**Population size and trends of southern giant petrels (*Macronectes giganteus*) nesting at Signy Island, South Orkney Islands**

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**Abstract**

The southern giant petrel (*Macronectes giganteus*) has a circumpolar distribution and breeds on subantarctic islands and a few continental Antarctic sites. Although this species has recently been down-listed to ‘Least Concern’ by the World Conservation Union (IUCN), there are strong fluctuations in abundance and variable long-term trends recorded at different sites. Systematic, long-term monitoring is essential to determine drivers underlying its population dynamics. Here, we examine long-term changes in population size and productivity of southern giant petrels at Signy Island, South Orkney Islands. Comparing estimated numbers of breeding pairs over the whole island in 2000/01, 2005/06, 2009/10 and 2014/15 with historical data revealed several phases of population change; a 64% decline (6.2% per annum) from 1968/69 to 1984/85, a 162% increase (6.2% per annum) to 2000/01, stability until 2005/06, a 56% decline (18.3% per annum) to 2009/10, and stability until 2014/15. This represents a 1.8% decline per annum between 1968/69 and 2014/15. Annual counts within focal study areas suggested a more rapid increase from 1996/97 to 2006/07, but the same downward trend from 2006/07 to present, underlining potential pitfalls in inferring trends from part-island counts. There was also a 20% decline in breeding success from 1996/97 to 2014/15. Our results indicate substantial fluctuations in southern giant petrel abundance at Signy Island over 4-5 decades, and a recent decline in breeding numbers and success. As the southern giant petrels breeding at the South Orkney Islands represent ~5-10% of the global population, continuation of these declines would be of high conservation concern.

**Keywords:** Antarctica, petrel, productivity, population, fluctuations, Procellariidae

# Introduction

The southern giant petrel (*Macronectes giganteus*) is currently designated by the IUCN as “Least Concern”, having been down-listed from “Near-threatened” in 2009, following a re-appraisal of population trends ([IUCN 2014](#_ENREF_18)) The species has a circumpolar breeding range that includes numerous subantarctic archipelagos, islands off Patagonia and coastal Antarctica, and, in the South Atlantic region, extends from Gough Island and the Patagonian Shelf to the southern Antarctic Peninsula ([Hunter 1984](#_ENREF_17); [Patterson et al. 2008](#_ENREF_25); [Woehler et al. 2001](#_ENREF_36)). The total world breeding population is estimated to be approximately 50,000 pairs, although many of the counts on which this is based were collected more than a decade ago and there are considerable data gaps ([ACAP 2014b](#_ENREF_2)). Information on population trends is even patchier because continuous monitoring is in place at few sites ([ACAP 2014b](#_ENREF_2); [Wienecke et al. 2009](#_ENREF_35)). Globally, southern giant petrels were believed to have suffered a 20% decline in breeding numbers between the early 1980s and late 1990s ([Patterson et al. 2008](#_ENREF_25)). However, this figure must be viewed with caution since not all breeding sites were surveyed repeatedly over this time ([Wienecke et al. 2009](#_ENREF_35)), and between 15% and 40% of all adult birds may defer breeding in any given season ([Voisin 1988](#_ENREF_34)). In addition, because censuses are often opportunistic, inconsistencies and biases in long-term trends can result from variability in the timing of counts; reliability is particularly low from surveys late in the season if these are not corrected for previous breeding failure ([Lynch et al. 2008](#_ENREF_19); [Patterson et al. 2008](#_ENREF_25)). Furthermore, counts are not comparable if techniques differ among survey sites or years, including the count unit ([e.g. nests, adults, eggs, chicks, Creuwels et al. 2005](#_ENREF_10)) or if the boundaries of the count area change ([Creuwels et al. 2005](#_ENREF_10); [Patterson et al. 2008](#_ENREF_25)).

