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RESEARCH

Drone-based monitoring and geomorphology of southern giant petrel nests near Palmer Station, western Antarctic Peninsula

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Abstract

Human activities and climate change threaten seabirds globally, and many species are declining from already small breeding populations. Monitoring of breeding colonies can identify population trends and important conservation concerns, but it is a persistent challenge to achieve adequate coverage of remote and sensitive breeding sites. Southern giant petrels (*Macronectes giganteus*) exemplify this challenge: as polar, pelagic marine predators they are subject to a variety of anthropogenic threats, but they often breed in remote colonies that are highly sensitive to disturbance. Aerial remote sensing can overcome some of these difficulties to census breeding sites and explore how local environmental factors influence important characteristics such as nest-site selection and chick survival. To this end, we used drone photography to map giant petrel nests, repeatedly evaluate 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, and statistical models predicted suitable nest-site locations based on local spatial characteristics, explaining 72.8% of deviance at these sites. These findings demonstrate the efficacy of drones as a tool to identify, map, and monitor seabird nests, and to quantify important habitat associations that may constitute species preferences or sensitivities. These may, in turn, contextualize some of the diverse population trajectories observed for this species throughout the changing Antarctic environment.

Keywords Drones · Procellariiformes · Wildlife monitoring · Geomorphology · Remote sensing · Spatial modeling

Introduction

It is a difficult but necessary challenge to monitor seabirds across the remote habitats in which they breed. Though they comprise a relatively small number of species among birds, seabirds are key predators of marine and coastal ecosystems, contributing to and reflecting the health of those systems (Croxall et al. 2012; Dias et al. 2019). Seabird species generally have life-history traits that limit rates of population growth and recovery; these characteristics make them especially vulnerable to threats from human activities and related ecological changes. Many species have already experienced rapid declines and, in aggregate, the monitored portion of seabird populations decreased globally by 70% between 1950 and 2010 (Paleczny et al. 2015), though many populations are still poorly documented. Among seabirds, the order Procellariiformes—albatrosses and petrels—contains some of the most threatened species (Cooper et al. 2006; Croxall et al. 2012), including those that have experienced the largest decreases (Paleczny et al. 2015). Albatrosses and large petrels are pelagic foragers that are particularly threatened by the risks of fisheries bycatch, hunting and disturbance by humans, bioaccumulation of plastics and other marine pollutants (Roman et al. 2019), depredation by alien species, pathogens, and the ecological and environmental effects of global climate change (Dias et al. 2019). Albatrosses and petrels receive targeted conservation measures under the

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Agreement on the Conservation of Albatrosses and Petrels (Cooper et al. 2006), though gaps persist in their legal protections on the high seas (Beal et al. 2021), and some identified threats, such as climate change and pollution, continue to intensify without abatement (Phillips & Waluda 2020). Monitoring at breeding sites can characterize how different populations shift under these stressors, but can also yield evidence of ingested debris (Phillips & Waluda 2020), metabolized pollutants (Trevizani et al. 2022) and fisheries interactions (Patterson et al. 2008). Among decreases and data deficiencies, more and better monitoring is a top identified priority in conservation literature for seabirds (Croxall et al. 2012).

The southern giant petrel (*Macronectes giganteus*) is a long-lived procellariiform seabird that breeds on subantarctic islands and at coastal sites around the Antarctic continent from ~ 40 to 68˚S (Techow et al. 2010). They are opportunistic predators and among the principal scavengers of the Southern Ocean and its coastal ecosystems (reviewed in Mills et al. 2021). Some breeding populations are relatively well-studied and the species is currently classified as "of least concern" (BirdLife International 2018), but trends vary widely by region, with noted decreases in some breeding localities (Dunn et al. 2016; Miller 2005). Many populations still have insufficient or inconsistent observations, obscuring current population trends amid the dynamics of inter- and intra-annual variability (Creuwels et al. 2005; Patterson et al. 2008; Wienecke et al. 2009), even as their high-latitude habitats transform physically and ecologically under the influence of global climate change (Rogers et al. 2020). Male and female giant petrels (genus *Macronectes*) are highly dimorphic: males grow significantly larger bodies and bills with corresponding differences in foraging behavior and prey (Gonzáles-Solís & Croxall 2005). Both sexes frequently forage > 100 km from their nesting sites and can range > 1000 km in a single foraging trip, but females forage primarily at sea over greater distances whereas males generally travel shorter distances, scavenging along coastal sites when prey and carrion are available (Gonzáles-Solís & Croxall 2005; González-Solís et al. 2000; Granroth-Wilding & Phillips 2019; Mills et al. 2021; Poncet et al. 2020; Quintana et al. 2010). Terrestrial food sources of southern giant petrels include mostly seal carrion, but also penguin and seal feces (Casaux et al. 1997; Corá et al. 2020; González-Solís et al. 2000), live and dead seabirds (Dilley et al. 2013; Le Bohec et al. 2003; Punta, 1995) and fur seal (*Arctocephalus gazella*) pups near breeding sites (Nagel et al. 2022). The significant difference in the foraging strategies between sexes makes giant petrel populations vulnerable to different anthropogenic changes, with females particularly vulnerable to risks of bycatch, related fisheries interactions, and ingestion of floating plastic debris (Phillips & Waluda 2020; Roman et al. 2019), and males more reliant on the availability of carrion (Gianuca et al. 2019). In some populations, penguins comprise 50–80% of prey by mass in giant petrel diets (Hunter 1983; Ridoux 1994), and long-term decreases in some southern giant petrel breeding populations may be attributable to recent decreases in Adélie (*Pygoscelis adeliae*) and chinstrap (*P. antarctica*) penguin populations on the Antarctic Peninsula associated with regional warming and decreasing sea ice cover (Dunn et al. 2016; Ryan et al. 2008).

A common method of monitoring seabird populations is to census breeding pairs at a site and estimate their reproductive success (Arneill et al. 2019; Creuwels et al. 2005; Croxall & Prince 1979; Johnson & Krohn 2001), as breeding success critically underwrites the population trends of seabirds. Like most seabirds, giant petrels have altricial young and invest much time and resources into raising their offspring (Marchant & Higgins 1990; Schreiber & Burger 2001). Both males and females participate in an approximately 60-day incubation period followed by a ~ 120-day rearing period until fledging (Cimino, unpublished data; Conroy 1972). Parents alternate between periods of foraging and fasting while attending the nest and undergo a contemporaneous annual molt that, together, incur high energetic demands and underscore the importance of seasonal food availability and local environmental suitability during breeding (De Bruyn et al. 2007; Lownie et al. 2022). However, among seabirds, giant petrels are particularly sensitive to direct and indirect human disturbance (Warham 1962). Even careful human activity near nesting sites induces both physiological responses, such as increased heart rates (Pfeiffer & Peter 2004), and behavioral responses, such as adults abandoning nests and regurgitating food, and chicks spitting proventricular oil when threatened (Warham 1962), all of which incur energetic costs and, in the case of abandonment, can expose eggs and chicks to predation. Additionally, research bases near nesting sites can attract a high number of predator and scavenger species, such as skuas or kelp gulls, owing to anthropogenic activities (e.g., disturbances, organic waste disposal), and decreases have been recorded at multiple populations near research stations (Chupin 1997; Krüger 2019; Nel et al. 2002; Rootes 1988). Amid the rapidly changing conditions of the western Antarctic Peninsula, efforts to study and monitor this species, and especially their breeding rates, are hindered both by their remote breeding locations and by 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 & Fletcher 2017; Edney & Wood 2021), achieving the dual objectives of increased monitoring and decreased human disturbance for sensitive species like southern giant petrels. As an ancillary outcome, remote sensing can also describe the

spatial distribution of nest sites and the geomorphology in which they are located. Many seabirds distribute their nests unevenly across a landscape as they select for specific habitats or terrain features that suit their environmental needs or preferences. The geomorphological characteristics of nesting habitat may therefore contribute to differences in colony growth and size between sites, and likely influence chick survival and long-term 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 influence local microclimatic conditions. For example, wetness and exposure to wind and sunlight can temper broader climatic conditions, such as air temperature and snow accumulation. Breeding pairs tend to nest largely in snow-free areas, and extreme snowfall appears to negatively affect breeding success (Dunn et al. 2016; Schulz et al. 2014). 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).

Using commercially available drones, we mapped breeding giant petrel nests, monitored them over time, and examined potential geomorphological drivers that may influence nest-site selection and chick survival. 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 of November–May (Holdgate 1963). The southern giant petrel population near Palmer Station increased from the 1970s to 2008, but trends have not been described more recently (Parmelee & Parmelee 1987; Patterson et al. 2008).

