Electronic Supplementary Material

Cross-hemisphere migration of a 25-gram songbird

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Contents

1. Light-level geolocator data and analyses
   1.1 Assessing the potential effect of geolocators on birds
   1.2 Calibration of light-level geolocators
   1.3 Estimation of the onset of migration (figure S1)
   1.4 Estimation of migration routes (figures S2, S3)
   1.5 Estimation of wintering grounds - outliers

2. Stable-hydrogen isotope analyses
   2.1 Additional details on stable-hydrogen isotope analysis
   2.2 Estimation of δD discrimination value
   2.3 Assignment test: incorporating analytical and process error
   2.4 Comparison of δD values between winter- and breeding-grown feathers
   2.5 Comparison of δD values in wing coverts with geolocator data
1. Light-level geolocator data and analyses

1.1 Assessing the potential effect of geolocators on birds

Although tagging birds is invasive, the increase in flight costs are thought to be small [1], though drag [2,3], as well as energy expenditure [4] may increase. To examine the potential effects of geolocators, in 2008, we attached dummy geolocators, with the same weight and shape as real geolocators, to 12 northern wheatears housed in an indoor aviary at the Institute of Avian Research, Wilhelmshaven, Germany. Over a six month period, we did not observe any differences in the flight behaviour of birds compared to controls (without dummy tags), and found that treatment birds gained mass during the migration period similar to controls, and as would be expected for birds in the wild. The leg-loop harnesses fit irrespective of changes in the body mass and we did not observe any feather or skin damage.

1.2 Calibration of light-level geolocators

Pre-deployment data were gathered in order to calibrate the devices. We set the light-level threshold defining sunrise and sunset to 32 arbitrary data units [5] and, using the calibration data, this corresponded to our adopted sun elevation angle of 3.5°. Accuracy of single fixes of three geolocators to a reference site (54° 11’ N, 07° 55’ E; 20 May – 27 May 2009) in an open habitat during precalibration was limited to 76 ± 33 km (n = 39). Here, light-level threshold was set again to 32 [5]. Longitudinal deviation from the reference site was 45.6 ± 35 km and latitudinal deviation 47.1 ± 37.6 km (n\textsubscript{fixes} = 39). To illustrate the accuracy during precalibration independent of season and latitudinal effects, we give the noon deviation (3.3 ± 2.1 min, n = 18) and midnight deviation (2.6 ± 2.2 min, n = 21).

1.3 Estimation of the onset of migration using geolocators

The program “TransEdit” was used to analyze the light data. All transitions were checked for obvious shading events during the day and lighting events during the night and all “unnatural” transitions were omitted [5,6]. Geolocators provide two fixes per day (one at noon and one at midnight). Because the
migration routes of both the Alaska and Canadian birds had a large longitudinal component, we
identified periods of migration based on longitude alone (see figure S1).
Autumn migration

Spring migration
Figure S1. All raw (unsmoothed) longitudinal fixes (midnight and midday) over season for the Alaskan (AK-1, AK-2, and AK-3; three upper) and the eastern Canadian (CN-1; lower panel) northern wheatears. Black numbers indicate the dates corresponding to onset of autumn and spring migration and end of autumn and spring migration. Plots on the left side describe autumn migration and on the right side spring migration. Dotted black line indicates breeding site longitude. Longitudinal data for bird AK-1 are shown until geolocator failure on 30 April 2010. AK-2 migrated for ten days and AK-3 for seven days north of the 70° latitude where, due to 24 hr daylight, no fixes were derived. Be aware that (1) the x-axis (season) for spring migration and (2) the y-axis (longitude) differ between the Alaskan and the Canadian birds.

1.4 Estimation of migration routes

a) Alaska (AK)

Generally, we derived the migratory pathways between the breeding area, stopover sites, and wintering areas directly from the two fixes provided by light-level geolocators. We did not use latitudinal data within a week on either side of the two equinoxes (22 September 2009, 20 March 2010), because latitude information is then usually unreliable [7]. In these cases, estimating whether a bird arrived at or departed from a stopover site relied on longitudinal data, see also [5,6,8,9].

