NUKLEONIKA 2020;65(2):153–157
doi: 10.2478/nuka-2020-0025

ORIGINAL PAPER

Seasonal variation of radon and CO_2 in the Važecká Cave, Slovakia

Iveta Smetanová, Karol Holý, Ľubica Luhová, Kristian Csicsay, Dagmar Haviarová, Lucia Kunáková

Abstract. The continuous monitoring of ^{222}Rn activity concentration, CO_2 concentration, and microclimatologic parameters (internal air temperature and relative humidity) in the Važecká Cave (Northern Slovakia) is being carried out at three monitoring stations, namely, Gallery, Lake Hall, and Entrance Hall. Radon activity concentration and CO_2 concentration exhibited a clear annual variation. The daily average of radon concentration ranged 1300–27 700 Bq/m^3 at the Lake Hall station and 3600–42 200 Bq/m^3 at the Gallery station. Radon reached its maximum in the summer months, from June to September. The annual maximum of CO_2 concentration is registered approximately one month later than radon maximum. The annual variation of radon and CO_2 is controlled by the seasonal change of ventilation regime associated with the seasonal variation of the difference between the temperature measured inside the cave and the atmospheric temperature.

Keywords: Carbon dioxide • Cave • Monitoring • Radon • Temperature • Variation

I. Smetanová✉, L. Luhová, K. Csicsay
Earth Science Institute, Slovak Academy of Sciences
Dúbravská cesta 9, 840 05 Bratislava, Slovakia
E-mail: geofivas@savba.sk

K. Holý
Faculty of Mathematics, Physics and Informatics
Comenius University
Mlynská dolina, 842 48 Bratislava, Slovakia

D. Haviarová, L. Kunáková
State Nature Conservancy of the Slovak Republic
Slovak Caves Administration
Hodžova 11, 031 01 Liptovský Mikuláš, Slovakia

Received: 10 December 2019
Accepted: 20 January 2020

Introduction

Radon (^{222}Rn) is a radioactive noble gas with a half-life of 3.82 days, produced by the decay of radium (^{226}Ra) in uranium (^{238}U) decay series. Due to its unique characteristics (chemically inert, relatively long half-life), radon has been widely used as a natural tracer in various environmental studies. The monitoring of radon in the cave atmosphere is also performed for the radiological risk assessment for cavers and cave visitors [1–4].

The radon activity concentration in the atmosphere of the karst systems depends on a complex interrelation among several different factors, including outside–inside temperature differences, the degree by which outside air mixes with cave air, humidity of the cave interior, precipitation amount and its infiltration to the cave environment, ^{226}Ra content in host rock and cave sediments, rock and cave sediments porosity, ^{222}Rn exhalation rate from the surfaces in the cave, and volume and shape of the cave [1, 5–8]. Meteorological conditions are considered as a major influence on radon variability in the rock environment. However, the relationship between radon and meteorological parameters remains poorly understood, and interpretations are often ambiguous. Seasonal and diurnal variations of radon are often explained by the changes in air temperature, and an important factor is air pressure [5, 9–11]. The influence of meteorological conditions on the radon temporal variations depends mostly on the shape of the cave, the position of the cave entrance, and the number and directions of cracks and fissures connecting the cave rooms with the outdoor atmosphere [8, 12]. Besides radon, carbon dioxide is often used as a tracer gas in ventilation studies in underground environments [11, 13–15]. The main sources of CO_2 in caves are diffusion from the epikarst, degassing of drip waters, decomposition of organic matter, precipitation of calcite from supersaturated solutions, and anthropogenic flux by breathing of the visitors [11, 14, 16].

In this article, we present the annual variation of ^{222}Rn activity concentration and CO_2 concentration measured continuously in the Važecká Cave (Northern Slovakia) between November 2015 and September 2019.

