Influence of Geomorphology on Southern Giant Petrel Nest Site Selection and Chick Survival near Palmer Station, western Antarctic Peninsula

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Abstract

Acute human activities and climate change threaten seabirds globally, but bird populations in remote areas are difficult to monitor. Many breeding populations of southern giant petrels (Macronectes giganteus) exemplify this challenge, and limited monitoring shows variable population trends throughout their circumpolar range. Aerial remote sensing can overcome these difficulties and reveal how local environmental factors influence habitat suitability and availability for nest site selection and chick survival. We used drone photography to map giant petrel nests, monitor chick survival and quantify associated physical and biological characteristics of the landscape at two neighboring breeding sites on Humble Island and Elephant Rocks, along the western Antarctic Peninsula in January–March 2020. Nest sites occurred in areas with relatively high elevations, gentle slopes, and high wind exposure. Statistical models predicted suitable nest site locations based on geomorphology and proximity to seal wallows and penguin colonies, and explained 73% of deviance at these sites, suggesting that suitable habitat conditions may help predict undiscovered and future nest sites across local landscapes. These findings quantify important habitat associations that may constitute species preferences or sensitivities and may, in turn, contextualize some of the diverse population trajectories observed for this species throughout the changing Antarctic environment.

INTRODUCTION

Seabirds are the most threatened group of birds, at risk globally due to climate change and acute human stressors, such as fisheries and pollution (Croxall et al. 2012). The monitored portion of the global seabird population declined by almost 70% between 1950 and 2010 (Paleczny et al. 2015), and although some higher latitude populations were excluded, polar species are similarly threatened. The southern giant petrel (Macronectes giganteus) is a wide-ranging, long-lived member of the Procellariidae family, that breeds on subantarctic islands and at coastal sites around the Antarctic continent from ~ 40˚S to 68˚S (Croxall et al. 2012). Population trends vary widely across region, and populations appear to have decreased in some remote breeding localities (Miller 2005; Dunn et al. 2016); however, many breeding sites still have insufficient or inconsistent observations, obscuring current population trends and underscoring the need for long-term monitoring across inter- and intra-annual variability (Creuwels et al. 2005; Patterson et al. 2008; Wienecke et al. 2009). With their circumpolar range and patchy distribution of breeding habitats, a variety of factors may influence population trends, and a fine-scale understanding of nest site selection and chick survival rates could better inform occupancy patterns, aiding conservation efforts across different segments of the species’ range.

One common approach to monitoring seabird populations is to census breeding pairs at a site and estimate their reproductive success (Paleczny et al. 2015), as breeding success critically underwrites the population trends of seabirds. Only a few seabird species have precocial young, and most must invest much time and resources into raising their offspring (Schreiber and Burger 2001). Giant petrels typify this altricial reproductive strategy; parenting is energetically demanding, and both males and females participate in a 60-day incubation period (Marchant and Higgins 1990). Parents alternate between
periods of foraging and fasting while at the nest, and body reserves of both parents decrease during the breeding period (González-Solís et al. 2000). These energetic demands underscore the importance of potential nearby food sources and a protected nest area to enhance parental condition as well as reproductive success (De Bruyn et al. 2007). Giant petrels are both predators and scavengers, feeding mainly on forage species at sea and land-based food including penguin and seal feces and carcasses (González-Solís et al. 2000; Corá et al. 2020), live seabirds (Punta 1995; Le Bohec et al. 2003; Dilley et al. 2013) and fur seal (Arctocephalus gazella) pups near breeding sites (Nagel et al. 2022). In some locations, penguins comprise 50–80% of prey by mass in giant petrel diets (Hunter 1983; Ridoux 1994). Therefore, the recent decreases in Adélie (Pygoscelis adeliae) and chinstrap (P. antarctica) penguin populations due to regional warming and decreasing sea ice cover likely contribute to long-term decreases in southern giant petrel breeding populations in segments of their breeding range (Ryan et al. 2008; Dunn et al. 2016).

Their altricial reproductive strategy also makes giant petrel populations particularly vulnerable to long-term climatic and anthropogenic stressors (Gianuca et al. 2019), such as human disturbance, environmental pollution, plastic ingestion, predation by introduced animals, and loss of nesting habitat (Warham 1962; Conroy 1972; Phillips et al. 2016). Human activity near nesting sites induces both physiological and behavioral responses that can cause lower breeding success, and research bases can attract a high number of predators such as skuas or kelp gulls, which predate unattended eggs (Rootes 1988; Chupin 1997; Pfeiffer and Peter 2004; Krüger 2019). As carnivores that both predate and scavenge, adult southern giant petrels are likely buffered from acute local fluctuations in food and habitat availability by their diverse diet and vast foraging extents (Gianuca et al. 2019). Nevertheless climatic factors can mediate parental behavior and energetics through a variety of mechanisms: strong winds can improve flight efficiency, and warm temperatures can expand ice-free waters for foraging, increase availability of snow-free nesting sites, and increase mortality, and therefore carrion availability, of select prey species (Creuwels et al. 2005; Gianuca et al. 2019). Complex interactions of human activity, climatic conditions, and prey availability therefore influence the breeding success and long-term population trends of southern giant petrels. Amid the rapidly changing conditions of the western Antarctic Peninsula, efforts to study and monitor this species, and especially their breeding rates, are frustrated by their remote breeding locations and their sensitivity to human disturbance.