For the AK birds, we did not consider latitude during autumn migration from 9 September – 16 October 2009 in AK-1, from 15 September – 18 October in AK-2, and from 13 September – 11 October 2009 in AK-3 (figure S2). These dates were selected based on the variation of the raw fixes from the assumed migration route, see figure S2 for raw fixes and corresponding assumed migration routes. As onset of spring migration occurred in all three cases well after spring equinox, we did not have to omit any fixes for the estimation of spring migration route due to such uncertainties. Cleaned data set of birds AK-1, AK-2, and AK-3 contained 410, 486, and 483 fixes for the time periods 18 August 2009 – 30 April 2010, 20 August 2009 – 23 May 2010, and 20 August 2009 – 24 May 2010 (departure from the breeding area until arrival at breeding area). The low number of fixes from bird AK-1’s geolocator was due to premature failure on 1 May 2010. The other two geolocators collected light data until they were downloaded on 5 July 2010.
To determine a likely migration route between stopover sites, we smoothed latitude data where possible by local polynomial regression \textit{loess} fitting with raw longitude data as the predictor [10]. Obvious latitudinal outliers (e.g. close to the equinoxes and due to light interferences) were omitted. Because we used the raw longitude data to predict latitude using \textit{loess}, we did not correct for variation in longitude. Raw longitude data and the smoothed latitude estimations were used to indicate migration routes (figure S2).

The R code for smoothing latitude estimation: A \textit{loess} is calculated with a data set describing the migration route between stopovers but excluding obvious outliers. We then used the \textit{predict} function of R by considering all data – including the outliers – to predict latitude estimations also for the outliers.

\[
\text{Smoothed latitude} = \text{predict(loess(raw latitude data \sim raw longitude data, data excluding outliers, span=1, degree=2), data including outliers)}
\]

To indicate the deviation of raw latitudinal data to each migration route given its longitude data, we calculated the shortest (great circle) distances of each considered raw fix (excluding outliers) to the estimated smoothed latitude of the corresponding longitude (figure S2). Figure S2 indicates that precision of fixes varies strongly with season. Around equinoxes latitude cannot be reliably estimated. Furthermore, topography and shading events may increase the inaccuracy of fixes further. By using a smoothed line to indicate the migratory route, we likely underestimate the overall migration distance and migratory speed because, in doing so, we did not consider small scale movements of the birds. Migration distances were calculated using great circle distances [10] along the smooth lines between stopover sites.
Figure S2. Interpolated geolocators tracks of two males (AK-1, AK-2) and one female (AK-3)
northern wheatears that bred in central Alaska, USA (65.6° N, 145.4° W; black dot). Blue = autumn
migration (mid August–mid November 2009), orange = spring migration (end March – mid May
2010). Dashed lines indicate rejection of data due to high uncertainty in latitude estimates (equinoxes
or light interference) or 24 hr daylight. Data logger of bird AK-1 failed during spring migration; the
last known fix is hypothetically joined along the shortest distance with the breeding area. Latitude data
were smoothed by local polynomial regression fitting with raw longitude data as the predictor (see text
for further information). In these cases, raw longitude data and the smoothed latitude estimations were
used to indicate the smoothed migratory routes between the corresponding stopover sites. Continuous
lines indicate these tracks. Accuracy of these tracks is estimated for each section as mean ± SD
distance (km) of the original fixes to the smoothed line and the number of considered fixes. Relevant
sections are indicated by bars and/or breeding/wintering area. Blue dots encircled black are all raw
fixes from autumn migration, orange dots encircled black are all raw fixes from spring migration.

b) Eastern Canadian Arctic (CN)

Because the CN bird started autumn migration (25 September 2010) close to the autumn equinox (23
September 2010), we could not estimate the actual migration route across the North Atlantic. After
reaching Western Europe, the bird basically migrated southwards. The initial movements after the
Atlantic crossing were still rather close to the autumn equinox (30 September 2010 and subsequent
days). Furthermore, as one can see in figure S3, the sequence of fixes did not show to a clear migration
route leading to the wintering grounds. Hence, we simplified the migration route as a straight line. The
onset of spring migration (14 March 2011) coincided with spring equinox (21 March 2011) so that
migration route from Africa to Western Europe was not possible to estimate. However, we could
estimate where the bird crossed the Atlantic with a higher degree of accuracy during the spring
because the crossing took place significantly after spring equinox and started most likely around
10.04.2011. Figure S3 shows the raw fixes during migration for the CN bird.
**Figure S3.** Interpolated geolocators tracks of one male (CN-1) northern wheatear that bred in eastern Canada (63.7°N, 68.5°W; black dot). Blue = autumn migration (mid August – mid November 2009), orange = spring migration (end March – mid May 2010). Dashed lines indicate rejection of data due to high uncertainty in latitude estimations. Raw fixes of the Canadian bird during migration. Blue dots encircled black are all raw fixes from autumn migration, orange dots encircled black are all raw fixes from spring migration. Large blue dots are raw fixes from the autumn Atlantic crossing.
1.5 Estimation of wintering grounds - outliers

The estimation of the wintering grounds is explained in the main text. We excluded obvious outliers (18 ± 3, mean ± s.d., range = 16 – 24 in bird AK-1; none in bird AK-2; 3 ± 2, range = 2 – 7 in bird AK-3; and 14 ± 3, range = 13 – 21 in CN-1 with sun elevations ranging from -2° to -4.5° in steps of 0.5° for each bird) due to weather or bird behaviour, i.e. seeking shelter in dark hollows during day.
2. Stable-hydrogen isotope analyses

