Contributions to Geophysics and Geodesy Vol. 42/3, 2012 (243–254)

Temperature regime of Kateřinská Cave

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Abstract: Air and rock surface temperature regime was monitored in Kateřinská Cave in Moravian Karst (Czech Republic, South Moravia). Highly accurate temperature sensors with data logger were used for air temperature measurement. Rock surface temperature was monitored by infrared thermometer and infrared thermal camera. Statistical and graphical processing and 2D map were carried out. The rock surface and air temperature increase as the distance from the entrance increases. The highest dynamics of interior air temperature (amplitude 14.3 °C) and the lowest average temperature (4.03 °C) were detected near the entrance. At a distance of 10 m from the entrance the minimum rock surface temperature was –8.74 °C and maximum 8.60 °C. Rock temperature amplitude decreases as the distance from the entrance increases (at the distance of 271-280 m reached the minimum value 1.19 °C). The strongest correlation between internal temperature in remote part of the cave and external temperature was found when external data series shifted 22 days backward. Maximum temperatures in remote part are affected by attendance. Maximum daily amplitude (MDA) in remote parts reached up to 0.69 °C while MDA near the entrance (up to 4.27 °C) is caused by external weather.

Key words: cave microclimate, thermal monitoring, rock temperature, attendance

1. Introduction

Microclimatic conditions of cave systems are unlike an external environment characterized by lower daily and annual amplitude of air temperature and air humidity, higher relative air humidity, low evaporation and seasonal course of the velocity and direction of air flow. The air temperature inside the cave varies in range of several tenths to few degrees Celsius. The

doi: 10.2478/v10126-012-0010-y

average annual air temperature in the cave is very close the outside value (*Šebela and Turk, 2011* and others). The natural cave temperature regime is primarily influenced by heat flow from overburden and stratum and by water and air flow from external environment *(Stoeva and Stoev, 2005).*

For the cave temperature regime, the transport of heat and moisture into the cave system and the influence of airflow is usually critical *(de Freitas and Littlejohn, 1987).* Variability of atmospheric pressure is among factors affecting air circulation in the cave *(Badino, 2010).* Seasonality of cave microclimate is characterized by isothermal temperature distribution with a strong outflow of cool air from the cave during the summer. A strong cold air flow into the cave accompanied by an inverse temperature distribution has been registered in the winter *(Smithson, 1993).* According to *Huppert et al. (1993), Gillieson (1996)* and others energy flow and temperature regime of accessible caves are influenced by heat input from visitors bodies and by thermal energy from lighting. *Kermode (1979)* attributed 3.6% of temperature changes to visitors and lighting effects in Waitomo Cave. At high relative humidity all this energy is not transferred into measurable temperature increases, but can be utilized for evaporation or condensation. *Luetscher et al. (2008)* refer that about 40% of energy consumed by this way. Solid rock plays an important role as air temperature controller and stabilizer in the caves.

Detailed knowledge of cave microclimate provides necessary information for karst formation research, expansion of plant and animal species in caves and helps find out suitable caves for speleotherapy etc. *(Musil et al., 1993).* The monitoring outputs are also important for the accessible caves management *(Gillieson, 1996; de Freitas, 1998). Jernigan and Swift (2001)* present and describe difficulties in cave microclimate modeling. Good agreement between modeled and measured air temperatures was achieved only near entrance area of Mammoth Cave.

2. Material and methods

Area of interest

Temperature regime was monitored in Kateřinská Cave in Moravian Karst (Czech Republic, South Moravia). Dominant parts of the cave area are:

entrance hall and the three large horizontal halls – "Hlavní dóm" hall ($96 \times 45 \times 20$ meters), "Bambusový lesík" hall and "Dóm chaosu" hall. Dóm chaosu hall is vertically connected with an upper floor of the cave ("Dantovo peklo"). Total length of all known passages is 950 m. The cave entrance is closed by a door with a hole for migrating bats. Annual attendance in Kateřinská Cave varies from 30 to 50 thousand persons (up to 900 visitors a day, maximum of 60 per group). The cave is closed to protect wintering bats from early December to late February. According to widely used criteria *(Podstawczyska-Charciarek and Bienias, 2001)* the cave is largely dynamic with the air exchange through the entrance and stacks in Hlavní dóm hall and Dóm chaosu hall.

