

1 **Accepted Journal of Avian Biology 25/8/16 MS JAV-1119 R2**

2 **Cyprus Wheatears *Oenanthe cyprica* likely reach sub-Saharan African wintering**
3 **grounds in a single migratory flight**

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12 Long-distance migratory flights with multiple stop-overs, multiple wintering sites, and small-scale
13 connectivity in Afro-Palearctic migrants are likely to increase their vulnerability to environmental change
14 and lead to declining populations. Here we present the migration tracks and wintering locations of the first
15 six Cyprus Wheatears to be tracked with geolocators: a species with high survival and a stable
16 population. We therefore predicted a non-stop flight from Cyprus to sub-Saharan wintering grounds, a
17 single wintering area for each individual and a wide spread of wintering locations representing low
18 migratory connectivity at the population level. The sub-Saharan wintering grounds in South Sudan, Sudan
19 and Ethiopia were likely reached by a single flight of an average straight-line distance of 2,538 km in ca.
20 60 hours, with an average minimum speed of 43.1 km/h. The high speed of migration probably ruled out
21 stop-overs greater than a few hours. Cyprus Wheatears migrated from Cyprus in mid-late October and
22 most probably remained at a single location throughout winter; three out of five birds with available data
23 may have used a second site <100 km away during February; all returned between the 7 – 22nd March
24 when accurate geolocation data are not possible due to the equinox. Wintering locations were spread
25 over at least 950 km. There were no tag effects on survival. Cyprus Wheatears showed a migratory
26 strategy in accordance with their observed high survival rate and demonstrated a routine flight range that
27 allows much of the Mediterranean and the Sahara to be crossed in a rapid two and a half-day flight.

28

29 Long-distance migratory journeys involving a series of sites and use of small wintering areas are likely to
30 decrease individual survival and so increase vulnerability of migrant populations to environmental change
31 (Vickery et al. 2014, Cresswell 2014). Multiple stop-overs and wintering sites may make migrants more
32 vulnerable because loss of any one site may reduce survival, and environmental change is more likely to
33 affect at least one of multiple sites – the “multiple jeopardy” hypothesis (Newton 2004, Cresswell 2014).
34 Furthermore, optimal migration theory predicts that migrants will maximise the distance travelled during
35 any one migration flight (Alerstam et al. 1990). Small-scale connectivity will also increase vulnerability
36 because any environmental change of a fixed area will affect a larger proportion of a population that has a
37 smaller range (Simberloff 1995, Jones et al. 2008). Determining the degree to which these factors affect
38 survival is therefore likely to be crucial to understanding how variation amongst migrant populations leads
39 to declines (intra- and inter trends are highly variable, e.g. see European Bird Census Council 2012) and
40 so where to focus any future potential conservation actions to halt declines (Vickery et al. 2014).

41 Here we investigate the number of stop-over and wintering sites, and the geographical spread of these
42 sites (i.e. connectivity) in a long-distance migrant species, the Cyprus Wheatear *Oenanthe cyprica*.
43 Cyprus Wheatears breed only in Cyprus (Collar 2005), and are one of the most abundant and widely
44 distributed species there (Flint and Stewart 1992) with a large and probably stable population (Collar
45 2005, Randler et al. 2010). The Cyprus Wheatear is a migratory species that has a wintering range just
46 south of the Sahara in East Africa, with its core in Sudan and Ethiopia (although information only comes
47 from limited and frequently anecdotal sight records, Collar 2005), a straight line distance of ca. 2,600 km.
48 Cyprus Wheatears also have one of the most southerly breeding locations in Europe for a long-distance
49 migrant, and so have the potential to be able to reach these wintering grounds in a single flight (with
50 potential maximum flight ranges for similar size migrant passerine species estimated at > 2,500 km, see
51 Delingat et al. 2008, Arizaga et al. 2011). This flight distance would not require refuelling stop-overs.
52 Furthermore this flight distance could potentially be achieved with 2-3 days continuous flight, as has just
53 been probably confirmed as possible for other small passerine migrants (Adamik et al. 2016, Ouweland
54 and Both 2016).

55 Here we present the migration tracks and wintering locations of the first six adult Cyprus Wheatears to be
56 tracked with geolocators. We first established that the tagging methodology itself did not affect survival

57 (see Blackburn et al. 2015) and so that we could be confident that our results came from a representative
58 sample of returning birds. We then predicted that:

- 59 1. There would be no or very short stop-overs during migration
- 60 2. Individuals would have a single wintering site
- 61 3. Spread of individuals on the non-breeding ground will be at the large scale (>1000 km).

62 **Methods**

63 The study was conducted from 2014 to 2015 in a 130 ha area at about 1800 m a.s.l. at the National
64 Forest Park of Troodos (NFP of Troodos; 34°56'11"N 32°51'48"E), located at the centre of Troodos
65 massif that ranges from the northwest to the southeast part of the island of Cyprus. The study was carried
66 out during the breeding season as part of a longer term study of survival and productivity in Cyprus
67 Wheatears (Xenophontos and Cresswell 2015a). The study area supports the one of the densest
68 breeding Cyprus Wheatear populations on the island (Flint and Stewart 1992).

69 Observations and data recording started in the last week of March each year when the first individuals
70 arrived at the breeding grounds, and regular monitoring continued until the end of August, with sporadic
71 visits until October. Birds were captured with spring traps (baited with maggots and conspecific song
72 playback) throughout the season (but especially during arrival and territory establishment for the adults)
73 and ringed with individual combinations of colour rings (with permission from the Game Fund, Ministry of
74 Interior and BirdLife Cyprus). Individuals were sexed (by plumage), and all birds were aged as first winter
75 (within their first year) or adults (>1 years old) based on their plumage characteristics (Jenni and Winkler
76 1994). The larger study contained 324 individuals that were colour ringed from 2010-2013 (110 males, 91
77 females and 123 chicks) see Xenophontos & Cresswell (2015b): of these individuals, there were 22 male
78 and 19 female adult birds remaining (the species has very high site fidelity and high survival) on the study
79 site in 2014 and thus available for this study. Between the 2nd – 15th May 2014, we colour-ringed an
80 additional 5 adults and 27 1st year males, 7 adults and 22 1st year females including 24 individuals (adults:
81 5 males and 4 females; 1st year: 7 males and 8 females) that were fitted with geolocators. In total: 81
82 untagged birds and 24 tagged birds were present on the study site in May 2014 and so available for
83 assessment of tag effects on return rates the following year.

84 Tags were fitted using the harness design and methodology in Blackburn et al. (2015). In summary: we
85 deployed 24 geolocators of model ML6740 developed by the British Antarctic Survey (BAS), 13 with a 10
86 mm (0.64, 0.02 SE g) and 11 with 5 mm (0.57, 0.01 SE g) light-stalk positioned at a fixed angle of 45°.
87 The average mass of the elastic loop harness was 0.05, 0.01 SE g (measured from harnesses removed
88 from birds on recovery of the tag). We used leg-loop harnesses, made from elastic material (Rappole and
89 Tipton 1991). Pre-constructed elastic harnesses took approximately 1 minute to fit and birds were
90 released immediately at their capture location. Untagged birds were captured, handled and colour-ringed
91 as per tagged birds, except that no tag was fitted. Both the mass and the wing length of birds fitted with
92 tags was the same as the untagged group: mass of untagged birds 16.2, 0.2 SE g vs tagged birds 16.6,
93 0.4 SE g, $F_{1,99} = 0.8$, $P = 0.36$; wing length of untagged birds 84.3, 0.2 SE g vs tagged birds 84.2, 0.4 SE
94 g, $F_{1,100} = 0.04$, $P = 0.84$; note that sample sizes are smaller than the $N = 105$ total tagged and untagged
95 birds because some untagged birds had missing biometric data.

96 Recaptures and resightings were carried out from, May 14th – 23rd in 2015 between the hours of 07:00
97 and 18:30. Seven males and seven females with tags were resighted back on the study site. We
98 recaptured 6 birds using mist nets at the nest site. The two-week capture period that was available was
99 entirely during the incubation stage: males do not visit the nest at this period and also did not respond
100 vigorously to playback of calls except in one case; consequently males rarely approached nets and only
101 1/7 males was caught compared to 5/6 females (one female was likely depredated during incubation
102 between initial resighting and capture attempts). Return rates were compared between tagged and
103 untagged birds to determine if the tagging process may have affected survival and so may have biased
104 our sample, but no tag effects were found (see Supplementary Material: Tag Effects). Resightings of
105 untagged birds were carried out during systematic visits to all of the territories where untagged birds were
106 resident the year before during the two week capture period and during further visits to territories where
107 birds were found to be absent in a subsequent 6 week period.

108 *Geocator data analyses*

109 Of the 6 loggers retrieved, 5 provided data for the entire migratory cycle and 1 failed a month after the
110 bird had reached the wintering ground. Raw data were downloaded, viewed and preliminarily edited using
111 the BASTrack software suite (British Antarctic Survey, Cambridge, UK; see Fox 2010 for an overview of
112 the following processes). We adjusted for clock drift, assuming that any drift was linear. We used a

113 threshold value of 2, which is close to civil twilight. False twilight events due to shading from weather or
114 vegetation were identified and removed with the 'minimum dark period' filter (we used 4 hours). Data
115 were then visually inspected to ensure that only one sunrise and sunset occurred within any 24-hour
116 period.

117 Further analyses were carried out using R 2.13.1 (R Development Core Team 2014). We used the
118 LoessFilter in the R package 'GeoLight' (Lisovski and Hahn 2012) to validate twilight events and identify
119 those influenced by shading events at dawn and dusk: a polynomial regression of twilight events
120 identified residuals that were greater than 3 times the interquartile range and are therefore likely to be
121 erroneous (Lisovski and Hahn 2012); these were all checked individually to determine if they were in fact
122 migratory movements or indicative of systematic errors (see Supplementary Material, Figs. 1a – f).

123 Because conditions away from the breeding grounds are unknown, we carried out two calibrations to
124 determine the correct sun elevation angle (SEA, which influences latitude) for winter (SEAW) and
125 summer (SEAS). For SEAS we used the LocatorAid software, which uses known residency times and
126 summering location to calculate the corresponding breeding ground SEA: we used the SEAS that gave
127 the best average location fit to the study site for all six birds rather than determining individual SEAS to be
128 consistent with what we had to do for the SEA in winter (see below). We attempted to find the correct
129 winter angle using the Hill-Ekstrom calibration method (Hill and Braun 2001, Ekstrom 2004, see Tottrup et
130 al. 2012) in which we selected the value that gave the least amount of variation in latitude. A value of -3.5
131 was determined for 3 individuals, and we used this value for the remaining individuals for which the
132 calibration did not yield a meaningful result.

133 Once a corresponding SEAW and SEAS were known for each logger, noon and midnight locations were
134 derived from sunrise and sunset times using the 'coord' function in the Geolight package (Lisovski and
135 Hahn 2012), where latitude is calculated from the length of the solar day and night, and longitude from
136 local solar noon and midnight. Latitude data ± 15 days of the vernal and autumnal equinoxes (20 March
137 and 22 September) are inaccurate because day length does not vary, and so were excluded from all
138 analyses. Latitudes ± 16 -20 days from the equinoxes were used conservatively and any suspect data
139 excluded. Latitude and longitude data from individual months and stationary periods was found to be
140 reasonably normally distributed.