Geographical and geological setting

The Važecká Cave (N 49°3.35393', E 19°58.30753') is located in the northern part of the Low Tatra Mountains on the north edge of the Važec Karst area, at the contact of the Kozie chrbty Mountains and the Podtatranská Basin. The cave is 530 m long and opened to the public from February to the end of November. The entrance to the cave is situated 8 m above the recent river bed of Biely Váh River, at an altitude of 784 m a.s.l. [17, 18]. The cave is characterized by subhorizontal halls, without a significant vertical segmentation. The rock massive thickness above the Važecká Cave is about 15–20 m.

The genesis of the Važecká Cave was mainly affected by an erosion activity of the Biely Váh River and the tectonic activity of WNW-ESE faults. The Važecká Cave is developed in the Middle Triassic dark-grey Limestones of the Gutenstein Formation of the Hronic Unit. The cave originated mainly by an inflow of aggressive allochthonous water and flood-water injections from the Biely Váh River into exposed and faulted carbonates. Its formation was enhanced by water seeping from precipitation and circulating through the karst aquifer and by surface waters sinking into the underground [19]. A large part of the cave is covered by water-transported sediments. Allochthonous gravels and sands with granite pebbles were transported into the cave during its fluvial formation. Consequently, they were covered by unsorted sediments consisting mainly of loam, slightly rounded limestone clasts, Palaeogene sandstone, weathered granite pebbles, and fossil faunal remains. Above unsorted sediments, fine-grained sediments were deposited in several sequences as a result of repeated flood-water injections from the surface river and floods caused by waters circulating through adjacent karstified limestones [19].

Monitoring site

The radon research in the Važecká Cave started in June 2012 at the station Gallery. From November 2015, three microclimate monitoring stations, operated by the Slovak Caves Administration, were

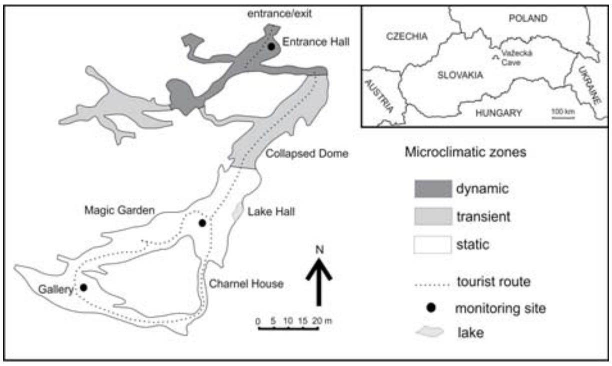

Fig. 1. Ground plan of the Važecká Cave with marked microclimatic zones [20] and monitoring sites.

established in the cave: Gallery, Lake Hall, and Entrance Hall (Fig. 1).

The Važecká Cave can be divided into three microclimatic zones [20]. The first dynamic zone (Fig. 1) spans the area from the cave entrance to the Stone Dome, where the monitoring station Entrance Hall (783.14 m a.s.l.) is situated. Transitional, the static-dynamic zone (Collapsed Dome) reached up to the Lake Hall. The Lake Hall (787.84 m a.s.l.) and the Gallery (789.40 m a.s.l.) stations are situated in the third, a thermodynamically static zone, where the highest air temperature was recorded, with low-temperature changes during a year.

All three monitoring stations are situated on a tourist route and equipped with sensors for continuous high-resolution monitoring of ^{222}Rn activity concentration, CO_2 concentration, temperature, and relative humidity of the cave atmosphere. External parameters, such as rainfall, atmospheric temperature, relative humidity, wind speed, and wind direction, are registered by the outdoor meteorological station, situated close to the cave entrance. Atmospheric pressure data were taken from the meteorological station operated by the Earth Science Institute of Slovak Academy of Sciences in Stará Lesná, 40 km NE from Važec village.

The monitoring of radon is performed using the passive detector Barasol BMC2 (450 mm^2, Si diode, Algade, France), which records alpha particle emissions. Radon enters the sensing volume by diffusion through three cellulose filters, which trap all the solid daughter products. The sensitivity of the instruments is in the order of 50 Bq/m^3 per impulse/hour. The bottom of the Barasol probe is situated approximately 1 m above the cave floor. The detector is placed in a distance of 2 m or more from the cave walls, depending on the monitoring site geometry. The CO_2 concentration is continually monitored by Carbocap sensor GMP 222 (Vaisala, Finland), with a measuring range of 0–10 000 ppm. Data from the stations are collected automatically or manually, with a sampling period of 10 min. From these measurements, hourly and daily averages are calculated. Data gaps of 3 h or less were filled by linear interpolation.

