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Using super-high resolution satellite imagery to census threatened albatrosses

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This study is the first to utilize 30-cm resolution imagery from the WorldView-3 (WV-3) satellite to count wildlife directly. We test the accuracy of the satellite method for directly counting individuals at a well-studied colony of Wandering Albatross *Diomedea exulans* at South Georgia, and then apply it to the closely related Northern Royal Albatross *Diomedea sanfordi*, which is near-endemic to the Chatham Islands and of unknown recent population status due to the remoteness and limited accessibility of the colonies. At South Georgia, satellite-based counts were comparable to ground-based counts of Wandering Albatross nests, with a slight over-estimation due to the presence of non-breeding birds. In the Chatham Islands, satellite-based counts of Northern Royal Albatross in the 2015/2016 season were similar to ground-based counts undertaken on the Forty-Fours islands in 2009/2010, but much lower than ground-based counts undertaken on The Sisters islands in 2009/2010, which is of major conservation concern for this endangered albatross species. We conclude that the ground-breaking resolution of the newly available WV-3 satellite will provide a step change in our ability to count albatrosses and other large birds directly from space without disturbance, at potentially lower cost and with minimal logistical effort.

Keywords: aerial survey, albatross, population monitoring, remote sensing, satellite imagery, Very High Resolution, Worldview-3.

Over the last decade, Very High Resolution (VHR) satellite imagery has been used in a number of studies to identify and count animals directly. Most of these have focused on the polar regions, where breeding locations are remote and the contrast between animals and their surrounding environment often is high (Larue & Knight 2014). A small proportion of these projects have counted individual animals, including Polar Bears *Ursus maritimus* (Stapleton *et al.* 2014), seals (LaRue *et al.* 2011, McMahon *et al.* 2014), wildebeest *Connochaetes* spp. (Yang *et al.* 2014) and Southern Right Whales *Eubalaena australis* (Fretwell *et al.* 2014), and most were part of small-scale, proof-of-concept studies. Population sizes of penguins have been estimated at larger scales by satellite, including in the case of two species across the Antarctic continent by extrapolation from the area of penguin huddles, or of guano staining (Fretwell *et al.* 2012, Lynch & Larue 2014). To date, no remote-sensing study has used satellite imagery to count directly all the individuals of one species at a global scale. However, with the recent launch of new, higher-resolution satellites, this may now be possible.

Seabirds are among the most threatened groups of birds according to the Red List of the World Conservation Union (IUCN) (Croxall *et al.* 2012). Albatrosses and large petrels are particularly at risk, largely as a result of incidental mortality (bycatch) in fisheries and, for some species, disease, predation or habitat destruction by introduced alien species at breeding colonies (Phillips *et al.* 2016). Of the six species in the Great Albatross genus *Diomedea*, two are listed by IUCN as Critically Endangered, one as Endangered and three as Vulnerable, and almost all pairs of these species nest in remote islands in the southern oceans (Phillips *et al.* 2016). These are among the

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largest of flying birds, and have some of the longest wingspans, and the upper body in the adults of most species is predominantly white. They are therefore excellent models for testing the limits of detection of individual animals using WorldView-3 imagery, particularly as information on their population trends is integral to their conservation.

This study focuses on two species, Wandering Albatross *Diomedea exulans* and Northern Royal Albatross *Diomedea sanfordi*, which are classified as Vulnerable and Endangered, respectively (Phillips *et al.* 2016). Wandering Albatross has a circumpolar distribution, with breeding populations at South Georgia, Prince Edward Islands, Iles Kerguelen, Iles Crozet and Macquarie Island, an estimated global population of *c.* 8360 pairs, and is considered to be decreasing largely because of incidental mortality in long-line fisheries (Jiménez *et al.* 2014, Phillips *et al.* 2016). Northern Royal Albatross has a much more restricted breeding range that is confined almost entirely to three islands in the Chatham group (< 1% of the population breed on the South Island, New Zealand), and is the fifth rarest of the 22 albatross species, with a global population estimated at *c.* 5800 pairs in 2002 (Phillips *et al.* 2016). Northern Royal Albatross is classified as Endangered on the basis of its small area of occupancy and its high rate of population decline predicted from poor breeding success in the late 1980s and 1990s. This followed a severe cyclonic storm in 1985 which stripped soil and vegetation from nest-sites and led to high rates of failure from egg breakage, exposure to high temperatures and flooding during incubation (Robertson 1998). As the breeding islands are unpopulated, small, remote and difficult to access, monitoring of population size and productivity from aerial or ground surveys has been intermittent. However, the increase from an estimated 5200 breeding pairs in 1995 to 5800 breeding pairs in 2002 at the Chathams indicates a partial recovery (Bird Life International 2017).