141 Maps were plotted using the raster, rgdal, rgeos and mapproj libraries in R. Breeding location was
142 determined as the mean of all summer locations (calculated using SEAS) for July, the month where
143 latitude and longitude showed the minimum variation, and is plotted on the location map as the mean
144 location for all six birds (i.e. the location of the breeding and tagging site at Troodos; during May – August
145 inclusive, at least, all tagged birds were present and breeding on the study site). Raw data plots (e.g. Fig.
146 1) and seven day moving average plots of both summer and winter latitude were examined to detect
147 onset and finish of migration (Supplementary Figure 1a-f), which was taken to be a consistent, sharp
148 decrease in latitude exceeding any variation in the week preceding it, followed by an abrupt sharp
149 termination of the decrease. Autumn migration periods were distinct and outwith the major error period on
150 either side of the equinox, which were characterised by a gradual decrease in latitude and followed by a
151 gradual increase in latitude over the period of weeks (Supplementary Figures 1a-f).

152 Supporting analysis was carried out using the function changeLight in the geolight package in R (Lisovski
153 and Hahn 2012). This identifies stationary periods by examining the probability that sunrise and sunset
154 times have changed suddenly using an automated algorithm. Unfortunately this was not suitable for our
155 data, and the highest probabilities of movement (regardless of varying data filtering, threshold or period
156 options – see Supplementary Figures 2a-f) were identified in all six birds as during the breeding season
157 when we had visual confirmation of them being on the study site in Cyprus. Furthermore, the clear
158 discontinuities in sunrise and sunset traces (that are clearly visible as location changes in Figure 1) that
159 we used to manually identify as migration periods – and that are coincident with the visual disappearance
160 of Cyprus Wheatears from Cyprus in the autumn – were not identified in any way, for any of the six birds,
161 as non-stationary periods (Supplementary Figures 2a-f). Raw sunset and sunrise plots from geoLight did
162 allow us to identify the likely period of onset of return migration, which was identified simply as a relatively
163 large discontinuity occurring in both sunrise and sunset plots simultaneously (marked with arrows on
164 Supplementary Figures 2a-f).

165 Attempts were made to further corroborate periods of migration (particularly with respect to non-stop
166 flights) by looking at the individual light curves because during long non-stop migration flights (that
167 inevitably must involve flying during the day) relatively unvarying high light intensity values are recorded
168 (Adamik et al. 2016). But traces from all six loggers, on all days during and outwith migration, had
169 considerable diurnal variation in light intensity such that this method could not be applied with any
170 confidence.

171 Winter locations (calculated using SEAw) were plotted as the mean for all individual winter locations for a
172 calendar month, or pooled for the entire winter period, along with two standard errors were plotted in all
173 cases except for the bird with the tag that failed on the 15th November, where locations are plotted just for
174 October and November. Note that geolocator locations are individually imprecise at the level of tens of
175 kilometre for longitude and hundreds of kilometres for latitude (Fudickar et al. 2012), and are subject to
176 systematic errors due to local environmental factors such as vegetation and topography changing
177 effective sunrise and sunset times (Lisovski et al. 2012).

178 We explored whether there were significant within winter movements (i.e. those detectable with
179 geolocators) by statistically examining variation in latitude and longitude with General Linear Models of
180 each variable separately in terms of Julian date and month, including the interaction of Julian date *
181 month because any systematic changes in latitude or longitude within a month were likely to represent
182 error because of gradually changing environmental variables (such as the systematic daily shift of sunrise
183 position with respect to a hill that casts a shadow). Raw data and fitted lines from these models were then
184 plotted to facilitate reasonable visual identification of sudden changes that would indicate that the bird had
185 actually changed position (Supplementary Figures 1a-f). We assume in all cases that the birds have one
186 or more clear, small-scale wintering territories rather than “wandering” during the winter (Cresswell 2014),
187 which applies to all studies of wintering wheatear species (see Blackburn and Cresswell 2016). Post-hoc
188 Tukey comparisons were also carried out on models of longitude and latitude by month, comparing June,
189 November, December, January and February to test if any monthly differences in position were
190 statistically different.

191 Distances between the known breeding site and the mean of all wintering locations for an individual (see
192 Figure 3), or between winter locations (see Supplementary Figure 2) were measured using the ruler tool
193 in Google Earth to the nearest 10 km (i.e. the great circle distance). The time taken to reach the wintering
194 ground in hours was taken as the total number of continuous individual locations from the first location
195 away from the breeding ground to the first location at the wintering ground multiplied by 12 (because
196 there was one location every 12 hours).

197 **Results**

198 The six tagged Cyprus Wheatears left Cyprus between the 14th – 28th October, arriving at their wintering
199 location on average 2.1 days later, with a total straight line travel distance on average of 2,538 km (2,190

200 – 3,070 km) and an average minimum travel speed of 43.1 km/h, assuming birds fly non-stop both night
201 and day (Table 1; Figure 2). If the Cyprus Wheatears flew at the measured flight speed of migrating
202 Northern Wheatears, i.e. 47 km/h (Bruderer and Boldt 2001), this means that the average maximum total
203 stop duration during the 60 hour migration period was < 6 hours. All wheatears were still on their wintering
204 grounds at the end of February and started their return migration between the 7th and 22nd of March
205 (mean 17th March, 2.7 days SE; see Supplementary Figure 2 a-f): Cyprus Wheatears spent 4.5 – 5
206 months on the wintering grounds.

207 The birds wintered in Sudan, South Sudan or Ethiopia (Figure 3), spread over 350 km of Longitude and
208 930 km of Latitude, with the furthest straight line distance between any location being 950 km. There was
209 no strong evidence for multiple wintering sites for any of the five birds that had data throughout the winter
210 period except in February (Supplementary Figures 1a-f and 2). For three of these five birds there was
211 some evidence that they moved on average 80 km (20 SE) to a second site during February (longitude
212 changed significantly between months, see Supplementary Material Figs 1a, b & d), but note that this is at
213 the threshold of detectability for geolocator accuracy (Lisovski et al. 2012).

214 **Discussion**

215 Our results support our predictions that Cyprus Wheatears have a migratory strategy consistent with a
216 relatively high annual survival for a trans-Saharan migrant. Our first key result is that Cyprus Wheatears
217 move from their breeding ground to a likely single wintering ground in just 60 hours (2.5 days) on
218 average, covering an average distance of ca. 2,500 km. This gives an average minimum flight speed of
219 ca. 43.1 km/h if we assume no stop-overs. Typical flight speed of migrating passerines has been
220 measured in the field as between 40 – 55 km/h, with most small chats being at the lower end of this range
221 (Bruderer and Boldt 2001). It is very likely therefore that the flights from Cyprus to the wintering grounds
222 were non-stop. The variation in speed of migration from 31 – 51 km/h likely reflects measurement error,
223 but could also have arisen through variable wind speeds, with head or tail winds slowing or speeding rate
224 of travel respectively (Erni et al. 2005). Alternatively, if we assume that all individuals did fly at an
225 assumed maximum speed of 55 km/h (Bruderer and Boldt 2001), then individuals may have made a
226 number of short stops of average duration of 15.8 (4.6 SE, range 3.2 – 28.1 hours). But, parsimoniously,
227 and considering the very low resolution of the locations in time (every 12 hours) and inaccuracy
228 (particularly in latitude of the order of several hundred kilometres (Lisovski et al. 2012), so that average

229 values are accurate, but not individual values), it seems most likely that the Cyprus Wheatears completed
230 their migration in a single, non-stop flight of ca. 2,500 km. This is a realistic flight range for a maximally
231 fuelled bird of this size (Delingat et al. 2008, Arizaga et al. 2011, Risely et al. 2015). This also implies that
232 Cyprus Wheatears flew both day and night, even though typically wheatears are considered to be
233 nocturnal migrants as with many other passerine species (see Adamik et al. 2016).

234 There are two general implications from this result – first, that crossing the Sahara in a single non-stop
235 flight can be easily routinely achieved by small passerines and can be the norm, and second, that
236 minimising stop-overs is likely to increase survival. Firstly, routine, non-stop crossing of the Sahara by
237 small passerine migrants has always been considered to be a theoretical possibility, yet measurement of
238 this has only been achievable recently using geolocators (Adamik et al. 2016, Ouweland and Both 2016).
239 A parallel study of Whinchats *Saxicola rubetra* that uniquely tagged birds on their wintering grounds, also
240 found strong evidence for non-stop flights (in the sense that any stops can only be of the order of hours
241 and not days) over the Sahara (Blackburn et al. unpublished data). These results are particularly
242 important because it suggests that non-stop crossing a barrier of 2,500 – 3000 km may be commonplace
243 for even small passerines (Jones 1995, Alerstam 1990). Observations of migrant passerines strategically
244 resting or foraging in oases in the Sahara (e.g. Bairlein 1985) perhaps may not give a representative idea
245 of typical migration, although it is clear that many migrants that could cross the Sahara non-stop may stop
246 for part of the day, probably to maintain water balance (Biebach 1986, Biebach 1995): short stops, of the
247 order of a few hours, by the Cyprus Wheatears in this study have not been ruled out. Crossing the Sahara
248 will represent a problem for many individuals though (Strandberg et al. 2010) and, for example, the 42%
249 of tagged Cyprus Wheatears that did not return in our study may have died during the migration period.
250 Even if the barrier crossing is not an issue, however, the barrier may represent a problem in terms of
251 fuelling before or after (Bayly et al. 2012, Arizaga et al. 2013). Cyprus Wheatears, however, move
252 between their wintering and breeding grounds without the uncertainty of these necessary refuelling stops.

253 Secondly, we note the association of relatively high over winter survival in Cyprus Wheatears (>50% for
254 juveniles and >70% for adult males in some years Xenophontos and Cresswell 2015b) and a migration
255 without refuelling stops (or staging sites) which is to be expected if increasing the number of stop-overs
256 reduces survival. We cannot explicitly test this hypothesis (survival ~ no. of stop-overs) with a sample size
257 of only one population, and therefore can give no strong conclusions without further consistent examples.
258 A future meta-analysis based on populations that vary in the number of stop-overs, all other things being

259 equal (or statistically controlled for), relating overwinter survival to the number of stop-overs, would be
260 predicted to show a negative relationship between survival and number of stop-overs. Information on
261 stop-overs and true survival from the same population are very rare currently. But analyses that have
262 looked at population status (a potential proxy for individual survival) and distance of migration (a likely
263 proxy for number of staging sites, when controlling for phylogeny) have found this negative relationship,
264 although interestingly only in the Afro-Palearctic migration system where most species migrate distances
265 that require staging (>3000 km), and not in the Nearctic system where many species winter within a
266 single flight's span (Jones and Cresswell 2010).

267 Another important result from this study is the size of the wintering range that we measured. Only six
268 birds were tagged and these were spread over ca. 1000 km suggesting medium to large scale
269 connectivity for this population breeding over an area of only <4 km² (Cresswell 2014). The recorded
270 wintering range for Cyprus Wheatears is between Chad and Eritrea (Collar 2005), which further reduces
271 migratory connectivity to a wintering range of ca. 1,800 km, although visual identification error due to
272 similarities with Pied Wheatears *Oenanthe pleschanka* (Sinclair and Ryan 2003) may make this reported
273 range somewhat inaccurate. There is every reason to suggest that this range is available to our breeding
274 population, considering that we only had a sample of size of six individuals.

