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Microhabitat-scale thermal determinants of body temperature in *Anatololacerta anatolica* from Mount Spil, Western Anatolia

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Abstract

Lizards, as ectothermic organisms, are largely dependent on the thermal characteristics of their habitats for the maintenance of their biological processes. This research aims to quantitatively elucidate the correlation between the body temperature (T_b) of the *Anatololacerta anatolica* population on Mount Spil (Manisa), Western Anatolia, and core environmental variables at the microhabitat level, including surface temperature (T_s), air temperature (T_a), solar radiation, and wind speed. Field surveys were conducted between April and October 2025, during which cloacal body temperature data obtained from 89 individuals were analyzed alongside simultaneous microhabitat parameters.

Descriptive statistical data confirmed that the species is an active thermoregulator, as the mean body temperature of the lizards (32.32 ± 4.53 °C) was found to be statistically significantly higher than both the surface temperature (30.6 ± 6.97 °C) and the air temperature (28.1 ± 4.04 °C). Multiple regression analyses demonstrated that T_s and solar radiation are the strongest positive predictors of T_b. Principal component analysis (PCA) results, explaining approximately 76% of the total variance, determined that T_b, T_s, and solar radiation clustered on the primary axis (PC1), while wind speed was situated on an independent axis (PC2) that is statistically decoupled from this radiative thermal system.

The findings indicate that *A. anatolica* adopts a strategy integrating both solar radiation and thermal substrates, specifically heliothermy and thigmothermy, during the process of heat acquisition. It was observed that the species suppresses the convective cooling effect of wind through strategic microhabitat preferences, such as utilizing rock crevices and the base of vegetation, thereby exhibiting the Bogert effect to stabilize its thermal safety margins. Consequently, within the framework of climate change scenarios, it is essential to prioritize microhabitat-scale thermal heterogeneity and the continuity of thermal refugia over macroclimatic averages when evaluating the thermal sensitivity of the species.

Key Words

Anatolian rock lizard, climate sensitivity, ectothermic organism, solar radiation, surface temperature, thermal ecology, wind speed

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PENSOFT

Introduction

Ectothermic organisms, such as reptiles, amphibians, and most invertebrates, are unable to produce sufficient metabolic heat to regulate their internal temperature and therefore depend on external heat sources to achieve the body temperatures (T_b) required to sustain their physiological, ecological, and behavioral processes (Vitt and Caldwell 2014; Reppa et al. 2023). The strategies that ectotherms employ to cope with environmental thermal variability fall along a continuum between two extremes: thermoconformers, whose body temperature closely tracks the temperature of their immediate environment, and thermoregulators, which actively maintain T_b within a narrower preferred range by exploiting spatial and temporal thermal heterogeneity through behavioral and, to a lesser extent, physiological mechanisms (Hertz et al. 1993; Bakken and Angilletta Jr 2014). Distinguishing between these strategies is fundamental to understanding the thermal ecology of a species and its potential vulnerability to climate change.

During thermoregulation, lizards exploit several heat sources that operate through distinct physical pathways. Solar radiation, high-energy radiation in the ultraviolet, visible, and shortwave-infrared spectra (≈290–3000 nm), is generally considered the primary heat source for diurnal lizards and is transferred by radiation (Gans 1982; Vitt and Caldwell 2014). Substrate temperature (T_s, also denoted $T_{substrate}$) is the temperature of the soil, rock, sand, or leaf litter with which the lizard is in direct contact and transfers heat by conduction (Bakken 1992; Crawford et al. 1983; Menezes and Rocha 2011; Bonavita et al. 2025). Air temperature (T_a) is the temperature of the surrounding medium measured outside the animal's thermal and hydrodynamic boundary layers and influences T_b mainly through convective exchange (Gans 1982; IUPSThermal-Commission 2001; Hertz et al. 1993). Lizards that raise T_b primarily by basking in direct sunlight are classified as heliotherms, whereas those that rely mainly on conductive exchange with warm substrates are classified as thigmotherms (Gans 1982; Şahin and Kuyucu 2021; Dıblan et al. 2026). Many species, in fact, combine both strategies, and wind can further modify heat balance by enhancing convective heat loss when T_b exceeds T_a (Villavicencio et al. 2007; Virens and Cree 2022).

