ADDITIONAL FILE 1:

Pair bonds during the annual cycle of a long-distance migrant, the Arctic Tern *Sterna paradisaea*

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ADDITIONAL METHODS

Most nests of geolocator-tagged birds were marked with numbered stones. Previous work in the same colony had resulted in a high return rate of geolocator tagged birds, and there was no evidence that the geolocators had affected breeding or foraging success (Redfern and Bevan 2020a). Therefore, the risk of a substantial reduction in breeding success in pairs where both birds had geolocators was likely to be low. The potential effects of geolocators on breeding performance, particularly with respect to pairs where both parents were tagged with the devices, were assessed with respect to productivity (number of chicks raised to near fledging age) in 2017, and clutch size in 2018 using Fisher's Exact test. With respect to productivity in 2017, data from weekly monitoring visits to the west and east sides of the study site (Inner Farne Courtyard) for nests active from the start of the season until 10 June were used for comparison with the productivity of nests of birds with geolocators. The outcomes of nests with geolocators were also derived from these data where possible. Vegetation growth during the season and access constraints limited the extent of monitoring, and the mobility of chicks, despite the use of ringing, makes it difficult to be confident about the absolute accuracy of productivity monitoring but was the best that could be done within site constraints to minimise disturbance to nesting birds. For comparisons of clutch size between geolocator-tagged pairs in 2018 with the colony as a whole, nests (n= 238) established within the period 20-25 May 2018 in the courtyard of Inner Farne were used for comparison.

In the study site, the age-corrected body mass of a sample of Arctic Tern chicks is measured by the author annually as part of a long-term study into environmental factors affecting breeding success. Total head length (Green 1980), a measure of chick size and a proxy for age, and body mass was measured for a sample of 51 chicks in the study area on one date (24 June 2017). The chicks were measured at ages > *ca.* 9 days old to ensure a linear relationship between log(mass) and log(head length). In the year of tagging the sample included chicks from some nests of geolocator tagged birds. These data were analysed using the *emmeans* R-package (Lenth 2019) to compare the size-corrected body mass of chicks from nests with and without geolocator-tagged parents using a linear model of log(mass), the dependent variable, in relation to log(total head length) with geolocator status (none, one or two) as an additive explanatory factor.

ADDITIONAL RESULTS AND DISCUSSION

(1) Study site: nest locations, movements between years and age of first breeding

Grid locations of nests within the Courtyard study area (Fig. S1a) for pairs that remained together are shown in Table S1, and for nests of individual birds for which pair status changed between years in Table S2.

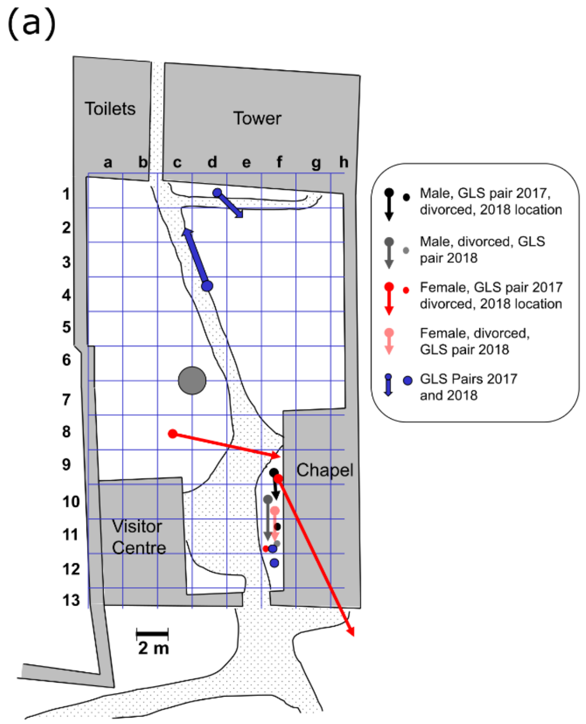
Arctic Terns at the study site and some adjacent colonies have been ringed as chicks and adults annually from 1997 and the age of some of the birds tagged with geolocators in pairs was known accurately. Some of the other birds were previously ringed in the colonies as breeding adults, and only a minimum age can be given (see main text). These minimum ages were based on the age of first breeding of Arctic Terns in the colony: retrap data for Arctic Terns ringed as chicks on Brownsman (Farne Islands), Inner Farne or Coquet Island (longitude -1.54°; latitude 55.33°) and the interval (years) to their first recapture across the islands as breeding adults caught on the nest show (Fig. S1b) that Arctic Terns from Northumberland colonies can breed from an age of 2 years old- *i.*e., in their 3rd calendar year.