Although the accuracy of the underlying census data are variable, recent analyses nevertheless suggest there are major differences among breeding islands and island groups in the long-term population trajectories of southern giant petrels ([Creuwels et al. 2005](#_ENREF_10); [Lynch et al. 2008](#_ENREF_19); [Patterson et al. 2008](#_ENREF_25); [Quintana et al. 2006](#_ENREF_27); [Reid and Huin 2008](#_ENREF_28); [Woehler and Croxall 1997](#_ENREF_37)). There is also clear evidence for substantial fluctuations in numbers from one season to the next at a number of localities, including the Falkland Islands, South Shetland Islands, and western Antarctic Peninsula ([Gonzalez-Zevallos et al. 2013](#_ENREF_16); [Lynch et al. 2008](#_ENREF_19); [Patterson et al. 2008](#_ENREF_25); [Quintana et al. 2006](#_ENREF_27); [Reid and Huin 2008](#_ENREF_28)). The reasons for this high variability in long-term trends are unknown, not helped by the lack of information on adult or juvenile survivorship ([ACAP 2014b](#_ENREF_2); [Patterson et al. 2008](#_ENREF_25); [Van Den Hoff 2011](#_ENREF_32)). Suggested causes of the long-term declines range from the effects of human disturbance, and habitat destruction or predation by invasive species on land ([ACAP 2014b](#_ENREF_2); [Braun et al. 2012](#_ENREF_4); [Gonzalez-Solis et al. 2000](#_ENREF_15); [Micol and Jouventin 2001](#_ENREF_21); [Rootes 1988](#_ENREF_29)), to increased mortality caused by conflict with fisheries and possibly sub-lethal or lethal impacts of increased pollutant loads ([ACAP 2014b](#_ENREF_2); [Copello and Quintana 2003](#_ENREF_7); [Favero et al. 2003](#_ENREF_11); [Gonzalez-Solis et al. 2000](#_ENREF_15); [Nel and Nel 1999](#_ENREF_22); [Nel et al. 2002](#_ENREF_23)). Hence, more comprehensive long-term data on demography and threats are essential if we are to properly understand the key drivers of population change in this species.

An estimated 7% of global numbers of southern giant petrels breed in the South Orkney Islands ([ACAP 2014b](#_ENREF_2)), although given the uncertainties associated with many counts, this value should be viewed with caution. Within the South Orkneys, published data on southern giant petrel nests or chicks are available for Laurie Island ([Coria et al. 1996](#_ENREF_8); [Coria et al. 2011](#_ENREF_9)), and for Signy Island, where there appeared to have been a long term decline by 1984/85, based on a rough estimate of 5000 individuals in 1936 ([Ardley 1936](#_ENREF_3)), and more accurate counts at various stages of breeding in 1968/69 ([3200 pairs, Conroy 1972](#_ENREF_6)), 1975/76 ([1600 pairs, Brook 1975](#_ENREF_5)) and 1984/85 ([1093 pairs, Price 1985](#_ENREF_26)). Whether this decline at Signy was reflected in numbers elsewhere in the South Orkney Islands, and whether the downward trend has persisted to the present day remained unknown. Here, we present a 17-year dataset on changes in numbers and breeding success of southern giant petrels in nine areas at Signy Island monitored annually in austral summers 1996/97 to 2014/15, and more comprehensive all-island censuses in four seasons (2000/01, 2005/06, 2009/10 and 2014/15). We compare these data with historical records at Signy Island, and results from censuses at another island, Laurie Island, in the South Orkney archipelago, and evaluate trends and variability in counts at these localities for comparison with populations elsewhere.

# Materials and Methods

Study site and species

The study was carried out on southern giant petrels breeding at Signy Island, South Orkney Islands (60°42΄S, 45°36΄W, Fig. 1). At this site, this species breeds in scattered groups that vary in size from 5-162 nests, with each aggregation consisting of nests less than 15 metres apart (also see Creuwels et al. ([2005](#_ENREF_10))). All breeding southern giant petrels on the island are located along the west coast (Fig. 1). The nests are found on rocky outcrops or gently sloping ground above cliffs of an approximately uniform elevation, and are exposed to the prevailing winds ([Conroy 1972](#_ENREF_6)).