Because these heat sources vary at very fine spatial scales, macroclimatic data (e.g., weather-station air temperatures or gridded climate surfaces such as WorldClim) are often poor proxies for the temperatures actually experienced by ectotherms (Bakken and Angilletta Jr 2014; Lembrechts and Lenoir 2020; Sears and Angilletta Jr 2015; Sears et al. 2016). Vegetation cover, rock crevices, orientation, slope, and substrate type create fine-scale thermal mosaics that provide opportunities for behavioral thermoregulation (Adolph and Porter 1993; Díaz 1997; Li et al. 2017). By selecting favorable microhabitats, lizards can maintain T_b near their preferred range even when macroclimatic conditions would predict otherwise—a phenomenon known as the Bogert effect, in which behavioral buffering of the thermal environment may slow the pace of physiological evolution and mask the climatic vulnerability of a species (Logan et al. 2019). Assessing the thermal biology of ectotherms therefore requires measurements at the microhabitat scale, integrating T_s, T_a, solar radiation, and wind.

The Anatolian rock lizard, *Anatololacerta anatolica* (Werner 1902), is a small diurnal lacertid endemic to western Anatolia, distributed from north of the Büyük Menderes River to Bursa in the northwest and extending eastward into Central Anatolia at elevations up to ~1,600 m (Karakasi et al. 2021; Şahin et al. 2022). Two subspecies are currently recognized, of which *A. a. anatolica* occurs in northwestern Anatolia, including Mount Spil (Oğuz 2020). The species typically inhabits rocky areas with dense vegetation and proximity to moisture and is frequently found under stones at ambient temperatures of 25–30 °C (Oğuz 2020). Previous work has reported a preferred T_b of approximately 34.5 °C in adults (Oğuz 2020), but data on how individuals in natural populations integrate solar radiation, substrate temperature, air temperature, and wind at the microhabitat scale remain scarce. Potential threats include habitat loss, disturbance of rock shelters, and, notably, climate change: bioclimatic modeling predicts a northward contraction of suitable habitat for the genus under future climate scenarios (Bozkurt 2022; Oğuz 2020; Şahin et al. 2022). Understanding whether *A. anatolica* is a thermoconformer or a thermoregulator, and whether it relies mainly on heliothermy or thigmothermy, is therefore essential for realistic projections of its climatic sensitivity.

The primary objective of this study is to quantify the relationship between T_b and the microhabitat-scale thermal variables T_s, T_a, solar radiation, and wind speed in *Anatololacerta anatolica* from Mount Spil (Manisa, western Anatolia). Specifically, this study aims to (i) determine whether the population behaves as a thermoconformer or an active thermoregulator, (ii) identify whether it relies predominantly on heliothermic or thigmothermic heat acquisition, (iii) evaluate potential sex differences in thermal parameters, and (iv) evaluate the direction and magnitude of the influence exerted by each environmental variable on T_b. The findings are intended to contribute to the characterization of the species' thermal niche and to provide a baseline for assessing its potential vulnerability to future environmental change.

Material and methods

Study area

This study was conducted on Mount Spil (38.52°N, 27.42°E), located within the boundaries of the Lower Gediz Sub-Basin in the Aegean Region of Türkiye.

The study area lies to the south of Manisa city center and east of İzmir province, covering an area of approximately 27,435 ha. Elevation ranges from 50 m at the base to 1,517 m at the summit of Karadağ Peak (Çağlar 2024). Mount Spil lies within the Mediterranean Phytogeographical Region; vegetation consists primarily of Mediterranean maquis (*Quercetum coccifera*), forests (*Pinus brutia* and *Pinus nigra*), and transitional mountain steppe zones (Duman 1985; Kumlutaş et al. 2001; Semenderoğlu et al. 2020; Çağlar 2024).

According to the Köppen-Geiger classification, the region experiences a Csa-type Mediterranean climate, marked by hot, dry summers and mild, wet winters (Peel et al. 2007). Long-term data (1930–2025) from the Manisa Meteorological Station indicate an annual average temperature of 16.9 °C. The average maximum temperature occurs in July (35.1 °C), while the average minimum is recorded in January (3.1 °C). Average winter temperatures range between 6–8 °C, and in summer, temperatures typically exceed 28 °C. Recorded extremes include a maximum of 45.5 °C and a minimum of –17.5 °C (General Directorate of Meteorology of the Republic of Türkiye 2025).

Focal species

The focal organism used in this study is *Anatololacerta anatolica* (Werner 1902), a diurnal lacertid endemic to western Anatolia. On Mount Spil, the populations belong to the nominotypical subspecies *A. a. anatolica*, which is distributed throughout northwestern Anatolia (Oğuz 2020; Şahin et al. 2022).

