COBISS: 1.01

A CASE STUDY OF ANTHROPOGENIC IMPACT ON THE CO_2 LEVELS IN LOW-VOLUME PROFILE OF THE BALCARKA CAVE (MORAVIAN KARST, CZECH REPUBLIC)

ŠTUDIJ VPLIVA OBISKOVALCEV NA KONCENTRACIJE CO_2 V MANJŠIH IN SLABO POVEZANIH JAMSKIH PROSTORIH: PRIMER IZ JAME BALCARKA NA MORAVSKEM KRASU V REPUBLIKI ČEŠKI

Marek LANG*[1], Jiří FAIMON[1] & Camille EK[2]

Abstract UDC 551.442:543.272.62(437.3)

Marek Lang, Jiří Faimon & Camille Ek: A case study of anthropogenic impact on the CO_2 levels in low-volume profile of the Balcarka Cave (Moravian Karst, Czech Republic)

Anthropogenic impact on CO_2 levels was studied in the low-volume chamber connected with the low-profile corridor in Balcarka Cave, the show cave in Moravian Karst, during the period of limited ventilation. Modeling showed that the natural CO_2 levels were controlled by the CO_2 fluxes (up to ~ 3.14×10^{-2} mol s^{-1}) from adjacent spaces. These fluxes changed with cave airflows and ventilation modes. Two main components of anthropogenic impact were recognized: (1) visitor breathing and (2) visitor movement. The CO_2 input derived from individual visitor groups varied from 1.96×10^{-4} to 2.45×10^{-3} mol s^{-1}, which was the significant part of the CO_2 fluxes from adjacent spaces. The visitor movement induced the airflows up to 0.2 $m^3 s^{-1}$. They exceeded the natural airflows (up to 3.2×10^{-3} $m^3 s^{-1}$) by factor of more than 60. These airflows caused cave ventilation mode's switching and, significant drop of CO_2 fluxes/levels due to changed ventilation. The study therefore indicates that various anthropogenic influences in show cave can balance and neutralize each other, in dependence on cave morphology and seasonal conditions.

Keywords: airflow, anthropogenic impact, carbon dioxide, dynamic model, show cave, ventilation mode.

Izvleček UDK 551.442:543.272.62(437.3)

Marek Lang, Jiří Faimon & Camille Ek: Študij vpliva obiskovalcev na koncentracije CO_2 v manjših in slabo povezanih jamskih prostorih: primer iz jame Balcarka na Moravskem krasu v Republiki Češki

Raziskovali smo vpliv obiskovalcev na koncentracijo CO_2 v jamski dvorani z majhno prostornino v turistični jami Balcarka na Moravskem krasu. Dvorana je z drugimi deli jame povezana z manjšim rovom, raziskave pa so potekale v času, ko je naravno prezračevanje majhno. Z modeliranjem smo pokazali, da so naravne vrednosti CO_2 določene s tokom iz sosednjih prostorov. Te dosegajo vrednosti do ~ 3.14×10^{-2} mol s^{-1} in se spreminjajo z intenzivnostjo naravnega prezračevanja. Obiskovalci na koncentracijo CO_2 vplivajo z dihanjem in gibanjem po jami. Tok CO_2, ki ga prispevajo skupine obiskovalcev, znaša med $1{,}96 \times 10^{-4}$ mol s^{-1} in $2{,}45 \times 10^{-3}$ mol s^{-1}, kar je primerljivo z naravnimu dotokom. Zračni tok zaradi gibanja obiskovalcev pa znaša do 0,2 $m^3 s^{-1}$, kar je 60 krat toliko, kot je tok naravne ventilacije v času meritev. Tako prisilno prezračevanjen na opazovanem mestu pomembno znižuje koncentracijo CO_2. Obiskovalci torej na različne način vplivajo na koncentracijo CO_2, pri čemer se ti vplivi lahko tudi izničijo.

Ključne besede: zračni tok, antropogeni vpliv, ogljikov dioksid, dinamični model, turistična jama, način prezračevanja.

INTRODUCTION

Carbon dioxide (CO_2) plays a key role in carbonate karst system by participating on rock karstification (Stumm & Morgan 1996), karst water hydrogeochemistry (Spötl *et al.* 2005; Faimon *et al.* 2012b), calcite speleothem formation (Dreybrodt 1999; Frisia *et al.* 2011) or speleothem corrosion (Sarbu & Lascu 1997; Dublyansky & Dublyan-

---

[1] Department of Geological Sciences, Faculty of Sciences, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic.
[2] Department of Geology, University of Liège, 4000 Liège, Belgium

Received/Prejeto: 10.02.2014

sky 1998; Tarhule-Lips & Ford 1998). The soil/epikarstic CO_2 is derived from autotrophic/heterotrophic respiration (Kuzyakov 2006). In soils, CO_2 concentrations can vary between 0.1 and 10 % vol. (Miotke 1974; Troester & White 1984). In the cave atmosphere, CO_2 levels range from 0.1 to 1.0 % vol. (Faimon *et al.* 2012c). Generally, enhanced soil/epikarstic CO_2 partial pressure, $^{(SEK)}P_{CO_2}$, is responsible for limestone dissolution and cave development (Baldini *et al.* 2006). The lower CO_2 partial pressure in cave atmosphere, $^{(C)}P_{CO_2}$, controls CO_2 degassing and calcite precipitation (speleothem growth) (Holland *et al.* 1964).

The instantaneous CO_2 concentrations in cave atmosphere are generally result of balancing the total CO_2 flux into cave with the flux out of cave (Faimon & Ličbinská 2010). The input flux includes (1) natural flux, connected mainly with a direct CO_2 flux from epikarst and with dripwater degassing (Holland *et al.* 1964; Bourges *et al.* 2001; Baldini *et al.* 2008) and (2) anthropogenic flux (stemming from person exhaling in the caves open to visitors) (Faimon *et al.* 2006; Lang *et al.* 2015). Additional local CO_2 fluxes inside cave could be associated with the airflow exchanging between the individual cave passages with different CO_2 concentrations. The CO_2 output flux from cave is associated chiefly with cave airflow.

