

Supplementary materials

Results

Long-term weather trends

For the period over which data for all three weather stations (Hot Birds Research Project [HBRP], Twee Rivieren [TR], and Van Zylsrus [VZ]) overlapped (2011 – 2020), T_{\max} (mean maximum daily air temperature [T_{air}]) from all three weather stations (Lin's correlation coefficient: VZ~TR, $\rho.c = 0.94$, $r^2 = 0.89$; HBRP~VZ, $\rho.c = 0.94$, $r^2 = 0.94$; HBRP~TR = 0.90, $r^2 = 0.92$) and T_{\min} (mean minimum daily T_{air}) between all three regions (VZ~TR, $\rho.c = 0.95$, $r^2 = 0.90$; HBRP~VZ, $\rho.c = 0.96$, $r^2 = 0.93$; HBRP~TR = 0.94, $r^2 = 0.89$) were highly correlated (Figure S1).

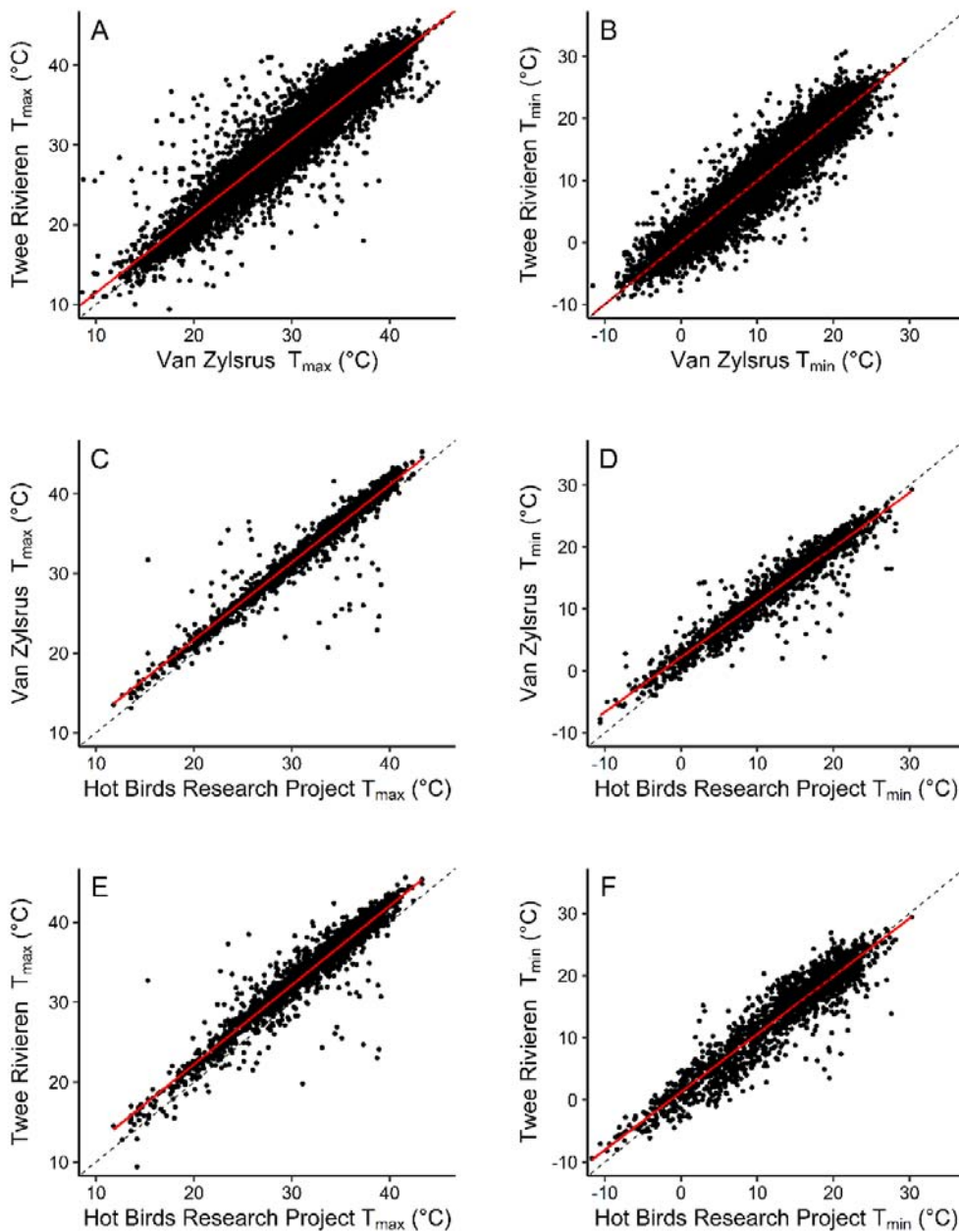


Figure S1. Correlation between (A, C, & E) T_{max} (mean maximum daily air temperature [T_{air}]) and (B, D, & F) T_{min} (mean minimum daily T_{air}) for the Hot Birds Research Project (HBRP; the on-site weather station), Twee Rivieren (~120 kms from the study site), and Van Zylsrus (~30 km from the study site) weather stations between 2011 – 2020. Dotted line represents 1:1 relationship.

