

Evidence of climate warming in Iberian caves

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Article

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Abstract

Caves are generally regarded as thermally stable and climatically buffered environments, yet their temperatures can respond to long-term surface changes. We tested whether subterranean warming reflects the accelerated climate change affecting Western Europe, using high-resolution temperature records from two caves in the Western Iberian Peninsula: Vale Telheiro and Algar do Pena. Cave records were compared with surface climatic variables, and temporal trends evaluated using Mann-Kendall tests and Sen's slope estimators. Both caves evidenced significant warming, but with different relationships with surface climatic variables. Vale Telheiro warmed approximately $0.111^{\circ}\text{C year}^{-1}$, while the surface trend was weaker and not statistically significant; temperatures followed inverse seasonal cycles, with a lag of approximately five months. Algar do Pena warmed approximately $0.053^{\circ}\text{C year}^{-1}$, while surface temperature increased more rapidly. This cave showed stronger seasonal coupling and a shorter delay (approximately two months). These patterns demonstrate that cave warming does not simply reproduce the magnitude or timing of surface warming. Instead, cave-specific thermal buffering, ventilation, hydrology and heat-transfer processes seem to determine how regional climate change is expressed underground. Our findings extend evidence of cave warming to southwestern European karsts, highlighting the importance of long-term monitoring for anticipating impacts on thermally sensitive subterranean ecosystems.

Introduction

Caves are frequently regarded as climatically isolated environments. Across the globe, caves reflect the average annual surface temperature, while additional factors such as precipitation and wind also exert influence, resulting in distinct cave thermal patterns [1]. Therefore, caves function as natural laboratories for studying climate change and its ecological impacts [2].

Subterranean ecosystems cover at least 19% of Earth's land surface, holding nearly 99% of Earth's liquid freshwater resources and provide critical life-support services [3]. Among them, caves provide essential ecosystem services such as groundwater storage, refuge to several species, tourism and educational services [4, 5]. Caves support numerous short-range, endemic and highly specialized species that remain unprotected [6], but are responsible for water purification and ensure the ecological balance of caves [7]. Cave adapted species are known to have low thermal plasticity and a narrow thermal range [7, 8]. However, the effects of climate change of subterranean ecosystems remain largely unknown. Particularly, data of long-term climate monitoring is required for understanding temperature variability in caves, and only now those are becoming technologically available [9, 10].

Evidence of climate change has already been observed in four caves in the European Alps, where a warming trend of 0.2°C per decade was recently documented [10], in Austria, although over a shorter time-period, with an estimated increase of 0.5 and 0.3°C per decade [11] and in the Postojna Cave System in Slovenia, in the Črna Jama where air temperature data from 2014 to 2017 shows higher temperature than recorded in historical data [12].

The Iberian Peninsula and particularly the Mediterranean South are considered a climate change hotspot, as it warms significantly faster than the global average [13, 14], being a critical area for studying the impact of cave climate warming. We study multi-year temperature records from two Portuguese caves, measured *in situ* every two hours, to analyze warming trends, and compare these trends with surface temperature variation and to test whether cave thermal regimes track the accelerated surface warming reported for the region.

Methods

Study sites

Algar do Pena Cave (39.465303, -8.806878) is the largest subterranean chamber in Portugal, located in the Estremenho Karst Massif, the largest karst massif of Portugal. It has a single entrance at an elevation of approximately 345 m, reaches a depth of 98 m and has an estimated total area of over 1,400 m² [15]. The site is associated with Middle Jurassic limestone formations [15]. Climatically, this cave lies within a transitional Atlantic-Mediterranean climatic zone, with cooler temperatures and higher annual precipitation than the Algarve.

