



TESTING THE APPLICABILITY OF A NON-CONTACT IR THERMOMETER FOR WALL SURFACE TEMPERATURE MEASUREMENTS IN A CAVE ENVIRONMENT: A CASE STUDY FROM THE DYNAMIC CÍSAŘSKÁ CAVE (MORAVIAN KARST)

PREIZKUŠANJE PRIMERNOSTI BREZKONTAKTNEGA INFRARDEČEGA TERMOMETRA ZA MERJENJE TEMPERATURE POVRŠINE STEN V JAMSKEM OKOLJU: ŠTUDIJA PRIMERA IZ DINAMIČNE JAME CÍSAŘSKÁ (MORAVSKI KRAS)

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Abstract

Marek Lang, Jiří Faimon, Markéta Gregorová, Jindřich Štelcl & Filip Chalupka: Testing the applicability of a non-contact IR thermometer for wall surface temperature measurements in a cave environment: A case study from the dynamic Císařská Cave (Moravian Karst)

The surface temperature of cave walls is important, particularly as a factor controlling water condensation and calcite corrosion, as well as in paleoclimatic reconstructions of external annual temperatures. The use of a non-contact IR thermometer (NCT) could provide an alternative method for monitoring wall surface temperature in inaccessible passages of the cave. However, temperatures obtained by the standard NCT showed increased error. The accuracy of the NCT was tested by comparison with a calibrated contact thermometer (CCT), which revealed a systematic error of -8.2 ± 1.2 °C for the right wall and -8.3 ± 0.9 °C for the left wall. Calibration with the equations $T = 0.478 \times \text{NCT} + 8.254$ (right wall) and $T = 0.554 \times \text{NCT} + 8.308$ (left wall) corrected this error. Uncertainty was tested by repeated measurements on a calibration area of 1.7 m² in the cave, resulting in a random relative error of 4.25 % for dry wall surfaces and 4.95 % for wet wall surfaces. Although a relative error of 5 % is common for major instrumental methods, it is near the applicability limit for karstological interpretations.

Keywords: cave airflow, Císařská Cave, non-contact IR thermometer, temperature calibration, wall surface temperature.

Izvleček

Marek Lang, Jiří Faimon, Markéta Gregorová, Jindřich Štelcl & Filip Chalupka: Preizkušanje primernosti brezkontaktnega infrardečega termometra za merjenje temperature površine sten v jamskem okolju: študija primera iz dinamične jame Císařská (Moravski kras)

Temperatura površine jamskih sten je pomembna, zlasti kot dejavnik, ki vpliva na kondenzacijo vode in korozijo kalcita ter pri paleoklimatskih rekonstrukcijah zunanjih letnih temperatur. Uporaba brezkontaktnega infrardečega termometra bi lahko bila alternativna metoda za spremljanje temperature površine sten v nedostopnih jamskih prehodih. Toda temperature, izmerjene s standardnim brezkontaktnim infrardečim termometrom, so pokazale večjo napako. Natančnost brezkontaktnega infrardečega termometra je bila preverjena s primerjavo s kalibriranim kontaktnim termometrom, ki je pokazal sistematično napako $-8,2 \pm 1,2$ °C na desni steni in $-8,3 \pm 0,9$ °C na levi steni. Kalibracija z enačbama $T = 0,478 \times \text{NCT} + 8,254$ (desna stena) in $T = 0,554 \times \text{NCT} + 8,308$ (leva stena) je to napako odpravila. Negotovost je bila preverjena s ponovnimi meritvami na območju kalibriranja, velikem 1,7 m² v jami, pri čemer je bila ugotovljena naključna relativna napaka v vrednosti 4,25 % za suhe stenske površine in 4,95 % za vlažne stenske površine. Čeprav je 5-odstotna relativna napaka običajna za glavne instrumentalne metode, se ta vrednost približuje meji uporabnosti za krasoslovne interpretacije.

Ključne besede: tok zraka v jami, Císařská jama brezkontaktni infrardeči termometer, kalibracija temperature, temperatura površine stene.

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1. INTRODUCTION

The temperature of the wall surface, T_{WS} , is an important microclimatic parameter of the cave carbonate systems playing a role in several processes. First, it controls the process of water condensation on the cave walls (Sarbu and Lascu, 1997; Dublyansky and Dublyansky, 1998; de Freitas and Schmekel, 2006). The condensed water vapor from the cave air forms water droplets or a film that is (1) in equilibrium with the actual P_{CO_2} in the cave air, but (2) undersaturated with respect to the carbonates that form the cave walls. This water is responsible for the destruction of the cave, using the dissolution process called condensation corrosion (Dreybrodt et al., 2005; Ford and Williams, 2007). The driving force of water condensation is principally given by the temperature difference ΔT_C between the dew point, T_{DP} , and T_{WS} . At the positive ΔT_C value, the water condenses on the walls of the cave, while the negative value leads to the evaporation of current water in the cave atmosphere. The T_{DP} value is especially a function of relative humidity, but could also be significantly influenced by anthropogenic water vapor in show caves (Lang et al., 2024). The monitoring of T_{WS} values is also important in the validation of methods for determining paleotemperatures from autochthonous cave deposits during paleoclimatic reconstructions (Fairchild et al., 2006). Although this utilization is based on an assumption that calcite growth is especially influenced by cave air temperature, T_{air}^{cave} (Tremaine et al., 2011; Kluge et al., 2014; Daëron et al., 2019), growing speleothems are in contact with the cave walls and/or ceiling and the T_{WS} should be with T_{air}^{cave} in equilibrium.

The instantaneous T_{WS} distribution is generally controlled by cave airflows, driven by the temperature difference ΔT_{AF} between the exterior, T_{air}^{ext} , and interior, T_{air}^{cave} (Pflitsch and Piasecki, 2003; Russell and MacLean, 2008; Kowalczyk and Froelich, 2010; Faimon et al., 2012). Based on the sign of ΔT_{AF} , three ventilation modes can be distinguished in dynamic cave: (i) an upward airflow (UAF) ventilation mode, (ii) a downward airflow (DAF) ventilation mode, and (iii) a transitional ventilation mode (Faimon et al., 2012). In principle, the extent of T_{WS} variances throughout the cave is not uniform and differs both vertically in individual cave corridors and spatially throughout the cave. The vertical temperature gradients are given by (i) different dynamics of cave airflows at lower/higher levels of cave passages, (ii) thermal conduction through the rocks, and (iii) the corridor morphology influencing emissivity of wall surface via cave airflows. The spatial temperature distribution throughout the cave is distinct in the passages closer to cave entrances, corresponding to the heterothermic zones, and in the deeper cave passages, representing the homothermic zones (Lu-

etscher and Jeannin, 2004). Whereas in the heterothermic zone, the diurnal and seasonal temperature cycles are well expressed, the homothermic zone refers to the temperature attenuation approaching an asymptotic value (the seasonal temperature amplitude does not exceed a few tenths of °C) (Obleitner et al., 2024). In principle, the convection length from the exterior depends on mean annual rate of cave airflows and mean radius of cave corridors (Sedaghatkish et al., 2024). On the other hand, the temperature stability of the homothermic zone can be disturbed, e.g., by opening/closing new entrances, which could contribute to changes of ventilation paths throughout the cave (Lang et al., 2017).

For the temperature monitoring of cave walls, contact methods allowing measurement of (i) T_{WS} on the wall surface or (ii) T_{RM} inside the wall/rock massif, are commonly used. While the T_{WS} is measured by various types of contact thermometers, the T_{RM} measurement requires a thermometer with narrow sensor (e.g., thermocouple) placed in a hole inside the wall. Based on several studies, the depth of the sensor location should vary between 1×10^{-2} m (Martin et al., 2006) and 8×10^{-1} m (Luetscher et al., 2008). However, the necessity of direct contact with monitored object does not allow to use these methods for monitoring of inaccessible cave passages (e.g., ceilings or abysses). In this context, the non-contact methods, including especially an IR camera and an IR thermometer, could represent an alternative way. Although the application of the IR thermometers in cave microclimatic studies are during the last decades increasingly frequent (Cuezva et al., 2011; Curtis and Kyle, 2011; Štředová et al., 2014), e.g., for testing of vertical ventilation through the karst ventarole under DAF ventilation mode, the IR cameras are rather used to locate hidden sinkholes or breathing spots (Rinker, 1975; Wynne et al., 2008). On the other hand, monitoring by IR thermometer is also limited by some factors that could distort the resulting values. These factors are associated with (i) thermometer setting (the emissivity of calcite forming the cave walls varies between 0.90 and 0.95) and (ii) character of the cave walls (water droplets may reflect radiation produced by IR thermometer).

In this work, we focused the measurement of T_{WS} by a non-contact IR thermometer (NCT) in Císařská Cave, a dynamic cave in the Moravian Karst (Czech Republic). Overall, the study aims to explore the possibilities of using non-contact methods in studying the microclimate of caves based on an example of one selected NCT. The primary goal of this work was to test the applicability of conventional NCT for measuring temperature in inaccessible parts of the cave. Based on calibrated contact ther-

monometer (CCT) data, the secondary goal was to describe the seasonal development of T_{WS} in the Císařská Cave and

to compare these data with external data and the number of visitors.

2. SITE OF STUDY

The site of study, Císařská Cave (49° 23' 12.5" N, 16° 46' 8.2" E), is situated in the northern part of the Moravian Karst (MK) near the village of Ostrov u Macochy (Faimon et al., 2012; Faimon & Lang, 2013). The position and sketch map of the cave are given in Figure 1a.

