Supplementary Material: Integrating fine-scale behaviour and microclimate data into biophysical models highlights the risk of lethal hyperthermia and dehydration

Materials and Methods

We parameterised a NicheMapR biophysical model, integrating behaviour and physiology using continuous time-activity focal data on the behavioural decisions and trade-offs at moderate to high T_{air}s for babblers (du Plessis *et al.*, 2012; Bourne *et al.*, 2020, 2021a), fiscals (Cunningham *et al.,* 2013, unpublished data) and hornbills (van de Ven, 2017). These data were collected over multiple breeding seasons in the southern Kalahari Desert at Kuruman River Reserve [for babblers (2016 – 2019) and hornbills (2012 – 2015), KRR (26˚58' S, 21˚49' E)] and Tswalu Kalahari Reserve [for fiscals (2011 – 2012), TKR (27˚17' S, 22˚23' E)] in South Africa. Focal observations consist of an observer continuously monitoring and recording behaviour of one individual for a set period of time (focal session), repeated over a set focal time period. Here focal sessions consisted of 20-min, 15-min and 30-min continuous time-activity focal observations per species respectively (Bourne *et al.*, 2020, 2021a, Cunningham *et al.,* 2013, van de Ven, 2017). These focals sessions were repeated four times during 2-hr (hornbills and babblers) and 1.5-hr (fiscals) focal periods which we broadly grouped into morning, midday and afternoon categories (Table S1). During each focal session, an observer recorded microsite (location of perch, exposure to sun) and activity to the nearest second. Data for fiscals and hornbills were analysed as the proportion of time spent in each microsite per time category, whereas data for babblers were analysed as the proportion of observations where an individual was reported in each microsite per time category.

The detailed observational data were randomly split into two sub-categories, one used to train the behavioural model and the other to test the behavioural model predictions. The training data were further subsetted into hot (T_{max} > 35 °C) and cool (T_{max} < 35 °C) days and the associated probability of exposure (sun vs shade) and location (ground vs off-ground) were calculated under current and future climate conditions. Here, the behavioural model was set up for each day of the year with daily maximum T_{air} values added using the microclimate model (run at 1.2 m above ground) to classify days as hot or cool. Thereafter the behavioural model was run to assign location and exposure for each hour of the day based on the species-specific probability models described above. Hourly operative environmental temperature (T_e) values derived from the microclimate model were then assigned to each hour of the day depending on the exposure-location category and incorporated into the biophysical model described below.

Average biomass captured was allometrically estimated for fiscals based on feeding requirements needed to sustain field metabolic rates using the equations described by (Nagy, 1987), and differences in prey capture rates in shaded versus sunny microsites (Cunningham et al., 2015). Feeding rates were calculated as dry matter ingested and converted to wet biomass by adding the estimated % water available in common prey items. Babblers, hornbills and fiscals commonly prey on small beetle and termite larvae, with the species regularly consumed being similar to mealworms *Tenebrio molitor* in terms of preformed water [~ 56% water, (Siemianowska et al., 2013)]. Hornbills and fiscals also regularly consume larger prey items such as spiders [order Arachnida, ~ 70% water, (Carrel, 1990)] and solifuges [order Solifugae, ~ 80% water (Grant, 1955)] (Dean, 2005; van de Ven et al., 2019), with hornbills occasionally consuming small birds and mammals. Diets of hornbills and fiscals were assumed to be similar to each other, producing ~ 0.4, 1.07 and 0.56g of metabolic water per gram of protein, lipid and carbohydrate consumed, respectively (Hainsworth, 1981).

