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CO_2 AND TEMPERATURE VARIATIONS DURING PEAK TOURIST SEASON IN LEPE JAME (POSTOJNA CAVE, SLOVENIA)

DINAMIKA CO_2 IN TEMPERATURE MED VRHUNCEM TURISTIČNE SEZONE V LEPIH JAMAH (POSTOJNSKA JAMA, SLOVENIJA)

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Abstract UDC 551.44:551.584(497.4)

Matija Perne, Marija Zlata Božnar, Primož Mlakar, Boštjan Grašič, Dragana Kokal & Franci Gabrovšek: CO_2 and temperature variations during peak tourist season in Lepe jame (Postojna Cave, Slovenia)

We present and analyze measurements of CO_2 concentration and air temperature taken during the peak tourist season of 2017 in Lepe Jame, a poorly ventilated passage within Postojnska Jama, Slovenia. During the study, the passage was visited by between 5500 and 6500 visitors per day. Both parameters show pronounced diurnal fluctuations, primarily driven by visitor activity. As part of our campaign, we tested and confirmed the effectiveness of enhanced ventilation—achieved by opening the artificial tunnel connecting Postojnska Jama to Črna Jama—in preventing excessively high CO_2 concentrations. The measure is, however, questionable, as it affects the microclimate in Črna Jama. Although CO_2 concentration and temperature are correlated, notable differences emerge in the shapes of their respective rise and recession curves. Temperature increases more rapidly with the arrival of visitors, while it decreases more slowly after visiting hours compared to CO_2. This lag is attributed to thermal storage: heat from visitors is absorbed by the cave walls during the day and gradually released into the cave during the night.

Keywords: karst, cave climate, show cave, carbon dioxide, cave monitoring.

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Matija Perne, Marija Zlata Božnar, Primož Mlakar, Boštjan Grašič, Dragana Kokal & Franci Gabrovšek: Dinamika CO_2 in temperature med vrhuncem turistične sezone v Lepih jamah (Postojnska jama, Slovenija)

V članku obravnavamo meritve koncentracije CO_2 in temperature zraka med vrhuncem turistične sezone leta 2017 v Lepih jamah – razmeroma slabo prezračenem rovu Postojnske jame, skozi katerega je dnevno prehajalo med 5500 in 6500 obiskovalcev. Oba parametra kažeta izrazita dnevna nihanja, ki so večinoma posledica prisotnosti obiskovalcev. Analiziramo tudi vpliv dodatnega prezračevanja z odprtjem umetnega tunela, ki povezuje Postojnsko jamo s Črno jamo. Ta ukrep učinkovito preprečuje prekomerno kopičenje CO_2 ob dneh, ko bi bile zaradi zunanjih vremenskih razmer in velikega števila obiskovalcev sicer pričakovane visoke koncentracije, a je z vidika vpliva na klimo Črne jame nesprejemljiv. Čeprav sta koncentracija CO_2 in temperatura medsebojno povezana, se krivulji njunega naraščanja in upadanja pomembno razlikujeta. Temperatura se ob prihodu obiskovalcev hitro zviša, njen upad po zaključku obiskov pa je počasnejši kot pri CO_2. Zakasnitev pripisujemo izmenjavi toplote z jamskimi stenami – toplota, ki jo oddajajo obiskovalci, se čez dan shranjuje v stenah in ponoči prehaja nazaj v jamo.

Ključne besede: kras, jamska mikroklima, turistična jama, ogljikov dioksid, monitoring jam.

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1. INTRODUCTION

Air quality in the external atmosphere in the EU is regulated by Ambient Air Quality Directive (Directive 2024/2881, 2024). Numerous air parameters in indoor work premises are subject to controls as well (Uredba, 2018). However, there are also environments that are neither indoor nor outdoor yet struggle with accommodating crowds of visitors. This article seeks to shed light on the issue of air quality inside a karst cave which receives a lot of visitors.

Caves are a karst phenomenon with an extraordinary tourist appeal (Figure 1). The classical Karst region in Slovenia includes prominent show caves, such as Škocjanske Jame (Škocjan Caves), a UNESCO World Heritage site, and the 24-kilometer-long Postojnska Jama (Postojna Cave), the most visited European cave.

Here, an electric train takes visitors to the central part of the cave (Gabrovšek et al., 2014), where they then take a footpath through the halls and passages. The influence of touristic use of the cave is being monitored, where climate monitoring presents an important part. The cave is well instrumented, with the backbone of climate monitoring consisting of four automatic meteorological stations that continuously record temperature, CO_2 concentration, and airflow (Figure 2). Two of the stations are located along the tourist section of the cave, while the other two are positioned in dead-end side passages.

Presence of tourists influences the CO_2 concentration due to breathing. In poorly ventilated cave passages, the CO_2 increase due to exhaled air can be quite significant. Building standards are concerned with CO_2 either because of its direct health effects (Küçükhüseyin, 2021) or because it indicates general bad air quality (Lowther et al., 2021). In the karst underground, CO_2 performs additional functions. It is a reactant influencing the main karst process of limestone dissolution (Covington et al., 2013). Increasing its level in the cave could slow down flowstone deposition or even turn it into dissolution (Surić et al., 2021; Kukuljan et al., 2021b) and may affect the activity of underground animals (Römer et al., 2018).