Using orthomosaics and digital surface models (DSMs) generated from aerial drone surveys carried out in January–March, 2020 (conventionally described as summer 2019/2020), we identified southern giant petrel nest sites in their landscape context to monitor the colony and examine its habitat characteristics. We tracked chick survival across repeat surveys during the period of observation, and we mapped nests' geomorphological attributes (elevation, aspect, slope, wind shelter, topographic wetness index) and their proximity to megafauna (penguin colonies and seal aggregations) that represent potential sources of food and disturbance. We then used these maps to investigate how local habitat characteristics influence nest locations and potentially nest success. Recognizing that site selection and breeding success is driven by multiple scales of spatial and temporal influences, we nevertheless expected to find statistical relationships to describe the fine-scale preferences and requirements that determine southern giant petrel breeding habitat among the relatively sparse and changing terrestrial habitats of the western Antarctic Peninsula.

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 km^2 with highly variable terrain, whereas Elephant Rocks is smaller (0.034 km^2), and comprises low-lying beaches and discrete rocky features. We surveyed Elephant Rocks on 14 January, 12 February, 21 and 28 February, 2,7, 17 and 23 March in 2020; we surveyed Humble Island on 15 and 30 January, 22 February, and 3, 17 and 21 March in 2020 (Fig. 1). Surveys used a DJI Phantom 4 Pro drone with a default camera payload; this multirotor aircraft had been used for a combined > 100 scientific flights over land near Palmer Station without any observed disturbance to ground-nesting avifauna during drone operations during the time of the study. 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 above sea level 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 with a maximum flight speed of 11 m/s. 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 surface modeling techniques (Nex & Remondino 2014; Westoby et al. 2012). 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 georeferenced 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

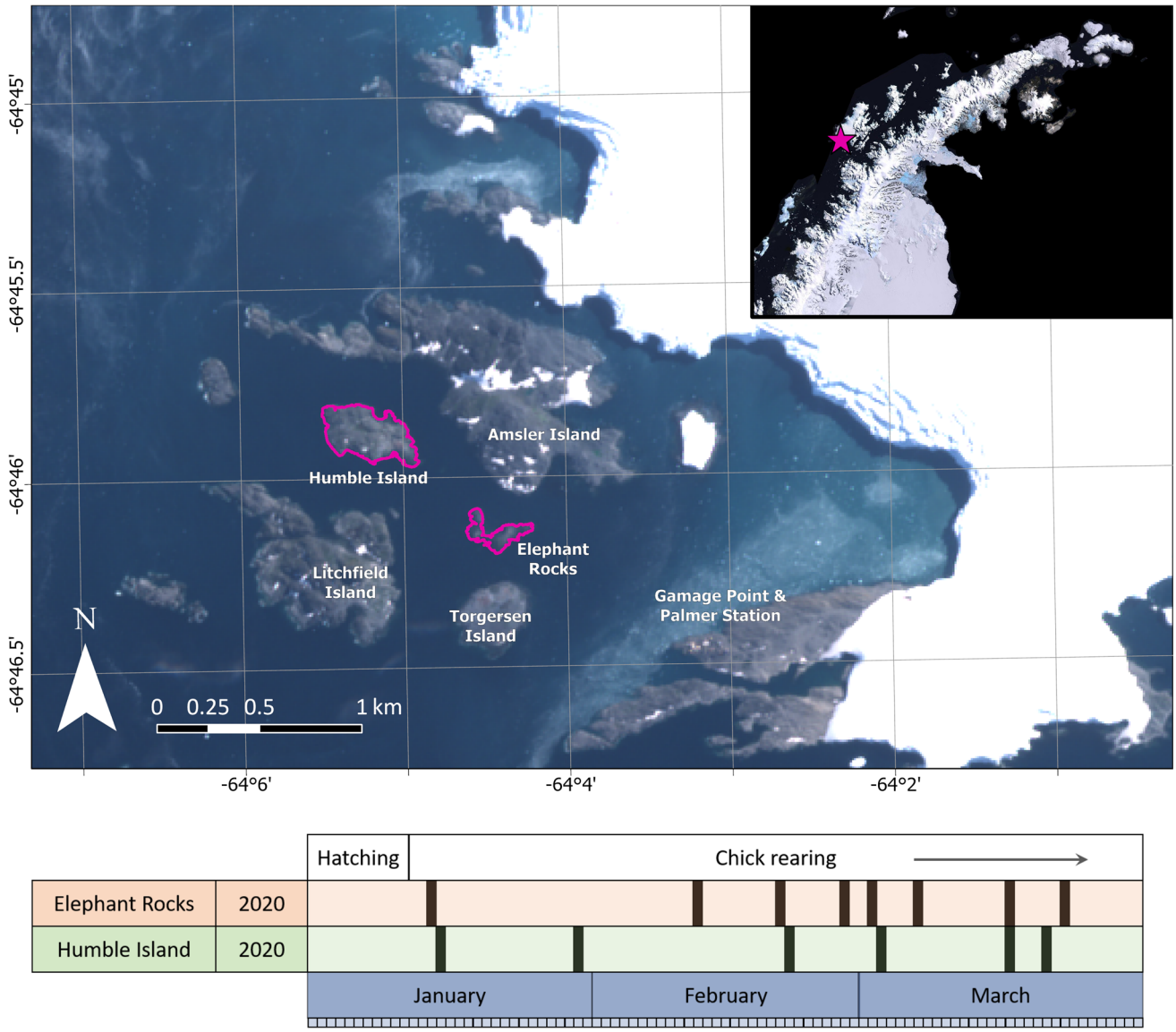

Fig. 1 Locations and dates of drone surveys at Humble Island and Elephant Rocks in 2020. Satellite imagery (top) shows the focal sites (magenta) in local and regional context along the western Antarctic Peninsula. A timeline (bottom) describes survey dates (black bars) in relation to the giant petrel breeding period; the end of the hatching period (early–mid-January) is a general approximation for last hatch dates in this region (pers. obs). 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)

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 14,809–03.

Nest site geomorphology and habitat predictors

For each site, Humble Island and Elephant Rocks, we selected a high-quality DSM based on visual inspection to ensure realistic values and exclude any obvious errors. We down-sampled 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, using elevation values from the complete DSM product. 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). Elevation was extracted from the down-sampled 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 variables were selected with the rationale that they contribute to a nest's stability and exposure to snowfall, snowmelt, wind, extreme temperatures, and related factors that might influence a site's suitability for nesting. Wind shelter indices were generated relative to the prevailing wind direction, which we estimated 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 the mean and standard deviation of a prevailing direction as $7.5 \pm 30°$ for the study period. This mean and its variance 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.

We also located elephant seal wallows in the landscape 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 located 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 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. Among neighboring islands, Amsler Island also hosts elephant seal wallows, but these are farther than the aggregations of Humble and Torgersen and therefore did not influence nearest-distance maps.

Nest monitoring and chick survival from drone imagery

We examined drone imagery at full resolution of 1.5–3 cm pixel^{-1} GSD to visually identify and locate giant petrel nest sites, and the 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. 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. Our survival metric is qualified to the observation period, which ended in March 2020, even though chicks typically fledge in May. Previous observations suggest that most nest failures occur 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 (Hunter 1984; Marchant & Higgins 1990). Older, feathered chicks had a survival rate over 90%, which contextualizes that our estimates of chick survival are likely much higher than estimates that include the entire egg laying and incubation periods (Hunter 1984; Chupin 1997).

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 and absence locations consisted of 100 background points randomly generated across each site (total $n = 200$) above the highest high-tide line and at least 1 m away from the center of any nest-site to ensure that background points did not overlap nest sites; we did not account for possible exclusionary buffers around nest sites, but nearly contiguous nests have been seen before in our study area. We extracted geomorphological attributes for each active nest-site and background point 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 $\kappa = 0$ describes a uniform distribution of values (Jammalamadaka, 2001).

We conducted an exploratory analysis of nest survival using pairwise comparisons to examine differences between the characteristics of successful nests and nests that failed; we did not model these relationships on account of the low sample size (19 failed nests among 86 total). We used 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 also calculated nearest-neighbor distances between nests using the "near" tool in ArcGIS.

We used generalized additive models (GAMs) in the "mgcv" package in R (Pedersen et al. 2019; Wood 2023) to model the probability of nest occurrence in response to habitat predictors (Cimino et al. 2019). GAMs used the following structure:

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

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, with boundary knots at 0° and 360° to define the cyclic interval. All other splines were fitted using default parameters without fixing the number or placement of knots. Site was modeled 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, we fit all possible combinations of predictors in a full candidate model and used backwards stepwise selection. We discarded predictors if the resulting model yielded a lower value of the Akaike information criterion for small sample size (AIC_c), which we calculated using the "MuMIn" package in R (Bartoń, 2023; Burnham & Anderson, 2004). The resulting model had the lowest AIC_c, and we report adjusted R^2, percent deviance explained, estimated degrees of freedom, and AIC_c for the full model, selected model, and alternative models that each discarded one of the selected predictors. For the selected model, we plotted the partial effect of each explanatory variable, and we quantified the relative contribution of each variable by calculating the difference in percent deviance explained between the selected model and an alternative model fitted without that variable but retaining all other variables from the selected model.

