Running title: geolocator deployment and impacts on survival

No detectable effect of geolocator deployment on the short- or long-term apparent survival of a tropical seabird.

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A wide range of biologging devices are now commonly deployed to study the movement ecology of birds, but deployment of these devices is not without its potential risks and negative impacts on the welfare, behaviour and fitness of tagged individuals. However, empirical evidence for the effects of tags is equivocal. Global location sensing (GLS) loggers are small, light level recording devices that are well suited to studying the large-scale migratory movements of many birds. However, few published studies have examined their impact on adult survival, a key demographic rate for long-lived species, such as seabirds. To address this, we collate a long-term mark-recapture data set in conjunction with a 10-year GLS tagging programme and examine the impact of tarsus-mounted GLS loggers on the adult apparent survival probabilities of a medium-sized tropical gadfly petrel. We found no evidence to indicate that deployment of GLS loggers affected apparent adult survival probabilities either in the short-term, i.e., during deployment, or in the long-term, i.e., from carrying a device at some point in the past. Annual adult apparent survival was estimated at 0.965 (CIs 0.962, 0.968) during 1993-2018. Our findings suggest that using GLS loggers to document the movements of medium-sized gadfly petrels over multiple years is a viable technique without negatively impacting adult survival. This result has potential relevance to movement ecology studies of other ecologically and morphologically similar seabirds through GLS logger deployments.

Keywords: Pterodroma, tropical seabird, long-term study, mortality, geolocators, biologging, migration, tag impact.

A wide range of biologging devices (hereafter referred to as tags) are now commonly used to study the movement ecology (e.g., foraging and migratory behaviour) of birds. For example there are more than 1,550 seabird datasets deposited in the Seabird Tracking Database (www.seabirdtracking.org) (BirdLife International 2021) and animal tracking data repository Movebank (www.movebank.org) (Wikelski *et al.* 2021). However, the deployment of tags is not without its potential risks and adverse consequences on welfare and behaviour. This is evidenced by the extensive literature documenting and quantifying the effects of tags on; breeding propensity and success, parental care, offspring quality, body condition, foraging behaviour, energetic expenditure, mortality, social behaviour and physical impairment in individual birds and the consequences of these effects on research findings (Barron *et al.* 2010, Vandenabeele *et al.* 2011, Bridge *et al.* 2013, Bodey *et al.* 2018, Geen *et al.* 2019). While these meta-analyses show mixed evidence for the effects of tags they also highlight that not all published studies consider undertaking a direct examination of the potential impacts on the welfare, behaviour and fitness of tagged individuals (Vandenabeele *et al.* 2011, Geen *et al.* 2019). During the last 30 years, the proportion of tracking studies including an examination of the effects of tag deployments has declined (Geen et al. 2019, but see Gillies et al. 2020 for a recent example of where this has been comprehensively examined). Many studies now rely on precedents and procedures described elsewhere for ecologically and/or morphologically similar species and apply these alongside a proviso that tags and associated attachments should be less than 5% of an individual’s mass, which has been revised to a 3% threshold (Phillips *et al.* 2003, Barron *et al.* 2010, Bodey *et al.* 2018). This latter point is likely due, in principle, to ongoing device miniaturisation and recognition that in some studies devices equating to 5% body mass could have effects on behaviour (Phillips *et al.* 2003, Bodey *et al.* 2018). However, the progress of this may be countered by miniaturisation allowing the inclusion of more components, thereby increasing the functionality of tags but not necessarily reducing the relative mass of a tag to an animals body mass (Portugal & White 2018).

With an inevitable increase in the number of tracking studies and the continuing trend towards tags with greater capabilities, smaller dimensions, lower mass and improved memory and battery life, deployments are only likely to increase in the future. Global location sensing loggers, commonly known as geolocators and hereafter referred to as GLS, are light level recording devices and one of the smaller tags available (Burger & Schaffer 2008, Bridge *et al.* 2013). GLS work on the principle of solar geolocation and are frequently used to track the large-scale migratory movements of a wide range of bird taxa (Costantini & Møller 2015, Weiser *et al.* 2016, Kürten *et al.* 2019, Brlík *et al.* 2020). However, like other tags, the deployment of GLS has been shown to influence a range of fitness metrics in birds, such as condition, breeding performance and survival (Costantini & Møller 2015, Weiser *et al.* 2016, Brlík *et al.* 2020, Pakanen *et al.* 2020) with the level of impact often increasing in relation to the relative load of the GLS deployed (Brlík *et al.* 2020) and differing according to attachment method (Costantini & Møller 2015, Brlík *et al.* 2020).