Sensors

Critical areas with the highest temperature dynamics and the most significant impact of visitors were defined based on preliminary results of short-term measurements. A highly accurate temperature sensors Hobo U23 Pro V2 with data logger were placed at those critical places (sensors IS5 – IS7 and vertical profile – VP sensor), into the entrance corridor (sensors IS1 – IS4) and in front of the cave (external sensor – ES) – see Fig. 1.

The accuracy of the HOBO U23 V2 is $\pm 0.21\,^{\circ}$C, with a resolution of $0.02\,^{\circ}$C. It took one minute for the interior sensor to capture air temperature differences caused by human attendance and other visitors. Seasonal dynamics including the periods with high attendance was described based on the whole year monitoring.

An infrared thermometer Raytek MX4 Raynger with the resolution of $0.1\,^{\circ}$C and accuracy of $1.0\,^{\circ}$C was used for surface temperature of the rock massif measurement. The device allows to set material emissivity (recommended value for limestone $\varepsilon = 0.98$). The rock surface temperature was measured along the tour route and blind corridor in the southwest part of the cave at 0.03 sec intervals at a height of 1.50 m above the ground. An interval of monitoring was fortnightly (during the dynamic temperature episodes) or monthly (during the stable episodes). The constant speed of the sensor movement was controlled by the BOSS DB-60 digital metronome.

Thermal evaluation of selected objects was carried out by infrared camera Fluke Ti55 IR with thermal sensitivity $\leq 0.050\,^{\circ}$C (by $30\,^{\circ}$C) and the absolute accuracy of $\pm 2\,^{\circ}$C or 2%.

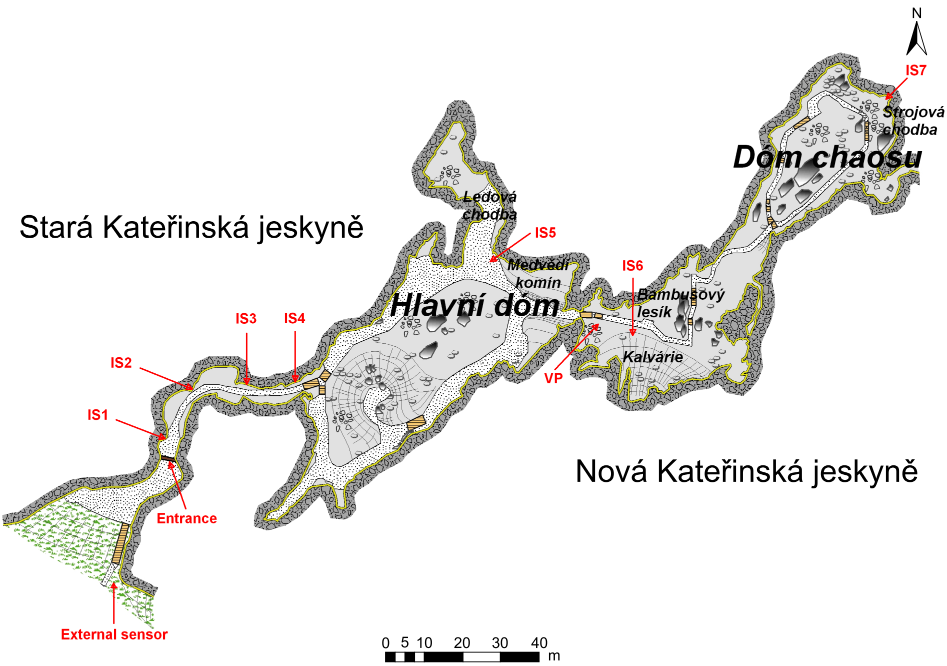

Fig. 1. Map of Kateřinská Cave with temperature sensors location (edited by Boček and Klíma, 1910 in *Boček, 1922*).

Evaluation of results

Fifteen minute averages were used for the air temperature evaluation from January 2010 to March 2012 i.e. three cold and two hot seasons.

"Maximum daily amplitude" (MDA) was calculated to identify the short-term temperature fluctuations. MDA was calculated as maximum temperature within 24 hours (from 7 am of the first day to 7 am of the second day) minus temperature at 7 am of the first day. MDA describes an influence of visitors and extreme weather events on the cave temperature regime.

The evaluation and statistical expression of the data were generated in the STATISTICA software (StatSoft, ver. 7). The data from the IR thermometer measurement was interpolated by the kriging method in SURFER software (Golden Software, ver. 8.03).

