# Supporting Information

Title: ‘Contrasting effects of tropical cyclones on the annual survival of a pelagic seabird in the Indian Ocean’.

The information provided in this section relates to additional details on the methods used to (i) establish where adult petrels migrated to (ii) explore the impact of tropical cyclones on juvenile survival, (iii) summary information on tropical cyclones in the Indian Ocean and (iv) the results of goodness-of-fit tests for both single state and multistate models used to explore the impact of tropical cyclones on juvenile survival.

## Materials and methods

### *Exposure of petrels to tropical cyclones*

### Adult petrel distribution

Locations of the petrels during their overwinter migrations were estimated using the R package ‘TripEstimation’ (Sumner *et al.*, 2009, Thiebot & Pinaud, 2010) run in the software R (R Core Team, 2008). Location estimations are constrained by a land mask, known location start and end points (Round Island), spatial boundaries $20^{o}$E & $110^{o}$E, $48^{o}$S & $30^{o}$N (based on prior viewing of estimated locations in BAS Track software), behavioural parameters taken from the similar sized Baraus’s petrel (*Pterodroma baraui*) from nearby Reunion Island (Pinet *et al.*, 2011) and the sea surface temperature (SST) recorded by the loggers. The latter data is used in a matching process with weekly average Reynolds satellite SST data at a $1^{o}$ resolution, downloaded from the POET-PODAAC website (http://poet.jpl.nasa.gov/) for the specified area and has been shown to improve the estimation of latitude (Thiebot &  Pinaud, 2010). We set the low and high temperature threshold values at $10^{o}$ and $35^{o}$ C, based on a preliminary viewing of the downloaded SST files from the loggers and SST records for the specified study area, with a matching parameter of 2 (Thiebot &  Pinaud, 2010). Individual logger pre-and post-deployment calibration data were included in the location estimation process to account for any discolouration (i.e. potential reduction in the light sensor's sensitivity) of the geolocator's surface during deployment. During the equinoxes the accuracy of geolocation is known to be impaired and the effectiveness of the SST matching process in resolving this is contingent on the presence of a spatial gradient in SST data. In the Indian Ocean in April and October a unique eastward wind pattern occurs over the equator resulting in a band of warm equatorial water (Schott &  McCreary Jr, 2001). This corresponds to the periods following the equinoxes and the absence of any gradient in SST, could thereby reduce the accuracy of the estimated locations generated at this time in this region. In order to be confident that the locations estimated by the 'TripEstimation' package were valid for the equinox periods we applied a post-estimation speed based filter (>80km/h) to the location data where petrels were deemed to be crossing the equator in these two months to identify any erroneous locations, which were subsequently removed. 24 overwinter tracks included a crossing of the equator in either (or both) period(s) and required adjustments, with on average the removal of 9.2 (2.4%) (range; 1(0.3%)-28(6.75%)) locations. Petrels remained in the Indian Ocean and were widely distributed North of $40^{0}$ S. We divided these locations according to the three different cyclone seasons and generated kernel density estimations (plate carrée projection, cell size 10km and search radius of 180km) for each cyclone season.

*Petrel survival*

Juvenile survival

Round Island petrels fledge at 90-100 days old, leave the breeding colony and then spend a period at sea before returning. For recent cohorts of petrels ringed between 2001 and 2010 94% of all petrels recaptured for the first time were ≤6 years old. We therefore generated 853 recapture histories from 1993 to 2012 for cohorts of petrels ringed only as chicks between 1993 and 2006, to ensure a sufficient time period for recapture at Round Island (i.e. 6 years post ringing). Cohorts of chicks ringed between 2007 and 2012 were excluded.