Emerging remote sensing technologies offer new methods of regular, comparable observations over breeding colonies in inaccessible or protected localities (Borrelle and Fletcher 2017; Edney and Wood 2021), achieving the dual objectives of increased monitoring and decreased human disturbance for sensitive species like southern giant petrels. Using commercially available drones, we mapped breeding giant petrel nests and examined potential geomorphological drivers that may influence nest site selection and chick survival. Seabirds tend to distribute their nests unevenly across a landscape, as they select for specific habitats or terrain features that are heterogeneously distributed across polar landscapes. The geomorphological characteristics of nesting habitat may contribute to differences in colony growth and size between sites, and likely affects chick survival and population dynamics (Cimino et al. 2019; Schmidt et al. 2021). Southern giant petrels generally nest in rocky areas (in Antarctica) or vegetated
areas (in the sub-Antarctic) where elevation, slope and aspect of nest sites influences local microclimatic conditions. For example, wetness and exposure to wind and sunlight can temper broader climatic conditions, such as air temperature and snow accumulation. As extreme snowfall appears to negatively affect breeding success, breeding pairs tend to nest largely in snow-free areas (Schulz et al. 2014; Dunn et al. 2016). Selection of protected nest sites may be important, as low temperatures and wind gusts can expose unattended chicks to inclement weather. Unusually severe weather—including low sea surface temperature, high ice cover, high wind speeds, and heavy snowfall—has also been associated with a high incidence of reproductive failure among tagged individuals (Schulz et al. 2014).

We investigated habitat attributes of nests at two neighboring sites near Palmer Station on the western Antarctic Peninsula: Humble Island and Elephant Rocks (< 1 km apart, Fig. 1), where southern giant petrels co-occur with Antarctic fur seals, southern elephant seals (Mirounga leonina) and Adélie penguins. Elephant Rocks hosts a breeding colony of southern elephant seals during the austral spring and molting Antarctic fur seals during the austral fall, while Humble Island is home to a colony of Adélie penguins during spring–summer, scattered fur seals, and non-breeding wallows of elephant seals. These species are present throughout the giant petrel breeding cycle (Nov.–May), and periodically visit the sites throughout the winter (Holdgate 1962). The southern giant petrel population near Palmer Station has increased from the 1970s to 2008, but trends have not been described more recently (Parmelee and Parmelee 1987; Patterson et al. 2008).

Using orthomosaics and digital surface models (DSMs) generated from aerial drone surveys flown in January–March, 2020 (conventionally described as summer 2019/2020), we identified and characterized southern giant petrel nest sites by their geomorphological attributes (elevation, aspect, slope, wind shelter, topographic wetness index) and the proximity to megafauna (penguin colonies and seal aggregations) that represent potential terrestrial food resources. We also estimated reproductive success based on temporal changes in the presence or absence of chicks at their nest sites in orthomosaic imagery. These fine-scale remote sensing techniques can track changes in land cover and habitat suitability, nest sites and reproductive success over time at high spatiotemporal resolutions, and provide a new valuable tool set for estimating and contextualizing the reproductive dynamics of seabird populations with minimal human effort and disturbance to the birds (LaRue et al. 2014).

METHODS AND MATERIALS

Drone surveys and ground-truthing

We surveyed southern giant petrel nests on Elephant Rocks (64°44’S, 64°4’W) and Humble Island (64°44’S, 64°5’W) from January to March 2020 (Fig. 1). Humble Island covers 0.094 km² with highly variable terrain, whereas Elephant Rocks is smaller (0.034 km²), and comprises low-lying beaches and discrete rocky features. Drone surveys were flown over Elephant Rocks on 14 January, 12 February, 21 and 28 February, 2, 7, 17 and 23 March in 2020; surveys were flown over Humble Island on 15 and 30 January, 22 February, and 3, 17 and 21 March in 2020 (Fig. 1). Surveys were flown using a DJI Phantom 4.
Pro drone with a default camera payload. This multicopter aircraft has been used for a combined >100 scientific flights over land near Palmer Station without any observed disturbance to ground-nesting avifauna during drone operations. The drone was launched and recovered from boats or landing sites away from wildlife to minimize disturbance during low-altitude flight. The drone system surveyed from 55 to 110 m altitude within visual line of sight of the operator, collecting spectrally uncalibrated color imagery at 1–3 cm pixel\(^{-1}\) ground sample distance (GSD) along parallel transects. All surveys included at least one flight collecting imagery at 1-cm GSD (55 m altitude) to achieve sufficient detail to identify wildlife, with sufficient overlap between adjacent photographs such that all ground features could be collocated in two or more photographs; a subset of surveys also included a flight collecting imagery at 3-cm GSD (110 m altitude) with higher overlap to facilitate three-dimensional terrain modeling using structure-from-motion techniques. These surveys were sometimes complemented with oblique photography to achieve a variety of perspectives for the structure-from-motion techniques. In addition, both islands were ground-truthed with a survey-grade GPS system (Trimble R7, Sunnyvale, California, with a Zephyr Geodetic Base L1/L2 Antenna, part number 41249-00), using differential corrections from the adjacent PAL2 base station (Johns 2006). Ground truth surveys used a system of semi-permanent natural features as ground control points (GCPs), such as boulders, peaks, and cracks in bedrock that could be located precisely in drone imagery. Drone imagery was then processed into orthomosaic and DSM products using a standard photogrammetric workflow with ground control points in Pix4D Mapper version 4.6.4. All drone surveys were conducted under Antarctic Conservation Act permit ACA 2020-016 and NOAA permit 14809-03.