Vale Telheiro Cave (37.170140, -8.034781) is a limestone single-entrance cave in the Barrocal Karst Massif, in the Algarve, the southernmost area of Portugal. It is a subterranean biodiversity hotspot, harboring more than 25 cave-adapted species, including the giant pseudoscorpion *Titanobochica magna* (Pennisi, 2016; Reboleira, 2025), reaches a depth of 20 m and extends more than 241 m horizontally. This cave develops from an entrance chamber into a network of branching, irregular passages and chambers [18]. Its uneven surfaces and interconnected spaces create a maze-like layout, the reason for another name given to the cave: Labyrinth Cave. It has recently been classified as one of the geosites of the UNESCO Algarvensis Geopark (Reboleira et al., 2026). The region has a Mediterranean climate characterized by warm, dry summers and mild, wet winters.

Temperature monitoring

Temperature was measured using a HOBO TidbiT v2 datalogger (accuracy of $\pm 0.21^{\circ}\text{C}$ and a resolution of 0.02°C) installed on the sediment deep into the cave in: 1) Algar do Pena Cave, every two hours from March 2018 to May 2026; and 2) Vale Telheiro Cave, every two hours from October 2019 to April 2026, and hourly from 30 December 2009 to 30 June 2011.

A separate hourly temperature record from Vale Telheiro, covering 30 December 2009 to 30 June 2011 was included to extend the temporal comparison. The historical and contemporary Vale Telheiro records were treated as separate monitoring periods, and no values were interpolated across the July 2011 to October 2019 monitoring gap.

Data processing

Temperature records were processed in R using the `readxl`, `dplyr`, `tidyr`, `ggplot2`, and `Kendall` packages. Cave timestamps were converted to calendar dates and daily measurements were aggregated to daily mean temperatures using all available observations for each day. For Algar do Pena, a continuous daily calendar was created between the first and last monitoring dates. Days without observations were retained as missing values, and no interpolation was performed. Missing monitoring periods were represented as gaps and highlighted in the graphical comparisons. For Vale Telheiro, the historical and contemporary periods were assigned separate identifiers so that lines were not drawn across the long monitoring gap, treated as separate monitoring periods, and no values were interpolated across the July 2011 to October 2019 monitoring gap. Daily cave-temperature series were plotted using `ggplot2`. Cave and surface temperatures were presented both as overlaid time series and in vertically separated panels to facilitate comparison while accommodating their different ranges of variability.

Comparison with surface climatic variables

Surface conditions were characterized using ERA5 reanalysis data [19]. ERA5 hourly single-level temperature data were obtained from the Copernicus Climate Data Store for each cave's coordinates and for the same time-period as the cave's temperature record. Candidate variables were skin temperature, 2 m air temperature, soil temperature at levels 1–4 (0–7, 7–28, 28–100 and 100–289 cm), total precipitation and surface pressure. ERA5 values were extracted at the cave coordinates from the NetCDF grid. Temperatures were converted from Kelvin to degrees Celsius, converted to local time, and hourly ERA5 values were aggregated to daily means to match the temporal resolution of the processed cave-temperature data. The daily cave temperature and ERA5 temperature datasets were joined by date. Monthly means were calculated from all available paired daily observations. For the long-term Vale Telheiro analysis, the 2009–2011 and 2019–2026 cave and surface skin temperature records were combined while retaining the intervening years as missing months. Trend significance was evaluated using the Mann–Kendall test applied to monthly mean temperatures. The magnitude of each trend was estimated using a seasonal Sen's slope. Pairwise slopes were calculated between years within each calendar month, pooled across calendar months, and summarized by their median. Because year differences were used in the calculation, slopes were expressed directly in $^{\circ}\text{C year}^{-1}$. Tests were two-sided and statistical significance was assessed at $\alpha = 0.05$. To characterize the annual relationship between surface and cave temperatures, daily values were aggregated to monthly means. ERA5 skin temperature was used as the primary surface-temperature variable because it most closely represented the surface-soil measurements. Analyses of the annual thermal pattern were restricted to complete calendar years. Monthly means were first calculated within each year and subsequently averaged by calendar month across years to obtain a 12-month climatological cycle for each cave and surface series. The similarity and direction of the cave and surface annual cycles were evaluated using the Pearson correlation between contemporaneous monthly means, without shifting either series. The calendar months containing the minimum and maximum cave and surface temperatures were also identified.