Sex was determined in the field based on primary sexual characteristics: males were identified by the presence of hemipenes, while females were identified by the absence of this trait (Budak and Göçmen 2008). Individuals with snout–vent length (SVL) ≥ 55 mm were classified as adults, following skeletochronological data reported for this species by Yakin and Tok (2015); smaller individuals were recorded as juveniles and excluded from sex-specific analyses. All animals were measured (SVL; ±0.01 mm) and weighed (±0.01 g) in the field immediately after body temperature recording and released at the point of capture.

Field measurements

Fieldwork was conducted between April and October 2025, during which data were collected from 125 individuals. Upon capture of a lizard, the "capture–immediate measurement" technique was employed (Taylor et al. 2021), using an infrared thermometer equipped with a fast-response J-type thermocouple (Fluke 561™ Infrared Thermometer; 0.1 °C resolution) to measure body temperature (T_b) via cloacal insertion (1–10 mm depth), and the reading was recorded within 10 s (Carretero 2012; Barroso et al. 2016; Taylor et al. 2021). The rapidity of measurement was essential to minimize the potential influence of heat transfer from the researcher's hand or stress-induced changes in the lizard's body temperature (Gans 1982; Carretero 2012; Barroso et al. 2016).

The surface temperature (T_s) of the microhabitat at the exact point of capture was measured using the same infrared thermometer (Fluke 561™; 0.1 °C resolution) (Barroso et al. 2016). To ensure accuracy, the device was pre-calibrated to account for factors such as measurement distance and the emissivity of the surface (Carretero 2012; Taylor et al. 2021). Air temperature (T_a) was measured 1 cm above the ground with a digital thermometer integrated with a J-type thermocouple (Uni-T UT-320DTM Mini) (Maia-Carneiro and Rocha 2013; Ortega et al. 2019; Stellatelli et al. 2018); the sensor and probe were kept under shaded conditions to avoid direct exposure to solar radiation (Ortega et al. 2016; Rivera-Rea et al. 2023). Solar radiation was recorded using an Apogee MP-200™ pyranometer (Crawford et al. 1983), and wind speed was measured with a Testo 410™ anemometer (Dodd 2016) at the height corresponding to the lizard's position (1–10 cm above ground) to ensure ecologically relevant data (Crawford et al. 1983).

Statistical analysis

All analyses were performed in R (version 2026.01.0+392) using the packages tidyverse, ggplot2, FactoMineR, factoextra, corrplot, lubridate, car, lme4, MuMIn, GGally, effsize, magrittr, and MASS (Bates et al. 2015; Husson et al. 2016; Kassambara and Mundt 2016; Ripley et al. 2013; Wei and Simko 2017; Wickham 2011, 2016). Of the 125 individuals sampled in the field, 89 had complete records for T_b and all four microhabitat variables and were retained for statistical analysis.

The following analyses were carried out, each with a specific objective: (i) paired-sample *t*-tests were used to test whether T_b differed from T_s and from T_a in the same individuals, i.e., whether the population behaves as an active thermoregulator rather than a passive thermoconformer. (ii) Cohen's *d* was computed as an effect size to quantify the biological magnitude of the T_b–T_s and T_b–T_a differences, complementing the *p*-values. (iii) Pearson correlation analysis on all pairs of thermal variables was used to describe the overall association structure of the thermal environment (magnitude and sign of the linear relationships, without controlling for other variables). (iv) Multiple linear regression with T_b as the response and T_s, T_a, solar radiation, and wind speed as simultaneous predictors was used to identify which environmental variables have a unique, independent effect on T_b once the others are held constant; the standardized regression coefficients (β) provide the direction and magnitude of each variable's influence

on T_b. Variance inflation factors (VIFs) were computed to check for multicollinearity (VIF < 5 considered acceptable). (v) A reduced (parsimonious) model containing only the two *a priori* strongest predictors (T_s and solar radiation) was compared with the full model using the second-order Akaike information criterion (AICc); ΔAICc < 2 was interpreted as indicating similar empirical support. (vi) Partial regression plots and effect plots were used to visualize the marginal contribution of each predictor to T_b after controlling for the others. (vii) Principal component analysis (PCA) on environmental variables plus T_b (standardized to unit variance) was used as a descriptive, dimension-reducing technique to summarize the covariance structure of the thermal environment and to visualize how T_b relates, as a whole, to the underlying radiative–thermal and convective gradients. Thus, the correlation and regression analyses quantify the direction and magnitude of each variable's influence on T_b, whereas PCA is used only as an exploratory description of the overall covariance pattern. To assess potential sex differences in thermal parameters, Welch's two-sample *t*-tests were applied to compare mean T_b, SVL, and body mass between males and females, with effect sizes quantified using Cohen's *d*. To evaluate whether body size influences field T_b—as would be expected if thermal inertia were a significant factor—simple linear regression was performed with SVL and body mass as predictors of T_b, restricted to adult individuals.