**Nest site geomorphology from drone imagery**

For Humble Island and Elephant Rocks, we selected a high-quality DSM based on visual inspection to ensure realistic values and excluded any obvious errors. We downsampled each DSM product to 0.2 m GSD using bilinear interpolation in ArcGIS (ESRI ArcGIS Desktop v10.5.1 and 10.7.1); this scale was relevant to the estimated nest size of giant petrels (~0.7 m in diameter). We describe all elevation data relative to the EGM96 geoid, which corresponds to a mean sea level of -1.129 m and a highest high-tide line of -0.31 m, based on tide-gauge measurements collected at Palmer Station between 2018 and 2020 (Antarctic Meteorological Research and Data Center, United States Antarctic Program unpublished data). We excluded all terrain below the highest high-tide line from analysis. From the resulting DSMs, we generated eight raster products describing geomorphological habitat attributes that may influence giant petrel nesting habitat: elevation, slope, aspect, topographic wetness index (a terrain-derived proxy of soil moisture), visible sky (a measure of terrain openness), sky view factor (a measure of terrain openness), wind exposition index (a measure of topographic exposure to winds from all directions) and wind shelter index (a measure of topographic exposure to winds from a defined direction). Wind shelter indices were generated for each year relative to the prevailing wind direction during the study period. Elevation was extracted from the downsampled DSM, while aspect and slope were calculated using their respective tools in ArcGIS. All other variables—wind shelter index, wind exposition index, topographic wetness index, visible sky, and sky view factor—were calculated using their respective tools from System for Automated Geoscientific Analyses (SAGA) 8.2.1 (Conrad et al. 2015). These selected variables are expected to
mediate or estimate direct exposure to snowfall, snowmelt, wind, or extreme temperatures, among other factors that might influence a site’s suitability for nesting. Slope might also influence nest stability and drainage.

We estimated the prevailing wind direction for the period of January–March 2020 using measurements from the automated weather station at Palmer Station (Lazzara et al. 2012) located < 2.5 km away from each site; from these data, we generated wind-rose diagrams and determined mean and standard deviation in prevailing directions of 7.5 ± 30° for the study period. The mean and spread were used as input parameters to calculate wind shelter index across both sites, and both wind exposition index and wind shelter index were calculated using a neighborhood radius of 10 m.

**Nest activity and chick survival from drone imagery**

We examined drone imagery at full resolution of 1.5–3 cm pixel$^{-1}$ GSD to visually identify giant petrel nest sites, nearby penguin colonies and wallows of elephant seals. We considered giant petrel nests to be active if they contained incubating adults or chicks during any of the surveys. Inactive nests were omitted from the analysis; notably, this excluded nests that may have been attended and abandoned before the first drone survey of each year. If a chick was present in at least one survey from the early chick-rearing phase (January–February) and once more in March, it was considered to have survived to May (fledging). Our survival metric is qualified to the observation period, which ended in March, even though chicks typically fledge in May. Previous observations suggest that most nest failure occurs during the egg laying and incubation period due to desertion, infertility, or egg cracking, and during the early guard period, when newly hatched chicks die from starvation or exposure (Cimino unpublished, Hunter 1984). Older, feathered chicks had a survival rate over 90%, which contextualizes our estimates of breeding success to be likely much higher than estimates that include the entire egg laying and incubation periods (Chupin 1997).

Elephant seal wallows were identified by the presence of mud and a dark brown staining where three or more elephant seals were present during more than one survey. Penguin colonies were identified by the presence of guano with a reddish-brown staining in two surveys from mid-January (14–22 January). Wallows and colony areas were used consistently by seals and penguins, respectively, throughout the observation period and are relatively conserved between years. Wallows and colony areas were delineated on maps as hand-drawn convex polygons, and the two generally occurred in close proximity, so we combined both feature types to create a map of distance to nearest megafauna or potential food resource. Elephant rocks did not include a persistent wallow or penguin colony during the mid-summer months, so we calculated distances to the nearest wallows or colonies on the adjacent islands, Humble and Torgersen islands.