Results

Positive temperature trends were observed for both caves located in different karst massifs, indicating a warming rate ranging between + 0.053 to 0.111°C per year over the monitoring period, positively correlated with surface temperature (ERA5 surface skin temperature) (Fig. 2, Table 1).

Algar do Pena Cave, in Estremenho Karst Massif, showed a significant positive trend ($\tau = 0.86$, $p < 0.05$), despite short-term fluctuations and periods of missing or uncertain data. Sen's slope indicated a warming rate of + 0.053°C per year. Over the same period, ERA5 surface skin temperature also showed a positive trend, with a Sen's slope of + 0.198°C per year, and this trend was statistically significant ($\tau = 0.243$, $p = 0.004$). The climatological monthly cave-temperature series was positively correlated with ERA5 surface skin temperature ($r = 0.614$). Surface skin temperature reached its maximum in August and minimum in January, whereas cave temperature reached its maximum in October and minimum in February. The monthly cross-correlation was strongest when surface temperature preceded cave temperature by two months ($r = 0.967$).

Vale Telheiro Cave showed a significant positive trend in monthly temperature anomalies after accounting for serial autocorrelation using the Mann–Kendall test ($\tau = 0.955$, $p < 0.05$) (Table 1, Fig. 3). Sen's slope indicated a warming rate of + 0.111°C per year. Over the same period, ERA5 surface skin temperature also exhibited a positive Sen's slope (+ 0.037°C per year), but this trend was not statistically significant ($\tau = 0.054$, $p = 0.572$). Vale Telheiro Cave temperature exhibited a delayed relationship with ERA5 surface temperature. Across the six complete monitoring years (2020–2025), the monthly cave and surface temperature cycles at Vale Telheiro were consistently inversely related, i.e., temperature in the cave is higher when temperature at the surface is lower. The climatological monthly cave-temperature series was strongly negatively correlated with ERA5 surface skin temperature ($r = -0.799$), while correlations calculated separately for individual years were all negative and ranged from – 0.645 to –0.924. Surface skin temperature reached its maximum in July and minimum in January, whereas cave temperature reached its minimum in June and maximum in December.

Comparison with observations from 2009–2011 showed that temperatures in Vale Telheiro Cave followed a pattern like that observed in more recent years (Fig. 3, Table 2). When looking only at 2009–2011, no significant temperature trend was detected in either the cave or ERA5 skin-temperature data. Cave temperature showed no estimated change, while surface temperature had a non-significant estimated decline of 0.011°C per year.

Table 1

Temperature trends in Vale Telheiro and Algar do Pena caves and their corresponding surface environments. Results are based on seasonal Mann–Kendall tests and seasonal Sen’s slope estimates calculated from monthly mean cave and ERA5 skin temperatures. Positive values of Mann–Kendall’s (tau) and Sen’s slope indicate increasing temperatures. $p < 0.05$ was considered statistically significant.

Cave	Location	p-value	Sen’s slope (°C per year)	Mann–Kendall tau
Vale Telheiro	Cave	< 0.05	+ 0.111	0.955
Vale Telheiro	Surface skin ERA5	0.572	+ 0.037	0.054
Algar do Pena	Cave	< 0.05	+ 0.053	0.861
Algar do Pena	Surface skin ERA5	0.00444	+ 0.198	0.243

Table 2

Seasonal temperature trends in the historical data from Vale Telheiro Cave and its corresponding surface environment. Results are based on seasonal Mann–Kendall tests and seasonal Sen’s slope estimates calculated from monthly mean cave and ERA5 skin temperatures. Positive values of Mann–Kendall’s (tau) and Sen’s slope indicate increasing temperatures. $p < 0.05$ was considered statistically significant.

Location	p-value	Sen’s slope (°C per year)	Mann-Kendall tau
Cave	1	0	0
Surface	0.705	-0.011	-0.143

For each cave, ERA5 soil temperature, 2m temperature, total precipitation and surface pressure were also tested for confounding effects but no significant effect was found (Tables S1 and S2).