The biophysical model solves an energy balance equation (equation 1), computing metabolic heat production and EWL required to maintain physiologically stable T_bs in a specific environment.

$$Q_{gen} - Q_{resp} - Q_{evap} = Q_{feather} = Q_{rad} + Q_{conv} + Q_{cond} + Q_{evap,feathers} - Q_{sol} \quad [1]$$

here, Q_{gen} represents heat generated from metabolism, Q_{resp} the heat lost via respiration, Q_{evap} cutaneous heat lost, and Q_{fur} heat lost through the pelage. These values all needs to balance heat exchange via thermal radiation Q_{rad}, convection Q_{conv}, conduction Q_{cond} and evaporation from the feathers $Q_{evap,feathers}$, and solar heat gain Q_{sol}. Thus, conductive, convective, radiative and evaporative heat exchange with the surrounding environment are considered using the endoR_devel interface in R to call a set of Fortran routines (Kearney *et al.*, 2021). The model can be adjusted for species-specific behavioural and thermoregulatory responses using the endoR_devel function. We adjusted the endoR_devel to represent the general behavioural and physiological requirements of a bird in response to skin temperature, which was then run with species-specific biophysical traits (e.g. body dimensions) and physiological responses (e.g. base skin wetness) (see Conradie et al., 2023 Table S1 for values used). Detailed description of the sequence of behavioural and physiological responses are presented in Conradie et al. (2023), as well as a comparison of the model performance when these behavioural responses are not included (Figure S1 of Conradie et al., 2023).

Table and figures

Table S1. Focal observation duration, sample size and time categories for southern yellow-billed hornbills (A, *Tockus leucomelas*), southern pied babblers (B, *Turdoides bicolor*) and southern fiscals (C, *Lanius collaris*).

Species	Number of individuals	Duration of continuous focal observations (minutes)	Morning focal periods	Midday focal period	Afternoon focal periods	Reference
Southern Yellow-billed Hornbills (*Tockus leucomelas*)	32	30	Sunrise – 10h59	11h00 – 14h59	15h00 - sunset	van de Ven 2017
Southern Pied Babblers (*Turdoides bicolor*)	62	20	07h00 – 8h59 9h00 – 10h59	11h00 – 12h59 13h00 – 14h59	15h00 – 16h59 17h00 – 19h00	Bourne et al., 2020; 2021
Common Fiscals (*Lanius collaris*)	12	15	06h00 – 7h30 7h30 – 9h00	12h00 – 13h30 13h30 – 15h00	15h00 – 16h30 16h30 – 18h00	Cunningham et al., 2013

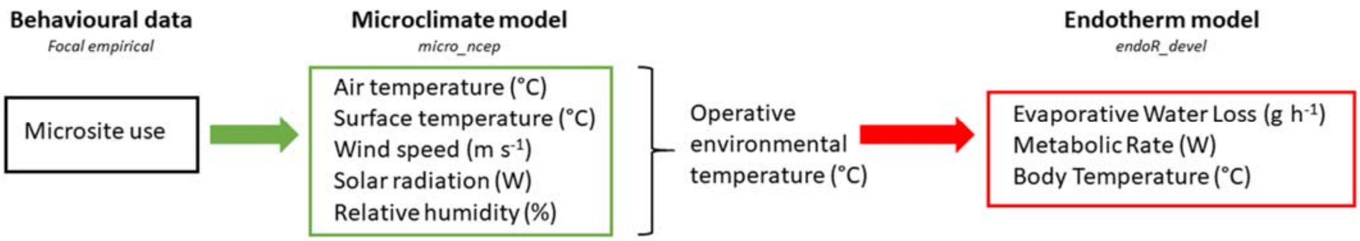

Figure S1 Flow diagram illustrating the input and output parameters from the behaviour data (black square), microclimate model (green square) and biophysical model (red square), used to predict thermoregulation under natural conditions.

