17]. As these major components could not be quantified to absolute reflectance, absolute values for the subsurface features could not be retrieved, we therefore used raw Digital Number (DN) values from the satellite to give an indication of relative illumination across the image.

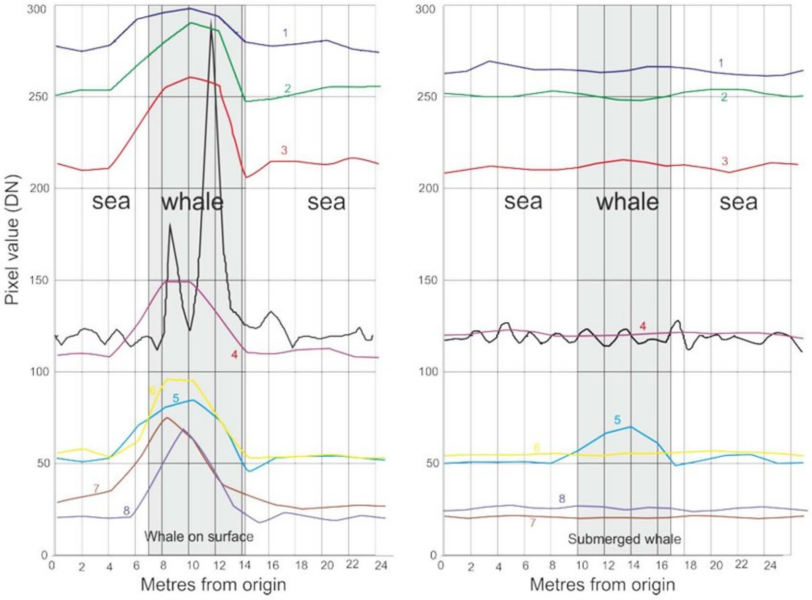

Figure 3. The sensor response through cross sections through two whale-like (correct shape and size) features assumed to be whales. The left hand figure is from a feature at the surface, the right hand figure shows a submerged feature. Note that while all bands show the surface feature, only band 5 (the Coastal Band) identifies the submerged feature.
doi:10.1371/journal.pone.0088655.g003

Automatic detection

Using ENVI5 image processing software and ArcGIS automatic detection of whale-like features in the water column was tested using maximum likelihood supervised classification, unsupervised classification (isoData and k-means) and thresholding of specific bands.

Supervised classifications need the signatures input information of the pixel values for each class in order to classify the image. These signatures are usually manually input by the user. The algorithm then segregates all the pixels in the image into classes representing the signatures.

Unsupervised classifications classify the image into component parts based solely on information held within the image; isoData uses a clustering algorithm to determine the natural grouping of cells, while k-means calculates initial class means evenly distributed in the data space, then iteratively clusters the pixels into the nearest class using a minimum-distance technique.

Histogram thresholding [24] requires a degree of experimentation to calculate the best thresholds to use. Through an iterative process we formulated thresholds that maximized signal (in this case suspected whales), and reduced the amount of noise or false positives (single pixels from small objects and mixed pixels). As whales are large features they should be represented by multiple bright pixels, noise will result in single pixels, although inevitably there could be a small number of whales at depths that return only single pixels, so that some valid single pixels should still occur. Using the histograms of whale DN values as a guide we built thresholds that maximized the ratio of multiple pixels to single pixels in the panchromatic and coastal bands.

To construct a test dataset the image was divided up into a grid and whale-like features were manually digitized and coded into three classes: probable whale (features that were whale-shape and whale-sized) possible whale (including weaker signals, bubble slicks and some groups of seabirds are classed as possible whales), or features only visible in Band 5 (The third class are objects identified only in the water penetrating coastal band, are interpreted as sub-surface feature that are also potentially whales). This process was conducted multiple times to ensure the lowest possible errors of omission.