The T_{max} data from VZ and TR was systematically higher than those from the HBRP (VZ mean 1.38 °C ± 1.54 SD higher; TR, mean 2.13 °C ± 1.79 SD higher; Figure S1). To create a single long-term weather dataset for use in further analyses, these values had to be adjusted. VZ and TR T_{max} data were therefore adjusted down by the mean difference between them and the HBRP data. The adjusted values then fell along the

1:1 ratio line, resulting in Lin's correlation coefficients $\rho.c = 0.99$ for all three correlations (Figure S2).

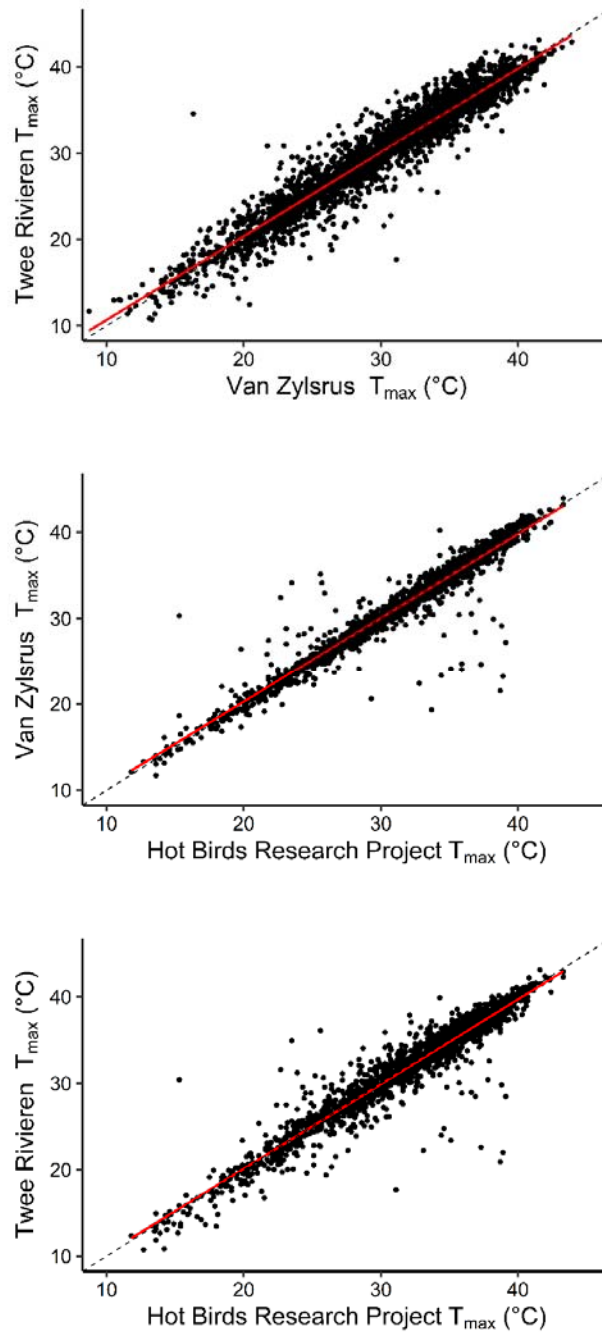


Figure S2. Correlation between T_{max} (mean maximum daily air temperature [T_{air}]) data from the Hot Birds Research Project (HBRP; the on-site weather station), Twee Rivieren (~120 kms from the study site), and Van Zylsrus (~30 km from the study site) weather stations between 2011 – 2020. Dotted line represents 1:1 relationship.

