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Supplementary material

Appendix 1

Supplementary methods and results:

Ruddy shelduck were captured and instrumented with satellite transmitters during 2007-2008 at Qinghai Lake (36.44°N, 100.17°E), China (n=26), and Chilika Lake (19.69°N, 85.30°E), India (n=4) as part of a wider study into the transmission of avian influenza (Gaidet et al. 2010). Captured birds were sexed (via cloacal examination), aged (adult or juvenile) and weighed (to the nearest 5 g using a spring balance). All birds were caught using leg nooses and fitted with a Microwave Telemetry (Columbia, MD, USA) model PTT-100 solar-powered Argos/GPS platform transmitter terminal (PTT) using a Teflon backpack harness. The PTTs measured 66 x 23 x 21.6 mm (length x width x height) and weighed 30 g, which represented approximately 2.2 ± 0.08% of the birds' body mass. PTTs were programmed to record GPS latitude and longitude every two hours with a horizontal accuracy of ± 18 m. PTTs also recorded altitude (3D GPS) to either the nearest meter (n=16 tags) or nearest 10 meters (n=14 tags) with an accuracy of ±22 m.

Tracking data were obtained from the Argos System (http://www.argos-system.org/en), processed using Microwave Telemetry software and hosted on Movebank (www.movebank.org), an online free repository for animal tracking data, under the study names "FAO-USGS China-Qinghai" and "FAO-USGS India 2009". Due to the higher location accuracy afforded by GPS, Doppler-derived Argos location estimates that were also collected were not used in this study.

Only birds that were successfully tracked for at least one complete migration (defined as leaving the wintering grounds and arriving at the breeding ground or *vice versa*) were included, resulting in 15 individual shelduck datasets comprised by 44 migratory flights; 14 tagged in China and one in India (Table A1). A general linear model was used to examine if individual bird mass, age or sex influenced tracking duration. Age of the birds at tagging was not related to subsequent PTT duration (adult: mean 649 days, juvenile mean 658 days; GLM, $F_{2,\,10}$=0.38, p=0.69) (although one bird was not aged during tagging). In addition, neither the sex of the bird (females = 489 days, males= 765 days; GLM, $F1_{,\,10}$ = 2.82, p=0.124) nor the bird's body mass (mean 1.3 kg, GLM, $F_{1,\,10}$=0.286, p=0.604) were found to have a significant effect on tracking duration. The 15 ruddy shelduck that completed at least one full migration (n=7 females and 8 males, body mass range 1.1 to 1.7 kg) transmitted a total of 10,817 GPS locations (median deployment duration 554 days, range 218 - 1,204), of which 304 locations during a migratory flight (Table A1).

Tracking data were processed to calculate the speed and rate of ascent or descent between successive GPS locations during the ruddy shelduck's migratory flights. First, the minimum, great circle distances between successive locations were calculated in R (R Development Core Team 2011) using the package 'Raster' (Hijmans 2015). The travel time for each distance calculation was derived from the GPS timestamps, and then transit speeds were calculated for each movement vector.

We determined when birds were migrating by plotting the displacement distance from the site of deployment to every successive location (displacement plots): migratory flights present clearly in the plots as step changes of very rapid displacement (Hawkes et al. 2012b). In between these flights were 'stop overs' (short resting periods between bouts of longer distance flight), breeding periods and wintering periods. These relatively stationary periods were confirmed by both geographic location (e.g. known breeding locations) and chronology (e.g. known wintering periods) and can be robustly identified in the displacement plots as those periods with little to no change in displacement between successive locations. All stop over or breeding and wintering ground locations were removed from the data set to leave only the locations representing birds moving between stop over sites during migration. Classification of stopover (or breeding and wintering) locations could be further confirmed with a histogram to exhibit two modal groups of instantaneous ground speeds, one below 5 m s^{-1} and a second group with a wider range of speeds considered to be flying locations (Fig. A1). For the purposes of the present study, climbing flight was considered to be any two successive locations that were two hours apart during which at least 500 m altitude was gained (i.e. at least 0.069 metre of altitude $second^{-1}$).

We aimed to compare the most optimal flight path possible in relation to minimised altitude and favourable wind conditions with the actual flight paths taken by the shelduck in this study. Firstly, the ground elevation under each shelduck location was determined in ArcMap (ESRI, 2011) by overlaying the GPS coordinates on the National Aeronautics and Space Administration/National Geospatial-Intelligence Agency 90 m shuttle radar topography mission (SRTM) (http://www2.jpl.nasa.gov/srtm/) Digital Elevation Model (DEM). Ground height was compared to the GPS altitude to estimate the flight height above the ground. In 16 cases (0.03% of all locations) flight heights relative to the ground were <0 m and they were excluded from further analysis due to the likelihood of inaccuracy in one or both data sets.