It consists of a network of narrow corridors with a total length of about 250 m connecting relatively small

chambers formed in the Devonian Lmst. of the Macocha Fmt. A part of the cave is flooded by almost stagnant karst water, and therefore the cave environment is modified by concrete sidewalks and steel bridges over the cave pools. The total volume of the cave is estimated to ~ 11,500 m³. The thickness of the overburden ranges between 15 and 35 m. Due to two entrances at altitudes of

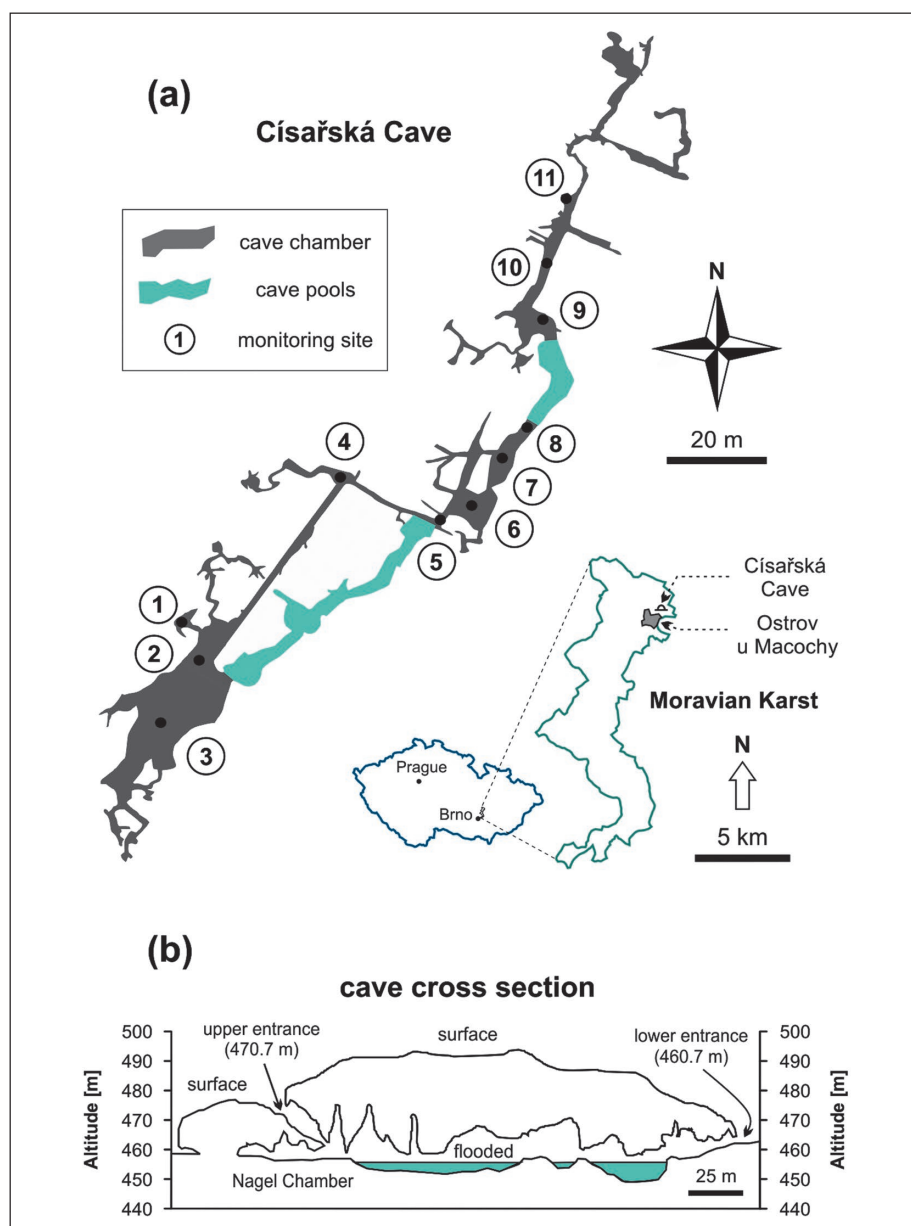


Figure 1: Císařská Cave: the sketch map with its position (a) and the vertical profile (b) based on Absolón (1970). The numbers denoting the monitoring sites are consistent with Table 1.

Table 1: Summary of the monitoring sites in the Císařská Cave (Moravian Karst).

Site number	Site description	Cave sector	Acronym	Height/width [m]	Monitoring
#1	Upper Entrance	UES	UE	4.3/2.7	individual & long-term
#2	Gallery	UES	G	3.1/2.2	individual
#3	Nagel Chamber	UES	NC	2.5/2.4	individual
#4	Adit - End	MCS	A-E	4.7/2.7	individual
#5	Lehárna Chamber - Bottom	MCS	LC-B	5.6/3.4	individual
#6	Lehárna Chamber	MCS	LC	9.3/1.3	individual & long-term
#7	Lehárna Chamber - Top	MCS	LC-T	5.9/4.9	individual
#8	Pools I	MCS	P I	7.8/3.8	individual
#9	Pools II	LES	P II	4.5/13.6	individual
#10	Entrance Corridor	LES	EC	9.9/5.2	individual
#11	Lower Entrance	LES	LE	4.2/1.7	individual & long-term

UES = Upper Entrance sector; MCS = middle cave sector; LES = Lower Entrance sector

460.7 m (Lower Entrance) and 470.7 m (Upper Entrance) (Figure 1b), the cave air circulation is typically dynamic. Both entrances are equipped with steel doors, in which there are windows of 20×20 cm in size (total area of 0.04 m^2). Since September 1997, the Císařská Cave is used for speleotherapy practiced by a Children Sanatorium with speleotherapy situated in the nearby town of Ostrov u Macochy (Children Sanatorium with Speleotherapy, 2025). About 50 children stay in the cave each weekday for ~ 3.5 hours (Figure 3c) from which the first half is focused on physical activities in the Nagel Chamber (NC) with the total volume of $\sim 2950 \text{ m}^3$ (Faimon et al., 2006)

and during the second half, children rest in the Lehárna Chamber (LC). To cover the whole area, eleven monitoring sites were homogeneously distributed through the entire cave. Based on their position, individual monitoring sites were divided into three sectors: (1) the Upper Entrance sector (UES), (2) the middle cave sector (MCS), and (3) the Lower Entrance sector (LES) (see Table 1). Two groups of monitoring sites of different character were distinguished: (i) the group of corridor-type sites covered 6 locations totally (the UE, A-E, P I, P II, EC, LE sites) and (ii) the group of chamber-type sites included 5 locations totally (the G, NC, LC-B, LC, LC-T sites). The

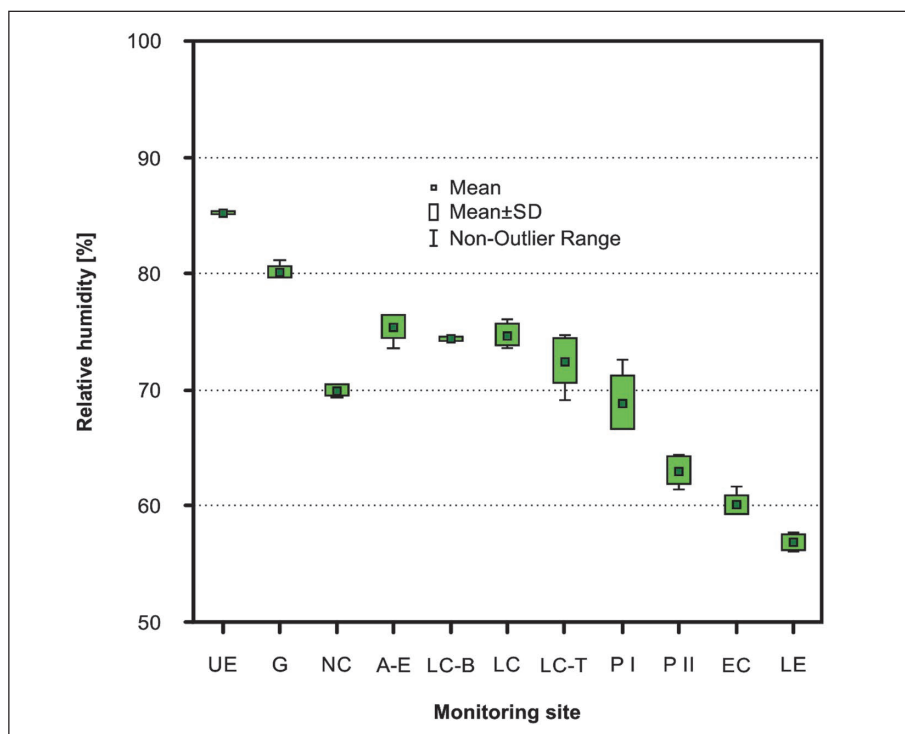


Figure 2: Distribution of cave relative humidity across the Císařská Cave under transitional ventilation mode (3 March 2026). The abbreviations of the monitoring sites are consistent with Table 1.

corridor-type sites were characterized by a relatively narrow profile with a mean width from 1.7 m (the LE site) to 5.2 m (the EC site) except the P I site, where the corridor was expanded by an area of cave pool, and a mean height reaching up to 9.9 m (the EC site). The chamber-type sites were situated in two largest chambers, the Nagel Chamber and the Lehárna Chamber.

The humidity conditions in the Císařská Cave were described based on a single measurement conducted on 3 March 2026. According to the mean values, cave relative humidity systematically decreased from 85.3 % at the

UE site to 56.9 % at the LE site (Figure 2). An exception to the prevailing trend was the A-E site, where a relatively significant increase of 5.5 % was observed. In addition to the decreasing cave humidity between individual monitoring sites, relatively significant fluctuations were also identified within individual sites. Although the widest ranges of 3.0 to 6.0 % were found in deeper cave passages (the LC-T, P I and P II sites), much lower ranges of 1.6 % or even 0.2 % were observed near the entrances (the UE and LE sites).