Survey methods

All surveys consisted of direct ground counts carried out by a minimum of two observers. Each area was surveyed at least twice on the same day (and to ensure consistency, surveys were repeated until the two count totals were within 10%), and the mean count used in further analyses. Egg laying takes place in October-November at Signy Island (mean laying data 4th November, [Conroy 1972](#_ENREF_6)), (range 30th October to 8th November), and apparently occupied nests (AONs; Creuwels et al. 2005), at which an adult appeared to be incubating, were counted in December or early January after all pairs were assumed to have laid. AONs were used as a proxy for the number of breeding pairs on the island, following Creuwels et al. ([2005](#_ENREF_10)). Positions of nesting groups were recorded with a hand-held GPS (Garmin GPS 60). To reduce disturbance, nests were usually viewed from a distance of 30-40m, and closer only if necessary. Incubating birds always remained on their nests when approached during censuses, whereas birds that were not incubating often took flight, which reduced the likelihood of counting nonbreeders or failed breeders. AONs were counted between 6 December and 2 January in nine study areas (M1-5, M6, M7, M8 and M9; Fig.1) in all austral summers from 1996/97 to 2014/15, with the exception of 1997/98 and 2010/11, and over the entire island in 2000/01, 2005/06, 2009/10 and 2014/15. In 1997/98 and 2010/2011, counts could not be carried out until late January for logistical reasons, and, given the late stage (post-hatching), the data are not considered further here. Counts from five study areas (M1-5) were pooled due to close proximity, which rendered it impossible to reliably distinguish individual area boundaries.

Counts of chicks were made in areas M1-M9 every year from 6-26 March in 1997 to 2015. By this date, chicks were approximately two months old (mean hatching date 5th January, [Conroy 1972](#_ENREF_6)), and no longer brooded or guarded by a parent, which made counting straightforward. It was not possible to count chicks any later in the season because no personnel remained on the island after late March. Although southern giant petrel chicks do not fledge at Signy Island until late April ([Conroy 1972](#_ENREF_6)), survival of chicks from March until fledging was >97% both at Signy in 1968/69 ([Conroy 1972](#_ENREF_6)) and at Bird Island, South Georgia from 2005/06 to 20013/14 (BAS unpublished data). Therefore, the count of chicks at Signy Island in March, divided by the number of breeding pairs (estimated from AONs; see below), was considered to be a good proxy for breeding performance ([Quintana et al. 2006](#_ENREF_27)), and is referred to hereafter as ‘breeding success’.

Correction factors

The mean laying date in both 1963/64 and 1968/69 on Signy was 13 November ([Conroy 1972](#_ENREF_6)), which is very similar to the annual mean values of 10-12 November in 2005/06 to 2014/15 on Bird Island, South Georgia (British Antarctic Survey unpublished data). Hatching success in 1968/69 ([60.3%; Conroy 1972](#_ENREF_6)) is also very similar to the overall mean in 2000/01 to 2013/14 at Bird Island of 60.0% (British Antarctic Survey unpublished data). This suggests timing of breeding and failure rate during incubation are broadly comparable at the two sites. At Bird Island, all marked nests (*n* = 128 to 195) in a well-demarcated study area were monitored each year between 2005/06 and 2014/15 on visits every 1-2 days during the laying period, and weekly thereafter. Correction factors based on the mean proportion of nests that had failed by the same date at Bird Island in 2005/06-2014/15 (except 2009/10 when hatching success was exceptionally low), were applied to the counts in December at Signy Island to estimate the original number of breeding pairs (hereafter ‘estimated breeding pairs’). Historical population estimates for Signy were also available from data presented in Conroy ([1972](#_ENREF_6)) and Rootes ([1988](#_ENREF_29)) .

Population trends were explored using log-linear regression models with Poisson error terms using the program TRIM (Trends and Indices for Monitoring Data; Pannekoek and van Strien 1996). This allowed for missing observations, and took into account over-dispersion and serial autocorrelation. A stepwise selection procedure was used to identify change points that were significant at P < 0.01, based on Wald tests. Rates of population change per year are presented as exp ((1/ty2-y1) x ln(Ny2/Ny1))-1, where Ny1 is the initial count, Ny2 is the count in a subsequent year, and ty2-y1 is the interval in years. In addition, changes in estimated breeding pairs and breeding success (untreated and log-transformed) were evaluated using generalized linear (GLM) and first order polynomial regression models with a Poisson and Gaussian error structure, respectively, using the *glm* function in program R. Best fitting parameters were obtained by maximum likelihood estimation using the iterative re-weighted least squares (‘Fisher’) approach. Significance of model fits was measured using *z*-statistics, with two-tailed *p*-values. Relative support for models was evaluated by comparing Akaike Information Criterion (AIC) scores. Statistical calculations were performed using the R Project for Statistical Computing ([www.r-project.org](http://www.r-project.org)).