3. Results and discussion

Air temperature

The results of air temperature monitoring inside Kateřinská Cave are presented in Table 1 (sensors IS1 – IS7). External weather was also evaluated (ES). The highest dynamics of interior temperature (amplitude 14.3 °C) and the lowest average temperature (4.03 °C) were measured near the entrance (IS1 sensor, 5 m from the cave entrance). The average amplitude in the entrance corridor was 11.53 °C while in "Hlavní dóm" hall it was just 1.52 °C, in smaller "Bambusový lesík" hall it was 2.49 °C and in "Dóm chaosu" hall it was 1.28 °C. Significant effect of the external conditions was observed up to 130 meters from the entrance. The average temperature increased as the distance from the cave entrance increased.

Table 1. Statistical parameters of internal and external temperatures in Kateřinská Cave (entire period)

	ES	IS1	IS2	IS3	IS4	IS5	IS6	IS7
Average	5.91	4.03	4.61	5.21	5.13	7.43	7.62	8.05
Std. deviation	8.68	3.13	2.57	1.96	2.41	0.36	0.52	0.22
Minimum	-20.78	-6.34	-4.55	-0.50	-2.51	6.60	6.08	7.53
Maximum	32.77	7.69	8.23	8.07	8.23	8.12	8.57	8.81
Amplitude	53.55	14.03	12.78	8.57	10.74	1.52	2.49	1.28
MDA	21.98	4.27	2.36	1.89	1.91	0.49	0.50	0.69
Term of MDA	11.5.11	4.12.10	14.2.12	27.1.10	30.3.11	28.11.10	4.6.10	6.7.10

Changes in horizontal and vertical profile in the entrance corridor are visible in its central part. Temperature stratification in this part is influenced by changed speed and partially changed air flow direction as well as by the changes of entrance corridor profile. Changes of the cave bottom profile and inverse temperature stratification also influence the air temperature at the end of the entrance corridor. Sensor IS4 is influenced by air inflow from upper "Hlavní dóm" hall into the entrance corridor.

Lower minimums and higher maximums of air temperature near IS6 (area "Kalvárie") show the influence of the external environment on air temperature. Under the dome ceiling, air flows through the rubble of the unknown parts of the cave system. Air temperature is influenced here by rock thermals and access to the exterior.

The maximum temperature increases with distance from the entrance and reaches up to 8.81 °C. Remote part of Kateřinská Cave (sensor IS7, 295 m from the entrance) showed seasonal dynamics just about 1.28 °C. The strongest correlation between internal temperature (sensor IS7) and external temperature (ES) was found when external data series shifted approximately 22 days backward (R = 0.822). It means at least 22 days delay of warming or cooling of the cave. Surrounding of IS7 is probably influenced by air flow from the upper floors of Kateřinská Cave (Dantovo peklo).

The air transfers the heat to rock massif when flowing through the upper floor. Maximum temperatures of IS7 (analogically as IS6) are affected by attendance (see MDA up to 0.69 °C). The sensor IS6 recorded the highest MDA on June 4 2010, i.e. the days with high number of visitors (June 3 – 913 visitors and June 4 – 511 visitors). The sensor IS7 recorded the highest MDA in July 2010 (July 4 – 676 visitors, July 5 – 790 visitors and July 7 – 607 visitors).

In contrast, MDA near the entrance were caused by external weather. For example, MDA of 4.27 °C (sensor IS1) was achieved within approximately week-long episode of permanent freezing weather with temperatures up to –15.5 °C. MDA of 2.36 °C occurred during the long-term episode with very low temperatures (up to –18.5 °C).

Local measurements of internal air temperature were interpolated and plotted into 2D map (Fig. 2). A significant winter temperature difference between entrance corridor and other halls of Kateřinská Cave is obvious. Intense input of cold air from the external environment caused significant

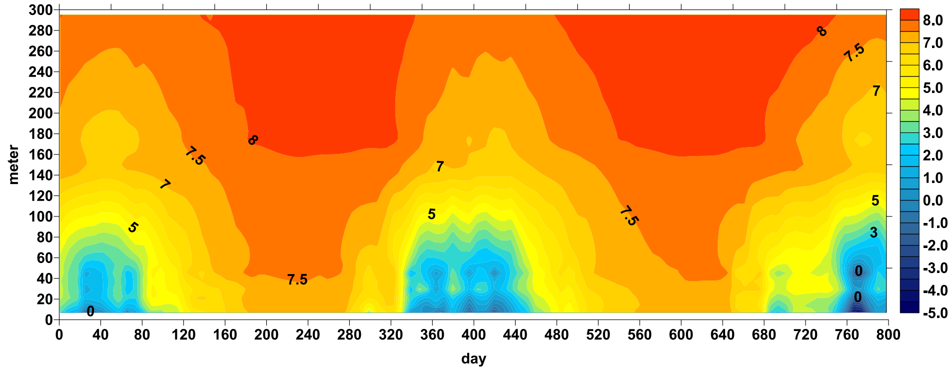

Fig. 2. Air temperature in Kateřinská Cave from January 2010 to March 2012.

cooling up to a distance of about 120-130 m from the entrance.