GLS are well suited to studying the large-scale migratory movements of many, particularly pelagic, seabird species. For example, 66% of the 130 species currently included in the Seabird Tracking Database are tagged with GLS (BirdLife International 2021). These devices can be deployed on seabirds using a range of attachment methods (Burger & Schaffer 2008), however the most commonly employed technique is to attach the tag to a leg ring (i.e. tarsus mounted). A recent review identified 50 seabird studies examining the impact of tarsus-mounted GLS on individual fitness metrics, such as body condition, reproductive performance and return rate (Kürten *et al.* 2019). However, while most studies made some examination of the impact on body mass only 14 studies examined the impact on return rates. Furthermore, studies explicitly assessing the medium- to long-term impact of GLS deployment on survival rates by using mark-recapture modelling techniques were lacking. Return rates cannot be used as proxies for survival rates due the biases introduced by individuals being potentially missed (Lebreton *et al.* 1992). Instead, mark-recapture modelling techniques are needed to account for this structure in the data. The apparent lack of published mark-recapture studies examining the effects of tags may well reflect the long-term effort required to collect these datasets (Horswill *et al.* 2018), which are also likely to exceed the duration of a tracking study. As a result, our understanding of the long-term impacts of GLS deployments on the survival of seabirds remains extremely limited.

Procellariiformes (del hoyo *et al.* 2014) is an order of seabirds that comprises four families. Of these Diomedeidae (albatrosses) and Procellariidae (including gadfly petrels), have declined faster than any other family of seabirds (Croxall *et al.* 2012). Key threats to these species include bycatch in fisheries and invasive alien species at breeding colonies (Dias *et al.* 2019). Therefore, having a good understanding of their at-sea distribution outside of the breeding season and any potential spatial overlap with threats such as fisheries bycatch is key to their conservation and to date this information has largely been derived from the deployment of tags such as GLS. For example, 60 of the 138 recognised Procellariiformes species, have GLS-derived datasets in the Seabird Tracking Database (BirdLife International 2021). Seabirds typically have slow life history strategies, and Procellariiformes are the most extreme order, for example some species have a very delayed age of first breeding and some are also biennial breeders (Saether & Bakke 2000). As a result, impacts on rates of adult survival are likely to be highly influential to the population dynamics and viability of these species. Therefore, given the current (and potential) use of GLS to study their ecology, and a trend towards making tag deployments of greater than one year, it is crucial that any effects on survival are understood (Geen *et al.* 2019).

In this study, we use long-term mark-recapture data in conjunction with a 10-year GLS tagging programme to examine the impact of GLS deployments on adult apparent survival in medium-sized tropical gadfly petrels which breed on Round Island (Mauritius). Specifically, we examine the effects of GLS deployments on apparent survival probabilities; (i) during GLS deployment (i.e., short-term impacts) and (ii) from the point that a GLS is deployed, including following recovery (i.e., long-term impacts). To the best of our knowledge this represents the first study to date, to use an experimental and statistical approach to examine the effect of GLS loggers on the apparent survival probability of Procellariiformes. Thus, this research provides a comprehensive assessment of the impacts of a widely used tag type on a key demographic driver of population dynamics in a long-lived seabird. The findings of this study, advance our understanding of the ethical and welfare considerations associated with the use of tags to monitor seabird movements.

METHODS

Study site, species and data collection

This research was conducted on the gadfly petrels breeding at Round Island Nature Reserve (219ha) (19.85^{o} South 57.78^{o} East) Mauritius, Indian Ocean (Supporting Information Fig. S1). The classification of the petrel on Round Island has proved confusing since its discovery in 1948, and while it is currently classified as the Trindade Petrel (*Pterodroma arminjoniana*) recent genetic evidence suggests that there are at least three species of *Pterodroma* (*P. arminjoniana*, *P. heraldica* and *P. neglecta*) breeding and hybridising on the island (Brown *et al.* 2010, Brown *et al.* 2011, Booth Jones *et al.* 2017). Round Island Petrels, as they are known locally, hereafter referred to as Petrel(s), are a long-lived medium-sized petrel (300-600 g), which nests on the surface under rock ledges and herbaceous vegetation all year round (Nicoll *et al.* 2017). We define a Petrel year, based on population-level breeding effort and the number of Petrels on the island in any given month, as June to May following (Nicoll *et al.* 2017), thereby spanning two calendar years and is referred to by the first calendar year, i.e., year 2001 = 2001/2002. When not breeding, Petrels are pelagic, typically performing a six-month migration to other regions in the Indian Ocean (Nicoll *et al*. 2017).

In 1993, a population monitoring programme was initiated involving regular surveys of breeding sites (Supporting Information Fig. S1) across the island and the ringing of chicks (aged > 70 days) and adults (with South African Bird Ringing Unit numbered rings on the right tarsus). Petrels are captured by hand at or near known nest sites across the island (Supporting Information Fig. S1) (for details see Nicoll *et al*. 2017). Prior to the establishment of a permanent field station on the island in 2001, the survey was conducted as part of four, 1-week management trips each year. Post 2001, the Petrel population has been monitored monthly. In total, 3,497 Petrels were ringed between 1993 and 2019, with on average 548 (SD = 108.4) adults recaptured each Petrel year. Recaptured adults could be of known age if originally ringed as a chick on the island or of unknown age if ringed as an adult.