Daily rainfall was not correlated between the three weather stations (VZ~TR, $\rho.c = 0.19$, $r^2 = 0.03$; HBRP~VZ, $\rho.c = 0.52$, $r^2 = 0.30$; HBRP~TR = 0.36 , $r^2 = 0.14$), however, breeding season (19 October – 24 March) rainfall was highly correlated between the HBRP and the VZ ($\rho.c = 0.66$, $r^2 = 0.97$) and TR ($\rho.c = 0.78$, $r^2 = 0.86$) weather stations (Figure S3).

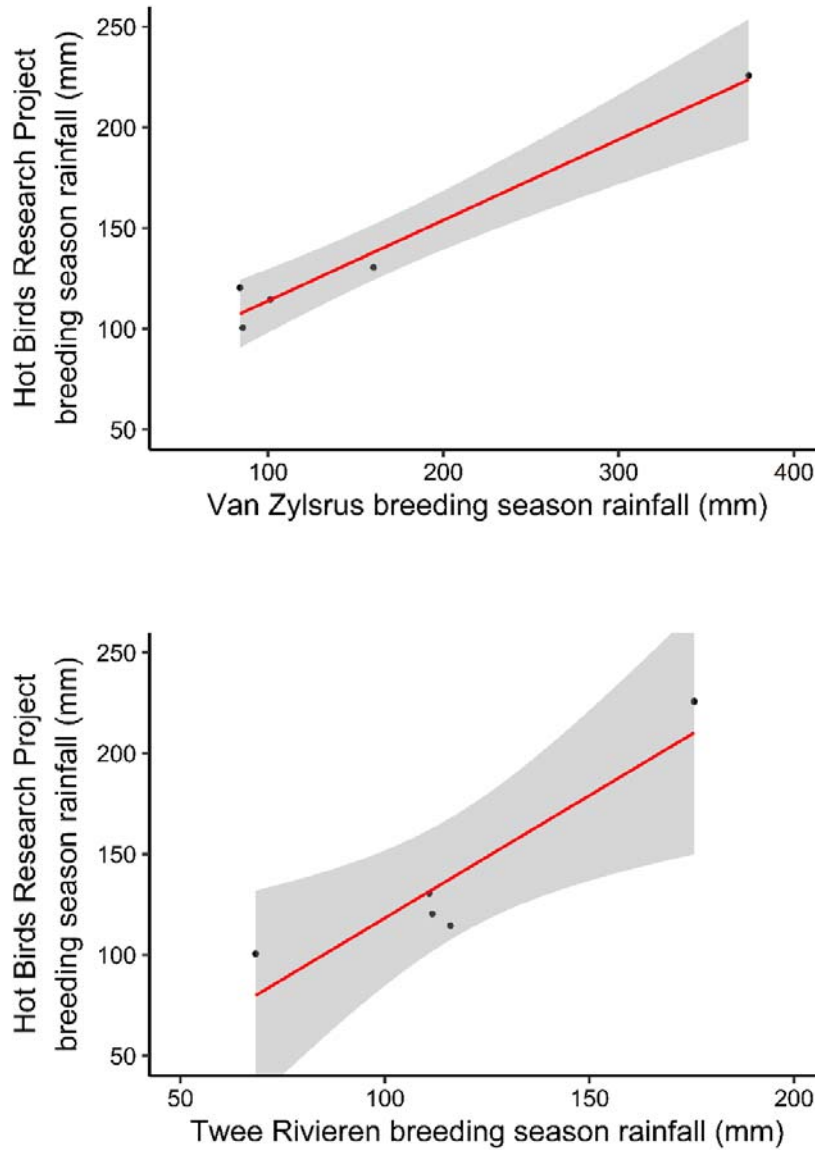


Figure S3. Correlations between breeding season (19 October – 24 March) rainfall data from the Hot Birds Research Project (HBRP; the on-site weather station), Twee Rivieren (~120 kms from the study site), and Van Zylsrus (~30 km from the study site) weather stations. 95% confidence intervals are shown.

No trends were apparent in mean T_{min} or rainfall during the non-breeding season (25 March – 18 October each year; Figure S4).