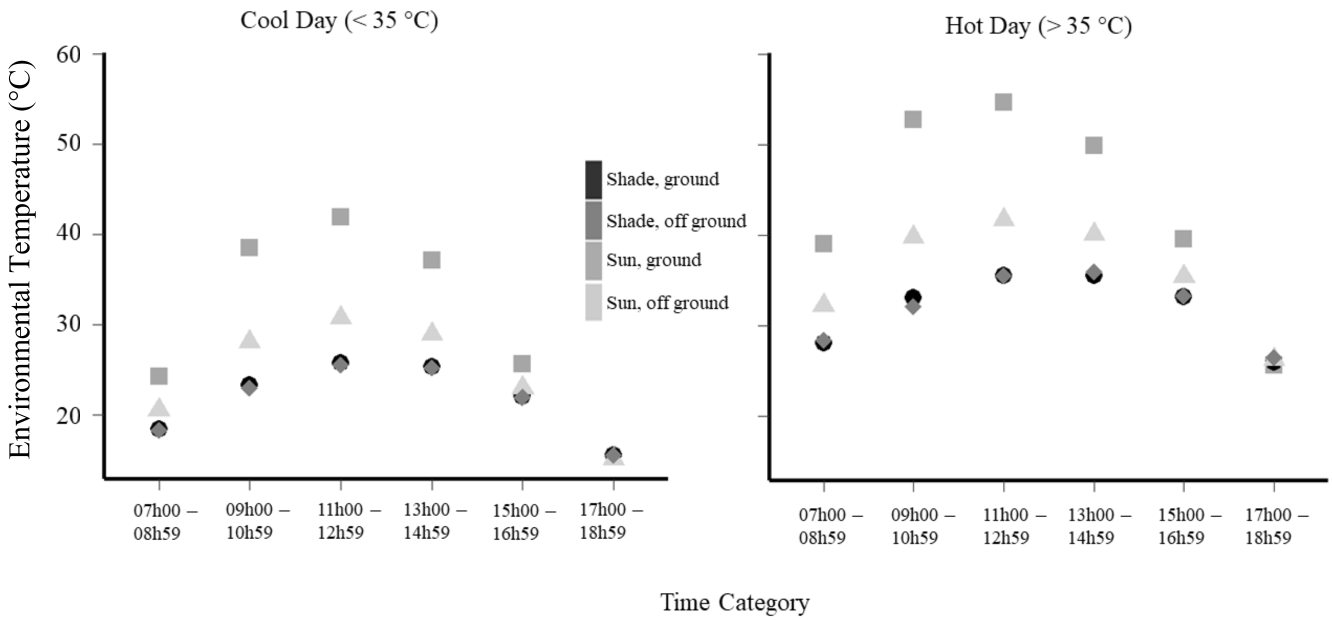

Figure S2 Average modelled operative environmental temperatures available on hotter (T_{max} > 35 °C) versus cooler (T_{max} < 35 °C) summer days (October – February 2015 - 2020) for each microsite category [sun (~ 10% shade), shade (~ 50% shade), low perch, high perch] using the NicheMapR microclimate modelling package