3. METHODS

3.1 BASIC MONITORING

Basic monitoring consisted of two phases associated with (1) the documentation of the dimensions and humidity conditions of individual monitoring sites and (2) the monitoring of primary temperature data. Based on the complex morphology of the selected sites, their dimensions were determined by height and width measured in their centre. It was measured by CEM LDM-100 laser distance meter (measuring range from 5×10^{-2} to 100 m with an accuracy of $\pm 1.5 \times 10^{-3}$ m). Relative humidity was recorded by the Termiplus data logger (measuring range 0 to 100 % with an accuracy ± 4 %) at each site at 10-second intervals for 1 minute and the resulting values were expressed as mean values. The primary data were collected during (i) a long-term monitoring campaign with data logging from April 2022 to February 2023 and (ii) regular single measurements in the period from 6 May 2022 to 5 January 2023. Long-term monitoring was focused on the $T_{\text{air}}^{\text{cave}}$, $T_{\text{air}}^{\text{ext}}$ and the number of visitors. The $T_{\text{air}}^{\text{cave}}$ was recorded by Termio-2 data loggers, the thermocouples with an accuracy of ± 0.07 °C in the range from -10 to 100 °C. The $T_{\text{air}}^{\text{ext}}$ was obtained from the meteorological station Macocha (49° 37' 24" N; 16° 72' 97" E) (Cave Administration of the Czech Republic, 2025) situated about 3.3 km southwest of the Císařská Cave. Single measurements, conducted in seven campaigns, were connected with the monitoring of the T_{ws} . During individual campaigns, surface temperature of both the right wall, $T_{\text{ws}}^{\text{right}}$, and the left wall, $T_{\text{ws}}^{\text{left}}$, was measured at all monitoring sites. The data were detected at 1 m above the cave floor using the BOSCH PTD1 IR thermometer (measuring range from -20 to 200 °C with an accuracy of ± 3.0 °C in the range from -20 to 10 °C, ± 1.0 °C in the range from 10 to 30 °C, ± 3.0 °C in the range from 30 to 90 °C, and ± 5.0 °C in the range from 90 to 200 °C). It is important to note that the measurement distance from

the cave wall of 1 m was used as the value specified and recommended by manufacturer and the thermometer emissivity was set to 0.95.

3.2 REFERENCE MONITORING

Reference monitoring was represented by (1) two reference campaigns focused on wall surface temperatures and (2) two verification campaigns focused on the impacts of selected factors on the measured wall surface temperature. The first reference campaign corresponded to the single measurement of basic monitoring expanded by the contact thermometer FTA104PH (measuring range from -50 to 500 °C with an accuracy of ± 1.5 °C) linked to the ALMEMO 2290-4 V5 Ahlborn data logger (Germany), which served as the reference thermometer. The differences between wall surface temperatures measured by CCT and NCT revealed a systematic error, however the comparison of these data led to the creation of calibration curves for correction of basic data. Moreover, data of $T_{\text{ws}}^{\text{right}}$ and $T_{\text{ws}}^{\text{left}}$ obtained during this campaign were statistically processed in Statistica 12 (Statsoft, 2025) for their transformation into stationary data. The individual datasets were recalculated to equidistant data and standardized via differencing using the equation $x = x - x_{(\text{lag})}$ with lag set to 1. Second reference campaign was performed to determine the random error of temperatures measured by NCT. It included two series of wall surface temperature measurements on cave wall of 1.3×1.3 m in size (total area of 1.7 m²) with dry and wet surface. Both these areas were divided into three columns and nine rows, which provided 27 measuring points totally. The verification campaigns tested the impact of (i) the vertical position (ceiling/floor surface temperature) and (ii) the horizontal position (distance from the cave wall) of the NCT during the measurement. Ceiling/floor surface temperatures

were measured at all monitoring sites simultaneously with the T_{WS} measurements and the measured values were subsequently averaged. The campaign focused on the impact of the monitoring distance was conducted on 11 February 2026 at the NC, A-E, and LC sites. Note that the sites were chosen for their position in deeper cave passages and relatively large volume and the number of measured values at each site corresponded to accessible area near the monitored wall.

3.3 PROCESSING OF DISTRIBUTION MAPS

The spatial distribution of T_{WS} was visualized using GIS software ArcMap (Esri, Redlands, CA, USA). The visu-

alization process consisted of three steps including (i) georeferencing of the individual monitoring sites based on the cave map (Figure 1a), (ii) transformation of the individual measurements into the spatial layers, and (iii) data interpolation performed using the Inverse Distance Weighting (IDW) method. The IDW parameters were set with a fixed search radius and a defined number of nearest neighbors (typically 8) to ensure a reliable estimation of intermediate values while avoiding over-smoothing. The interpolated rasters were classified into temperature intervals using a consistent color gradient to allow visual comparison between different campaigns.

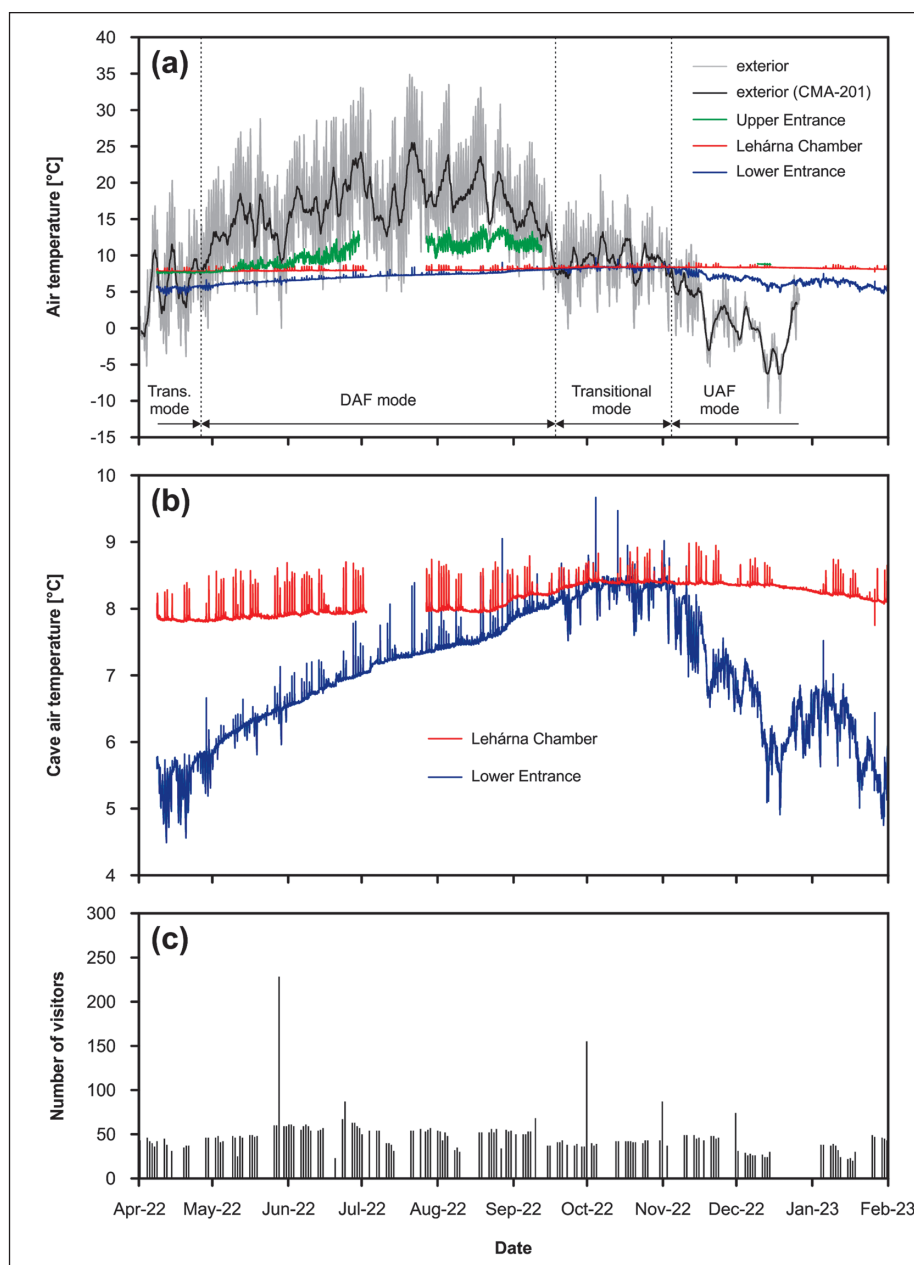


Figure 3: Evolution of the cave air temperature at different monitoring sites in the Císařská Cave in dependence on the external air temperature (a) and the anthropogenic impact on the Lehárna Chamber and the Lower Entrance (b) during different visitor regimes (c)

4. RESULTS

4.1 EXTERNAL/CAVE AIR TEMPERATURES

The evolution of $T_{\text{air}}^{\text{ext.}}$ and $T_{\text{air}}^{\text{cave}}$ during the long-term monitoring (April 2022 to February 2023) is given in Figure 3. Throughout the monitored period, $T_{\text{air}}^{\text{ext.}}$ values varied in a wide range from -11.7 to 34.9 °C and showed strong annual oscillations with maxima in July and minima in February (Figure 3a). $T_{\text{air}}^{\text{cave}}$ fluctuated between 4.5 and 14.2 °C and different characters of time series from individual monitoring sites were identified. Although

temperatures monitored near both entrances showed relatively wider ranges of values of 5.2 °C (LE site) and even 6.7 °C (UE site), a much narrower range of 1.2 °C was observed in the Lehárna Chamber (LC site) in deeper cave passages (Table 1). The temperature difference between the exterior and the LC site allowed to distinguish three ventilation modes throughout the monitored period: (1) downward airflow (DAF) ventilation mode at higher $T_{\text{air}}^{\text{ext.}}$ (May to September), (2) upward airflow (UAF) ventila-