The driving force of cave airflow is primarily the pressure difference resulting from distinct air densities (de Freitas *et al.* 1982). Since density is particularly a function of temperature, cave airflows are mostly related to the temperature difference, $\Delta T = T_{exterior} - T_{cave}$ [°C], where $T_{exterior}$ is external air temperature and T_{cave} is cave air temperature (Christoforou *et al.* 1996; Pflitsch & Piasecki 2003; Russell & MacLean 2008; Kowalczk & Froelich 2010; Faimon & Lang 2013). Based on the sign of the temperature difference, two ventilation regimes are distinguished. If $T_{exterior} < T_{cave}$, upward airflows are typical; the cave is in the upward airflow ventilation mode (UAF mode). If $T_{exterior} > T_{cave}$, the cave airflow direction is opposite; corresponds to the downward airflow ventilation mode (DAF mode) (see Faimon *et al.* 2012a for details). Based on ventilation extent, Faimon *et al.* (2012a) defined two different ventilation periods of a dynamic cave: (1) the period of active ventilation and (2) the period of limited ventilation. During the active ventilation period, the duration of given ventilation mode exceeds the air residence time in cave. In such a case, the air in the whole cave is completely exchanged. During the limited ventilation period, the duration of given ventilation mode is shorter than the air residence time in the cave. In this case, the airflow direction turns before the complete cave air exchange is reached. Then, only cave entering passages are ventilated.

It is well known that the CO_2 concentrations in show caves are influenced by visitors. This phenomenon was documented by many studies, e.g., Merenne-Schoumaker (1975), Faimon *et al.* (2006), Liñán *et al.* (2008), Milanolo & Gabrovšek (2009), Šebela *et al.* (2013), or Lang *et al.* (2015). It is generally believed that anthropogenic CO_2 contributes to total cave CO_2 level by the net positive flux derived from visitor exhaling. As this article has shown, however, cave visitors can induce some additional so-called "parasitic phenomena" that affect cave ventilation and disturb or even inverse the expected CO_2 increments.

The goal of this study was (1) to analyze comprehensively the anthropogenic impact on the CO_2 levels in the low-profile passages in the Balcarka Cave during the season of limited ventilation, (2) to model quantitatively this effect, and, thus, (3) to contribute to the better understanding the anthropogenically impacted processes in show caves.

METHODS

SITE OF STUDY

The study was performed in the Balcarka Cave in the northern part of Moravian Karst near the village of Ostrov u Macochy (Faimon *et al.* 2012c; Lang *et al.* 2015). Mean annual precipitation in the study area is about ~ 700 mm; mean annual temperature of external atmosphere is about ~8 °C. The cave has been formed in the Upper Devonian limestones of the Macocha Formation. The cave total rock overburden thickness reaches up to ~40 m. The position and sketch map of the cave are given in Fig. 1. The cave consists of a two-level complex of relatively narrow corridors of the total length about 350 m and chambers with rich speleothem decoration. Due to a complex morphology (two levels, three known entrances, and some presumed hidden openings), the cave shows typical dynamic air circulation. The cave is open to tourists with a visitor rate of 30,000 to 40,000 persons per year. As the monitoring site, the Small Chamber of about ~110 m^3 of total volume situated approximately 50 meters from the cave entrance was chosen (Fig. 1). The chamber has been developed on the low-profile cave passage with the cross section from 2 to 5 m^2. The chamber input pas-

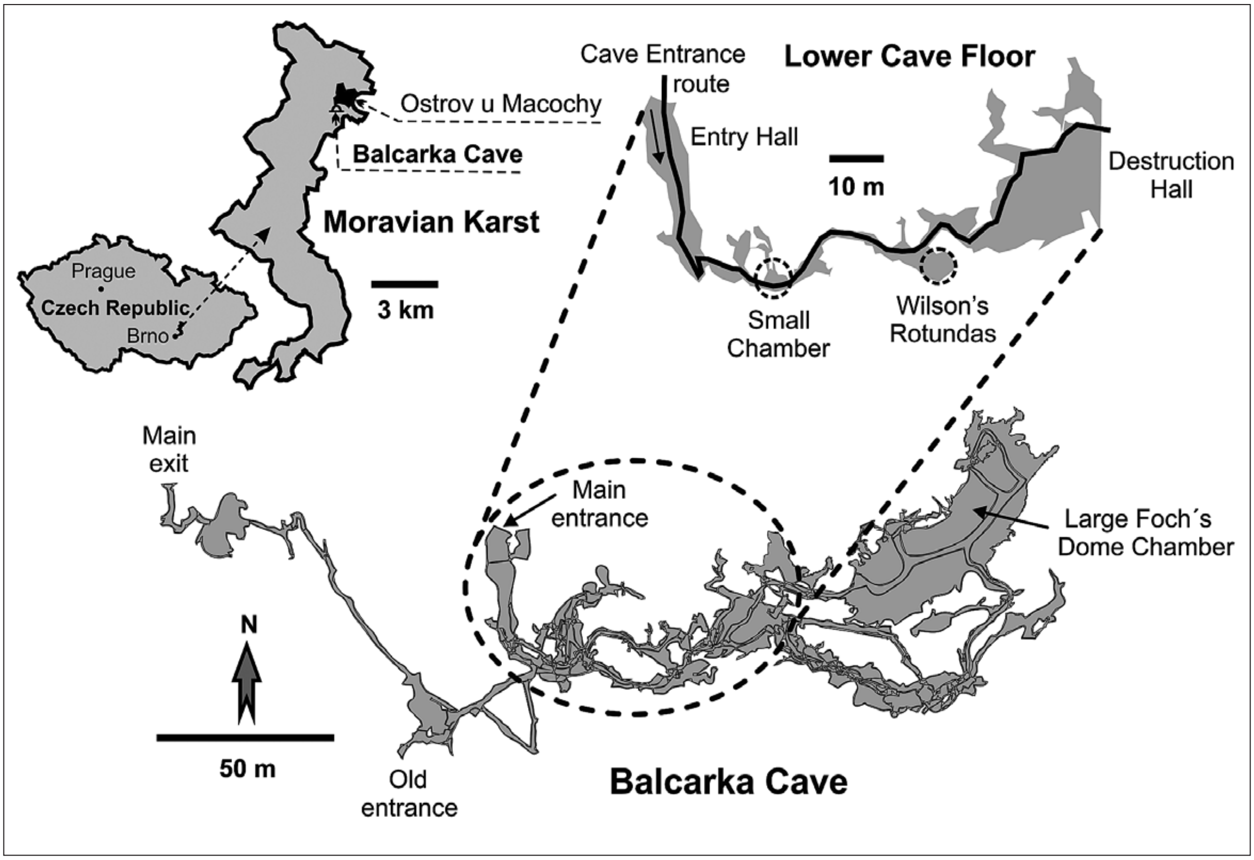

Fig. 1: The cave position and sketch map of the monitoring site.

sage is represented by the narrow corridor with descending staircase from the Entrance Hall. The output passage from the chamber is represented by the narrow corridor of about ~60 meters long leading to Wilson's Rotundas and widening in the Destruction Hall.

