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A continent-wide search for Antarctic petrel breeding sites with satellite remote sensing

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ABSTRACT

The Antarctic petrel (*Thalassoica antarctica*) has been identified as a key species for monitoring the status and health of the Southern Ocean and Antarctic ecosystems. Breeding colonies of the Antarctic petrel are often found on isolated nunataks far from inhabited stations, some up to hundreds of kilometers from the shoreline. It is difficult therefore to monitor and census known colonies, and it is believed that undiscovered breeding locations remain to be found. We developed an algorithm that can detect Antarctic petrel colonies and used it to complete a continent-wide survey using Landsat-8 Operational Line Imager (OLI) imagery in Antarctica up to the southernmost extent of Landsat's orbital view at 82.68°S. Our survey successfully identified 8 known Antarctic petrel colonies containing 86% of the known population of Antarctic petrels. The survey also identified what appears to be a significant population of breeding birds in areas not known to host breeding Antarctic petrel colonies. Our survey suggests that the breeding population at Mt. Biscoe (66°13′S 51°21′E), currently reported to be in the 1000s, may actually be on the order of 400,000 breeding pairs, which would make it the largest known Antarctic petrel breeding colony in the world. The algorithm represents a first-ever attempt to apply satellite remote sensing to assess the distribution and abundance of the Antarctic petrel on a continent-wide basis. As such, we note several algorithm shortcomings and identify research topics for algorithm improvement. Even with these caveats, our algorithm for identifying Antarctic petrel colonies with Landsat imagery demonstrates the feasibility of monitoring their populations using satellite remote sensing and identifies breeding locations, including Mt. Biscoe, that should be considered high priorities for validation with directed field surveys.

1. Introduction

Effective wildlife management relies on accurate population estimates, but it is a challenge to provide such estimates for seabird species inhabiting remote areas of the Southern Ocean and the Antarctic continent. In particular, continent-wide population estimates for the Antarctic petrel (*Thalassoica antarctica*) are highly uncertain, though the most recent population estimate (van Franeker et al., 1999) of 10–20 million individuals (4–7 million breeding pairs) makes them one of the most abundant birds in Antarctica (Harris et al., 2015). Current population estimates were compiled from ship-based observations in the Weddell Sea, Prydz Bay, and Ross Sea regions and extrapolated to other regions of the Antarctic petrel's circumpolar distribution. Although this population estimate represents the best available science on the abundance of this species, the authors of the original survey readily acknowledged the “limitations in methodology and interpretation of at-sea censuses.” In addition to considerable uncertainty surrounding Antarctic petrel abundance, there is tremendous uncertainty regarding the geographic distribution of their breeding sites. van Franeker et al. (1999) identified 35 breeding locations, but they account for only around 500,000 pairs (i.e., ~1 million breeding individuals), or under a quarter of the estimated total breeding population. This knowledge gap stems from the difficulty of accessing Antarctic petrel breeding locations and the logistical challenges of surveying birds that often nest on remote and inaccessible mountain slopes 200 km (or farther) from shore. Given that vast regions of Antarctica remain largely unexplored, coupled with the striking discrepancy between known breeding locations and estimates of total population, it is likely that a significant number of Antarctic petrel breeding locations remain to be found.

Interest in refining Antarctic petrel population estimates is motivated by their role as a top predator in the Southern Ocean where they act as a central-place forager of Antarctic krill (*Euphausia superba*), fish, and squid during the breeding season (Ainley et al., 1992; Descamps et al., 2016a; Hodum and Hobson, 2000; Lorentsen et al., 1998; Nicol,

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1993). Indeed, it has been estimated that 680,000 metric tonnes of krill are consumed by Antarctic petrels each year (Descamps et al., 2016b). This amount is comparable to the southwest Atlantic's krill "trigger limit" of 620,000 t set by the member nations of the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR). CCAMLR established such limits to ensure a sustainable krill stock for both fisheries and krill-dependent species (CCAMLR, 2016). To that end, the Antarctic petrel was identified as one of several key "dependent species" included in the CCAMLR Ecosystem Monitoring Program (CEMP). While CEMP recognizes the need to monitor population changes in this species, it also recognizes that the distribution and abundance of the Antarctic petrel are not well understood (Kock, 2000).

Satellite remote sensing may play an important role in establishing a continent-wide baseline on the distribution and abundance of the Antarctic petrel. Remote sensing is an established tool used to locate and inventory Emperor and Adélie penguin breeding locations (e.g., Fretwell and Trathan, 2009; Schwaller et al., 2013; Lynch and LaRue, 2014). While the technical feasibility of using satellite imagery to identify flying seabird colonies has been recently demonstrated in a study of a single Landsat scene (Fretwell et al., 2015) the use of satellite remote sensing for large-scale Antarctic petrel surveys has not been explored.

Antarctic petrel colonies are visually similar in many ways to penguin colonies but there are some important differences between the two that affect the accuracy and errors of detection. Like those of penguins, Antarctic petrel colonies can be very large and, when closely packed nests are situated on the surface of exposed rock outcrops, they can be identified in satellite images by the associated guano stain. On the other hand, Antarctic petrel colonies are found on steeper slopes than penguins and are therefore subject to more weathering and shadowing, which can obscure the guano stain and decrease the probability of detection. Furthermore, the petrel diet can have a higher proportion of fish-to-krill than the penguin diet (Descamps et al., 2016a; Hodum and Hobson, 2000) and petrel guano could thus be deficient in the chemical constituents (krill carotenoids and chitin) that make penguin guano such a unique and easily detectable target with remote sensing methods.

