Cave airflow mechanism of a crevice-type cave: A case study from Czechia

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Abstract: At present, crevice-type caves are investigated mainly by means of geomorphic and geophysical methods. Microclimatic research of this type of caves is underrepresented and is often limited to temperature and humidity measurement only. Yet, microclimatic research of such caves can significantly help in the management and conservation of caves, speleological exploration or analysis of speleothems. Being the first ever research of ventilation within a crevice-type cave, a complex analysis of cave ventilation was performed within the Velká Ondrášova Cave, a crevice-type cave in the Outer Western Carpathians, Czechia. Long-term temperature recording, airflow tracing within the cave, and a total of nine monitoring field sessions (conducted between February and April 2015, in August 2015, and March 2018) provided data on temperature and airflow inside and outside the cave, serving as a basis for an analysis of ventilation rates, airflow routes within the cave, instability of the cave airflow, and the general ventilation mechanism of the cave. Based on the data, the average cave airflow velocity $0.27\text{--}0.61\text{ m}\cdot\text{s}^{-1}$ corresponding to the ventilation rates $540\text{--}1,260\text{ m}^3\cdot\text{h}^{-1}$ ($\sim 13,000\text{--}30,000\text{ m}^3/\text{day}$) was estimated as a rough value of the ventilation, given the complex morphology of the cave. The Helmholtz resonator appeared to be an unsuitable model for an explanation of the instability within the cave airflow velocity. A regression analysis of the cave airflow highlighted the temperature gradient as an important predictor explaining almost 80% of the analyzed cave airflow variability. However, statistical testing suggested the outdoor wind to be also a relevant driving force of the cave ventilation, accounting for the active cave airflow regime during summer.

Keywords: crevice-type cave, cave microclimate, cave airflow, temperature gradient, Outer Western Carpathians

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INTRODUCTION

Crevice-type caves (CTCs) qualify as a type of pseudokarst caves and belong among frequent landforms of various types of slope failures (Margielewski & Urban, 2017). They originated by a gravitationally induced disintegration of rock massif (Vitek, 1983). Within the research of the CTCs, primarily geological, geomorphological, and geophysical studies are usually conducted (Finlayson, 1986; Self, 1990; Demek & Kopecký, 1996; Pánek et al., 2011; Lenart et al., 2014; Margielewski & Urban, 2017; Tábořík et al., 2017) to provide important data on slope deformation (e.g., material type, structure, depth, velocity of movement). Our understanding of the CTCs can also be significantly complemented by their microclimatic investigation. This kind of research within the CTCs has so far been limited

to measurements of temperature and humidity, the results being used especially for speleological exploration (Lenart, 2012) and the monitoring of bats (Wagner et al., 1990). Later, temperature observation has also become a part of landslide geotechnical monitoring instrumentation (Baroň et al., 2003; Klimeš et al., 2012).

However, one of the crucial factors controlling cave microclimate is represented also by cave ventilation (Geiger, 1966; Cigna, 1968), a variable that is often being neglected. Cave airflow studies frequently serve for the management and conservation of show caves (Fernandez-Cortes et al., 2006; Russell & MacLean, 2008), optimization of speleotherapy (Faimon & Lang, 2013), or investigation of speleothems. Cave ventilation co-determines the physical and chemical state of the cave atmosphere via changes in microclimatic variables and consequently governs (i)

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speleothem growth/destruction and (ii) the chemical and isotope content of speleothems. The latter factor is utilized when performing paleoenvironmental reconstructions based on studies of speleothems. A thorough understanding of cave ventilation is therefore required if reliable paleoproxies are to be obtained from speleothems (Mattey et al., 2010; Baker et al., 2014). Despite their less frequent occurrence within the CTCs, speleothems have already been analyzed by means of the ^{14}C and U-series dating methods in a number of CTCs, with the results helping to decipher landslide ages in some areas (e.g., Pánek et al., 2009; Farrant et al., 2014; Urban et al., 2015; Lenart et al., 2018). However, unlike with karst caves, there is a lack of studies dealing with the ventilation of any type of pseudokarst caves.

In this paper, a basic qualitative and quantitative assessment of the cave airflow and ventilation mechanism of the Velká Ondrášova Cave (VOC) is provided, aiming to be an introductory study of the ventilation regime of an exemplary CTC. Airflow routes within the entire cave were determined by using an inert chemical tracer. The cave airflow velocity was being systematically measured during nine individual monitoring sessions. Furthermore, wind intensity was also being recorded on the surface. As a supportive tool for the airflow analysis, temperature monitoring in both long-term and short-term modes was carried out. Employing the airflow oscillations under investigation, the suitability of the Helmholtz resonator for an explanation of the ventilation instability has been examined. An insight into the airflow mechanism of the cave is provided by performing a set of selected statistical analyses. These are focused on two predictors: (i) the temperature difference between inner and outer cave air and (ii) the outdoor wind. Although there are other possible triggers of cave ventilation (e.g., pressure changes) that can be considered as a driving force of cave ventilation, they are not the subject of the present study.

VELKÁ ONDRÁŠOVA CAVE

The study site is located on the northwestern spur of Lysá hora (1,323 m a.s.l.), which is the highest peak of the Moravian-Silesian Beskids, formed by the Cretaceous gently inclined flysch beds of the Outer Western Carpathians in Czechia (Fig. 1). The cave

entrance, accessible at 920 m a.s.l., is situated at the southeastern termination of the distinct double-crested ridge in the upper part of the vast deep-seated Lukšinec landslide dated to 3.5–5 ka BP by ^{10}Be (Břežný et al., 2018). The Velká Ondrášova Cave (VOC) represents a typical dilation-type (describing formation mechanism) and initial-type (describing morphogenesis) crevice-type cave according to the classification provided by Margielewski & Urban (2017). Beyond a narrow cross-section ($\sim 0.54 \text{ m}^2$) of the entrance part, which was used for microclimate monitoring sessions and which leads to the distinctly vast Entrance Dome (ED), the cave splits up into two morphologically different parts – the Left Branch (LB) and the Right Branch (RB), both composed of a step-like system of interconnected abysses and domes (Lenart et al., 2014). Being the topmost level of the LB, the Upper Shaft is situated shallow below the surface and sporadically changes into a boulder cave *sensu* Margielewski & Urban (2017). The bottom of the mapped system is situated in the RB, 35 m below the entrance. The known cave corridors reach a cumulative length of 217 m (Wagner et al., 1990).