Results

Study site characteristics

Humble Island and Elephant Rocks have many similar properties, being neighbors of the same archipelago, but some geomorphological characteristics differ between the two sites (Fig. 2). Elevation extends slightly higher at Humble Island, spanning up to 16 m, whereas Elephant Rocks is mostly flat with the highest point being 6 m. Many of the beaches of Elephant Rocks were excluded from habitat analysis because they sit below the highest high-tide line. Both locations feature some rugged terrain with areas of steep slopes and complex geomorphology (Fig. 2); both also include lower elevation areas that are prone to wetness, and flat regions that are exposed to prevailing winds.

Identification and distribution of giant petrel nests and chick survival

Both active and inactive nest sites were generally on rocky terrain, and each nest was encircled by excrement, reflecting its usage. Adults were observed on nest sites in January, and chicks were visible by February at latest, often accompanied by nearby adults, and in surveys through March. Growth and changes in feather color were evident in imagery at these resolutions of 1.5–3 cm pixel^{-1} GSD, though not measured, and we were able to distinguish between the presence and absence of chicks at or near nest sites, enabling survival estimation over the period of observation. On occasion we observed that chicks had wandered a short distance away from the nest, but this was rare during the period of observation and was unlikely to result in a falsely classified absence, especially across multiple surveys.

Giant petrels nested in small, scattered groups on each island; only a few individuals nested alone and on the

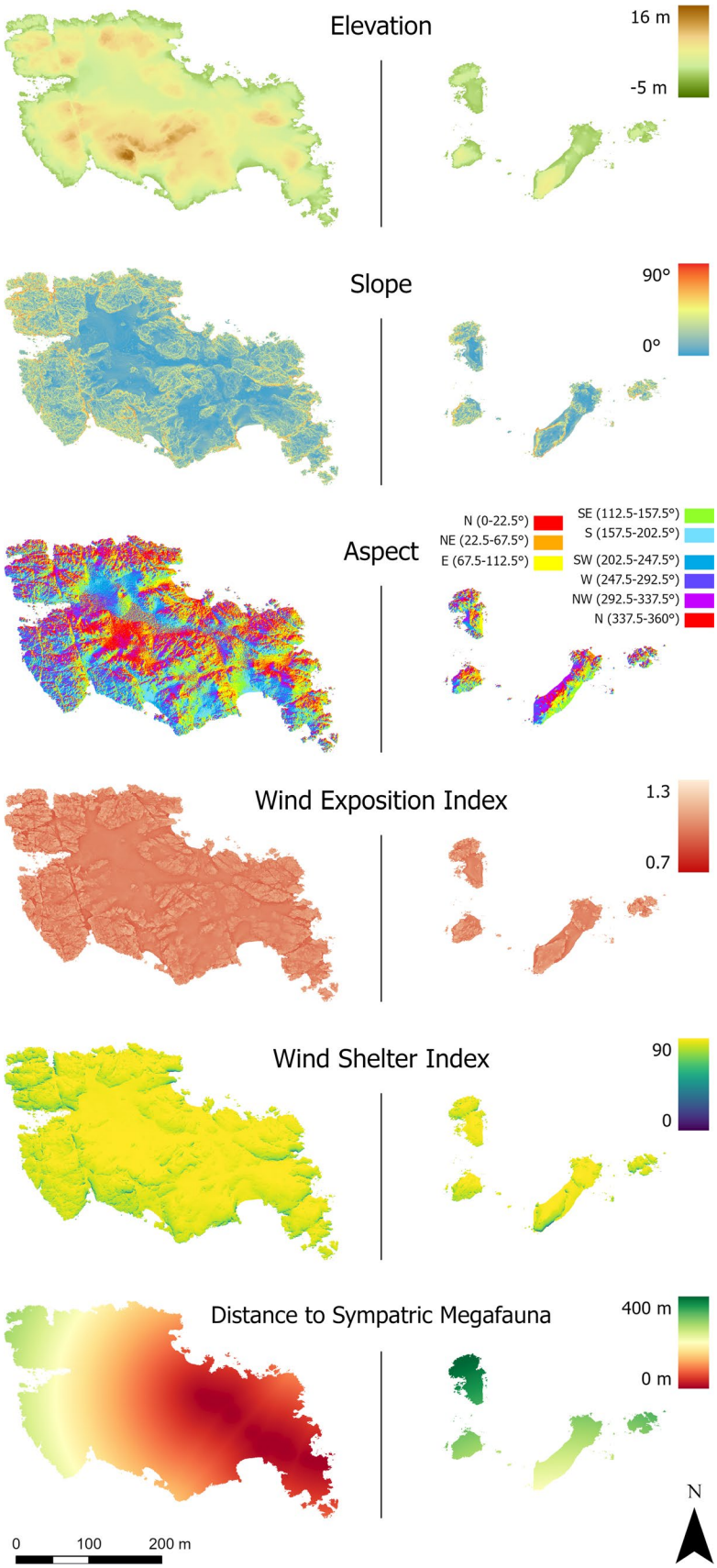

Fig. 2 Maps of habitat attributes at Humble Island (left) and Elephant Rocks (right) used for modeling and statistical comparisons. Maps describe only terrain above the highest high-tide line, therefore excluding intertidal beaches. Wind exposition index describes the relative exposure of terrain to wind from all directions (0.7 = low exposure, 1.3 = high exposure), and wind shelter index describes the relative exposure of terrain (0 = low exposure, high shelter) to the prevailing wind direction, 7.5 ± 30° as measured by an automated weather station located < 2.5 km away at Palmer Station

periphery (Fig. 4). Nest centers were located 7.2 ± 12.1 m from one another, as close as 1.2 m (a nearly contiguous pair on the northwest cluster of Elephant Rocks), and as far as 86.2 m (a solitary nest on the southwest islet of Elephant Rocks). On Humble Island, 52 nests were active in mid-January (first survey), and 41 of those chicks survived (79%) until mid–late-March (last survey). At Elephant Rocks, 26 (76%) of 34 nests were successful. Chick survival rate was therefore similar between sites.

Successful nests were located predominantly on aspects around the southeast direction (140°, 0.6) compared to unsuccessful nests, which were more oriented around the northwest aspect (298°, 0.3) by a significant difference ($U^2 = 0.19$, $0.01 < p < 0.05$; Fig. 5). Successful nests were also located on slightly higher slopes (7.48 ± 3.90°) than unsuccessful nests (4.40 ± 2.76°) by a small but significant difference ($t_{84} = 3.21$, $p < 0.01$); other measured habitat attributes did not differ significantly between successful and unsuccessful nest sites ($p > 0.05$, all; Fig. 5).

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, identifying influential habitat characteristics. The selected model had the lowest AIC_c among all candidate models and retained most candidate variables (Table 1). Aspect and site were dropped from candidate models as their omission lowered AIC_c scores and did not significantly decrease the percent deviance explained or R^2. This yielded a single selected model whose explanatory variables were elevation, slope, wind exposition index, wind shelter index, and distance to megafauna. The model performed well in terms of explaining deviances using a combination of explanatory variables (deviance explained = 72.8%). Slope contributed the most to explained deviance, followed by wind exposition index, distance to megafauna, elevation, and wind shelter index, and the selected model described 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 most nest sites were clustered relatively 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, among influential variables.

Using the selected model for nest occurrence (Table 1, Fig. 6) with raster products describing spatial attributes of potential habitat above the highest high-tide line (Fig. 2) we predicted habitat suitability for nest sites on Humble Island and Elephant Rocks (Fig. 4). High elevation regions (peaks and ridges) at both islands were some of the most suitable habitats, which generally aligned with the observed distribution of active nest sites that informed the model (Fig. 4).