In this paper, we report on the first attempt to retrieve Antarctic petrel breeding locations from satellite data at the continental scale. We report on the theoretical basis of our Antarctic petrel detection algorithm, the expected colony detection errors of commission and omission, and the overall results of our continent-wide survey using Landsat-8 Operational Line Imager (OLI) data. We provide supplementary materials that allow others to reproduce and verify our results. These materials also identify a large number of potential Antarctic petrel breeding colonies. Thus, this work represents the first steps toward the discovery of previously unknown Antarctic petrel colonies and toward a more comprehensive, routine monitoring of this key Antarctic species.

2. Methods

2.1. The satellite dataset

Fig. 1 illustrates the 1098 locations of the 3944 Landsat-8 Operational Land Imager (OLI) scenes collected for the analysis reported here. The data set consists of scenes acquired between 16 November 2013 and 28 March 2016 from 60.44°S to the southernmost extent of the Landsat-8 orbital view at 82.68°S. Only scenes covering known rock outcrops as defined by the Antarctic Digital Database (http://www.add.scar.org) were selected for analysis because the Antarctic petrel does not nest on snow surfaces (Mehlum et al., 1988). Even with this initial data reduction, the resulting dataset consisted of ~4 Tbytes of imagery or approximately 1.5×10^{14} pixels.

2.2. The search algorithm

The algorithm used to search for Antarctic petrel nesting colonies is based on an Adélie penguin colony search algorithm (Schwaller et al., 2013; Lynch and Schwaller, 2014). The algorithm uses 6 reflectance bands from the Landsat-8 OLI: the blue, green, red, near infrared, shortwave infrared-1, and shortwave infrared-2 bands. The algorithm transforms the 6 reflectance bands of each pixel into 5 spherical coordinate bands since doing so was found to improve the separation of penguin colony pixels from other targets (Schwaller et al., 1989). Using the transformed data, a training set of pixels was selected from known Antarctic petrel breeding areas. The algorithm calculates an ellipsoidal surface in the transformed data space that optimally separates Antarctic petrel colony pixels from pixels selected over other targets, including rock outcrops and soils of various types, snow, ice, and open water (see Schwaller et al., 2013 for details on data transformation and optimization). The equation of the transformed ellipse can be summarized as a 6 by 6 transformation matrix, one dimension greater than the number of spherical coordinate bands. The transformation matrix used in this study is provided in Appendix A. The algorithm retrieval can be reproduced using any Landsat-8 OLI image, the transformation matrix, and the additional steps described in Appendix A.

The training set used to calculate the transition matrix consisted of 206 pixels from three Antarctic petrel colonies at Svarthamaren (135), Mt. Biscoe (61), and Mt. Paterson (10). In addition, 29,912 pixels were collected over other ground targets. These samples included areas of soil and rock collected near the research stations San Martin, Mendell, Marimbio, and Davis; pixels collected in the vicinity of Cape Bird, Cape Hallet, and Cape Crozier (but not over the Adélie penguin colonies at these sites); and pixels collected in the Prince Charles Mountains around 70°48′S 68°12′E. Additional pixels were collected for the training set over ice and snow in the vicinity of the Mawson and Juan Carlos research stations. Pixels over snow, ice, and rock were collected in the vicinity of Cape Adare (again, not over the penguin colony) and in east Antarctica around 67°24′S 59°24′E. The results of the training found that 201 of the Antarctic petrel colony pixels were correctly classified and 5 incorrectly classified as "other ground type;" 29,911 of the other ground type pixels were correctly classified and 1 of the other ground type pixels was classified as belonging to the Antarctic petrel colony class. This classification yielded a correlation of 0.985 as calculated by Kendall's tau, which is statistically significant at $p < 0.0001$.

2.3. Slope and elevation filtering

The ASTER global digital elevation model (GDEM; Rees, 2012) was used to help filter the pixels identified by the algorithm as belonging to the Antarctic petrel colony class. Filtering was necessary because of the relatively high errors of commission associated with the algorithm. The filter exploits the knowledge that Antarctic petrels nest on elevated cliffs and mountain slopes (Mehlum et al., 1988). The GDEM was used to select Landsat OLI pixels located on surfaces with a slope ≥ 17° and with an average height above terrain (HAT) of 20 m. HAT was calculated by selecting a 15 by 15 ASTER GDEM pixel region centered around a given Landsat-8 pixel, then subtracting the center pixel elevation from the average elevation of GDEM pixels in the lowest 20th percentile of the 15 × 15 pixel region. The GDEM filtering removed flat areas and areas in depressions from consideration as potential Antarctic petrel nesting areas.

2.4. Slope calculation

The ASTER GDEM is stored as 1° by 1° tiles, with 3601 center-referenced pixels per tile. The pixel dimension in the latitude direction is constant (approximately 31 m) but the pixel dimension in the longitude direction varies with latitude. Pixel dimension in the longitude

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