The origin of the mass movement controls the dynamic temperature regime of the cave. Although the cave is accessible only through one entrance, we assume there exist many other narrow openings represented by gravitationally widened joints or inter-boulder gaps.

The external annual air temperature of the area is $\sim 3^\circ\text{C}$ and the average 211 days with rainfall result in total annual precipitation exceeding 1,400 mm (climatic data from the Lysá hora Weather Station, provided by Czech Hydrometeorological Institute, 2019). As a protected bat wintering site, the cave is closed by a lockable bar and is visited only by cavers performing bat monitoring.

METHODS

The study of the cave airflow within the Velká Ondrášova Cave was performed using the following three approaches: (i) a qualitative assessment of airflow within the cave by means of a chemical tracer, (ii) auxiliary air temperature monitoring inside and outside the cave environment, and (iii) airflow velocity measurement inside and outside the cave. The microclimatic data were obtained during long-term continuous measurement and monitoring field

Fig. 1. Geographical location of the Velká Ondrášova Cave, Moravian-Silesian Beskids.

sessions. The field sessions provided both temperature and airflow short-term data for a statistical and spectral analysis dealing with the cave airflow mechanism. During the long-term measurement, only temperature data were collected, illustrating the temporal changes of a variable closely connected with the cave airflow. The processing and analysis of time series data were performed using the STATISTICA 10 software (TIBCO Software Inc., 2019).

Temperature monitoring

Air temperature within the cave was continually measured from December 2012 to February 2013 and from July 2013 to November 2014 with CS02 dataloggers (Petr Holub, measuring range from -50°C to $+50^{\circ}\text{C}$, resolution 0.06°C , accuracy $\pm 0.5^{\circ}\text{C}$) with a 1-hour time step. Some of these data were compared with the mean daily air temperature data from the Lysá hora Weather Station (Czech Hydrometeorological Institute, 2019). The temperature sensors were placed in three different parts of the cave (see Fig. 2 for locations of the loggers): (i) the ED, a shallow part of the cave near the entrance, (ii) the bottom of the LB, (iii) the bottom of the RB, the deepest accessible point of the Velká Ondrášova Cave, ~ 35 m below the entrance level.

The on-the-spot temperature gauging within the monitoring sessions was performed with a WS8610 thermometer (Garni technology, measuring range from -30°C to $+70^{\circ}\text{C}$, resolution 0.1°C , accuracy $\pm 1^{\circ}\text{C}$), logging the data with a 5-min time step into the built-in datalogger. During the sessions, the thermometer sensors were placed at the following positions (the corresponding variables are indicated in the parentheses): (i) outside the cave, ~ 15 m from the cave entrance to avoid the thermal influence of the cave on the measurement (T_{out}); (ii) outside the cave, in close proximity of the cave entrance (T_{out}^*); (iii) in the Entrance Dome, matching the sensor location of the continual temperature monitoring (T_{in}). The temperature of the cave air (T_f) flowing across the narrowed cross-section situated behind the entrance was recorded with a thermistor included in the AM-4214SD thermo-anemometer (Lutron, measuring range from -50°C to $+1300^{\circ}\text{C}$, resolution 0.1°C , accuracy $\pm 0.4\% + 0.5^{\circ}\text{C}$). Based on the monitoring, the temperature gradient ΔT was determined as a difference between the temperatures measured inside and outside the cave (i.e., $\Delta T = T_{in} - T_{out}$). Similarly, the temperature gradient ΔT^* (i.e., $\Delta T^* = T_{in} - T_{out}^*$) was defined, influenced by the closeness of the cave entrance.

Fig. 2. Ventilation pattern of the Velká Ondrášova Cave, recorded in winter 2013; marked on the cave plan by Wagner et al. (1990); the cross-sections out of scale.

Ventilation monitoring

The ventilation pattern of the whole length of the Velká Ondrášova Cave was investigated by determining the approximate direction and intensity of airflow movement using an airflow tester kit (Dräger Safety). It includes an aspirator bulb, which blows the air into the testing tube filled with sulfuric acid, exuding a temperature-neutral chemical tracer that makes the air movement visible on the testing site (Fig. 3). The spatial distribution of the air mass movement throughout the cave was observed by means of this technique in summer 2012 and winter 2013.

Fig. 3. Detection of directions and approximate intensity of the air movement in the Right Branch of the Velká Ondrášova Cave (photo by J. Lenart).

There were six monitoring sessions between February 2015 and April 2015, one in August 2015, and two more in March 2018. They involved a measurement of the cave airflow velocity (AF_{in}) within the narrow cross-section beyond the entrance (see Fig. 2 for the position) and of the wind velocity (AF_{out}) recorded outside the cave. The cave airflow was measured with the AM-4214SD thermo-anemometer sensor (measuring range from 0.06 to $20 \text{ m}\cdot\text{s}^{-1}$, resolution $0.01 \text{ m}\cdot\text{s}^{-1}$, accuracy $\pm 5\%$), sampled with a 5-sec time step with a built-in datalogger. In order to get an idea about the ventilation, the linear velocity of the cave airflow ($\text{m}\cdot\text{s}^{-1}$ units) was consecutively recalculated into volume velocity ($\text{m}^3\cdot\text{s}^{-1}$ units), counting the flow area of $\sim 0.54 \text{ m}^2$, otherwise, linear velocity was utilized for analysis.