The aims of this study were to test the accuracy and utility of using WorldView-3 imagery to count great albatrosses, and to determine the population size and trends of Northern Royal Albatross. To validate the method, we compared counts of Wandering Albatross nests derived from satellite imagery (apparently occupied sites, AOSs) with counts of nests from ground surveys at a well-studied location at South Georgia, where nests are monitored intensively throughout the breeding season. We then used WorldView-3 imagery to count Northern Royal Albatrosses, which nest in broadly similar habitats in terms of topography and vegetation height at the Chatham Islands, to generate an up-to-date population estimate for this endangered species.

METHODS

Study areas

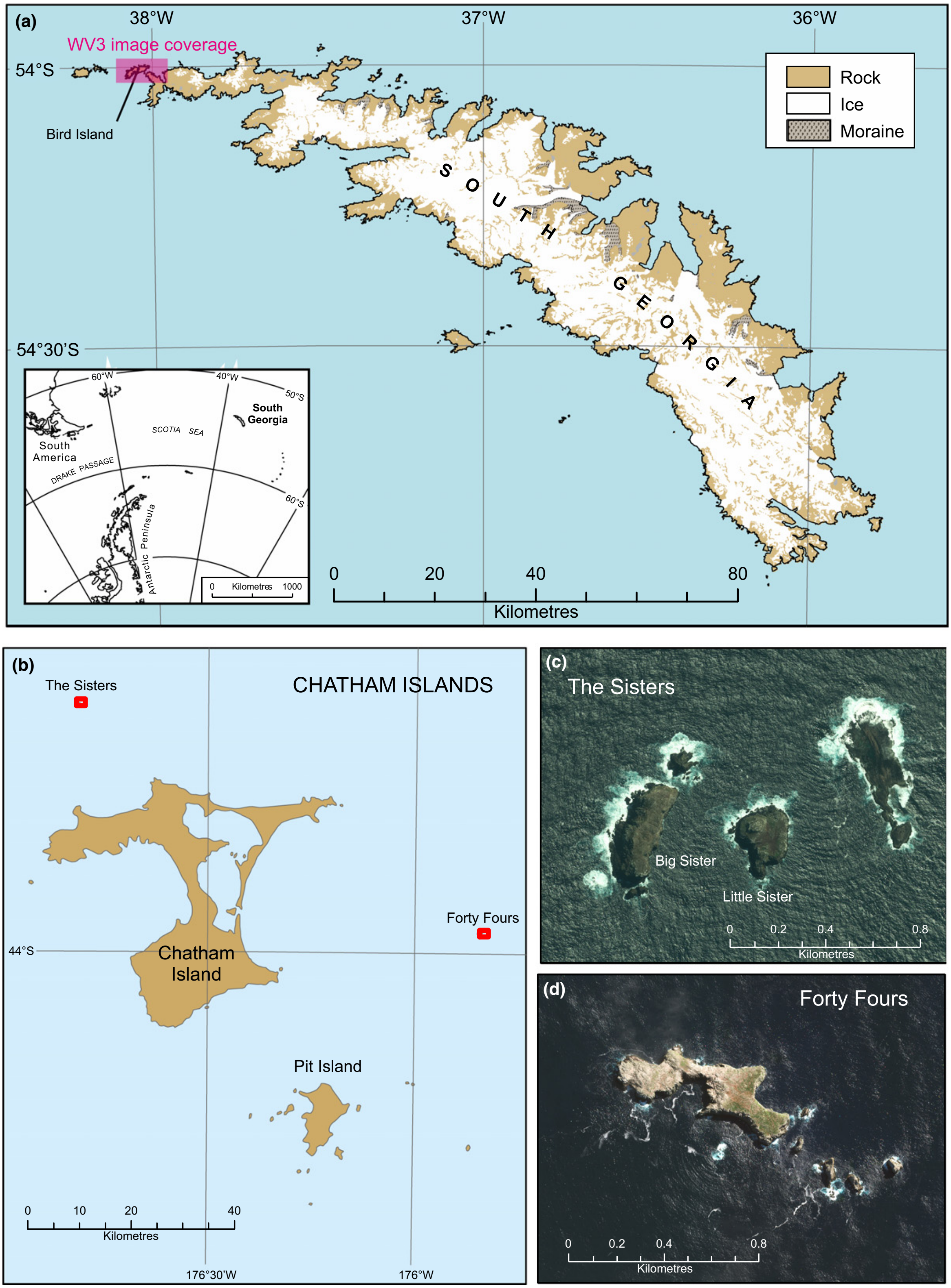
Bird Island (54°00′S, 38°03′W) is a small island (*c.* 4.5 km^2) to the west of mainland South Georgia (Fig. 1). It held 61% of the breeding population of Wandering Albatross at South Georgia in the austral summer of 2003/2004, equivalent to around 10% of the global population (Poncet *et al.* 2006, Phillips *et al.* 2016). The birds nest in relatively flat areas of the tussock grass *Poa flabellata*, which they used to construct nest mounds.