MONITORING

Time series of the CO_2 concentrations and cave/external temperature were monitored during a two-day campaign in September 2013. All monitored variables were logged at minute time steps. CO_2 concentrations were detected in the Small Chamber at about 2 meters above the cave floor. CO_2 concentrations were measured by a hand-held device 2-channel IR-detector FT A600-CO_2H linked with ALMEMO 2290-4 V5, Ahlborn, Germany (measuring range: 0 to 10,000 ppmv; accuracy: ±50 ppmv + 2 vol. % of measured value in the range of 0 to 5000 ppmv; resolution: 1 ppmv or 0.0001 vol. %). For modeling, the volume concentration (in ppmv unit) was consecutively recalculated into molar concentration (mol m^{-3}), based on the Ideal Gas Law and given temperature/pressure,

$$c_{CO_2}\,[\text{mol m}^{-3}] = \frac{P}{10^6\,R\,T}\,[\text{ppmv}], \tag{1}$$

where P is barometric pressure [Pa], R is the universal gas constant [R = 8.3144621 J kg^{-1} K^{-1}] and T is temperature [K].

The temperatures for ΔT calculations were logged (i) in the exterior, approximately 50 meters outside the cave, and (ii) in the Small Chamber. Temperature was measured by COMET S3120 data loggers (measuring range: −30 to +70 °C; accuracy: ±0.4 °C).

The visitor numbers and entering time were logged in front of the cave. Time necessary for reaching the site of study (including the guide's commentary) was 7.6±0.1 minutes. For modeling, the time of the site reaching was finely tuned in the range of ±0.5 minute to be consistent with the increasing CO_2 concentration.

RESULTS AND DATA ANALYSIS

DATA

The raw data (48-hour-long time series) of CO_2 concentration together with the temperature difference $\Delta T = T_{exterior} - T_{cave}$ and cave attendance are given in Fig. 2. The CO_2 concentrations principally show a strong variability depending on the temperature difference and airflow direction (Fig. 2a). Two periods of cave visiting connected with walking through the Small Chamber occurred during the monitoring campaign: one period covered 8 tours including 169 persons totally, the second period covered 9 tours including 100 persons totally (Fig. 2b). The data were collected during the season of limited cave ventilation, when external temperatures ranged from 0.8 to 13.8 °C. Based on the almost constant cave site temperature, (T_{cave} ~8.7 to 9.3 °C), the temperature difference ΔT ranged from −8.6 to 5.1 °C (Fig. 2c). The positive values of ΔT correspond to downward airflows (DAF ventilation mode) and the negative values correspond to upward airflows (UAF ventilation mode) (Faimon *et al.*, 2012a; Faimon & Lang, 2013). During DAF mode, the CO_2 concentrations increased: the maxima of CO_2 concentrations reached up to 4.00×10^{-2} mol m^{-3} (930 ppmv) and 3.45×10^{-2} mol m^{-3} (800 ppmv) in the first and second period of DAF mode, respectively. During UAF mode, the CO_2 levels decreased to the minima values of about 2.80×10^{-2} mol m^{-3} (650 ppmv) on average. During both the DAF ventilation periods, the anthropogenic influence is clearly conspicuous on the „natural“ CO_2 levels in the chamber as some disturbances and peaks.

MODELING

Following Lang *et al.* (2015), the conceptual model describing the evolution of CO_2 concentrations in the monitored chamber was proposed. The model consists of three reservoirs, the monitored Small Chamber, and two adjacent reservoirs (Fig. 3). Whereas the monitored chamber is understood as a perfectly mixed reactor, the reservoirs in its vicinity are the source of mass CO_2 fluxes. The ad-