**Results**

Population trends

The total estimated breeding pairs (based on AONs corrected for breeding failure) in the areas M1 –M9 monitored annually at Signy Island increased by 169% (10.4% per annum) from 1996/97 (230 pairs) to a peak in 2006/07 (618 pairs), then decreased substantially, by 46% (7.4% per annum) to 2014/15 (335 pairs) (Table 1, Fig. 2). In stepwise selection in TRIM, only one change point was deleted (2006) indicating all other changes in slope were significant. Similarly, in the GLM, the relationship between the number of estimated breeding pairs and year showed a poor fit to a linear trend, but a significant fit to both first and second order polynomial models with Poisson error structure (Supplementary Figure 1). The second order polynomial, suggesting an increase followed by a decline over the study period, was a better fit to these data, with much lower AIC. However the residual deviance on both models was high, indicating the data are over dispersed and not fully explained by these simple models (Supplementary Figure 1).

The estimated number of breeding pairs for the entire island changed little (by 2% overall, or 0.4% per annum) between 2000/01 (2869 nests) and 2005/06 (2931 nests), then decreased substantially, by 55% (18% per annum), to 2009/10 (1303 nests), before increasing slightly, by 4% (0.7% per annum), to 2014/15 (Table 2, Fig.2). This represented a decline of 53% (5.2% per annum) from the first to last of these more recent surveys (2000/01 to 2014/15). In contrast, the changes in estimated breeding pairs in corresponding periods in the study areas on Signy that were counted annually (M1-M9) were a substantial increase (10.5% per annum) between 2000/01 and 2005/06, followed by a decline; overall, the decline from 2000/01 to 2014/15 was 5.6% (0.4% per annum), which is less than on the island as a whole (Table 1, Fig.2). Changes in population size in areas M1-M9 were therefore not in parallel with those apparent from the four all-island surveys that took place within the time period.

Comparison between the more recent counts and historical data for the whole of Signy Island indicates a 56% decline (1.8% per annum) between 1968/69 and 2014/15 (Table 2, Fig. 2). However, this masks the changing trends within that period: a very substantial decline (by 64% or 6.2% per annum) between 1968/69 and 1984/85 and an increase of 162% (6.2% per annum) to 2000/01, the first year of the recent surveys (Table 2, Fig.2). In the stepwise selection procedure in TRIM, the changes in slope associated with each successive survey were all significant.

Breeding success

Breeding success (chicks counted in March/estimated breeding pairs) varied substantially (from 8.5% to 61.7%) in the study areas (M1-M9) over the period from 1996/97 to 2014/15 (Table 1, Fig. 2). Breeding success was higher in the late 1990s than in more recent years (Table 1, Fig. 2). The best fitting general linear model was a first order polynomial, showing a decline in breeding success over time (Supplementary Figure 1).

### Discussion

Population trends at Signy Island

In terms of recent trends, the whole-island counts at Signy indicate that the number of breeding pairs of southern giant petrels was relatively stable from 2000/01 to 2005/06, but then declined to 2009/10. This decline, but not the prior period of stability, is mirrored in counts of the nine study areas (M1-M9) (Fig. 2). Although the trends are somewhat similar in direction, the differences in magnitude indicate the limitations of infererence from part-site compared with whole-island counts. The increase of breeding pairs in the M1-M9 study areas from 2000/01 to 2005/06 is likely to represent immigration of established breeders from elsewhere on the island. Our results therefore have important implications for monitoring methodologies in general, in highlighting the need to supplement frequent monitoring of small areas that can be achieved without extensive effort with less frequent whole-island censuses, for better inferring wider-scale population trends. Critically, the limitations of some aspects of the survey design at Signy Island should be recognised. Since some southern giant petrel pairs would have failed in their breeding attempt and abandoned their nests prior to our annual fieldwork, we employed a correction factor to estimate the original number of pairs that laid based on data on failure rates collected over many years at Bird Island, South Georgia. We also made the assumption that no chicks counted in the survey in March fail to fledge, so realised breeding success may be lower than estimated here.