Concentration of carbon dioxide is influenced by cave ventilation (Covington & Perne, 2016; Gabrovšek, 2023; Kukuljan et al., 2021a). In the presented case, we expect the air flow to be mainly driven by buoyancy (chimney effect), where in the summer regime discussed here, the airflow is stronger when the outside temperature is higher (Gabrovšek, 2023).

The measurements discussed in this work are from August 2017 and include a period of three days during which the ventilation was enhanced through the opening of an artificial tunnel (Figure 1, we use term *enhanced ventilation* for this).

We present the analysis of CO_2 concentrations and temperature near the footpath in Lepe Jame (Figure 1), and the influence of visitors in conditions of normal and enhanced ventilation on the observed quantities. We also deduce the dynamics and the transport mechanisms of CO_2 and heat in the cave from the daily variations of CO_2 concentration and temperature in both ventilation regimes. To achieve that, we use the effects of visitors as test signals to probe the cave as a thermal system.

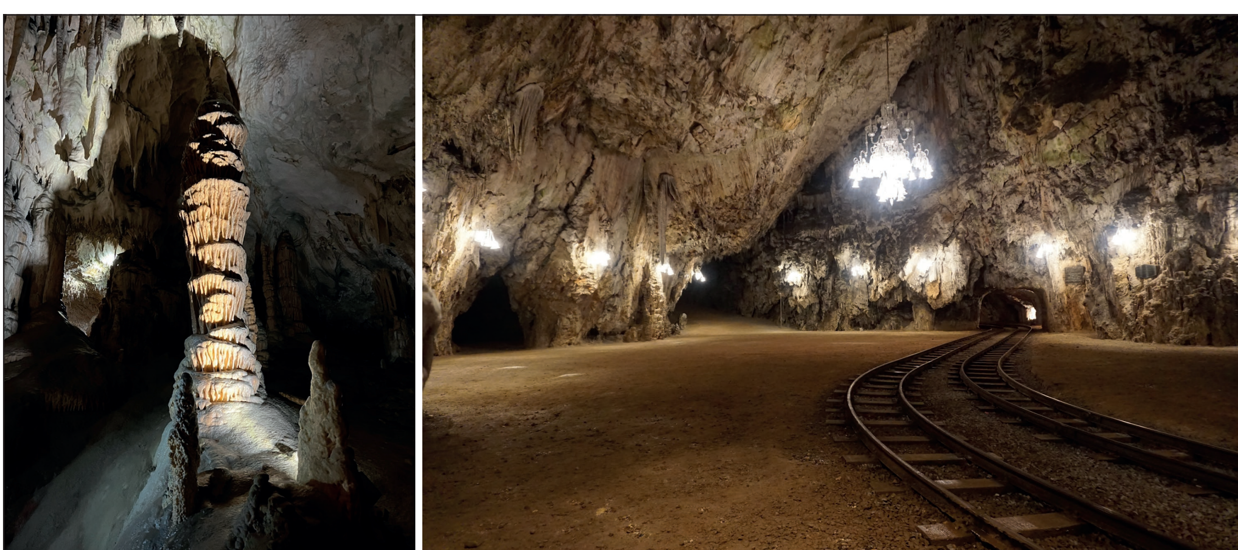

Figure 1: Postojnska Jama (Postojna Cave) is the longest show cave of Dinaric Karst, with the number of tourist visiting annually approaching 1 million.