**Statistical analyses**

We statistically compared and modeled how geomorphology and proximity to food sources may influence nest site selection in giant petrels. Active nest sites were identified from drone imagery, whereas absence locations consisted of 100 background points randomly generated across each site (total $n =$...
above the highest high-tide line and at least 1 m away from the center of any nest site. We extracted
gemorphological attributes for each active and background nest site from the raster datasets and
calculated distance to megafauna. We checked these variables for collinearity across both islands, and
variables with Pearson correlation coefficients > 0.5 were removed from subsequent analysis to reduce
redundant comparisons and model overfitting. For example, slope was collinear with sky view factor ($r = -0.79$),
visible sky ($r = -0.68$) and topographic wetness index ($r = -0.50$), all of which we excluded from
subsequent analysis, retaining only slope as the simpler variable and most parsimonious solution. We
therefore used the explanatory variables of elevation, slope, aspect, wind exposition index, wind shelter
index, and distance to megafauna. Descriptive values are reported as mean ± standard deviation for all
attributes except aspect, which is reported as µ, κ parameters from a maximum likelihood estimation of a
von Mises wrapped normal distribution for circular data, where κ is a measure of concentration around
angle µ, and κ = 0 describes a uniform distribution of values (Jammalamadaka 2001).

We tested for differences between (1) the characteristics of all active nest sites (successful and failed)
and those of background data, pooled across sites, (2) the characteristics of active nest sites at Humble
Island and those at Elephant Rocks, and (3) the characteristics of active nest sites that were successful
and those of failed nests, pooled across sites. We pooled data across both islands for all comparisons of
means except those that explicitly and only tested the difference between islands. All comparisons of
means consisted of independent samples $t$ tests if groups showed equal variance, or Welch's two-sample
$t$ test if they did not, and we used $\alpha = 0.05$ with Bonferroni corrections for multiple comparisons. We used
Watson's goodness of fit tests to determine whether samples of aspect data could be parameterized with
a von Mises distribution or described as a uniform circular distribution (the null hypothesis), and we
compared between samples of aspect data using Watson's two-sample test of homogeneity. All
descriptive and comparative statistics for aspect were calculated using the "CircStats" package in R
(Jammalamadaka 2001).

We used generalized additive models (GAMs) in the “mgcv” package in R (Cimino et al. 2019; Pedersen et
al. 2019) to model the probability of nest occurrence in response to habitat predictors. GAMs used the
following structure:

$$
\logit (p) = c + f_1 (x_1) + f_2 (x_2)
$$

where $p$ is a probability parameter denoting a binary outcome of either 1, representing nest occurrence, or
0, representing nest absence; $c$ represents an estimated constant and $x_i$ represents habitat predictor
variables modified by smoothing functions $f_i$. GAMs modeled variable relationships nonlinearly using
thin-plate regression splines and smooths, except for aspect which was modeled using a cyclic cubic
smoothing spline to account for its circular data type. Site was included as a categorical fixed effect,
considering that the two islands likely differed in many ways not described by modeled variables, and
smooths were selected by maximum likelihood.
For each candidate model containing the suite of predictor variables, all possible combinations of predictors were fit using *dredge* within the "MuMIn" package in R (Barton 2009). We selected models that explained the most variation using the Akaike information criterion for small sample size ($\text{AIC}_c$). We report all models with a $\Delta\text{AIC}_c < 2$ from the model with lowest $\text{AIC}_c$ (i.e., had substantial support), and we report percentage of deviance explained, adjusted $R^2$ and Akaike weight supporting model performance. For each model, we plotted the partial effect of each explanatory variable to visually confirm that all reported models predicted the same relationship between the response and explanatory variable, and no model assumptions were violated.

RESULTS

Identification and distribution of giant petrel nests and chick survival

We identified active giant petrel nests at both Humble Island and Elephant Rocks in survey imagery (Fig. 2). Giant petrels nested in small, scattered groups on each island; only a few individuals nested alone and away from the colony periphery. Active and abandoned nest sites were on rocky terrain and each nest was encircled by excrement, suggesting repeated usage (Fig. 3). Adults were observed on nest sites during January, and chicks were present by February at latest, often accompanied by nearby adults. Chicks were visible in surveys through March, and anecdotally, coarse growth and changes in feather color were evident in imagery at these resolutions of 1.5–3 cm pixel$^{-1}$ GSD. We were able to distinguish between the presence and absence of chicks at or near nest sites, enabling coarse survival estimation (Fig. 3, 4). On occasion, we observed that chicks wandered a short distance away from the nest, but this was rare at this early part of the season.

On Humble Island in 2020, 52 nests were active in mid-January (first survey), and 41 (79%) chicks survived until mid–late-March (last survey). At Elephant Rocks, 26 (~ 76%) of 34 nests were successful (Fig. 2). Chick survival rate was therefore similar between sites.

Study site and nest site characteristics

Geomorphological characteristics differed between the two sites (Fig. 5). Elevation is notably different between the two islands, spanning up to 16 m on Humble Island, whereas Elephant Rocks is mostly flat, with a highest point of 6 m. Additionally, many of the beaches of Elephant Rocks were excluded from habitat analysis because they fall below the highest high-tide line. Both locations feature some rugged terrain with steep slopes and complex geomorphology (Fig. 5); both also include lower elevation areas that are prone to wetness, and flat regions that are exposed to prevailing winds.