The wind velocity outside the cave was gauged with a M309 mechanic anemometer (TFA Dostmann, measuring range from 0.2 to $30 \text{ m}\cdot\text{s}^{-1}$, resolution $0.1 \text{ m}\cdot\text{s}^{-1}$, accuracy $\pm 5\%$), mounted on a photographic tripod $\sim 1.3 \text{ m}$ above the ground, and recorded with a camera for later reading off with a 5-sec time step. Time synchronization of all the monitoring devices during the sessions was ensured with a DCF-77 radio signal reception.

RESULTS AND ANALYSIS

Ventilation pattern

A qualitative assessment of the ventilation within the cave took place twice, in summer and winter: (i) on June 1, 2012, in conditions of $\Delta T \sim -15.1^\circ\text{C}$ and (ii) on February 28, 2013, when $\Delta T \sim 3.4^\circ\text{C}$. During

the first observation in summer, no perceptible air currents were detected in the cave interior, except for the airflow identified within superficial parts of the cave and in the entrance. The results of the second investigation in winter are presented in Figure 2. The ventilation of the Upper Shaft and the shallow levels of the cave tends to be rather weak to perceptible and horizontally oriented, while the deeper levels of the cave and the bottommost parts of the branches are characterized by mainly very weak horizontal currents and vertical upward currents. Horizontal currents are almost absent or very weak in the deep levels of the LB, where downward currents were also detected. Although the ED and the wider crevices in the LB and in the Upper Shaft seem to be static, weak air currents flow along their walls.

Long-term temperature data

Along-standing monitoring of the cave air temperature was carried out during winter 2012/2013 (henceforth the winter monitoring) and between July 2013 and November 2014 (henceforth the annual monitoring). The resulting data from the winter monitoring within three cave sites (parts of the ED, LB, and RB) are compared with the outside temperature in Figure 4 (for locations of the loggers see Fig. 2). While the outside temperature fluctuated between -12.9°C and 8.0°C within the winter data, the RB proved to be the most stable part of the cave with a mean temperature of $3.2^\circ\text{C} \pm 0.3^\circ\text{C}$. The LB appeared to be slightly more dynamic with a temperature ranging from 1.1°C to 4.8°C . Based on the winter data, the ED seems to be quite steady, despite its relative proximity to the cave entrance.

During the annual monitoring, only the data from the ED and the RB are available due to loss of the logger located in the LB. A comparison of the ED and LB air temperatures recorded during the annual monitoring is shown in Table 1 and Figure 5. During the annual period, the ED is characterized by a temperature range from 2.4°C to 12.1°C with a mean value of $6.3^\circ\text{C} \pm 2.6^\circ\text{C}$. Compared with the RB, the ED

Fig. 4. Long-term temperature data recorded at the study site during winter monitoring (from December 1, 2012 to February 28, 2013): OUT – outdoor temperature, ED – Entrance Dome, LB – Left Branch, RB – Right Branch (see Fig. 2 for location of the sites).

data reflect a strong seasonality. An annual amplitude of almost 10°C contrasts with the stable and for most of the year colder microclimate of the bottommost part of the RB, characterized by an annual amplitude of 1°C and an average temperature of 3.2°C ±0.2°C.

Table 1. Descriptive statistics of the annual monitoring data (temperature) from two monitoring sites within the Velká Ondrášova Cave – Entrance Dome and Right Branch.

	Entrance Dome	Right Branch
Mean [°C]	6.3	3.2
Median [°C]	6.4	3.2
Mode [°C]	2.7	3.3
Standard deviation [°C]	2.6	0.2
Variance	6.7	0
Coefficient of variation	0.41	0.07
Range [°C]	9.7	1
Minimum [°C]	2.4	2.7
Maximum [°C]	12.1	3.7
Kurtosis	-1.3	-0.8
Skewness	0.1	0.1

Fig. 5. Long-term annual temperature monitoring of two sites within the Velká Ondrášova Cave – Entrance Dome and Right Branch compared with the mean daily air temperature data from the Lysá hora Weather Station.

Field session data

Yielding over 22 hours' worth of data, nine monitoring field sessions were conducted in various outdoor conditions during 2015 (February 1, 2015; February 7, 2015; February 22, 2015; March 7, 2015; March 28, 2015; April 10, 2015; August 27, 2015) and spring 2018 (March 2, 2018; March 5, 2018; Fig. 6). The mean values and standard deviation of important microclimatic variables measured during the sessions are available in Table 2. Within these sessions, the outdoor temperatures T_{out} ranged from -8.6°C to 22.8°C, implying a fluctuation of the temperature gradient ΔT between -13.8°C and 11.4°C. The temperature T_f varied from 3.9°C to 5.4°C, with the exception of the summer session on August 27, 2015, when the value of 15.3°C was recorded. During sessions characterized by strong wind conditions outside the cave, increased variability of the temperature of the flowing cave air T_f , documented by a heightened standard deviation reaching up to ~0.6°C, correlates with the variance of outdoor wind speed AF_{out} and the cave airflow velocity AF_{in} .

AF_{out} was undetectable during two sessions (February 1, 2015 and February 7, 2015), while during the March 28, 2015 session, the highest mean value exceeding 2.85 m·s⁻¹ was recorded. Wind gusts often reached up to 4–5 m·s⁻¹ with a maximum of 7.3 m·s⁻¹ (March 5, 2018). Strong wind conditions with distinct gusts were recorded during the sessions on March 28, 2015; April 10, 2015; August 27, 2015; and March 5, 2018; while the sessions on February 22, 2015; March 7, 2015; and March 2, 2018 were characterized by only random weak wind flurries interrupting quite calm wind conditions.