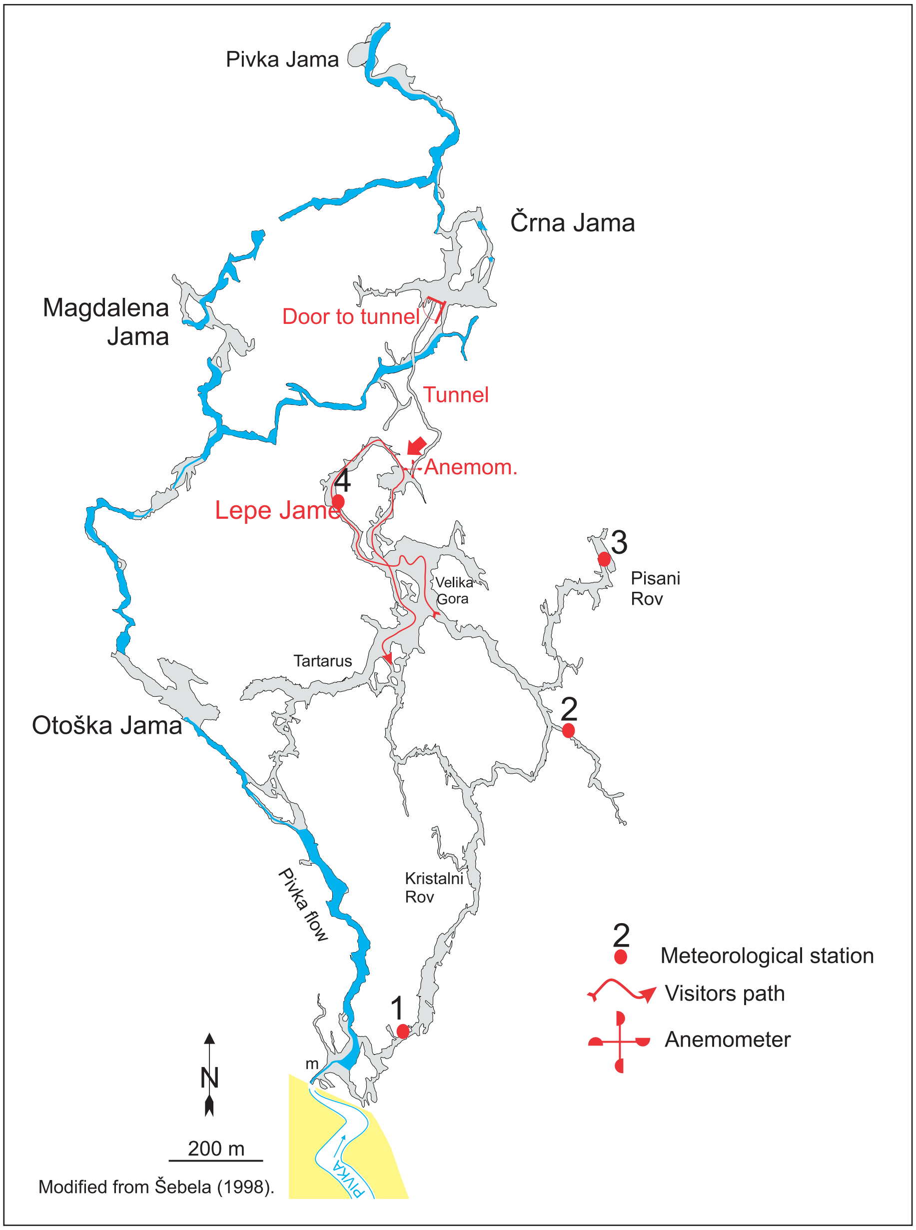

Figure 2: Map of Postojnska Jama with locations of meteorological stations. In this work we discuss the Lepe Jame (Station 4) site.

2. CO_2 AND MICROMETEOROLOGICAL MEASUREMENTS IN CAVES

A cave is an underground space large enough for humans to enter (Field, 1999). Large caves in particular lend themselves to tourism. Visits of tourists have a direct impact on the cave and its atmosphere. The first indication is the temperature increase due to the energy input; visitors literally warm up the cave. Depending on the scale and ventilation of the cave, this impact can be either almost negligible or important. The second important impact of visitor presence in the cave is the CO_2 increase in the cave atmosphere. In poorly ventilated caves, the rise in CO_2 is the most noticeable effect of visits (Milanolo & Gabrovšek, 2009). Both impacts can be quantified only if there are adequate measurements available.

Automatic micrometeorological measurement systems inside the cave environment function in the same way as comparable systems in the external atmosphere. The key difference is in the quite specific cave conditions that the electronic modules used have to withstand. The main issue is the constant high relative humidity, which causes condensation on the electronic elements unless they are adequately protected. With the proper measuring system, it is possible to directly quantify the impact