Results

Visual inspection of the image showed that a number of offshore objects, that were both the right shape and size (5 – 15 m) to be whales, could be identified in both the colour and the panchromatic bands (see figure 2). Most of these objects were visible across all bands although in most cases the high resolution of the panchromatic band rendered the objects in greater detail (figure 4). Visual inspection can only utilize three bands as the red, blue and green element of the onscreen image, we compared combinations of pansharpened bands to find the band-combinations in which whales were most visible, the best overall results were retrieved using a combination of bands 1 (red),8 (NIR2) and 5 (coastal). The panchromatic band alone displayed a higher noise ratio that other bands; possibly a result of the higher resolution picking up more surface refraction from wavelets, ripples and small waves. Other surface features such as aggregations of seabirds were also visible in this band. These smaller features were a confusing element when attempting to develop automatic

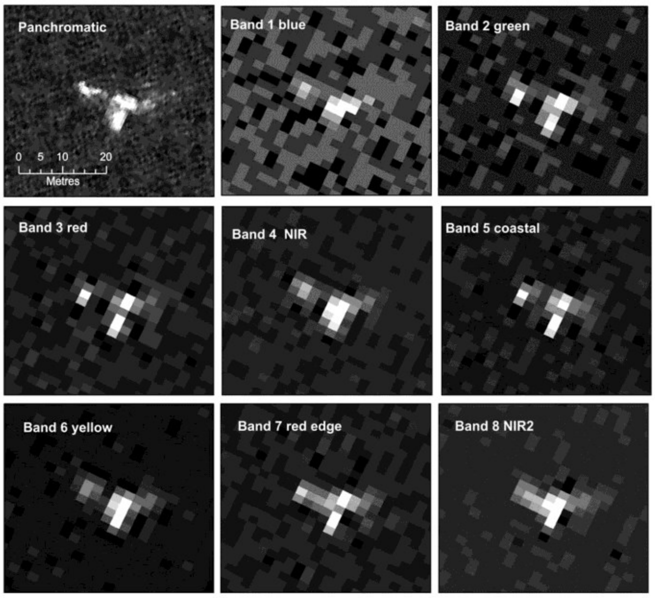

Figure 4. A single band images of a probable right whale in the satellite image from each of the eight multispectral bands and the panchromatic band of the WorldView2 data. Note that the higher resolution of the panchromatic band gives more detail, but it this increased detail also renders the object into several parts. Other bands show less detail, but have the advantage of homogenizing the object into one group of pixels, an important consideration when attempting to build automatic identification routines. Reprinted under a CC BY license with permission from British Antarctic Survey and DigitalGlobe.
doi:10.1371/journal.pone.0088655.g004

recognition algorithms. The coastal band (band 5) identified a number of features not apparent in the other data that were interpreted as sub-surface features. Manual counts of the gridded dataset found 55 probable whales, 23 possible whales and 13 objects identified in Band 5 only.

Returns from the four automatic analysis routines were assessed against the manually digitized data (figure 5). In this analysis we assume that manual detection detects all whales visible on the surface. Results from the supervised maximum likelihood classification returned many errors of commission in comparison to the unsupervised classification. The supervised classification also has the disadvantage of needing the input of user-derived signatures which take additional effort and inserts user bias into any classification. No meaningful results could be obtained using this method. The two unsupervised classification methods gave reasonable results, but the results that best matched the manually counted data came from a simple thresholding of single bands (table 1). The two most effective bands were the panchromatic and the water penetrating Band 5, which slightly outperformed the more detailed panchromatic analysis (see table 1). The single best routine was thresholding of the coastal Band 5; this technique found 84.6% of all manually digitized whales and 89% of the objects manually classed as probable whales, with 23.7% false positives. However, thresholding also requires user input to identify thresholds and therefore the greater accuracy of the technique needs to be balanced against the need for extra manual input.

Discussion

How do we know it is a Southern right whale?

There are many objects in the image that resemble whales, but the question remains; how do we know it is a Southern right whale? The answer to this can be broken into three criteria used to identify any objects in remotely sensed imagery:

1. The object is the right size and shape to be a whale
2. The object is in a place we would expect to find whales
3. There are no (or few) other types of objects that could be misclassified as whales to cause errors of commission.

In this study we have digitized and automatically identified objects that are the right size (up to 16 m long) and shape. Although the size of the whales has an upper limit the lower limit is difficult to assess as the deeper the whale in the water column the less we are likely to see. The shape is generally ellipsoidal, although this can vary due to rolling, tail slapping and bubbles and other ripples associated with the animal. In the location of the study at the time the image was taken we expect to see a high density of whales in the image, especially mothers which, at this time of year, are forced to swim at the surface to support their calves.