The radon activity concentration and CO_2 concentration in the Važecká Cave exhibited annual,

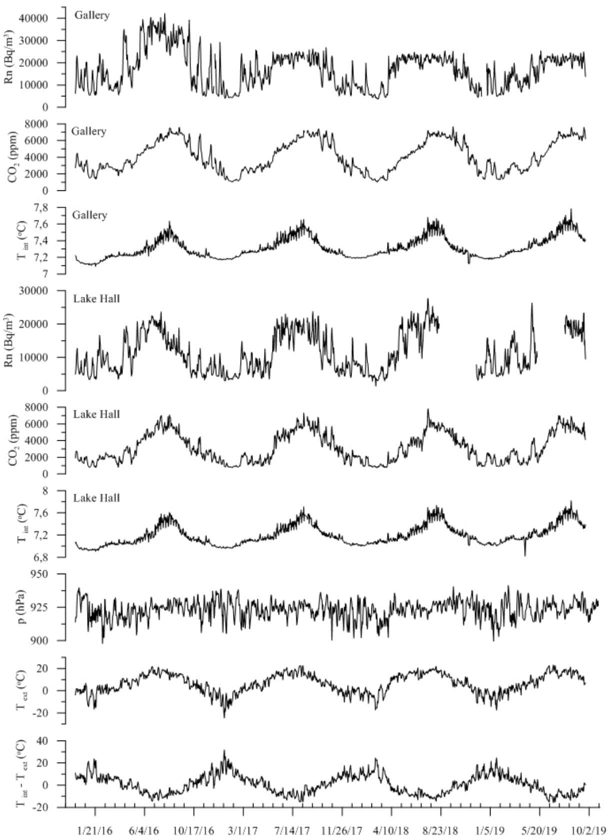

Fig. 2. The time series (daily averages) measured between November 2015 and September 2019 at the monitoring stations inside (Rn, CO_2, temperature T_{int}) and outside the Važecká Cave (atmospheric temperature T_{ext}) and atmospheric pressure measured at the Stará Lesná station.

nonperiodic short-term and periodic daily variations. Due to the CO_2 sensor malfunction and many gaps in the radon time series from the Entrance Hall station, in this article, the time series from the Gallery and the Lake Hall stations are compared. The interpretation of the daily variation of radon and CO_2 was outside the scope of this study.

Results and discussion

Radon activity concentration, CO_2 concentration, and air temperature measured at the stations Gallery and Lake Hall in the Važecká Cave exhibited a clear annual variation, with the maximum in the summer months (Fig. 2). The spatial differences in radon activities among stations were confirmed. The highest radon levels were found in the Gallery, which is situated at the most distant place from the cave entrance, with the daily average of radon concentration ranging from 3600 ± 190 Bq/m³ to 42 200 ± 590 Bq/m³. In the Lake Hall station, the radon concentration ranged from 2780 ± 150 Bq/m³ to 27 700 ± 480 Bq/m³. However, the radon concentration in the Gallery was significantly higher solely in 2016, in the following years of the monitoring, the measured radon concentrations reached similar maximum levels.

Multiday radon variations lasting up to 15 days were observed, and most of them were registered simultaneously at both stations (R^2 = 0.63). The coincidence of peaks was much better in the winter months when the amplitude of peaks in the Lake Hall reached up to 20 000 Bq/m³ and up to 26 000 Bq/m³ in the Gallery.