The Chatham Islands (44°23′S, 176°17′W) group lies 680 km east of New Zealand and consists of one large island, 10 smaller islands and other sea stacks. Ninety-nine per cent of the global population of Northern Royal Albatross breed on three of the smaller islands: Big and Little Sister (usually termed the Sisters) and, further to the east, the Forty-Fours (Phillips *et al.* 2016) (Fig. 1). The three small islands in the Chatham Group are precipitous and have no easy access, ground visits are extremely difficult, and the distance of the islands from mainland New Zealand means that aerial surveys are expensive. The other 1% of the global population breed at Taiaroa Head on the South Island, New Zealand, which is accessible and is monitored regularly.

Satellite imagery

One of the main limitations in the use of satellite data for counting individual animals is their

Figure 1. The location of the two study areas. (a) Bird Island, South Georgia. The pink area depicts the area covered by the WorldView-3 satellite image taken on 10 January 2016. (b) The location of The Sisters and Forty-Fours in the Chatham Islands. The red areas depict the areas covered by the WorldView-3 satellite images; these images are in (c) and (d). Cloud-free satellite imagery covered the full extent of the study area.


(a)
38°W
37°W
36°W
WV3 image coverage
54°S
Bird Island
Rock
Ice
Moraine
SOUTH GEORGIA
54°30'S
60°W
40°W
50°S
South Georgia
SCOTIA SEA
South America
DRAKE PASSAGE
60°S
Antarctic Peninsula
0 Kilometres 1000
0
20
40
80
Kilometres
(b)
The Sisters
CHATHAM ISLANDS
Forty Fours
44°S
Chatham Island
Pit Island
0 10 20 40
Kilometres
176°30'W
176°W
(c)
The Sisters
Big Sister
Little Sister
0 0.2 0.4 0.8
Kilometres
(d)
Forty Fours
0 0.2 0.4 0.8
Kilometres

resolution (Laliberte & Ripple 2003). In March 2015, the U.S. Congress relaxed restrictions on the spatial resolution of commercial satellite imagery from 50 to 30 cm, ushering in a new era of super-high resolution optical satellite imagery for scientific and other applications. The threshold size of objects that can be seen from space is now much smaller, and the definition and the reliability with which they can be discriminated are much improved. WorldView-3 is currently the only satellite providing commercial imagery at sub-40-cm resolution, offering optical imagery at a spatial resolution of 31 cm in the panchromatic band, and of 1 m in the visible and near-infrared bands (http://www.satimagingcorp.com/satellite-sensors/worldview-3/). This more than doubles the potential density of pixels from 4 pixels/m^2 (for a 50-cm resolution image) to 10.4 pixels/m^2 (31-cm resolution). For wildlife applications, there are therefore now more species for which individual animals are potentially visible, or can be visualized at considerably higher definition by satellite.