275 Location data during the winter obtained by geolocation is imprecise and small-scale shifts in wintering
276 range cannot be elucidated from geolocator data (Lisovski et al. 2012). There was, however, some
277 consistent sign from three of the individuals that they moved wintering location during February, probably
278 for the few weeks directly before migration. Errors become larger near the equinox (compare the drift in
279 locations in late August when we know the Cyprus Wheatears are not moving to those in February shown
280 in Supplementary Figures 1a-f) so these may just be artefacts. Nevertheless, evidence from colour-ringed
281 Whinchats visually monitored on their over-wintering territories suggests that they leave these territories
282 to fatten up at least two weeks before they migrate over the Sahara, although many migrant Whinchats
283 from elsewhere fatten up successfully in the same area (Risely et al. 2015). The implication is that Cyprus
284 Wheatears may leave their winter territory to fatten up in the local area, moving a few tens of kilometres,
285 before migrating. This detail is important because it implies better or different habitat from the winter
286 territory is required for pre-migratory fattening but further direct studies on the wintering ground are
287 needed to confirm this.

288 This study provides an example of where a long distance migration over the Sahara is associated with a
289 population with high survival. This may well be because it involves a non-stop flight that removes the
290 potential uncertainty in fuelling for migration: if this is the case then Cyprus Wheatears only fatten up once
291 at their breeding site and probably once at or close to their wintering site, and wintering sites are spread
292 over a large area of Africa. Measuring the number and location of migratory stop-overs and the degree of
293 connectivity in this way is probably crucial to understand why the population dynamics of any migratory
294 species vary (Cresswell 2014, Vickery et al. 2014), and we need data for many more species before we
295 can focus any conservation efforts to the breeding, staging or wintering periods.

296 **Acknowledgements**

297 We would like to thank Chris Goodwin who funded the tags used in this study.

298

299 **References**

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398 (*Oenanthe cypriaca*), an endemic migrant. -*Journal of Ornithology*, **In press**.

399 Table 1: Age (1 = first breeding year birds, 2+ = birds in at least their second year of breeding) and sex of
 400 the six birds with tags that were recaptured, their capture date in May 2014 and recapture date in May
 401 2015, and their migration details obtained from the geolocators they carried.

402

Logger	Sex	Age	Tagged May 2014	Recaptured May 2015	Depart Cyprus Oct	Arrival winter Oct	No. transit locations	Distance km	Non-stop speed km/h	Depart winter Mar
L57	F	2+	1	15	28	31	6	3070	42.6	16
L89	F	1	3	23	14	16	5	2670	44.5	20
L100	F	1	2	18	21	23	5	2610	43.5	20
L107	M	1	1	20	29	30	4	2460	51.3	22
S123	F	1	1	18	22	24	6	2230	31.0	-
S126	F	1	2	19	23	24	4	2190	45.6	7
MEAN					23	25	5.0	2538	43.1	17

403 L = long stalk & S = short stalk tag

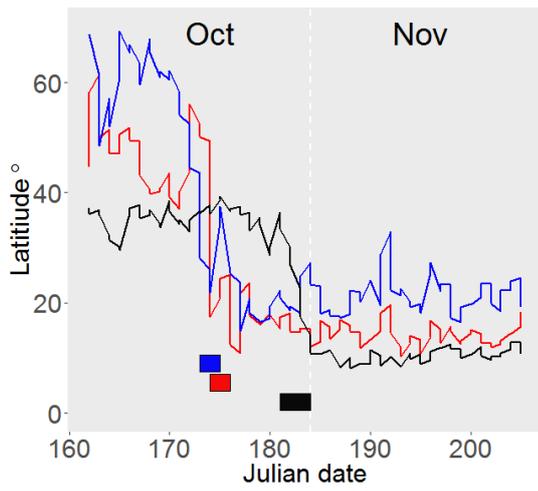
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406 Figure 1: Latitudes recorded every 12 hours for three representative birds to show variation in values and
407 the clear rapid decline in latitude used to identify the migratory period (marked with the rectangles at the
408 bottom of the Figure). Further supporting detail to identify moving and stationary periods is provided in the
409 Supplementary Material, Figures 1a-f.

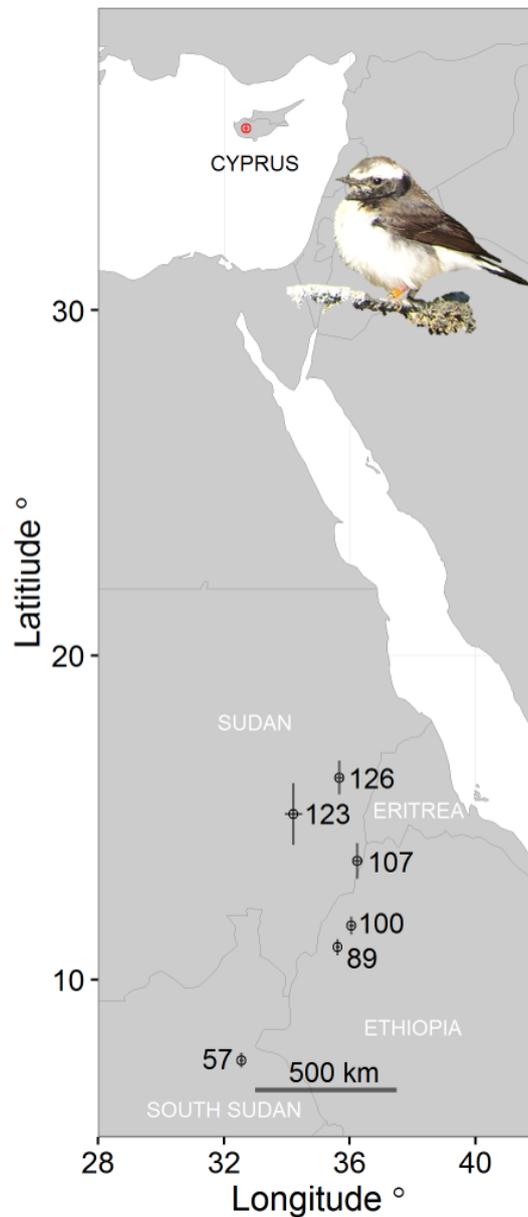
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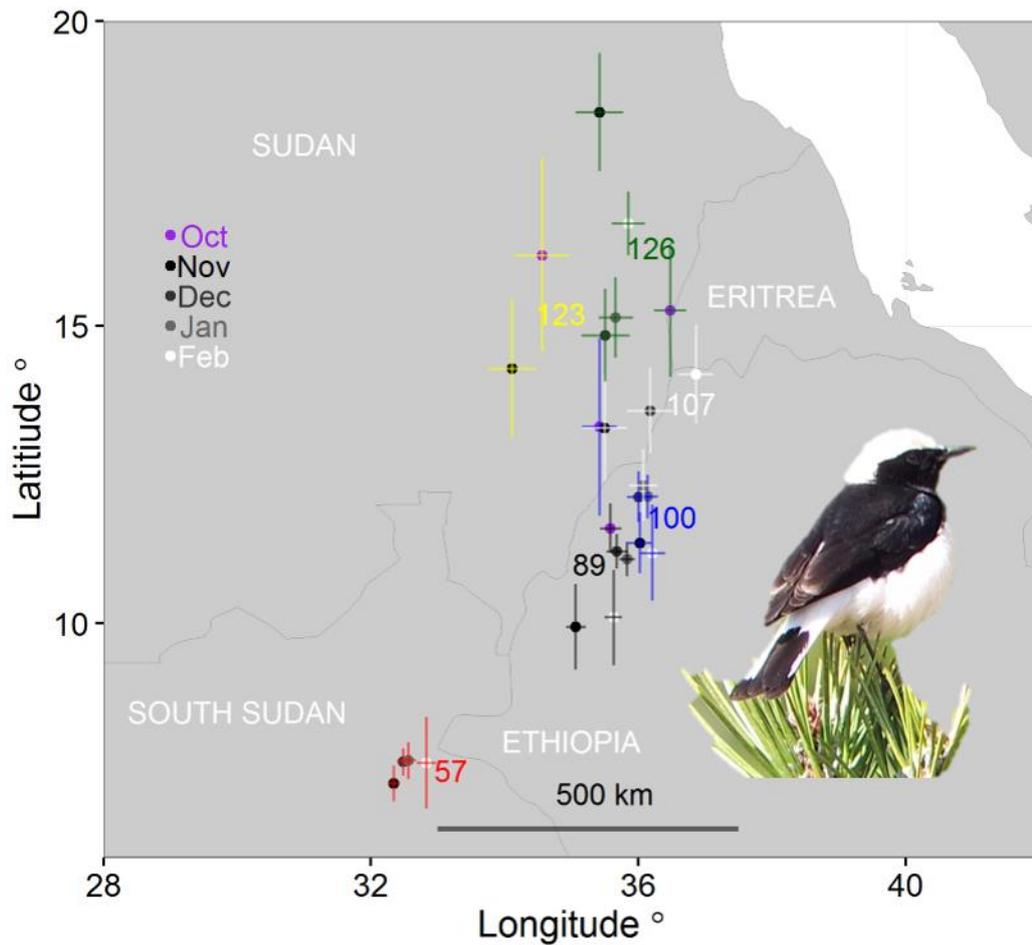
413 Figure 2: Wintering locations for each of the six geolocator tagged birds (numbered in black
414 corresponding to Table 1). The points are the mean location for all locations recorded Oct – Feb inclusive
415 outwith migration (\pm 2 standard errors for longitude and longitude), except for one logger which failed in
416 mid-November (logger 123). All winter locations outwith migration were within South Sudan, Sudan or
417 Eritrea. The red point shows the average mean of all locations for July for all six birds and shows the
418 location of the breeding site at Troodos, Cyprus (\pm 2 standard errors for longitude and longitude but the
419 error bars are too small to see at this scale). Inset – female Cyprus Wheatear.



420

421

422 Figure 3: Wintering locations for each of the six geolocator tagged birds (numbered corresponding to
423 Table 1). The points are the monthly mean location for all locations recorded Nov – Feb (Oct also if this
424 was outwith migration, except for one logger which failed in mid-November, in yellow), colour coded
425 according to month as per inset monthly key; +/- 2 standard errors for longitude and longitude, colour
426 coded for each individual. Smaller scale maps of monthly variation are included in Supplementary
427 Material Figures 1a-f. Inset – male Cyprus Wheatear.