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

	Variables	R^2	Deviance explained	edf	AIC_c
Selected model	elevation, slope, wind exposition index, wind shelter index, distance to megafauna	0.77	72.8%	10.73	120.86
Full candidate model	aspect, elevation, slope, wind exposition index, wind shelter index, distance to megafauna, site	0.77	73.0%	11.99	123.78
Alternative model 1 *-wind shelter index*	elevation, slope, wind exposition index, distance to megafauna	0.74	71.0%	11.58	130.53
Alternative model 2 *-elevation*	slope, wind exposition index, wind shelter index, distance to megafauna	0.73	68.3%	9.95	133.95
Alternative model 3 *-distance to megafauna*	elevation, slope, wind exposition index, wind shelter index	0.68	64.8%	11.69	151.54
Alternative model 4-*wind exposition index*	elevation, slope, wind shelter index, distance to megafauna	0.66	62.5%	10.14	155.62
Alternative model 5-*slope*	elevation, wind exposition index, wind shelter index, distance to megafauna	0.62	58.5%	11.77	174.92

The selected model represents the best-performing model selected by omitting variables from the full candidate model if their inclusion did not lower AIC_c or significantly increase deviance explained in fitted models. Models are described by R^2, deviance explained, effective degrees of freedom (edf), and AIC_c. Alternative models were each fitted omitting one of the five variables from the selected model (italicized in name). These alternatives were used to estimate the relative contribution of each variable as the difference in deviance explained between the selected model and the alternative model fitted without that variable

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 instance. This study leveraged the low logistical cost of drone operations to achieve not only nest counts, but also surveillance of focal sites over a period of the breeding season and mapping of nest locations and their spatial attributes. These achievements from drone surveillance represent 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. Drone surveys represent a promising methodology for sensitive species like southern giant petrels as they are potentially less invasive than common ground-level survey methods (Fudala & Bialik 2022), but they do entail other risks of disturbance (Borrelle & Fletcher 2017). For example, drones can disturb wildlife with their acoustic or visual profiles, incurring physiological stress and behavioral changes (Fudala & 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 (Bishop et al. 2022; Borrelle & Fletcher 2017; Raoult et al. 2020), 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 describe chick development, as growth and changes in feather color were evident though not measured over time (Fig. 3). The spatial distribution of observed nest sites illustrated how most birds tended to nest in groups with only a few dispersed nests (Fig. 4), though we did not examine any effects of this spatial structuring on nest-site selection or chick survival. This study was limited by the short time periods during which data were collected—data collection began in January, as eggs were already hatching, and concluded in March, even though chicks had not yet fledged at that time. To achieve more complete estimates of chick survival and breeding

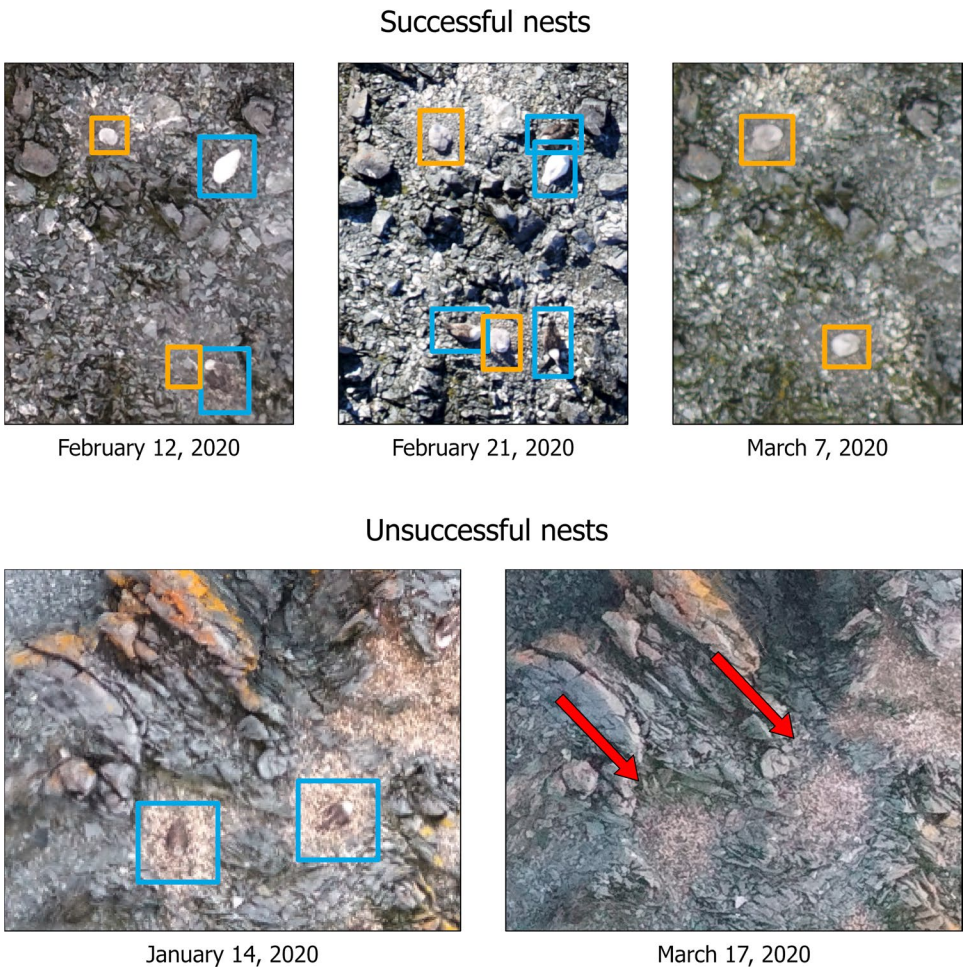

Fig. 3 Examples of (top) two successful southern giant petrel (*Macronectes giganteus*) nests on Elephant Rocks, and (bottom) two unsuccessful nests at the same site. Attending adults (blue boxes) are visible at successful nests in February but absent in March, and chicks (orange boxes) are visible in all surveys at successful nests. Attending adults (blue boxes) are also visible at failed nests in January and February (not shown), but these nests were consistently unoccupied (red arrows) by adults or chicks in all March surveys, and wandering chicks were not observed nearby. (Color figure online)

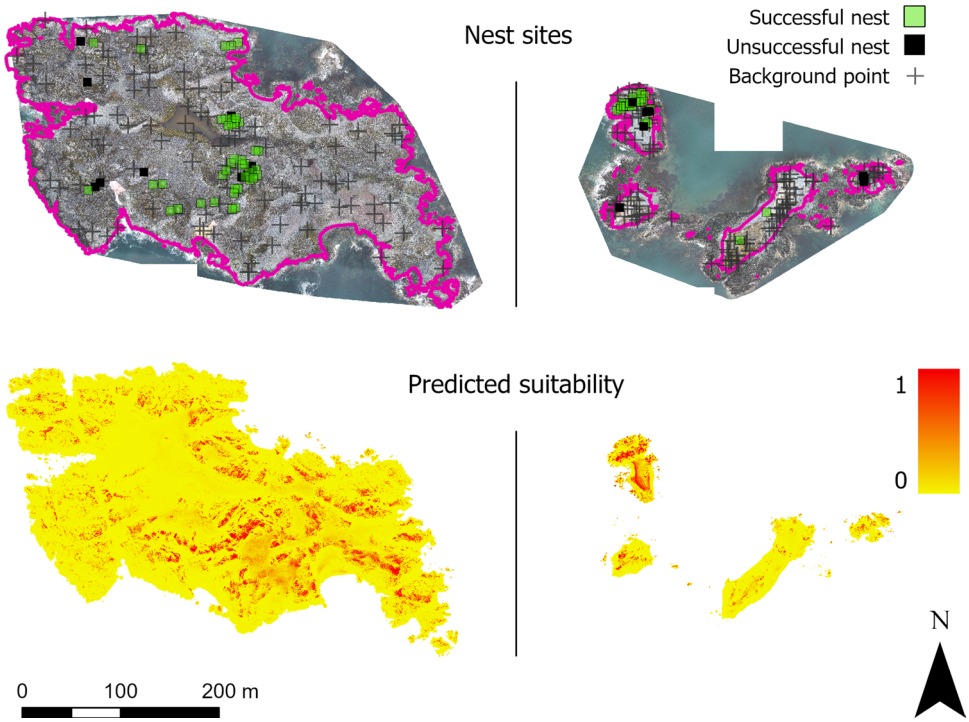

Fig. 4 Nest sites (top) and predicted suitable habitat (bottom) for southern giant petrels (*Macronectes giganteus*) on Humble Island (left) and Elephant Rocks (right), western Antarctic Peninsula. Magenta contours (top) mark the highest high-tide line, crosses mark randomly generated background points ($n = 100$ per site) used for presence–absence modeling. Orthomosaics were captured on February 21 and February 23, 2020. Habitat suitability maps (bottom) were predicted from a GAM of nest occurrence in 2020 using habitat characteristics (Fig. 2). Predictions used a selected best-performing model (Table 1) and describe predicted habitat suitability (1 = high suitability, 0 = low suitability) as a function of geomorphology and proximity to megafauna. Potential habitat (yellow–red colored area) is estimated for all land above the highest high-tide line. (Color figure online)

success, 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 from aerial perspectives when they are brooded by their parents, but early nest monitoring can still provide information on parental exchanges or nest failure, if parents abandon the nest after egg or chick loss. The most accurate estimates 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 could verify the presence of eggs or small chicks under presumed breeders, but present a much higher risk of disturbance. A more inclusive metric of "apparently occupied nests" may inform estimates of breeding success with greater uncertainty but without requiring ground-based investigations, and frequent coverage from aerial surveys might reveal non-breeders at early stages of the breeding season. Our findings are confined to their short observational period and the limited frequency of revisits, but as an exploratory survey protocol they demonstrate the efficacy of this monitoring technique. If scaled to the full breeding season and sustained across years, regular monitoring of this type can characterize not only colony size, spatial dynamics, and chick survival, but also the timing of key phenological events and stages in the breeding cycle, in aggregate, as seabird life histories entrench or adapt to the transforming climate and ecosystem of the western Antarctic Peninsula.