Results

Overview of thermal measurements

Between April and October 2025, 125 field observations were collected from *Anatololacerta anatolica* on Mount Spil, Manisa. Measurements included cloacal body temperature (T_b), surface temperature (T_s), air temperature (T_a), solar radiation, and wind speed (Suppl. material 2: table S1). Among these, 89 T_b values met quality criteria for inclusion in further analysis (e.g., reliable cloacal measurements and paired environmental data). Mean field body temperature was 32.32 ± 4.53 °C (range: 18.4–39.6 °C), which was significantly higher than both mean T_s (30.6 ± 6.97 °C; paired *t*-test: $t(88) = 3.34$, $p = 0.001$) and mean T_a (28.10 ± 4.04 °C).

Body temperature vs. surface temperature

A paired *t*-test showed that *A. anatolica* maintained T_b significantly higher than T_s ($t(88) = 3.34$, $p = 0.001$; mean difference = 1.76 °C, 95% CI [0.71, 2.81]), although the effect size was small (Cohen's $d = 0.27$). The distribution of T_b–T_s differences (Fig. 1) was right-skewed, with most individuals maintaining T_b slightly above T_s.

Predictors of body temperature: Multiple regression analysis

A multiple linear regression with T_b as the response and T_s, T_a, solar radiation, wind speed, SVL, body mass, and sex as predictors was statistically significant ($F(8, 78) = 20.13$, $p < 0.001$), explaining 67.4% of the variance in body temperature (adjusted $R^2 = 0.640$) (Table 1). Among the environmental predictors, T_s ($\beta = 0.261$, SE = 0.061, $p < 0.001$), solar radiation ($\beta = 0.00451$, SE = 0.001, $p < 0.001$), and T_a ($\beta = 0.188$, SE = 0.091, $p = 0.043$) were significant positive predictors of T_b. Wind speed was not significant at the conventional α = 0.05 level ($\beta = 0.151$, SE = 0.092, $p = 0.106$). Body size variables (SVL: $\beta = -0.093$, $p = 0.288$; body mass: $\beta = 0.368$, $p = 0.231$) and sex (female vs. male: $\beta = 1.169$, $p = 0.076$; juvenile vs. male: $\beta = -0.033$, $p = 0.984$) did not contribute significantly to the model once environmental predictors were held constant.

Table 1. Multiple linear regression results for body temperature (T_b).

Predictor	*β*	SE	*t*	*p*
(Intercept)	17.880	3.966	4.507	**< .001**
Surface temperature	0.261	0.061	4.270	**< .001**
Air temperature	0.187	0.091	2.056	**< 0.05**
Wind speed	0.150	0.092	1.634	0.106
Solar radiation	0.0045	0.00110	4.190	**< .001**
SVL	-0.092	0.086	-1.071	0.287
g	0.367	0.304	1.208	0.230
sexF	1.169	0.649	1.800	0.075
sexJuv	-0.032	1.666	-0.02	0.984

Note. Model fit: $R^2 = 0.673$, adjusted $R^2 = 0.640$; $F(8, 78) = 20.13$, $p < 0.001$; residual standard error = 2.697. Bold *p*-values indicate statistical significance at α = 0.05.

Variance inflation factors (VIFs) indicated no multicollinearity among the environmental predictors (VIF range: 1.15–2.19). However, SVL and body mass showed elevated VIFs (10.61 and 7.44, respectively), reflecting the expected collinearity between these two morphometric variables; their nonsignificance in the full model should therefore be interpreted cautiously. The environmental predictor set (T_s, T_a, solar radiation, wind) remained unaffected by this collinearity (Suppl. material 2: table S2).