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429

430 **Cyprus Wheatears *Oenanthe cyriaca* likely reach sub-Saharan African wintering**
431 **grounds in a single migratory flight**

432

433 **Marina Xenophontos, Emma Blackburn & Will Cresswell**

434

435 **Supplementary Material:**

436 Tag effects
437 Figures 1a-f
438 Figures 2a-f

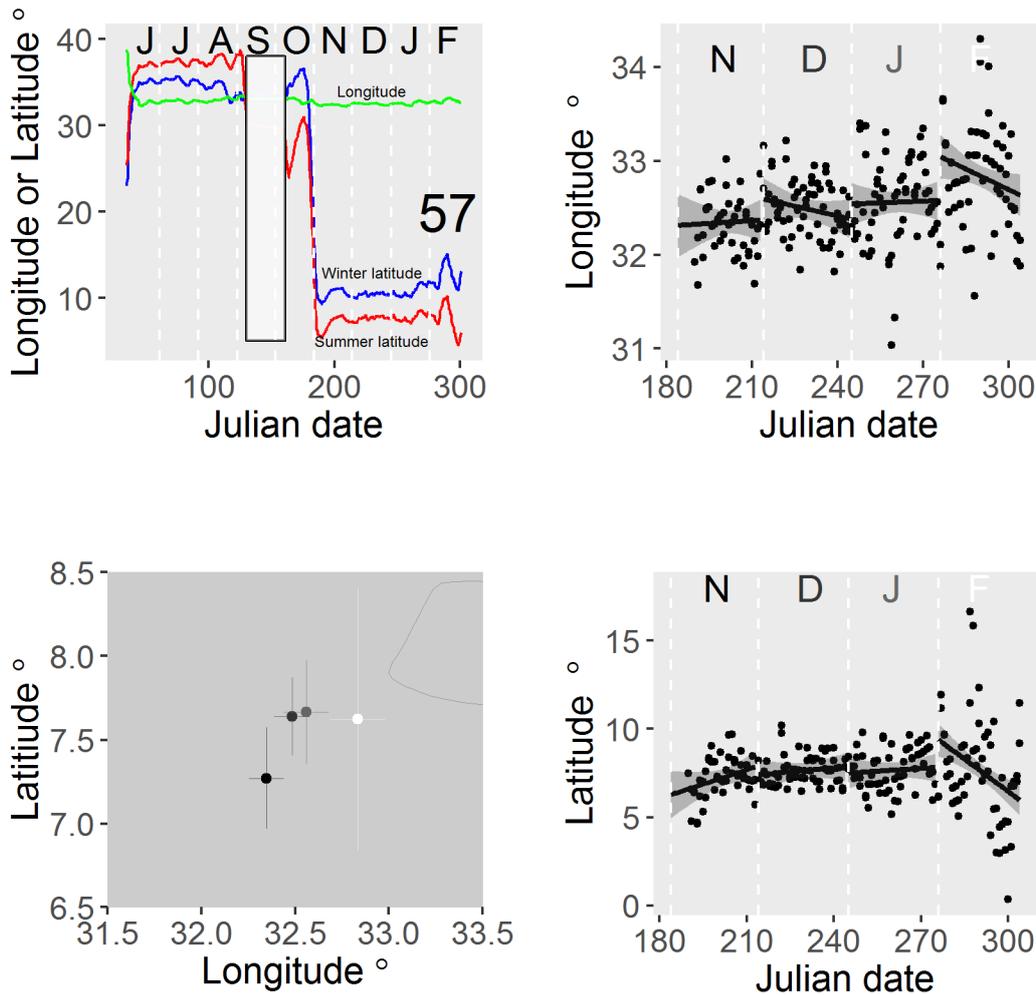
439 **Tag Effects:**

440 Tag effects were assessed to determine if returning birds were a representative sample. We compared
441 the ratios of returning and non-returning birds for both tagged and colour-ringed only birds using a chi-
442 square test. The binomial probability of return of a tagged bird (a proxy for survival because birds return
443 to the same breeding grounds – see Xenophonos & Cresswell 2015b) was also modelled as a binomial
444 variable with predictors, presence/absence of a tag, age (1st year and 2nd year or older), sex, mass at
445 capture and wing length. The effect of the use of two different light stalk lengths and other potential
446 confounding tagging variables was assessed by including light stalk length (5 mm or 10 mm, because
447 longer light stalks may increase drag), order of fitting, and proportion added mass of the tag (mass of the
448 tag/mass of the bird at capture because tags on lighter birds would represent a heavier relative load) (see
449 Blackburn et al. 2015).

450 Overall tag presence or design did not affect Cyprus Wheatear return rates. The return rate of tagged
451 birds (58.3%) was very similar to that of colour-ringed only birds (55.6%): $\chi^2_1 = 0.001$, $P = 0.99$. Seven
452 out of 12 males and seven out of 12 females returned to the tagging site. The probability of return of a
453 Cyprus Wheatear did not depend on tag presence (0.34, 0.51 SE, $z = 0.7$, $P = 0.51$), age (0.55, 0.43 SE,
454 $z = 1.3$, $P = 0.21$), sex (0.33, 0.52 SE, $z = 0.6$, $P = 0.54$) or wing length (0.13, 0.14 SE, $z = 1.0$, $P = 0.33$)
455 but the probability of return was significantly greater for birds of lower mass when captured (-0.35, 0.16
456 SE, $z = -2.2$, $P = 0.026$). Any effects of mass on survival were independent of sex (sex*mass interaction,
457 0.50, 0.39 SE, $z = 1.2$, $P = 0.21$) and tag presence (mass*tag presence interaction, 0.16, 0.31 SE, $z =$
458 0.5, $P = 0.61$). Considering only tagged birds, there were no significant effects of probability of return of a
459 tagged Cyprus Wheatear dependent on length of light stalk (-0.31, 0.97 SE, $z = -0.3$, $P = 0.75$), order of
460 fitting (0.08, 0.07 SE, $z = 1.1$, $P = 0.26$) or proportion added mass by the tag (2.8, 1.6 SE, $z = 1.7$, $P =$
461 0.09), controlling for age, sex and wing length (all also non-significant).