There are only a limited number of other confounding artefacts that could cause errors of commission: No other large marine mammals are reported to frequent this bay, right whales are the only large whale species that regularly use the shallow calving grounds of Peninsula Valdés [24]. Orcas, much smaller in size, are common in the area, although at a different time of the year, and

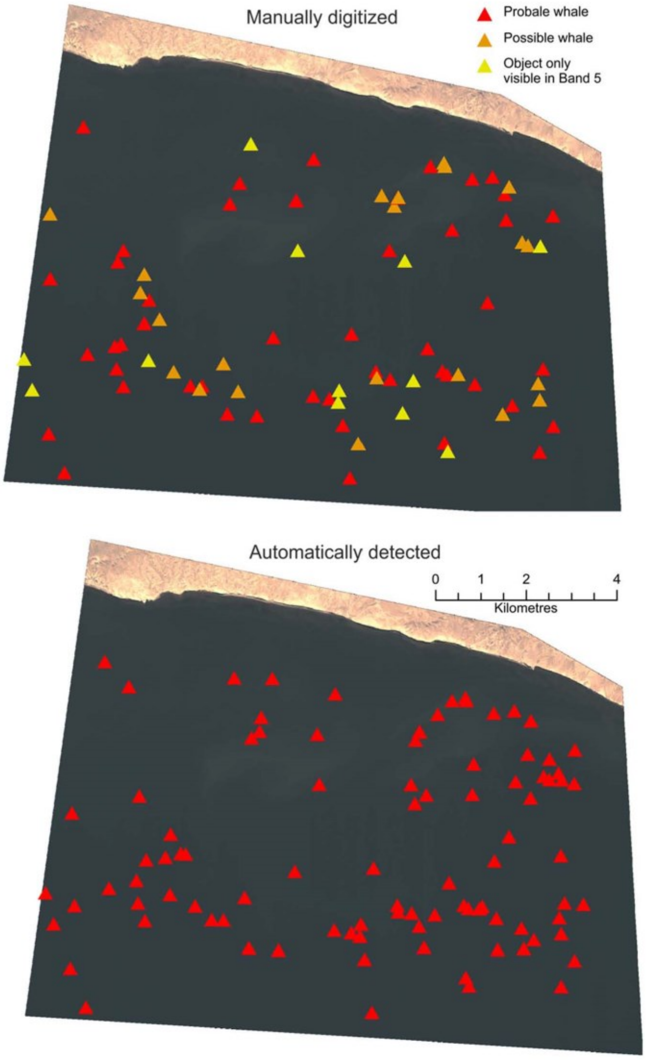

Figure 5. Comparison between manually identified and automatically identified whales. Manually identified whales (top) have been broken into three classes; shapes that are whale-like and whale-sized are classed as probable whales, other objects are classed as possible whales, but may include bubble slicks and some groups of seabirds. The third class are objects identified only in the water penetrating coastal band, these are interpreted as sub-surface feature that are potentially whales. The bottom image shows the whale-like objects identified from the thresholding analysis of the coastal band.
doi:10.1371/journal.pone.0088655.g005

are unlikely to be confused with right whales. This is an important criteria for the study area as it seems unlikely that different baleen species could be differentiated with the resolution of currently available satellite data. Of the other possible confounding factors the most likely are subsurface rocks in very shallow areas, seabird groups, surface bubbles and boats. Surface bubbles and seabird groups may include whales beneath them but it is unlikely that a single image of this resolution can elucidate whether a whale exists within these features. Therefore, when digitizing we classed whale-like features as "probable whales" and weaker signals, that may include seabird groups and surface bubbles, as "possible whales". Some of these issues, such as discrimination between whales and

Table 1. Assessment of results from four automatic detection techniques in relation to manually digitized whales; results from two unsupervised classification techniques and two Thresholding analyses.

	Manually digitized		**Unsupervied iso means**	**Unsupervised kmeans**	**Threshold Panchromatic**	**Threshold Band 5**
total signals	91	total signals	158	102	64	101
probable	55	probable matches	44	42	43	49
possible	23	possible matches	16	11	14	15
Band 5 only	13	band 5 matches	1	0	0	13
		total found	61	53	57	77
		% found	67.0	58.2	62.6	84.6
		% of probable	80.0	76.4	78.2	89.1
		total missed	30	38	34	14
		% missed	33.0	41.8	37.4	15.4
		false positives	97	49	7	24
		% false positives	61.4	48.0	10.9	23.8
		% good	38.6	52.0	89.1	76.2

doi:10.1371/journal.pone.0088655.t001

subsurface rocks, could be resolved with the purchase of multiple imagery or stereo-pairs where movement of whales between images would eliminate the possibility of rocks awash or at the surface. Boats should be identifiable by their uniform pale colouration, wakes or strong outlines which discriminate them visually from the typical signatures of whales. In the previous Abileah study using lower resolution imagery stationary boats could be clearly identified [17]. The WorldView2 imagery used in our study has 2.5 times as many pixels per unit area as the IKONOS data and we would therefore expect that boats either stationary or moving could be discriminated from whales in the manual search. In the section of Golfo Nuevo contained in our image no such features were identified.