Discussion

Evidence of recent warming was detected in two caves in central and southern Portugal over approximately six to eight years of monitoring, with estimated cave-temperature trends of 0.053–0.111°C yr⁻¹. These findings extend evidence of cave warming beyond Alpine environments [10] to Atlantic and Mediterranean karsts. The contrasting warming rates and surface-coupling patterns observed between the two caves indicate that they do not passively transmit the regional climate signal, but instead filter it according to site-specific properties such as thermal buffering, ventilation regime and heat-transfer pathways.

The two caves showed contrasting warming patterns. Vale Telheiro warmed faster than the surface trend (no significant difference from surface skin temperature), whereas in Algar do Pena the surface warmed significantly faster than the cave. These differences highlight that caves’ thermal buffering does not imply lack of vulnerability to surface climate change. While Algar do Pena attenuated the external temperature signal, Vale Telheiro showed a stronger cave warming trend, than evidenced by local

surface temperature alone, exceeding the non-significant ERA5 trend. This suggests that Vale Telheiro's temperature reflects a longer-term buildup of climatic forcing, not just what the surface skin temperature happens to be at any given moment [20]. In other words, a cave can keep a narrow seasonal temperature swing while its long-term average still steadily shifts. How fast that shift happens, and when it becomes detectable, depends on how heat moves into each specific cave through the rock, through water, or through air exchange [10, 21].

Long-term temperature monitoring data in Vale Telheiro Cave in the Portuguese Algarve show accelerating cave warming in recent years ($+0.111^{\circ}\text{C year}^{-1}$). Previously, this cave was characterized by remarkable thermal stability and an annual temperature amplitude of only 0.4°C , with a strong lag relative to surface temperatures [1]. Our long-term cave temperature monitoring also showed an approximately five-month lag relative to surface temperatures, with an inverse seasonal pattern in which cave temperature peaks coincided with surface temperature minima [1]. Despite the higher warming rate compared with Algar do Pena, none of the ERA5 variables tested were significant over the study period. Therefore, continued monitoring is needed to determine whether the recent warming rate is sustained or reflects short-term climatic variability.

The difference between the cave and ERA5 trend should not be interpreted as evidence that Vale Telheiro is thermally disconnected from the surface. ERA5 skin temperature represents a gridded surface proxy, whereas the logger records temperature at soil level inside the cave, after heat has been transferred through rock, air circulation and infiltrating water. These pathways integrate surface forcing over different spatial and temporal scales and can damp, delay or seasonally invert the signal reaching the cave, that may also reflect the high variability of surface skin temperature over a relatively short monitoring period relative to the 30-year record conventionally used to characterize climate [22]. Accordingly, the contrasting slopes are best interpreted as evidence of a site-specific thermal response rather than the absence of surface control [1, 10].

Vale Telheiro is relatively shallow but highly thermally buffered, while Algar do Pena is deeper yet follows the surface seasonal cycle more closely. Algar do Pena Cave showed a shorter thermal lag than Vale Telheiro, with cave temperature responding to ERA5 surface temperature after approximately two months, likely reflecting differences on heat transfer at each cave, due to other specific variables. The two-month lag at Algar do Pena is compatible with more rapid coupling to external conditions than the five-month lag at Vale Telheiro.

Evidence of climate change in caves is now documented at least in six caves in Europe, in two different climates [10]. The observed cave temperature trends are consistent with regional warming, but other cave specific factors like cave ventilation, hydrology, logger position, entrance effects, and local disturbance may also influence multi-year cave temperature records. Our results are consistent with previous works that also documented evidence of climate change in caves [10, 11]. Expressed per decade, the recent cave trends correspond to approximately $+0.53^{\circ}\text{C}$ at Algar do Pena and $+1.11^{\circ}\text{C}$ at Vale Telheiro, compared with about $+0.2^{\circ}\text{C}$ per decade reported for four Alpine caves [10]. Nevertheless,