Table S1. Nest locations (Grid squares in Fig. S1a) of pairs that remained together in 2017 and 2018

Female	Male	Grid location in 2017	Grid location in 2018
G27	G62	*11f*	*11f*
G16	G70	*1d*	*2e*
G26	G44	*12f*	*12f*
G65	G40	*4d*	*2c*

Table S2. Nest locations (Grid squares shown on Fig. S1a) of pair members that changed between years; pairs within years are indicated by * and **. See main text for details; note that the 2017 partner of G80 did not return in 2018, and the pair G66 with G69 in 2018 was a new partnership between these geolocator-tagged birds that were both paired to untagged birds in 2017. Geolocator-tagged pairs in 2018 are relevant to geolocator effects on clutch size.

Female	Male	Grid location in 2017	Grid location in 2018
G84		*11f**	*11f**
	G61	*11f*	*11f**
	G30	*11f**	*11f*
G33		*9f***	*Outside Courtyard*
	G31	*9f***	*10f*
	G66	*10f*	*11f***
G69		*10f*	*11f***
G80		*8c*	*9f*



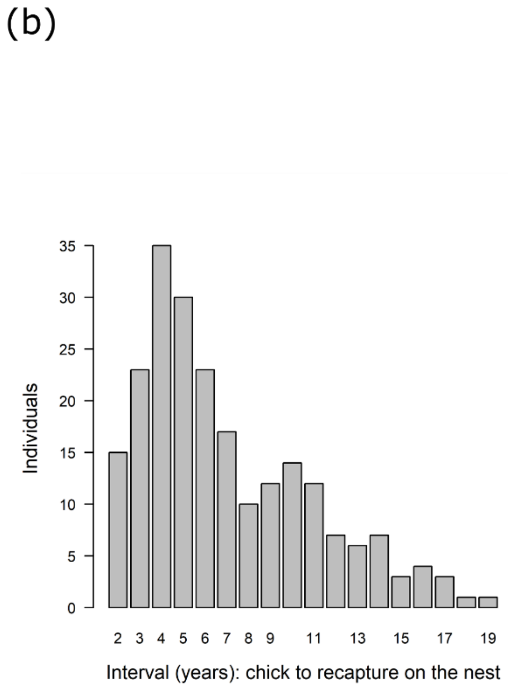


Figure S1. (a) Plan of Courtyard study area on Inner Farne, Northumberland, based on Google Earth satellite images. Buildings, walls and stone structures are represented in grey; outlined stippled areas are paths or walkways, white areas are vegetated tern nesting areas. The blue grid lines represent a virtual grid (marked on recording maps) used to record nest locations to numbered and lettered squares estimated by reference to Courtyard features. Filled circles and circles with arrows represent nest locations and year-to-year movements of individual birds or pairs as defined by the key. (b) Bar plot showing the interval in years between being ringed as a chick and the first recapture on the nest as a breeding adult (abscissa), and the number of individuals in each year-interval category (ordinate).

(2) Productivity estimates

All except one of the geotagged-pair nests were successful in 2017, raising at least one chick to fledging age; the pair that failed (G16-G70) suffered from nest predation. Chicks raised to near-fledging age in nests active within the study area in the same period as the nests of geolocator-tagged birds were used for comparisons of productivity, and comprised 157 chicks from 149 nests in the west side and 74 chicks from 112 nests on the east side of the Courtyard study area, giving a combined total of 231 chicks from 261 nests. For the 11 nests that had one geolocator-tagged parent, one failed because the eggs were apparently infertile and one failed as a result of desertion (unknown reason). Ten chicks were raised from these nests. From the seven nests where both parents were tagged with a geolocator, eight chicks were raised; one nest failed initially when eggs were damaged by a visitor (member of the public) to the island, but this pair successfully raised a chick from a replacement clutch, and one nest failed as a result of predation. There was no apparent difference in productivity with respect to the number of chicks raised to fledging age between nests with one tagged adult (productivity 0.91 chicks/nest) or with both adults tagged (productivity 1.14; Fisher's Exact test, P = 1), and there was no difference in productivity between nests from geolocator-tagged birds or the Courtyard Arctic Tern nests overall (productivity 0.89; Fishers Exact test, P = 0.73).