On several potential whale objects there is a strong return at one end of the feature which is likely to be from calluses on the whale's head, a feature which could aid automatic detection. Several objects identified as whales could be interpreted as pairs, or as a mother and calf, others may be displaying behaviour such as tail slapping, rolling or blowing (see figure 6). These behaviours present challenges for automatic analyses.

The results from the automated analysis suggest that a thresholding of the water penetrating Band5 returns the best results, finding 89% of features classed as probable whales in the manual count. Thresholding a single band is a very simple technique, although it does require some user input to identify the best thresholds. The greater accuracy of the technique (in relation to the more automated unsupervised analysis) needs to be balanced against the need for extra manual input in relation to other methods. These results however are promising and suggested that larger surveys over whole calving areas, which could potentially measure thousands of square kilometres, could be automated with a degree of success using these techniques.

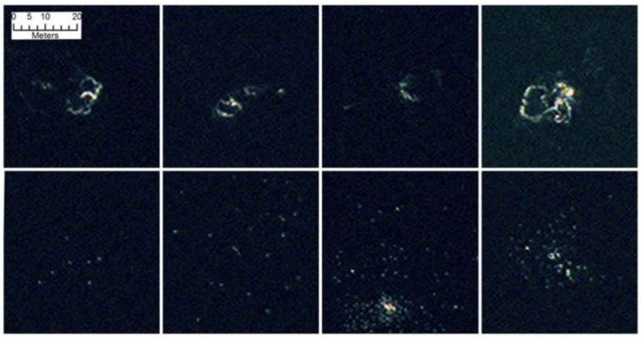

Figure 6. Examples of possible confounding features found in the image (false colour bands 1-8-5). The top row shows examples of surface features that are probably bubbles from subsurface whales. Whether the whales are still under the bubble areas is difficult to ascertain. The lower row show clusters white dots, probably seabirds. Seabirds have been recorded to feed on whales at Península Valdés (see discussion). The third (and possible fourth) of these images shows a larger white object that could be a whale (or whale carcass) although once more it is impossible to tell with any certainty in this imagery. Reprinted under a CC BY license with permission from British Antarctic Survey and DigitalGlobe.
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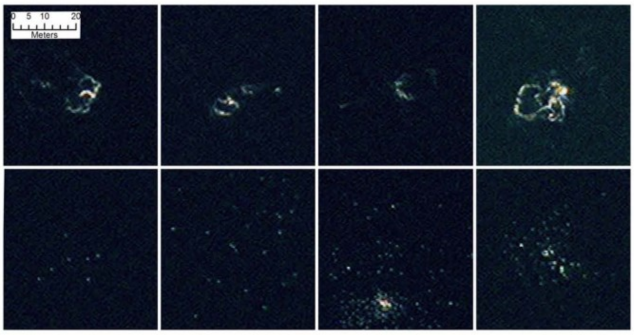

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doi:10.1371/journal.pone.0088655.g006

Appendix 3

Expanded methods

This short section expands upon the remote sensing methods used in the publish papers

Paper 1

The primary data source for this analysis was Landsat ETM+ data. A top-of-atmosphere correction was made on the digital numbers using a SRFI script in the software TNTMips. No standard atmospheric model exists for the Antarctic Peninsula region, but it is considered that due to the clean, cold atmosphere water vapour and atmospheric aerosols have minimal impact on remote sensing analysis (see details in the Landsat Image Mosaic paper by Bindschadler et al. 2008 for further details).

The Landsat images were referenced to a highly detailed coastline map using a "shift" algorithm in AcrGIS. This routine shifts, or slides a raster by a fixed amount in the x and y dimensions. It does not change pixel values or reprocess them.

As well as NDVI a number of other vegetation indices were trailed, these included the Enhanced Vegetation Index (EVI) and the Green-Red vegetation index (GRVI). Neither was a successful as NDVI in identifying the ground truthing vegetation areas; the complexity of the EVI resulted in more noise at the areas with mixed pixels, whilst the GRVI suffered as not all Antarctic vegetation is green. The NDVI index was chosen as it worked best in this simple environment where canopy affects and leaf size and angle are not an issues.