Parsimonious model and AIC evaluation

A reduced model with T_s and solar radiation alone remained statistically robust ($F(2, 86) = 58.00$, $p < 0.001$), accounting for 60.2% of the variance in T_b (Suppl. material 2: table S3). The AICc favored the full model (AICc = 451.50) only slightly over the reduced model (AICc = 453.09), with ΔAICc = 1.59; therefore, both models are

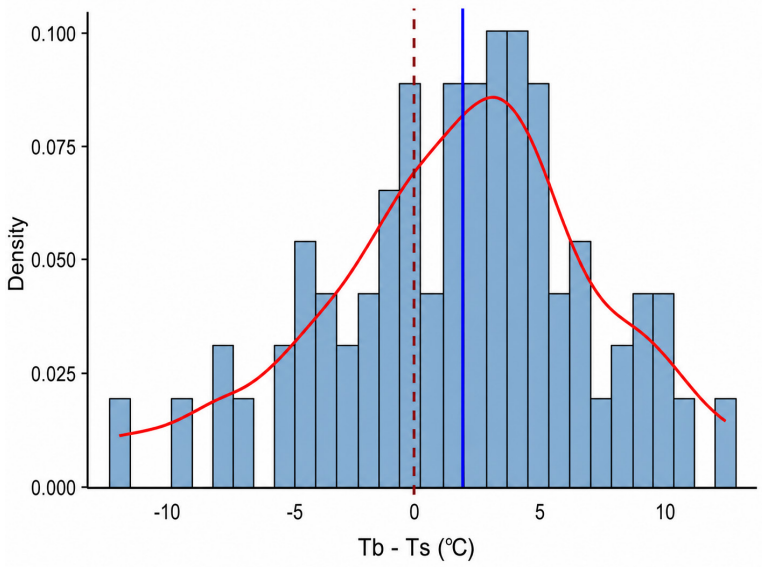

Figure 1. Frequency distribution of the body-temperature excess over surface temperature ($\Delta T = T_b - T_s$, °C) for 89 *Anatololacerta anatolica* individuals. The solid red line is a Gaussian kernel-density estimate of the ΔT distribution. The vertical dashed line marks the thermal equilibrium between T_b and T_s (ΔT = 0), i.e., the thermoconformity reference. The vertical solid line marks the observed average thermal excess of T_b over T_s (ΔT = +1.76 °C). Values to the right of ΔT = 0 correspond to individuals whose T_b exceeds T_s.

similarly supported. Effect plots (Fig. 2) illustrate the consistent positive effect of both T_s and solar radiation on T_b; the effect of wind was weak and uncertain (Suppl. material 2: fig. S1).

Sex differences in body temperature and body size

A total of 40 males, 38 females, and 11 juveniles were recorded; sex-specific analyses were restricted to adults. Males and females did not differ significantly in SVL (males: 62.13 ± 7.43 mm; females: 60.23 ± 5.96 mm; Welch's t = 1.23, df = 72.06, p = 0.223) or body mass (males: 7.01 ± 2.42 g; females: 6.24 ± 1.22 g; t = 1.79, df = 58.37, p = 0.078). Despite the absence of size differences, females maintained significantly higher field body temperatures than males (females: 33.59 ± 5.17 °C; males: 31.44 ± 5.22 °C; Welch's t = –2.05, df = 75.78, p = 0.044; Cohen's d = –0.47, 95% CI [–0.91, –0.01]) (Fig. 3).

Body size was not a significant predictor of field T_b in adult individuals. Neither SVL (β = 0.131, t = 1.66, p = 0.101, R^2 = 0.036) nor body mass (β = 0.239, t = 0.87, p = 0.387, R^2 = 0.010) explained a meaningful proportion of variance in T_b, suggesting that thermal inertia does not play a detectable role in shaping field body temperatures in this population.

Correlational patterns

A correlation matrix (Suppl. material 2: fig. S2) confirmed strong positive associations between T_b and T_s (r = 0.703) and between T_b and solar radiation (r = 0.669). T_a showed a moderate correlation (r = 0.502), while wind speed showed a weak correlation (r = 0.113).

Principal component analysis

Principal component analysis (PCA) was used as a descriptive, exploratory tool to summarize the covariance structure of the thermal environment and to visualize how the four significant environmental variables and T_b jointly arrange themselves along orthogonal axes; it is not used here as an inferential test of the effect of environmental variables on T_b. For that, regression and correlation analyses were used.

Two principal components jointly accounted for ≈76% of the total variance. PC1 (55.1% of the variance) represents a combined thermal–radiative gradient, with high loadings from T_b, T_s, solar radiation, and T_a; PC2 (20.9% of the variance) was dominated by wind speed and is essentially orthogonal to PC1 (Table 2, Suppl. material 2: table S4, figs S2, S3).

Table 2. Contribution distribution of thermal variables to PCA axes (PC1–PC2) (%).