In order to estimate wind conditions experienced by the shelducks during flight, weather data were obtained from the European Centre for Medium-Range Weather Forecasts in the global ECMWF Interim Reanalysis package ‘’ERA, interim” http://www.ecmwf.int/en/research/climate-reanalysis/era-interim (Dee et al. 2011). The data comprise U (west to east flow) and V components (south to north flow) of wind, along with 37 pressure levels, which model wind at a series of altitudinal intervals. Of the 37 pressure levels within the ERA interim dataset the shelduck occupied the lowest 17. Wind data were extracted for each duck location in time and space (longitude, latitude and altitude) using the R packages ‘NetCDFs’ (Michna 2014) and ‘Geosphere’ (Hijmans 2016). These were used to calculate wind speed and wind direction using vector arithmetic. To ascertain if the ruddy shelduck used favourable wind conditions to aid migratory flights, take-off locations and times for each bird at wintering and breeding grounds in 2009 were identified. A take-off location was determined as the last location before a migratory sequence of movements. For each take-off location, wind speed and direction was extracted over a two week period every six hours (one week prior to take off and one week post) to obtain the average conditions at each location. These averages were then compared with the wind conditions when the birds departed from the site. In order to deduce whether ducks could have obtained more wind assistance by flying at a different altitude, wind data from the ERA-interim was extracted at the nearest available pressure level (mB). A range of altitudes was created from 1,000 m above the bird to 1,000 m below at each in-flight location in 50 m altitudinal intervals. This was converted to pressure (mB) to correspond with the ERA-interim dataset. This was repeated for three days prior to and three days after each in-flight location, at six hour intervals to greater understand the variation in wind conditions over time. In this analysis wind direction is calculated as the direction wind blows from, in order for more intuitive comparison with bird bearing.

Bar-headed geese are known to minimise altitude while crossing the Tibetan Plateau, travelling through valleys where possible (Hawkes et al. 2012a). In order to understand if ruddy shelduck also use this strategy, flight locations were compared with a null model of random altitudes across the flyways used by each duck. First, in order to account for the spatial extent of the flyway used by each individual (and thus not artificially inflating elevations by including ground over which the ducks were unlikely to fly) minimum convex polygons were calculated for each duck's migratory flight using the R package 'Raster' (Hijmans 2015). Then, the number of locations obtained within this polygon for the corresponding duck was recorded. Finally, for each duck location, 100 locations were randomly generated within the polygon using R to create a null model, and their corresponding ground elevations were extracted from the SRTM DEM. The proportion of locations above 4,500 m was recorded for each bird's flight path and the corresponding null set of locations. We used a paired t-test to examine the hypothesis that ground elevations in the null model would be higher than the locations where the ruddy shelduck were observed to fly.

Figure A2: Plots a-h: Variation in wind conditions across space (a, c, e, g) and time (b, d, f, h) as ruddy shelducks flew across the Tibetan Plateau in 2009 (borders indicated in g and h with black line). The difference in bird bearing and wind direction (TW-tail wind) displayed in (e and f) was calculated using circular arithmetic. AGR (g and h), where AGR less than one indicates the birds were benefitting from the wind conditions and greater than indicates the winds impeded the bird flight (Gill et al.

2014). Green points in (e-h) indicate the birds' true location. Blue points indicate the angular difference (TW, where 0= true tail wind, and 180= true headwind) or AGR experienced across the range of pressure levels or 6-hourly time windows the bird could have experienced.

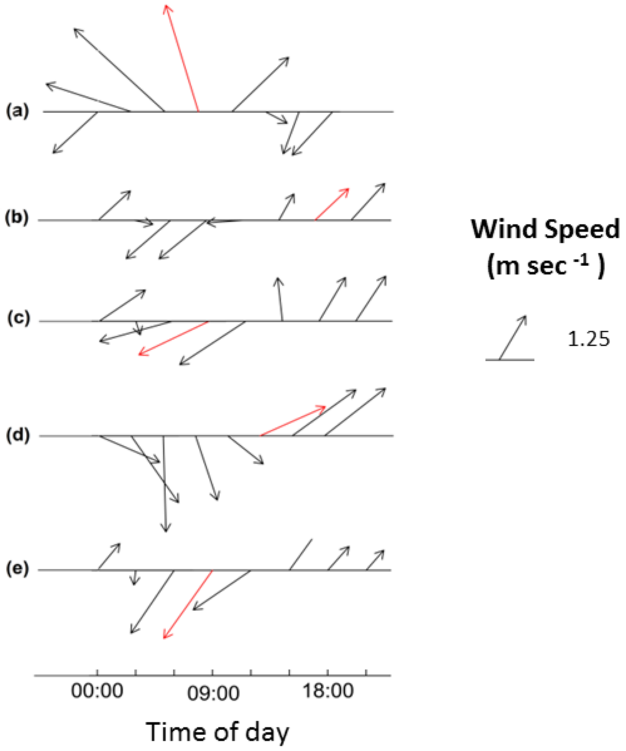

Figure A3: Feather plots showing wind speed (arrow length) and cardinal direction (arrows pointing according to meteorological convention, i.e. the arrow points towards the direction *from* which the wind flows) during the top five fastest climbs per duck (n=80 climbs in total). Wind conditions are displayed for the complete day of each climb, with the red arrow indicating the time period when the climb began. Ruddy shelduck IDs and migration direction are: **a**: 82127 (south), **b**: 82126(south), **c**: 82121 (north), d: 74820 (north), and **e**: 74813 (north).