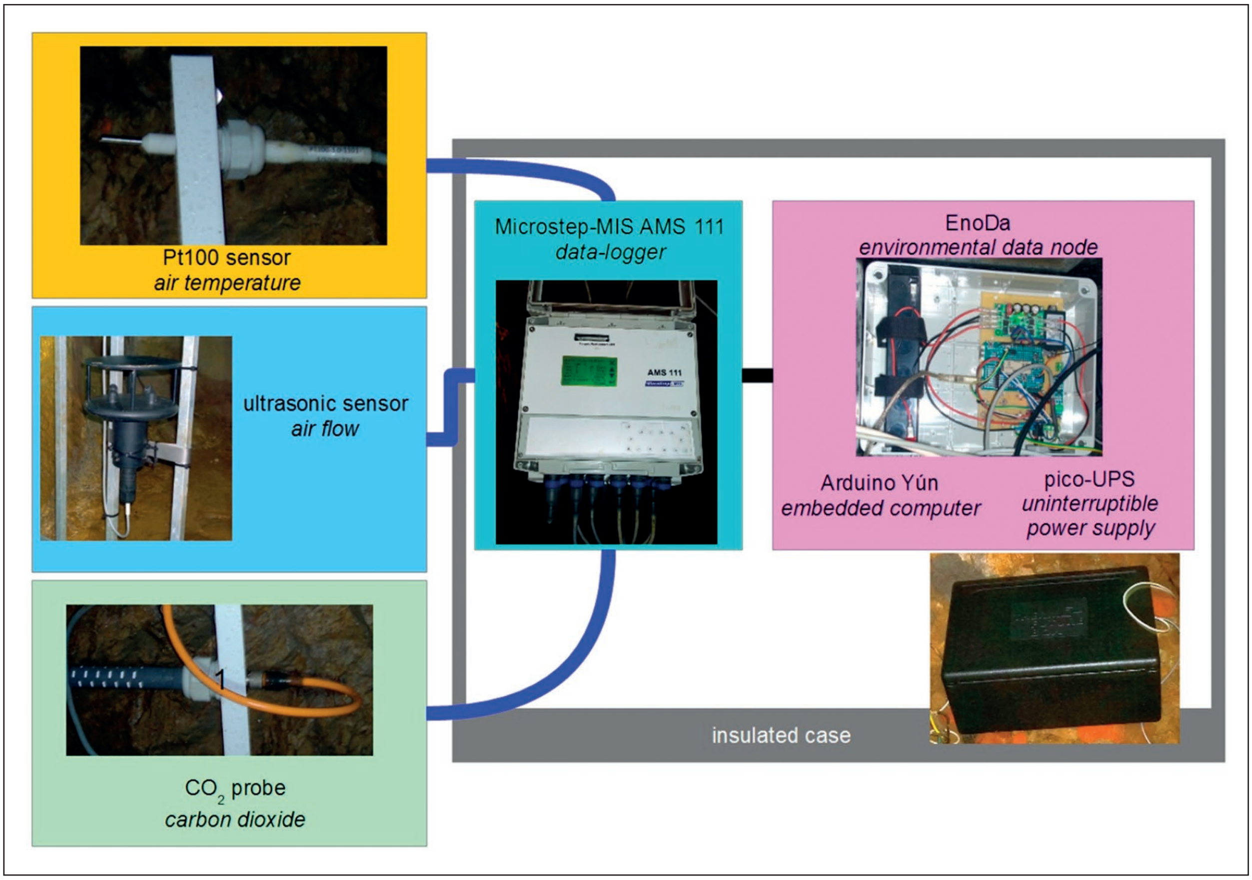

Figure 3: Diagram and constituents of automatic micrometeorological station with temperature, CO_2 and airflow probes, AMS data-logger, and storage/data processing unit.

Figure 4: Meteorological station at Lepe Jame location. Left, mast with instruments, two temperature sensors (2 m, and 3.5 m above ground) and CO_2 sensor at 3.5 m. Right: Position of station in the passage; tourist trail is about 2 m behind the researcher.

of visitors. In Figure 3, a diagram of an automatic micrometeorological station is presented (Mlakar et al., 2020).

Lepe Jame (Beautiful Caves) is a 300 m long passage, where visitors walk along a 1 m wide path; visitors walk about 10-15 minutes through the passage. The passage is poorly ventilated, the airflow velocity is below 0.01 m/s, a threshold for typical ultrasonic anemometers. The automatic micrometerorological station is set up in the passage (Figure 4), about 4 m from the footpath, to track the CO_2 concentration and temperature. The measurements show diurnal patterns correlated with the presence of visitors. CO_2 can be treated as an independent, direct indicator of the number of visitors, provided that other parameters, especially cave ventilation, remain relatively constant.

When daily maximum CO_2 concentrations at the Lepe Jame site get particularly high (above 2000 ppm), the manager used to control it by opening the door to the artificial tunnel connecting Postojnska Jama and Črna Jama. While most of the additional ventilation does not directly traverse Lepe Jame, it does cause measurable changes that we discuss in this work.

3. MEASUREMENT RESULTS AND STATISTIC ANALYSIS OF THE THREE-DAY ARTIFICIAL VENTILATION

The analysis in this work is based on the data acquired between 7 August and 24 August 2017, coinciding with the peak tourist season in Postojnska Jama. During this period, visits occurred daily from approximately 9:00 AM to 7:00 PM, with 6000 daily visitors on average. As part of the study, the tunnel door was opened on 14 August 2017 at 1:00 PM and closed on 16 August 2017 at 5:00 PM, the period we refer to as the enhanced ventilation period.

The time series shown on Figure 5 depict the measurements for the entire period, including the three-day period that was subject to the enhanced ventilation indicated (marked by a rectangle). Cave temperature and CO_2 show a clear diurnal cycle, which is apparently correlated with external temperature, but the correlation is not causal. The cycle of both parameters is related to the presence of visitors. Diurnal temperature amplitude is about 0.5°C, and amplitude of CO_2 concentration 1200 ppm.

Figure 6 shows temperature and CO_2 concentration between August 13th (6 am) and August 14th (6 am). A small peak at 8 am precedes the main rise of both parameters, starting at 9:30, when the first group of visitors arrives. The T and CO_2 curves show different characteristics; temperature shows higher variability during the day, but much slower recession after the visits.

To further illustrate the diurnal patterns of observed parameters during the selected period, a sunflower diagram (Figure 7) is used. This visual tool displays data for each hour of the day as a circular, hourly segmented histogram, where each segment represents one hour. Within each hour, the distribution of parameter values is shown through a color-coded bar, divided into intervals (or "buckets") of parameter ranges. Each bucket is assigned a specific color, and the length of each colored part within the hourly segment is proportional to the relative frequency measurements falling into that interval.

This format allows for an intuitive visualization of how parameter values vary throughout the day within the selected period, clearly indicating when specific values occur most frequently. In particular, it is well suited to highlighting daily peaks, revealing both their timing and duration in a compact and interpretable form.

The sunflowers in Figure 7 depict the analysis of 10-minute values, so that each one-hour section consists of at least six values. Each column presents sunflowers for the time period given on the headline.

The first column shows parameters for the week preceding the period of the enhanced ventilation. The next three columns present measurements during the three days of enhanced ventilation – one for each day – followed by a column for the week after the door closure.

Once the enhanced ventilation started at 1 pm on 14 August 2017, the CO_2 concentrations dropped with a delay of a few hours, by late afternoon reaching the levels typical of night time (1st row in Figure 7). The daily maxima during the enhanced ventilation are significantly lower than in the other days with similar weather. Lower daily maxima only occur during intense weather phenomena noticeable in the outside temperature, such as on 7, 9, and 18 August.

The third sunflower in the 1st row in Figure 7 depicts the second day of the enhanced ventilation. The peak CO_2 concentrations are now significantly lower than on most other days, whilst the hourly pattern still resembles the one before the opening (upper left sunflower).