Drivers of chick survival

We found that a large proportion of nests, first observed 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 and 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. 5), 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

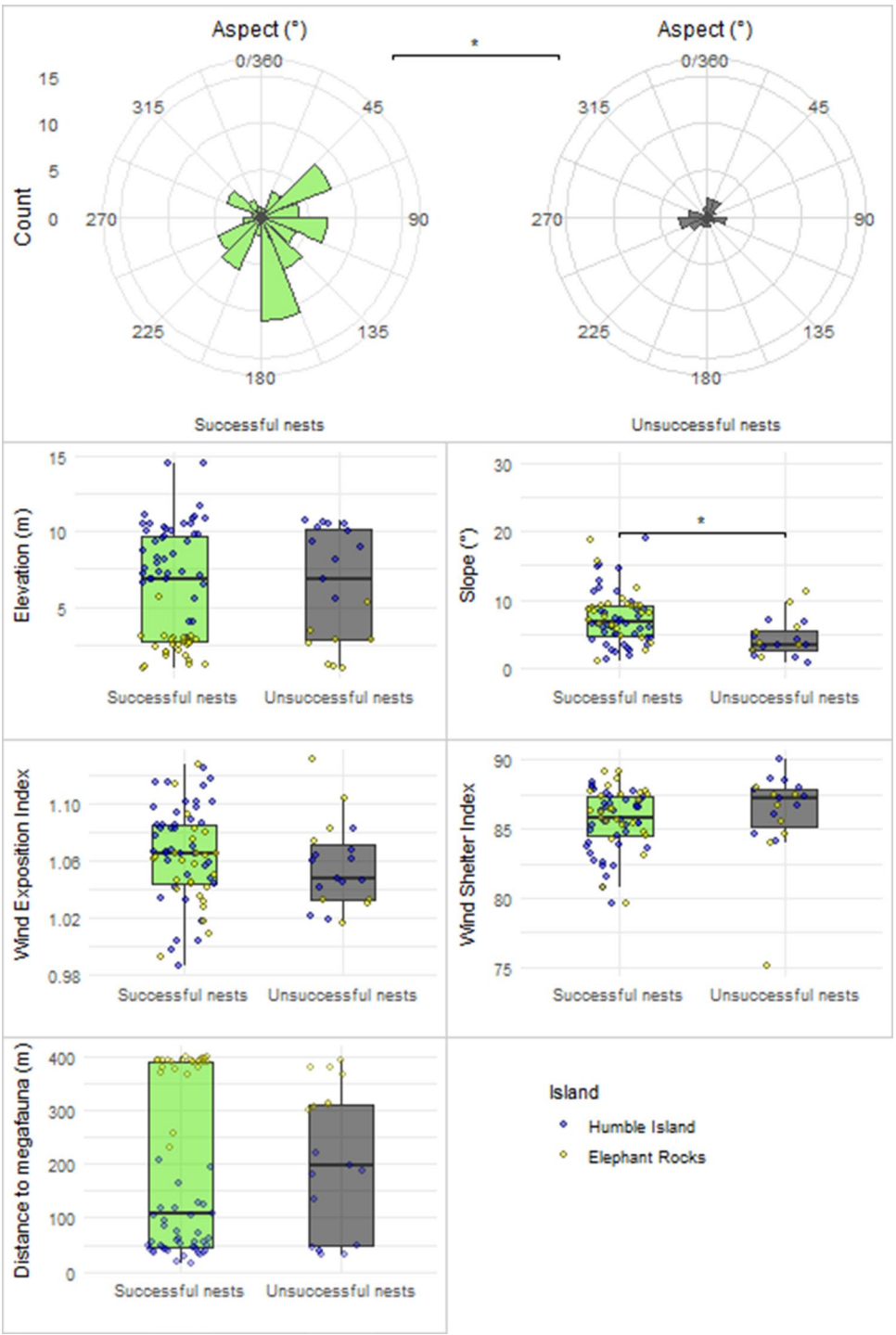

Fig. 5 Measured attributes at successful nest sites (green) and unsuccessful nest sites (gray) across Elephant Rocks and Humble Island in 2020. Polar histograms (top) describe the distribution of aspects at nest locations: the length of each wedge describes the number of locations situated on an aspect within that range of directions. Boxplots describe the mean (horizontal line), the range from the first to third quartile (box) and the calculated maximum and minimum values (whiskers) of measured variables at nest sites. Horizontal brackets with asterisks mark statistically significant differences between successful and unsuccessful nests based on Watson's two-sample test of homogeneity (aspect) or *t* test comparison of means (slope). Raw data values are overlaid as semi-transparent points on box plots, colored by the island from which they were sampled, to illustrate the underlying distributions that we pooled for these comparisons of means. (Color figure online)

sloped as to facilitate drainage without compromising chick safety. Additionally, successful nests were oriented predominantly on southern and eastern aspects, whereas failed nests were more distributed around northern and western aspects. We speculate that possible causes may relate to greater insolation and faster snowmelt on northern aspects, though snow was mostly absent by the time of surveys in 2020; still, these differences should be considered in future investigations. As birds generally choose and retain nest sites that accommodate their breeding success, we only evaluated survival within a very limited range of values where nests occurred in 2020, and not a diverse range of successful and unsuccessful attempts, as might be found at a newly colonized or expanding breeding-site. With a changing climate and a regional trend toward more precipitation, and increasingly more as rain rather than snow, some habitat variables may

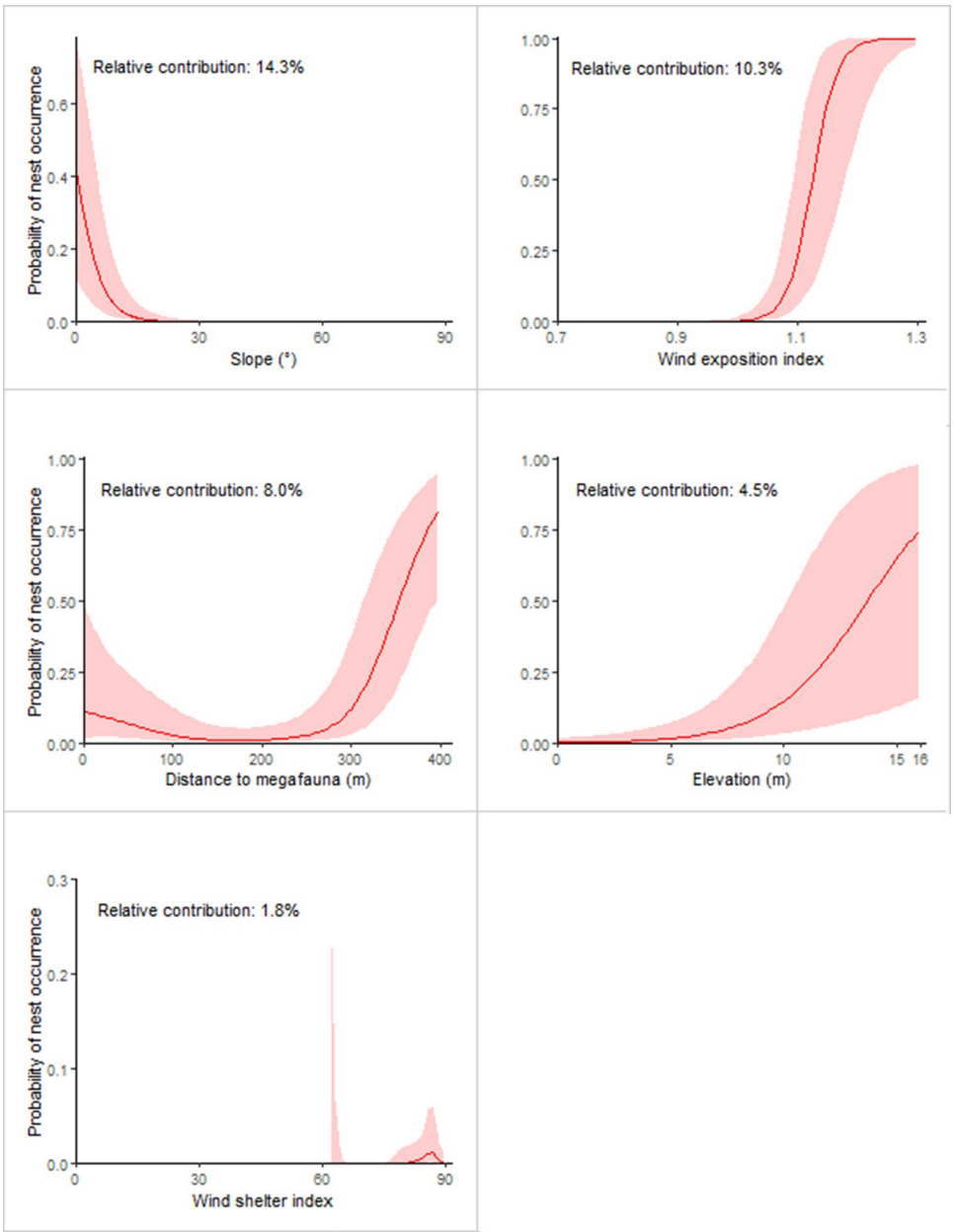

Fig. 6 Marginal effects of the mean for the selected GAM of nest occurrence (red lines) with 95% confidence intervals (shaded ribbons). Relative contributions are given for each variable, describing the effect of their inclusion to the selected model's percent deviance explained. This value is calculated as the difference in percent deviance explained between the selected model and an alternative model that was fitted without the focal variable, but retained all other variables from the selected model. (Color figure online)

exert a higher influence on chick survival in the future as prevailing conditions depart from historic norms even at long-established colonies.