(3) Body mass changes and clutch sizes of geolocator-tagged pairs

For the six pairs of geolocator-tagged birds retrieved in 2018 (Table S3), there was no significant difference in mass of individual birds between initial tagging and recapture (all birds, n=12, One-sample t-test, P= 0.7; females, P= 0.93; males, P= 0.6). The mean clutch size at the time of recapture was 2.3 (median 2), which was greater than the mean clutch size for nests established within the same period for the Courtyard study area as a whole (1.97; median 2). In particular, two of the pairs had clutch sizes of three eggs. Of the six females in these 2018 pairs, five had a retrap history with one to eight recaptures in years before 2017. For these females, their clutch size in 2018 was the same, or in one case (G27- 3 eggs) larger, than in 2017, and the same or larger (two birds) than their mean clutch sizes over all previous recaptures (Table S3). These data suggest that the geolocators did not have a detrimental effect on the breeding performance of tagged pairs and that individual birds were able to adapt successfully to any negative effects.

Table S3. Clutch sizes and capture/re-capture mass of pairs in 2018.

Female					***Male***		
Code	*Clutch*	*Prior mean* (n)*	*Mass 2017 (g)*	*Mass 2018 (g)*	*Code*	*Mass 2017 (g)*	*Mass 2018 (g)*
G27	3	2.25 (4)	106.7	108.9	**G62**	102	95.5
G16	2	1.33 (3)	104.6	106.1	**G70**	103.3	100.6
G84	2	2= (4)	101.9	106.9	**G61**	105.1	105.6
G69	3	3= (2)	121.7	114.7	**G66**	113.2	105.9
G26	2	2= (8)	99.7	97.1	**G44**	111	118.1
G65	2	2 (1)	103.8	105.7	**G40**	97.4	98.9

*Mean clutch size in previous years (number); =, all clutches equal.

(4) Size-corrected body mass of chicks from nests of geolocator-tagged birds

Five chicks from nests where both parents were tagged with geolocators and five chicks from nests with one parent tagged with a geolocator were included by chance in the sample of chicks measured within the study area as part of routine annual monitoring of chick mass. Overall, the size-corrected body mass of these 10 chicks was not significantly different to chicks from nests without a geolocator-tagged parent (contrast estimate 0.044, SE 0.028, df 48, t= 1.567, P= 0.124). However, the analysis was repeated with parental geolocator status split into three levels: no parents with a geolocator (None), one parent with geolocator (One) or both parents with geolocator (Both) (Figure S2a). Although the mean body mass of chicks from nests with two geolocator-tagged parents was not significantly different from chicks without a geolocator-tagged parent (contrast estimate: -0.0024, SE 0.036, df= 47, t= -0.066, P= 0.998) or chicks with one geolocator-tagged parent (contrast estimate: 0.094, SE 0.05, df= 47, t= 1.915, P= 0.146), the mean body mass of chicks from nests with one geolocator-tagged parent was significantly different to chicks without a geolocator-tagged parent (contrast estimate: 0.0915, SE 0.037, df= 47, t= 2.48, P= 0.044). The biological mechanism of this apparent effect on chicks with one geolocator-tagged parent is unclear.