Variable	Contribution to PC1 (%)	Contribution to PC2 (%)
Tb	27.95	2.01
Ts	27.82	0.45
Ta	18.90	4.87
Wind	0.02	91.96
Solar	25.31	0.71
Total	100.00	100.00

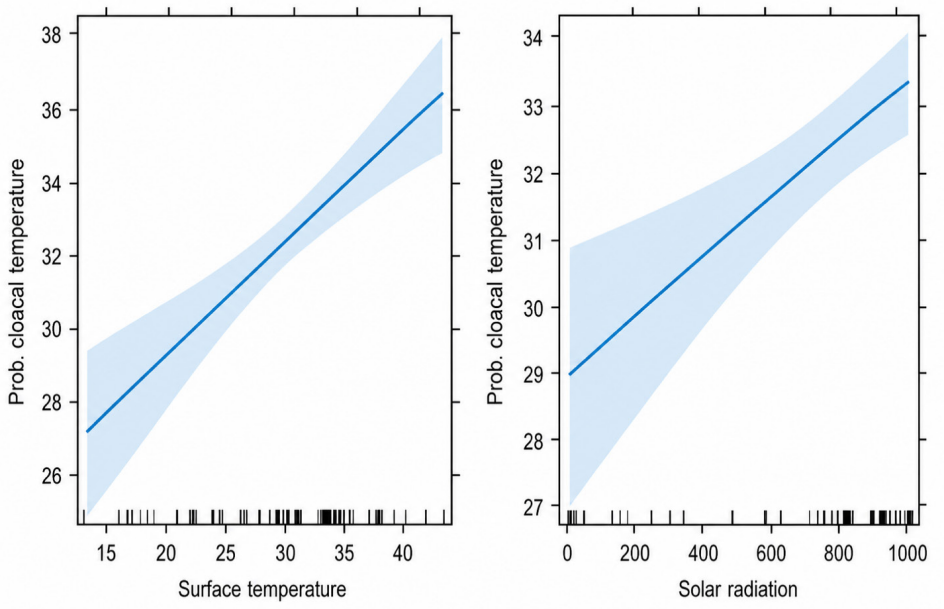

Figure 2. Effect plots for the significant predictors of body temperature (T_b). Both surface temperature (T_s) and solar radiation show consistent positive relationships with T_b, illustrating their independent contributions to body temperature after controlling for all other predictors in the model.

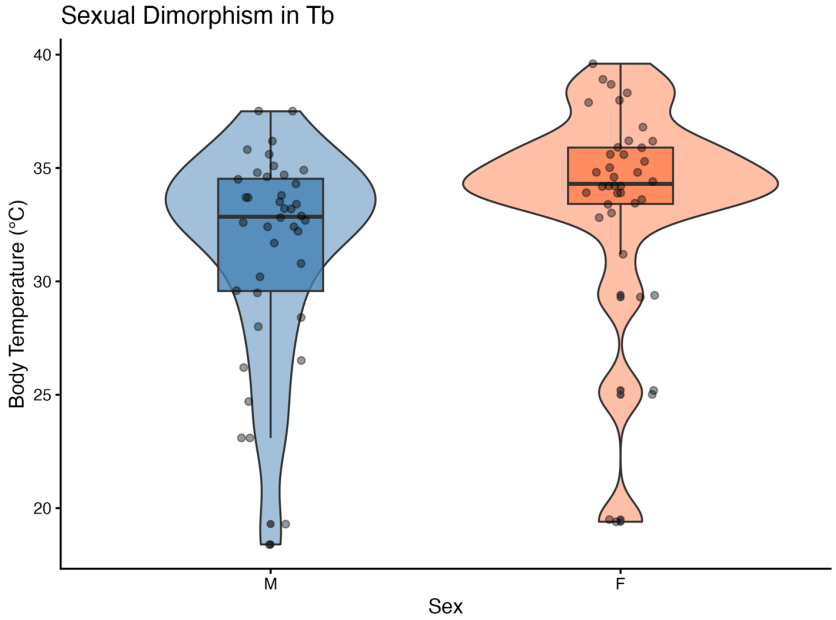

Figure 3. Violin and box plots comparing field body temperature (T_b) between male and female adult *Anatololacerta anatolica* (n = 40 males, 38 females). Females maintained significantly higher T_b than males (Welch's t = –2.05, p = 0.044; Cohen's d = –0.47).