During cold periods the cave temperature regime is affected by indented vertical and horizontal profile of the entrance corridor. It forms an air flow direction and causes the increase of air temperature at the distance of approximately 30 m from the entrance.

Thermally highly stable area with maximum long-term temperature changes just to 1 °C arises at the distance of 180 m from the cave entrance.

Temperature of the rock massif

Measurement of rock temperature changes is normally done by sensors placed in drilled holes into the rock i.e. by destructive method *(Luetscher et al., 2008)*. Non-destructive methods i.e. infrared thermometer or infrared thermal camera are much more suitable for highly-valuated karst areas. An infrared thermometer Wahl Heat Spy was used for measuring the temperature of a cluster of rock and bat by *Clawson et al. (1980)*. Impact of bat roosting on bell holes (blind vertical cylindrical cavities in cave roofs) was evaluated by the Raytek ST60 infrared thermometer *Lundberg and McFarlane (2009)*.

Measurements in Kateřinská Cave showed that external temperature changes affected the rock massif temperature and thus the air temperature in some places inside the cave. The strongly affected places are: small area at "Speleo-corridor" (in northwestern part of the "Hlavní dóm" hall) and area Kalvárie. However, the surface temperature of the rock massif is mainly affected by the airflow inwards and outwards the cave. "Suchý žleb" gorge morphology and thickness of rock above the cave significantly reduces interior temperature influence by radiation energy. Gorge slope above the cave is covered with forest. The air flow direction depends on changes in external temperature. External air temperature about 5 °C means a threshold value of air flow direction reversion, which is typical for such dynamic caves *(Hebelka et al., 2007; Piasecki and Sawiski, 2007)*.

In the winter an external cold air flows immediately above the active surface into the cave. This air mass absorbs heat from the rocks and sediments. Warm internal air from remote parts of the cave flows above this cold air layer. A layer of warmer air forms under the cave roof and cooling of the rock is thus slower and less intense. Rock surface temperature stratification is demonstrated by thermal camera image from the entrance hall

(February 2012) – see Fig. 3. Ice stalagmites have been generated in the front part of entrance corridor. They are not formed on a higher level than approximately 1.20 m. In combination with an absence of ice stalactites it proves an assumption of warmer air layer in upper part of the corridor.

In summer, warm air flows through the chimneys into the entrance corridor and overtakes heat to the rock. In the winter the rock above a corridor bottom is colder and thus absorbs more heat and energy from the air then the rock under the roof.

The rock surface temperature measured by manual infrared thermometers in Kateřinská Cave is shown in Fig. 4. The chart is based on average values of all measurements. Rock surface temperature measured in ten meter segments along the tourist route was evaluated. The most significant temperature difference was recorded in the winter. In the summer the rock massif temperature is stable with permanent lower value in the entrance area, which is probably caused by intense ventilation.

The rock surface temperature as well as the air temperature fluctuated

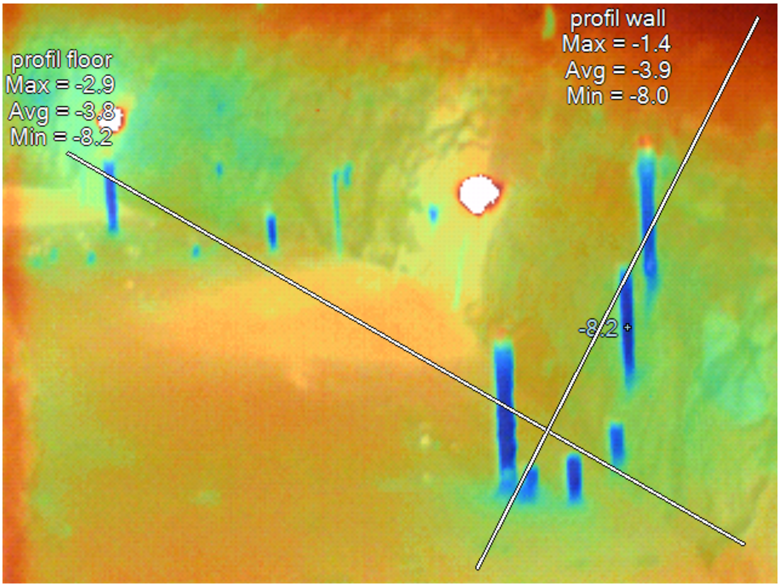

Fig. 3. Stratification of surface temperature in the entrance corridor in Kateřinská Cave.