Comparisons with historical data (Conroy 1972 and Rootes 1988), suggest that prior to our surveys, the population at Signy Island had declined from 3,067 pairs in 1968/69 to 1,600 pairs in 1975/76, and then to 1,093 pairs in 1984/85, before a substantial increase to the 2,869 pairs recorded in the first whole-island count conducted in 2000/01 by our study (Table 2). Unfortunately, there is little information on survey effort and rigour, and more than a decade passed between each of the historical counts. Hence, conclusions about longer-term population trends should be made cautiously. Nevertheless, these survey data appear to indicate several phases of population change for southern giant petrels at Signy Island; a substantial decline from the late 1960s to mid 1980s, a major increase to the early 2000s, and then a subsequent decline from the late 2000s to the present.

Long-term monitoring of sympatric Adélie *Pygoscelis adeliae* and chinstrap *P. antarctica* penguins at Signy Island indicates significant declines at specific study colonies after the mid 1990s, in parallel with regional warming and a reduction in seasonal sea ice ([Forcada and Trathan 2009](#_ENREF_12); [Forcada et al. 2006](#_ENREF_13)). These declines, since corroborated by surveys of the entire island, have continued to the present (British Antarctic Survey unpublished data). Since penguins are known to form an important part of their diet at Signy Island ([Conroy 1972](#_ENREF_6)), the recent decline in southern giant petrels may be influenced by the ongoing decline in penguin abundance, or by the same environmental factors. A comparative analysis of the dynamics of these populations would be required to determine these relationships in more detail ([e.g., Forcada and Trathan 2009](#_ENREF_12)).

Population trends across the South Atlantic

The population trends at Signy Island can be viewed in the context of those at other sites within the South Orkney Islands. Counts of Laurie Island indicate an increase in breeding pairs of 2.9% per annum from 1994/95 to 2010/11 ([ACAP 2014a](#_ENREF_1); [Coria et al. 2011](#_ENREF_9)). Given that the data from Signy Island also indicate an increase from the mid 1990s to the mid 2000s, but follow this with a steep decline in numbers and breeding success (Fig. 2), more recent data from Laurie Island would be very useful for determining if the recent decline at Signy Island is apparent elsewhere in the South Orkneys.

Populations of southern giant petrels have shown large fluctuations in recent decades at broader scales (ACAP 2014a), with increases on the Falkland Islands (Reid and Huin 2008), Gough Island (Cuthbert and Sommer 2004), some sites in the South Shetland Islands (Lynch et al. 2008), and the northern part of the Danco Coast, Antarctica (Gonzalez-Zevallos et al. 2013), stable numbers at the Frazier Islands (Creuwels et al. 2005), and decreases at Pointe Géologie, East Antarctica (Micol and Jouventin 2001), Heard, Macquarie, Marion and King George islands (Patterson et al. 2008). Although many time series are from different periods and counts from many islands are unavailable, the most recent synthesis concluded that globally, southern giant petrels were increasing (ACAP 2014a).

Given that southern giant petrels at other island groups in the South Atlantic are mostly increasing, the reason for the recent decline at Signy Island is unclear. Breeding success has declined since the late 1990s/early 2000s, but was still >40% in most years up to and including 2006/07 (Fig. 2). As southern giant petrels do not breed until 5-13 years of age ([Conroy 1972](#_ENREF_6)), and the first year that the population decline became apparent in the study areas monitored annually was 2007/08, it seems that the drop in the number of breeding birds cannot be the consequence of reduced productivity in preceding years leading to a shortage of new recruits. Evidence from other studies indicates that on average, 30% of potential breeding adults do not breed each year ([Hunter 1984](#_ENREF_17); [Quintana et al. 2006](#_ENREF_27); [Voisin 1988](#_ENREF_34)). Hence, the recent decline could potentially reflect higher breeding deferral, perhaps in response to natural variability in snow cover or some other localised factor that has also affected breeding success, rather than a widespread deterioration in the environment that has reduced adult survival. If so, the apparently unfavourable conditions for breeding may be temporary. However, it is clearly important to determine the trends in both population size and breeding success by continued monitoring at Signy Island, ideally coupled with surveys of other breeding localities using standardised methodologies elsewhere within the South Orkney Islands.