The study was based on WorldView-3 VHR satellite images, with the visible bands (2/3/5) pan-sharpened to provide a 31-cm resolution colour image using the Gram Schmidt algorithm in ENVI image processing software. To account for topographic distortion and to ensure that GPS ground-truthed nest locations matched as closely as possible the pixels in the image, the satellite imagery of Bird Island, South Georgia (54°00′S, 38°03′W), was orthorectified using a high resolution (5-m cell size), photogrammetrically compiled digital elevation model (DEM) (British Antarctic Survey, 2000). As no ground-truthing data for the Chatham Islands were available, orthorectification was not possible. The image of Bird Island, South Georgia (54°00′S, 38°03′W), was acquired on 10 January 2016, by which time all pairs of Wandering Albatrosses have laid, based on the latest egg date in the intensive study area (5 January), and a small percentage failed (see Results). Images of the Forty-Fours and of the Sisters in the Chatham Islands were acquired on 12 February 2016 and 19 February 2016, respectively. This corresponds to the mid- to late-brood guard period for Northern Royal Albatrosses. Hence, one adult (rarely two) from each pair were likely to be present at each nest with a chick, and non-breeders may also have been in attendance, although, given the later stage in the season, at a smaller proportion of sites than in the image of Bird Island. In addition, an archived image of the Sisters was available from 29 December 2015; this date corresponds to the mid-incubation period for Northern Royal Albatross. This was not possible on the Forty-Fours as, unlike for the Sisters, there was no archival image available for the Forty-Fours from Digital Globe for earlier in the 2015/2016 season. The satellite imagery was clear and cloud-free, and covered 100% of the islands. Counts of these images (see below) were compared with those in photographs taken in aerial surveys in late December 2009.

Ground-truthing data

Wandering Albatrosses at Bird Island have been monitored intermittently from 1958 and annually since 1980. This involves daily visits to a study area of 100–150 nests that are staked and mapped (with a handheld GPS, accurate to < 10 m) to determine laying, hatching and fledging dates, and weekly visits at other times to determine timing of nest failure and breeding success. All other breeding areas on the islands are visited every 1–2 weeks during incubation. All nests with eggs are staked and mapped with handheld GPS, and the nests visited at least monthly thereafter to determine breeding success or timing of failure.

Non-breeder estimation

In addition to birds incubating eggs and the presence of a few partners, pre-breeders (birds that have never bred), deferring breeders and a small number of failed breeders attend the colony in the early- to mid-breeding season (these last three groups of birds are termed ‘non-breeders’). It is necessary to adjust for the presence of these non-breeders (errors of commission) to estimate the number of breeding pairs from counts of birds in satellite (or other) imagery. Hence, counts of Wandering Albatrosses in seven digital camera photographs taken from vantage points overlooking nesting sites at Bird Island during early to mid-incubation (15 January to 14 February 2015) were compared with ground counts of the number of nests with eggs in those areas. The birds in each of these photographs were counted twice to improve accuracy.

Detectability of individual great albatrosses

Great albatrosses breed on elevated, flat or gently sloping terrain, and tend to prefer areas of tussock

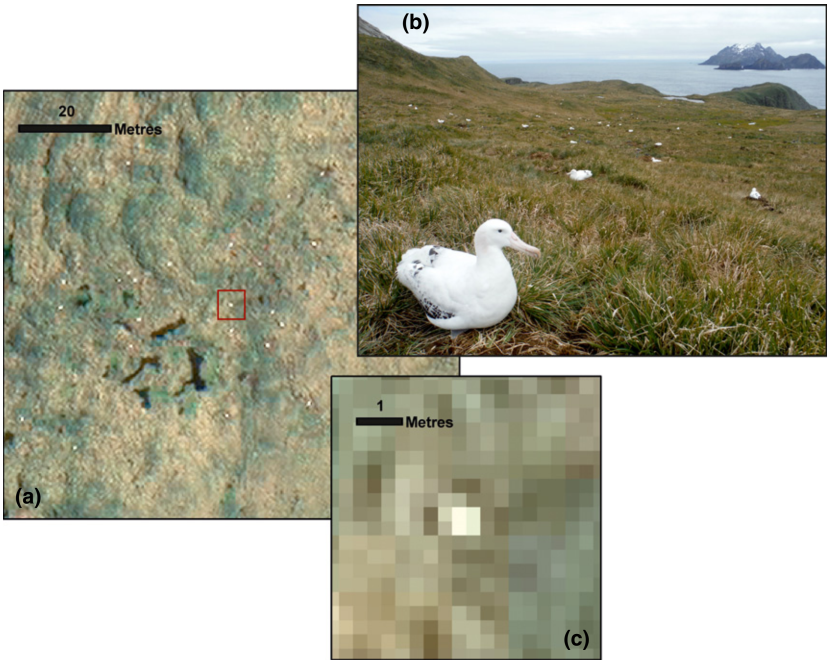


Figure 2. (a) Part of the WorldView-3 satellite image of Bird Island showing the distribution of white dots. (b) Photograph of Bird Island for comparison (photo credit: R.A. Phillips). (c) Close-up of a representative white dot in (a), indicating pixel composition.