Geolocator deployment

GLS (either British Antarctic Survey MK15, 16x14x6mm; 2.5 g, or Migrate Technology Intigeo C230/C330, 17x19x8mm; 3.3 g) were deployed on adult Petrels, at Round Island, between November 2009 and June 2016 to document migratory movements outside of the breeding season (see Table 1 for timings and numbers) (Nicoll *et al.* 2017). GLS were deployed and recovered primarily during the regular breeding site surveys and during specific 1-week expeditions in November 2009, 2010, 2011 and 2012. Petrels were caught by hand and GLS were attached to the left tarsus via 1 mm or 0.75 mm thick Salbex rings (an industrial grade PVC, Sallu Plastics, UK). GLS were fixed to the Salbex ring via a single cable tie and the ring applied to the leg like a standard colour ring with an overlap and closed using superglue. The total weight of the attached device was less than 4.0 g; ~1.0% of the mean adult mass. All birds receiving a GLS device were also identifiable by a South African Bird Ringing Unit metal ring placed on the other tarsus. We deployed 421 GLS on 392 adult Petrels (some Petrels were tagged with GLS twice in succession). Of these 141 were of known age. The breeding status of Petrels at the time of GLS deployment was known with certainty for only 20% of deployments (i.e., Petrels were captured while observed incubating or brooding). 80% of deployments were on Petrels captured while resting on the island and sex of individuals could not be determined in the field. Recovered GLS were deployed on Petrels for an average of 1.86 years (range; 0.62-7.52 years).

Body mass

We used Petrel body mass as a metric of individual condition. Petrels were weighed when GLS were deployed and recovered using an 800 g Pesola spring balance. Not all Petrels were weighed at the point of GLS recovery. For each Petrel where multiple GLS deployments occurred we only included body mass measurements for the first deployment and recovery to avoid any influence of prior tagging on this metric. Paired t-tests were used to explore the impact of GLS deployment on body mass.

Data analysis

We used ringing and recaptures of 2,701 adult Petrels between June 1993 and May 2019 to construct individual recapture histories. For Petrels ringed as adults the ringing event was the start of their recapture history and for those ringed as chicks we used the first (re)capture occasion as an adult (i.e., more than one year old) as the start of the recapture history (Nicoll *et al.* 2017). We used a Cormack Jolly Seber (CJS) mark-recapture model implemented in Program MARK 6.2 (White & Burnham 1999) rather than a multi-state model (Brownie *et al.* 1993) to compare the apparent survival probabilities of Petrels tagged with GLS devices

(GLS-petrels) with those that were not (non-GLS-petrels). The CJS model was preferred to a multi-state approach due to the unnatural, observer-imposed groups (equivalent to states) that Petrels were placed in as GLS were deployed and recovered and the associated limitations (see Supporting Information Appendix S1for further details). An individual's recapture history was assigned to between one and three of the following groups, reflecting GLS deployment and recovery during the study period: (i) no GLS deployment, (ii) during GLS deployment and (iii) post-GLS deployment, i.e., once GLS were recovered. For a GLS-petrel recapture history, for input into Program MARK, with GLS deployment and recovery events in bold font the assignment across the three groups would resemble:

No GLS deployment - *000000110010**1**000000000 -1 0 0;*

During GLS deployment - *000000000000**1**000**1**00000 0 -1 0;*

Post-GLS deployment - *0000000000000000**1**01010 0 0 1;*

The last three columns represent group assignment, with *-1* indicating that the recapture history ceased at the final recapture event. A recapture history for a non-GLS-Petrel (i.e., did not carry a GLS) would be assigned to the first group only, i.e., no GLS deployment, but with a *1* rather than a *-1* as the indexer.

Previous analyses of the mark-recapture data set for a prior period 1993-2012 indicated that adult Petrel apparent survival was constant but recapture probabilities varied from year to year (Nicoll *et al.* 2017). To test the underlying assumptions that (i) adult Petrel apparent survival was constant rather than time-dependent, (ii) recapture probabilities might differ between years and (iii) recapture probabilities within years might differ between Petrels (whilst carrying a GLS, after having carried a GLS or never having carried a GLS), we compared the set of models shown in Table 2. Model selection was based on corrected

Akaike's Information Criteria (QAIC) using a difference in QAIC threshold of ≥ 2 (Burnham & Anderson 2002). The most parsimonious model (Model 1) was then taken as the starting model to test for effects of GLS deployments on short- and long-term apparent survival.

Petrel apparent survival is specified as constant over the duration of this study and there is no compelling evidence for any inter-annual variation (see Table 2). However, to confidently explore the impacts of GLS deployments on apparent survival we only compared apparent survival of non-GLS-Petrels and GLS-petrels during the period of GLS deployments, i.e., 2009 to 2018. To explore the impact of tagging Petrels with GLS on their apparent survival during the period of deployment, we constructed two nested models to test the null hypothesis that apparent survival would be no different during deployment than for non-GLS-Petrels during the same period. Our alternative hypothesis was that apparent survival probabilities of adult Petrels during GLS deployment would be lower. The two models only differed in how apparent survival was specified, i.e., different between GLS and non-GLS-Petrels or not (Table 3). We used likelihood ratio tests in Program MARK to compare the two models and hence test the validity of our null hypotheses.