The 4th sunflower in the 1st row indicates a rise in the CO_2 concentrations after closing of the door on 16 August 2017 at 5 pm. In the week following the shut-down of the enhanced ventilation, the daily pattern of CO_2

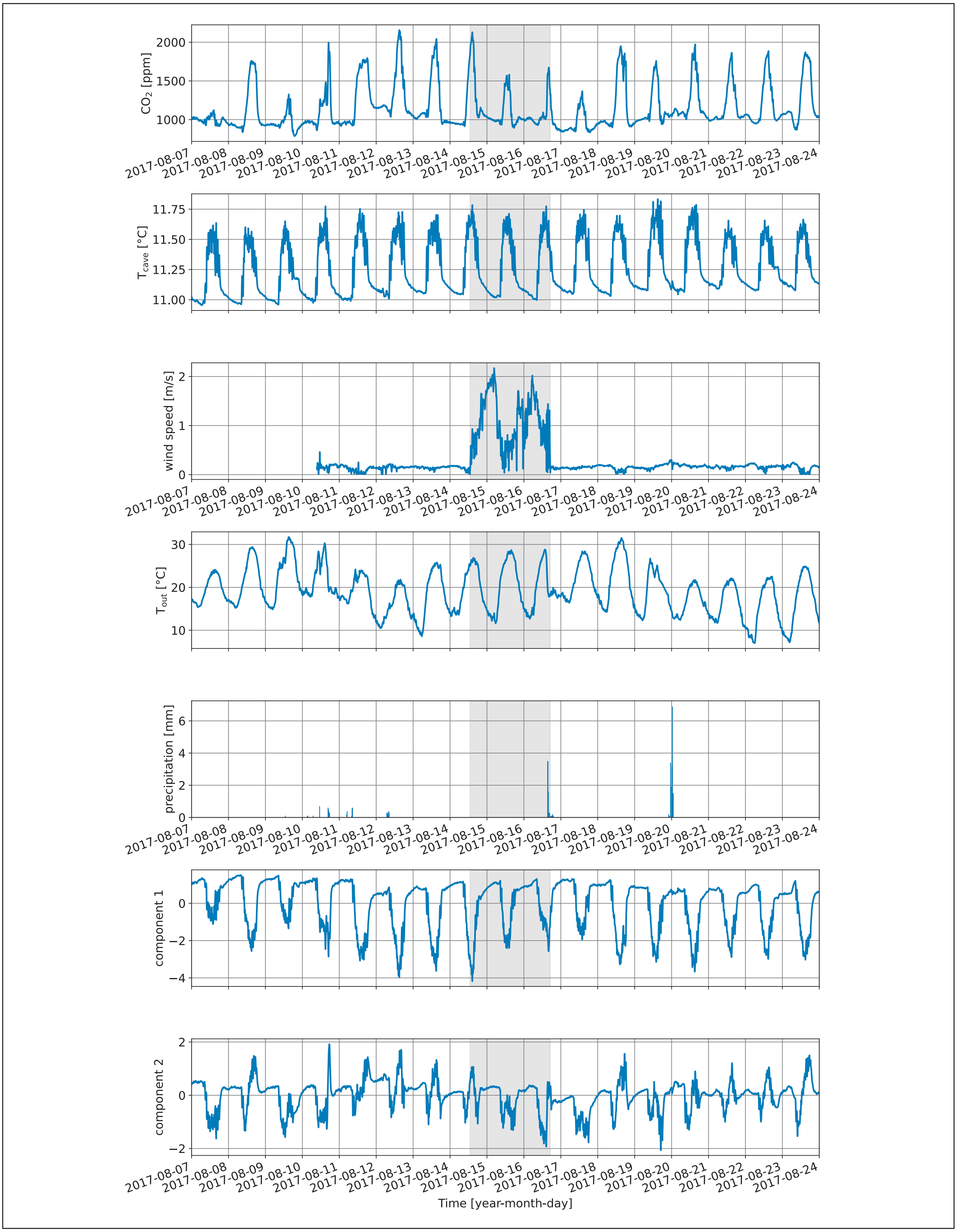

Figure 5: Time series of the measured and computed quantities sampled every 10 minutes. CO_2 concentration, temperature in the cave, airflow velocity in the tunnel, external temperature, and precipitation are measured, and principal components of temperature in the cave and CO_2 concentration are derived. Grey rectangle marks period of enhanced ventilation.