The average cave airflow velocity AF_{in} fluctuates from 0.27 to 0.61 m·s⁻¹ with a maximum reaching up to 1.25 m·s⁻¹. In the cross-sectional area of ~0.54 m², the mean values of volumetric airflow velocity range between 0.15 and 0.35 m³·s⁻¹ with a maximum of up to 0.71 m³·s⁻¹.

Cave airflow oscillations

Typical oscillations occur when recording the cave airflow velocity. A detailed mechanism of their origin remains unclear, however, Cigna (1968) and Plummer (1969) suggest that the concept of the Helmholtz resonator could explain the signal oscillations. In theory, the resonator is described as an air reservoir with rigid walls and defined geometry. The reservoir is vented through a neck with a determined sectional area and reservoir volume. Based on Rothman (1989) and French (2005), the resonance frequency f [Hz] is given by

$$f = \frac{c_s}{2\pi} \sqrt{\frac{A_r}{L_r V_r}} \quad (1)$$

where c_s is the speed of sound in air [~330 m·s⁻¹], A_r is the cross-section area of the resonator neck [m²], L_r is the length of the resonator neck [m], and V_r is the total volume of the resonator [m³].

Six 15-min segments of cave airflow velocity were selected from the winter/spring 2015 monitoring sessions (February 1, 2015; February 7, 2015; February 22, 2015; March 7, 2015; March 28, 2015; and April 10, 2015) to verify a potential consistency of the taped cave airflow oscillations with the model of the Helmholtz resonator. These signal segments were subjected to Fast Fourier Transform (Rao et al., 2010; Heilbronner & Barrett, 2014) to convert the data and unfold them in frequency domain. Based on the resulting spectral densities and the application of Fisher's test of periodicity (Fisher, 1929; Siegel, 1980), the procedures have identified over 50 significant periods/frequencies corresponding in particular to intervals of 20–50 s / 50–20 mHz. The spectral density maximum of each of the selected records corresponds to the periods of 24, 32, 33, 39, 180, and 450 sec. The results are shown in Figure 7. Considering the resonator parameters, the highest identified statistically significant frequency f equals ~62.5 mHz (16-sec period), A_r ~0.54 m², and L_r ~5 m; the calculated cave volume V_r corresponds to ~76,000 m³. When modifying the frequency f to 30 mHz (33-sec period), the figured V_r equals ~330,000 m³.

Table 2. Mean and standard deviation of the microclimatic variables measured during the monitoring sessions.

Monitoring session	AF_{in}	AF_{out}	T_f	T_{out}	ΔT
	[m·s ⁻¹]	[m·s ⁻¹]	[°C]	[°C]	[°C]
1-Feb-2015	0.46 ± 0.03	—	5.1 ± 0.0	-1.3 ± 0.4	4.6 ± 0.4
7-Feb-2015	0.44 ± 0.03	—	4.9 ± 0.0	-7.8 ± 0.1	11.1 ± 0.1
22-Feb-2015	0.27 ± 0.07	0.14 ± 0.34	5.4 ± 0.2	3.9 ± 0.7	-0.6 ± 0.7
7-Mar-2015	0.37 ± 0.04	0.09 ± 0.24	5.0 ± 0.1	0.6 ± 0.4	2.7 ± 0.4
28-Mar-2015	0.31 ± 0.12	2.85 ± 0.83	3.9 ± 0.6	0.6 ± 0.4	2.7 ± 0.4
10-Apr-2015	0.36 ± 0.14	2.24 ± 0.83	4.6 ± 0.2	9.2 ± 0.5	-6.0 ± 0.5
27-Aug-2015	0.40 ± 0.21	1.40 ± 0.60	15.3 ± 0.5	22.8 ± 0.4	-13.8 ± 0.4
2-Mar-2018	0.61 ± 0.03	0.32 ± 0.45	4.2 ± 0.3	-8.6 ± 0.1	11.4 ± 0.1
5-Mar-2018	0.56 ± 0.18	2.59 ± 1.12	4.1 ± 0.1	-0.4 ± 1.5	2.9 ± 1.5

AF_{in} – cave airflow velocity, AF_{out} – speed of outdoor wind, T_f – flowing cave air temperature, T_{out} – outdoor temperature unaffected by proximity of the cave entrance, ΔT – temperature gradient unaffected by the entrance proximity.

Fig. 6. Field session monitoring data – time series of the measured variables: cave airflow velocity AF_{in} [m·s⁻¹], external wind velocity AF_{out} [m·s⁻¹], flowing cave air temperature T_f [°C], and outdoor atmosphere temperature T_{out} [°C]. Each of the sessions is characterized by the average temperature gradient ΔT . Monitoring sessions: a) 1-Feb-2015, b) 7-Feb-2015, c) 22-Feb-2015, d) 7-Mar-2015, e) 28-Mar-2015, f) 10-Apr-2015, g) 27-Aug-2015, h) 2-Mar-2018, i) 5-Mar-2018. For better mutual comparison, 30-min intervals are separated by gray dashed lines.

Regression analysis

Many authors have already shown that cave airflow can be described as a function of density differences between the cave and the outdoor air mass (Cigna, 1968; Cigna & Forti, 1986; Wigley & Brown, 1971; de Freitas et al., 1982; Spötl et al., 2005; Kowalczyk & Froelich, 2010). A rearrangement of the empirical Darcy–Weisbach equation for turbulent flow in pipes enables a definition of the speed of cave airflow as a function of temperature conditions, cave morphology, and its geometry (Atkinson et al., 1983; Lismonde, 2002). Based on simplified assumptions, confirmed by, e.g., Atkinson et al. (1983), Fernández-Cortés et al. (2006), Baldini et al. (2008), or Faimon et al. (2012), cave airflow can also be expressed as a function of the temperature gradient, introducing this variable as an alternative and simplifying airflow predictor.