To explore the impact of GLS deployments on the long-term apparent survival of Petrels we constructed two nested models to test the null hypothesis that there is no variation in long-term apparent survival of adult Petrels due to GLS deployments. Our alternative hypothesis was that apparent survival probabilities of adult Petrels having carried GLS would be lower. As before, the two models only differed in how apparent survival was specified (Table 4) and were compared using a likelihood ratio test in Program MARK.

We used U-CARE v.2.3.2 (Choquet *et al.* 2009) to assess the goodness of fit of the global model (i.e., time and group-dependent). Goodness of fit test statistics are shown in the Supporting Information Appendix S2 and indicate that both transience (test 3.SR) and trap dependence (test 2.CT) occur only in the no-GLS deployment group. We believe it was not detected in the during or post gls deployment groups due to a small sample size, as the capture and recapture of all individuals were based primarily on methods used as part of the standardised survey. Given this and the small, estimated variance inflation factor (c-hat) of 1.27 (see Supporting Information Appendix S2) we did not control for transience and trap-dependence in our initial model due to the more parametrised nature of the resulting models. We did explore the possibility of controlling for transience in survival via a two-age class structured model (with no group effect) and used the resulting apparent survival probabilities to estimate the proportion of transience. However, there was no statistical support for this model (QAICc 27828.25, Number of parameters 27, QDeviance 12198.05) compared to model 6 Table 2 and we estimated the proportion of transience to be 0.003. While we do not formally account for the apparent 'lack of model fit', as identified by the GOF tests, this evidence suggests that this may in fact have arisen by chance, where c-hat is very close to 1, and hence any biases associated with this on estimated apparent survival rates may be negligible. We did account for the overdispersion identified, by the application of a variance inflation factor (c-hat) of 1.27 in Program MARK.

Recapture probability was specified as time- and group-dependent between 1994 and 2018 to reflect the variation in survey effort over the study period (Nicoll *et al.* 2017), and any possible difference in effort invested in targeting Petrels with GLS for recapture (see Table 2).

Potential confounding factors

As our study was not based on a formal experimental design there could be a range of biases associated with GLS-Petrels compared to non-GLS-Petrels with consequences for the results. While we were unable to formally test for these by including covariates in the survival modelling approach, due to missing data for many individuals leading to model convergence issues, we retrospectively tested (where possible) for potential biases between GLS-Petrels and non-GLS-Petrels that might mask any real differences in apparent survival probabilities. Firstly, we tested (*t*-test) for any age differences between 141 known aged Petrels at the point of GLS deployment with a set of known aged non-GLS-Petrels recaptured during the same period. Secondly, we compared (*t*-test (log transformed)) the body mass of 373 GLS-Petrels (not all Petrels were weighed when GLS were deployed) at the time of GLS deployment with non-GLS-Petrels weighed at the point of ringing. Finally, we examined (*t*-test (arcsine transformed)) if the hybrid status of the Petrels on Round Island (Brown *et al.* 2010, Brown *et al.* 2011, Booth Jones *et al.* 2017) via the genetic makeup of individuals (i.e., the contribution of one source population in this case Trindade - see Supporting Information Appendix S3 for details as to how this was estimated for individuals) varied between GLS-Petrels (220 individuals) and non-GLS-Petrels.

RESULTS

Body mass

In total, 327 (78%) of the 421 GLS deployed were recovered by May 2019 (see Table 1 for details). For 178 GLS deployments body mass estimates were available at deployment (mean = 378 g, SD = 48) and recovery (mean = 382 g, SD = 40). There was no significant difference between body mass before and after GLS deployments (paired *t*-test (log transformed): $t = 1.35$, $d.f. = 177$, $P = 0.178$).

Recapture probability

Annual recapture probabilities were year and group-specific (Table 2, model 3 vs model 6). Further examination of any inter-group similarities (Table 2, models 1 and 2) indicated that recapture probabilities did not differ between Petrels during GLS and post GLS deployment but were typically higher than for non-GLS-Petrels (Fig. 1).

Effects of GLS deployment on apparent survival

Apparent annual survival during GLS deployments was not significantly different from non-GLS-petrels (likelihood ratio test between models in Table 3, $\chi^2 = 1.02$, *d.f.* = 1, $P = 0.313$). During deployment apparent annual survival was estimated at 0.963 (95% CIs; 0.940-0.978) and for non-GLS-Petrels 0.951 (95% CIs; 0.943-0.960) during 2009-2018 (Fig. 2).

There was no statistical support for an effect of GLS deployments on long-term apparent survival (likelihood ratio test between models in Table 4, $\chi^2 = 0.76$, *d.f.* = 1, $P = 0.384$). Annual apparent survival probability of Petrels not carrying a GLS device was estimated at 0.951 (95% CIs; 0.943-0.960) and 0.960 (95% CIs; 0.942-0.973) for Petrels carrying or having carried a GLS logger in the past (see Fig. 2).

Apparent survival probability

Adult apparent survival varied little over the study period (see Table 2 and Supporting Information Fig. S2a and b) and was estimated as 0.965 (CIs 0.962, 0.968) for the study period 1993-2018.