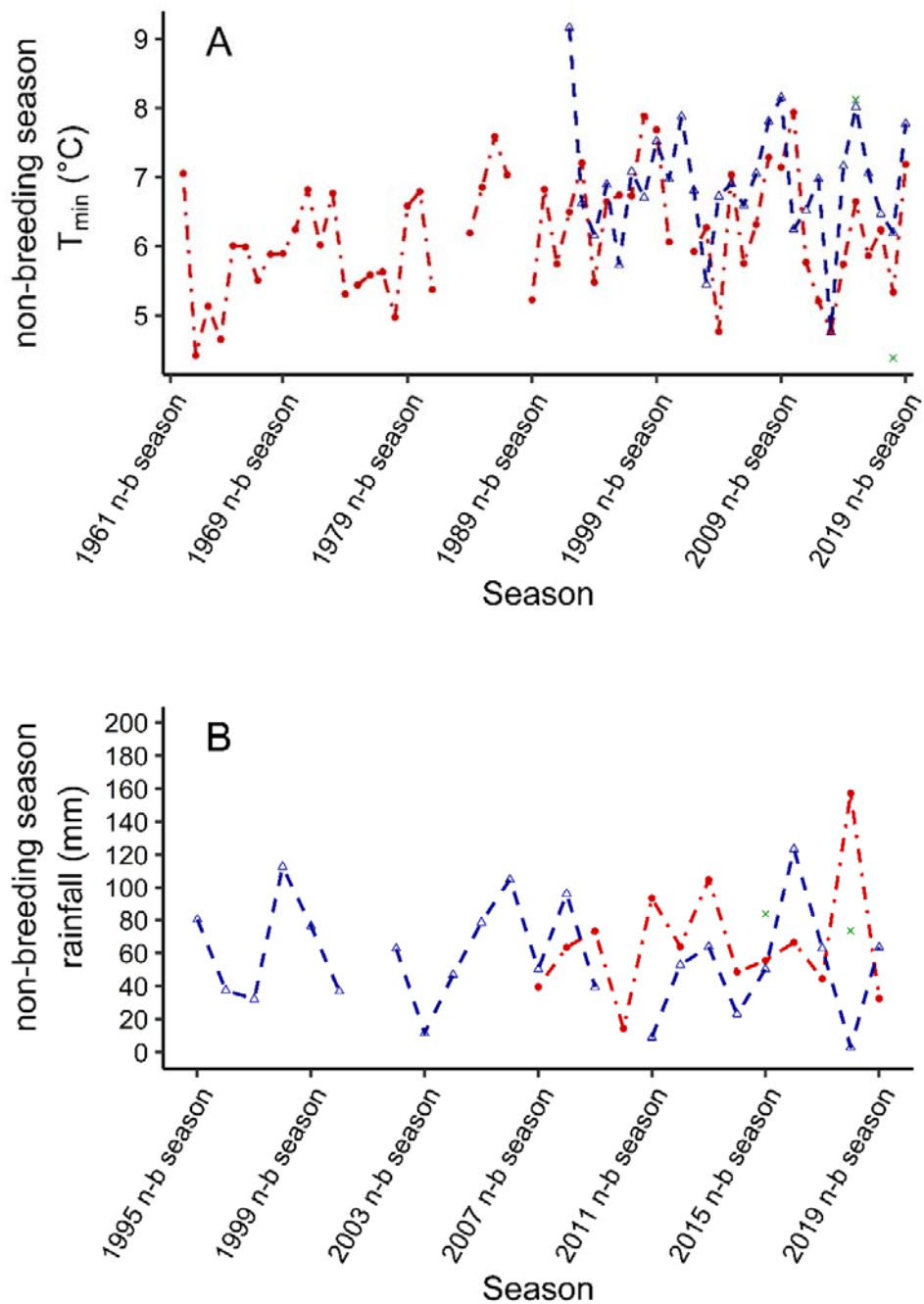


Figure S4. Trends in (A) T_{\min} (mean minimum air temperature [T_{air}]) and (B) cumulative rainfall during the Southern Yellow-billed Hornbills (*Tockus leucomelas*) non-breeding season (n-b season; 25 March – 18 October) from the Hot Birds Research Project (HBRP; the on-site weather station, green crosses), Twee Rivieren (red circles, ~120 kms from the study site), and Van Zylsrus (blue triangles, ~30 km from the study site) weather stations. Note the difference in axes.

Long-term breeding trends

The model average of these four top models revealed that survival during the nestling period was positively correlated with an increased number of days post-hatch spent in

the nest by the female (estimate 1.08 ± 0.38 ; $p = 0.005$), and negatively correlated with an increased percentage $\text{Days}T_{\text{thresh}}$ during the nestling period (estimate -0.86 ± 0.37 ; $p = 0.021$; Table 2; Figure S5).