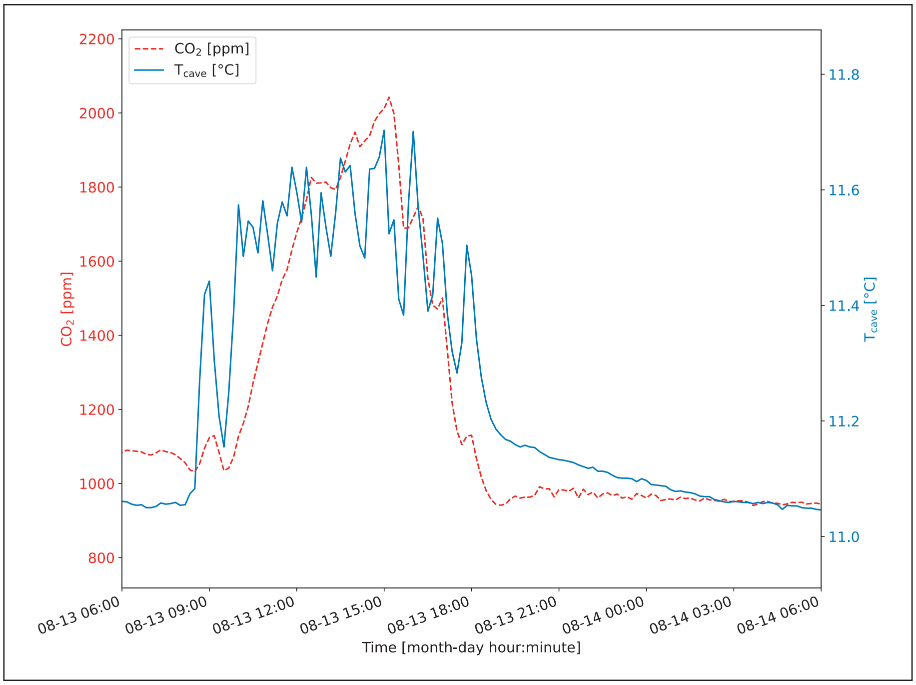

Figure 6: 24 hour (6am to 6am) series of temperature and CO_2 in Lepe Jame.

concentrations bounced back to the values preceding the enhanced ventilation period.

To explore the measurements further, we focus on a correlation between CO_2 concentrations and temperature. The correlation coefficient between temperature and CO_2 concentration in Lepe Jame is 0.68, demonstrating that the quantities vary together.

We standardize both signals (by subtracting the mean and dividing by standard deviation) and perform PCA to obtain the two components shown as time series in Figure 5 together with the measured quantities. The first component shows how the temperature and CO_2 concentration vary together and explains 84 % of their total variance, while the remaining 16 % of total variance is explained by the second component representing the difference between the two signals. That is, the large first component means that temperature and CO_2 concentration are large, while the large second component represents high temperature at low CO_2 concentration.

On a typical day, the second component rises as the visits start, corresponding to the immediate rise of the temperature due to presence of tourists in the immediate vicinity of the measurement station, while the CO_2 concentration has not risen much yet as it has not been transported to the station from the more remote tourists yet. The component then decreases with the additional increase of CO_2 concentration as CO_2 concentration reaches the daily equilibrium. Toward the end of the opening hours, the component tends to start increasing again, as the temperature keeps rising while the CO_2 concentration is stable. Immediately after closure, there is a complex interplay of CO_2 concentration and temperature decrease, followed by further temperature decrease throughout the night after the return of the CO_2 concentration to its nightly low, leading to slow decrease of the component.

Correlation coefficients between CO_2 concentration and outside temperature, and cave temperature and outside temperature, are 0.41 and 0.68, respectively. They may be coincidental, as the outside temperature happens to be high during the opening hours of the cave.

To observe correlations on a daily scale, we detrend the signals by subtracting their daily means. Correlation coefficients between detrended CO_2 concentration and cave temperature, CO_2 concentration and outside temperature, and cave temperature and outside temperature are 0.72, 0.63, and 0.82, respectively. The two coefficients involving the outside temperature considerably increase due to detrending, as the daily patterns match well, while the outside differences from day to day are not reflected in the cave signals.

Correlation coefficients between daily means of the same signals are 0.50 for CO_2 concentration and cave temperature, -0.39 for CO_2 concentration and outside temperature, and -0.03 for cave temperature and outside temperature. Positive correlation between CO_2 concentration and cave temperature may reflect the number of tourists, while negative correlation between CO_2 concentration and outside temperature may result from better ventilation on warmer days. The influence of the outside temperature on the cave temperature on the observed timescale seems to be negligible.