Coinciding short-term peaks were registered also in CO_2 time series (R^2 = 0.90). A good correlation was found between the daily averages of radon and CO_2 concentration registered in the Lake Hall station (R^2 = 0.74), while at the Gallery their correlation was weaker (R^2 = 0.55). Contrary to radon, the spatial difference between CO_2 concentrations was not very distinct, it reached the almost same values at both monitoring stations (Fig. 2). The daily averages of CO_2 ranged from 750 ppm to 7800 ppm in the Lake Hall and from 1000 ppm to 7700 ppm in the Gallery. Internal temperatures at both stations exhibited almost the same course (R^2 = 0.99). The daily courses of radon, CO_2 and temperatures measured inside and outside the cave during a year were calculated from the daily averages of data measured between November 2015 and September 2019 (Figs. 3 and 4). The daily average of radon concentration was negatively correlated with the temperature difference (R^2 = 0.81 for the Lake Hall, R^2 = 0.80 for the Gallery). Similarly, the daily average of CO_2 concentration was negatively correlated with the temperature difference (R^2 = 0.72 for the Lake Hall, R^2 = 0.63 for the Gallery).

Based on the results, two ventilation regimes were distinguished in the Važecká Cave, influenced

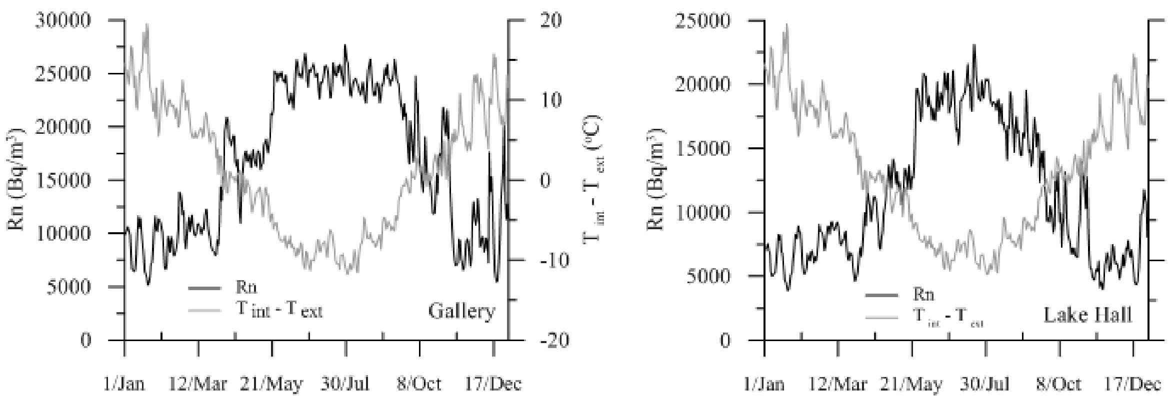

Fig. 3. The daily average of ^{222}Rn activity concentration and the difference in internal and external temperature, calculated from November 2015 to September 2019, at the Gallery (left) and Lake Hall station (right).

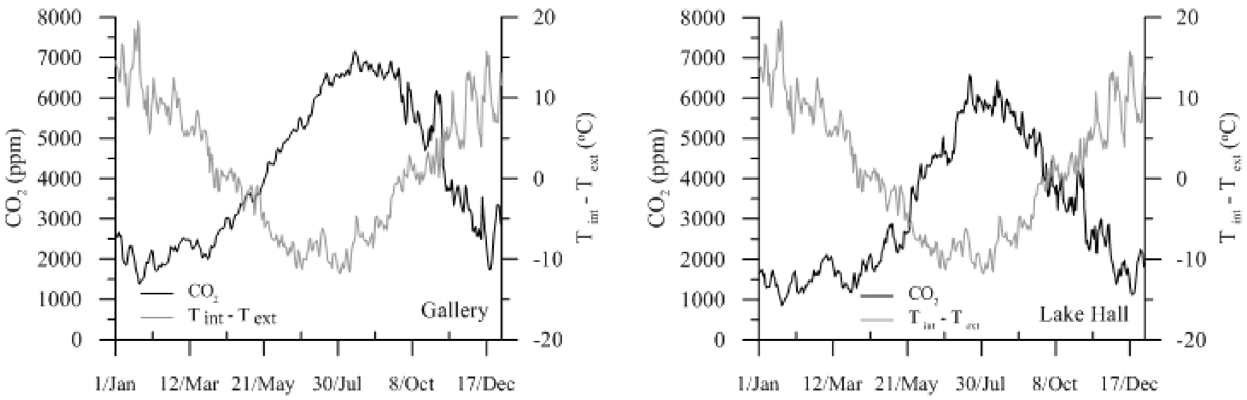

Fig. 4. The daily average of CO_2 concentration and the difference in internal and external temperature, calculated from November 2015 to September 2019, at the Gallery (left) and Lake Hall station (right).