Potential confounding factors

On average Petrels of known age at GLS deployment were around one year younger (7.4 years) than non-GLS-Petrels (8.3 years) ($t = 2.045$, *d.f.* = 725, $P = 0.043$). GLS-Petrel body mass (mean = 381 g, SD = 49.1) was not different to that of non-GLS-Petrel body mass (mean = 382 g, SD = 51.8; $t = 0.207$, *d.f.* = 569, $P = 0.836$). The hybrid status of a Petrel did not vary between GLS-Petrels and non-GLS-Petrels ($t = 0.465$, *d.f.* = 481, $P = 0.642$).

DISCUSSION

We used a long-term mark-recapture dataset in a CJS model framework to examine the impact of GLS deployments (for up to 7.5 years) on the apparent survival probabilities of adult Petrels on Round Island. We show that adult apparent survival probabilities were not negatively affected either during GLS deployment or in the long-term, (i.e., because of GLS deployments). These findings indicate that GLS can be deployed on Petrels, and potentially on other similar sized or larger gadfly petrels, without negatively impacting a key demographic rate of these long-lived species.

Our findings regarding the impact of GLS on adult Petrel apparent survival agree with other studies on skuas, terns and shearwaters that have used return rates as a proxy for short-term survival (Carneiro *et al.* 2016, Kürten *et al.* 2019, Gillies *et al.* 2020). Leg-mounting of tags is generally considered one of the lower-impact attachment methods (Barron *et al.* 2010, Geen *et al.* 2019) and only two of the 14 studies reviewed by Kürten *et al.* (2019) found a negative impact of leg mounted GLS on seabird return rates. Differences between the 14 studies was in part attributed to variation in the size of the GLS relative to the body mass of the tagged species (Kürten *et al.* 2019) and a similar pattern was observed by Geen *et al.* (2019) where the probability of reporting a significant tag-effect in a study increased with increasing relative tag mass. It therefore seems likely that the small size of our GLS devices relative to the body mass of the Petrels (< 1%) may well explain why there was no detectable effect on apparent survival. This result supports the general finding from the published literature that leg mounted GLS weighing up to 1% of an individual's body mass typically have a negligible apparent impact, during deployment, on the survival of adult seabirds (Bodey *et al.* 2018, Geen *et al.* 2019). What is novel about our findings is that we also identified no apparent impact of GLS deployment on the long-term apparent survival of Petrels over multiple years. This is not something that has been previously explored but has been identified as a priority for investigation in seabirds (Geen *et al.* 2019, Kürten *et al.* 2019). This finding will be reassuring for researchers who frequently deploy GLS on seabirds for multiple years, to examine repeatability and plasticity in movement outside of the breeding season (Fayet *et al.* 2016, Phillips *et al.* 2017, Campioni *et al.* 2020).

We acknowledge that our study was not based on a formal experimental design and hence there could be a range of biases associated with GLS-petrels compared to non-GLS-petrels with consequences for the results. These potential biases are often associated with life history stage, age and a range of fitness metrics (Authier *et al.* 2013, Bodey *et al.* 2018). While we were unable to control for these during the selection of individuals for GLS deployments, we retrospectively tested (where possible) for potential biases between GLS-petrels and non-GLS-petrels that might mask any real differences in apparent survival probabilities. We found that GLS-petrels were on average around one year younger (7.4 years) than non-GLS-petrels (8.3 years). However, we believe this is unlikely to have any bearing on the results as adult survival probabilities are relatively stable in long-lived seabirds (with a life-span of > 30 years), with the exception of a potential decline in survival in old age classes associated with actuarial senescence (Anderson & Apanius 2003, Fay *et al.* 2018, Tompkins & Anderson 2019) in line with life history theory (Jones *et al.* 2008). Unfortunately, this cannot be explored in these Petrels using the current data set due to the duration of the mark-recapture programme and the limited number of individuals in the older age classes. We found no evidence to suggest that our sampling approach had selected for any difference in the ‘fitness’ of individuals, either in terms of body mass or genetic makeup. We therefore believe that the sample of Petrels selected to carry GLS were representative of the wider Petrel population on Round Island during this study. Finally, we were unable to explore the potential impact of GLS deployments on breeding success because the nesting ecology of the study species and the long-term monitoring programme on Round Island currently prevent us from monitoring breeding success at the individual-level.

GLS were deployed on and recovered from Petrels during specific 1-week expeditions each year between 2009 and 2012 and during the monthly Petrel surveys between November 2009 and May 2019. The recapture probabilities of GLS-petrels were typically greater than non-GLS-Petrels (see Fig. 2) and by accounting for this in our models (in Tables 3 and 4) we can make direct comparisons of apparent survival probabilities between groups. We believe these differences in recapture probabilities was due to a combination of (i) fieldworker incentive and effort to recover GLS, and (ii) study design associated with GLS deployments across Round Island. Fieldworkers may well have been particularly motivated to target the recapture of Petrels carrying GLS due the ‘added data value’ associated with recovery of GLS both during and outside of Petrel surveys. Indeed, clusters of breeding sites where GLS were known to have been deployed in 2009 and 2010 were targeted for repeated searches outside of the monthly Petrel surveys, during 2010, 2011 and 2012. In addition, due to the precipitous topography of Round Island (it is the remnant of a volcanic rim) not all nesting areas (i.e., colonies) are equally accessible and during monthly Petrel surveys accessibility is strongly influenced by the weather. In unsuitable weather conditions certain areas may be omitted from the surveys. Hence, from the outset the majority of GLS (~75%) were deployed in the most readily accessible Petrel colonies (see Supporting Information Fig. S1), where ~62% of adult Petrel recaptures occurred during the study period, with the aim of maximising GLS recoveries.