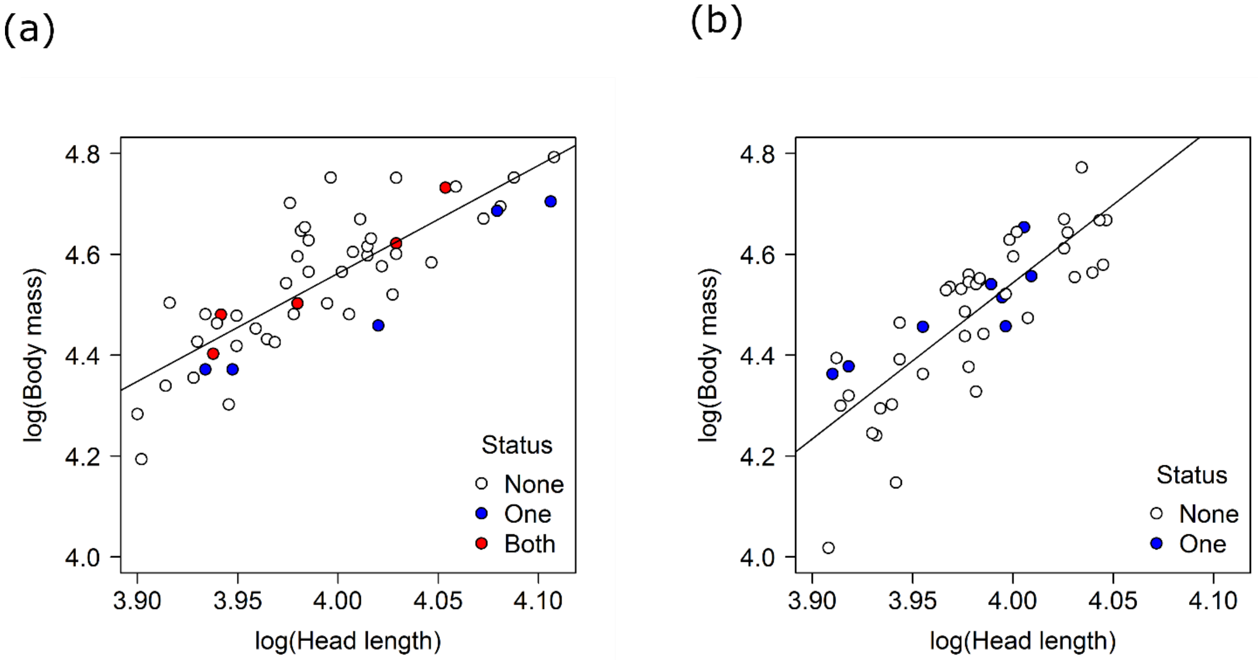


Figure S2. (a) Log(Body mass, g) plotted against log(Head length, mm) for Arctic Tern chicks in 2017. The line is the fitted linear model for all data. Open circles, no geolocator (None); blue-filled circles, one parent with geolocator (One); red-filled circles, both parents with geolocators (Both). (b) Log(Body mass, g) plotted against log(Head length, mm) for Arctic Tern chicks from nests with or without one geolocator-tagged parent in the same study area in 2015. Other details as in (a).

Strategies for brood provisioning by pairs may be flexible (Griffioen et al. 2019) and subject to negotiation (Johnstone and Hinde 2006), but if the attachment of a geolocator is a handicap, the response of the other partner may depend on the extent of handicap, and information flow between partners and chicks (Johnstone & Hinde 2006). It is conceivable then, that, depending on environmental conditions and the extent of any handicap, partners may respond differently to compensate when both are handicapped compared to when only one bears a handicap. In a recent study on Arctic Terns, the fitting of a leg-flag resulted in a reduction in chick provisioning by the manipulated bird but the unhandled partner compensated so that brood provisioning rate was unchanged (Seward et al. 2020). That study was not designed to compare responses in nests where both pair members were manipulated but does show that within pairs of Arctic Terns compensation for changes in partner circumstance can occur.

In an analysis of eight chicks from nests with one geolocator-tagged parent in the Inner Farne Courtyard study site in 2015 (no pairs were tagged in that year), there was no difference in body mass compared to chicks from nests of birds without a geolocator (contrast estimate: -0.04, SE 0.034, df= 45, t= -1.18, P= 0.245; Figure S2b). Bearing in mind the small sample size, the lower size-corrected body mass for 2017 chicks with one geolocator-tagged parent compared to those with two tagged parents could be a consequence of random sample variation. Otherwise, the extent of handicap introduced by the geolocator and the consequences for brood provisioning might depend on the quality of foraging conditions and available prey and thus vary from year to year.

(5) Geolocators and overall breeding performance

Overall, there was no measurable effect of geolocators on the breeding performance of pairs both carrying the devices. The productivity of nests with one or both parents tagged with a geolocator was as good as other nests in the study site. However, given the small sample size, productivity estimates such as these are of low resolution for detecting negative effects of geolocators. Clutch-size data (assuming no egg dumping by other females), in combination with measurements of body mass, are perhaps more informative because a reduction of one or both parameters might be expected if geolocators were a significant handicap for the females (Slagsvold and Lifjeld 1990). However, not only was the average clutch size greater than the mean for the study site as a whole, but for individual females with previous nest-capture histories their clutch sizes were equal to or better than their means in previous years. Bearing in mind that geolocator-induced handicap might be masked if foraging conditions were better than usual in the season of recapture, the clutch sizes, lack of significant differences in body mass between capture and recapture (either for females or all tagged birds), and the high (96%) return rate of this cohort, suggest that any negative effects of the geolocators on life style or daily energetics of Arctic Terns are within the capacity of most individuals to adapt and compensate. Nevertheless, lack of evidence is not the same as lack of effect and individuals less able to adapt will be outliers making an insufficient contribution to reject null hypotheses in statistical analyses of small samples.

(6) Longitude trajectories in the non-breeding area

The locational behaviour of pairs in the Antarctic is represented by plots of longitude versus time (days) as shown in Fig. S3.