### Juvenile survival: Two-age class CJS model

We used single-state CJS models in Program MARK to examine the influence of tropical cyclones on juvenile survival. Because juvenile petrels spend their first year at sea and are thus unobservable we fixed the first recapture at zero, while the subsequent recapture probabilities as ‘adult’ birds returning to Round Island are time-dependent to reflect any year to year variation. This permits the estimation of apparent annual juvenile survival. However, this does introduce issues with the selection of suitable GOF tests to examine how well the data meet the underlying assumptions of the CJS framework and hence identification of a suitable global model; in particular that all individuals have the same probability of being recaptured and all individuals have the same probability of surviving from one year to the next (Lebreton *et al.*, 1992). Based on our understanding of Round Island petrel ecology and published estimates of other petrel species survival (Jones *et al.*, 2011, Waugh *et al.*, 2006), we know that there would be differences in juvenile and adult recapture probabilities (to date juvenile petrels have never been recaptured at Round Island during this life history stage) and we would expect that juvenile and adult survival would differ. Therefore, our global model contained both age and time-dependence in $\Phi$ and $P$ with juvenile recapture fixed at zero ($\Phi_{j(\mathrm{t}),a(\mathrm{t})}\ P_{j(.),a(\mathrm{t})}$) and hence we applied the Median $\hat{c}$ approach to GOF testing in Program MARK, which is appropriate when the general model is not fully time dependent (Brown *et* *al.*, 2006, Cooch & White, 2013). Akaike's Information Criteria (AIC) was corrected for any over-dispersion (i.e. including a variance inflation factor - see Results: Goodness of fit) as QAICc (Burnham & Anderson, 2002). We then explored the impact of tropical cyclones on juvenile survival only, using the following approach. We first fixed adult survival to be constant (as this was not a parameter of primary interest) and then constrained $\Phi_{\mathrm{j}}$ to be a function of four measures of cyclone activity in turn; IO, SIO Region, SIO Local and NIO Annual. All models were tested based on *ANODEV* with the relevant reference models (i.e., $\Phi_{j(\mathrm{t}),a(.)}\ P_{j(.),a(\mathrm{t})}$ & $\Phi_{j(.),a(.)}\ P_{j(.),a(\mathrm{t})}$) (Grosbois *et al.*, 2008). If more than one measure of cyclone activity were found to be influential then additive models were constructed to examine the combined effects of cyclone activity at different spatial scales on apparent juvenile survival. This was done by taking the model containing the measure of cyclone activity which explained the greatest model deviance and adding the other measures of cyclone activity in turn and revising the relevant reference model accordingly (i.e., $\Phi_{j(\mathrm{t}),a(.)}\ P_{j(.),a(\mathrm{t})}$ & $\Phi_{j(\mathrm{principal\ covariate}),a(.)}\ P_{j(.),a(\mathrm{t})}$).

## Juvenile survival: Three-age class CJS model

We adopted the same approach as for the two-age class model, but constrained recapture rates only to be a function of three age classes; juveniles, two year olds and three years and older, with time-dependence only in the third age class. Juvenile recapture rate was always fixed at zero, while the recapture rate for two year olds was always constant and not time-dependent. The latter is due to the typically limited number of recaptures in this age class each year (in some years there were none) and hence how this precludes the model from generating meaningful time-dependent recapture estimates.

## Juvenile survival: Multistate model

Multistate models can often result in numerous model parameters, many of which are in effect redundant, therefore to avoid this we fixed a number of parameters based on reasonable biological assumptions relevant to our study system (Spendelow *et al.*, 2002). Juveniles (state 1) are not seen once they have fledged from Round Island therefore their recapture rate is fixed at zero. The recapture rate for birds in state 2 is fixed at zero. The first time-dependent estimate for the recapture rate in the adult state 3 is fixed at zero as no adults existed at this point in time. Juveniles cannot become adults without passing through the unobservable state two, therefore the transition rate from state 1 to state 2 was fixed at one and adults cannot become juveniles so the transition rate from state 3 to state 1 was fixed at zero. Unpublished tracking data with geolocators indicates that adult petrels at Round Island return to the breeding colony each year, therefore once a bird has been recorded in state 3 it cannot revert back to state 2 so the transition rate from state 3 to 2 was fixed at zero.

## Results

### *Cyclones*

Table S1. Summary of cyclone frequency and maximum sustained wind speeds (km/h) in the Southern and Northern Indian Ocean (1993-2012).

| | Northern Indian Ocean | | Southern Indian Ocean |
|---|---|---|---|
| Category | Arabian Sea (AS) | Bay of Bengal (BoB) | Southern Indian Ocean (SIO) |
| Cyclonic storms (63-87 km/h) | 21 | 33 | 86 |
| Severe cyclonic storms (88-117 km/h) | 10 | 8 | 71 |
| Very severe cyclonic storms (118-220 km/h) | 9 | 19 | 110 |
| Super cyclonic storm (>221 km/h) | 2 | 4 | 12 |

### *Juvenile survival*

#### Single state CJS model

Table S2. Goodness of fit statistics for the global model ($\Phi_{(t)}$ $P_{(t)}$) in the examination of apparent adult survival conducted in Program U-CARE.

| Test | $\chi^2$ | P | *df* |
|---|---|---|---|
| Overall | 274.85 | <0.001 | 198 |
| 3.SR | 36.40 | 0.007 | 18 |
| 3.SM | 105.67 | 0.02 | 78 |
| 2.CT | 29.34 | 0.03 | 17 |
| 2.CL | 103.80 | 0.08 | 85 |

#### Multistate model

Table S3. Results of the goodness-of-fit tests for the multistate capture-mark-recapture model run in U-CARE. For the MITEC and MLTEC both $\chi^2$ and G- test statistics are shown.

| Test | $\chi^2$ (G-stat) | P (P-value for G –stat) | DF |
|---|---|---|---|
| 3GSM | 56.97 | 0.13 | 46 |
| MITEC | 0.126 (0.238) | 1.0 (1.0) | 11 |
| MLTEC | 55.61 (59.82) | 0.133 (0.069) | 45 |
| JMV | 112.65 | 0.221 | 102 |

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