by the changes in the difference between internal temperature measured at the monitoring sites inside the cave and atmospheric temperature. During the summer regime (from April to the end of September), the difference between temperature measured inside the cave and the atmospheric temperature was negative. In this time of year, radon and CO_2 reached its annual maximum. In the winter regime (from October to the end of March), when the difference between the internal temperature and atmospheric temperature was positive, radon and CO_2 levels at both monitoring sites exhibited their annual minimum (Fig. 3).

The annual variation of CO_2 concentration was similar to the annual variation of radon activity concentration (Fig. 4); however, CO_2 maximum appeared approximately one month later than the radon maximum. The maximum of radon concentration was registered between June and September, while the maximum of CO_2 concentration appeared from July to September. This type of a ventilation regime and seasonal variation of radon or CO_2 concentration was often observed in the horizontally developed caves [2, 11, 12, 14, 15] and in horizontal tunnels [9].

Conclusions

The seasonal variability of radon, CO_2, and environmental parameters measured inside and outside the Važecká Cave were analysed. Both radon activity concentration and CO_2 concentration are characterized by the high summer and low winter levels. Significant short-term variations of radon and CO_2 were registered, simultaneously at both monitoring stations in the cave. The summer and winter ventilation regime was confirmed in the Važecká Cave, associated with the seasonal change in the difference between internal and atmospheric temperatures. The annual variation of radon activity concentration and CO_2 concentration seems to be governed by the annual variation of natural ventilation of the cave.

Acknowledgment. This work was supported by the Scientific Grant Agency of Ministry of Education of Slovak Republic (VEGA projects no. 2/0083/18 and no. 1/0213/18).

ORCID

K. Csicsay http://orcid.org/0000-0003-1891-3863
L. Luhová http://orcid.org/0000-0002-8556-9081
I. Smetanová http://orcid.org/0000-0001-8527-9423

References

1. Lario, J., Sánchez-Moral, S., Cañaveras, J. C., Cuezva, S., & Soler, V. (2005). Radon continuous monitoring in Altamira Cave (northern Spain) to assess user's annual effective dose. *J. Environ. Radioact*., *80*, 161–174. DOI: 10.1016/j.jenvrad.2004.06.007.
2. Thinová, L., & Burian, I. (2008). Effective dose assessment for workers in caves in the Czech Republic: Experiments with passive radon detectors. *Radiat. Prot. Dosim*., *130*(1), 48–51. DOI: 10.1093/rpd/ncn118.
3. Alvarez-Gallego, M., Garcia-Anton, E., Fernandez-Cortez, A., Cuezva, S., & Sanchez-Moral, S. (2015). High radon levels in subterranean environments: monitoring and technical criteria to ensure human safety (case of Castañar cave, Spain). *J. Environ. Radioact*., *145*, 19–29. DOI: 10.1016/j.jenvrad.2015.03.024.
4. Somlai, J., Hakl, J., Kavasi, N., Szeiler, G., Szabo, P., & Kovacs, T. (2011). Annual average radon concentration in the show caves of Hungary. *J. Radioanal. Nucl. Chem*., *287*, 427–433. DOI: 10.1007/s10967-010-0841-9.
5. Przylibski, T. A. (1999). Radon concentration changes in the air of two caves in Poland. *J. Environ. Radioact*., *45*, 81–94.
6. Dueñas, C., Fernández, M. C., Cañete, S., Carretero, J., & Liger, E. (1999). ^{222}Rn concentrations, natural flow rate and the radiation exposure levels in the Nerja Cave. *Atmos. Environ*., *33*, 501–510.
7. Lu, X., Li, L.Y., & Zhang, X. (2009). An environmental risk assessment of radon in Lantian Karst Cave of Shaanxi, China. *Water Air Soil Pollut*., *198*, 307–316. DOI: 10.1007/s11270-008-9847-0.
8. Bahtijari, M., Vaupotič, J., Gregorič, A., Stegnar, P., & Kobal, I. (2008). Exposure to radon in the Gadime

Cave, Kosovo. *J. Environ. Radioact.*, *99*, 343–348. DOI: 10.1016/j.jenvrad.2007.08.003.