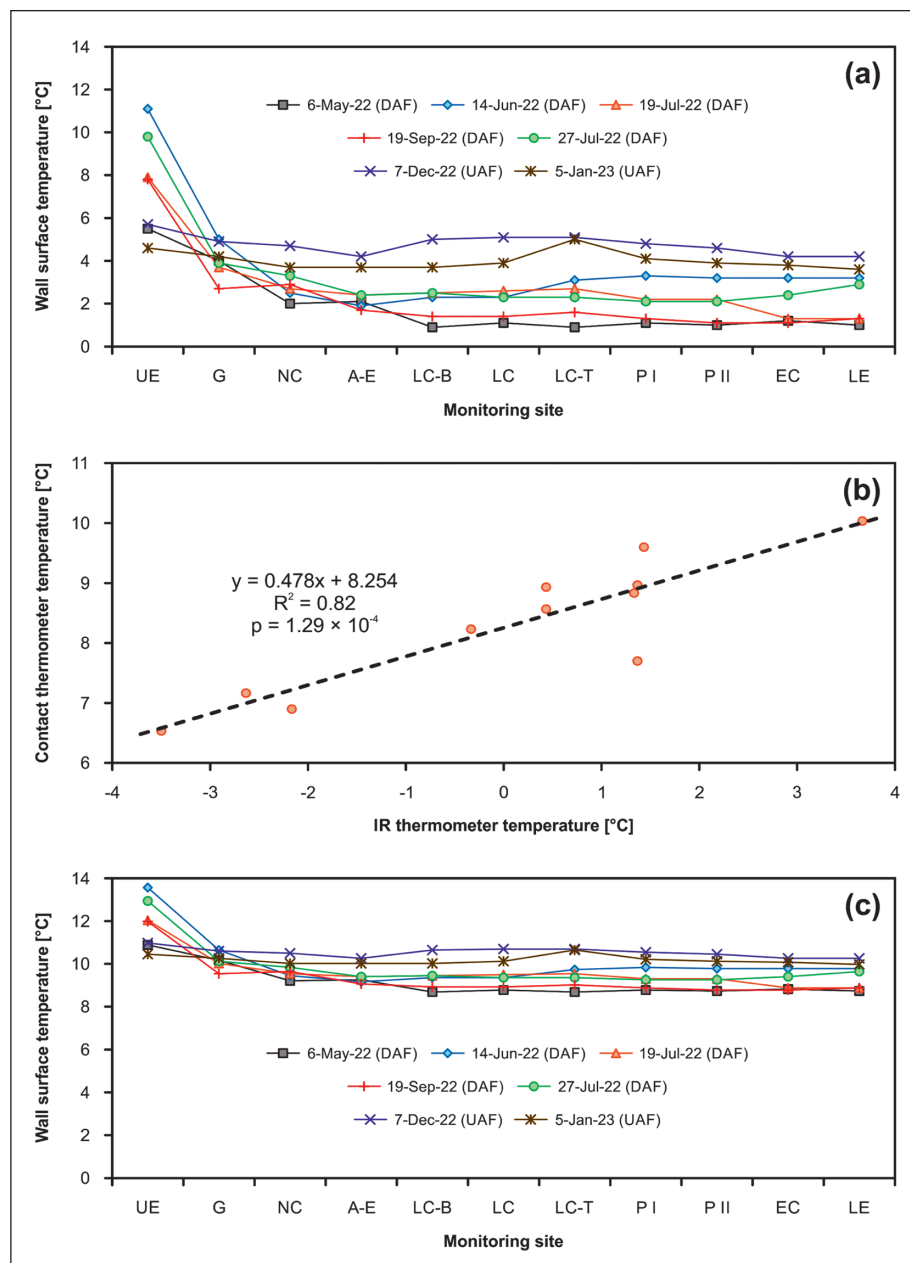


Figure 4: Surface temperatures of the right walls: the raw data measured by non-contact IR thermometer during basic monitoring (6 May 2022 to 5 January 2023) (a), relation between temperatures measured by calibrated contact thermometer and non-contact IR thermometer during reference monitoring (5 April 2023) (b), and the corrected data from the basic monitoring (c). The position of walls corresponds to the direction from the Upper Entrance towards the Lower Entrance. The abbreviations of the monitoring sites are consistent with Table 1.

tion mode at lower $T_{\text{air}}^{\text{ext}}$ (November to March) and (3) transitional ventilation mode at balanced temperatures (April and October). Two visiting regimes connected with walking through the LE and LC sites occurred during the monitored period: (i) the regular speleotherapeutic stays of the children groups (up to 68 persons) and (ii) the stays associated with cultural events (up to 228 persons) (Figure 3c). The anthropogenic influence is clearly visible on the “natural” $T_{\text{air}}^{\text{cave}}$ levels at both the LE and LC sites as some disturbances and peaks reaching up to 1.5 °C (Figure 3b).

4.2 WALL SURFACE TEMPERATURES

4.2.1 Basic data

During the basic monitoring, the T_{ws} values varied in a wide range between 0.8 and 11.1 °C and the detailed T_{ws} ranges of the right/left walls at all monitoring sites corresponded to 10.2 °C (right walls) and 8.1 °C (left walls), respectively (Figures 4a and 5a). The data show that all time series exhibit a similar pattern with the highest values at the UE site, followed by a gradual decrease at the G, NC, and A-E sites (Table 1) and relatively stable values at the remaining sites. On the other hand, the initial

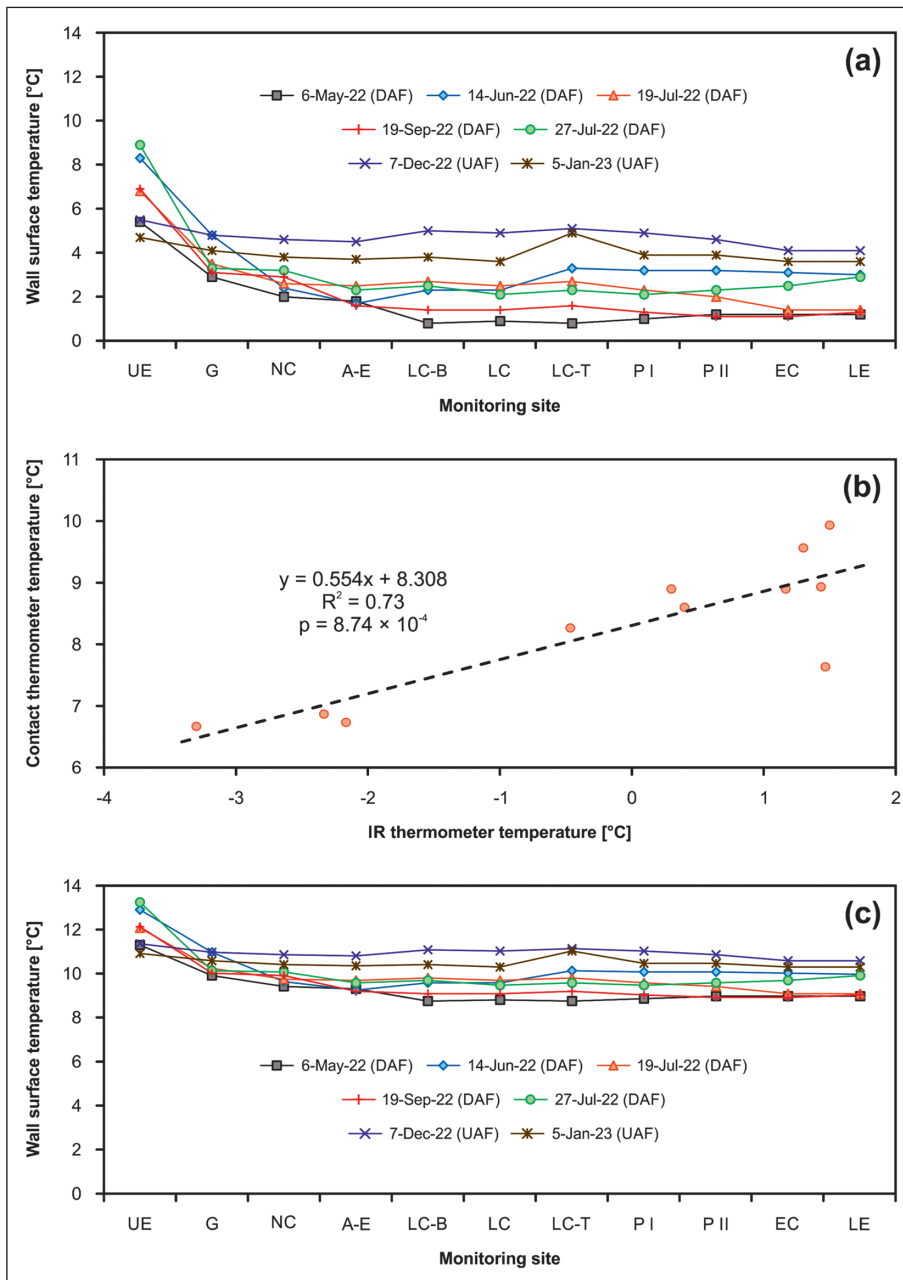


Figure 5: Surface temperatures of the left walls: the raw data measured by non-contact IR thermometer during basic monitoring (6 May 2022 to 5 January 2023) (a), relation between temperatures measured by calibrated contact thermometer and non-contact thermometer during reference monitoring (5 April 2023) (b), and the corrected data from the basic monitoring (c). The position of walls corresponds to the direction from the Upper Entrance towards the Lower Entrance. The abbreviations of the monitoring sites are consistent with Table 1.

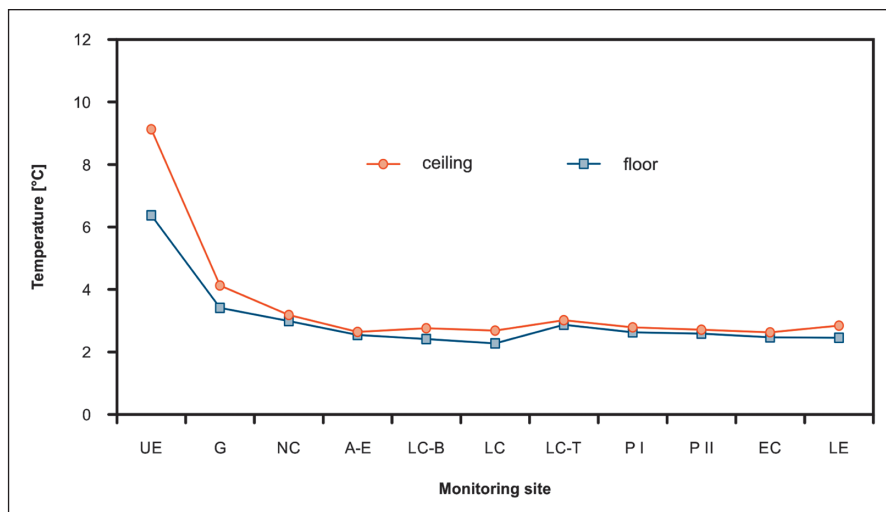


Figure 6: Mean temperatures of ceiling/floor measured by non-contact IR thermometer during basic monitoring (6 May 2022 to 5 January 2023). The abbreviations of the monitoring sites are consistent with Table 1.

decreases in the DAF time series (3.4 to 9.2 °C) are significantly greater compared to the slight decreases (0.9 to 1.5 °C) in the UAF time series. Furthermore, the same temperature sequences of individual campaigns with maxima during December and minima in May and/or September were described for both walls from all sites except the UE site. Comparison of the T_{WS}^{right} and T_{WS}^{left} at individual sites during DAF mode showed the highest temperature differences at the UE (up to 2.8 °C) and G (up to 1.1 °C), while lower differences (up to 0.3 °C) were found at the remaining cave sites. In contrast, the temperature differences between both walls in the UAF time series did not exceed 0.3 °C.