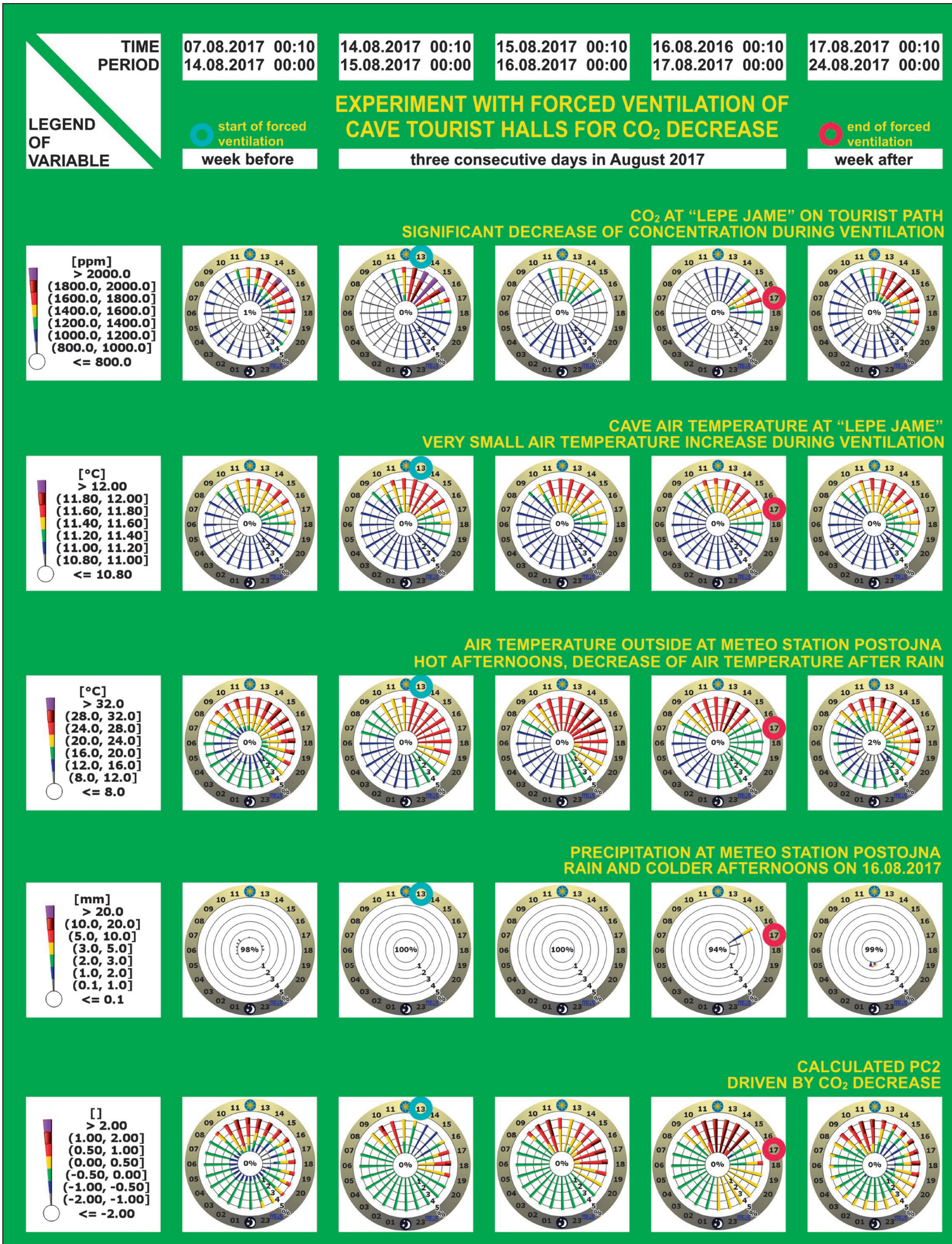

Figure 7: Sunflower diagram of observed parameters. 1st row: CO_2 concentration, 2nd row: air temperature at Lepe Jame, 3rd row: external air temperature, 4th row: precipitation in Postojna, 5th row: parameter PC2 resulting from PCA analysis of CO_2 and temperature.

4. DISCUSSION

To discuss the observation in a more general aspect, we start with a simple model. If the cave air and the visitors formed an isolated system, the rates of increase of the temperature and CO_2 concentration would be related because the production of each CO_2 molecule by human metabolism converts a known amount of chemical energy into heat. Let us assume that the Respiratory Quotient (RQ)—the ratio between carbon dioxide produced and oxygen consumed during aerobic metabolism by visitors—is 0.8 (Patel & Bhardwaj, 2025). Human energy expenditure can be calculated from O_2 consumption and CO_2 production according to formula:

$$Q = c_1 \cdot V(\mathrm{O_2}) + c_2 \cdot V(\mathrm{CO_2})$$ (Schoffelen & Plasqui, 2017)

where Q is energy $V(O_2)$ is the volume of oxygen consumed, $V(CO_2)$ is the volume of carbon dioxide produced, both at standard conditions, and the coefficient values are c_1 = 15.78 kJ/l, c_2 = 5.19 kJ/l (Schoffelen & Plasqui, 2017). Taking into account that $V(CO_2) = RQ\ V(O_2)$, the formula for our needs simplifies into $Q = c_3\ V(CO_2)$, where c_3 = 24.92 kJ/l at our value for RQ.

The temperature change of air can be calculated as

$$dQ = C_p n dT,$$ (OpenStax & LibreTexts, 2025)

where C_p is the molar heat capacity at constant pressure and n is the amount of air. Assuming C_p and n are constant, the formula becomes

$$\Delta T = \frac{Q}{C_p n} = \frac{Q V_m}{C_p V} = \frac{c_3 V(\mathrm{CO_2}) V_m}{C_p V} = \frac{V(\mathrm{CO_2})}{V} \cdot \frac{c_3 V_m}{C_p} = \frac{V(\mathrm{CO_2})}{V} \cdot F$$

Here, V_m = 22.4 l / mol (LibreTexts, 2025) is molar volume of air at standard conditions assuming ideal gas law. Taking into account that C_p = 29.12 kJ / (kmol K) (The Engineering ToolBox 2004), the value of the coefficient F is $F = c_3\ V_m / C_p$ = 19,200 K. That is, if the volume of CO_2 produced was equal to the total volume, the air would warm up by 19,200 K, and if it was one millionth of the total volume, corresponding to 1 ppm increase in CO_2 concentration, it would warm up by 0.0192 K (Schoffelen, 2017). The increase of CO_2 concentration of 1200 ppm, which is a typical daily fluctuation in Lepe Jame, would thus result in the temperature increase of 23 K in an isolated system. That is, if a certain number of people is contained in a certain volume of air, all the heat released by their metabolism heats up the air, and the air is not exchanged, the air temperature will increase by 23 K as the CO_2 concentration increases by 1200 ppm. The effects of humidity are neglected in the computation even though they may not be negligible. The observed daily fluctuation of around 1 K is approximately 4.3 % of this value.