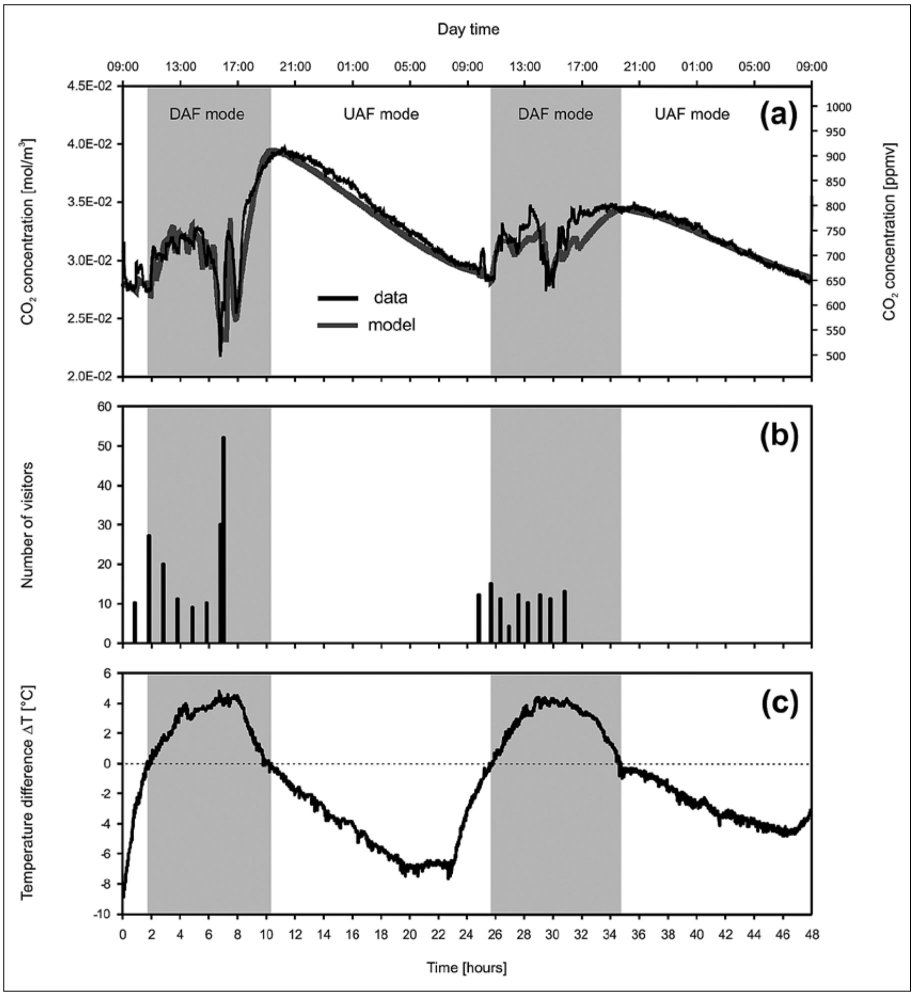

Fig. 2: Balcarka Cava data (Small Chamber): CO_2 concentrations (the grey line represents modeled curve) (a), visitor numbers per individual tours (b), and temperature difference ΔT (c). See text for details.

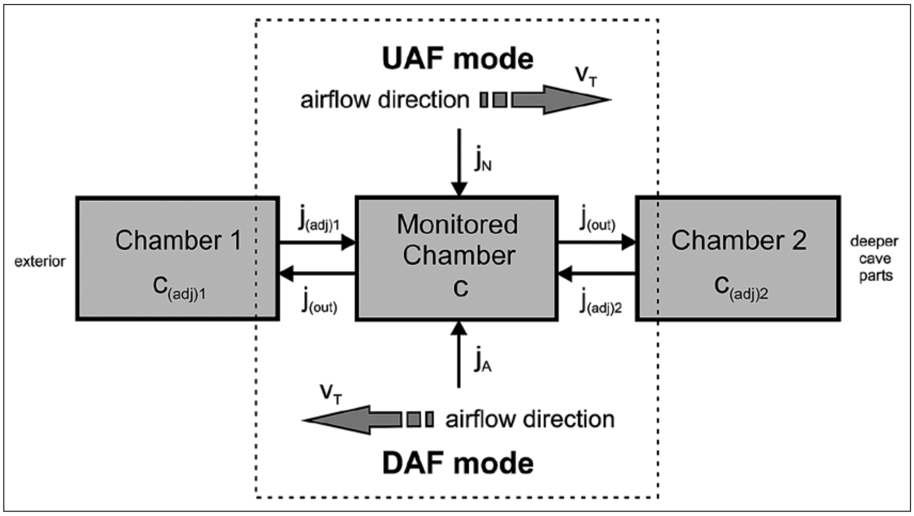

Fig. 3: Conceptual model of CO_2 dynamics in cave chamber atmosphere. Based on Lang et al. (2015).

jacent Chamber 1 represents cave entrance passages and the adjacent Chamber 2 corresponds to the deeper cave passages. The instantaneous CO_2 concentrations in the monitored chamber (the Small Chamber) are given by balancing all the CO_2 fluxes into/out of the chamber. The inputs are (1) natural flux, j_N (the fluxes derived from the diffusion from soils/epikarst and dripwater degassing entering directly the Small Chamber), (2) anthropogenic flux, j_A, derived from human breathing, (3) the input flux from adjacent chamber, $j_{(adj)}$ (driven by cave ventilation), and (4) the output flux, $j_{(out)}$, from the Small Chamber into the adjacent chamber (connected with the cave ventilation). The individual fluxes heading into a reservoir (chamber) are considered positive and the flux heading out of a reservoir is considered negative.

The individual CO_2 fluxes into/out of the reservoir are defined as follows: the natural flux, j_N [mol s^{-1}] is unknown parameter that will be found at modeling. The anthropogenic flux j_A [mol s^{-1}] is given by

$$j_A = j_{(AP)}\,A, \qquad (2)$$

where $j_{(AP)}$ is anthropogenic personal flux [mol s^{-1}] (CO_2 flux normalized to one person) and A is attendance [number of visitors].

The fluxes $j_{(adj)}$ and $j_{(out)}$ [mol s^{-1}] linked to the cave ventilation are expressed as

$$j_{(adj)} = v_T\,c_{(adj)} \qquad (3)$$

and

$$j_{(out)} = -v_T\,c, \qquad (4)$$

where v_T is total volumetric velocity of the airflow through the cave chamber [m^3 s^{-1}], $c_{(adj)}$ is CO_2 concentration in adjacent cave spaces [mol m^{-3}], and c is an instantaneous CO_2 concentration in the Small Chamber atmosphere [mol m^{-3}].

The total volumetric airflow through the cave chamber, v_T, comprises the natural airflow (v_N) and an anthropogenic airflow (v_A). The total volumetric airflow was calculated as

$$v_T = v_N + v_A. \qquad (5)$$

The natural volumetric airflow, v_N [m^3 s^{-1}], was expressed as a function of the temperature difference, ΔT (pressure fluctuations in external atmosphere were ignored). Based on Faimon & Lang (2013), airflows were modeled as turbulent flow

$$v_N = k_{\Delta T}\sqrt{|\Delta T|}, \qquad (6)$$

where $\Delta T = T_{exterior} - T_{cave}$ [°C] and $k_{\Delta T}$ is a proportionality constant [m^3 s^{-1} deg$^{-1/2}$].

The anthropogenic volumetric airflow, v_A [m^3 s^{-1}], was derived as

$$v_A = v_{(AP)} + k_A\,A, \qquad (7)$$

where $v_{(AP)}$ is constant velocity [m^3 s^{-1}] depending on the cross section area of individual person and person moving velocity, and the product $k_A A$ is an effectiveness term (k_A is a proportionality constant [m^3 s^{-1}] and A is attendance [visitor number]).

The total CO_2 flux into reservoir is the sum of all individual fluxes,

$$j = \frac{dn_{CO_2}}{dt} = \frac{Vdc}{dt} = j_N + j_{(AP)}\,A + v_T\,c_{(adj)} - v_T\,c\,, \qquad (8)$$

where n_{CO_2} is total content of carbon dioxide in the chamber atmosphere [mol], t is time [s] and V is the reservoir volume [m^3]. Other symbols have their standard meaning.