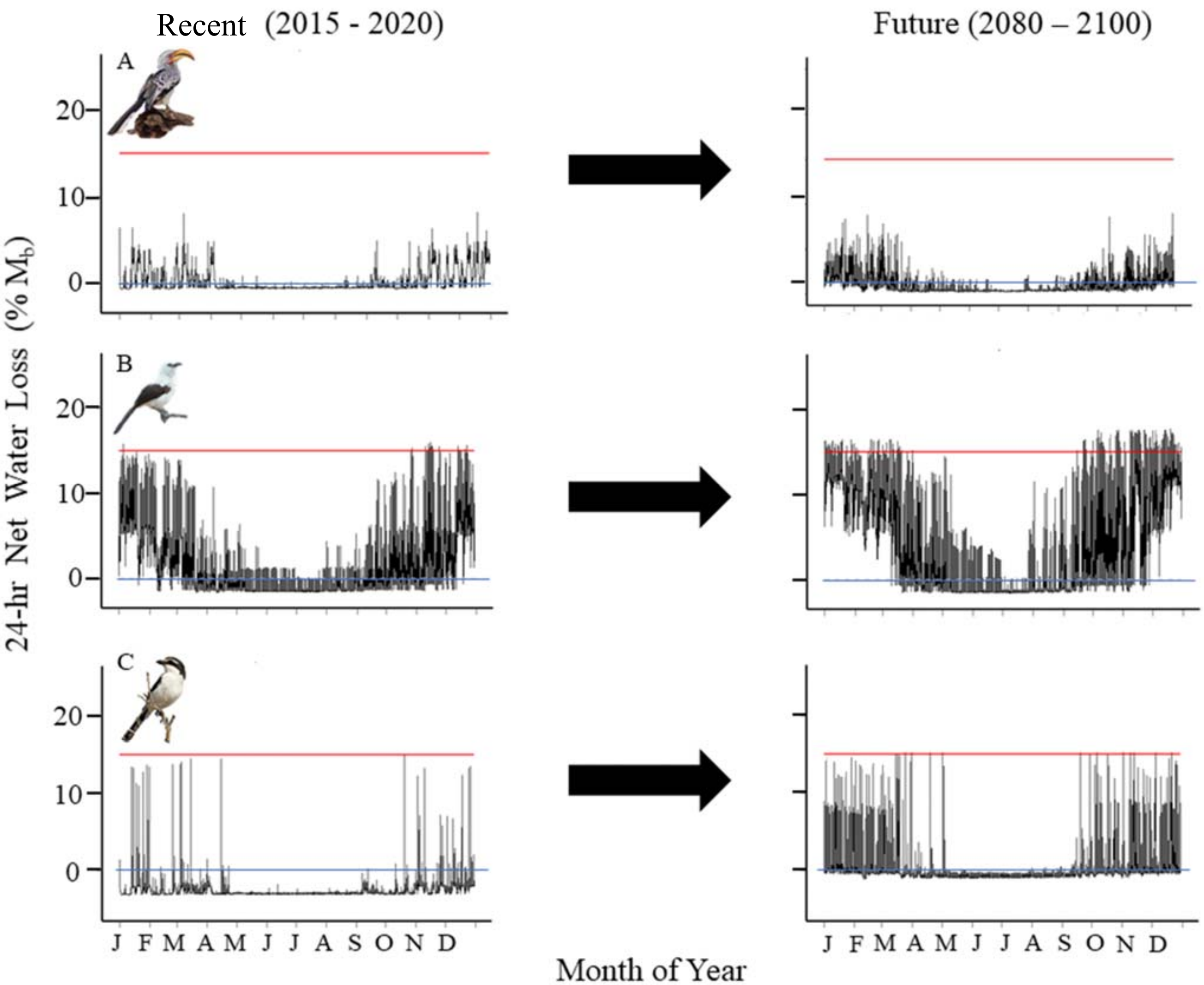

Figure S2. Predicted 24-hour water loss (% M_b) assuming no drinking as a function of predicted evaporative water loss and water influx (dietary and metabolic water) for southern yellow-billed hornbills (A, *Tockus leucomelas*), southern pied babblers (B, *Turdoides bicolor*) and southern fiscals (C, *Lanius collaris*) estimated from modelled environmental temperature under recent (2015 - 2020) and a moderate future scenario (RCP 4.5; 2080 – 2100). Environmental temperatures were modelled based on the probability of exposure (sun vs shade) and location (low perch vs high perch) throughout the day (07h00 – 18h00) using the *NicheMapR* package. Red lines indicate lethal dehydration risk (cumulative EWL ~ 15% M_b), and blue lines indicate 24-hour net zero water loss. Bird images courtesy of Warwick Tarboton