or other grassy vegetation that provides the material for their nests. The head, back and upper tail of adult Wandering or Northern Royal Albatrosses are largely white, although with dark vermiculation on some feathers, and they have a body length of 107–135 cm (Bird Life International 2017). Individual birds are therefore likely to show as several white pixels in the WordView-3 satellite imagery, given the 31-cm cell size (Fig. 2). The upper-wing surface also includes dark feathers, and so the size of the white dot is not necessarily much bigger in a bird with extended wings that is displaying on the ground, or a bird in flight.

Satellite image counts

As albatrosses were clearly evident as white dots in the satellite imagery, these were counted by eye on screen directly from the WorldView-3 image, in separate polygons of 200 × 200 m (roughly the area that fits within a single screen at the scale the birds were counted). Dots on the image were digitized manually in ArcMap 10.1 (Environmental Systems Resource Institute, Redlands, CA, USA). Due to the positional errors associated with a handheld GPS, and the distortion inherent in the orthorectified image, matching of individual nest locations recorded on the ground with those in the satellite imagery was not possible on a one-to-one basis, and therefore our main comparisons were of total counts of Wandering Albatrosses on Bird Island.

Previous studies have found that oblique aerial photographic surveys provide an effective means of counting various species of albatrosses in remote locations (Robertson *et al.* 2008, Wolfaardt & Phillips 2013). In a comparison of different techniques, Robertson *et al.* (2008) found that aerial photography identified more of the nesting birds than other methods (yacht-based photography, ground counts, quadrat sampling and point-distance sampling), and that there was minimal variance (0.28%) between duplicate counts. Super-high resolution satellite imagery provides a similar resource to aerial photography, but has a coarser resolution, and we found that the variance among counters was somewhat higher than from aerial photography (see Results). We therefore increased the number of counters of the digital satellite imagery to four, to understand better the variance between counters. However, the large coverage of satellite imagery has the advantage that stitching errors, a known source of error in aerial photography mosaics, are avoided.

RESULTS

Analysis of the oblique digital photography for non-breeding birds

The number of Wandering Albatrosses counted in hand-held digital photographs exceeded those in the ground counts of nests in the same areas at Bird Island by 0.4% to 58.3%, or 11.1% overall, based on mean values in areas counted twice (Table 1). The greatest discrepancy (58.3%) was for the area with the fewest nests and the highest proportion of non-breeders. We assumed counts of AOSs from a satellite image to over-estimate the overall number of nests by 11.1%.

Manual counts of Wandering Albatrosses at Bird Island from satellite imagery

The four observers counted 935, 910, 871 and 862 AOSs of Wandering Albatrosses at Bird Island in the satellite image taken on 10 January 2015. The mean value of these figures is 894.5, with a coefficient of variation (sd/mean) of 3.8%. The mean figure of 894.5 from the satellite survey is 18.6% higher than for the 754 nests in which eggs were laid, and 20.1% higher than for the 745 nests active on that date (nine nests had failed by 10 January, the date on which the satellite image was taken). The over-estimates are due largely to the presence of non-breeders, flying birds and errors of commission where features such as rocks or light substrate were assumed to be birds. Based on the oblique digital photographs, the expected number of individuals in the satellite image was $754 \times 1.111 = 837.7$ birds, which is 6.5% lower than the number of AOSs counted from the satellite image.