Discussion

The results show that, in the Mount Spil population of *Anatololacerta anatolica*, $_{Tb}$ is significantly associated with microhabitat-scale thermal variables, with T_s and solar radiation emerging as the strongest predictors. Mean T_b (32.32 ± 4.53 °C) was significantly higher than both mean T_s (30.6 ± 6.97 °C) and mean T_a (28.1 ± 4.04 °C), indicating that the population is an active thermoregulator rather than a passive thermoconformer. The right-skewed distribution of T_b–T_s differences (Fig. 1) is consistent with active microhabitat selection rather than complete thermal equilibrium with the environment, in line with Hertz et al. (1993). Similar patterns—mean T_b statistically higher than T_s and T_a—have been reported in *Lacerta trilineata* and *Lacerta viridis* (Vacheva et al. 2025), *Phymaturus* spp. (Alés et al. 2017; Vicenzi et al. 2017), *Leiocephalus schreibersi* (Marcellini and Jenssen 1989), and *Liolaemus* spp. (Valdez Ovallez et al. 2023), where such differences have been attributed to basking and substrate-based heat gain.

The mean field T_b recorded in the present study (32.32 ± 4.53 °C) (Suppl. material 2: table S1) falls slightly below the preferred body temperature (Tpref ≈ 34.5 °C) reported for this species under laboratory conditions (Oğuz

2020). This discrepancy is not unexpected, as field T_b integrates periods of inactivity, movement, and thermal transition that a laboratory-derived set-point temperature does not capture (Hertz et al. 1993). Similar offsets between field T_b and laboratory T_{pref} have been documented in other lacertid species (Aguado and Braña 2014; Zamora-Camacho et al. 2016), and their magnitude is commonly used as a proxy for the costs and precision of thermoregulation. To our knowledge, comparable field body temperature data for other *Anatololacerta* species are not yet available in the published literature, which limits direct intergeneric comparisons within the genus. These results are therefore situated in the broader context of sympatric western Anatolian lacertids (Şahin and Kuyucu 2021), which show broadly similar patterns of microhabitat-driven thermoregulation.

Although the Pearson correlation between T_b and T_s was slightly stronger than that between T_b and solar radiation, *A. anatolica* behaves primarily as a heliothermic—rather than a purely thigmothermic—species for several complementary reasons. First, mean T_b was significantly higher than mean T_s, so individuals are not simply equilibrating with the substrate, as would be expected of a strict thigmotherm; the T_b–T_s correlation rather reflects the fact that solar-heated substrates and basking individuals share the same radiative forcing. Second, in the multiple regression, both T_s and solar radiation remained significant, independent positive predictors of T_b (Table 1), showing that solar radiation contributes to T_b over and above T_s. Third, sun-exposed substrates are themselves heated largely by incoming solar radiation, so T_s carries a strong radiative signal; the fact that T_s, T_a and solar radiation load together on PC1 (Suppl. material 2: table S4) is consistent with this interpretation. The species is therefore best described as combining heliothermy with a component of thigmothermy, with solar radiation acting as the ultimate heat source (Gans 1982; Şahin and Kuyucu 2021).

Regression analyses further indicate that *A. anatolica* tracks microhabitat thermal heterogeneity rather than relying on macroclimatic averages. This is consistent with growing evidence that macroclimatic data are often inadequate proxies of the temperatures actually experienced by ectotherms (Bakken and Angilletta Jr 2014; Lembrechts and Lenoir 2020; Nordberg and Schwarzkopf 2019; Sears and Angilletta Jr 2015; Sears et al. 2016). Microhabitat heterogeneity provided by rock outcrops and vegetation on Mount Spil likely buffers individuals against extremes in T_a, in line with the Bogert effect—behavioral thermoregulation that partly decouples T_b from macroclimate and may mask genuine physiological vulnerability (Logan et al. 2019). Several studies have shown that lizards in high-altitude or thermally variable environments can maintain T_b well above T_a by exploiting solar radiation (Brewster and Beaupre 2019; Ortega and Martin-Vallejo 2019; Sunday et al. 2014).

The positive, independent effects of T_s and solar radiation on T_b indicate that individuals exploit local thermal opportunities efficiently. Nevertheless, the relatively small mean T_b–T_s difference (1.76 °C; $d = 0.27$) suggests that, although the difference is statistically significant, its biological magnitude is modest and the species interacts closely with the thermal properties of its immediate substrate, consistent with the moderate thermoregulatory strategies reported by Bonavita et al. (2025).