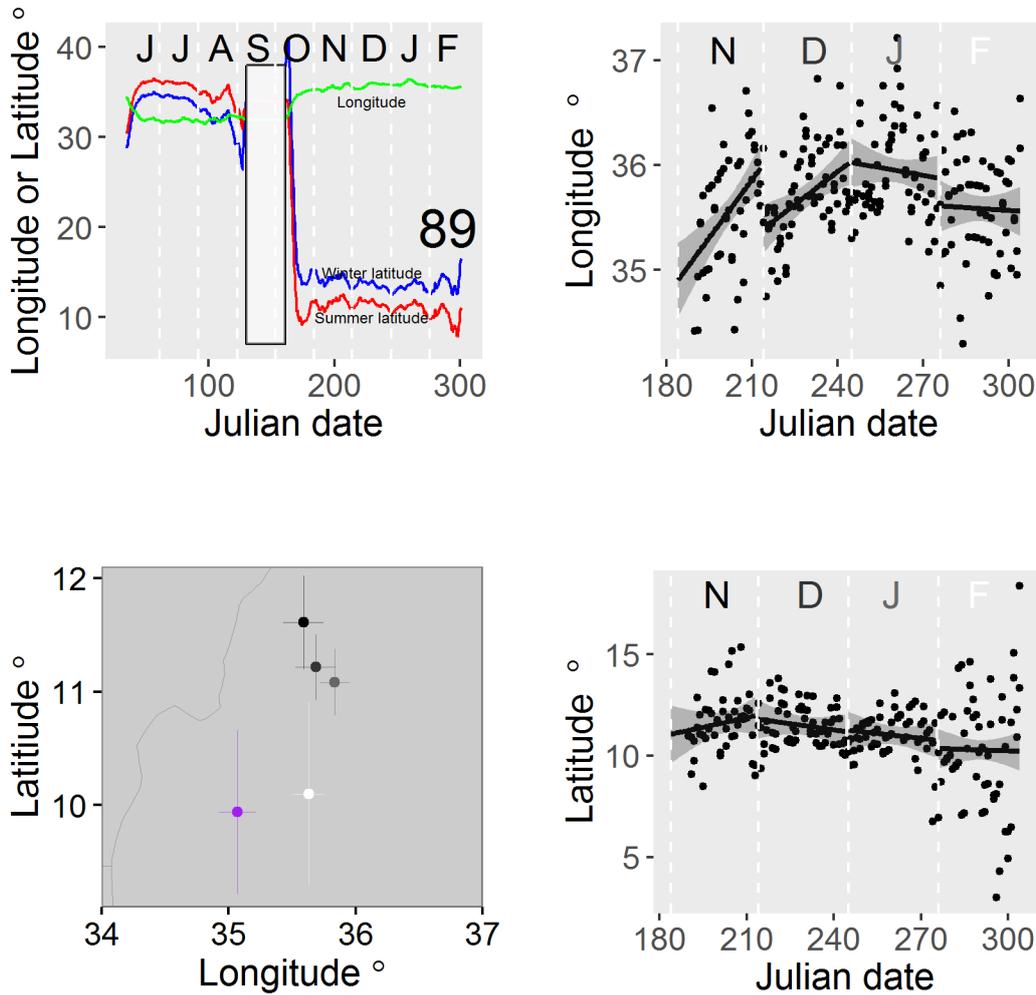
462

463 Supplementary Figure 1a: Variation in latitude and longitude derived from geolocator sunrise and sunset
 464 times for Bird 57. Top left panel shows 7-day moving average values (green for longitude, red for latitude
 465 using the summer sun elevation angle and blue for latitude using the winter sun elevation angle; the
 466 shaded bar indicates when all data were broadly unreliable because of the equinox). Bottom left panel
 467 maps mean (± 2 SE) monthly averaged locations (Nov black, Dec dark grey, Jan light grey, Feb white).
 468 The two right hand panels show monthly variation in the raw data with fitted lines (± 2 SE) for the
 469 interaction term of Julian date * month to illustrate systematic deviations with time that are likely to
 470 represent errors due to environmental variation rather than actual shifts in position. Post-hoc Tukey tests
 471 showed all winter months significantly different from June, and during the winter there was no significant
 472 variation by latitude, but all winter months differed significantly from Feb in longitude, suggesting a late-
 473 winter movement in February.
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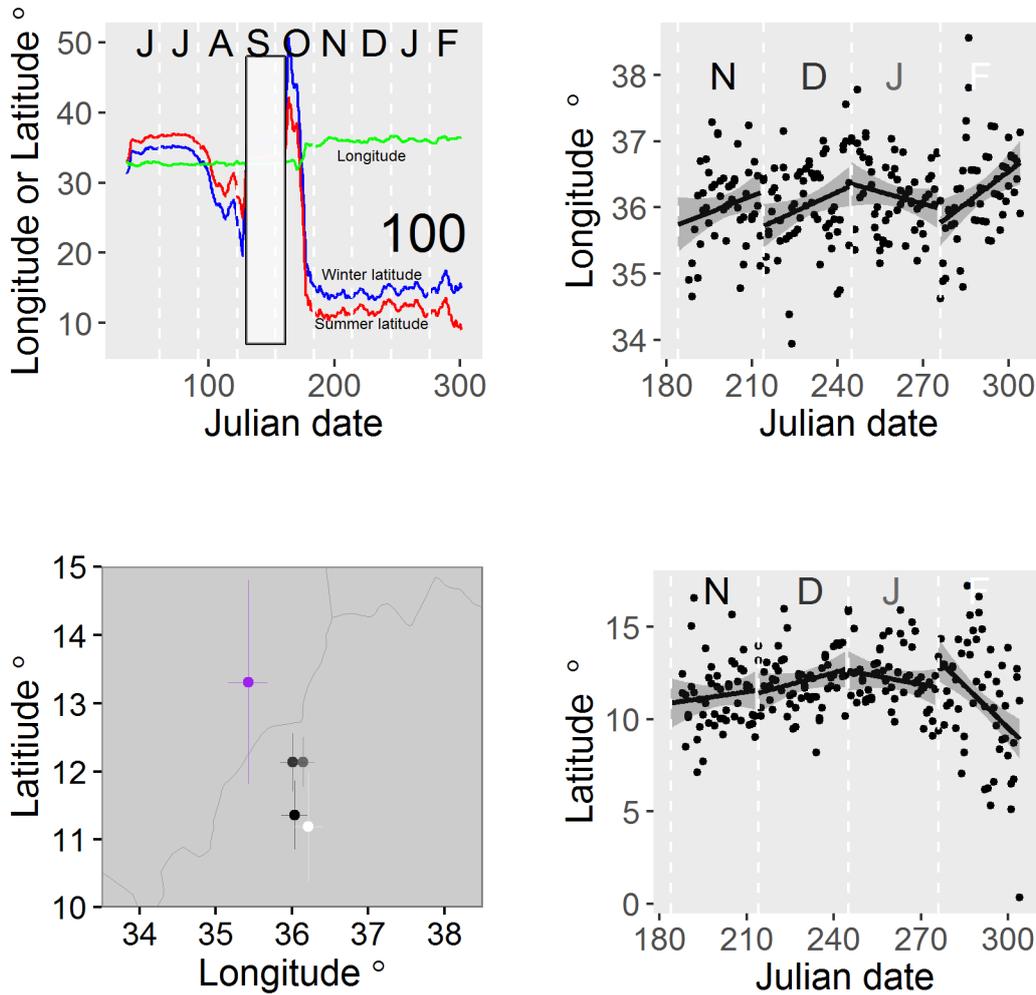
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478 Supplementary Figure 1b: Variation in latitude and longitude derived from geolocator sunrise and sunset
 479 times for Bird 89. Top left panel shows 7-day moving average values (green for longitude, red for latitude
 480 using the summer sun elevation angle and blue for latitude using the winter sun elevation angle; the
 481 shaded bar indicates when all data were broadly unreliable because of the equinox). Bottom left panel
 482 maps mean (± 2 SE) monthly averaged locations (Oct purple, Nov black, Dec dark grey, Jan light grey,
 483 Feb white). The two right hand panels show monthly variation in the raw data with fitted lines (± 2 SE)
 484 for the interaction term of Julian date * month to illustrate systematic deviations with time that are likely to
 485 represent errors due to environmental variation rather than actual shifts in position. Post-hoc Tukey tests
 486 showed all winter months significantly different from June, and during the winter Nov & Dec but not Jan,
 487 differed from Feb in latitude, and Jan differed significantly from Feb in longitude, suggesting a late-winter
 488 movement in February.
 489



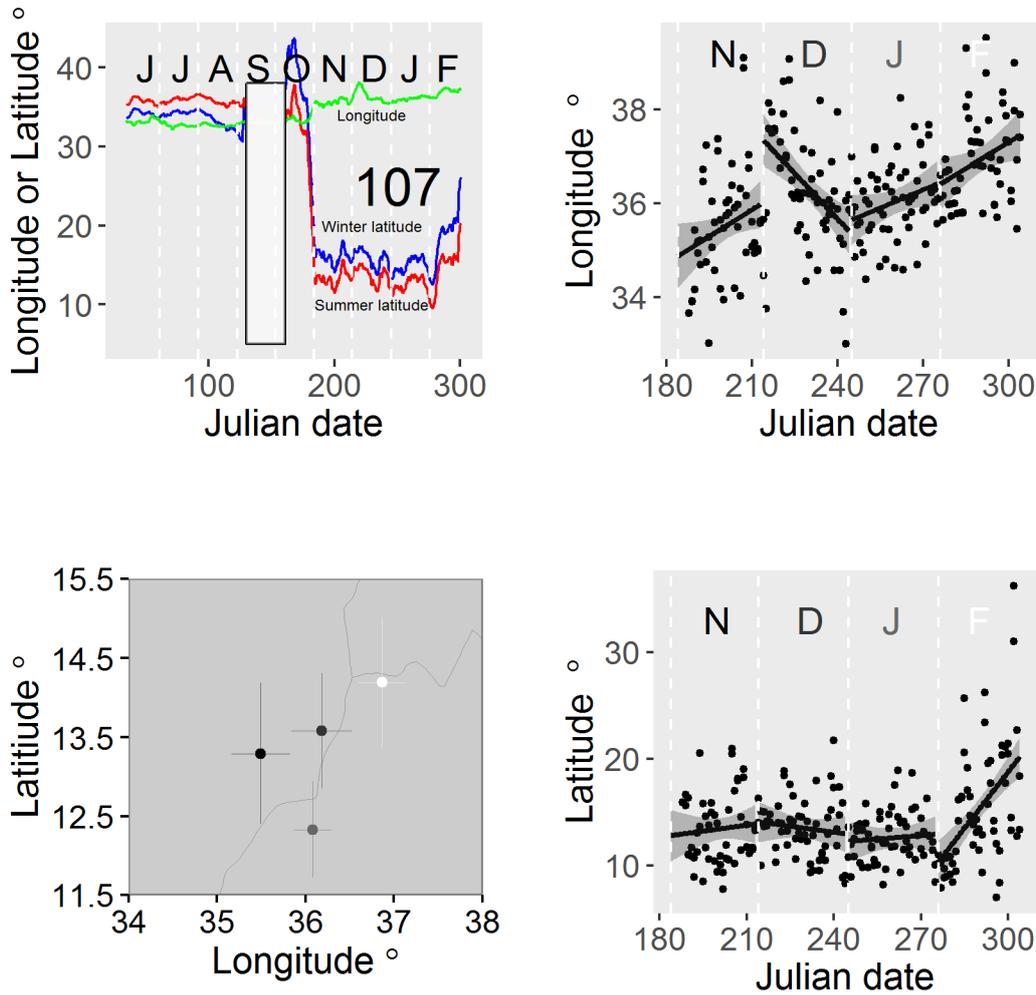
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492 Supplementary Figure 1c: Variation in latitude and longitude derived from geolocator sunrise and sunset
 493 times for Bird 100. Top left panel shows 7-day moving average values (green for longitude, red for
 494 latitude using the summer sun elevation angle and blue for latitude using the winter sun elevation
 495 angle; the shaded bar indicates when all data were broadly unreliable because of the equinox). Bottom left panel
 496 maps mean (± 2 SE) monthly averaged locations (Oct purple, Nov black, Dec dark grey, Jan light grey,
 497 Feb white). The two right hand panels show monthly variation in the raw data with fitted lines (± 2 SE)
 498 for the interaction term of Julian date * month to illustrate systematic deviations with time that are likely to
 499 represent errors due to environmental variation rather than actual shifts in position. Post-hoc Tukey tests
 500 showed all winter months significantly different from June, and during the winter Dec & Jan but not Nov
 501 differed from Feb in latitude, but there was no significant within-winter variation in longitude, suggesting
 502 that there was only weak evidence for any within-winter movement.
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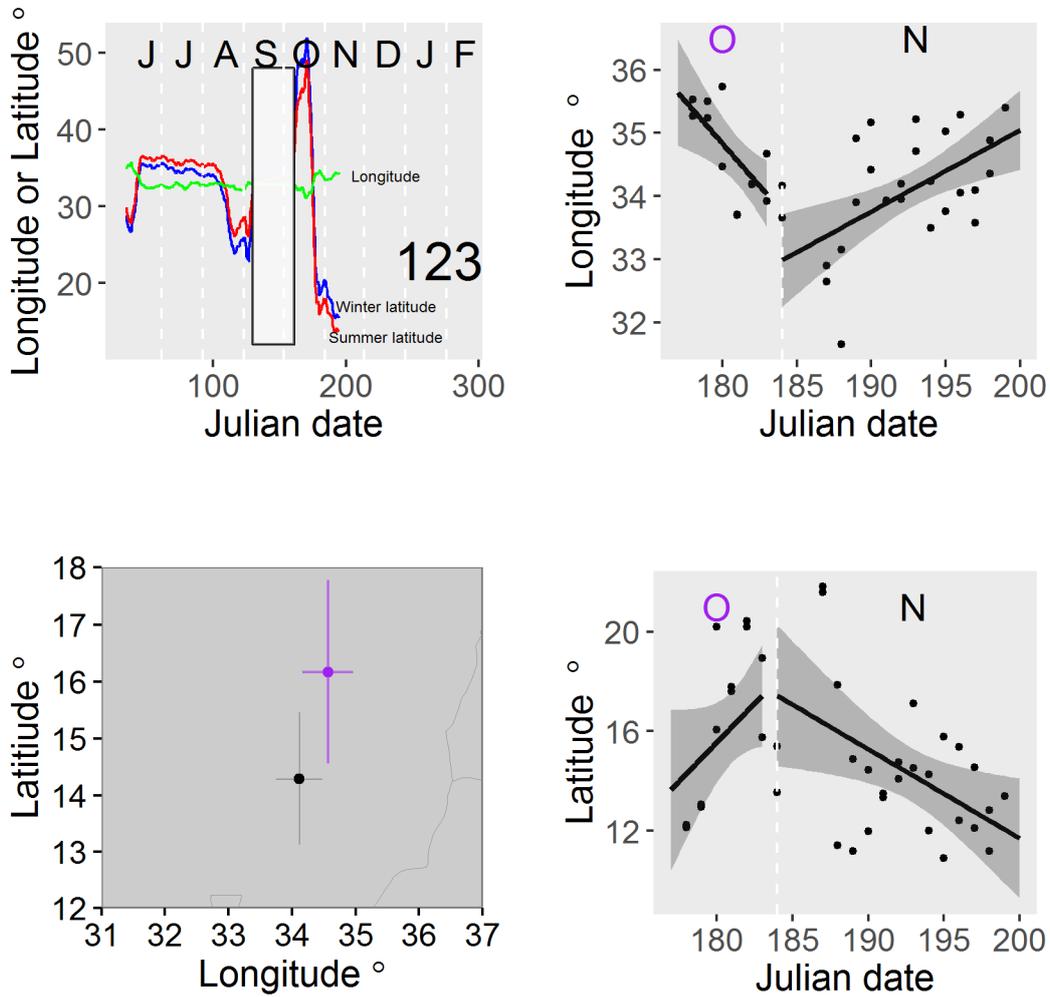
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507 Supplementary Figure 1d: Variation in latitude and longitude derived from geolocator sunrise and sunset
 508 times for Bird 107. Top left panel shows 7-day moving average values (green for longitude, red for
 509 latitude using the summer sun elevation angle and blue for latitude using the winter sun elevation angle;
 510 the shaded bar indicates when all data were broadly unreliable because of the equinox). Bottom left panel
 511 maps mean (± 2 SE) monthly averaged locations (Nov black, Dec dark grey, Jan light grey, Feb white).
 512 The two right hand panels show monthly variation in the raw data with fitted lines (± 2 SE) for the
 513 interaction term of Julian date * month to illustrate systematic deviations with time that are likely to
 514 represent errors due to environmental variation rather than actual shifts in position. Post-hoc Tukey tests
 515 showed all winter months significantly different from June, and during the winter all months differed from
 516 Feb in latitude, and all months differed significantly from Feb and Nov in longitude, suggesting a possible
 517 movement in Dec and a more likely late-winter movement in Feb.
 518