Drivers of nest occurrence

Habitat mapping and spatial modeling showed 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. Slope and wind exposure were the two most influential variables for modeling, based on relative contributions to deviance explained (Fig. 6). Both high elevation (6.32 ± 3.70 m compared to 3.27 ± 2.74 m background habitat) and higher 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 or adjacent terrain (Clay et al. 2020). Adults often take-off or land within 0–5 m of the nest-site (pers. obs.), and therefore require suitable terrain at or near the nest to come and go safely and efficiently. However, unlike larger procellariiforms (Momberg et al. 2023; Schoombie et al. 2023), crash-landings do not appear to be a significant risk to giant petrels; they are rarely but occasionally observed near Palmer Station, and have not been associated with any known mortality at these sites. High elevation also removes nest sites from potential disturbance by penguins and elephant seals as they transit to and from colonies and wallows, respectively, at generally lower elevations. The gentle

slopes (6.80 ± 3.88° compared to 18.43 ± 16.00° background habitat) likely decrease the risk of eggs or chicks falling from the nest, though notably some slight slope was associated with more successful nests (Fig. 5). This might suggest the importance of drainage in the wet climate of maritime Antarctica, and 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 from nests to penguins and seals yielded a relatively complex non-monotonic relationship in its marginal effect from the selected GAM (Fig. 6); this likely reflects chiefly the difference in prey presence 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 clustered near megafauna (< 150 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 (Fig. 5). 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. Distance to megafauna was moderately influential among the five variables of our selected model (Fig. 6), which suggests that the described relationship does successfully explain some of the observed distribution for modeling. But it is also possible that this metric is capturing correlated spatial relationships of other distance-based factors not considered in this study, such as conspecific attraction, landscape-scale environmental characteristics, or historic influences that are no longer present—such as more and larger Adélie penguin colonies and nearer glacier termini with associated katabatic winds. On the other hand, the absence of a clear, monotonic relationship between nest sites and their proximity to megafauna may result from the relatively small size of these seal and penguin aggregations, compared to larger colonies and haul-outs, and the scale of distances that we considered, recognizing that pelagic foraging trips of this species regularly span hundreds of kilometers (Copello et al. 2011; Finger et al. 2023; González-Solís et al. 2000, 2002).

Seal and penguin aggregations undoubtedly do contribute to the success of some southern giant petrel colonies, even if they are not coupled to nesting sites at a local scale. Southern giant petrels commonly forage in regions occupied by penguin and pinniped colonies (Copello et al. 2011; Finger et al. 2023), and carrion availability appears to promote higher fledgling production (Patterson et al. 2008). Megafauna aggregations represent a convenient energy source to breeding adults, especially during incubation when adults may fast up to 15 days (Corá et al. 2020). Amid a largely pelagic diet, predictable land-based food sources allow birds to return to the nest more frequently for feedings and spend more time attending to the chick (De Bruyn et al. 2007). Critically, the breeding cycles of potential prey influence whether seal placentas or vulnerable young are available to scavengers and predators, so nearby megafauna provide the maximum benefit to nearby nest sites only if carrion availability aligns with the chick-rearing period. On Marion Island, breeding success of northern giant petrels (*M. halli*) positively correlated with the abundance of rockhopper penguins (*Eudyptes chrysocome*) and the number of southern elephant seal pups; at the same site, southern giant petrel breeding success 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). Such associations appear to explain why many colonies are located near penguin and pinniped colonies at a regional scale (Copello et al. 2008), but at a local scale, we speculate that the potential resource benefit of immediately adjacent megafauna may interact with a high risk of disturbance near colony sites. Transiting penguins and pinnipeds likely deter petrels from some potential nesting sites, posing a risk of frequent disturbance or trampling in habitats that are accessible by other megafauna. 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 that occur at Humble Island generally occupy different habitats: elephant seal wallows generally occur at lower elevations, often in muddy terrain, penguins tend to nest at middle elevations, and southern giant petrels were observed at 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. 5), elevation might drive habitat partitioning more than horizontal distance at some sites. Based on risk of disturbance or damage, it is likely that petrels preferentially select sites that do not intersect the movement of penguins and seals, rather than prioritizing proximity to potential food sources on land.

The mapping and modeling efforts of this study describe a very limited spatiotemporal window of observation, describing only two islands with observations anchored to photographs and derived products collected in 2020. Southern giant petrels undoubtedly select nest sites based on a variety of factors that unfold across multiple spatial scales, spanning local terrain and regional landscapes, and multiple temporal scales, from the immediate effects of disturbances to the interannual consistency that typifies this species' strong site fidelity (Poncet et al. 2020). Nevertheless, given that habitat models performed well and explained 72.8% of deviance in active nesting sites, we suggest that spatial modeling with drone-derived data can characterize important geomorphological

and biotic preferences of the southern giant petrel in this and other regions at a local scale, and contextualize possible future shifts in abundance or nesting habitat as Antarctic environments change. Prediction from spatial models may even suggest suitable sites where colonies do not currently 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, altering its suitability as a breeding-site. As nest-site selection was positively influenced by wind variables in our study (Fig. 6), changes to prevailing windspeeds and directions could drive giant petrels to abandon current sites or adopt new locations more suitable for take-off, landing, and fledging. Local and regional environmental changes will likely modulate the suitability of breeding habitat for many species along the western Antarctic Peninsula, particularly challenging species that show high fidelity to deteriorating breeding sites. Continued study will therefore help describe and explain the fate of this and other populations as they respond to the emerging climatic regimes of the western Antarctic Peninsula.

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Author contributions G.L., H.V., M.C., and D.J. conceived the idea, design, and study, G.L. collected the data, G.L., H.V., M.C., D.J., and D.P. wrote, edited, and revised the manuscript, G.L., H.V. and M.C. developed and implemented the analysis, and D.J. and M.C. contributed substantial materials, resources, and funding.

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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).

Declarations

Competing interests The authors declare no competing interests.

Conflicts of interest The authors declare no conflicts of interest.

Ethical approval All drone surveys were conducted under Antarctic Conservation Act permit ACA 2020–016 and NOAA permit 14809–03.

References

Arneill GE, Perrins CM, Wood MJ, Murphy D, Pisani L, Jessopp MJ, Quinn JL (2019) Sampling strategies for species with high breeding-site fidelity: a case study in burrow-nesting seabirds. PLoS ONE 14(8):e0221625. https://doi.org/10.1371/journal.pone.0221625

Bartoń, K. (2023). *MuMIn: Multi-Model Inference* (1.47.5) [Computer software]. https://cran.r-project.org/web/packages/MuMIn/index.html

Beal M, Dias MP, Phillips RA, Oppel S, Hazin C, Pearmain EJ, Adams J, Anderson DJ, Antolos M, Arata JA, Arcos JM, Arnould JPY, Awkerman J, Bell E, Bell M, Carey M, Carle R, Clay TA, Cleeland J, Catry P (2021) Global political responsibility for the conservation of albatrosses and large petrels. Sci Adv 7(10):eabd7225. https://doi.org/10.1126/sciadv.abd7225

Bindschadler R, Vornberger P, Fleming A, Fox A, Mullins J, Binnie D, Paulsen SJ, Granneman B, Gorodetzky D (2008) The Landsat Image Mosaic of Antarctica. Remote Sens Environ 112(12):4214–4226. https://doi.org/10.1016/j.rse.2008.07.006

BirdLife International. (2018). *Macronectes giganteus. The IUCN Red List of Threatened Species. 2018*, e.T22697852A132608499. https://doi.org/10.2305/IUCN.UK.2018-2.RLTS.T22697852A132608499.en

Bishop AM, Brown CL, Christie KS, Kettle AB, Larsen GD, Renner HM, Younkins L (2022) Surveying cliff-nesting seabirds with unoccupied aircraft systems in the Gulf of Alaska. Polar Biol 45(12):1703–1714. https://doi.org/10.1007/s00300-022-03101-9