Our data on airflow were approximated with three relevant regression models, although many more models could be examined, combining more airflow predictors, as follows from de Freitas et al. (1982) or Faimon et al. (2012).

Ohata et al. (1994) and Luetscher & Jeannin (2004) have demonstrated that the speed of cave airflow is proportional to the square root of the temperature gradient ΔT . Therefore, the first model examining this relation is the square root model (SRM),

$$AF_{in} = b_0 + b_1 \sqrt{|\Delta T|} \quad (2)$$

where AF_{in} represents the speed of cave airflow [m·s⁻¹] as a dependent variable, ΔT is the temperature gradient [°C] introduced as an independent variable, b_0 is an intercept, and b_1 is a coefficient. The second approach is represented by the linear model (LM),

Fig. 7. Spectral analysis of selected 15-min segments of the cave airflow data from six monitoring sessions: a) 1-Feb-2015; b) 7-Feb-2015; c) 22-Feb-2015; d) 7-Mar-2015; e) 28-Mar-2015, f) 10-Apr-2015. Hamming weights: 0.0357, 0.2411, 0.4464, 0.2411, 0.0357.

$$AF_{in} = b_0 + b_1 \Delta T \quad (3)$$

and, finally, the quadratic model (QM) approximated the airflow data,

$$AF_{in} = b_0 + b_1 \Delta T + b_2 (\Delta T)^2 \quad (4)$$

where the additional coefficient b_2 is used. The fitting of the experimental airflow data and the b_0 , b_1 , and b_2 calculations were done using the least square method (Gelman & Hill, 2007) (Table 3). However, only the cave airflow data attributed to $AF_{out} \sim 0$ (zero-valued speed of outdoor wind) enter the analysis (number of observations, $n = 4,206$) to avoid any variance of the data caused by a dynamic driver, which is analyzed separately in the next chapter.

Table 3. Parameter estimates of the discussed regression models.

		Parameter estimates			
		estimate	SE	t-value	p-value
LM	b_0	0.3016	0.0014	215.7	0
	b_1	0.0243	0.00033	73.9	0
SRM	b_0	0.2135	0.00219	97.4	0
	b_1	0.0972	0.00118	82.2	0
QM	b_0	0.273	0.00107	254.9	0
	b_1	0.0517	0.00047	108.8	0
	b_2	-0.0032	0.00005	-66.0	0

For a better idea of the problem, the relation of complete cave airflow data to temperature gradient ($n = 15,324$) is given in Figure 8A; while the regression analysis of filtered data, the model parameters, and the results of analysis of variance (ANOVA) are shown in Figure 8B and in Table 4. Verifying statistical significance, none of the p -values of the models and their parameters exceed the 0.05 level of significance. Based on coefficients of determination, the best-fitting regression model was the QM ($R^2 = 0.79$), while less

well-fitting values were demonstrated by the SRM ($R^2 = 0.62$) and the LM ($R^2 = 0.57$). The intercept value b_0 ranges between 21.35×10^{-2} and 30.16×10^{-2} , the coefficient b_1 varies from 2.43×10^{-2} to 9.72×10^{-2} , and the single parameter b_2 reaches -0.32×10^{-2} .

Statistical testing

During strong wind intervals, visible water steam was clearly recognized in front of the cave. A brief look on the raw session data suggests the influence of external wind on the cave ventilation. The sessions that logged strong external wind conditions are characterized by a cave ventilation frequently reaching up to $1 \text{ m} \cdot \text{s}^{-1}$, and by a distinct variance (Fig. 6). The possible connection between the outdoor wind and the cave ventilation is verified in a statistical manner. Therefore, correlation analysis and testing for variance were chosen to examine potential links between the variables recorded during the monitoring sessions.

The dataset containing all recorded and derived variables went through filtering. However, unlike in the regression analysis, only the data attributed to $AF_{out} > 0$ ($n = 5,224$) enter the correlation analysis, examining possible relations between the variables AF_{in} , AF_{out} , T_f , T_{in} , T_{out} , T_{out}^* , ΔT , and ΔT^* . Representing outliers, data from the summer session on August 27, 2015 were also excluded and analyzed separately.

Examining the $AF_{out} - AF_{in}$ relation within the filtered data has shown no link between these variables (correlation coefficient $r = 0.09$). However, a moderate negative correlation between AF_{out} and the temperature of flowing cave air T_f ($r = -0.56$) has emerged within the correlation matrix (Table 5). As has been shown by the analysis, the external wind speed AF_{out} is connected to the outdoor temperature T_{out}^* ($r = -0.42$) and the derived temperature gradient ΔT^* ($r = 0.42$). The $AF_{in} - \Delta T$ ($r = 0.34$) and $AF_{in} - \Delta T^*$

Table 4. Results of the analysis of variance (ANOVA) of the discussed models.

Model	R ²	Regression			Residual			F-value	p-value
		SS	DF	MS	SS	DF	MS		
LM	0.57	19.76	1	19.7622	15.21	4203	0.0036	5459.8	0
SRM	0.62	21.56	1	21.5577	13.42	4203	0.0032	6752.8	0
QM	0.79	27.51	2	13.7537	7.47	4202	0.0018	7738.7	0

Fig. 8. Relationship between cave airflow velocity AF_{in} and temperature gradient ΔT from field monitoring data: A – all unfiltered session data ($n = 15,324$); B – regression models of filtered data ($n = 4,206$) characterized by zero-valued wind velocity AF_{out} . Red-colored data are the selected data fitted with the SRM, QM and LM.

($r = -0.19$) relations were evaluated as weakly correlated. Within the excluded dataset containing the summer data of August 27, 2015, analysis outcomes have pointed out a weak relation of $AF_{in} - AF_{out}$ ($r = 0.36$).