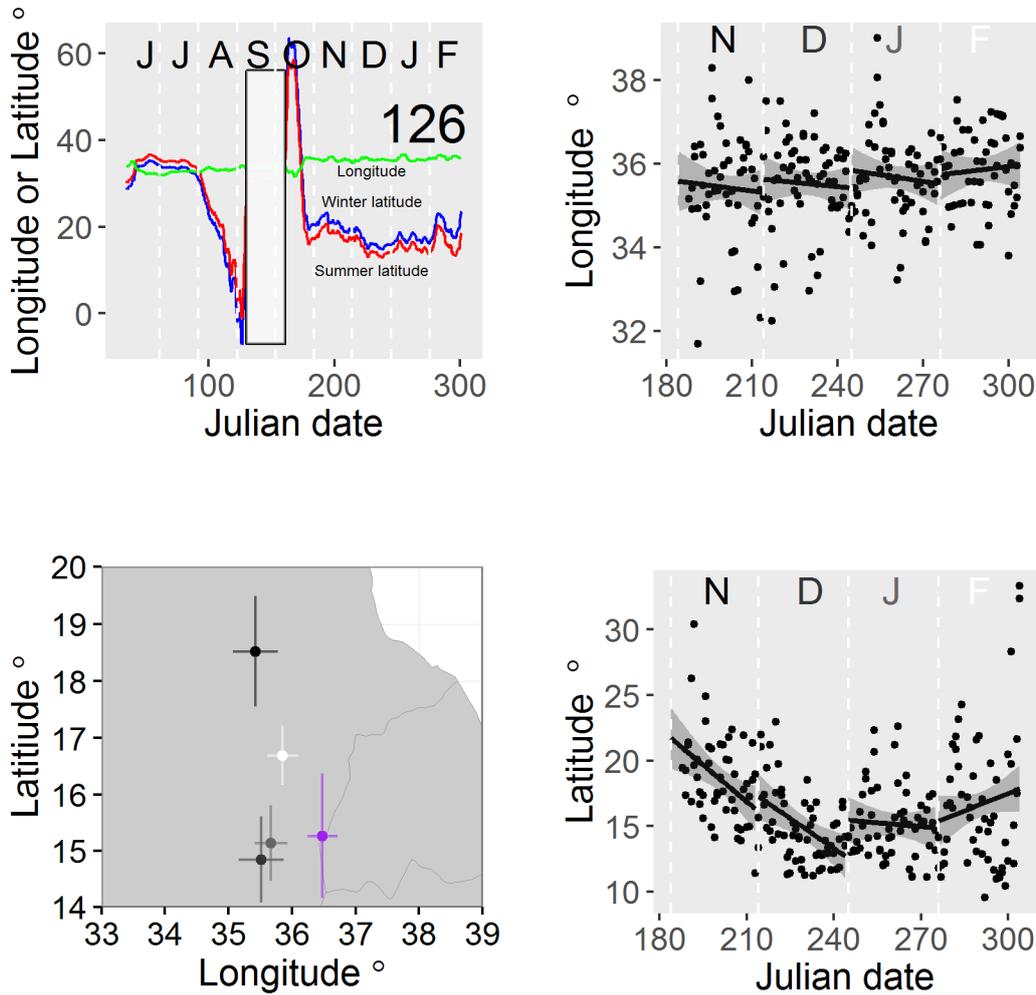
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521 Supplementary Figure 1e: Variation in latitude and longitude derived from geolocator sunrise and sunset
 522 times for Bird 123. Top left panel shows 7-day moving average values (green for longitude, red for
 523 latitude using the summer sun elevation angle and blue for latitude using the winter sun elevation angle;
 524 the shaded bar indicates when all data were broadly unreliable because of the equinox). Bottom left panel
 525 maps mean (± 2 SE) monthly averaged locations (Oct purple, Nov black – the geolocator failed in Nov).
 526 The two right hand panels show monthly variation in the raw data with fitted lines (± 2 SE) for the
 527 interaction term of Julian date * month to illustrate systematic deviations with time that are likely to
 528 represent errors due to environmental variation rather than actual shifts in position. Post-hoc Tukey tests
 529 showed all winter months significantly different from June, but no significant variation in latitude or
 530 longitude between the two months for which there were data available.
 531



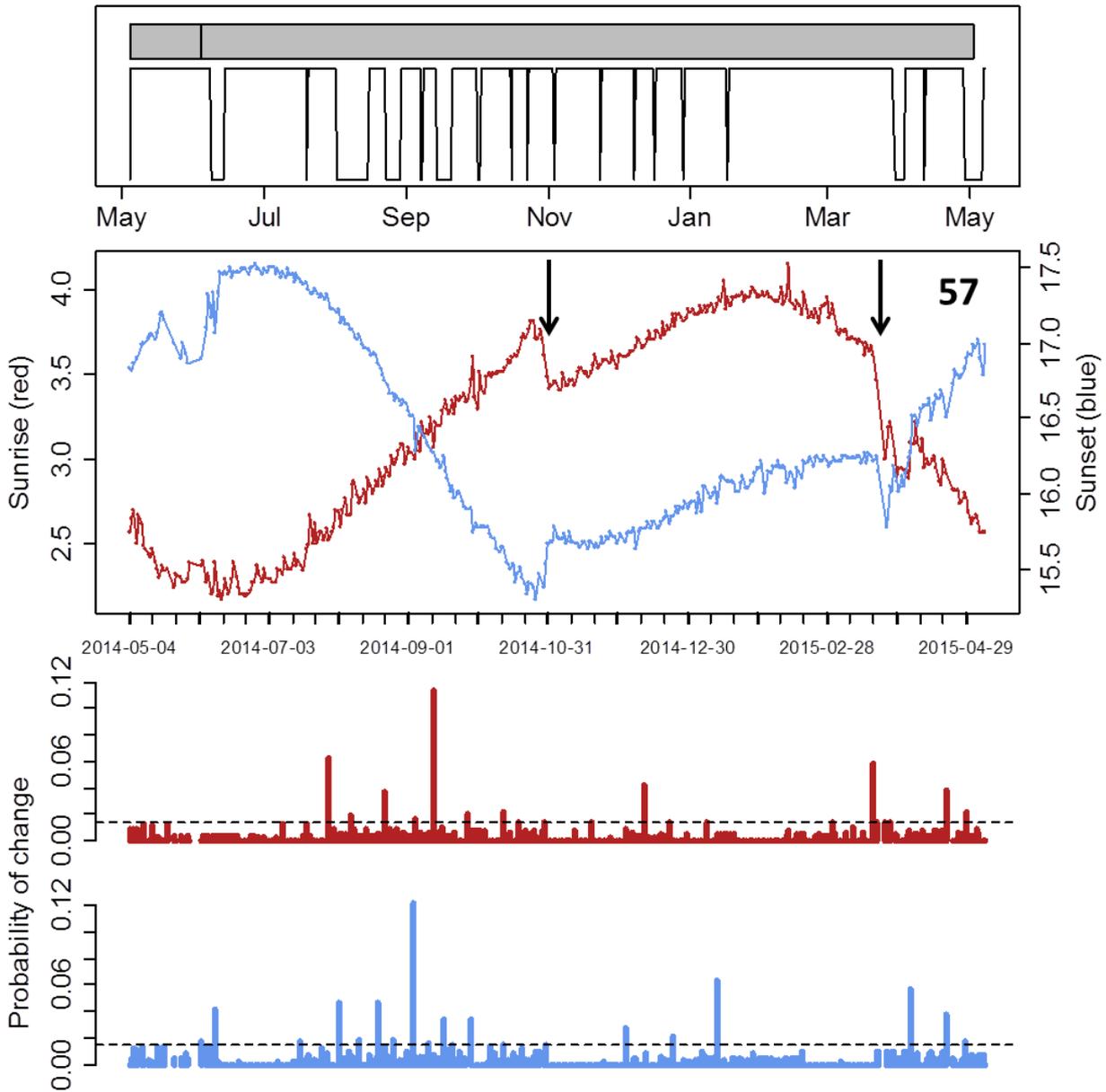
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534 Supplementary Figure 1f: Variation in latitude and longitude derived from geolocator sunrise and sunset
 535 times for Bird 126. Top left panel shows 7-day moving average values (green for longitude, red for
 536 latitude using the summer sun elevation angle and blue for latitude using the winter sun elevation angle;
 537 the shaded bar indicates when all data were broadly unreliable because of the equinox). Bottom left panel
 538 maps mean (± 2 SE) monthly averaged locations (Oct purple, Nov black, Dec dark grey, Jan light grey,
 539 Feb white). The two right hand panels show monthly variation in the raw data with fitted lines (± 2 SE)
 540 for the interaction term of Julian date * month to illustrate systematic deviations with time that are likely to
 541 represent errors due to environmental variation rather than actual shifts in position. Post-hoc Tukey tests
 542 showed all winter months significantly different from June, and during the winter Dec & Jan differed from
 543 Nov & Feb in latitude, but there was no significant within-winter variation in longitude, suggesting that
 544 there was only weak evidence for any within-winter movement.
 545