Even at its most abundant, Antarctic vegetation is often patchy and has fuzzy boundaries. Using discrete polygons to ground truth this distribution led to a problem with mixed pixels at the edges of polygons. However, due to the temporal difference between the imagery and the ground truthing, it was impossible to separate the difference of mixed pixels from the possible growth or spatial change of vegetation in the intervening period. These two problems – of mixed pixels and change of spatial in the extent of vegetation, are the likely source of the 10-30% of pixels of 0 - 0.05 NDVI which fall within the GPS control area.

Paper 2

This paper was opportunistic and the methodology was quite simple. The base imagery was a mixture of LIMA (Landsat Image Mosaic of Antarctica) tiles and Landsat ETM+ imagery. Initially an automated algorithm was deployed to find imagery. This used the LIMA tiles that had already been processes to top-of-atmosphere reflectance. Working on the assumption that sea ice should be pure white, or slightly blue in shaded areas, a simple subtraction method was applied, subtracting the blue band from the red band. A threshold was then set for each of the tiles of 3% of the highest reflectance value in the scene to eliminate mixed pixels and noise. Pixels where the equation:

$red - blue \leq (0.03R^{max})$ - where R^{max} is the maximum top-of-atmosphere reflectance in the red band.

This process successfully eliminated white snow and ice and blue ice and shadows, leaving areas of brown or red stained snow which, on sea ice, were assumed to be guano.

Due to the complex process algorithms used to colour balance the LIMA tiles there is a considerable amount of noise in the LIMA dataset at pixel level. This noise meant that manual checks had to be completed on all automatically identified locations, diminishing the usefulness of an automated algorithm. The automated, red minus blue, process was used on approximately one third to one half of all the coastal scenes, however it was found that manual analysis was both quicker and more effective, so at least half of all the coastline was completed using manual checks.

Paper 3

This paper was more methodological, both in remote sensing and statistical analysis. Here we will expand on the remote sensing methodology:

The analysis was done in ArcGIS, other software was tested, but as the operations were conducted in two different countries, which both had access to ArcGIS software, the decision was made that this would be the software of choice. Quickbird 2 imagery was used in the majority of cases in a limited number of instances panchromatic Quickbird 1 images and one Geoeye image were also used. The Quickbird 2 imagery has four spectral bands (blue, green. Red and near-infrared) a spatial resolution of 2.54m in the colour bands and 61 cm in the panchromatic bands at nadir. The method of discriminating penguins from the background environment was based upon an existing methodology put forward by Barber-Meyer et al. 2007, which used a supervised classification system to highlight the huddles of emperor penguins. Once the area of emperor penguins had been defined a penguin density factor was applied to calculate the number of penguins in in colony. The first step was to identify emperor penguin breeding sites. The locations from the Landsat analysis were used and additionally the whole coastline of Antarctica was re-check for signs of penguin colonies, VHR imagery was downloaded at sites of known or suspected colony locations to confirm if there were indeed emperor penguins there and Quickbird quicklooks were used in addition to the Landsat ETM+ tiles used in the previous work. Forty six colonies were identified from Landsat and VHR imagery. All but one these colonies were analysed with imagery from a single breeding season (2009), the exception being one small colony that was analysed from 2008 data.

To improve upon the Barber-Meyer methodology the Quickbird imagery was pansharpened using an Intensity/Hue/saturation method. Doing this on-the-fly in ArcMap does not allow for the use of an infrared channel, but by using the "Create Pansharpeden Raster Dataset" tool in ArcCatalogue allows the extra infrared band to be utilized. The supervised classification, uses the "Maximum Likelihood Classification" tool in ArcGIS. The first step is create a signature point dataset. Point were digitized identifying classes of guano, shadow, snow penguins and potentially other areas (dark-shadow, light-guano etc.). Between two too six classes were used, but more commonly four was sufficient. Up to 100 signatures were created for each class in each image, the number of signatures varies depending upon image complexity and the spectral separation between classes. Once the class signatures are identified these are used in the maximum likelihood classification to divide the image into the relevant classes. The method is manually intensive as often the first attempt needs to be refining, with more signature or more classes being added or adjusted until the resulting classification matches a visual check. Usually between two too nine attempts were made. The more complex images, where heavy guano staining or striping affected the image, tended to be the ones where more classes were required. Several colonies were particularly difficult (those images classes as poor in the image notes on table 1 in the paper), these images were assessed by two operators until a consensus could be made on the classification. Two images, from Cape Washington and Haswell Island, were especially problematic and no consensus could be made on the counts. These two images were classed as "bad" and alternative images were source and re-analysed until a consensus could be made. Half the images were assessed by myself and half by Michelle LaRue at the Polar Geospatial Center in Minneapolis. In cases of heavy striping of shadowed areas images were cropped into two or more image segments and individual classification assessments carried out on each subset.