direct comparison requires caution because the records differ in duration, continuity, cave setting, and methodology. Also, other factors play a role on cave climatic variability, such as cave geometry, surface connection, seasonal ventilation, thermal storage in the surrounding rock and fitting soil, and percolating water can all affect both the amplitude and timing of the cave's thermal response [1, 10, 21, 23]. Additionally there is a possibility that these caves are affected by the cold-air trap cave concept as in the both of them the entrance sits above a passage that slopes downward into the mountain, forming a bag- or sack-shaped chamber while in the chimney effect we have two entrances or more entrances at different elevations [24–26]. During winter, when outside air is colder than the cave, that dense cold air sinks in and settles at the bottom, displacing the lighter "warm" cave air, which rises out the entrance. But in summer the outside air becomes warmer than the trapped air inside, the cold air stays trapped in the cave due to density differences, creating a stable stratification where the cold layer is unable to rise and escape past the warm air blocking the entrance. There is no return convection loop, so the cave becomes insulated, slowly warming through conduction rather than air exchange [25, 26]. The high recent rates reported here should therefore be treated as signals that deserve continued observation rather than fixed rates for future projection.

The recent warming rate observed in our study, may have ecological impacts in thermally stable cave environments [1], especially dealing with world-class hotspots for subterranean biodiversity, as Vale Telheiro Cave. Subterranean-adapted fauna is known to have narrow eco-physiological constraints, and to express low thermal plasticity, variable among life stages, being juveniles more vulnerable to warming than adults [3, 8]. Moreover, warming in such type of caves, may have unprecedented impacts, due the confined nature of those complex subterranean ecological network and interactions, characteristic of biodiversity hotspots, likely to trigger an ecological cascading effect with catastrophic effects [27].

Long-term monitoring is essential for assessing subterranean responses to regional warming. A monitoring design combining replicated cave loggers with an entrance weather station, hydrological and ventilation data would help disentangle the processes driving for the observed differences among caves. Standardized quality-control procedures and details calibration records would further enhance the reliability and comparability of measurements across sites and over time [2, 9].

Declarations

Funding

This research was developed under the Prize Belmiro de Azevedo-FCT (ref. 2023.10009.PRIZE), and the Chair in Sustainability of Subterranean Ecosystems – Loulé, created by protocol between the Faculty of Sciences of the University of Lisbon, Câmara Municipal de Loulé and Bondstone. It was supported by Portuguese National Funds through “Fundação para a Ciência e a Tecnologia” within CE3C Unit funding (doi.org/10.54499/UID/00329/2025), CHANGE (doi.org/10.54499/LA/P/0121/2020), and FCT PhD grant (2026.03983.BD). It is also framed within the College on Polar and Extreme Environments (Polar2E) of the University of Lisbon.

Author Contribution

M.J.M. Conceptualization, Formal analysis, Visualization, Data curation, Investigation, Writing – original draft. A.S.P.S.R. Conceptualization, Methodology, Fieldwork, Formal analysis, Data curation, Resources, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition, Project administration, Supervision.

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Data Availability

The raw cave-temperature measurements from Vale Telheiro and Algar do Pena are available in Zenodo at <https://doi.org/10.5281/zenodo.22827122>. The ERA5 reanalysis data analysed in this study are available from the Copernicus Climate Data Store at <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=download>.

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<https://doi.org/10.5281/ZENODO.22827122>