After rearranging, it gives

$$\frac{dc}{dt} = \frac{j_N}{V} + \frac{j_{(AP)}\,A}{V} + \frac{v_T\,c_{(adj)}}{V} - \frac{v_T\,c}{V}. \tag{9}$$

Eq. (9) was solved numerically by the Euler's method (see, e.g., Greenspan 2006) with the time step of 0.2 minute. The values of individual model parameters (j_N, $c_{(adj)}$, $k_{\Delta T}$, $j_{(AP)}$, k_A) were firstly roughly adjusted by trial and errors and then fine-tuned by least squares method. The loss function was minimized numerically by the Newton's method. The result of modeling is presented in Fig. 2 as a thick grey line; regression parameters are given in Tab. 1. Note that the different values of $c_{(adj)}$ were used for individual periods of DAF mode ($c_{(adj)\ DAF1}$, $c_{(adj)\ DAF2}$) and UAF mode period ($c_{(adj)\ UAF}$). The chamber total volume V ~110 m^3 was used for modeling.

Principally, the steady state in cave CO$_2$ concentrations can be reached by preserving given conditions for a sufficiently long period. At steady state, the total flux is zero (it corresponds to dc/dt = 0). For the steady state concentration, Eq. (9) yields

$$j_N + j_{(AP)}\,A + v_T\,c_{(adj)} - v_T\,c^{ss} = 0. \tag{10}$$

where c^{ss} is the CO$_2$ steady state concentration [mol s^{-1}].

The rearranging gives

$$c^{ss} = \frac{j_N}{v_T} = \frac{j_{(AP)}\,A}{v_T} + c_{(adj)}. \tag{11}$$

Tab. 1: Resulted model parametes (the Small Chamber, the Balcarka Cave).

Parameters		***Values***
V	[m^3]	110
j_N	[mol s^{-1}]	1.50×10^{-7}
$c_{(adj)\ DAF1}$	[mol m^{-3}]	1.57×10^{-1}
$c_{(adj)\ DAF2}$	[mol m^{-3}]	5.30×10^{-2}
$c_{(adj)\ UAF}$	[mol m^{-3}]	2.30×10^{-2}
$k_{\Delta T\ (DAF)}$	[m^3 s^{-1} deg$^{-1/2}$]	1.18×10^{-3}
$k_{\Delta T\ (UAF)}$	[m^3 s^{-1} deg$^{-1/2}$]	1.08×10^{-3}
$j_{(AP)}$	[mol s^{-1}]	4.90×10^{-5}
k_A	[mol s^{-1}]	3.40×10^{-3}
$v_{(AP)}$	[m^3 s^{-1}]	2.63×10^{-2}

DISCUSSION

NATURAL INFLUENCE

The CO$_2$ variations in the Small Chamber during the monitoring campaign roughly follow variations of the temperature difference, ΔT (Fig. 2). The mean CO$_2$ concentrations in the range from 2.2×10^{-2} to 4×10^{-2} mol m^{-3} (from 500 to 930 ppmv) are comparable with the values referred by Dragovich & Grose (1990), Spötl *et al.* (2005), Baldini *et al.* (2006), Lario & Soler (2010) or Lang *et al.* (2015). Based on the sign of temperature difference, 4 periods with different ventilation modes were distinguished in CO$_2$ signal: 2 periods of positive temperature difference, corresponding to the DAF mode and 2 periods of negative temperature difference, corresponding to the UAF mode (Fig. 2). The switching of DAF and UAF ventilation modes during diurnal cycle is typical for the *period of limited ventilation* (Faimon *et al.* 2012a).

The modeling showed that the natural CO$_2$ levels (the levels without any anthropogenic flux) in the chamber were controlled by the CO$_2$ fluxes from adjacent spaces driven by cave airflows. Whereas the lower CO$_2$ concentration (due to the interaction with external atmosphere) are transported from cave entrance passages at UAF mode, the higher CO$_2$ concentrations are transported from deeper cave passages or even epikarst at DAF mode (Lang *et al.* 2015) (Fig. 3). In fact, the CO$_2$ concentrations in adjacent spaces, $c_{(adj)}$, were not available due to (1) uncertainty in the detailed airflow path and (2) inaccessibility of these spaces. Therefore, the concentrations $c_{(adj)}$ were searched as the parameters at modeling by regression analysis (Tab. 1). The found values of adjacent CO$_2$ concentrations are roughly consistent with the values presented by Lang *et al.* (2015). The value corresponding to the first period of DAF mode significantly exceeds the values at the second period of persisting DAF mode. It indicates that the CO$_2$ source in adjacent sites can be quickly exhausted. In addition to the sites deeper in cave, the adjacent sites could be hidden upper floors or even some partly closed openings (e.g., sinkholes) representing a cross section into epikarst.

The direct natural CO_2 flux into the Small Chamber obtained from modeling was very low, j_N ~1.50×10^{-7} mol s^{-1} (Tab. 1). Based on the orthogonal projection plane of the cave chamber (about 28 m^2), the natural flux gave the mean specific flux normalized to 1 m^2 of 5.36×10^{-9} mol m^{-2} s^{-1}. This value is lower in comparison with the value $(0.28–1.1) \times 10^{-7}$ mol m^{-2} s^{-1} estimated earlier for the Balcarka Cave (Lang *et al.* 2015), the value of 7.59×10^{-8} mol m^{-2} s^{-1} for the Císařská Cave (Faimon *et al.* 2006), or the mean value of 6.51×10^{-6} mol m^{-2} s^{-1} for Srednja Bijambarska Cave (Milanolo & Gabrovšek 2009). Besides, this value is incomparable with the extreme value of 1.78×10^{-4} mol m^{-2} s^{-1} mentioned for the Aven d'Orgnac Cave by Bourges *et al.* (2001).

The total natural CO_2 flux into the Small Chamber is the sum of (i) direct flux and (ii) flux from adjacent spaces, driven by cave ventilation. Based on the ventilation mode, the $c_{(adj)}$ fluxes into the Small Chamber varied in the ranges from 1.50×10^{-7} to 3.14×10^{-2} mol s^{-1} (DAF mode) and from 1.50×10^{-7} to 4.6×10^{-3} mol s^{-1} (UAF mode). In comparison with the very low direct flux (j_N ~1.50×10^{-7} mol s^{-1}), the fluxes from the adjacent chamber spaces clearly dominate in the total natural CO_2 flux into the Small Chamber.