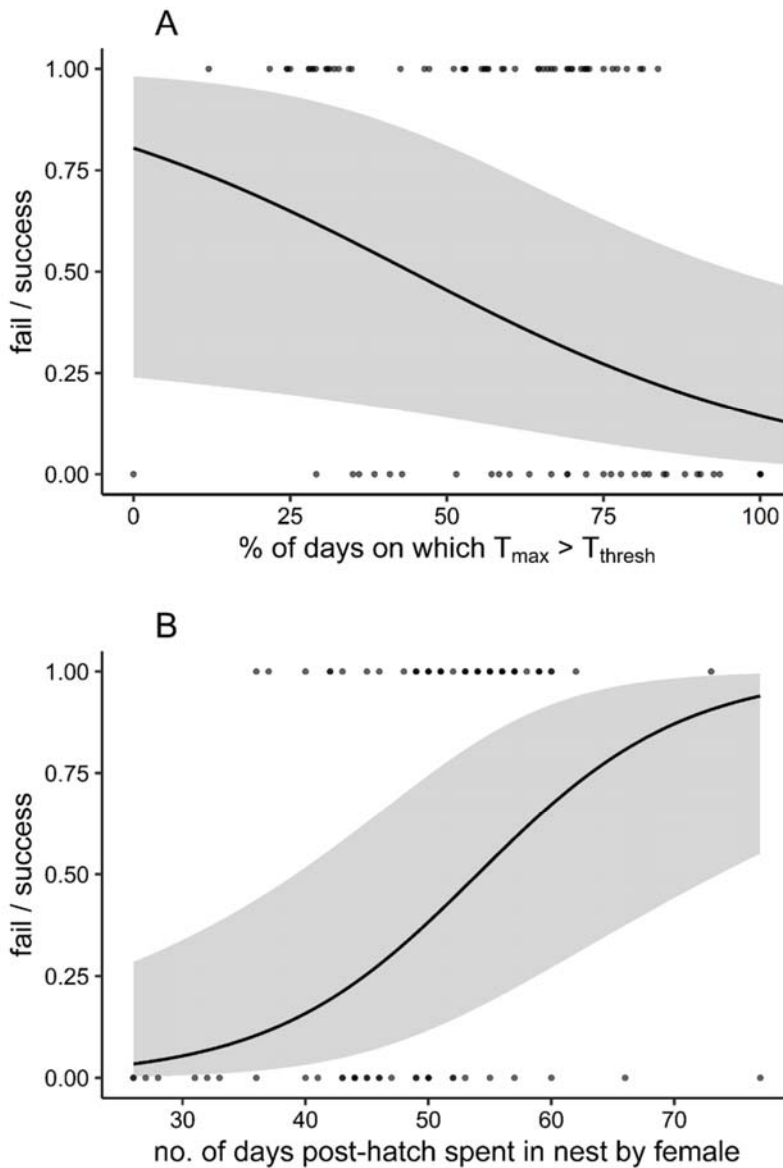


Figure S5. The binomial probability of success (0 = fail, 1 = success [fledging at least one chick]) for Southern Yellow-billed Hornbills (*Tockus leucomelas*) nests which hatched at least one chick as a function of (A) the percentage $\text{Days}T_{\text{thresh}}$ (days on which T_{max} (mean maximum daily air temperature [T_{air}] > T_{thresh} [$T_{\text{air}} = 34.5 \text{ }^\circ\text{C}$]), and (B) the number of days post-hatch spent in the nest by the female during the period from hatch to success / fail. Both relationships were significant, 95% confidence intervals are shown.

The effect of drought occurrence on survival during the nestling period was not significant in the averaged model (estimate 0.71 ± 0.92 ; $p = 0.444$, Table S2), although 4 out of 15 (26.7%) of chicks which hatched in drought seasons fledged, compared to 40 out of 56 (71.4%) of chicks in non-drought seasons (Figure S6).

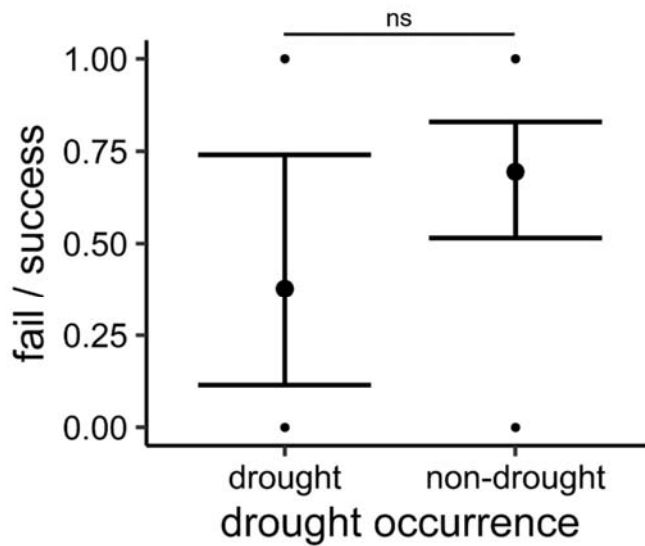


Figure S6. The binomial probability of success (0 = fail, 1 = success [fledging at least one chick]) for Southern Yellow-billed Hornbills (*Tockus leucomelas*) nests which hatched at least one chick as a function of the occurrence or absence of drought across the breeding season. Mean and upper and lower quartiles shown.