The variance between manual counts of satellite images by different observers showed some geographical consistency in terms of errors of commission; 88.5% of points counted > 15 m from a GPS nest location were identified by more than one of the four counters, suggesting that although there was no nest at these locations, a bird or bird-like object was present in the satellite image. On Bird Island the availability of a high-resolution DEM facilitated the investigation of outliers in terms of slope. Most (96.2%) of the GPS recorded nests were on slopes of less than 20°, indicating that Wandering Albatross do not breed on ground steeper than this. However, 13.4% of the outliers > 15 m away from GPS nest locations were on slopes over 20°; it is unlikely that these points were birds on the ground. This value increased to 40% of the objects where only one counter had identified a white dot > 15 m from the GPS nests. Rocks were also sometimes mistaken for birds, and there were also differences among the four analysts in the threshold size at which white dots were assumed to be birds. Although it was impossible exactly to match individual AOSs from the satellite survey with those on the ground, we compared the numbers in each 200-m cell (used to aid the counting procedure). Results indicated that the number of birds counted in each cell in the satellite image (AOSs) was closely correlated ($r = 0.994$, $n = 27$, $P < 0.001$) with the number of nests counted on the ground. In most cases (23 of the 27 cells that contained albatrosses), the count from the satellite image exceeded the ground count.

Manual counts of Northern Royal Albatrosses at the Chatham Islands

Due to resource constraints, one experienced image analyst whose count at Bird Island was closest to the mean of the four counters undertook the analysis of the Chatham Island imagery. Overall, counting at this site was considered to be slightly more difficult than at Bird Island, especially in areas where vegetation was lacking.

Table 1. Comparison of counts of Wandering Albatrosses in digital photographs of nesting areas at Bird Island with the number of nest-sites recorded during previous ground-based surveys.

Photo	Date	Count 1	Count 2	Mean	Ground-truthed nests	Percentage error
DSC_0107	15 January 2015	43	48	45.5	38	+19.7%
DSC_0181	15 January 2015	120	121	120.5	113	+6.6%
DSC_0182	15 January 2015	118	115	116.5	116	+0.43
DSC_4473	14 February 2015	45	50	47.5	30	+58.3%
Total		326	334	330	297	+11.1%

Table 2. Comparison of satellite and aerial counts* in 2016, 2015 and 2009 for the three breeding locations of Northern Royal Albatrosses in the Chatham Islands.

Island	Brood-guard, February 2016	Mid-incubation, 29 December 2015	Early incubation, November 2009*
Forty-Fours	2632	n.a.	2692
Big Sister	553	1096	1893
Little Sister	429	709	1159

Based on manual counts of the satellite images taken from 29 December 2015, there were 1096 and 709 AOSs, respectively, on Big Sister and Little Sister (Table 2). Manual counts of the satellite image from mid-February 2016 indicated considerably lower numbers of AOSs; 553 and 429 on Big Sister and Little Sister, respectively (Table 2). The count of 2632 AOSs on the Forty-Fours in February 2016 is very similar to the total count of 2692 from the aerial photographs taken there on 4–9 December 2009, so it can be assumed that breeding success on the Forty-Fours was much higher in this year than on the Sisters. The numbers of AOSs at the Sisters in the 2015/2016 season, particularly those from February 2016, were lower than those in the previous aerial survey in 2009, suggesting breeding numbers and/or breeding success was particularly poor in 2015/2016 (Table 2).

DISCUSSION

Accuracy of satellite remote-sensing of great albatrosses

The count of apparently occupied sites from the WorldView-3 satellite imagery of Bird Island provided a reasonable match with the number of Wandering Albatross nests in which eggs were laid, based on ground counts; the 20.1% over-estimate in the difference between satellite counts and ground observations could be explained largely by the presence of non-breeders. Based on the oblique digital photographs, the expected number of individuals in the satellite image was $754 \times 1.111 = 837.7$ birds, which is 6.5% lower than the number of AOSs counted from the satellite image.

At Bird Island, counts of AOSs from satellite images and photographs were higher than the number of nesting adults. Nesting Wandering Albatrosses are very conspicuous to ground counters and in oblique photographs, and by those dates all areas of the island had been visited several times; moreover, the topography of the island is such that few, if any, active nests would have been missed. We consider that the ground counts were accurate and that the satellite count did not include undiscovered nests at this site. Based on data from surveys in an area that is monitored daily, all pairs had laid by the time the satellite image was taken. Hence, we conclude that the discrepancy between the counts is related to the proportion of non-breeding birds visiting the island and a smaller number of errors of commission that could be rocks or flying birds. Non-breeders are mainly pre-breeding or deferring breeders, as few nests (nine of 754; 1.2%) had failed by the date of the satellite image, and members of those pairs are as likely to have been at sea as they were to have been present on the island. This level of nest failure is well within the variance of the satellite-based counts and hence adds only marginal error to the population estimate. From the analysis of the oblique photographs taken in early to mid-incubation, the percentage of non-breeding birds varied among areas, but determining whether this was due to time of day, date, habitat type or other factors (e.g. attractiveness of each area to pre-breeders) would require collection and analysis of a larger dataset. Hence, we would urge caution before using the ratio of non-breeders to breeders recorded in this study to correct counts of Wandering Albatross or other species of great albatrosses at other sites.