As a group, gadfly petrels (32 *Pterodroma* and 4 *Pseudobulweria species* (BirdLife International 2018)) are highly threatened (Dias *et al.* 2019). However, many of these species are also poorly studied (Rodríguez *et al.* 2019), such that continued study of their biology and ecology is crucial for guiding evidence-based conservation (Rodríguez *et al.* 2019). Currently data on the spatial ecology, recorded using GLS, are available for only 16 species (<50%) of gadfly petrel in the Seabird Tracking Database (BirdLife International 2021). Our study shows that leg-mounted GLS can be used to document non-breeding season movements over multiple years in medium-sized adult *Pterodroma* petrels, without negatively impacting survival. This result sets a potential precedent for their use in other studies of similar sized (or larger) gadfly petrels (equivalent to ~66% of species in the two genera) to establish their spatial ecology at sea and inform the prioritisation of conservation actions.

Many gadfly petrels breed on remote islands that are hard to access making it difficult to determine key demographic rates, such as adult survival, and examine population viability. Published estimates of *Pterodroma* survival based on mark-recapture analyses are, to the best of our knowledge, currently limited to Macronesian Gadfly Petrels (0.75-0.83) (Ramos *et al.* 2016) and the Grey-faced Petrel (*Pterodroma macroptera gouldii*) (0.89) (Jones *et al.* 2011). The mean rate of adult apparent survival estimated in this study for Petrels on Round Island (0.965) is substantially greater than the values reported for other gadfly petrels, and more in line with estimates for albatross species (Veran *et al.* 2007). Exactly why this is the case is unclear but in combination with the other published estimates it illustrates the wide range of adult survival probabilities currently exhibited by gadfly petrels.

Conclusions

The use of GLS to derive spatial and behaviour information from seabirds should always be recognized as a trade-off between the importance of the knowledge gained and the potential deleterious effects caused (Bodey *et al.* 2018). However, if knowledge about the latter is limited then making informed decisions regarding study design is challenging, especially for threatened species. Our study suggests that the deployment of GLS does not negatively impact annual adult apparent survival, either during deployment or in the long-term, in a medium sized long distance migrant seabird. Hence, for this species, and potentially other similarly sized or larger gadfly petrels, this type of biologging device may be suitable for documenting migration patterns without adversely affecting rates of adult survival, but we would encourage biologgers to consider the potential for impacts on behaviour when designing studies.

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ETHICAL NOTE

This long-term research involved the tagging (rings and geolocators) and recapture of petrels. All work followed the ethical standards set out by The Mauritian Wildlife Foundation and its partner and consulting organizations, the North of England Zoological Society, the Durrell Wildlife Conservation Trust and the International Zoo Vet Group. In addition, geolocator deployment and recovery were approved by the Zoological Society of London Animal Ethics Committee (Approval 237-BPE-711).

AUTHOR CONTRIBUTIONS

CGJ initiated the Petrel ringing programme, with support post-2000 from VT, NCC and MACN; MACN, KN, CGJ and VT conceived and initiated the petrel migration study; MACN, KN and NCC deployed and recovered geolocators; NCC, CGJ, VT and KR facilitated access and logistical support for fieldwork on Round Island via the Mauritian Wildlife Foundation and the National Parks and Conservation Service; MACN, KN and NR developed the research to examine the impact of GLS on Petrel survival rates; MACN conducted analyses with support from CH and NR; MACN wrote the manuscript and all authors commented on drafts. All authors approved the final manuscript.

Data Availability Statement

Petrel ringing records are deposited with the South African Bird Ringing Unit by the Mauritian Wildlife Foundation. Petrel recapture and body mass data are available from the authors on reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Fig. S1: The location of Round Island in the Western Indian Ocean, its topography and the distribution of Petrel nest sites across the island.

Fig S2: Apparent annual survival estimates for non-GLS-petrels (1993-2018) and GLS-petrels in the short- and long-term.

Appendix S1: Explanation for use of single-state rather than multi-state model structure in the survival analyses.

Appendix S2: Details of goodness-of-fit test outputs and specific test statistics.

Appendix S3: Characterisation of an individual Petrel’s genotype.

Table 1. A summary of the deployment and recovery of geolocators on Petrels on Round Island from 2009-2019.

Petrel season	Geolocator type	Number deployed	Number recovered (%) *
2009	BAS MK15	135	109 (81)
2010	BAS MK15	84	80 (95)
2011	BAS MK15	28	16 (57)
2012	BAS MK15	79	63 (80)
2014	Intigeo C250	49	33 (67)
2015	Intigeo C250/C330	21	12 (57)
2016	Intigeo C330	25	14 (56)

* GLS recovered between October 2010 and May 2019.