2.1 Additional details on stable-hydrogen isotope analysis

Stable-hydrogen isotope values of feathers were analyzed at the stable isotope laboratory of the Leibniz Institute for Zoo and Wildlife Research, Berlin, Germany. A small section of feather tissue was clipped from the tip of the feather (350 ± 7 µg) and loaded into silver capsules (IVA Analysetechnik e.K. Meerbusch, Germany). We filled 96 port microtiter trays with silver capsules loaded with feather samples and laboratory keratin standards with known δD values for non-exchangeable hydrogen. Trays were allowed to equilibrate with ambient air over more than seven days. Afterwards, trays were placed in a drying oven over one day at 50°C. Then, loaded capsules were transferred to a Zero Blank autosampler (Costech Analytical Technologies Inc., Cernusco, Italy) above the elemental analyzer (HT elemental analyzer HEKAtech GmbH, Wegberg, Germany). For at least 1 hour before combustion, samples were flushed in the autosampler with chemically pure helium (Linde, Leuna, Germany). We used a Delta V Advantage isotope ratio mass spectrometer (ThermoFischer Scientific, Bremen, Germany) that was connected via an interface (Finnagan Conflo III, ThermoFisher Scientific, Bremen, Germany) with the elemental analyzer. Reference H₂ gases were calibrated against international standards (IAEA NBS 22 and IAEA-CH-7). We used the comparative equilibration method [11] to account for the amount of exchangeable hydrogen in feather keratin. We used three laboratory standards that covered the range of expected δD values in our samples. These standards were also used to determine the δD of non-exchangeable hydrogen [11,12]. The stable hydrogen isotope ratios of the non-exchangeable hydrogen (mean ± s.d.) of the standards were: -133.6 ± 1.2‰, -109.1 ± 1.2‰ and -87.2 ± 1.0‰. In the sequential order of one autorun, keratin standards were placed at positions 1-6 (3 standards of 2 replicates) and at the 9th-11th position (3 standards).

2.2 Estimation of δD discrimination value

To determine how different growing season δD₈ values change the δD values of tail feathers (summer), we sampled tail feathers from different breeding areas including eastern Canada (Iqaluit), Iceland, 'marine' Scotland (Fair Isle), mainland Scotland, Morocco, Italy, western Germany (Rhineland-Palatinate), Sweden (Uppsala), eastern Siberia (Provenja, Russia) and central Alaska.
(Eagle Summit). The number of individuals sampled ranged from five to 30 northern wheatears per breeding area. We then correlated the mean δD values of tail feathers (δDₚ) from the different breeding areas with the growing season δDₚ values of the corresponding breeding areas ($R^2 = 0.94$; $n = 10$; δDₚ = 0.662δDₚ - 24.3‰) [13,14]. All subsequently given δD values, also in figure 1, were corrected using the regression equation for the discrimination factor between precipitation and feather δD values.

2.3 Assignment test: incorporating analytical and process error

To incorporate analytical error, we re-sampled each δD value of wing covert 100 times, drawing from a normal distribution where the mean was the δD value of the covert and the s.d. was taken from the mean repeatability of the internal standard ($± 1.9$, $n = 24$). We incorporated process error from the OIPC data by taking each of these values and calculating the likelihood assignment for each region based on a randomly drawn value taken from a normal distribution with a mean and standard deviation calculated from the sample of sites taken from the OIPC database. We considered a bird to have originated from the region with the highest number of standardized probabilities out of the 100 re-samples.

2.4 Comparison of δD values between winter- and breeding-grown feathers

The stable-hydrogen isotope values of wing covert feathers that originated from the wintering quarters differed significantly from the corresponding values of tail feathers moulted at the breeding area (AK birds: winter coverts: δD: -27.3 ± 18.5‰, mean ± s.d., $n = 9$; breeding-ground tail feathers δD: -174.3 ± 6.7‰, mean ± s.d., $n = 29$; ). Similarly, the δD values of fresh covert feathers of Baffin Island breeding birds differed significantly from the δD values of tail feathers known to grow at the breeding grounds only (winter area: δD: -40.4 ± 25.2‰, mean ± s.d., $n = 7$; breeding area: δD: -137.4 ± 12.2‰, mean ± s.d., $n = 102$).
2.5 Comparison of δD values in wing coverts with geolocator data

Only one the birds returning to the AK with a geolocator had moulted a wing covert feather during the previous winter in 2008/2009. Based on its δD value of this feather (-33.8‰), this individual was predicted to have overwintered in central Sahelian Africa. Based on geolocator data, this bird appeared to have overwintered in north-eastern Africa in 2009/2010.

References