Figures

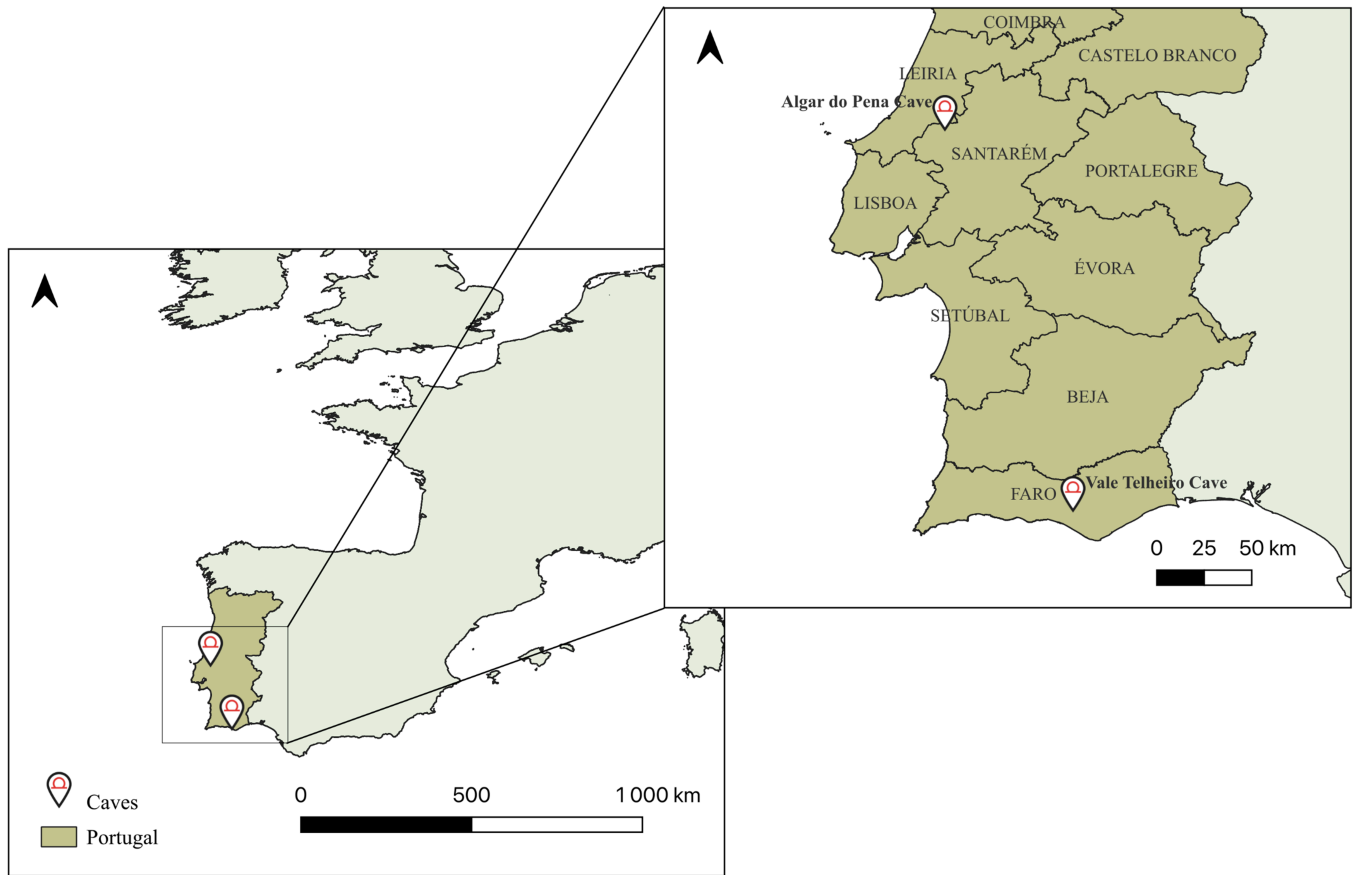


Figure 1

Location of the monitored caves in Portugal. Map rendered in QGIS 4.0.1.