We determined significant differences between active nest sites and background habitat based on terrain characteristics (Fig. 6) and proximity to colonies of penguins and wallows of seals. The aspects of active
nest sites showed significantly nonuniform directionality ($U^2 = 0.21, 0.25 < p < 0.05$) away from northwestern slopes (146°, 0.4), but was not significantly different that of background sites throughout available habitat ($U^2 = 0.18, 0.05 < p < 0.10$). The aspects of nests on Humble Island (158°, 0.13) and nests on Elephant Rocks (143°, 0.07) were not significantly different ($U^2 = 0.10, p > 0.10$), but those of successful nests (140, 0.6) and unsuccessful nests (298, 0.3) did differ significantly ($U^2 = 0.19, 0.01 < p < 0.05$).

Giant petrels nested at significantly higher elevations than background locations in available habitat ($t_{126.83} = 6.87, p < 0.01$), and at significantly gentler slopes ($t_{246.46} = -9.64, p < 0.01$) and higher exposure to winds ($t_{250.06} = 8.5542, p < 0.01$) than background habitat locations (Fig. 7). The topography of nests on Humble Island differed significantly from nests on Elephant Rocks with respect to elevation ($t_{228.06} = 14.91, p < 0.01$), slope ($t_{244.06} = 2.98, p < 0.01$), Wind Shelter Index ($t_{210.87} = 3.77, p < 0.01$), and distance to megafauna ($t_{284} = -28.30, p < 0.01$), and only the Wind Exposition Index values of nests did not differ significantly between islands ($t_{284} = -1.40, p = 0.16$) among tested habitat variables (Fig. 8). The slopes at successful nests (7.48 ± 3.90°) were slightly higher than those of unsuccessful nests (4.40 ± 2.76°) and this difference, though small, was significant ($t_{40.70} = 3.89, p < 0.01$); but other measured habitat attributes did not differ significantly between successful and unsuccessful nest sites ($p > 0.05$, all; Fig. 9).

**Models of giant petrel nest site occurrence**

GAMs described the relationships between active giant petrel nest sites and geomorphological and biological characteristics across the two study sites. Selected models had a $\Delta$AICc < 2 relative to the model with lowest AICc and retained most candidate variables (Table 1). Consistent explanatory variables were elevation, slope, wind exposition index, wind shelter index, and distance to megafauna. The models performed well in terms of explaining deviances using a combination of explanatory variables (deviance explained = 73%).
Table 1
Attributes of GAMs describing the probability of occurrence (presence vs. absence) of giant petrel nests in 2020 as a function of geomorphological attributes and distance to megafauna. Models 1–3 represent the best performing models with a $\Delta AIC_c < 2$, followed by the full candidate model. Models are described by $R^2$, deviance explained, degrees of freedom (df), $AIC_c$, difference from lowest $AIC_c$ and Akaike weight.

<table>
<thead>
<tr>
<th>Variables</th>
<th>$R^2$</th>
<th>Deviance explained</th>
<th>df</th>
<th>$AIC_c$</th>
<th>$\Delta AIC_c$</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1 elevation, slope, wind exposure index, wind shelter index, distance to megafauna</td>
<td>0.77</td>
<td>73.0%</td>
<td>12</td>
<td>120.9</td>
<td>0.00</td>
<td>0.49</td>
</tr>
<tr>
<td>Model 2 aspect, elevation, slope, wind exposure index, wind shelter index, distance to megafauna</td>
<td>0.77</td>
<td>73.0%</td>
<td>12</td>
<td>121.9</td>
<td>0.99</td>
<td>0.3</td>
</tr>
<tr>
<td>Model 3 elevation, slope, wind exposure index, wind shelter index, distance to megafauna, site</td>
<td>0.77</td>
<td>73.0%</td>
<td>13</td>
<td>122.6</td>
<td>1.71</td>
<td>0.21</td>
</tr>
<tr>
<td>Full candidate model aspect, elevation, slope, wind exposure index, wind shelter index, distance to megafauna, site</td>
<td>0.77</td>
<td>73.0%</td>
<td>13</td>
<td>123.8</td>
<td>2.91</td>
<td>0.10</td>
</tr>
</tbody>
</table>

All models described similar relationships between habitat and nest sites, yielding visually identical plots of partial effects among models (Fig. 10). Models describe a unimodal prevalence of nest sites at higher elevations, lower slopes, and higher wind exposure relative to unoccupied background habitat locations. There was a bimodal tendency to nest near or far from penguins and seals, reflecting that nest sites were located near penguins and seals (<100 m) at Humble Island or at a farther distance (>300 m) at Elephant Rocks. Wind shelter index contributed little to the probability of nest site selection.

Using “Model 1” for nest occurrence (Table 1, Fig. 10) with raster products describing spatial attributes of potential habitat above the highest high tide line (Fig. 5) we predicted habitat suitability for nest sites on Humble Island and Elephant Rocks (Fig. 11). High elevation regions (e.g., ridges) at both islands were some of the most suitable habitats (Fig. 5, 11), which generally aligned with the active nest sites that informed the model (Fig. 2).