Testing for variance has been used to determine whether the variability of AF_{in} under strong external wind conditions is significantly higher than its variance under calm wind conditions. The signal of cave airflow from session data was separated into two equally sized datasets based on AF_{out} . The first dataset represents a signal with non-zero wind velocity

($AF_{out} > 0$), while the other contains data characterized by a zero-valued speed of wind ($AF_{out} \sim 0$). Both the datasets have been tested with an F -test for equality of variance, whose results are shown in Table 6. The assessed variance equals 0.017 for the $AF_{out} > 0$ dataset and 0.008 for the $AF_{out} \sim 0$ set. Based on 4,205 observations, the F -test supports the alternative hypothesis that the variances of both datasets are not equal at 0.05 significance level. It is worth noting that the average of AF_{in} within the $AF_{out} > 0$ set is $0.32 \text{ m}\cdot\text{s}^{-1}$, while within the $AF_{out} \sim 0$ set, the average AF_{in} reaches $0.38 \text{ m}\cdot\text{s}^{-1}$.

Table 5. Correlation matrix of the logged and derived variables from the filtered session data.

	AF_{in}	T_f	T_{in}	T_{out}^*	T_{out}	ΔT^*	ΔT	AF_{out}
AF_{in}	1.00	-0.22	-0.60	0.19	-0.36	-0.19	0.34	0.09
T_f	-0.22	1.00	0.29	0.73	0.52	-0.73	-0.51	-0.56
T_{in}	-0.60	0.29	1.00	0.00	0.63	0.00	-0.60	-0.01
T_{out}^*	0.19	0.73	0.00	1.00	0.88	-1.00	-0.88	-0.42
T_{out}	-0.36	0.52	0.63	0.88	1.00	-0.88	-1.00	0.01
ΔT^*	-0.19	-0.73	0.00	-1.00	-0.88	1.00	0.88	0.42
ΔT	0.34	-0.51	-0.60	-0.88	-1.00	0.88	1.00	-0.02
AF_{out}	0.09	-0.56	-0.01	-0.42	0.01	0.42	-0.02	1.00

AF_{in} – cave airflow velocity, T_f – flowing cave air temperature, T_{in} – cave air temperature (Entrance Dome), T_{out}^* – outdoor temperature measured in front of the cave, T_{out} – outdoor temperature unaffected by proximity of the cave entrance, ΔT^* – temperature gradient influenced by the entrance proximity, ΔT – temperature gradient unaffected by the entrance proximity, AF_{out} – speed of outdoor wind.

Table 6. Results of the F -test of equality of variance: F – test statistic, F_{crit} – critical test statistic, P ($F \leq f$) – probability of null hypothesis truthfulness.

	$AF_{out} > 0$		$AF_{out} \sim 0$
Mean [$\text{m}\cdot\text{s}^{-1}$]	0.32		0.38
Variance	0.017		0.008
Frequency	4205		4205
F		2.06	
P ($F \leq f$)		0	
F_{crit}		1.05	

DISCUSSION

Airflow pattern and magnitude

In this study, we used a chemical tracer to visualize a low-velocity air movement and to map the airflow routes within the VOC. Besides utilizing diverse tracers (Halbert & Michie, 1971), other different methods can be used for airflow detection, such as the application of laser light sheet technique (Magne et al., 2017) or the use of neutral buoyancy balloons (de Freitas et al., 1982).

The results have shown a predominantly static character of most of the cave. In winter, the relatively warmer air mass within the cave tends to be transferred by numerous vents out of the cave. Although undetectable within most of the cave length in summer, the airflow was distinct within the shallowest parts of the cave. The monitoring session on August 27, 2015, executed in conditions of $\Delta T \sim -13.8^\circ\text{C}$, recorded a magnitude and variability of airflow comparable with data from winter sessions. Being affected by external wind, the ventilation regime of the VOC cannot be assessed by the traditional microclimatic classification by Geiger (1966). It follows from the complex cave anatomy that there are a number of vents above the cave, enabling an intensive bidirectional energy-mass exchange between the cave and its outer environment. It results in a rather dynamic temperature regime of the cave, as confirmed by over one-year-long continual temperature monitoring in the ED, pointing to an annual temperature amplitude of $\sim 10^\circ\text{C}$. In contrast, the deep parts of both the LB and the RB manifest a stable microclimate, as documented by a stagnant airflow and a total temperature amplitude below 1°C . Comparing the LB and the RB, the former turns out to be a little more dynamic than the latter, a fact confirmed by the previous monitoring performed by Lenart (2012) in 2009 and 2010. The RB is isolated within the central part of the ridge and reaches deeper levels of the rock massif (the temperature monitoring site is located ~ 35 m deep), while the relatively shallower passages of the LB run out southward quite close to the gravitationally induced rocky trench, situated ~ 20 m lower within the southwestern slope.

The mean cave airflow velocity AF_m reached values between 0.27 and $0.61 \text{ m}\cdot\text{s}^{-1}$ with a maximum exceeding $1.25 \text{ m}\cdot\text{s}^{-1}$, being comparable with similar values recorded in other caves, e.g., Hollow Ridge Cave in Florida, USA (Kowalczyk & Froelich, 2010); Fuji Ice Cave in Japan (Ohata et al., 1994); or King Solomons Cave in Tasmania (Russel & MacLean, 2008). The absolute values of the velocity exceed the rates of numerous known caves, e.g., Niedźwiedzia Cave in Poland (Pflitsch & Piasecki, 2003); Kartchner Caverns in Arizona, USA (Buecher, 1999); or the Císařská Cave in the Czech Republic (Faimon et al., 2012). However, e.g., Pflitsch et al. (2010) reported airflow rates reaching over $6 \text{ m}\cdot\text{s}^{-1}$ in S & G Cave in South Dakota (USA) and an airflow velocity rising up to almost $10 \text{ m}\cdot\text{s}^{-1}$ was recorded within the Vjetrenica (Windy) Cave in Herzegovina (Milanović, 2018).