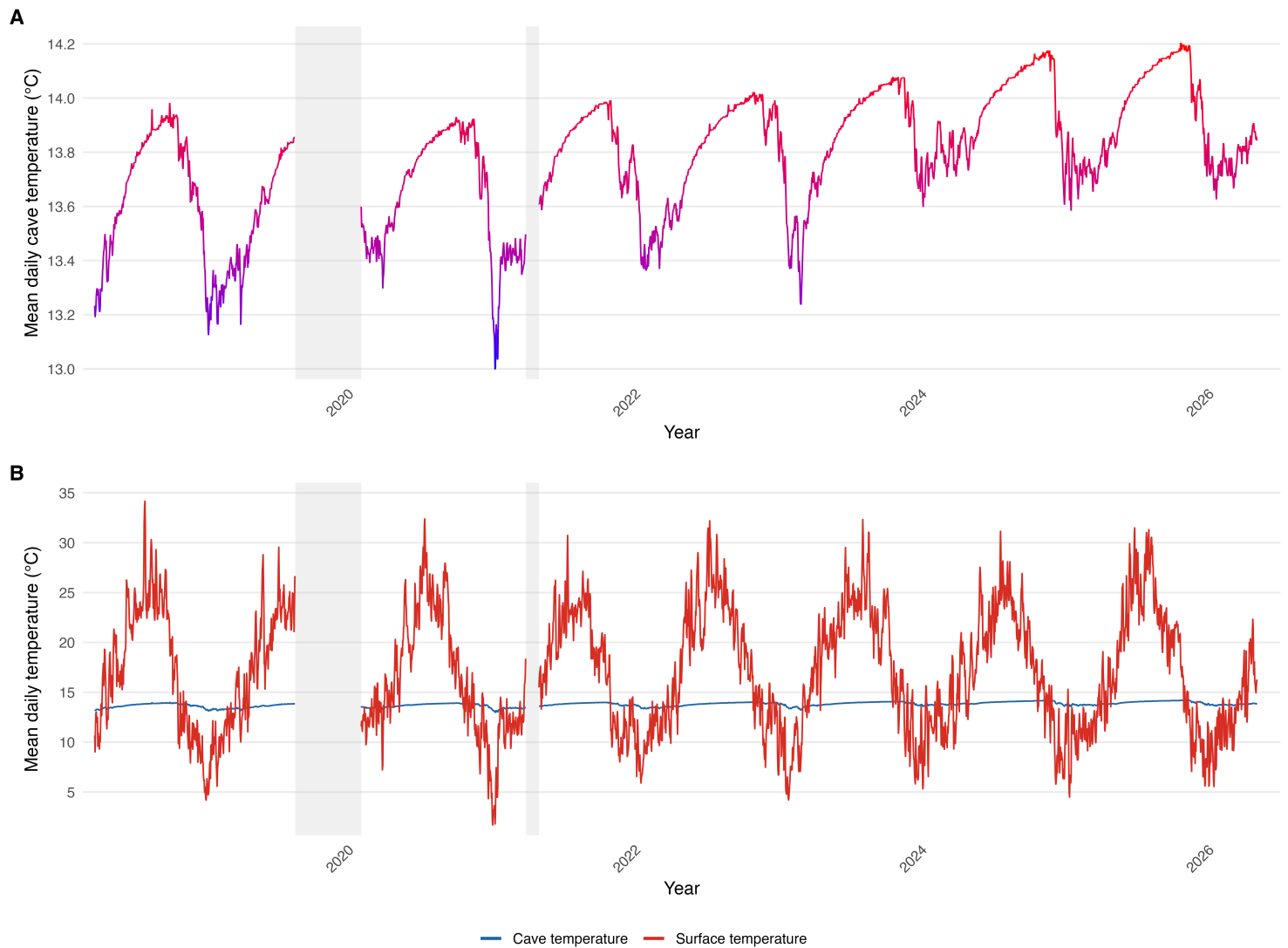


Figure 2

Daily cave and surface temperatures at Algar do Pena Cave. (A) Complete cave-temperature record (2018–2026). (B) Complete paired cave and surface temperature record (2018–2026). Blue and red lines represent mean daily cave temperature and ERA5 skin temperature, respectively. Grey shading represents dates where we have no cave temperature data.