ANTHROPOGENIC INFLUENCE

The CO_2 level in low-profile chambers can be anthropogenically influenced (1) directly, by visitor breathing during the tours (Faimon *et al.* 2006; Milanolo & Gabrovšek 2009; Lang *et al.* 2015), or (2) indirectly, via influencing the cave airflows.

Influence of visitor respiration

The anthropogenic impact of visitor breathing on CO_2 level in the Small Chamber is clearly visible (Fig. 2a). The CO_2 increases are represented by disturbances superimposed on the roughly smooth "natural" CO_2 level. Based on model results, the anthropogenic CO_2 fluxes during the individual visiting periods of the monitoring campaign varied between 4.42×10^{-4} and 2.45×10^{-3} mol s^{-1} (first period) or 1.96×10^{-4} and 7.35×10^{-4} mol s^{-1} (second period). The CO_2 flux related to one person, $j_{(AP)}$ ~ 4.90×10^{-5} mol s^{-1} person^{-1} (Tab. 1), is consistent with the value of 5.35×10^{-5} mol s^{-1} person^{-1} measured by Lang *et al.* (2015) in the Balcarka Cave earlier. However, this value is lower in comparison with the values of 2.90×10^{-4} mol s^{-1} person^{-1} presented by Faimon *et al.* (2006), 3.35×10^{-4} mol s^{-1} person^{-1} given by Milanolo & Gabrovšek (2009), or 1.49×10^{-3} mol s^{-1} person^{-1} reported by Dragovich & Grose (1990). The relatively wide range of CO_2 exhalation rate in caves may be given by different human activity (Iwamoto *et al.* 1994), gender (Sciacca *et al.* 2002), and age (Torno *et al.* 2001). Because of the low volume of the chamber, the whole visitor groups cannot stay there together, but they have to pass through the chamber individually ("one by one"). This visitor movement is reflected as rounded shapes of anthropogenic peaks on the natural CO_2 level (especially in the first visiting period) (Fig. 2).

An evaluation of anthropogenic impact can be conducted by comparing of the steady state concentrations for two different cases: (1) with and (2) without of anthropogenic flux. Without visitors in chamber, the calculation based on Eq. (11) yielded the steady state concentrations c^{ss} ~0.16 mol m^{-3} (3700 ppmv) for DAF mode. With visitors (at the peak anthropogenic flux of $j_A = 2.45 \times 10^{-3}$ mol s^{-1}), the calculation gave a paradoxically low steady state concentration, c^{ss} ~3.56×10^{-2} mol m^{-3} (823 ppmv). The lowering is result of the anthropogenic switching the DAF mode into UAF mode. Without the switching, the values would reach c^{ss} ~0.17 mol m^{-3} (3933 ppmv). This hypothetical value would be roughly consistent with c^{ss} ~0.15 mol m^{-3} (3471 ppmv) reported by Lang *et al.* (2015) in previous work in the Balcarka Cave and the c^{ss} ~0.12 mol m^{-3} (2690 ppmv) presented by Faimon *et al.* (2006) for the Císařská Cave.

Influence of visitor movement

Based on the Eq. (5), the total volumetric airflow in the cave chamber consists of two different components: (i) natural airflow (v_N) nad (ii) anthropogenic airflow (v_A). Whereas the external temperature is considered to be the driving force of natural cave airflow (de Freitas *et al.* 1982; Christoforou *et al.* 1996; Buecher 1999; Jernigan & Swift 2001; Pflitsch & Piasecki 2003; Russell & MacLean 2008; Kowalczk & Froelich 2010; Faimon & Lang 2013), the visitor movement inside the cave is the driving force for the anthropogenically induced airflow. The visitor group may represent a piston pushing ahead the air in cave corridor. According to the actual cave ventilation mode, two different limiting situations in cave chamber can be distinguished (Fig. 4). During the UAF ventilation mode, the direction of visitor movement is consistent with the natural airflow (Fig. 4a). Then, the total volumetric airflow in cave chamber, v_T, is given by a sum of both natural and anthropogenic volumetric airflows. During DAF ventilation mode, however, the direction of visitor movement is opposite to the natural airflow (Fig. 4b). Then, the resulting airflow is dependent on difference of both the individual velocities. If the $v_N > v_A$, the resulting volumetric airflow in the cave chamber remains consistent with the natural airflow. If the $v_N < v_A$, the airflow direction changes and the DAF ventilation mode switches into the UAF ventilation mode.

The natural airflow calculated based on the Eq. (6) reached up the peak values to 3.2×10^{-3} m^3 s^{-1} that belong to very weak airflows in comparison with the values presented in the similar studies (e.g. Faimon *et al.* 2006 or Milanolo & Gabrovšek 2009). Based on the constant personal velocity, $v_{(AP)}$ ~2.63×10^{-2} m^3 s^{-1} (Tab. 1), derived from the cross section area of individual person, person linear moving velocity, and attendance, the anthropogenically induced airflows, v_A, ranged from 4×10^{-2} to 0.2 m^3 s^{-1}. This shows that the anthropogenically induced airflows could exceed the natural airflows by more than 60 times. Thus, the movement of all the visitor groups caused the switching DAF mode into UAF ventilation mode. This effect is clearly visible in the first period of DAF mode (Fig. 2a). Movement of biggest group (52 visitors) corresponded to the anthropogenic volumetric airflows of 0.2 m^3 s^{-1}. This value significantly exceeds the natural volumetric airflows in cave of 2.5×10^{-3} m^3 s^{-1}, which caused the changing natural airflow direction and mode switching. The anthropogenic CO_2 flux of this group reached up to 2.45×10^{-3} mol s^{-1}. The enhanced flux causes the peak on local CO_2 minimum. As can be seen in Fig. 2, is narrower than the minimum of CO_2 level resulting from the visitor movement. This shows that the moving visitors' effect starts before visitor entering the chamber and finishes at exiting the visitors off the low-profile corridor. In contrast, the impact of breathing is just emphasized during visitor's presence in the chamber. The peak is submerged into CO_2 level minimum and it does not exceed the potential natural CO_2 levels. This clearly shows that total anthropogenic impact need not necessary increase the CO_2 in cave chamber.