Table 2. Models used to examine evidence for time-dependent apparent survival and group-dependent (i.e., GLS or no GLS) recapture rates of adult Petrels on Round Island. Models are ordered according to corrected Akaike's information criterion (QAICc) and notation is as follows; apparent survival (Φ), recapture probability (P), time dependent (t), constant (.), fully group dependent (GLS, i.e., during, post and no GLS deployments), partially group dependent distinguishing between (i) during GLS deployment only and post/no GLS deployments ($\mathrm{GLS}_{\mathrm{during}}$), and (ii) during/post GLS deployment and no GLS deployment ($\mathrm{GLS}_{\mathrm{deploy}}$). NP – number of model parameters and QDeviance – model deviance after correction for overdispersion.

Model	**QAICc**	**Delta QAICc**	**NP**	**QDeviance**
1. $\Phi(\mathrm{c})\ P(t{:}\mathrm{GLS}_{\mathrm{deploy}})$	27771.93	0.00	35	12126.63
2. $\Phi(\mathrm{c})\ P(t{:}\mathrm{GLS}_{\mathrm{during}})$	27776.64	4.71	35	12131.35
3. $\Phi(\mathrm{c})\ P(t{:}\mathrm{GLS})$	27779.67	7.75	43	12118.25
***4.** $\Phi(\mathrm{c{:}GLS}_{\mathrm{during}})\ P(t{:}\mathrm{GLS}_{\mathrm{deploy}})$	27794.77	22.84	67	12084.81
***5.** $\Phi(\mathrm{c{:}GLS}_{\mathrm{deploy}})\ P(t{:}\mathrm{GLS}_{\mathrm{deploy}})$	27796.99	25.068	66	12089.07
6. $\Phi(\mathrm{c})\ P(t)$	27825.34	53.42	26	12198.16
7. $\Phi(\mathrm{t})\ P(\mathrm{t})$	27838.05	66.12	49	12164.51

* These models were specified to generate time-dependent survival estimates for petrels whilst carrying GLS, i.e., in the short-term (model 4) and from GLS deployment onwards, i.e., in the long-term (model 5).

Table 3. Models used to examine the short-term impact of GLS deployments, i.e., while carrying a GLS, and apparent survival rates of Petrels on Round Island between 2009 and 2018. Models are ordered according to corrected Akaike's information criterion (QAICc) and notation is as follows; apparent survival (Φ), recapture probability (P), time dependence (t), constant (.), time periods (<2009 the period 1993-2008 and ≥2009 the period 2009-2018), apparent survival probabilities can differ between GLS and non-GLS-petrels (GLS), recapture probabilities differ between no GLS deployment and GLS deployment ($\mathrm{GLS}_{\mathrm{deploy}}$). NP – number of model parameters and QDeviance – model deviance after correction for overdispersion. Apparent survival estimates are provided with their 95% confidence intervals.

Model	**QAICc**	**NP**	**QDeviance**	**Population-level apparent survival probability (95% CI)**	**Apparent survival probability of petrels without GLS (95% CI)**	**Apparent survival probability of petrels with GLS (95% CI)**
1. $\Phi(<2009.,\geq 2009.)$ $P(t{:}\mathrm{GLS}_{\mathrm{deploy}})$	27762.34	36	12115.03	0.953 (0.945-0.961)	NA	NA
2. $\Phi(<2009.,\geq 2009.{:}GLS)$ $P(t{:}\mathrm{GLS}_{\mathrm{deploy}})$	27763.34	37	12114.01	NA	0.952 (0.944-0.960)	0.963 (0.939-0.978)

Table 4. Models used to examine the long-term impact of GLS device deployments, i.e., from the point of GLS device deployment onwards, and apparent survival rates of Petrels on Round Island between 2009 and 2018. Models are ordered according to corrected Akaike's information criterion (QAICc) and notation is as follows; apparent survival (*Φ*), recapture probability (*P*), time dependence (t), constant (.), time periods (<2009 the period 1993-2008 and ≥2009 the period 2009-2018), apparent survival probabilities can differ between GLS and non-GLS-petrels (GLS), recapture probabilities differ between no GLS deployment and GLS deployment ($\text{GLS}_{\text{deploy}}$). NP – number of model parameters and QDeviance – model deviance after correction for overdispersion. Apparent survival estimates are provided with their 95% confidence intervals.

Model	**QAICc**	**NP**	**QDeviance**	**Population-level apparent survival probability (95% CI)**	**Apparent survival probability no-GLS-petrels (95% CI)**	**Apparent survival probability GLS-petrels (95% CI)**
1. *Φ(<2009.,≥2009.) P(t:*$\text{GLS}_{\text{deploy}}$*)*	27762.34	36	12115.03	0.953 (0.945-0.961)	NA	NA
2. *Φ(<2009.,≥2009.:GLS) P(t:*$\text{GLS}_{\text{deploy}}$*)*	27763.59	37	12114.27	NA	0.952 (0.943-0.960)	0.960 (0.942-0.973)

Figure 1. Recapture probabilities for Petrels on Round Island 1994-2018. Non-GLS-petrels; solid line and filled squares, and GLS-petrels; dashed line and filled circles. Error bars are 95% confidence intervals. Notes: Estimates are generated from the most parsimonious time-dependent and group-specific model (Table 2, Model 1). GLS device deployment commenced in 2009 so the first recapture opportunity is in 2010.