Borrelle SB, Fletcher A (2017) Will drones reduce investigator disturbance to surface-nesting seabirds? Mar Ornithol 45:89–94

Burnham KP, Anderson DR (eds) (2004) Model Selection and Multimodel Inference. Springer, New York

Casaux R, Baroni A, Carlini A (1997) The diet of the Weddell seal Leptonychotes weddelli at Harmony Point. South Shetland Islands Polar Biol 18(6):371–375. https://doi.org/10.1007/s003000050202

Chupin I (1997) Human impact and breeding success in southern giant petrel Macronectes giganteus on King George Island (South Shetland Islands). Korean J Polar Res 8(1/3):113–116

Cimino MA, Patterson-Fraser DL, Stammerjohn S, Fraser WR (2019) The interaction between island geomorphology and environmental parameters drives Adélie penguin breeding phenology on neighboring islands near Palmer Station Antarctica. Ecol Evol. https://doi.org/10.1002/ece3.5481

Clay TA, Joo R, Weimerskirch H, Phillips RA, den Ouden O, Basille M, Clusella-Trullas S, Assink JD, Patrick SC (2020) Sex-specific effects of wind on the flight decisions of a sexually dimorphic soaring bird. J Animal Ecol. https://doi.org/10.1111/1365-2656.13267

Conrad O, Bechtel B, Bock M, Dietrich H, Fischer E, Gerlitz L, Wehberg J, Wichmann V, Böhner J (2015) System for automated geoscientific analyses (SAGA) v. 2.1.4. Geosci Model Dev. https://doi.org/10.5194/gmd-8-1991-2015

Conroy, J. W. H. (1972). *Ecological aspects of the biology of the giant petrel, Macronectes giganteus (Gmelin), in the maritime Antarctic* (Scientific Reports, 1–75). British Antarctic Survey. https://find.library.duke.edu/catalog/DUKE000487941

Cooper J, Baker GB, Double MC, Gales R, Papworth W, Tasker ML, Waugh SM (2006) FORUM—The agreement on the conservation of albatrosses and petrels: rationale, history, progress and the way forward. Mar Ornithol 34:1–5

Copello S, Quintana F, Pérez F (2008) Diet of the southern giant petrel in Patagonia: Fishery-related items and natural prey. Endanger Species Res 6(1):15–23. https://doi.org/10.3354/esr00118

Copello S, Dogliotti AI, Gagliardini DA, Quintana F (2011) Oceanographic and biological landscapes used by the Southern giant petrel during the breeding season at the patagonian shelf. Marine Biol. https://doi.org/10.1007/s00227-011-1645-3

Corá DH, Finger JVG, Krüger L (2020) Coprophagic behaviour of southern giant petrels (*Macronectes giganteus*) during breeding period. Polar Biol. https://doi.org/10.1007/s00300-020-02757-5

Creuwels JCS, Stark JS, Woehler EJ, van Franeker JA, Ribic CA (2005) Monitoring of a Southern Giant Petrel Macronectes giganteus population on the Frazier Islands, Wilkes Land. Antarctica Polar Biol 28(6):483–493. https://doi.org/10.1007/s00300-004-0663-8

Croxall JP, Prince PA (1979) Antarctic Seabird and Seal Monitoring Studies. Polar Rec 19(123):573–595. https://doi.org/10.1017/S0032247400002680

Croxall JP, Butchart SHM, Lascelles BEN, Stattersfield AJ, Sullivan BEN, Symes A, Taylor P (2012) Seabird conservation status, threats and priority actions: a global assessment. Bird Conserv Int. https://doi.org/10.1017/S0959270912000020

De Bruyn PJN, Cooper J, Bester MN, Tosh CA (2007) The importance of land-based prey for sympatrically breeding giant petrels at sub-Antarctic Marion Island. Antarctic Sci 19(1):25–30

Dias MP, Martin R, Pearmain EJ, Burfield IJ, Small C, Phillips RA, Yates O, Lascelles B, Borboroglu PG, Croxall JP (2019) Threats to seabirds: a global assessment. Biol Cons 237:525–537. https://doi.org/10.1016/j.biocon.2019.06.033

Dilley BJ, Davies D, Connan M, Cooper J, de Villiers M, Swart L, Vandenabeele S, Ropert-Coudert Y, Ryan PG (2013) Giant petrels as predators of albatross chicks. Polar Biol. https://doi.org/10.1007/s00300-013-1300-1

Dunn MJ, Jackson JA, Adlard S, Phillips RA (2016) Population size and trends of southern giant petrels (*Macronectes giganteus*) nesting at Signy Island South Orkney Islands. Polar Biol 39(7):1309–1317. https://doi.org/10.1007/s00300-015-1855-0

Edney AJ, Wood MJ (2021) Applications of digital imaging and analysis in seabird monitoring and research. Ibis 163(2):317–337. https://doi.org/10.1111/ibi.12871

Finger JVG, Krüger L, Corá DH, Petry MV (2023) Habitat selection of southern giant petrels: Potential environmental monitors of the Antarctic Peninsula. Antarctic Sci. https://doi.org/10.1017/S0954102023000147

Fudala K, Bialik RJ (2022) The use of drone-based aerial photogrammetry in population monitoring of southern giant petrels in ASMA 1, King George Island, maritime Antarctica. Global Ecol Conserv 33:e01990. https://doi.org/10.1016/j.gecco.2021.e01990

Gianuca D, Votier SC, Pardo D, Wood AG, Sherley RB, Ireland L, Choquet R, Pradel R, Townley S, Forcada J, Tuck GN, Phillips RA (2019) Sex-specific effects of fisheries and climate on the demography of sexually dimorphic seabirds. J Animal Ecol. https://doi.org/10.1111/1365-2656.13009

Gonzáles-Solís, J., & Croxall, J. P. (2005). *Differences in foraging behaviour and feeding ecology in giant petrels* (K. E. Ruckstuhl & P. Neuhaus, Eds.; pp. 92–111). Cambridge University Press. https://nora.nerc.ac.uk/id/eprint/17879/

González-Solís J, Croxall JP, Wood AG (2000) Sexual dimorphism and sexual segregation in foraging strategies of northern giant petrels, Macronectes halli, during incubation. Oikos. https://doi.org/10.1034/j.1600-0706.2000.900220.x

González-Solís J, Croxall J, Briggs D (2002) Activity patterns of giant petrels, Macronectes spp., using different foraging strategies. Marine Biol. https://doi.org/10.1007/s002270100684

Granroth-Wilding HMV, Phillips RA (2019) Segregation in space and time explains the coexistence of two sympatric sub-Antarctic petrels. Ibis 161(1):101–116. https://doi.org/10.1111/ibi.12584

Holdgate M (1963) Observations of birds and seals at Anvers Island, Palmer Archipelago, in 1955–57. British Antarctic Surv Bull 2:45–51

Hunter S (1983) The food and feeding ecology of the giant petrels Macronectes halli and Mgiganteus at South Georgia. J Zool. https://doi.org/10.1111/j.1469-7998.1983.tb02813.x

Hunter S (1984) Breeding biology and population dynamics of giant petrels Macronectes at South Georgia (Aves: Procellariiformes). J Zool. https://doi.org/10.1111/j.1469-7998.1984.tb02343.x

Jammalamadaka, S. R. and S., A. (2001). *Topics in Circular Statistics*. World Scientific Press.

Johns, B. (2006). *Antarctica-Infrastructure GPS Network: PAL2-Palmer Community Base Station P.S.* . UNAVCO, Inc. https://doi.org/10.7283/T5PV6HKR

Johnson CM, Krohn WB (2001) The importance of survey timing in monitoring breeding seabird numbers. Waterbirds: The Int J Waterbird Biol 24(1):22–33. https://doi.org/10.2307/1522239

Krüger L (2019) An update on the Southern Giant Petrels Macronectes giganteus breeding at Harmony Point, Nelson Island. Maritime Antarctic Peninsula Polar Biol 42(6):1205–1208. https://doi.org/10.1007/s00300-019-02504-5

Larsen GD, Falvo C, Tuohy C, Goerke M, Friedlaender AS, Nichols RC, Pallin L, Simms A, Groff D, Ciminio M, Johnston DW (2022) Aerial data from drone surveys of coastal habitats on the West Antarctic Peninsula during austral summer (January–March 2020 and February–March 2019). Duke Res Data Repos. https://doi.org/10.7924/r4sf2xs2w

Lazzara MA, Weidner GA, Keller LM, Thom JE, Cassano JJ (2012) Antarctic automatic weather station program: 30 years of polar observation. Bull American Meteorol Soc. https://doi.org/10.1175/bams-d-11-00015.1