According to Patterson et al. (2008), there are an estimated 3,400 breeding pairs of southern giant petrels in the South Orkney Islands. This appears to be an extrapolation from the data available up to 1999/2000 for some islands in the group (Signy and Laurie islands, Powell Island and nearby Christoffersen and Michelsen islands). However, there are no published survey data from the largest island, Coronation Island, which is likely to hold substantial numbers, given the suitability of the habitat and the high abundance of other breeding seabirds, including Adelie, chinstrap and gentoo penguins *Pygoscelis papua*, southern fulmars *Fulmarus glacialoides* and South Georgia shags *Phalacrocorax atriceps georgianus*. Combining the most recent surveys at Laurie Island of 624 pairs in 2010/11, ([ACAP 2014a](#_ENREF_1)), Powell Island ([613 pairs in 1982/83, Patterson et al. 2008](#_ENREF_25)) and Signy Island (1,330 pairs in 2009/10; this study), with a potential 1,000-1,500 breeding pairs at Coronation Island, which is not unreasonable given its large size, would suggest a total population for the South Orkney Islands of 3,500-4,000 pairs, similar to Patterson et al. (2008), and equivalent to 7-8% of the world total for this species ([ACAP 2014b](#_ENREF_2)). Given the importance of the population of this island group in global terms, it is clear that priorities for monitoring include surveys of Coronation Island (never surveyed) and Powell Island (last surveyed in 1982/83), and continued monitoring at Signy and Laurie islands to determine whether the decline at Signy Island is continuing or has become evident elsewhere.

Environmental drivers and future directions

We were unable to examine the effects, if any, of seasonally adverse weather conditions such as heavy snowfall prior to or during early incubation. Extreme snowfall can have a significant negative effect on surface-nesting petrels ([Van Franeker et al. 2001](#_ENREF_33)). Creuwels et al. ([2005](#_ENREF_10)) also note that breeding southern giant petrels take advantage of increased availability of open ground in seasons with less snow cover. In November 2007, extensive, deep snow cover was noted at Signy Island: all of the study areas (M1-9) were covered with drifting snow and many incubating adults were observed with only the top of their heads protruding (Dunn, pers. obs.). Such adverse conditions are likely to be responsible for the record low count of breeding pairs, and poor breeding success (Table 1). The collection of a range of environmental parameters, including air temperature and precipitation may therefore reveal relationships with population dynamics. Since both the identification of population changes and their environmental (including anthropogenic) drivers depend ultimately on the quality of the underlying data, standardised surveys are essential, particularly given the influence of stochastic events ([Patterson et al. 2008](#_ENREF_25)). Use of remote technology ([Newbery and Southwell 2009](#_ENREF_24); [Southwell et al. 2010](#_ENREF_30)), may also improve the quality of the data or validate assumptions about nest failure rates, overcoming the limitation of lack of personnel during the early and later stages of each breeding season. Remotely-sensed satellite imagery may offer a further alternative mechanism for estimating the size of seabird breeding populations; however, it may be difficult to distinguish breeding and non-breeding southern giant petrels from surrounding terrain when there may be little or no guano signature, and to obtain cloud-free imagery at the optimal times of year ([Fretwell et al. 2015](#_ENREF_14); [Lynch et al. 2012](#_ENREF_20); [Southwell et al. 2013](#_ENREF_31)).

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**Ethical Approval**

All procedures performed in studies involving animals were in accordance with the ethical standards of the institution or practice at which the studies were conducted.

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**Figure captions**

**Fig. 1** Map showing the location of South Orkney Islands, and distribution of southern giant petrel study areas on Signy Island. Black dots indicate approximate positions of all nesting areas on the island, including M1 to M9 (labelled).

### Fig. 2 Trends in southern giant petrels counted at Signy Island. (A) Estimated breeding pairs counted annually in study areas (M1-M9). (B) Breeding success (chicks/estimated breeding pairs) in study areas (M1-M9). (C) Total estimated breeding pairs on Signy Island.