In addition to the wall surface temperatures, the temperatures of the ceiling/floor at individual monitoring sites were also measured during basic monitoring campaigns. The purpose of these data collection was to evaluate the vertical temperature distribution at the monitoring sites. Since the distribution was quantified by a temperature gradient between ceiling and floor, the temperatures measured during individual campaigns at all monitoring sites were expressed as mean values. Based on the position of the site, both time series showed different trends for UES and MCS/LES (Figure 6). While the UES sites were associated with rapid temperature decreases from 9.1 to 3.2 °C (ceiling) and 6.4 to 3.0 °C (floor), a relatively constant temperature around the mean value of 2.6 °C was observed at the MCS/LES sites for both the ceiling and floor.

4.2.2 Reference data

The reference monitoring aimed to verify the extremely low T_{WS} values observed during the basic monitoring using the CCT. The measured T_{WS} values from both sensors varied in a wide range between -3.5 and 10.0 °C and the temperatures measured by CCT were significantly higher

than those obtained by NCT at all monitoring sites (Figure 7). The T_{WS} measured by CCT fluctuated from 6.5 to 10.0 °C and the ranges for right walls (3.5 °C) corresponded to left walls (3.2 °C). However, much lower values (-3.5 to 3.7 °C) and different ranges between right walls (7.2 °C) and left walls (4.8 °C) were detected by NCT. Independently on the used sensor, all time series showed a gradually decreasing trend without significant local extremes, except the passage between LC and P I sites, where NCT recorded increases of 1.7 °C (right wall) and 1.9 °C (left wall).

4.2.3 Corrected data

To calibrate the underestimated data from the basic monitoring, the temperatures obtained by CCT and NCT during the reference monitoring were plotted against each other, and the calibration equation was derived (Figures 4b and 5b). It is important to note that the equation was determined separately for the right walls and the left walls of individual monitoring sites. After an application of individual calibration equations on the T_{WS} values from the basic monitoring, the corrected values varied from 8.7 to 13.6 °C (right walls) and 8.8 to 13.2 °C (left walls) (Figures 4c and 5c). Comparison with the original data showed significant increases by up to 7.8 °C (right walls) and 8.0 °C (left walls). Based on the use of a single calibration equation on all time series of right wall and left wall, the revised time series from individual campaigns maintained their original pattern, with a gradual decrease at the UES sites and a relatively stagnant trend at the MCS/LES sites. Compared to the original data, the initial decreases of individual time series differed depending on the actual ventilation mode. Whereas the DAF time series showed decreases between 1.6 and 4.4 °C, much lower decreases between 0.4 and 0.7 °C were identified in the UAF time series. Similarly, the

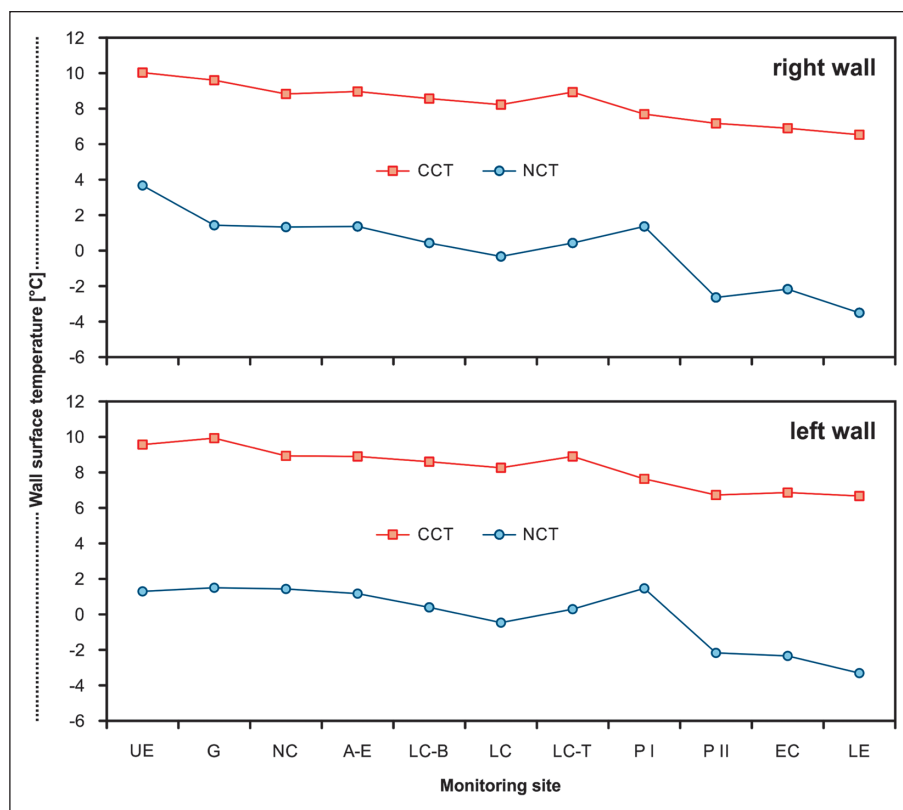


Figure 7: Surface temperatures of the right and left walls at the individual monitoring sites of the Císařská Cave measured by calibrated contact thermometer (CCT) and non-contact IR thermometer (NCT) during the reference monitoring campaign on 5 April 2023. The position of walls corresponds to the direction from the Upper Entrance towards the Lower Entrance. The abbreviations of the monitoring sites are consistent with Table 1.

T_{WS} maxima and minima of the most monitoring sites correspond to the original periods (December and May/September). The differences between T_{WS}^{right} and T_{WS}^{left} do not exceed 0.5°C independently on the actual ventilation mode, except the UE site in June, where the difference reached 0.7°C .

4.3 ERROR ANALYSIS

4.3.1 Systematic error

The reference monitoring campaign showed that the wall surface temperatures measured with NCT were distorted by a systematic error (Figure 7). It was quan-

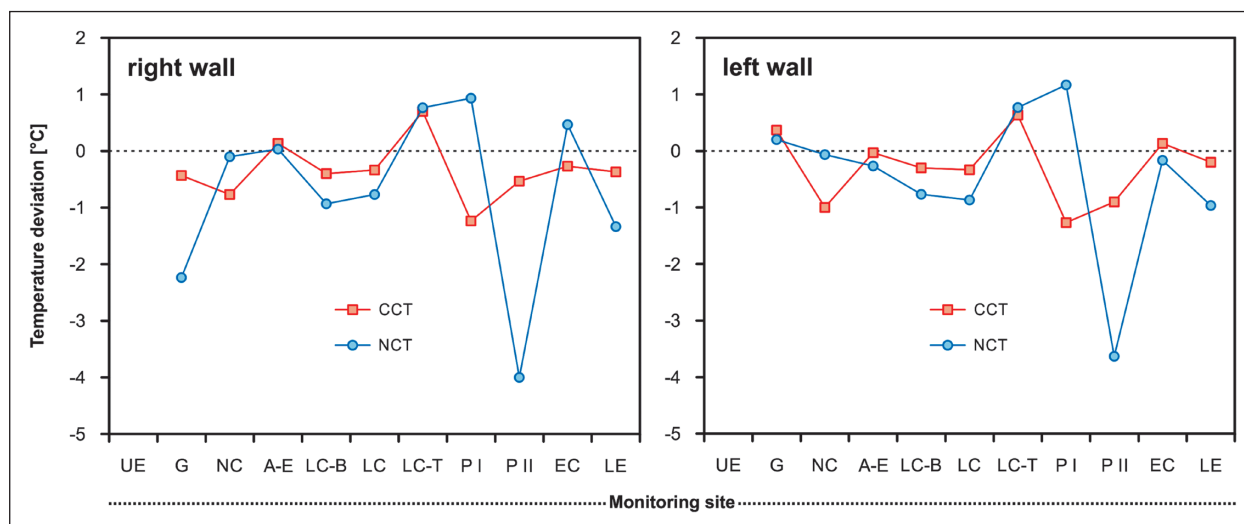


Figure 8: Standardized data of wall surface temperatures measured by calibrated contact thermometer (CCT) and non-contact IR thermometer (NCT) during reference monitoring campaign on 5 April 2023. The position of walls corresponds to the direction from the Upper Entrance towards the Lower Entrance. The abbreviations of the monitoring sites are consistent with Table 1.

Table 2: Repeated measurements of the surface temperature on the dry and wet cave wall by non-contact IR thermometer during an additional monitoring campaign on 27 October 2023.