In theory, some errors of commission could have resulted from the presence of other bird species in the same areas, particularly other albatrosses, Giant Petrels *Macronectes* spp. or Brown Skuas *Stercorarius lonnbergi*. However, the three other albatross species (*Thalassarche* spp. or *Phoebetria* sp.), skuas and the dominant (dark) colour morph of Giant Petrels at Bird Island are smaller and present a much darker upper surface; moreover, the other albatrosses are largely colonial and nest in much steeper terrain. Potential confusion is therefore likely only with the light colour morph of the Southern Giant Petrel *Macronectes giganteus*; however, this morph is very uncommon at Bird Island (four breeding and one non-breeding individual in 2004/2005 over the whole island; R. Phillips unpubl. data) and so the implications would be minor. The close correlation of satellite estimates from 30-cm resolution imagery to ground observation may herald a new era in the remote monitoring of individual birds, with potentially important applications for management and conservation.

Population trends and conservation of the Northern Royal Albatross

Comparison of the WorldView-3 satellite images obtained from February 2016 with results of previous aerial surveys in 2009 indicates similar numbers of pairs of Northern Royal Albatrosses breeding on the Forty-Fours in both of these years; in contrast, the results for the Sisters indicate substantial fewer birds present in 2016 than in 2009. There is no indication of a technical or other problem with the imagery. The image of the Sisters was of good quality, the birds were obvious and, moreover, there were considerable areas of flattish terrain with no AOSs on both the islands, unlike on the Forty-Fours, where almost all the available ground was occupied and nesting density was very high (Fig. 3).

The total of 982 birds on Big and Little Sister counted in February is only 32% of the previous count from aerial surveys of the two islands in December 2009 (Table 2). As at Bird Island, counts from both satellite imagery and aerial surveys at the Chatham Islands would have included non-breeding birds, so the number of active nests will be fewer than these totals. In addition, it is important to note that the images of the Chatham Islands were taken during different breeding phases, with those in February corresponding to the brood-guard period, which lasts for *c.* 4 weeks post-hatching in great albatrosses, during which time the parents take turns attending the chick (Tickell 1968). Relatively few failed breeders are still attending colonies by the time that chicks hatch at successful nests, at least in Wandering Albatrosses (British Antarctic Survey unpubl. data). However, differences in breeding stage *per se* would not explain the striking contrast between the apparently steep decline in counts on the Sisters over 6 years, and the stable population on the Forty-Fours.

The most likely explanation for the differences between the two Sisters and the Forty-Fours in apparent population trajectories or breeding success is provided by comparing the satellite-based counts of Northern Royal Albatrosses at the Sisters in February 2016 with those from the image acquired on 29 December 2015, a total of 52 days earlier, and from a previous aerial survey in November 2009 (Table 2). The image from 29 December 2015 corresponds to the mid-incubation period, and the numbers of AOSs were 57.9% and 61.2% of those counted in early incubation in November 2009. The December 2015 counts were much higher than those from February in the same season (these were just 29.2% and 37.1% of the numbers in November 2009). These counts provide a strong indication that failure rates from mid-incubation to the brood-guard period at the Sisters were considerably higher compared with those in great albatrosses at other sites, including the closely related Southern Royal

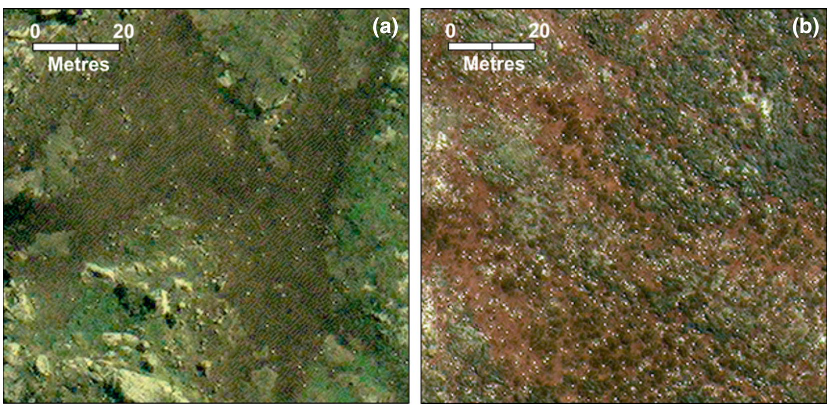


Figure 3. WorldView-3 satellite image snapshots of the Chatham Islands from February 2016 showing white dots assumed to be Northern Royal Albatrosses. (a) A typical area on Little Sister and (b) a typical area on the Forty-Fours; note the difference in densities of birds.