9. Barbosa, S. M., Zafrir, H., Malik, U., & Piatibratova, O. (2010). Multi-year to daily radon variability from continuous monitoring at the Amram tunnel, southern Israel. *Geophys. J. Int.*, *182*, 829–842. DOI: 10.1111/j.1365-246X.2010.04660.x.
10. Gregorič, A., Zidanšek, A., & Vaupotič, J. (2011). Dependence of radon levels in Postojna Cave on outside air temperature. *Nat. Hazards Earth Syst. Sci.*, *11*, 1523–1528. DOI: 10.5194/nhess-11-1523-2011.
11. Gregorič, A., Zidanšek, A., & Vaupotič, J. (2013). Reasons for large fluctuation of radon and CO_2 levels in a dead-end passage of a karst cave (Postojna Cave, Slovenia). *Nat. Hazards Earth Syst. Sci.*, *13*, 287–297. DOI: 10.5194/nhess-13-287-2013
12. Hakl, J., Csige, I., & Hunyadi, I. (1996). Radon transport in fractured porous media – experimental study in caves. *Environ. Int.*, *22*, S433–S437.
13. Fernandez-Cortes, A., Sanchez-Moral, S., Cuezva, S., Cañaveras, J. C., & Abella, R. (2009). Annual and transient signatures of gas exchange and transport in the Castañar de Ibor cave (Spain). *Int. J. Speleol.*, *38*(2), 153–162.
14. Kowalczk, A. J., & Froelich, P. N. (2010). Cave air ventilation and CO_2 outgassing by radon-222 modelling: how fast do the caves breathe? *Earth Planet. Sci. Lett.*, *2899*, 209–219. DOI: 10.1016/j.epsl.2009.11.010.
15. Milanolo, S., & Gabrovšek, F. (2009). Analysis of carbon dioxide variations in the atmosphere of Srednja Bijambarska Cave, Bosnia and Herzegovina. *Bound-Lay. Meteorol.*, *131*, 479–493. DOI: 10.1007/s10546-009-9375-5.
16. Faimon, J., Štelcl, J., & Sas, D. (2006). Anthropogenic CO_2-flux into cave atmosphere and its environmental impact: A case study in the Císařská Cave (Moravian Karst, Czech Republic). *Sci. Total Environ.*, *369*, 231–245.
17. Droppa, A. (1962a). Speleologický výskum Važeckého krasu (Speleological research of Važec karst area). *Geografical Journal*, *14*(4), 264–293.
18. Droppa, A. (1962b). *Važecká jaskyňa a krasové javy v okolí (Važecká Cave and karst phenomena in surrounding area)*. Bratislava, Slovakia: Šport.
19. Bella, P., Littva, J., Pruner, P., Bosák, P., Šlechta, S., Hercman, H., & Čížiková, K. (2016). Geologická stavba, morfológia a vývoj Važeckej jaskyne (Geological setting, morphology and evolution of the Važecká Cave, Slovakia). *Acta Carsologica Slovaca*, *54*(1), 5–31.
20. Zelinka, J. (2002). Termodynamická charakteristika Važeckej jaskyne (Termodynamic characterization of the Važecká Cave). In Výskum, využívanie a ochrana jaskýň, Zborník referátov z 3. Vedeckej konferencie, (Investiagation, protection and using of caves, conference proceedings), 14–16 November, 2001 (pp. 123–131). SSJ, Žilina, Slovakia: Liptovský Mikuláš Knižné centrum.