Bögli (1980) reported airflow velocity over $46 \text{ m}\cdot\text{s}^{-1}$ measured in the Pınargözü Cave (Turkey), exceeding the airflow velocity maximum of the VOC almost thirty-seven times.

As implied from the analysis, ventilation rates of the VOC during active ventilation regime correspond to $540\text{--}1,260 \text{ m}^3\cdot\text{h}^{-1}$, amounting to $\sim 13,000\text{--}30,000 \text{ m}^3$ per day. This result is comparable with data from Kartchner Caverns in Arizona, USA (Buecher, 1999), where the values of $\sim 12,000 \text{ m}^3$ per day were recorded. In contrast, air mass with the rates of $7,260 \text{ m}^3\cdot\text{h}^{-1}$, corresponding to $\sim 175,000 \text{ m}^3$ per day, is supposed to be ventilated in the Buddhist Cave, China (Christoforou et al., 1996). The values of $48,600 \text{ m}^3\cdot\text{h}^{-1}$ corresponding to $\sim 1,160,000 \text{ m}^3$ per day, were reported by Freitas et al. (1982) from the Glowworm Cave, New Zealand. However, owing to the heavily disintegrated rock environment of the VOC (Lenart et al., 2014), it may vent much more air mass by other conduits, represented by numerous cracks and relaxed zones within the rock massif above the cave. Thus, the above determined ventilation is related to just one vent and needs to be taken for a minimum value.

Cave airflow oscillations

Resonance of cave airflow has already been analyzed by many authors in the past (e.g., Moore & Nicholas, 1964; Eckler, 1965; Peters, 1965; Cigna, 1968; Plummer, 1969; Russel, 1974), recently in more detail by Bérest et al. (1999), Badino (2010), Faimon et al. (2012), Lang & Faimon (2012), and this phenomenon has been examined even on Mars (Williams et al., 2017). A prediction of cave volume and structure by means of the Helmholtz resonator seems to be feasible in certain cases (Plummer, 1969; Rothman, 1989). Spectral analysis applied to the cave airflow signal has detected multiple different frequencies, questioning the appropriateness of the resonance model applied to the VOC, since the cave resonance would produce only one principal frequency. According to assumptions based on the cave mapping by Wagner et al. (1990, Fig. 2), the volume inferred from the resonance model ($\sim 76,000 \text{ m}^3$) by applying the highest traced frequency seems to be meaningless. Modifying the model parameters in reasonable ranges does not cause the figured volume to approach its real value.

There are several aspects that could cause the model to fail: (i) the complex morphology of the cave, unsuitable for a definition of the reservoir geometry (a disputable cross-section and length of the reservoir neck), (ii) heavily fractured rock massif with numerous cracks blocked by different-sized colluvial material, resulting in multiple vents in the reservoir, (iii) evident dependence of the cave ventilation on external wind, suggesting that the variation of the external wind intensity could be responsible for the oscillations. Faimon et al. (2012) and Lang & Faimon (2012) mention similar factors disabling the model applicability in the case of the Císařská Cave (Czechia) and consider the fluctuating temperature gradients near the cave entrances as the primary cause of the

oscillations. In the case of the VOC, accumulation and wind-induced dispersion of the warm air mass in front of the cave entrance, responsible for the temperature variability, has been also observed. Their presence is documented by results of the correlation analysis, i.e., negatively correlated $T_f - \Delta T^*$ and positively correlated $AF_{out} - \Delta T^*$ links (see below).

Airflow as a function of the temperature gradient

Various models of cave airflow have already been proposed by a number of authors, including changes in inner/outer air temperature and/or air densities, cave wall temperature, atmospheric pressure, frictional properties of the cave for fluid flow, or site-specific geometric factors of the cave (e.g., de Freitas et al., 1982; Christoforou et al., 1996; Kowalczyk & Froelich, 2010; Faimon et al., 2012). In this study, using the same simple independent variable, three different regression models were compared with each other, confirming the dependence of the cave airflow on the temperature gradient ΔT . Indicating statistically significant relations at the 95% confidence level for all models, the LM accounts for 57% of total variance of the airflow data, while the SRM elucidates 5% more, documenting the usability of the simplified Darcy-Weisbach equation. Faimon & Lang (2013) reported a similar fitting of the SRM, explaining the ventilation within the Cisařská Cave. Ohata et al. (1994) and Luetscher & Jeannin (2004) proved the suitability of the SRM with better results, applying the model to caves with different geometries.

Nonlinearity of the airflow data was highlighted by the best-fitted QM, defining almost 80% of the airflow data variance. The QM suggests the cave airflow to culminate at $\sim 0.48 \text{ m} \cdot \text{s}^{-1}$, when ΔT reaches $\sim 8^\circ\text{C}$. According to this model, further ΔT increase could cause the cave ventilation to be attenuated. The natural nonlinearity of the Darcy-Weisbach equation explains this effect only partially (Jeannin, 2001). The decrease in ventilation may be explained by possible unequal cooling of the shallowest cave parts. The strongly fractured and disintegrated rock massif makes the air mass exchange between the outside and the shallow cave parts very intense, resulting in unequal cooling of some superficial segments and the successive slowing down of the ventilation. If time-delayed or unrepresentative cave air temperature T_{in} (not reflecting the cooling of the ventilated superficial parts) was recorded by measurement, the decrease in ventilation would be explainable.