Thermal conditions in nest boxes versus natural cavities

One top model was identified for T_{nest} , indicating that T_{nest} inside both nest boxes and natural cavities showed a significant positive relationship with outside T_{air} (estimate 1.03 ± 0.00 ; $p = 0.001$), but that there was a significant interaction between T_{air} and type of nest (estimate -0.49 ± 0.00 ; $p = 0.001$; Table S3 & S4). The slope of the relationship between T_{nest} and T_{air} was $0.55 T_{\text{nest}} \text{ } ^\circ\text{C} \cdot T_{\text{air}}^{-1}$ for natural cavities (estimate 0.55 ± 0.00 ; $p = 0.001$), compared to $1.03 T_{\text{nest}} \text{ } ^\circ\text{C} \cdot T_{\text{air}}^{-1}$ for nest boxes (estimate 1.03 ± 0.00 ; $p = 0.001$), suggesting that T_{nest} within natural cavities was buffered against T_{air} , while T_{nest} within nest boxes tracked T_{air} (Table S4; Figure S7). The difference between T_{nest} within nest boxes and natural cavities was most pronounced at higher T_{air} ; at $T_{\text{air}} > T_{\text{thresh}}$ the mean T_{nest} within nest boxes was $39.65 \text{ } ^\circ\text{C} \pm 3.23 \text{ SD}$, while the mean T_{nest} within natural cavities was $34.91 \text{ } ^\circ\text{C} \pm 3.68 \text{ SD}$ (Figure S7).

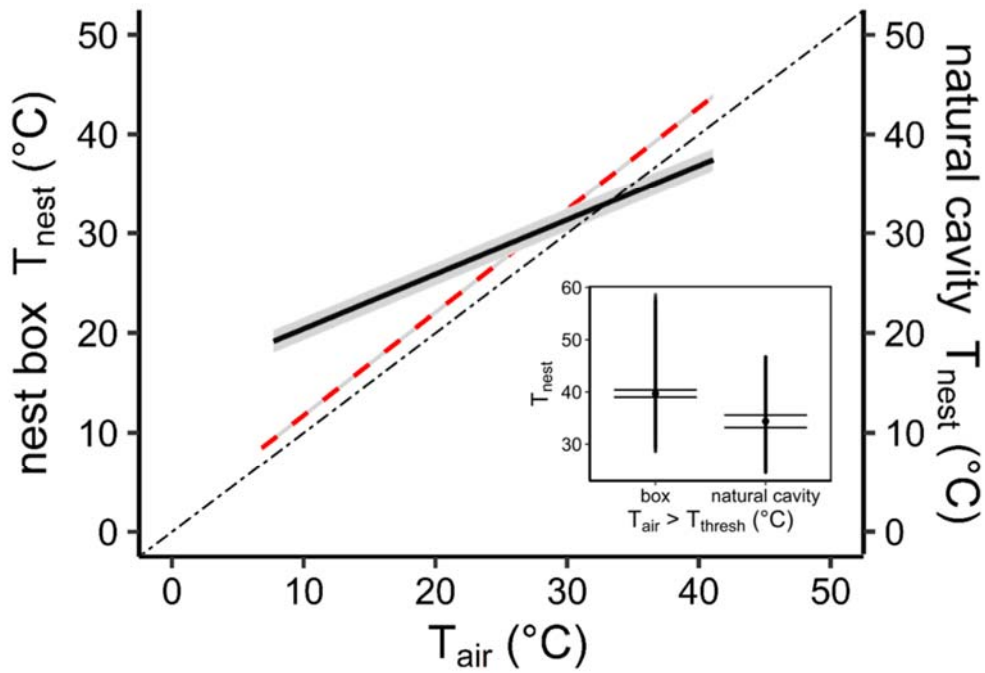


Figure S7. Air temperature (T_{air}) within nest boxes ($n = 27$, red dashed line) and natural cavities ($n = 9$, solid black line) as a function of T_{air} . Nest temperature (T_{nest}) measured using ThermoChron iButtons during Southern Yellow-billed Hornbills (*Tockus leucomelas*) breeding seasons (19 October – 24 March) between 2012 and 2015. T_{nest} within both nest boxes and natural cavities showed a significant positive relationship with T_{air} , but with significantly different slopes. 95% confidence intervals and 1:1 relationship (two-dash black line) shown. Inset box plot of mean and upper and lower quartiles of T_{nest} within nest boxes and natural cavities at $T_{air} > T_{thresh}$ ($T_{air} = 34.5$ °C).