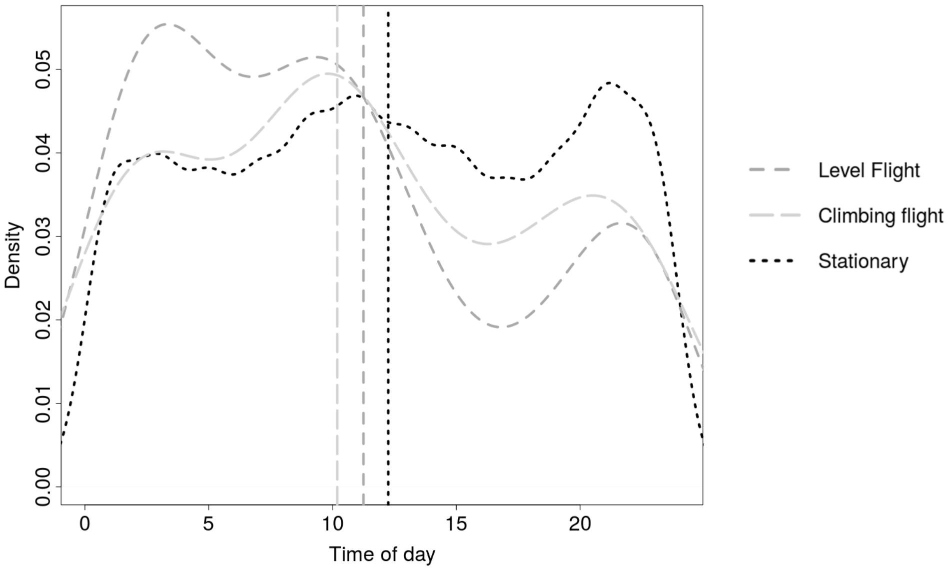

Figure A4: Relative frequency (density) of the time of day at which locations were obtained for ruddy shelducks that were stationary, in level flight, or in climbing flight. Vertical lines display mean time of day for each group (times displayed are local time).

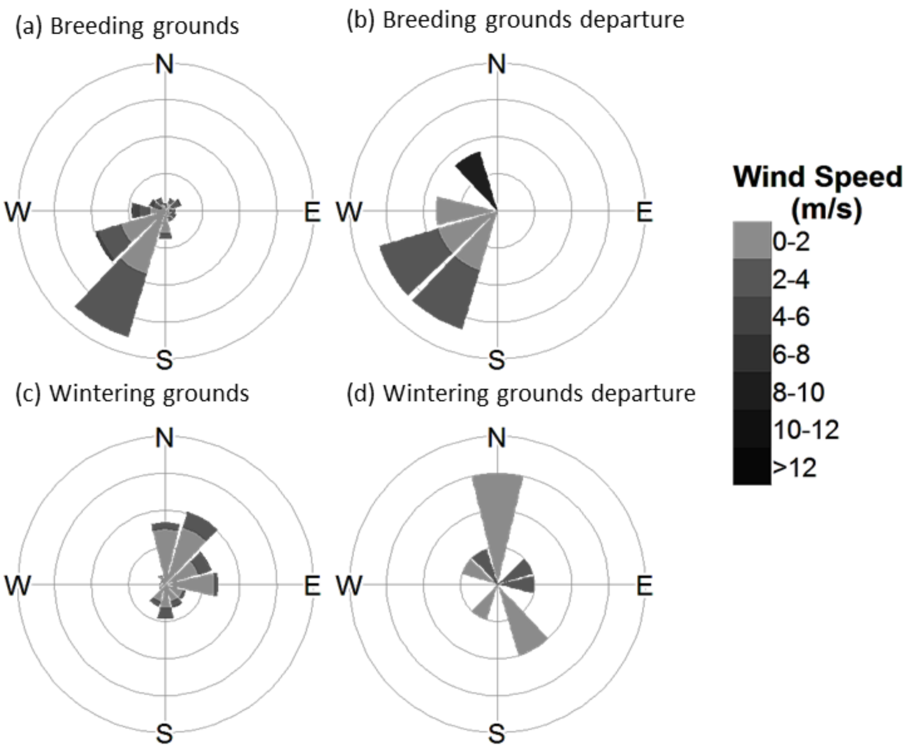

Figure A5: Rose plots comparing wind conditions when ruddy shelducks departed on migration. Shaded segments show wind direction according to the meteorological convention, pointing towards the direction from which the wind blows (cardinal directions indicated), and wind speed is indicated by grey shading. Relative frequency of wind speed and direction is shown by the size of each sector on the circular radial-axis, where % frequency is indicated by concentric circles with 10% increments. **(a)** Two week average conditions across each bird's departure location at breeding grounds, **(b)** average conditions during the 3hr window that ruddy shelduck began their migratory flights away from breeding grounds**. (c)** Wintering ground two week average conditions across take-off locations, **(d)** departure conditions averaged (across three hours) for shelducks leaving the wintering grounds.