Dry wall temperature [°C]			Wet wall temperature [°C]		
4.6	4.4	4.5	3.9	3.8	3.9
4.6	4.5	4.5	3.9	3.8	3.9
4.5	4.4	4.5	3.8	3.7	3.9
4.3	4.3	4.3	3.6	3.5	3.5
4.3	4.4	4.3	3.7	3.6	3.5
4.3	4.3	4.2	3.7	3.5	3.5
4.3	4.1	4.0	3.5	3.5	3.4
4.2	4.1	4.0	3.4	3.6	3.5
4.2	4.1	3.9	3.4	3.4	3.4

The measurement was conducted at A-E site on the reference area of 1.3×1.3 m. Individual columns/rows of the table correspond to the columns/rows of the reference wall area.

tified from the differences between the temperatures measured by NCT and CCT as a reference sensor, and corresponded to -8.2 ± 1.2 °C (right wall) and -8.3 ± 0.9 °C (left wall). For comparison of the deviations of temperatures measured by individual sensors, standardized temperature series were used. At most monitoring sites, the deviations of the temperatures measured by NCT exceeded those measured by CCT, and the maxima for the right and left wall reached up to 1.2 and 1.3 °C (CCT) and 4.0 and 3.6 °C (NCT) (Figure 8). The comparison of individual sensors showed the highest differences at the P II site (3.5 and 2.7 °C for the right and left wall) and the G site (1.8 °C for the right wall). To quantify relation between individual sensors, the deviations of the standardized temperature series for the right and left wall were tested using Spearman's correlation analysis. The resulting correlations for both walls were positive, however the values of the correlation coefficients were found to be insignificant at $\alpha = 0.05$ and varied from 0.16 (left wall) to 0.25 (right wall).

4.3.2 Random error

The calculation of a random error was based on data from additional monitoring campaign, and all the measured temperatures from both areas are given in Table 2. According to the humidity of the wall surface, significantly different values for individual areas were observed. While the temperatures of wall with dry surface varied in the range of 4.3 ± 0.18 °C, significantly lower temperatures in the range of 3.6 ± 0.18 °C were identified in case of wall with wet surface.

4.3.3 Dependence on monitoring distance

An effect of distance of NCT measurements on the resulting T_{WS} values was tested during the monitoring campaign conducted on 11 February 2026. Since the cave persisted in UAF ventilation mode, the sites situated to the UES (the NC site) and MCS (the A-E and LC sites) characterized by suppressed influence of external atmosphere were chosen for monitoring. Despite a relatively narrow range of measured T_{WS} of 1.6 °C (Figure 9),

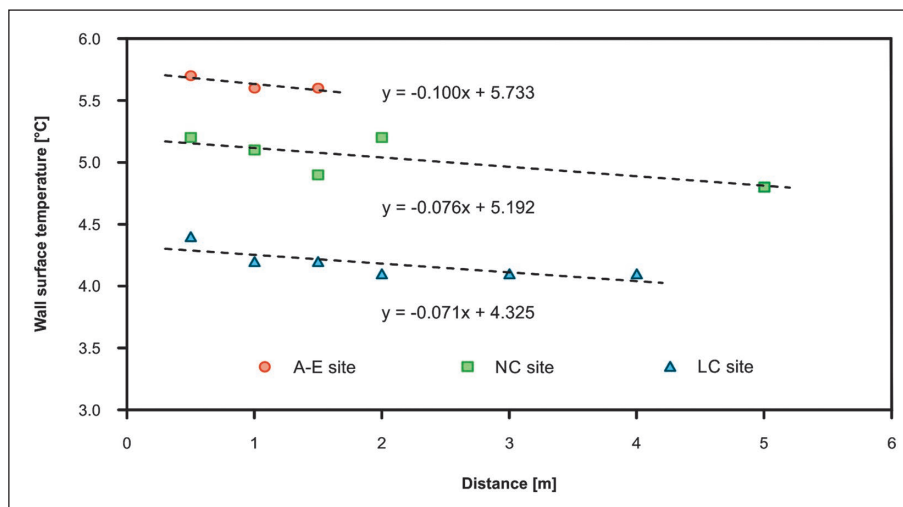


Figure 9: Dependence of wall surface temperature measured by non-contact IR thermometer on monitoring distance at monitoring sites situated in different sectors of the Císařská Cave under UAF ventilation mode during the campaign on 11 February 2026.

different temperature levels about mean values of 5.6 °C (A-E site), 5.0 °C (NC site), and 4.2 °C (LC site). On the other hand, all the monitoring sites showed the same decreasing pattern of T_{WS} with the slopes from 7.1×10^{-2} (LC site) to 0.1 (A-E site).

4.4 DISTRIBUTION OF WALL SURFACE TEMPERATURES

4.4.1 Spatial distribution

The spatial distribution of T_{WS} through the entire cave during both the DAF and the UAF ventilation mode is characterized by the box plots (Figure 10). It was determined by (1) the mean T_{WS} values and (2) total ranges of measured T_{WS} at individual monitoring sites. During the DAF mode, the mean T_{WS} values gradually decreased

through the LES sites, from the initial value of 12.1 °C at the UE site to values between 9.4 and 9.6 °C at the MCS and LES sites. Furthermore, this pattern was confirmed by an evolution of the ranges of measured T_{WS} values at individual sites: rapid decrease from 1.9 °C up to 0.2 °C at the first four sites, followed by values fluctuating between 0.7 and 1.1 °C. In contrast to an evolution during campaigns under DAF mode, the mean values of T_{WS} during campaigns under UAF mode, it varied in a much narrower range between 10.3 and 10.9 °C, with maxima at the UE and LC-T sites and minima at the EC and LE sites. The ranges of T_{WS} values varying from 0.5 to 1.1 °C roughly followed the trend of mean values with the same sites of maxima and minima except the LC-T site, where the minimum value was recorded.

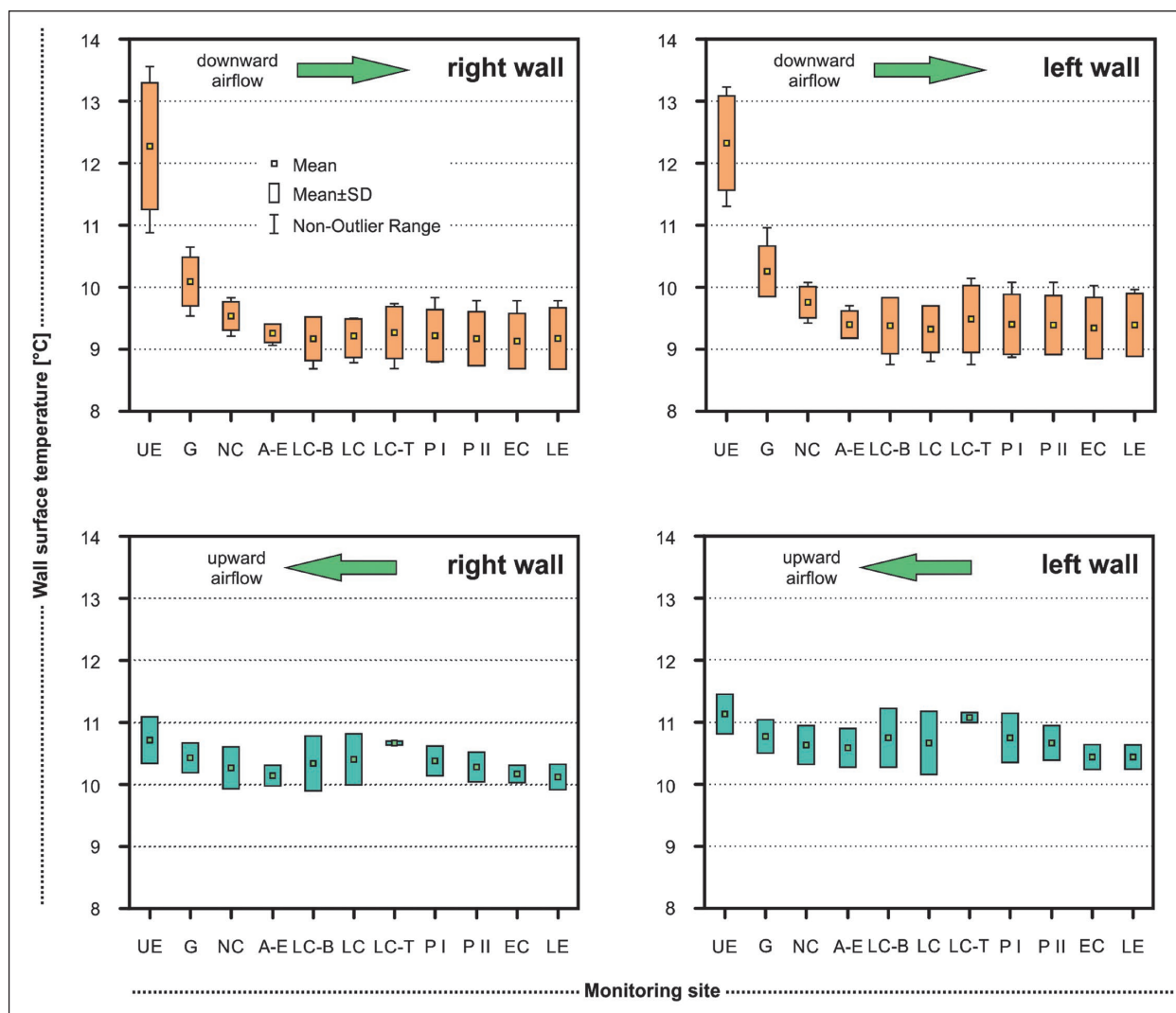


Figure 10: Distribution of the corrected right/left wall surface temperature measured by non-contact IR thermometer across the Císařská Cave during the campaigns under DAF (upper figures) and UAF (bottom figures) ventilation mode. The position of walls corresponds to the direction from the Upper Entrance towards the Lower Entrance. The abbreviations of the monitoring sites are consistent with Table 1.