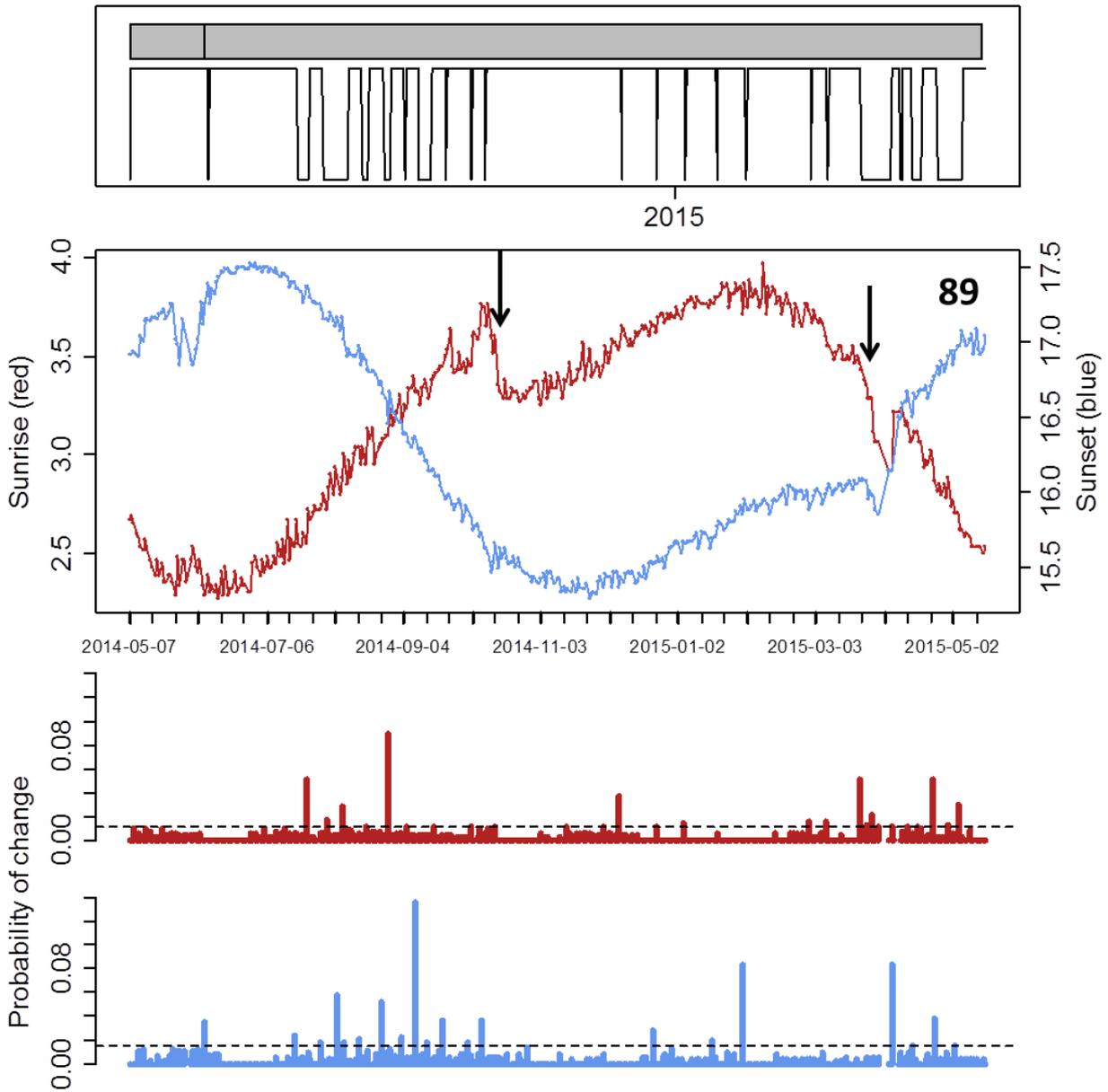
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549 Supplementary Figure 2a: Results for Bird 57 of the changeLight function analysis in the R package
 550 geolight to show the mismatch between its automated identification of points of likely change in position
 551 (top and bottom graph) and those obtained from visual examination of the raw sunrise and sunset times
 552 (middle graph with points of greatest change indicative of migration identified from manual inspection
 553 marked with bold arrows). Note that Cyprus Wheatears were known to be on the study site (i.e.
 554 stationary) from May until late September in all cases. Outputs are from default settings with a specified 5
 555 day stationary period and 0.9 quantile, and with identified outliers; varying these from 3 to 14 days, or
 556 0.75 to 0.95 quantiles, or without outliers, made little difference as to whether any of movement periods
 557 identified actually coincided with those identified from manual inspection, and whether stationary periods
 558 coincided with the periods that Cyprus Wheatears were known to be stationary.
 559



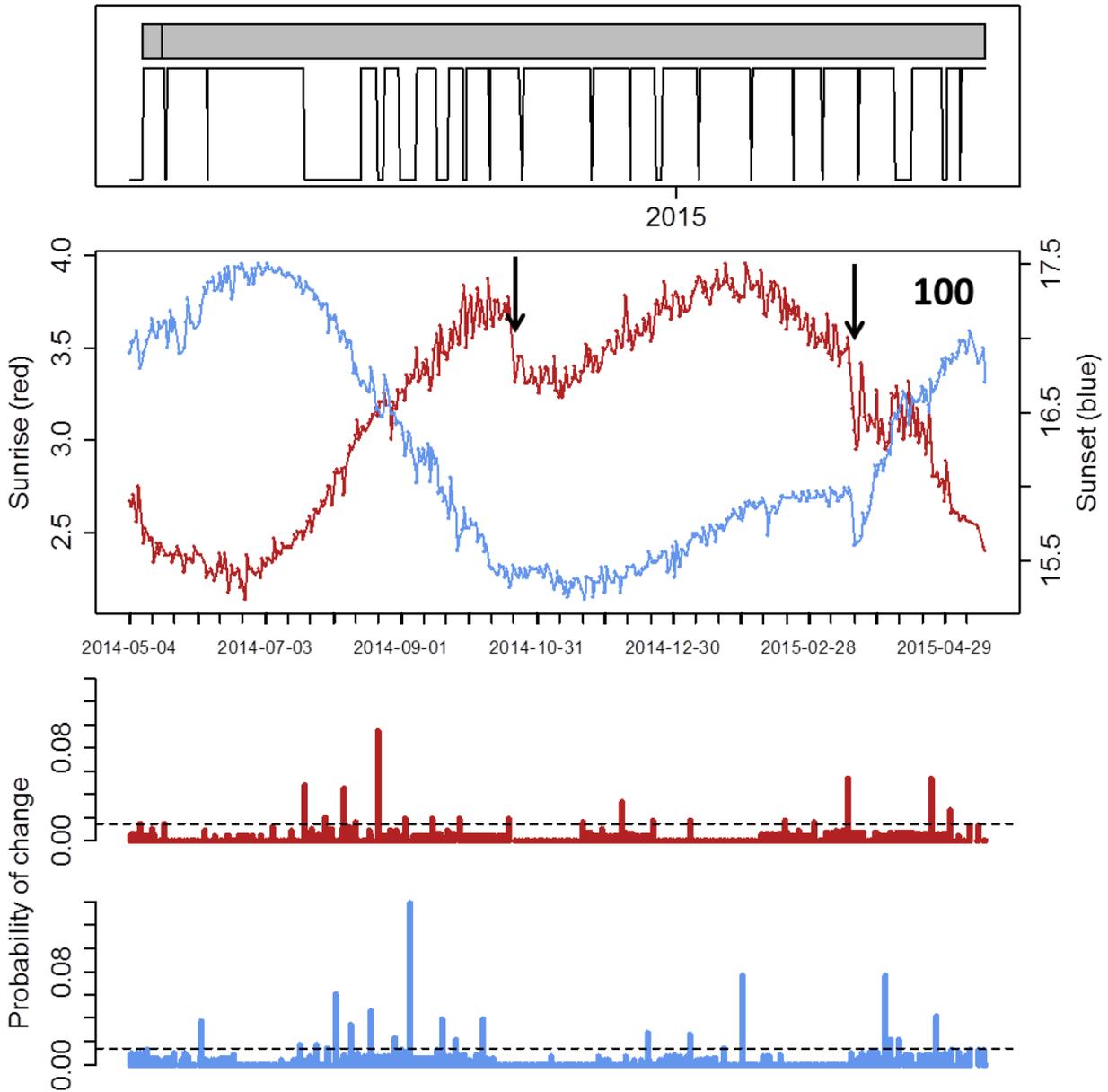
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562 Supplementary Figure 2b: Results for Bird 89 of the changeLight function analysis in the R package
563 geolight to show the mismatch between its automated identification of points of likely change in position
564 (top and bottom graph) and those obtained from visual examination of the raw sunrise and sunset times
565 (middle graph with points of greatest change indicative of migration identified from manual inspection
566 marked with bold arrows). Note that Cyprus Wheatears were known to be on the study site (i.e.
567 stationary) from May until late September in all cases. Outputs are from default settings with a specified 5
568 day stationary period and 0.9 quantile, and with identified outliers; varying these from 3 to 14 days, or
569 0.75 to 0.95 quantiles, or without outliers, made little difference as to whether any of movement periods
570 identified actually coincided with those identified from manual inspection, and whether stationary periods
571 coincided with the periods that Cyprus Wheatears were known to be stationary.
572