Airflow caused by a dynamic driver

The possible influence of wind outside a cave on air movement inside the cave is frequently mentioned by many authors (Geiger, 1966; Cigna, 1968; Tuttle & Stevenson, 1978; de Freitas et al., 1982; Pflitsch & Piasecki, 2003; Kowalczyk & Froelich, 2010). Generally perceived as a less usual mechanism, the moving of fluids in both inside (e.g., streams, flood) and outside the cave (e.g., external wind) are considered as a dynamic driver of cave ventilation (Cigna, 1968). However, the outdoor wind as a dynamic driver is often questioned (Christoforou et al., 1996; Russell

& MacLean, 2008; Lang & Faimon, 2013). Tuttle & Stevenson (1978) admit its role only in instances of caves with a short simple tunnel between their two or more entrances or shallow caves with a large entrance. On the contrary, Williams & McKay (2015) suppose the external wind to significantly control the balance of cave ice deposits in cases of specific cave morphology. Nachshon et al. (2012) quantified the effect of wind-induced venting of surface fractures within soil and rock environment based on field measurements and laboratory experiments.

No direct link between the external wind and the cave airflow has emerged from the correlation matrix, with the exception of the summer monitoring session. Analysis suggests that the temperature of the flowing cave air T_f could be inversely proportional to the outdoor wind AF_{out} ($r = -0.56$). It means that stronger wind could allow the colder cave air mass to be evicted from the cave. However, it is not clear whether the air from deeper cave levels participates in this ventilation or whether the cave works as a flow heater, warming up the air entering the superficial parts of the cave through the surface cracks. High absolute R -values (0.73) of the $T_f - \Delta T^*$ (T_{out}^*) relations are a simple consequence of warm air accumulation in front of the cave entrance. Equally, the $AF_{out} - \Delta T^*$ (T_{out}^*) links (absolute R -value 0.42) document the dispersion of the warm air mass induced by the increasing speed of outdoor wind.

Testing for variance, performed within two AF_{in} datasets differing in speed of wind AF_{out} , seems to be claiming the $AF_{in} - AF_{out}$ connection. The AF_{in} set, characterized by non-zero-valued wind velocity ($AF_{out} > 0$), reflects a significantly higher variance (by more than 110%) than the set documenting the cave airflow under calm wind conditions ($AF_{out} \sim 0$). This result suggests the external wind to be part of the driving forces of the cave ventilation. However, the $AF_{out} > 0$ dataset turns out to have a lower mean value of AF_{in} by almost 20%, compared with the $AF_{out} \sim 0$ dataset. It seems to be in contradiction with direct observations in the field, since strong wind conditions intensified water vapor formation near the cave, implying an increased cave airflow velocity. The discrepancy may indicate that intensive cave ventilation does occur through other cracks and vents under strong wind conditions, while the airflow within the entrance parts stagnates. It seems to be a plausible explanation, considering the geomorphic settings of the cave, the surface cracks and numerous relaxed zones identified above the cave (Pánek et al., 2011). However, further study is necessary to confirm this hypothesis.

At any rate, the external wind causes the superficial parts of the cave to be ventilated. It is probably achieved by inducing pressure changes by the wind at the ground-atmosphere boundary. This mechanism is called the Bernoulli effect (Nachshon et al., 2012) and explains the active ventilation regime of the cave in summer. However, a detailed knowledge of how exactly this effect works within the VOC is unclear, since no airflow data on the ventilation of other vents of the cave are available.

CONCLUSION

This work dealt with a complex analysis of the cave airflow and ventilation within the Velká Ondrášova Cave in the Outer Western Carpathians, Czechia. The results of long-term temperature monitoring have shown a strong seasonality of temperature within the near-surface parts of the cave, as an annual temperature amplitude of $\sim 10^{\circ}\text{C}$ was recorded in the Entrance Dome. Different temperature regimes of the Left and Right Branches of the cave have been explained by different depth, position, and morphology of both parts.

The temperature monitoring is in agreement with the airflow dynamics mapped inside the cave by a chemical tracer. During winter, air mass movements are detectable within almost the whole cave length, fading with the increasing depth of the cave. In summer, all the cave parts are static, except for the shallowest parts of the cave, representing vents within relaxed zones of rock massif and cracks blocked by colluvial sediments.

The cave airflow measurement pointed out an average velocity ranging between 0.27 and $0.61\text{ m}\cdot\text{s}^{-1}$ and a maximum velocity of $1.25\text{ m}\cdot\text{s}^{-1}$. However, the equivalent average ventilation rate $540\text{--}1,260\text{ m}^3\cdot\text{h}^{-1}$ corresponding to $\sim 13,000\text{--}30,000\text{ m}^3/\text{day}$ should be taken as a rough estimate of the real value, considering the extensive vent system of the cave determined by the complex cave morphology.

As suggested by statistical testing, ventilation of the superficial cave parts is probably caused by outdoor wind. It induces pressure fluctuations at the ground-atmosphere interface, triggering the ventilation of the shallow cave parts, a mechanism called the Bernoulli effect. However, during winter, the ventilation of deeper cave levels is driven by the temperature gradient, since almost 80% of the analyzed airflow variability has been explained by this predictor within regression analysis.

The model of the Helmholtz resonator appeared to be unsuitable for an explanation of the oscillations occurring on the records of the cave airflow velocity. The analyzed signal of the cave airflow was characterized by multiple frequencies in spectral domain. The cave volume of $\sim 76,000\text{ m}^3$ inferred from the resonance model by applying the highest traced frequency ($62.5\text{ mHz}/16\text{ s}$) seems to be meaningless, based on the mapping of the Velká Ondrášova Cave by Wagner et al. (1990). The resonance model failure could have been caused by the unsuitable cave geometry, heavily fractured rock massif, or the influence of external wind on the cave airflow. Confirmed by correlation analysis, repetitive accumulation and wind-induced dispersion of warm air occur in front of the cave entrance, being another possible trigger of the cave airflow oscillations.

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