Two checks were made on the consistency of the image classification; the first involved a number of colonies being cross-check by the other operator. The second was made by having three operators – myself, Michelle and Claire Porter at the Polar Geospatial Center, each assess the one of the image from each quality class. The image quality was divided into four classes based upon the difficulty inherent in making a successful classification. The classes were; good, fair, poor or bad – note that the bad images were rejected and alternative images were sourced. A typical image was chosen from each class and each operator analysed this image using the supervised classification technique. The results were compared for variance. It was found that the correlation between operators for the *good* image were within 2.5%, *fair* to within 7.5% and *poor* to within 15%. The bad image had a difference of up to 50%, but none of these classes of images were used in the final analysis. These confidence intervals were used along with other statistical assessments in calculating the probable population and confidence intervals at each of the 46 colonies (Table 3 in the paper).

To change the area figure output from the supervised classification we used a robust regression technique. . The robust regression is often used in population modelling and is considered to give a better fit to a distribution than the similar least-square-fit (LSF) technique which could be considered the standard regression method. Robust regression is less susceptible to the effects of statistical outliers than LSF. Outliers away from the average distribution in the more simple LSF analysis can anomalously skew the regression, so a robust regression, as its name implies, is considered statistically better than a standard LSF. The Robust regression was done in the R statistical package.

Paper 4

This paper was observation based. The analysis of the location of the emperor penguin colony on the Shackleton Ice Shelf was one of the few analytical parts of the paper. The location of the emperor penguin colony was plotted onto sea ice concentration data, modelled by the University of Bremen from passive microwave data from AMSR-E data (see Spreen et al. 2008. Sea ice remote sensing using AMSR-E 89-GHz channels. *JGR*. 113.C2) and is available at high temporal resolution (approximately once per week). We had information on the location of the Shackleton Ice Shelf emperor penguin colony for five years and by plotting the penguin colony locations onto the sea ice data a clear pattern emerged; when the sea ice concentration to the north of the ice shelf in late March was high the penguins located on the sea ice itself, but when there was no sea ice the colony relocated onto the ice shelf. Late March to early April is a critical time for emperor penguins as it is when the adult males prospect for colony locations. Once the colony located in one place it stayed there for the rest of the breeding season.

Paper 5.

This was a more analytical paper that developed an algorithm to find areas of guano using the spectral information from Landsat ETM+ imagery. The spectral analysis was applied to a single, top-of-atmosphere corrected Landsat 7 ETM+ scene, using the visible, near and shortwave infrared bands. The results were compared to the locations of known colonies and archival records. Several classification methods were trailed including two types of unsupervised classification (K-mean and iso-clusters) as well as the maximum likelihood supervised classification we had used for the emperor penguin study. The last technique we test was a Spectral Angle Mapper routine in ENVI software. Only the spectral Angle Mapper gave good results, the supervised classification, of which I had lot of experience, performed surprisingly poorly. The Spectral Angle mapper is a target finding algorithm which matches the spectral profile from training pixels and ranks each pixel in the image with an index of how close its profile is to the training pixels. As the routine uses to the angles between spectral bands, rather than the absolute values, it is immune to changes in overall illumination. We used training pixels from two well-known Adelie penguin colonies where closely packed birds gave pixels wholly covered in guano to minimise the effect of mixed pixels. Some trial-and-error was need to set the angle threshold and this was done by assessing the results of several test applications to the size and shape of well mapped Adelie penguin colonies, of which there are several in the area of the Landsat EM+ scene. The resulting output is a grid of pixels each with a number that can be considered a ratio of spectral nearness to the test pixels. By testing this against known locations it was found that the lowest third of returned pixels were not associated with any colonies, and so these were eliminated from the analysis. The resulting pixels were considered as likely guano sites.