4.4.2 Temporal distribution

To describe the seasonal evolution of the T_{WS} throughout the entire cave, T_{WS} data from four monitoring campaigns, 6 May 2022 (DAF1), 19 July 2022 (DAF2), 15 September 2022 (DAF3), and 7 December 2022 (UAF), were chosen. The selection criteria included (i) the coverage the entire monitored period and (ii) similar intervals between individual campaigns (~ 2.5 months). Individual campaigns were characterized by different $T_{air}^{ext.}$ varying from 0.2 °C (UAF) to 21.6 °C (DAF2) calculated as a mean external temperature of the monitoring day. For simplicity, the mean values of the T_{WS} at individual

monitoring sites were used for the map construction and the resulting temperature maps are given in Figure 11. The campaign carried out in May corresponding to the DAF ventilation mode showed a maximum of 11.1 °C at the UE site. The remaining UES sites and the MCS sites were characterized by systematic cooling of the cave walls up to 8.7 °C (the LC-B and LC-T sites) and a constant T_{WS} of 8.9 °C was maintained at the LES sites. Similarly to the previous campaign, the same pattern was found during the campaign from July. The T_{WS} values gradually decreased from the peak temperature of 12.1 °C at the UE site over the values between 9.4 and 9.7 °C at the

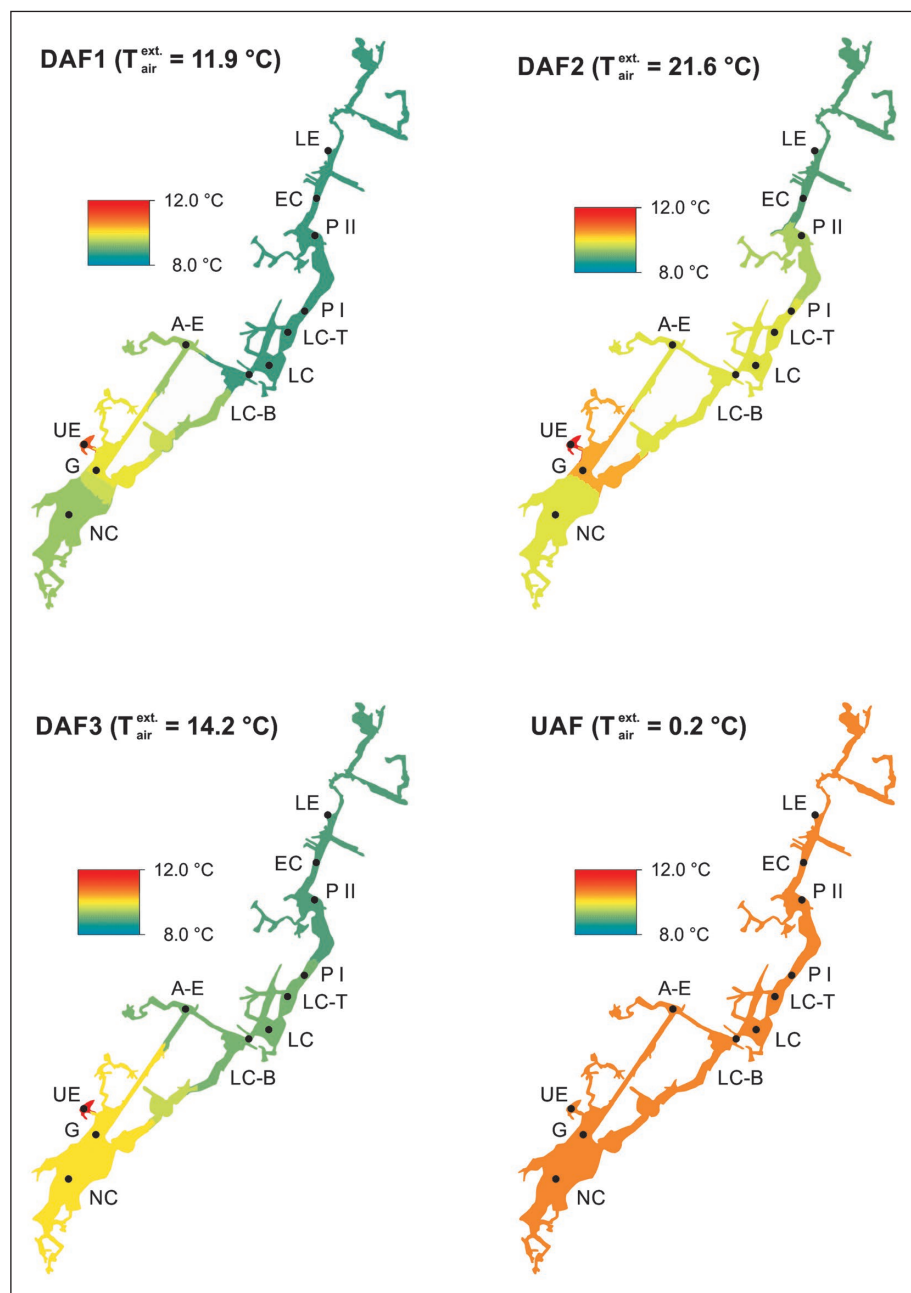


Figure 11: Distribution of corrected wall surface temperatures measured by non-contact IR thermometer (Čísařská Cave, Moravian Karst). DAF is downward airflow ventilation mode; UAF is upward airflow ventilation mode. The abbreviations of the monitoring sites are consistent with Table 1.

MCS sites up to 9.0 °C at the EC and LE sites. During the September campaign, the maxima at the UES sites were similar to the July values, but the T_{WS} values at the MCS sites were lower (9.0–9.1 °C) and the minima at the LES sites reached 8.8 °C. In contrast, a relatively different val-

ues were identified in December, when the cave persisted in the UAF ventilation mode. There were identified two T_{WS} decreases from 11.2 to 10.5 °C (UE site to A-E site) and 10.9 to 10.4 °C (LC-B site to LE site).

5. DISCUSSION

5.1 CAVE AIR TEMPERATURE

A relatively wide range of the T_{air}^{cave} between 4.5 and 14.2 °C found in the Čišařská Cave is consistent with the range of 2.4 to 15.4 °C reported by Faimon et al. (2012), and also covers a range of 7.8 to 12.9 °C presented by Faimon & Lang (2013) in the same cave earlier. Based on characters of T_{air}^{cave} time series at individual monitoring sites, two different temperature types of the heterothermic zone were identified within the cave. The LC site, located in the deeper cave passages, was characterized by a narrow T_{air}^{cave} range of 1.2 °C. According to the temperature classification of the cave passages developed by Obleitner et al. (2024), it belongs to the heterothermic zone. However, typical temperature ranges of the homothermic zone (a few tenths of °C) indicate that the LC site could represent a transitional passage between the heterothermic and homothermic zone. A possible factor that disrupts the homothermic character of the LC site could represent a hypothetical vent in the middle of the chamber that allows communication with the external atmosphere. A temperature similarity between the LC site and the homothermic zone was also confirmed by its mean T_{air}^{cave} of 8.4 °C, which should correspond to the long-term average of annual T_{air}^{ext} in the Moravian Karst (8.3 °C) (White, 1988). Contrary to the LC site, a much higher T_{air}^{cave} ranges, 5.2 °C and even 6.7 °C, at the LE and UE sites showed a strong impact of external conditions, leading to the formation of a heterothermic zone (de Freitas & Littlejohn, 1987; Luetscher et al., 2008; Sedaghatkish et al., 2024, 2025). Modeling of T_{air}^{cave} by Faimon & Lang (2013) showed that this effect predominates near the entrance through which the external air enters a cave with completely different conditions. Then, it can be deduced that this effect should be weakened near the outlet, through which the temperature balanced air from deeper parts leaves the cave.

The long-term monitoring of T_{air}^{cave} at the UE/LE sites proved this hypothesis, and two different distribution patterns were observed for different airflow directions (Figure 3a). If the cave persisted in the DAF ventilation mode, the warm external air entering the cave showed

both highest T_{air}^{cave} values and widest range at the UE site. As the air approached the LE site, its temperature remained near the mean T_{air}^{cave} . In contrast, an opposite pattern was identified during the UAF ventilation mode. The transport of cool external air into the cave by the LE site decreased the T_{air}^{cave} values varying in a narrower range, but the air leaving the cave through the UE site almost reached the mean T_{air}^{cave} . Furthermore, the ranges near the entrances, through which the external air enters a cave during individual ventilation modes, were highly unbalanced (the range at the UE site exceeded the LE site range). It could be the result of higher values of ΔT_{AF} during DAF ventilation mode reaching up to 27 °C, compared to ΔT_{AF} maxima of about 20 °C in UAF ventilation mode (Figure 3a). In addition, Faimon et al. (2012) also mention that the permanently strong airflow at the Upper Entrance in comparison with the Lower Entrance regardless of the airflow direction indicated a hidden opening representing another Lower Entrance.

5.2 WALL SURFACE TEMPERATURE

To evaluate the NCT as a potential approach for T_{WS} monitoring in cave environment, reference monitoring was performed. However, significantly lower values of both the right walls (8.2 ± 1.2 °C) and the left walls (8.3 ± 0.9 °C), corresponding to a systematic error, would lead to the rejection of this method. This hypothesis was supported by significantly higher deviations (up to 4.0 °C) in the standardized NCT time series compared to much lower deviations (up to 1.3 °C) corresponding to the standardized CCT time series (Figure 8). Moreover, an inconsistency of both sensors was proved by insignificant values of correlation coefficients of 0.16 and 0.25. Other factors limiting the measured T_{WS} values are associated with the NCT parameters, such as an emissivity value and/or a distance between an operator and the monitored surface during the measurement. Since the used NCT allows a selection from three emissivity degrees, corresponding to the values of 0.95, 0.85, and 0.75, an effect of individual emissivity degrees on the T_{WS} was tested in the cave environment. The results showed a rela-