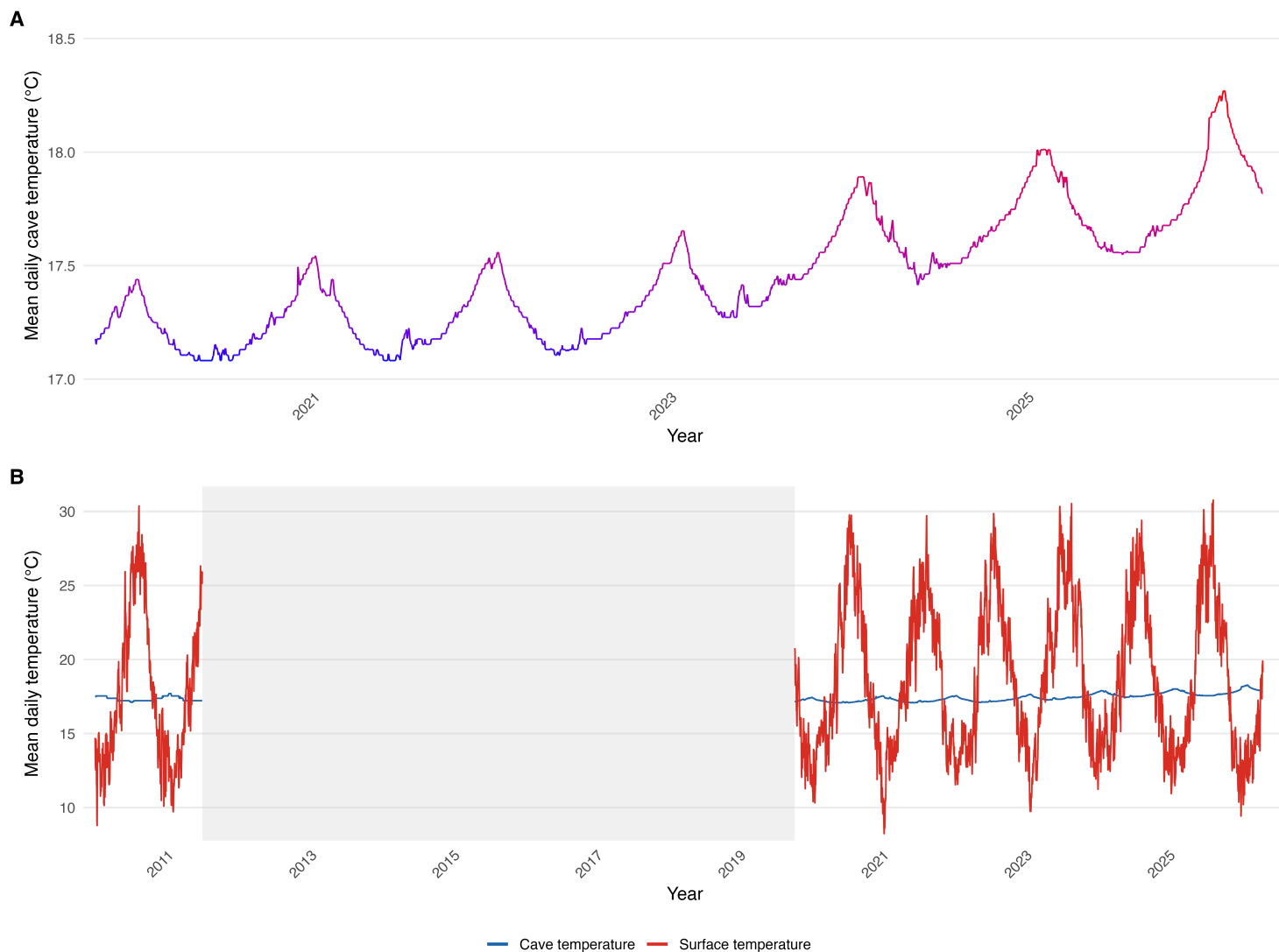


Figure 3

Daily cave and surface temperatures at Vale Telheiro Cave. (A) Cave-temperature record (2019–2026). (B) Complete paired cave and surface temperature record (2009–2026). Blue and red lines represent mean daily cave temperature and ERA5 skin temperature, respectively. Grey shading represents dates where we have no cave temperature data.