Supplement

Text S1. Accuracy of flight height

GPS loggers recorded altitude for each fix. The accuracy of the altitude can vary depending on the type and the operating mode of the logger. Accuracy of altitude is higher when fixes are made between shorter sampling intervals. To understand the accuracy of the altitude recorded by GipSy-5 loggers at a 1 s interval, four GipSy-5 loggers and a handheld GPS with a barometric altimeter for actual altitude reference (GPSMAP 64scJ, GARMIN, USA) was attached on the dashboard of a car. The car moved 3–4 hours with 0–60 km h^{-1} speed where the altitude was 2–334 m, on the same day and car described in Okado & Watanuki (2023; Appendix 2). The altitude was recorded by both the altimeter and by the GipSy-5 devices at a sampling interval of 1 s. The height difference between the two devices (error) shows normal distribution with the average value around zero. The average and SD of the absolute height difference was 7.1 ± 6.0 m when the loggers were linking with 4 satellites, and 6.9 ± 5.4 m when the loggers were linking with 6 satellites (J. Okado unpubl. data).

Text S2. Site-specific turbulence

Introduction: Updrafts/downdrafts and turbulence are complex and irregular fine-scale air gushes that may affect bird flight height (e.g. Possel et al. 2018, Scacco 2019). Local topography, air temperature, and temperature difference are factors that influence where these vertical air movements are likely to occur (Bohrer et al. 2012). Recently, vertical displacement of bird flight is gaining attention as an index for turbulence levels (Lempidakis et al. 2022).

Hence, we investigated whether if the vertical displacement of black-tailed gulls *Larus crassirostris* in each track-line, an index for turbulence levels, were dependent on-air temperature and varied with location of weather stations.

Methods: Vertical displacement was calculated using the median flight-height of the 90 track-lines and the flight height of 7547 GPS fixes along the 90 track-lines. Because birds were flying within 500 m of the weather stations at different speed and distance, track-line showed different durations (18–180 s). To standardizes the time, each track-line was subdivided into 18 s windows. For each 18 s window, vertical displacement was calculated by subtracting the median height calculated for the 18 s from flight height recorded every second. Then, vertical displacement range and interquartile range was calculated for each window. For each track-line, the window with the largest interquartile range was chosen to represent the vertical displacement of the track-line. If multiple windows had the same interquartile range, the window with the largest vertical displacement range was chosen.

For temperature, we downloaded the hourly-temperature data recorded by the five Automated Meteorological Data Acquisition System (AMeDAS) at the five weather stations where we did our work. The temperature recorded at the closest hour was matched with each track-line based on time and location. Daily temperature range was matched with each track-line based on date and location.

We built linear mixed-effects models (LMMs) to examine the effect of temperature and location on vertical displacement of bird flight. Interquartile range of vertical displacement was treated as the response variable. Weather station locations, temperature at the time of flight, and daily-temperature range was treated as fixed variables. Bird individual IDs was treated as random effect. To run the model, we used the 'lmer' function in the 'LME4' package (Bates et al. 2015). We then compared and ranked all possible LMMs using Akaike's Information Criterion (AIC) in the 'MuMIn' package (Barton 2018). Models with delta AIC values <2 were considered equally plausible (Burnham & Anderson 2003). All statistical analyses were performed using the open-source software R v.4.3.0 (R Core Team 2023).

Results and Discussion: The best model explaining the interquartile range of vertical displacement did not include location, temperature at the time of flight, nor the daily-temperature range of the day of flight (Table S1). We thus did not have strong evidence suggesting the effects of the site-specific local topography or air temperature on the birds' vertical displacement within each track-line. Assuming that the vertical displacement is an index for turbulence level (Lempidakis et al. 2022), at the scale and resolution of our data, there was no significant site-specific difference that may bias the vertical wind movement including turbulence.

Literature Cited

Barton K (2018) MuMIn: multi-model inference. R package version 1.40.4.

Bates D, Mächler M, Bolker B and Walker S (2015) Fitting linear mixed-effects models using lme4. J Stat Softw 67:1–48

Bohrer G, Brandes D, Mandel JT, Bildstein KL and others (2012) Estimating updraft velocity components over large spatial scales: contrasting migration strategies of golden eagles and turkey vultures. Ecol Lett 15(2):96–103

Burnham KP and Anderson DR (2003) Model selection and multimodel inference: a practical information-theoretic approach. Springer, Berlin

Lempidakis E, Ross AN, Quetting M, Garde B, Wikelski M, and Shepard ELC (2022) Estimating fine-scale changes in turbulence using the movements of a flapping flier. J R Soc 19(196):20220577

Okado J and Watanuki Y (2023) Flight altitudes of chick-rearing rhinoceros auklets *Cerorhinca monocerata* measured by GPS loggers. Mar Ornithol 51(1):109–114

Poessel, SA, Brandt J, Miller TA and Katzner TE (2018) Meteorological and environmental variables affect flight behaviour and decision-making of an obligate soaring bird, the California Condor *Gymnogyps californianus*. Ibis 160(1):36–53

R Core Team (2023) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. https://www.R-project.org/

Scacco M, Flack A, Duriez O, Wikelski M, Safi K (2019) Static landscape features predict uplift locations for soaring birds across Europe. R Soc Open Sci 6(1):181440 doi:10.1098/rsos.181440

Table S1. Summary table of fixed effect parameters for plausible models explaining the vertical displacement of each track-line ranked by AIC scores (delta AIC < 2). Interquartile range of vertical displacement was the response variable. Weather station locations (location), temperature at the time of flight (temperature), and daily-temperature range (daily range) were fixed explanatory variables. Bird individual IDs was treated as random effect.

Model Rank	Model	df	AIC	delta	weight
1	Vertical Displacement (IQR) ~ 1	3	522.06	0.00	0.456
2	Vertical Displacement (IQR) ~ Daily range	4	553.41	1.36	0.231
3	Vertical Displacement (IQR) ~ Temperature	4	553.88	1.81	0.184