tively rapid decrease of T_{WS} values between individual emissivity degrees by ~ 1.4 °C. It indicates that the emissivity value represents one of the key factors affecting T_{WS} measurement and, therefore, should be chosen based on (i) the manufacturer's recommendation and (ii) the measured material. In this study, the emissivity value of 0.95 was set up as the commonly used value for limestone (Mineo and Papalardo, 2021) forming the Čísařská Cave. An effect of monitoring distance was tested at several monitoring sites and a slight temperature decrease with a longer distance was proved (Figure 9). A relatively short distance of 1 m, recommended by the documentation of used NCT, partly limits key advantage of NCT associated with the ability to measure temperature in inaccessible cave passages (e.g., ceilings or vertical walls). Therefore, the useability of monitoring by NCT requires correction of obtained data by calibration curve. On the other hand, the comparison of calibration from April 2023, used in this study, with calibration performed in March 2026 showed seasonal dependence of this correction. While the DAF campaigns showed differences between both calibrations up to 0.8 °C, much higher differences up to 1.3 °C were identified during the UAF campaigns. Moreover, significantly lower differences up to 0.3 °C were registered in May and September. It indicates that separate calibration curves for individual ventilation modes are necessary. In addition to systematic error, the measured T_{WS} values are influenced also by a random error especially associated with the presence of water on the cave wall. It was tested by the repeated measurement of dry/wet wall in the Čísařská Cave and inserting these values into the relative error calculation gave values of 4.25 and 4.95 % for the dry and wet surfaces, respectively. Based on the expected wall surface temperature of about 8 °C, corresponding to the T_{air}^{cave} in the homothermic zone (Figure 3b), it would lead to a deviation of 0.3–0.4 °C. The revised T_{WS} values between 8.7 and 13.6 °C found by calibration of the basic T_{WS} data are consistent with the peak values reported by Středová et al. (2014) in the Kateřinská Cave (Moravian Karst) or with those measured by Azúa-Bostos et al. (2009) in an Atacama Desert Coastal Cave (Chile). Notably, both previous studies used non-contact techniques, but similar values were also obtained using temperature sensors inside the rock massif (see, e.g., Hebelka et al., 2011). However, these values are absolutely incomparable with the extreme values during cold seasons up to -2.0 °C presented by Turri et al. (2005), or even up to -8.8 °C mentioned by Středová et al. (2014) in the entrance passages of the Kateřinská Cave. The distribution of T_{WS} showed that the changes in temperature are controlled inversely by external conditions via cave airflows. According to the phase of the actual ventilation mode, two different periods of distinct

T_{WS} distribution can be distinguished: (i) the early/late period and (ii) the peak period (Figure 10). The first distribution model was designed for the May and September monitoring campaigns, corresponding to the early and/or late periods of the DAF ventilation mode, when the warmer external air flowed into the cave by the Upper Entrance. Note that the temperature of external air transported into the cave was determined as an average for seven days before the monitoring campaigns, and corresponded to 12.0 °C (May) and 14.0 °C (September). Such behavior was demonstrated in May and September, when transport of external warm air led to an increase of T_{WS} values at the UES monitoring sites up to 11.3 °C (May) and 12.1 °C (September). The remaining cave passages were characterized by a relatively stable T_{WS} about mean values of 8.8 and 9.0 °C in May and September, respectively. Similarly, the same pattern could be derived for the early and late periods of the UAF ventilation mode corresponding to March and November, when the colder external air entering the cave by the Lower Entrance cools the LES passages. The second distribution model was described during the July and December monitoring campaigns, representing the peak periods of the DAF and UAF ventilation modes. Contrary to the previous model, these campaigns were characterized by the longer distance of impact of external conditions. During DAF ventilation mode, warm external air with a T_{air}^{ext} maximum of up to 29.0 °C (Figure 3a) entered the cave through the Upper Entrance, and its impact was evident at both the UES and MCS monitoring sites. While T_{WS} values in the UES passages were comparable with those in May and September, increased values (9.3 to 9.8 °C) were found in the MCS passages. The mean cave T_{WS} value of ~ 9.0 °C corresponded to the last two monitoring sites (EC and LE). An opposite mechanism associated with the cooling of both the LES and MCS monitoring sites should operate during the UAF ventilation mode. However, the December monitoring campaign showed increased values of T_{WS} (up to 11.4 °C) throughout the cave, varying in a narrow range of ~ 1.0 °C (Figures 4c and 5c). This discrepancy could be caused by a combined effect of two factors: (i) weakened airflows due to the local T_{air}^{ext} maxima reaching up to 5.0 °C before the campaign and (ii) the heat transfer between cave pools and cave air. The spatial distribution of T_{WS} indicates an additional opening situated in the Lehárna Chamber that behaves like the Upper Entrance and plays an important role, especially during the DAF ventilation mode (Figure 10). Whereas an initial decrease of the ranges at UES sites showed systematic weakening of the effect of warmer external air, an increase of ranges at the MCS/LES sites indicated transport of an additional portion of the external air into the cave through the mentioned opening in the

Lehárna Chamber. In contrast, an opposite trend operating in two different cave passages (the LES/MCS sites and the UES sites) was identified during the UAF ventilation mode. In both these passages, the relatively lower T_{WS} ranges at initial sites were followed by gradually increasing ranges at the remaining sites except the LC-T site, where a heat production by cave pools led to a much narrower range of T_{WS} values. Note that the T_{WS} values at the LE/EC sites were decreased by the colder external air, but lower T_{WS} range at the A-E site was connected with a split of the main airflow path into two branches heading (i) to the opening in the Lehárna Chamber and (ii) to the Upper Entrance. These findings could play an important role in paleoclimatic reconstructions. It is well known that speleothems for this purpose should be taken from the homothermic zone due to its relatively temperature stability. Therefore, a wide range of T_{WS} reaching up to 2 °C at the UE site indicates that the speleothems from the passages near the Upper Entrance are not suitable for this purpose. On the other hand, these speleothems can be useful in the field of cave ventilation, e.g. for determination of active/non-active ventilation periods (Lutscher et al., 2011). In this context, however, it is necessary to check positions of chimneys and additional known/hidden openings that could play a role of the Upper Entrance. It could be represented e.g., by a vent in the Lehárna Chamber. Warmer external air sucked into the cave through these openings during the DAF ventilation mode increases temperature range in surrounding passages of about 1 °C (Figure 10), which distorts the boundaries of the homothermic zone.

5.3 CAVE AIRFLOW PATHWAYS

The comparison of temperatures of both the right and left walls at individual monitoring sites allowed to determine the preferential pathways of cave airflow. Despite the same pattern with prevailing higher T_{WS}^{left} values found during all campaigns, the airflow pathways should be

interpreted based on the actual ventilation mode. Note that the positions of the walls correspond to the direction of visitor movement from the Upper Entrance towards the Lower Entrance of the cave (the left/right wall is situated to their left/right hand). The higher temperatures of the left walls at the UES sites during the DAF ventilation mode indicated their slight heating by the warmer external air entering the cave through the Upper Entrance. Based on the profile of the UES passages, the route around the left walls also represents the shortest pathway for the cave air to reach the MCS passages. The occasional discrepancies from the prevailing pattern (the higher T_{WS}^{right} or balanced temperatures of both walls) during the DAF campaigns could be associated with the decrease of $T_{air}^{ext.}$ values below the T_{air}^{cave} values during the final period of the previous transitional ventilation mode or colder periods inside the DAF ventilation mode (Figure 3a). On the other hand, the lower temperatures of the right walls at the LES sites showed their slight cooling by relatively cold cave air (the T_{air}^{cave} at the LE site varied between 5 and 8 °C (Figure 3b)). In contrast, an opposite mechanism operated during campaigns in the UAF ventilation mode. While cold external air entering the cave through the Lower Entrance cooled the right walls at the LES sites, the left walls at the UES sites were heated by relatively warm cave air. To sum up, the mentioned mechanisms determined the right walls at the LES sites and the left walls at the UES sites as the preferential pathways of cave airflow independently on the actual ventilation mode. This behavior corresponds to the morphology of passages near the both cave entrances: the Lower Entrance is directly connected with the Entrance Corridor leading to the right into the deeper cave parts, and a large hole leading towards the Gallery site is situated directly behind the Upper Entrance. Both routes represent the shortest connection between cave entrances and the following monitoring sites.

6. CONCLUSIONS

In the Císařská Cave (Moravian Karst), the use of a non-contact method for monitoring wall surface temperature was tested. To evaluate the accuracy of this method in a cave environment and to compare it with the commonly used contact method, seasonal monitoring of wall surface temperature was conducted at selected locations throughout the cave. The monitoring included (i) seven baseline campaigns, during which the surface temperature of the right and left walls was

measured separately with NCT, and (ii) one reference campaign, during which measurements were supplemented with a CCT.

The data revealed a significant systematic error of -8.2 ± 1.2 °C for the right wall and -8.3 ± 0.9 °C for the left wall, which was corrected using calibration curves obtained from the reference campaign. The presence of water on the cave wall significantly reduces its surface temperature compared to a dry wall.

The relative error of the NCT measurements was similar in both cases, reaching 4.25 % for the dry wall and 4.95 % for the wet wall. Given the assumed wall surface temperature of 8 °C, these relative error values could result in a deviation in the range of 0.3 to 0.4 °C. Such deviations are at the limit of applicability for common karstological interpretations (e.g., paleoenvironmental reconstructions) and even exceed the limit for environmental-karstological interpretations (e.g., water vapor condensation and condensation corrosion). However, it can be anticipated that future technical developments will lead to a reduction in the relative error of commonly used IR thermometers, as their key advantage, the ability to measure temperature in inaccessible cave passages (e.g., ceilings or chasms). Therefore, the non-contact thermometers generally represent useful methods for basic monitoring of wall surface temperature and promising devices for future karstological and environmental studies. On the other hand, their use requires correct (i) set up (e.g., the appropriate emissivity degree), and (ii) methodology (e.g., suitable distance from the wall surface).

The study showed that the wall surface temperature depends on (1) the phase of actual ventilation mode and (2) the position of individual monitoring sites throughout the cave. The range of wall surface temperatures during the DAF ventilation mode (8.7 to 13.6 °C) significantly exceeded the range observed during the UAF ventilation mode (10.0 to 11.4 °C). Based on cave airflows, two models with distinct distribution of wall surface temperature were distinguished. Whereas the first model occurred in the early/late phases of actual ventilation mode and influenced only entrance passages of the cave, second model operating in the peak phases of actual ventilation mode showed impact of deeper cave passages. The spatial distribution of wall surface temperature indicated presence of the chimney in the Lehárna Chamber represented additional Upper Entrance. Its presence may significantly reduce the extent of the homothermic zone and distort temperature information in speleothems used during paleoclimatic reconstructions.

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