The PCA results show that T_b, T_s, solar radiation, and T_a load together on PC1, whereas wind speed loads almost exclusively on an orthogonal PC2. This pattern is consistent with previous work emphasizing the dominant, integrated role of radiative and substrate thermal variables in shaping ectotherm thermal ecology (Crawford et al. 1983; Paranjpe et al. 2014) and also with field studies in which wind is reported to influence operative temperature models but is frequently a secondary determinant of T_b (Almeida-Santos et al. 2015; Bakken 1992; Dzialowski 2005; Şahin and Kuyucu 2021). The loading of wind on an axis independent of the radiative–thermal gradient, together with its nonsignificant effect in the multiple regression, suggests that *A. anatolica* buffers convective cooling through microhabitat selection—use of rock crevices and the base of vegetation—while managing its thermal balance primarily via solar radiation and substrate temperature. Future studies incorporating Hertz et al.'s (1993) thermoregulatory effectiveness index (*E*), which requires both laboratory-derived preferred temperature ranges and field-deployed operative temperature models, would allow a formal quantification of thermoregulatory precision in this population.

Females maintained significantly higher field T_b than males, despite the absence of detectable differences in body size. Consistent with this, neither SVL nor body mass predicted field T_b in adult individuals, making a thermal inertia explanation unlikely. Sex-specific differences in field T_b are not uncommon among lacertid lizards and are frequently linked to the elevated thermoregulatory demands of vitellogenesis and gestation, during which females may actively seek warmer microhabitats to accelerate embryonic development (Kechnebbou et al. 2025; Vacheva et al. 2025). The moderate effect size suggests that, while the difference is statistically detectable, individual variation in thermoregulatory behavior remains considerable in both sexes. Full quantification of thermoregulatory effectiveness on Mount Spil will require complementary laboratory and operative-temperature data, which are identified as a priority for future work.

Conclusion

The Mount Spil population of *Anatololacerta anatolica* behaves as an active thermoregulator, maintaining T_b (32.32 ± 4.53 °C) significantly above both T_s and T_a. Multiple regression identified T_s and solar radiation as the only independent, significant positive predictors of T_b, while wind speed was statistically decoupled from the radiative–thermal system. The species combines heliothermy with a component of thigmothermy and buffers convective cooling through microhabitat selection, consistent with the Bogert effect. Females maintained significantly higher field T_b than males, independent of body size, suggesting sex-specific differences in thermoregu-

latory behavior or microhabitat use that warrant further investigation. These results highlight the importance of microhabitat-scale thermal heterogeneity and thermal refugia for the persistence of *A. anatolica* and emphasize that climate-change assessments based solely on macroclimatic air temperature are likely to underestimate its vulnerability. Estimation of preferred and operative temperatures in future studies will allow a formal quantification of thermoregulatory effectiveness and refine projections under climate change.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Artificial Intelligence (AI) use

Regarding the use of AI in the preparation of this manuscript, the authors declare the following:
During the preparation of this work, the author(s) utilized Gemini for writing and language editing purposes. Subsequent to using this tool/service, the author(s) reviewed and edited the content as necessary and assume full responsibility for the content of the publication.

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Author contributions

Conceptualization: MA, MKŞ. Data curation: ÇÇ, MA. Formal analysis: ÇÇ, MKŞ. Investigation: MA, ÇÇ. Methodology: MA, ÇÇ. Project administration: MA. Resources: ÇÇ. Software: MKŞ, ÇÇ. Supervision: MA, MKŞ. Validation: ÇÇ, MA. Visualization: MKŞ, ÇÇ. Writing - original draft: ÇÇ. Writing - review and editing: MKŞ, MA.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

Supplementary material 1

Revised field measurements

Authors: Çetin Çelik, Mehmet Kürşat Şahin
Data type: csv
Explanation note: Field measurements including microhabitat surface temperature (Ts), air temperature (Ta), wind speed, solar radiation, dorsal laser temperature (Tb_d), and probe cloacal temperature (Tb_p), as well as SVL, body mass, and sex data.
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Link: https://doi.org/10.3897/herpetozoa.39.e188838.suppl1

Supplementary material 2

Additional tables and figures

Authors: Çetin Çelik, Mehmet Kürşat Şahin
Data type: docx
Explanation note: **table S1.** Descriptive statistics for body temperature (T_b) and environmental variables for *Anatololacerta anatolica*. **table S2.** Multiple linear regression diagnostics: variance inflation factor (VIF) values. **table S3.** Simplified multiple linear regression results for body temperature (T_b). **table S4.** PCA eigenvalues and explained variance. **fig. S1.** Effect of wind speed (m/s) on body temperature (T_b) (°C). **fig. S2.** Principal component analysis (PCA) biplot of environmental variables and T_b. **fig. S3.** Correlation matrix: T_b and environmental variables.
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