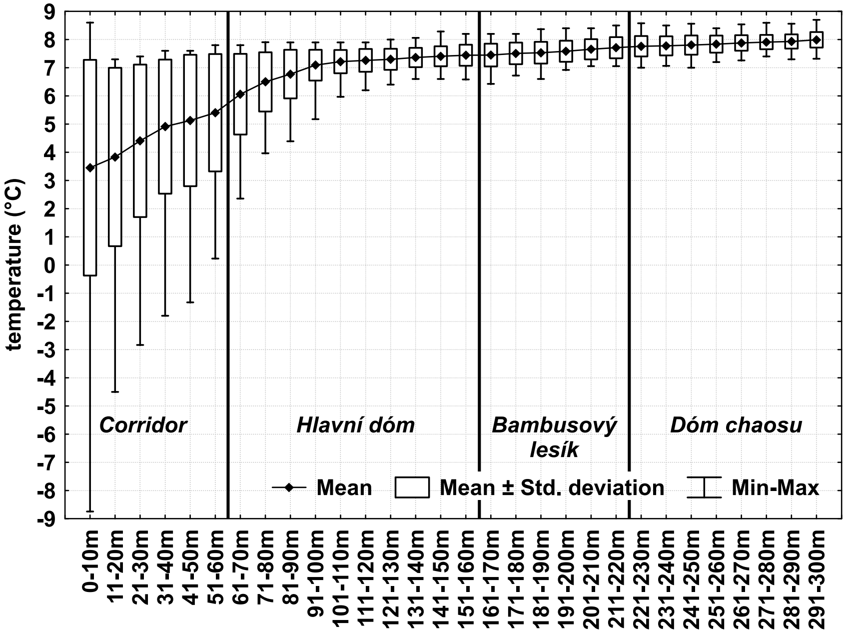

Fig. 4. Rock surface temperature in ten meter segments along the tourist route and basic statistical characteristics.

the most immediately near entrance. At a distance of 10 m from the entrance the minimum temperature was –8.74 °C and maximum was 8.60 °C. Rock massif temperature amplitude decreases as the distance from the entrance increases and at the distance of 271-280 m reaches the minimum value 1.19 °C. The average rock surface temperature increases significantly up to 110 m from the entrance. The further increase of average temperature and temperature amplitude in the remote parts of the cave are minimal. *Carrasco et al. (2002)* found out the rock massif temperature about 1 to 2 °C lower than air temperature in Nerja Cave (Malaga, Spain). Temperature of rock surface varied from 0.02 °C (high attendance) up to 0.15 °C (low attendance).

Average rock surface temperatures in the main parts of the cave are shown in Table 2.

Table 2. Average values of rock massif temperature in the main parts in Kateřinská Cave

	Corridor	Hlavní dóm	Bambusový lesík	Dóm chaosu
Average	4.52	7.04	7.60	7.87
Std. deviation	2.89	0.87	0.39	0.30
Minimum	-8.74	2.36	6.43	7.00
Maximum	8.60	8.29	8.58	8.70
Amplitude	17.34	5.93	2.15	1.70

4. Conclusion

The aim of the study was to quantify the effect of external conditions and attendance on the temperature regime in Kateřinská Cave. Evaluation of the results contributes to better karst protection, biological research, suitable management of caves open to public, speleotherapy etc.

The most dynamic part of Kateřinská Cave is the entrance corridor with annual air temperature amplitude higher than 14 °C i.e. severalfold higher dynamics than other parts of the cave. In the winter a relatively small space in the corridor is frozen due to the influence of low external temperatures (minimum internal temperature up to 6.34 °C). In the summer this part is significantly influenced by inflow of warm air trough entrance. Central part of the cave shows significant fluctuations of air and rock massif temperature. The probable reason is contact with the external environment in this place. Remote part of the cave shows seasonal dynamics up to 1.3 °C (maximum 8.81 °C, minimum 7.53 °C).

An assumption of limited conduction of radiation energy trough rock massif in Kateřinská Cave was refuted by localization of two zones with significantly seasonal course of rock temperature. It confirms a communication with surface. The zones were found out in “Speleo-corridor” and “Kalvárie”.