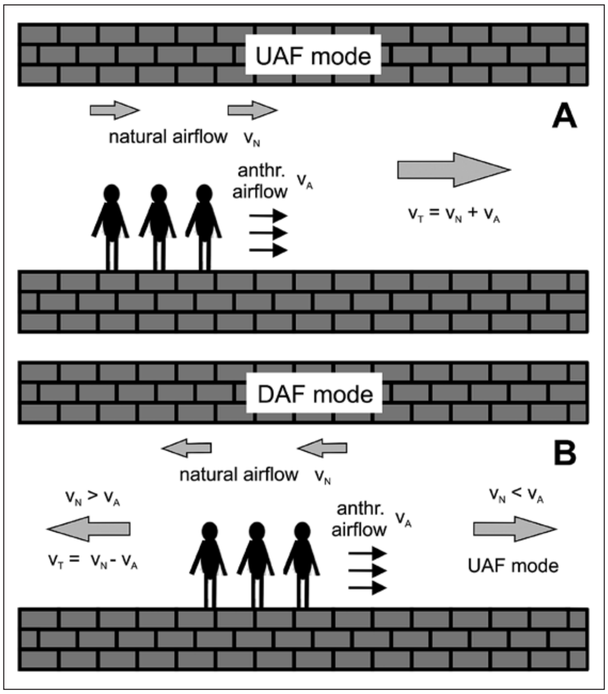

Fig. 4: Impact of visitor movement on airflow in cave chamber in UAF (A) and DAF (B) ventilation modes. For details, see the text above.

As shown on the Fig. 2a, the fitting of real CO_2 data by model curve shows some imperfections. This indicates that CO_2 behavior is influenced by further "parasitic phenomena", which are not covered in the model. Such phenomenon could be, e.g., the cave door opening. Although its effect was proved in the Small Chamber, data consistent with the presented results were not available.

The model has shown that the anthropogenic impact resulting from visitor movement acts not only in the monitored chamber itself, but also during the moving in the whole low-profile corridor. Therefore, the change of cave ventilation mode can affect the airflow and CO_2 levels also in the adjacent chamber passages. In case of shorter intervals between individual tours, the respiration impact of group inside the chamber could overlap with the movement impact of another group before the chamber or after the chamber. This indicates very complex effect of visitors in show caves.

CONCLUSIONS

Anthropogenic impact on CO_2 concentrations was studied in the Small Chamber created on the low-profile passages of the Balcarka Cave (Moravian Karst). The monitoring was implemented during the season of limited ventilation. The CO_2 levels without visitor presence were dependent on the CO_2 fluxes from adjacent spaces and driven by (1) the adjacent space CO_2 levels and (2) cave airflow. During UAF mode, lower CO_2 concentrations were transported into the studied chamber from the cave passages close to the cave entrance. This resulted in decrease of the chamber CO_2 level. During DAF mode, the chamber CO_2 level increased due to transport of higher CO_2 concentrations from the deeper cave passages or even from epikarst. The anthropogenic impact significantly disturbed this CO_2 behavior pattern.

The modeling showed two main anthropogenic phenomena influencing the CO_2 levels in the Small Chamber: (1) visitor breathing and (2) visitor movement in the low-profile corridor. Two airflow components were recognized from the modeling: (i) natural airflow and (ii) anthropogenically induced airflow. The model showed that the anthropogenically induced airflows exceeded the natural airflows by factor 12. This changed the natural airflow direction (DAF mode) running against the visitor into the direction consistent with visitor's moving (UAF mode). Then, the CO_2 levels increased by respiration decreased simultaneously due to the ventilation change into UAF mode. Therefore, the study has shown that various anthropogenic CO_2 impacts can balanced and neutralize each other under special conditions, e.g., during the period of limited ventilation, and/or in small spaces and narrow cave passages. Results of the study could be important for better cave management. They could also be of interest for karstologists and environmentalists.

ACKNOWLEDGEMENTS

The research was supported by funding from Masaryk University. Authors thank two anonymous reviewers who helped to improve the manuscript.

REFERENCES

Baker, A. & D. Genty, 1998: Environmental pressures on conserving cave speleothems: effects of changing surface land use and increased cave tourism.- Journal of Environmental Management, 53, 165–175.

Baldini, J.U.L., Baldini, L.M., McDermott, F. & N. Clipson, 2006: Carbon dioxide sources, sinks, and spatial variability in shallow temperate zone caves: Evidence from Ballynamintra Cave, Ireland.- Journal of Cave and Karst Studies, 68, 4–11.

Baldini, J.U.L., McDermott, F., Hoffmann, D.L., Richards, D.A. & N. Clipson, 2008: Very high-frequency and seasonal cave atmosphere PCO_2 variability: Implications for stalagmite growth and oxygen isotope-based paleoclimate records.- Earth and Planetary Science Letters, 272, 118–129.

Bourges, F., Mangin, A. & D. d´Hulst, 2001: Le gaz carbonique dans la dynamique de l'atmosphére des cavités karstiques: l'exemple de l'Aven d'Orgnac (Ardéche). Carbon dioxide in karst cavity atmosphere dynamics: the example of the Aven d'Orgnac (Ardéche).- Earth and Planetary Sciences, 333, 685–692.

Buecher, R.H., 1999: Microclimate Study of Kartchner Caverns, Arizona.- Journal of Cave and Karst Studies, 61, 108–120.

Christoforou, C.S., Salmon, L.G. & G.R. Cass, 1996: Air exchange within the buddhist cave temples at Yungang, China.- Atmospheric Environment, 30, 23, 3995–4006.

de Freitas, C.R., Littlejohn, R.N., Clarkson, T.S. & I.S. Kristament, 1982: Cave climate: assessment of airflow and ventilation.- Journal of Climatology, 2, 383–397.

Dragovich, D. & J. Grose, 1990: Impact of tourists on carbon dioxide levels at Jenolan Caves, Australia: an examination of microclimatic constraints on tourist cave management.- Geoforum, 21, 111–120.

Dreybrodt, W., 1999: Chemical kinetics, speleothem growth and climate.- Boreas, 28, 347–356.

Dublyansky, V.N. & Y.V. Dublyansky, 1998: The problem of condensation in karst studies.- Journal of Cave and Karst Studies, 60, 1, 3–17.