Table S1. Seasons with insufficient (data recorded on <90% of days within the period) T_{\max} (mean maximum daily air temperature [T_{air}]), percentage Days T_{thresh} (days on which $T_{\max} > T_{\text{thresh}}$ [$T_{\text{air}} = 34.5 \text{ }^{\circ}\text{C}$]), and rainfall data during breeding seasons (19 October – 24 March) and for insufficient mean minimum daily T_{air} (T_{\min}) and rainfall during non-breeding seasons (25 March – 18 October) to be included in analyses listed for each weather station: Twee-Rivieren (TR), Van Zylsrus (VZ), and Hot Birds Research Project (HBRP).

	Weather variable	Weather station	Seasons with insufficient data (<90% of days within period)					
Breeding season	T_{\max} & Days T_{thresh}	TR	1970/1971	1975/1976	1988/1989	2001/02	2009/2010	
		VZ	1991/1992	2002/2003	2003/2004	2006/2007	2009/2010	2016/2017
		HBRP	2011/2012	2012/2013	2013/2014	2015/2016		
	rainfall	TR	2006/2007					
		VZ	2002/2003	2009/2010	2010/2011	2011/2012		
		HBRP	2011/2012	2012/2013	2013/2014	2015/2016		
Non-breeding season	T_{\min}	TR	1960	1982	1983	1988	2001	2020
		VZ	2020					
		HBRP	2014	2016	2017	2019	2020	
	rainfall	TR	2020					
		VZ	1993	1994	2001	2010	2011	2020
		HBRP	2014	2016	2017	2019	2020	

Table S2. Model selection table for Bayesian generalised linear mixed models (BGLMer) for different stages of individual breeding attempts in Southern Yellow-billed Hornbills (*Tockus leucomelas*) as functions of female entry date, percentage DaysT_{thresh} (days on which T_{max} (mean maximum daily air temperature [T_{air}] > T_{thresh} [T_{air} = 34.5 °C]), drought occurrence, and the interaction between DaysT_{thresh} and drought occurrence on the binomial success or failure (successfully fledging at least one chick or not) of each entire breeding attempt (n = 88), nest survival from female entry until hatch / fail ('pre-hatch period'; n = 88), and nest survival from hatch until fledge / fail ('nestling period'; n = 88). Survival in the nestling period was also modelled as a function of the number of days the female was in the nest. Model selection also shown for BGLMer for female entry date and the number of days spent in the nest by the female as functions of drought occurrence. Model selection was based on Akaike's Information Criterion score adjusted for small sizes (AICc), with the top performing models (Δ AICc < 2) in bold. Where more than one top model was identified, the model average was calculated. *** indicate a significant effect for an explanatory variable within the top models.

Response variable	Model	(Int)	female entry date	% DaysT _{thresh}	drought occurrence	% DaysT _{thresh} * drought occurrence	number of days female in nest	df	AICc	Δ AICc	weight
success (1) or failure (0) of the entire breeding attempt	1	-1.676	-1.102***	-0.012	+	+***		6	93.7	0	0.961
	4	-1.647		-0.174	+	+		5	100.6	6.84	0.031
	3	-0.164	-0.794	-1.316				4	103.5	9.78	0.007
	6	-0.097		-1.217				3	109.2	15.47	0
	2	-1.567	-0.631		+			4	112.6	18.84	0
	7	-1.673			+			3	115.9	22.16	0
	5	-0.214	-0.723					3	119.7	25.96	0
survival (1) or failure (0)	1	0.880	-1.240***	0.160	+	+***		6	76.3	0	0.66
	3	0.700	-1.060		+			4	79.7	3.41	0.12
	2	2.280	-1.000	-0.620				4	79.8	3.53	0.11