Albatross *Diomedea epomophora* (Croxall *et al.* 1992, Waugh *et al.* 1997).

Poor breeding success, if sustained, will ultimately have a major impact on breeding numbers of Northern Royal Albatrosses at the Sisters. Indeed, high levels of breeding failure of this species throughout the Chatham Islands were linked to a cyclonic storm in 1985 (Robertson 1998); this reduced soil cover and destroyed most of the vegetation, and breeding success was only 18% from 1990 to 1996. Although the vegetation recovered gradually, and breeding success improved, there was an estimated 50–60% reduction in productivity over a 20-year period from 1985 to 2005 (Bird Life International 2017). Vegetation is needed for nest building and cushioning of eggs and young chicks. Incubating great albatrosses remove the vegetation from the area surrounding the nest and incorporate it into the nest mound, which renders the nest easily visible from above. Lack of vegetation around nests following the cyclones in the 1980s led to egg breakage, high temperatures and flooding (Robertson 2003). Although vegetation cover on the islands was considered to have improved by the late 1990s (Robertson 2003), our results indicate that breeding success is still considerably lower than before the storm. Values of the normalized difference vegetation index (NDVI) from Landsat data indicate that vegetation cover is good on the Forty-Fours, but still very poor on the Sisters (authors' unpubl. data). This fits well with our results, which indicated that the number of Royal Albatrosses on the Forty-Fours in February 2016 was similar to that in the 2009/2010 season, suggesting the population may be broadly stable, whereas numbers on the Sisters were much lower than in 2009/2010, suggesting high levels of egg or early chick failure.

The Northern Royal Albatross is long-lived, breeding for the first time at 8–10 years of age and with some adults still breeding aged > 50 years (Robertson 1993). Therefore, it will be many years before poor breeding success is reflected in the size of the adult population. Analysis in 2002 suggested that the number of breeding pairs may have remained relatively stable since the 1980s, in spite of the extensive reduction in productivity over a 20-year period (Robertson 2003). However, our data, collected over a decade later, indicate that low productivity is an issue at least in some years.

Wider applications

The approach used here to count great albatrosses using WorldView-3 satellite imagery has potential application to the other species in the genus (with the possible exceptions of Antipodean Albatross *Diomedea antipodensis* and Amsterdam Albatross *Diomedea amsterdamensis*, which have darker backs), and to other large (with a minimum body size of two pixels; 62 cm), surface-nesting seabirds or terrestrial birds with black or white plumage that contrasts with the surrounding substrate, including Short-tailed Albatross *Phoebastria albatrus*, gannets *Morus* spp., pelicans *Pelecanus* spp. and swans *Cygnus* spp., provided the nesting density is not too high for individuals to be resolved in the images. These species also have the advantage that they are colonial and the locality of nesting sites is often already known. For the satellite method to be the most economical available, these sites should be in remote areas that are difficult to access, otherwise conventional ground or aerial counts are likely to be cheaper and more effective. However, several of the species, particularly the great albatrosses, not only breed in remote locations, but are considered as threatened by IUCN and hence require regular monitoring for conservation purposes (Phillips *et al.* 2016). In these situations, WorldView-3, 30-cm imagery may be more cost-effective and safer than chartering aircraft or vessels, particularly given the vagaries of the weather. In many islands in the Southern Ocean, persistent cloud cover can be a problem for acquisition of satellite imagery. However, the incubation period of great albatrosses lasts several months, which will usually include a few cloud-free days. Acquisition of satellite data is also completely free of any type of disturbance that may be caused by drone, plane or ground surveys (Giese & Riddle 1999, Vas *et al.* 2015).

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archived in the NERC Polar Data Centre based at the British Antarctic Survey.

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