Le Bohec C, Gauthier-Clerc M, Gendner J-P, Chatelain N, Le Maho Y (2003) Nocturnal predation of king penguins by giant petrels on the Crozet Islands. Polar Biol. https://doi.org/10.1007/s00300-003-0523-y

Lownie TJR, Jubinville I, Williams TD, Phillips RA, Crossin GT (2022) Varying aerobic capacity in relation to breeding stage and reproductive success in giant petrels (Macronectes spp.). Comp Biochem Phys Part A: Mol Integr Physiol. https://doi.org/10.1016/j.cbpa.2022.111155

Marchant, S., & Higgins, P. J. (1990). *Handbook of Australian, New Zealand & Antarctic birds: Vol. 1 Ratites to Ducks*. Melbourne ; New York : Oxford University Press, 1990. /catalog/DUKE001811995

Miller C (2005) Southern giant petrels fading fast. Frontiers in Ecol Environ. https://doi.org/10.2307/3868654

Mills WF, Morley TI, Votier SC, Phillips RA (2021) Long-term inter- and intraspecific dietary variation in sibling seabird species. Mar Biol 168(3):31. https://doi.org/10.1007/s00227-021-03839-6

Momberg M, Ryan PG, Hedding DW, Schoombie J, Goddard KA, Craig KJ, Le Roux PC (2023) Factors determining nest-site selection of surface-nesting seabirds: a case study on the world's largest pelagic bird, the Wandering Albatross (Diomedea exulans). Ibis 165(1):190–203. https://doi.org/10.1111/ibi.13111

Nagel R, Coleman J, Stainfield C, Forcada J, Hoffman JI (2022) Observations of Giant Petrels (Macronectes sp.) Attacking and Killing Antarctic Fur Seal (*Arctocephalus gazella*) Pups. Aquatic Mammals 48(6):509–512

Nel DC, Ryan PG, Crawford RJ, Cooper J, Huyser OA (2002) Population trends of albatrosses and petrels at sub-Antarctic Marion

Island. Polar Biol 25(2):81–89. https://doi.org/10.1007/s003000100315
Nex F, Remondino F (2014) UAV for 3D mapping applications: a review. Applied Geomatics 6(1):1–15. https://doi.org/10.1007/s12518-013-0120-x
Paleczny M, Hammill E, Karpouzi V, Pauly D (2015) Population trend of the world's monitored seabirds, 1950–2010. PloS One. https://doi.org/10.1371/journal.pone.0129342
Parmelee DF, Parmelee JM (1987) Movements of Southern Giant Petrels ringed near U.S. Palmer Station. Antarctica Ring Migr 8:115–118
Patterson DL, Woehler E, Croxall J, Cooper J, Poncet S, Peter H-U, Hunter S, Fraser W (2008) Breeding distribution and population status of the Northern Giant Petrel Macronectes halli and the Southern Giant Petrel M. giganteus. Mar Ornithol 36:115–124
Pedersen EJ, Miller DL, Simpson GL, Ross N (2019) Hierarchical generalized additive models in ecology: an introduction with mgcv. PeerJ 7:e6876–e6876. https://doi.org/10.7717/peerj.6876
Pfeiffer S, Peter H-U (2004) Ecological studies toward the management of an Antarctic tourist landing site (Penguin Island, South Shetland Islands). Polar Rec 40(4):345–353. https://doi.org/10.1017/S0032247404003845
Phillips RA, Waluda CM (2020) Albatrosses and petrels at South Georgia as sentinels of marine debris input from vessels in the southwest Atlantic Ocean. Environ Int 136:105443. https://doi.org/10.1016/j.envint.2019.105443
Poncet S, Wolfaardt AC, Barbraud C, Reyes-Arriagada R, Black A, Powell RB, Phillips RA (2020) The distribution, abundance, status and global importance of giant petrels (*Macronectes giganteus* and M. halli) breeding at South Georgia. Polar Biol. https://doi.org/10.1007/s00300-019-02608-y
Punta G, H., G. (1995) Predation by Southern Giant Petrels Macronectes giganteus on Adult Imperial Cormorants Phalacrocorax atriceps. Mar Ornithol 23:166–167
Quintana F, Dell'Arciprete OP, Copello S (2010) Foraging behavior and habitat use by the Southern Giant Petrel on the Patagonian Shelf. Mar Biol 157(3):515–525. https://doi.org/10.1007/s00227-009-1337-4
Raoult V, Colefax AP, Allan BM, Cagnazzi D, Castelblanco-Martínez N, Ierodiaconou D, Johnston DW, Landeo-Yauri S, Lyons M, Pirotta V, Schofield G, Butcher PA (2020) Operational protocols for the use of drones in marine animal research. Drones. https://doi.org/10.3390/drones4040064
Ridoux V (1994) The Diets and Dietary Segregation of Seabirds at the Subantarctic Crozet Islands (Part 2). Mar Ornithol 22:129–192
Rogers AD, Frinault BAV, Barnes DKA, Bindoff NL, Downie R, Ducklow HW, Friedlaender AS, Hart T, Hill SL, Hofmann EE, Linse K, McMahon CR, Murphy EJ, Pakhomov EA, Reygondeau G, Staniland IJ, Wolf-Gladrow DA, Wright RM (2020) Antarctic futures: an assessment of climate-driven changes in ecosystem structure, function, and service provisioning in the Southern Ocean. Ann Rev Mar Sci 12(1):87–120. https://doi.org/10.1146/annurev-marine-010419-011028
Roman L, Paterson H, Townsend KA, Wilcox C, Hardesty BD, Hindell MA (2019) Size of marine debris items ingested and retained by petrels. Mar Pollut Bull 142:569–575. https://doi.org/10.1016/j.marpolbul.2019.04.021
Rootes DM (1988) The status of birds at Signy Island, South Orkney Islands. Br Antarct Surv Bull 80:87–119
Rush GP, Clarke LE, Stone M, Wood MJ (2018) Can drones count gulls? Minimal disturbance and semiautomated image processing with an unmanned aerial vehicle for colony-nesting seabirds. Ecol Evol 8(24):12322–12334. https://doi.org/10.1002/ece3.4495
Ryan PG, Sommer E, Breytenbach E (2008) Giant petrels Macronectes hunting northern rockhopper penguins Eudyptes moseleyi at sea. Ardea. https://doi.org/10.5253/078.096.0116
Schmidt AE, Ballard G, Lescroël A, Dugger KM, Jongsomjit D, Elrod ML, Ainley DG (2021) The influence of subcolony-scale nesting habitat on the reproductive success of Adélie penguins. Sci Reports. https://doi.org/10.1038/s41598-021-94861-7
Schoombie J, Schoombie S, Connan M, Jones CW, Risi M, Craig KJ, Smith L, Ryan PG, Shepard ELC (2023) Impact of wind on crash-landing mortality in grey-headed albatrosses Thalassarche chrysostoma breeding on Marion Island. Mar Ecol Prog Ser, WIND. https://doi.org/10.3354/meps14292
Schreiber, E. A., & Burger, J. (2001). *Breeding Biology, Life Histories, and Life History–Environment Interactions in Seabirds*. https://api.semanticscholar.org/CorpusID:199063107
Schulz UH, Krüger L, Petry MV (2014) Southern giant petrel Macronectes giganteus nest attendance patterns under extreme weather conditions. Zool Sci 31(8):501–206
Techow NMSM, O'Ryan C, Phillips RA, Gales R, Marin M, Patterson-Fraser D, Quintana F, Ritz MS, Thompson DR, Wanless RM, Weimerskirch H, Ryan PG (2010) Speciation and phylogeography of giant petrels Macronectes. Mol Phylogenet Evol 54(2):472–487. https://doi.org/10.1016/j.ympev.2009.09.005
Trevizani TH, Colabuono FI, Petersen ES, Petry MV, Taniguchi S, Montone RC, Figueira RCL (2022) Mercury and selenium levels in feathers of Southern Giant Petrels (*Macronectes giganteus*) from South Shetland Islands, Antarctica. J Trace Elements and Minerals 2:100020. https://doi.org/10.1016/j.jtemin.2022.100020
Warham J (1962) The Biology of the Giant Petrel *Macronectes giganteus*. The Auk. https://doi.org/10.2307/4082519
Westoby MJ, Brasington J, Glasser NF, Hambrey MJ, Reynolds JM (2012) 'Structure-from-Motion' photogrammetry: a low-cost, effective tool for geoscience applications. Geomorphology 179:300–314. https://doi.org/10.1016/j.geomorph.2012.08.021
Wienecke B, Leaper R, Hay I, van den Hoff J (2009) Retrofitting historical data in population studies: Southern giant petrels in the Australian Antarctic Territory. Endangered Species Res 8(3):157–164. https://doi.org/10.3354/esr00201
Wood, S. (2023). *mgcv: Mixed GAM Computation Vehicle with Automatic Smoothness Estimation* (1.9–1) [Computer software]. https://cran.r-project.org/web/packages/mgcv/