during the pre-hatch period	6	2.100	-1.080				3	80.7	4.41	0.07	
	4	0.300		-0.260	+	+	5	82.9	6.65	0.02	
	7	1.990		-0.800			3	85.6	9.31	0.01	
	5	0.250			+		3	86.7	10.43	0.00	
	8	1.790					2	89.2	12.86	0.00	
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	Avg.	-0.021	-0.106	-0.858***	+		1.081***	6			
	15	-0.498		-0.744***	+		1.118***	5	101.2	0	0.295
	7	0.534		-0.908***			1.135***	4	102	0.75	0.202
	8	0.532	-0.386	-1.044***			0.966***	5	102.9	1.69	0.127
	16	-0.389	-0.255	-0.859***	+		1.016***	6	103.1	1.91	0.113
survival (1) or failure (0) during the nestling period	31	-0.674		-0.469	+	+	1.125	6	103.5	2.29	0.094
	11	-0.991			+		1.082	4	104.2	2.99	0.066
	32	-0.657	-0.329	-0.419	+	+	0.996	7	105.3	4.13	0.037
	12	-1.029	0.188		+		1.160	5	105.9	4.74	0.028
	6	0.526	-0.817	-1.243				4	107.1	5.94	0.015
	14	-0.036	-0.744	-1.120	+			5	108.6	7.41	0.007
	3	0.428					1.096	3	108.7	7.5	0.007
	30	-0.590	-0.872	-0.326	+	+		6	110.2	8.97	0.003
	4	0.426	0.070				1.124	4	110.9	9.65	0.002

	13	-0.488		-0.742	+		4	111.8	10.59	0.001
	5	0.495		-0.913			3	112.7	11.47	0.001
	29	-0.604		-0.586	+	+	5	114	12.83	0
	9	-1.077			+		3	116.3	15.06	0
	10	-0.984	-0.269		+		4	117.7	16.49	0
	1	0.304					2	121.7	20.49	0
	2	0.342	-0.394				3	121.8	20.6	0
	Avg.	3.607			+		3			
Female entry date	2	3.672					2	1175.0	0	0.559
	1	3.760			+		3	1175.5	0.47	0.441
	Avg.	3.872			+		3			
Days post-hatch spent in the nest by female	2	3.843					2	665.3	0	0.551
	1	3.895			+		3	665.7	0.41	0.449

Table S3. Model selection for Bayesian linear mixed models (BLMer) of nest temperature (T_{nest}) of nests occupied by Southern Yellow-billed Hornbills (*Tockus leucomelas*) modelled as function of nest type (natural cavities versus nest boxes), air temperature (T_{air}), and an interaction between them. Model selection was based on Akaike's Information Criterion score adjusted for small sizes (AICc), with the top performing models ($\Delta \text{AICc} < 2$) in bold. *** indicate a significant effect for an explanatory variable within the top models.

Response variable	Model	(Int)	Nest type (box versus natural cavity)	T_{air}	$T_{\text{air}} * \text{Nest type (box versus natural cavity)}$	df	AICc	ΔAICc	weight
T_{nest}	1	1.443	+***	1.032	+***	6	3454226	0	1
	3	3.436		0.961		4	3580761	126534.6	0
	2	3.376	+	0.961		5	3580763	126536.5	0
	5	29.72				3	4895017	1440790.9	0
	4	29.65	+			4	4895018	1440791.9	0

Table S4. Model results for nest temperature (T_{nest}) of nests occupied by Southern Yellow-billed Hornbills (*Tockus leucomelas*) modelled as function of nest type (natural cavities versus nest boxes), air temperature (T_{air}), and an interaction between them. Model outputs are for the single top model, or model averages when there was more than one competing model within 2 ΔAICc (see column 'Number of top models'). All models contain the random factor 'season'.

Response variable	Model family	Number of top models	Independent variables	Estimate \pm SE (Adj SE for model averaged estimates)	t	df	p \leq	Upper 95% CI	Lower 95% CI
T_{nest}	Gaussian	1	T_{air}	1.03 \pm 0.00	2070.98	733733	0.001	1.03	1.03
			nest type (box versus natural cavity)	13.52 \pm 0.38	35.89	733733	0.520	14.25	12.78
			T_{air} * nest type (box versus natural cavity)	-0.49 \pm 0.00	-371.65	733733	0.001	-0.48	-0.49
			T_{air} (nest type = nest boxes)	1.03 \pm 0.00	2214.70	622885	0.001	1.03	1.03
			T_{air} (nest type = natural cavities)	0.55 \pm 0.00	347.22	110846	0.001	0.55	0.54