**DISCUSSION**

Drones and drone-derived imagery are increasingly used to monitor seabird populations (Rush et al. 2018), but such applications are commonly limited to a single targeted survey window. This study leveraged the low logistical cost of drone operations to achieve surveillance of focal sites to determine the reproductive success of southern giant petrels and quantify the spatial attributes of active and successful nests. The achievement of these objectives from drone surveillance represents a novel advancement in ornithological methods, requiring minimal human effort and on-site presence (1 drone...
operator for both islands and, for Humble Island, an additional boat operator), little time (approximately 30–80 min per survey), and no observed disturbance.

Ground counts of giant petrel nests and chicks require periodic visits, which can potentially disturb resident birds and can vary in consistency across different research teams, census timing and survey protocols (Fudala and Bialik 2022). Giant petrels are vulnerable to anthropogenic disturbance, as previous findings showed decreases in breeding populations near research stations, and individuals will regurgitate food or abandon nests in response to threats (Chupin 1997; Pfeiffer and Peter 2004; Agreement on the Conservation of Albatross and Petrels 2010). While human disturbance is not readily evident at our focal study sites near Palmer Station, it has contributed to decreased breeding activities or a higher rate of egg loss at other sites (Chupin 1997; Pfeiffer and Peter 2004; Patterson et al. 2008; Agreement on the Conservation of Albatross and Petrels 2010; Krüger 2019). The ability to monitor sensitive populations through remote sensing techniques could therefore address the conservation dilemma of monitoring giant petrels and other seabirds that are sensitive to terrestrial disturbance and breed in open habitats. Although drones are potentially less invasive than data collection at ground level, they do entail other risks of disturbance (Borrelle and Fletcher 2017). For example, drones can disturb wildlife with their acoustic or visual profiles, incurring physiological stress and behavioral changes (Fudala and Bialik 2022). Such potential disturbances can often be modulated by the choice of aircraft, flight planning (including speed and altitude), and situational awareness, depending on a study's objectives and limitations (Borrelle and Fletcher 2017; Raoult et al. 2020; Bishop et al. 2022), although more time is needed to discern possible effects of chronic exposure to drone stimuli.

The spatial and temporal resolutions of our remote sensing approach also allowed us qualitatively visualize chick development, as the growth and changes in feather color were evident albeit not measured over time, and the spatial distribution of observed nest sites illustrated how most birds tend to nest in groups with only a few dispersed nests (Fig. 2). This study was limited by the short time periods during which data were collected—data collection concluded in March, even though chicks had not left their nests at that time. These data were collected as part of an exploratory survey protocol, and future dedicated efforts should align to the phenology of the target species. In the case of southern giant petrels, to achieve more accurate chick survival rates, nests should be monitored from the approximate period of egg hatching until chicks fledge in May (Chupin 1997; De Bruyn et al. 2007). Small chicks are often not visible when they are brooded by their parents, but early nest monitoring can still provide information on parental exchanges or nest failure, as parents sometimes abandon nests after egg or chick loss. Such surveys would also need to account for the occurrence of non-breeders or failed breeders that occasionally occupy nest sites and can be mistaken for breeders during the incubation phase—complementary ground surveys can verify the presence of eggs or small chicks under presumed breeders. At a population scale, regular monitoring can describe key phenological events as they persist or shift alongside the transforming climate and ecosystem of the western Antarctic Peninsula.

**Drivers of nest occurrence**
Habitat surveillance indicated that southern giant petrels prefer to nest on relatively elevated terrain with gentle slopes and relatively high wind exposure at Humble Island and Elephant Rocks. Comparisons of means and GAMs of nest occurrence described how combinations of these factors likely influence nesting site selection. Both high elevation (6.32±3.70 m compared to 3.27±2.74 m background habitat) and high wind exposure (1.06±0.03 compared to 1.02±0.05 background habitat) may facilitate take-off for adults and fledging chicks when they depart the nest (Clay et al. 2020), and high elevation also removes nest sites from potential disturbance by penguins and elephant seals as they transit to and from colonies and wallows, respectively. The gentle slopes (6.80±3.88° compared to 18.43±16.00° background habitat) also likely decrease the risk of eggs or chicks falling from the nest, though notably some slight slope was associated with more successful nests, possibly indicating the importance of drainage in the wet climate of maritime Antarctica, especially along the western Antarctic Peninsula. Overall, these results suggest that higher elevation ridgetops are favorable, with their increased exposure to wind and superior drainage.

The distance to penguins and seals was not a significant predictor of nest occurrence or nest success in comparisons of means and yielded a relatively complex bimodal relationship in its marginal effect from GAMs. This likely reflects the difference in availability on the two islands, with Humble Island hosting penguin colonies and seal wallows, and Elephant Rocks merely situated between neighboring aggregations on Humble Island and Torgersen Island; generally, we found that nests were generally either close to megafauna (<200 m) when colonies and wallows were present on the island, or at a greater distance (>350 m) when they were absent from the immediate island but present nearby. These findings, together, suggest that distance from these aggregations does not exert a consistent effect on nest site selection or success within the bounds of this study.