Sunflowers depicting the situation before, during and after enhanced ventilation gave us a clear and quick picture of the impact of additional ventilation on CO_2 concentrations and air temperature in the cave. The analysis thus shows a time-limited and significant effect of enhanced ventilation on the CO_2 regime in the cave compared to other days without intense weather phenomena.

The visitors are much more efficient in causing fluctuations in CO_2 concentration than in temperature by a factor of around 23. This implies that CO_2 is much closer to an ideal tracer than temperature is. The exhaled CO_2 seems to easily stay in the air and affect the sensor, after which it is also easy to carry out of the cave by the draught, resulting in a decrease to the background level. The background level is low but not constant, presumably affected by natural processes. In contrast, the heat emitted by the visitors seems to be getting lost, delayed, or both. This should not come as a surprise, as the air is in thermal contact with the walls, enabling heat transfer between the two. The cave passages are surrounded by rock of decent thermal diffusivity and large surface due to macroscopic roughness. Furthermore, an important part of the heat emitted by the visitors is through radiation, heating up the walls directly (Hardy & DuBois, 1937). It should be noted that the observed CO_2 concentration increase results not only from the breathing of the visitors in the immediate vicinity of the sensor, but some of the CO_2 detected is transported to the sensor by draught along the cave passage for hundreds of meters. In contrast, the heat emitted hundreds of meters away along the passage has plenty of opportunity to be absorbed into the walls before reaching the micrometeorological station. One therefore observes the thermal signal to be damped (Luhmann et al., 2015).

Some of the heat stored in the cave walls may permanently leave the cave and get conducted to other fluids, such as outside air or percolating water. Some, however, re-enters the cave if the cave air cools down. This can happen across all timescales and is observed on the daily timescale in the presented data. In the evening, after the air has been exchanged and CO_2 advected away, CO_2 reaches the natural background level (Figure 5). However, the temperature is more persistent and only reaches the minimum just before the sharp increase at the start of the next days' visits (Figure 6). This demonstrates that the fresh air is being heated up as it extracts the stored heat from the cave walls, resulting in a more gradual temperature decrease as the cave walls cool down.

We see that daily CO_2 fluctuations are much more affected by enhanced ventilation than daily temperature fluctuations, where the effect is imperceptible (Figures 5 and 6). This can be explained by storage of heat versus lack of storage of CO_2 as well. CO_2 behaves as an ideal tracer, meaning that the increase in CO_2 concentration is inversely proportional to the draught as long as the air exchange is fast compared to the time scale of CO_2 source fluctuations (Kilpatrick and Cobb 1985). However, most of the heat is stored in the rock on the timescale of daily fluctuations rather than directly increasing the air temperature. An increase in draught changes the partitioning of the heat, resulting in a larger fraction of it being transported by the air rather than stored in the rock. In this regime, the temperature range thus does not decrease inversely proportionally to the air current but much more slowly.

The correlation coefficients between the outside temperature and both cave temperature and CO_2 concentration are high and increase further when the quantities are detrended. This increase demonstrates that the correlations are not causal in nature. If the outside temperature affected the conditions inside the cave, one would expect that the effect would be present on time scales of more than a day as well. Detrending would thus not increase the correlation coefficient, and the correlation coefficients between daily averages would be positive. One can therefore be confident that the main cause of daily fluctuations inside the cave is the presence of visitors.

5. CONCLUSIONS

Our assessment is focused on the air quality management in a large, mostly closed natural space subject to mass tourism. Air quality in karst caves open to tourists is related to number of visitors. Due to weak natural ventilation at Lepe Jame, variations of CO_2 concentration and temperature are a consequence of the presence of visitors.

August was chosen for the study period as this is the time with the highest number of visitors and often stable outside weather conditions not favouring strong natural ventilation. Nevertheless, the analysis of the impact in terms of CO_2 concentrations and cave air temperatures is not trivial as it still requires paying attention to the natural variability caused by changes in the outside weather.

We applied the sunflower analysis to clearly present the daily pattern of CO_2 concentrations and air temperature in the cave in a scenario of purely natural ventilation as well as in a scenario with enhanced ventilation. The analysis shows that the impact of visitors clearly manifests itself in the CO_2 concentrations and is quite repeatable under recurring conditions. Conversely, if the conditions change significantly, such as due to enhanced cave ventilation, the impact on the CO_2 concentrations is noticeable.

We show that we are able to track the impact of the large number of visitors with basic automatic measurements set up at the correct sites. At the same time, the measurements quantify the benefit of enhanced ventilation on the CO_2 concentrations in the cave.

The influence of visitors on cave air temperature is prominent as well; however, the effect of enhanced ventilation on temperature is very subtle. Nevertheless, the measurements of CO_2 concentration and temperature in parallel enable us to discern the difference between the behaviour of CO_2 and heat as cave air contaminants. We successfully determine the relative magnitudes of heat flows related to air convection and to air-rock heat exchange, informing us on the cave as a thermal system.

Assessing the desirability or non-desirability of the enhanced ventilation on parameters other than CO_2 concentration is beyond the scope of this article. The tunnel opening has a probable impact on the unique microclimate of Črna Jama (Šebela & Turk, 2018).

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