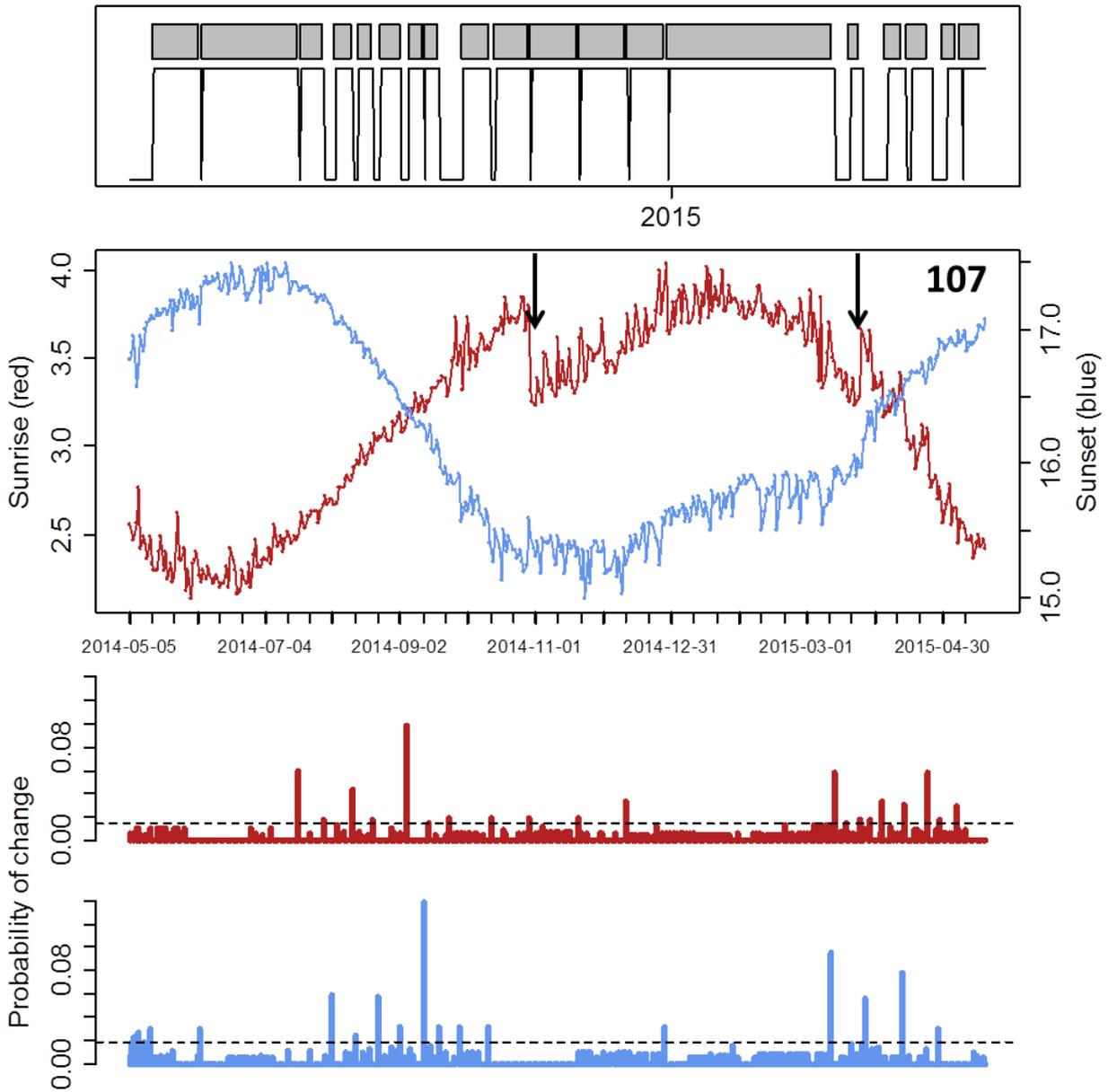
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575 Supplementary Figure 2c: Results for Bird 100 of the changeLight function analysis in the R package
 576 geolight to show the mismatch between its automated identification of points of likely change in position
 577 (top and bottom graph) and those obtained from visual examination of the raw sunrise and sunset times
 578 (middle graph with points of greatest change indicative of migration identified from manual inspection
 579 marked with bold arrows). Note that Cyprus Wheatears were known to be on the study site (i.e.
 580 stationary) from May until late September in all cases. Outputs are from default settings with a specified 5
 581 day stationary period and 0.9 quantile, and with identified outliers; varying these from 3 to 14 days, or
 582 0.75 to 0.95 quantiles, or without outliers, made little difference as to whether any of movement periods
 583 identified actually coincided with those identified from manual inspection, and whether stationary periods
 584 coincided with the periods that Cyprus Wheatears were known to be stationary.
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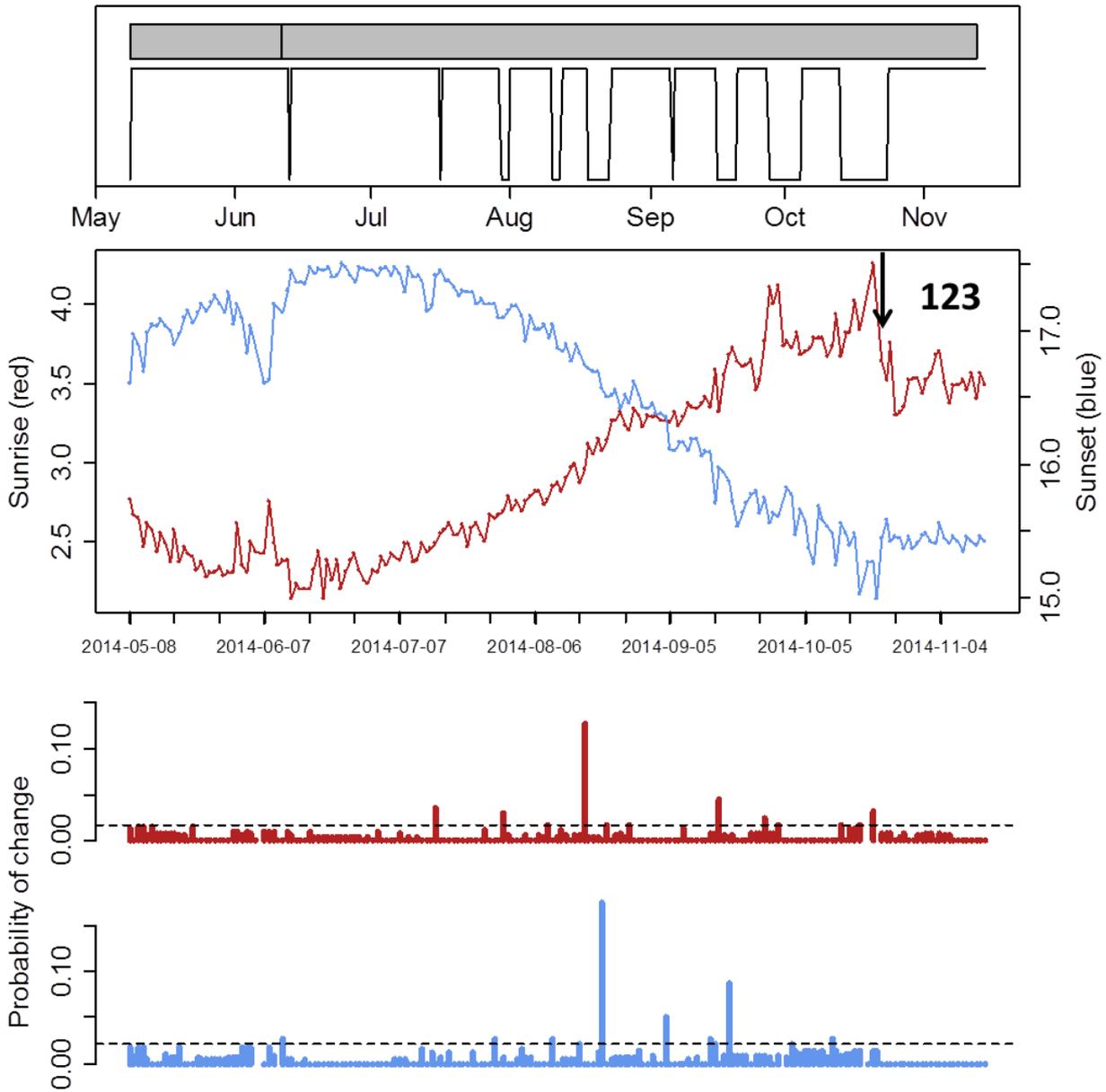
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588 Supplementary Figure 2d: Results for Bird 107 of the changeLight function analysis in the R package
589 geolight to show the mismatch between its automated identification of points of likely change in position
590 (top and bottom graph) and those obtained from visual examination of the raw sunrise and sunset times
591 (middle graph with points of greatest change indicative of migration identified from manual inspection
592 marked with bold arrows). Note that Cyprus Wheatears were known to be on the study site (i.e.
593 stationary) from May until late September in all cases. Outputs are from default settings with a specified 5
594 day stationary period and 0.9 quantile, and with identified outliers; varying these from 3 to 14 days, or
595 0.75 to 0.95 quantiles, or without outliers, made little difference as to whether any of movement periods
596 identified actually coincided with those identified from manual inspection, and whether stationary periods
597 coincided with the periods that Cyprus Wheatears were known to be stationary.
598



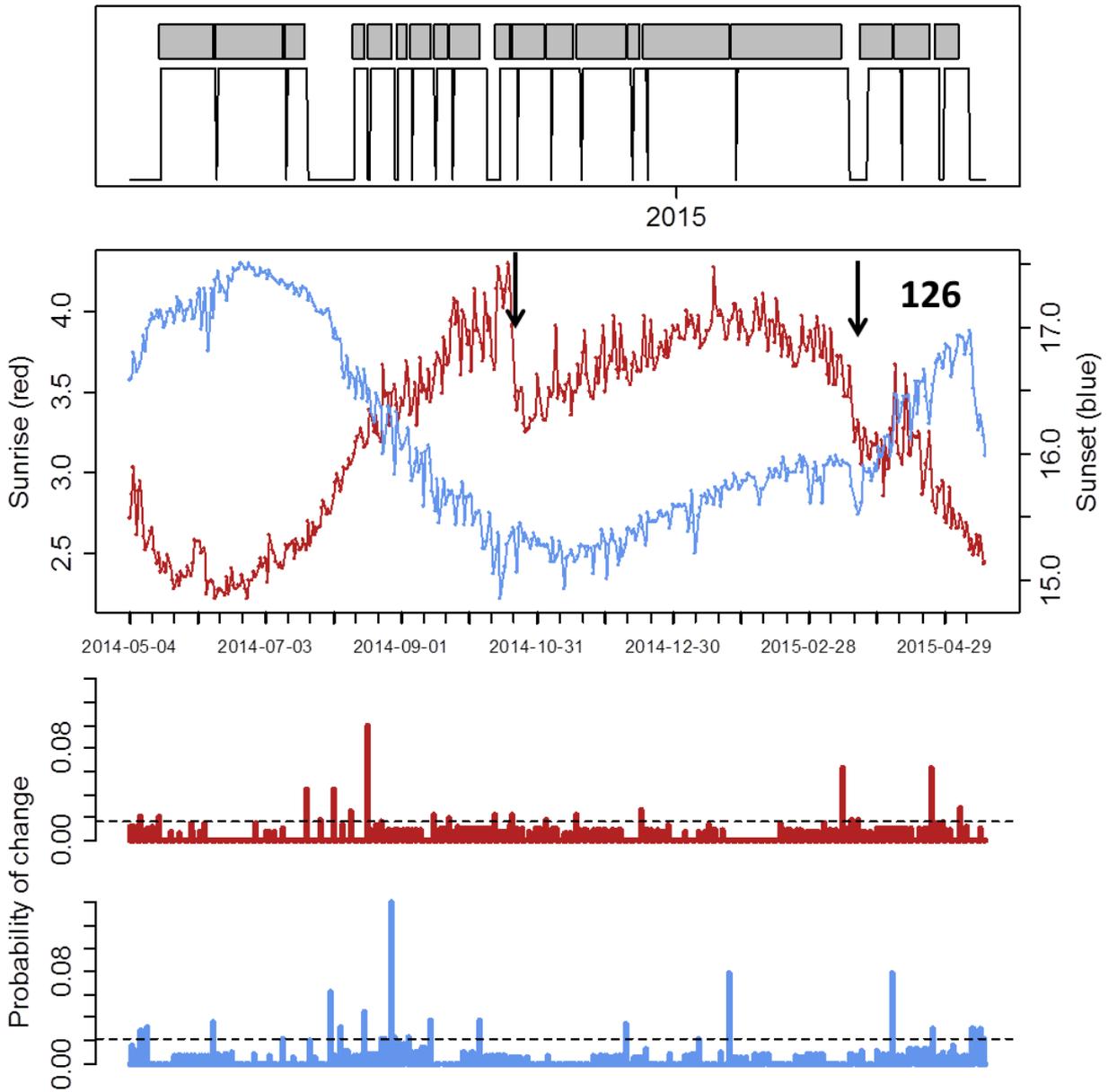
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601 Supplementary Figure 2e: Results for Bird 123 of the changeLight function analysis in the R package
 602 geolight to show the mismatch between its automated identification of points of likely change in position
 603 (top and bottom graph) and those obtained from visual examination of the raw sunrise and sunset times
 604 (middle graph with points of greatest change indicative of migration identified from manual inspection
 605 marked with bold arrows). Note that Cyprus Wheatears were known to be on the study site (i.e.
 606 stationary) from May until late September in all cases. Outputs are from default settings with a specified 5
 607 day stationary period and 0.9 quantile, and with identified outliers; varying these from 3 to 14 days, or
 608 0.75 to 0.95 quantiles, or without outliers, made little difference as to whether any of movement periods
 609 identified actually coincided with those identified from manual inspection, and whether stationary periods
 610 coincided with the periods that Cyprus Wheatears were known to be stationary.
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614 Supplementary Figure 2f: Results for Bird 126 of the changeLight function analysis in the R package
 615 geolight to show the mismatch between its automated identification of points of likely change in position
 616 (top and bottom graph) and those obtained from visual examination of the raw sunrise and sunset times
 617 (middle graph with points of greatest change indicative of migration identified from manual inspection
 618 marked with bold arrows). Note that Cyprus Wheatears were known to be on the study site (i.e.
 619 stationary) from May until late September in all cases. Outputs are from default settings with a specified 5
 620 day stationary period and 0.9 quantile, and with identified outliers; varying these from 3 to 14 days, or
 621 0.75 to 0.95 quantiles, or without outliers, made little difference as to whether any of movement periods
 622 identified actually coincided with those identified from manual inspection, and whether stationary periods
 623 coincided with the periods that Cyprus Wheatears were known to be stationary.
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