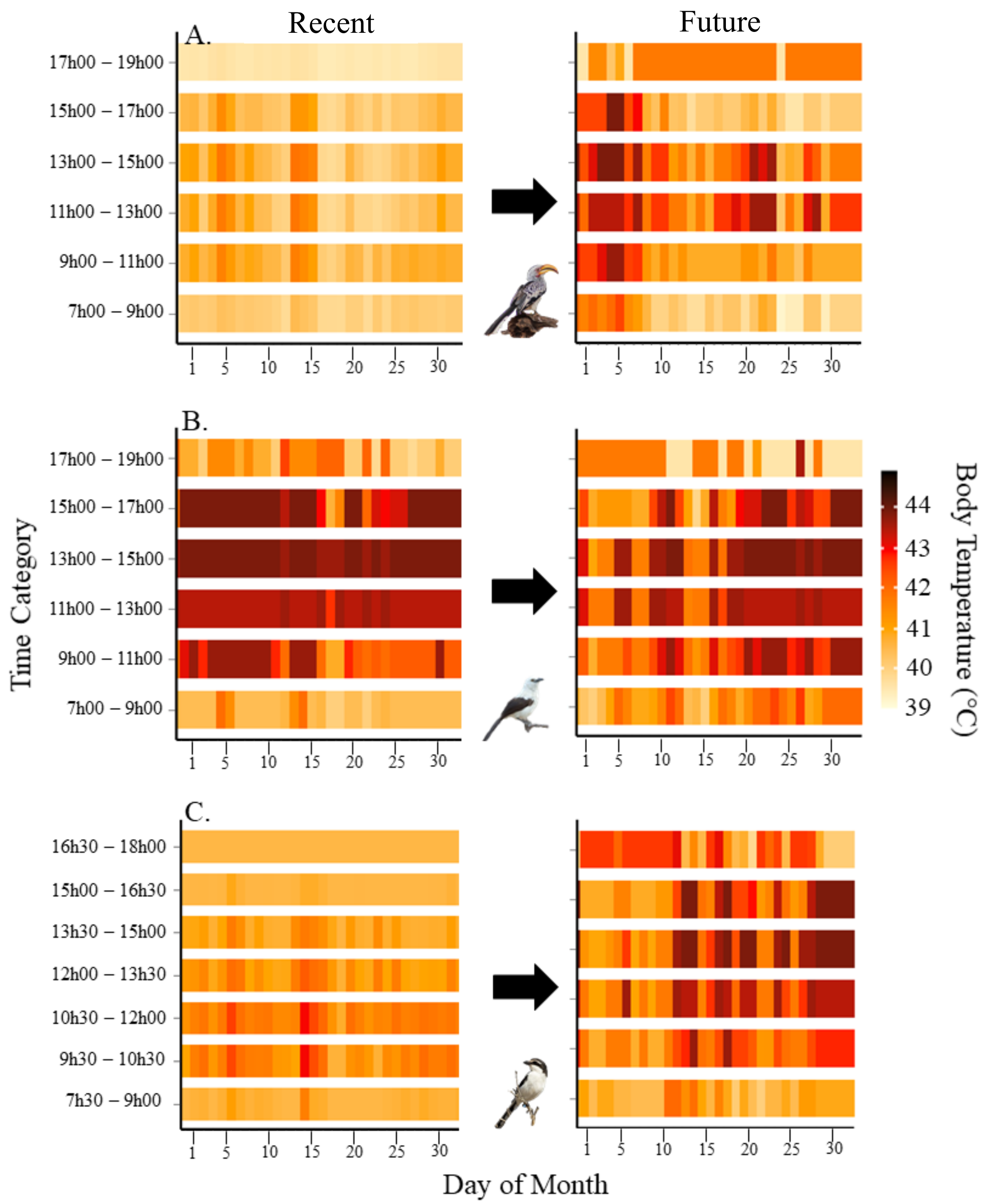

Figure S3. Predicted average body temperature (T_b) in southern yellow-billed hornbills (*Tockus leucomelas*; A), southern pied babblers (*Turdoides bicolor*; B) and common fiscals (*Lanius collaris*; C) for each day of an average month in summer (averaged over October – February) as a function of modelled microsite conditions under recent (2015 - 2020) and a moderate future scenario (RCP 4.5; 2080 – 2100). Microsite conditions were modelled based on the behavioural probability of exposure (sun vs shade) and location (low perch vs high perch) throughout the day (07h00 – 19h00) using the *NicheMapR* package. The bar code-like pattern, evident particularly for fiscals under future conditions, arises from the sharp contrast in behavioural repertoire assigned for days on which T_{max} > 35 °C compared to cooler days. Bird images courtesy of Warwick Tarboton