Figure 2. Annual apparent survival probabilities for adult Petrels on Round Island (2009-2018) estimated from models examining the short and long-term impacts of GLS deployments. Adult apparent survival probabilities were remarkably consistent and were not negatively affected either during GLS deployment or in the long-term, i.e., while carrying GLS and in subsequent years. Apparent survival estimates associated with potential effects during deployment are generated from model 2, Table 3; and apparent survival estimates associated with long-term potential effects are generated from model 2, Table 4. Error bars are 95% confidence intervals.

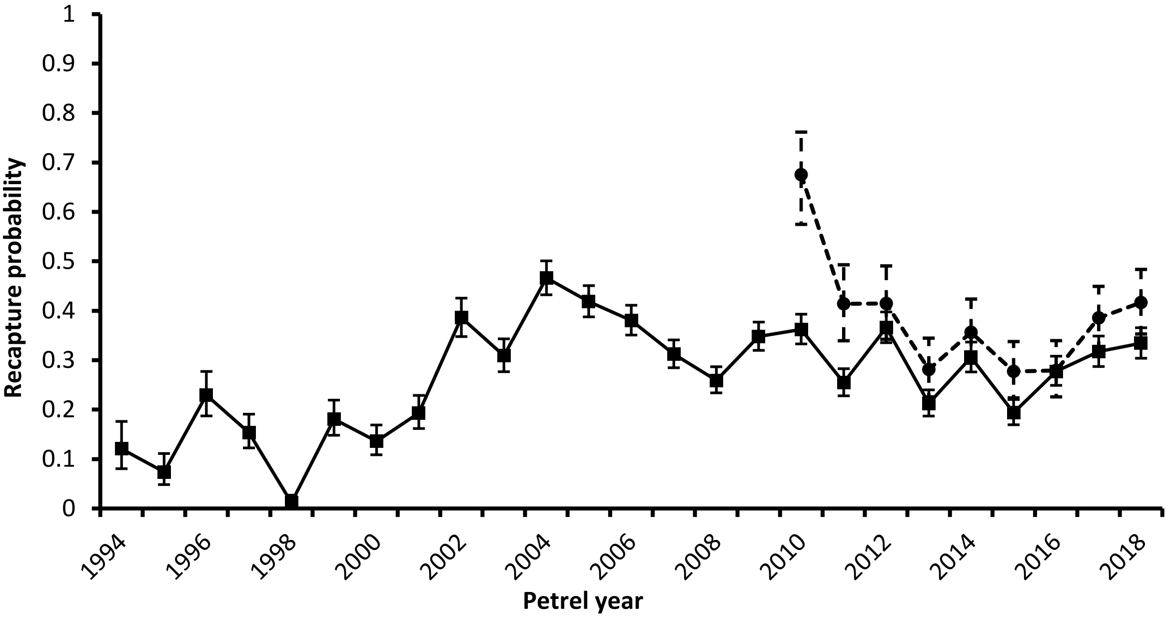
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Recapture probability
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
Petrel year

Figure 1.

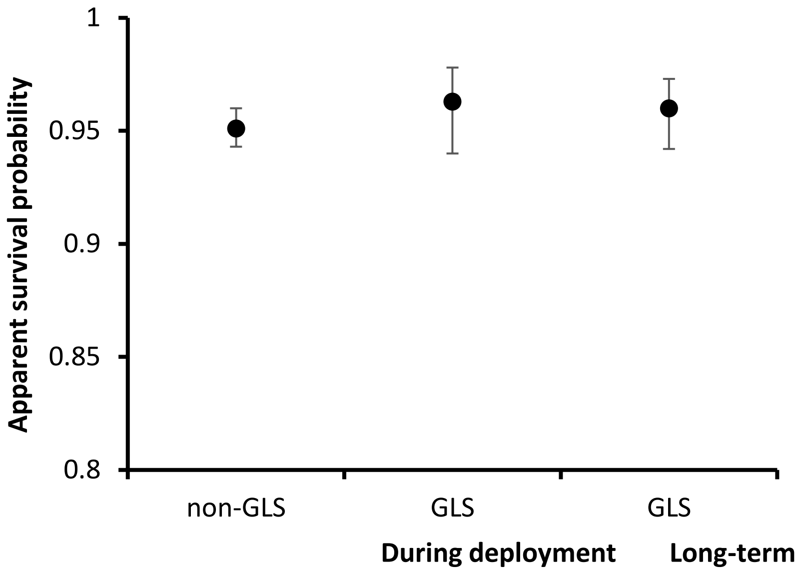
Apparent survival probability
1
0.95
0.9
0.85
0.8
non-GLS
GLS
GLS
During deployment
Long-term

Figure 2.