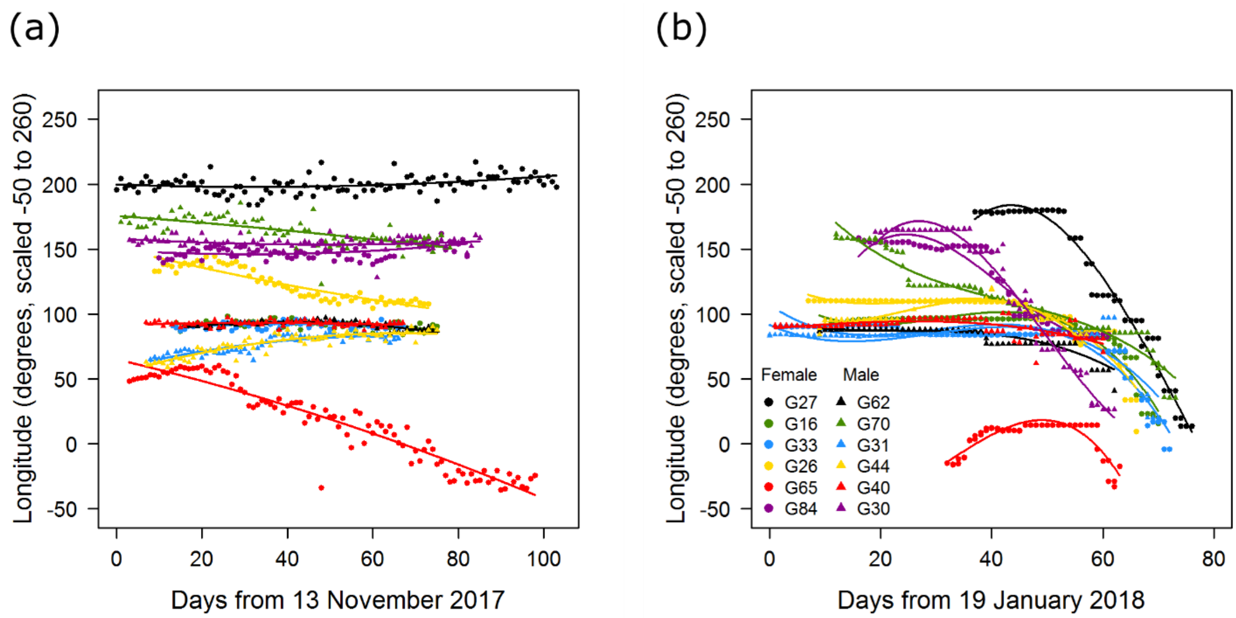


Figure S3. Longitude trajectories of pairs in 24-h daylight (a) and in the interval between the end of 24-h daylight and departure from the Antarctic ice zone (see Methods in the main text) (b). Each pair is a different colour with filled circles representing females and filled triangles males (see legend on b). Longitude (ordinate) is transformed to a linear scale from -50° to 260° (0 at Greenwich Meridian); abscissa, days from the first date at which the first bird enters 24-h daylight. In (a), second-order curves have been fitted to illustrate trajectories, whereas in (b) the greater complexity of movement compared to the 24-h daylight phase is represented by 3rd-order curves. The longitudes in (b) are derived from FLightR analyses, but in (a) are derived from estimates of the time of midnight (Greenwich Mean Time) by fitting curves to daily changes in light intensity (Redfern and Bevan 2020b).

ADDITIONAL REFERENCES

Green GH. Total head length. Wader Study Gr. Bull. 1980;29:18.

Griffioen M, Iserbyt A, Müller W. Handicapping Males Does Not Affect Their Rate of Parental Provisioning, but Impinges on Their Partners' Turn Taking Behavior. Front. Ecol. Evol. 2019;7. https://doi.org/10.3389/fevo.2019.00347.

Johnstone RA, Hinde CA. Negotiation over offspring care - How should parents respond to each other's efforts? Behav. Ecol. 2006;17:818–27.

Lenth R. Emmeans: estimated marginal means [Internet]. Aka Least-Squares Means; 2019. https://cran.r-project.org/package=emmeans

Redfern CPF, Bevan RM. Overland movement and migration phenology in relation to breeding of Arctic Terns *Sterna paradisaea*. Ibis (Lond. 1859). Blackwell Publishing Ltd; 2020a;162:373–80.

Redfern CPF, Bevan RM. Use of sea ice by arctic terns *Sterna paradisaea* in Antarctica and impacts of climate change. J. Avian Biol. 2020b; 1–12; doi: 10.1111/jav.02318.

Seward A, Taylor RC, Perrow MR, Berridge RJ, Bowgen KM, Dodd S, et al. Effect of GPS tagging on behaviour and marine distribution of breeding Arctic Terns *Sterna paradisaea* . Ibis (Lond. 1859). 2020;163: 197-212.

Slagsvold T, Lifjeld JT. Influence of male and female quality on clutch size in tits (Parus spp.). Ecology. 1990;71:1258–66.