Carrion can be an important food source for southern giant petrels in seasons and locales where it is available, and southern giant petrels often associate with regions occupied by penguins and pinnipeds (Copello et al. 2011). Carrion availability appears to promote higher fledgling production (Patterson et al. 2008), and represents a convenient energy source to breeding adults, especially during chick-rearing, when adults may fast up to 15 d (Corá et al. 2020). Amid a largely pelagic diet, the proximity of land-based food sources, when available, allows birds to return to the nest more frequently for feedings and spend more time attending to the chick (De Bruyn et al. 2007). On Marion Island, breeding success of northern giant petrels (M. halli) has been positively correlated with the abundance of rockhopper penguins (Eudyptes chrysocome) and the number of southern elephant seal pups; southern giant petrel breeding success was positively correlated with the number of king penguin (Aptenodytes patagonica) chicks, though not with population parameters of the elephant seal population (De Bruyn et al. 2007). The timing of breeding cycles of potential prey influences whether seal placentas or young penguins are available to scavengers and predators, so nearby megafauna provides the maximum benefit to nearby nest sites only if carrion availability aligns with the chick-rearing period. Coprophagia has also been observed by southern giant petrels visiting pinniped aggregations during their reproductive fasting periods (Corá et al. 2020), highlighting the additional dietary contributions of nearby terrestrial megafauna. The absence of a discernible relationship between nests and megafauna on Humble Island
and Elephant Rocks in our analysis could be attributed multiple factors, including the relatively small size of these aggregations compared to other sites, or the scale of distances that we considered, recognizing that pelagic foraging trips of this species regularly span hundreds of kilometers (González-Solís et al. 2000, 2002; Copello et al. 2011; Finger et al. 2023).

In addition to the potential benefits of nearby seals and penguins, some megafauna, particularly fur seals, likely act as a physical deterrent to some potential sites, posing a risk of frequent disturbance or trampling near breeding and haul-out habitats. Southern giant petrels may balance this risk of disturbance against food availability at close sites, or simply select nest sites that are further removed from the risk of disturbance by distance or elevation. The different species at Humble Island often occupy different habitats: elephant seal wallows occur at lower elevations, penguins tend to nest at middle elevations, and southern giant petrels generally preferred higher elevations than either elephant seals or penguins. Given the close horizontal distance between some giant petrel nests and seal wallows in some locations on Humble Island (Fig. 8), elevation might drive habitat partitioning more than horizontal distance. Based on risk of disturbance or damage, it is likely that petrels select sites that preferentially do not intersect the movement of penguins and seals, rather than prioritizing proximity to potential food sources on land.

Given that habitat models performed well and explained ~ 70% of deviance in active nesting sites, we suggest that this technique can be used to understand the geomorphological and biotic preferences of the southern giant petrel in other regions, and to contextualize possible future shifts in abundance or nesting habitat as Antarctic environments change. Habitat prediction from statistical models incorporating remote sensing data could even suggest sites of potential occupancy where colonies currently do not exist. Climate shifts, changing weather patterns, and glacial retreat can all shift the intensity and direction of prevailing winds, the ground temperature, and the accumulation of snow or pooled water, even at a geomorphologically stable location. As nest site selection was positively influenced by wind variables in our study (Figs. 7 and 10), nesting locations could be abandoned by birds in search of optimally exposed areas in the future.

**Drivers of chick survival**

We found that a large proportion of nests, first identified in January, remained successful through March, yielding limited information on the drivers of success and failure. We lacked significant information on non-local determinants of breeding success, such as parental foraging success or nest attendance, which can significantly contribute to breeding success or failure across developmental stages. We can therefore only speculate on the effects of environmental characteristics on chick survival based on our limited analysis. Chick survival was higher among nests with slightly steeper slopes, even though nests generally occupied sites with low slopes compared to background terrain (Fig. 9), which suggests that, even among preferred nesting conditions, an optimal range of habitat factors might promote chick survival—a site that is relatively flat, but sufficiently sloped as to facilitate drainage without compromising chick safety. As birds generally choose nest sites that facilitate the survival of their chicks, survival is only evaluated within the limited range of values where nests occur. With a changing climate and trend toward more
precipitation, and increasingly more as rain rather than snow, some habitat variables may exert a higher influence on chick survival in the future. Continued study could help describe and explain the fate of these and other current breeding sites under the emerging climatic regimes of the western Antarctic Peninsula.

CONCLUSION

Drone photography can be a valuable tool to monitor ground-breeding bird populations in remote areas by documenting population dynamics and reproductive success over time. Such methods provide valuable, reproducible data without incurring major disturbance to the breeding population or habitat, and they can observe otherwise inaccessible locations by flying from adjacent landings or nearby research vessels. Additionally, spatial data products from drone surveillance can reveal optimal selection criteria for nesting habitat. Nest habitat encompasses a suite of important spatial attributes that affect the behavior, ecology, and demographic trends of seabirds, but these critically engage with other less-localized biological attributes and processes to affect the fitness and survival of individuals and populations. Future studies would benefit from incorporating dynamic environmental factors, such as ocean conditions and weather events, expanding observations to other colonies and populations, observing the entire breeding period and across years, and accounting for parental behavior, feeding frequency and food quality. Drone techniques can monitor seabird populations when ground-level research is impossible or unsuitable, but in cases where both methods are viable, drone surveillance can complement the depth of conventional demographic monitoring with broad spatial coverage and high temporal frequency. This study analyzed limited observations from exploratory datasets and demonstrates the potential of drone imagery to describe even more subtle processes and dynamics, such as the spatial structuring of nests relative to one another. As drone methods are further refined and validated, these and other emerging techniques will unlock new opportunities to understand seabird ecology and population dynamics, especially in the most sensitive and inaccessible habitats.