Faimon, J., Štelcl, J. & D. Sas, 2006: Anthropogenic CO_2-flux into cave atmosphere and its environmental impact: a case study in the Císařská Cave (Moravian Karst, Czech Republic).- Science of the Total Environment, 369, 231–245.

Faimon, J. & M. Ličbinská, 2010: Carbon dioxide in the soils and adjacent caves of the Moravian Karst.- Acta Carsologica, 39, 463–475.

Faimon, J., Troppová, D., Baldík, V. & R. Novotný, 2012a: Air circulation and its impact on microclimatic variables in the Císařská Cave (Moravian Karst, Czech Republic).- International Journal of Climatology, 32, 599–623.

Faimon, J., Ličbinská, M., Zajíček, P. & O. Sracek, 2012b: Partial pressures of CO_2 in epikarstic zone deduced from hydrogeochemistry of permanent drips, the Moravian karst, Czech Republic.- Acta Carsologica, 41, 1, 47–57.

Faimon, J., Ličbinská, M. & P. Zajíček, 2012c: Relationship between carbon dioxide in Balcarka Cave and adjacent soils in the Moravian Karst region of the Czech Republic.- International Journal of Speleology, 41, 1, 17–28.

Faimon, J. & M. Lang, 2013: Variances in airflows during different ventilation modes in a dynamic U-shaped cave.- International Journal of Speleology, 42, 2, 115–122.

Frisia, S., Fairchild, I.J., Fohlmeister, J., Miorandi, R., Spötl, C. & A. Borsato, 2011: Carbon massbalance modeling and carbon isotope exchange processes in dynamic caves.- Geochimica et Cosmochimica Acta, 75, 380–400.

Greenspan, D., 2006: Numerical Solution of Ordinary Differential Equations for Classical, Relativistic and Nano Systems.- Wiley-VCH Verlag GmbH, Weinheim, Germany, pp. 216.

Holland, H.D., Kirsipu, T.V., Huebner, J.S. & U.M. Oxburgh, 1964: On some aspects of the chemical evolution of cave water.- Journal of Geology, 72, 36–67.

Iwamoto, J., Pendergast, D.R., Suzuki, H. & J.A. Krasney, 1994: Effect of graded exercise on nitric oxide in expired air in humans.- Respiration Physiology, 97, 333–345.

Jernigan, J.W. & R.J. Swift, 2001: A mathematical model of air temperature in Mammoth Cave, Kentucky.- Journal of Cave and Karst Studies, 63, 3–8.

Kowalczk, A.J. & P.N. Froelich, 2010: Cave air ventilation and CO2 outgassing by radon-222 modeling: How fast do caves breath?- Earth and Planetary Science Letters, 289, 209–219.

Kuzyakov, Y., 2006: Sources of CO_2 efflux from soil and review of partitioning methods.- Soil Biology and Biochemistry, 38, 425–448.

Lang, M., Faimon J. & C. Ek, 2015: Anthropogenically impacted CO_2 in the homothermic zone of cave during the period of limited ventilation.- International Journal of Speleology, 44 (2), 167–176.

Lario, J. & V. Soler, 2010: Microclimate monitoring of Pozalagua cave (Vizcaya, Spain): application to management and protection of show caves.- Journal of Cave and Karst Studies, 72, 3, 169–180.

Liñán, C., Vadillo, I. & F. Carrasco, 2008: Carbon dioxide concentration in air within the Nerja Cave (Malaga, Andalusia, Spain).- International Journal of Speleology, 37, 99–106.

Merenne-Schoumaker, B., 1975: Aspects de l´influence des touristes sur le microclimat de la grotte de Remouchamps. Tourist impact on Remouchamps Cave microclimate.- Annales de Spéléologie, 30, 273–285.

Milanolo, S. & F. Gabrovšek, 2009: Analysis of Carbon Dioxide Variations in the Atmosphere of Srednja Bijambarska Cave, Bosna and Herzegovina.- Boundary-Layer Meteorology, 131, 479–493.

Miotke, F.D., 1974: *Carbon dioxide and the soil atmosphere.*- Abhandlungen zur Karst- Und Höhlenkunde, Reihe A, Speläologie, 9, 1–49.

Pflitsch, A. & J. Piasecki, 2003: Detection of an airflow system in Niedzwiedzia (Bear) Cave, Kletno, Poland.- Journal of Cave and Karst Studies, 65, 160–173.

Russell, M.J. & V.L. MacLean, 2008: Management issues in a Tasmanian tourist cave: Potential microclimatic impacts of cave modifications.- Journal of Environmental Management, 87, 474–483.

Sarbu, S.M. & C. Lascu, 1997: Condensation corrosion in Movile cave, Romania.- Journal of Cave and Karst Studies, 59, 99–102.

Šebela, S., Prelovšek, M. & Turk, J., 2013: Impact of peak period visits on the Postojna Cave (Slovenia) microclimate.- Theoretical and Applied Climatology, 111, 1–2, 51–64.

Sciacca, J., Forbes, W.M., Ashton, F.T., Lombardini, E., Gamble, H.R. & G.A. Schad, 2002: Response to carbon dioxide by the infective larvae of three species of parasitic nematodes.- Parasitology International, 51, 53–62.

Spötl, C., Fairchild, I.J. & A.F. Tooth, 2005: Cave air control on dripwater geochemistry, Obir Caves (Austria): implications for speleothem deposition in dynamically ventilated caves.- Geochimica et Cosmochimica Acta, 69, 2451–2468.

Stumm, W. & J.J. Morgan, 1996: *Aquatic chemistry: Chemical Equilibria and Rates in Natural Waters.*- Third edition, Wiley-Interscience, New York, pp. 1022.

Tarhule-Lips, R.F.A. & D.C. Ford, 1998: Condensation corrosion in Caves on Cayman Brac and Isla de Mona.- Journal of Cave and Karst Studies, 60, 84–95.

Tormo, R., Bertaccini, A., Conde, M., Infante, D. & I. Cura, 2001: Methane and hydrogen exhalation in normal children and in lactose malabsorption.- Early Human Development, 65, S165-S172 [Suppl].

Troester, J.W. & W.B. White, 1984: Seasonal Fluctuations in the Carbon Dioxide Partial Pressure in a Cave Atmosphere.- Water Resources Research, 20, 153–156.