Cave environment is also influenced by heat emissions from visitors and lighting. Significant relationship between MDA and number of visitors was found by correlation analysis. The highest temperature fluctuation in a single day 0.5 °C was observed during the day with the highest daily attendance (913 visitors). The maximum daily fluctuation of other interior sensors (0.15 to 0.46 °C) was also observed in the same day. Air temperature changes in

"Hlavní dóm" hall due to outside weather conditions are significantly higher than those caused by visitors. Analysis of attendance influence on the cave temperature regime shows a 5-6 hour lasting auto-regulation of temperature regime even during high attendance.

Acknowledgments. The work was supported by the project of ME No. SP/2D5 /5/07 "Determination of cave microclimate depending on external weather conditions in CR show caves".

References

Badino G., 2010: Underground meteorology – "What's the weather underground?". Acta Carsologica, **39**, 3, 427–448.

Boček A., 1922: Moravian karst: A guard trough all area and its karst caves. Praha, Pavel Körbr, 155 p. (in Czech).

Carrasco F., Vadillo I., Liñán C., Andreo B., Durán, J. J., 2002: Control of environmental parameters for management and conservation of Nerja Cave (Malaga, Spain). Acta Carsologica, **31**, 1, 105–122.

Clawson R. L., LaVal R. K., LaVal M. L., Caire W., 1980: Clustering behavior of hibernating Myotis sodalis in Missouri. Journal of Mammalogy, **61**, 2, 245–253.

De Freitas C. R., 1998: Cave monitoring and management: the Glowworm Cave, New Zealand. In Cave management in Australasia XII. Proceedings of the 12th Australasian conference on cave and karst management, North Queensland, Australasian Cave and Karst Management Association, Carlton South, Victoria, 55–65.

De Freitas C. R., Littlejohn R. N., 1987: Cave climate: assessment of heat and moisture exchange. Journal of Climatology, **7**, 553–569.

Gillieson D., 1996: Caves: Processes, Development, Management. Oxford, Blackwell, 324 p.

Hebelka J., Piasecki J., Sawiski T., 2007: Air exchange in the Kateřinská Cave. First contribution. Aragonit, **12**, 136 p.

Huppert G., Burri E., Forti P., Cigna A., 1993: Effects of tourist development on caves and karst. In Karst terrains: environmental changes and human impact, Catena Supplement, **25**, 251–268.

Jernigan J. W., Swift R. J., 2001: A mathematical model of air temperature in Mammoth Cave, Kentucky. Journal of Cave and Karst Studies, **63**, 1, 3–8.

Kermode L. O., 1979: Cave corrosion by tourists. In Cave Management in Australasia III. Proceedings of the 3rd Australasian conference on cave tourism and management, South Australia, Australasian Cave and Karst Management Association, Carlton South, Victoria, 97–104.

Luetscher M., Lismonde B., Jeannin P. Y., 2008: Heat exchanges in the heterothermic zone of a karst system: Monlesi Cave, Swiss Jura Mountains. Journal of Geophysical Research, **113**, F02025. Doi:10.1029/2007JF000892.

Lundberg J., McFarlane D. A., 2009: Bats and bell holes: The microclimatic impact of bat roosting, using a case study from Runaway Bay Caves, Jamaica. Geomorphology, **106**, 78–85.

Musil R. et al., 1993: Moravian Karst – labyrints of knowledge (Moravský kras – labyrinty poznání). Adamov, Jaromír Bližňák, GEO program, 336 p. (in Czech).

Piasecki J., Sawiski T., 2007: Acoustic measurements of airflow in speleo-climatological studies. Karst and Cryokarst, Studies of the Faculty of Earth Sciences University of Silesia, No. 45, Sosnowiec – Wrocław, 237–256.

Podstawczyska-Bienias A., Charciarek T., 2001: Seasonal changes of air temperature and humidity in the caves in Ojców National Park. Dokumentacja Geograficzna, **23**, 75–86.

Smithson P. A., 1993: Vertical temperature structure in a cave environment. Geoarcheology, **3**, 3, 229–240.

Stoeva P., Stoev A., 2005: Cave air temperature response to climate and solar and geomagnetic activity. Memorie della Società Astronomica Italiana, **76**, 1042–1047.

Šebela S., Turk J., 2011: Local characteristics of Postojna Cave climate, air temperature, and pressure monitoring. Theoretical and Applied Climatology, **105**, 3–4, 371–386.