Declarations

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DATA AVAILABILITY
Analyses reported in this article can be reproduced using the data repository provided by Larsen et al. (2022). Aerial data from drone surveys of coastal habitats on the West Antarctic Peninsula during austral summer (January–March 2020 and February–March 2019). DOI: 10.7924/r4sf2xs2w

References


2. Antarctic Meteorological Research and Data Center Palmer Station PALMOS Automated Tide Data System tide gauge data, 1993-present (ongoing)


Figures
Figure 1

Locations and dates of drone surveys at Humble Island and Elephant Rocks in 2020. Satellite imagery (top) shows the focal sites (red) in local and regional context along the western Antarctic Peninsula. A timeline (bottom) describes survey dates (black bars) in relation to the giant petrel breeding period. Map projection: WGS 84/UTM zone 20S. Base imagery: Sentinel 2, true color, captured on February 18, 2020 (top), and 2008 Landsat Image Mosaic of Antarctica (top right inset) (Bindschadler et al. 2008).
Figure 2

Nest sites for southern giant petrels (*Macronectes giganteus*) on Humble Island (left) and Elephant Rocks (right) in 2020 February 21-23, western Antarctic Peninsula. Yellow contours mark mean sea level, crosses mark randomly generated background points (*n* = 100 per site).

Figure 3

Example of two successful southern giant petrel (*Macronectes giganteus*) nests on Elephant Rocks, from surveys on February 12, February 21 and March 7, 2020. Adults (blue boxes) are visible in February but absent in March, and chicks (orange boxes) are visible in all surveys.
Figure 4

Example of two unsuccessful southern giant petrel (*Macronectes giganteus*) nests on Elephant Rocks, from surveys on 14 January and 17 March 2020. Attending adults (blue boxes) are visible on nests in January and February (not shown), but nests were consistently unoccupied (red arrows) by adults or chicks in March surveys, and wandering chicks were not observed in nearby habitat.
Figure 5

Maps of habitat attributes at Humble Island (left) and Elephant Rocks (right). Only attributes considered for statistical analysis are shown. Maps have been masked to exclude terrain below the highest high-tide line, thus intertidal beaches are not shown. Wind shelter index describes the relative exposure of terrain (0 = low exposure, high shelter) to the prevailing wind direction.
Figure 6

Directional plots describing the aspect of nest sites or background locations in Humble Island and Elephant Rocks in 2020. Plots describe (left) the aspects of all observed active nest sites \( (n = 86) \) and a set of random background locations \( (n = 200 \text{ total}) \); (center) the aspects of active nest sites on each island; and (right) the aspects of all successful and unsuccessful nests. The length of each wedge is proportional to the number of locations (nests or background locations) situated on an aspect within that range of directions.
Figure 7

Measured attributes at active nest sites (red boxes) and sampled background locations (white boxes) across Elephant Rocks and Humble Island in 2020. Boxplots describe the mean (horizontal line), the range from the first to third quartile (box) and the calculated maximum and minimum values (whiskers). Horizontal brackets with asterisks mark statistically significant differences between nest sites and background locations for a given variable, based on t-test comparisons of means. Raw data values are overlaid as semi-transparent points, colored by the island from which they were sampled, to illustrate the underlying distributions that we pooled for these comparisons of means.
Figure 8

Measured attributes at active nest sites on Humble Island (blue boxes) and Elephant Rocks (yellow boxes) in 2020. Boxplots describe the mean (horizontal line), the range from the first to third quartile (box) and the calculated maximum and minimum values (whiskers). Horizontal brackets with asterisks mark statistically significant differences between islands for a given variable, based on t-test comparisons of means. Raw data values are overlaid as semi-transparent points, colored by the island from which they were sampled.
Figure 9

Measured attributes at successful nest sites (green boxes) and unsuccessful nest sites (gray boxes) across Elephant Rocks and Humble Island in 2020. Boxplots describe the mean (horizontal line), the range from the first to third quartile (box) and the calculated maximum and minimum values (whiskers). Horizontal brackets with asterisks mark statistically significant differences between nest sites and background locations for a given variable, based on t-test comparisons of means. Raw data values are overlaid as semi-transparent points, colored by the island from which they were sampled, to illustrate the underlying distributions that we pooled for these comparisons of means.
Figure 10

Marginal effects of the mean for GAMs of nest occurrence across both islands in 2020 (red lines) with 95% confidence intervals (shaded ribbons). Marginal effects were calculated for a single model, which was visually identical to every other selected model.
Figure 11

Habitat suitability maps of Humble Island (left) and Elephant Rocks (right) predicted from a GAM of nest occurrence in 2020. Predictions used “Model 1” (Table 1) and describe predicted habitat suitability (1 is high suitability, and 0 is low) as a function of geomorphology and proximity to megafauna. Potential habitat (colored area) represents all land above the highest high-tide line.