Theor Appl Climatol (2011) 105:371–386
DOI 10.1007/s00704-011-0397-9

ORIGINAL PAPER

Local characteristics of Postojna Cave climate, air temperature, and pressure monitoring

Stanka Šebela · Janez Turk

Received: 11 August 2010 / Accepted: 2 January 2011 / Published online: 19 January 2011

Abstract In Postojna Cave, air temperature and pressure monitoring has been conducted since July 21, 2008. Air pressure in the cave at three monitoring sites fluctuates synchronically with outside air pressure. Temperature data for Postojna 1 and 3 show good correlation with outside climate conditions for the period 2009–2010. The temperature at Postojna 1 was increasing constantly from March to May 2009, while at Postojna 2, it was decreasing. Postojna 1 has a seasonal trend in accordance with outer trend, while seasonal trend at Postojna 2 is just contrary to outside trend. Microclimate studies at Postojna 2 show local variability, especially in winter, and exhibit special microclimate conditions that may be due to ventilation of unknown passages in the back.

1 Introduction

Air temperature and pressure monitoring in Postojna Cave was conducted primarily to better understand radon emanations connected with microtectonic displacements of two monitoring sites (Gosar et al. 2009; Šebela et al. 2010). After preliminary results, the study was extended to develop an understanding of the microclimate conditions of three selected sites in the cave (Fig. 1). The show cave has numerous visitors, and basic monitoring was established to better understand underground climate, especially in response to exterior climate. Regular monitoring of air temperature and air pressure started on July 21, 2008 at the Postojna 2 site. Since March 10, 2009, hourly measurements of air pressure and air temperature have been taken at Postojna 1. Since April 28, 2009, hourly measurements of air pressure and air temperature have been taken in Lepe Jame (Postojna 3). Finally, commencing on October 10, 2009, monitoring at the surface above Otoška Jama (Fig. 1, monitoring site 4) has also been carried out well. Four monitoring sites were studied, with three of them in the cave and one on the surface above the cave.

A recognized characteristic of caves in a karst system is that they are continuously exchanging air, CO_2, and water with the outside environment through different size openings (Bourges et al. 2006). Temperature data of air and water recorded between February and November 1963 in two large cave systems in West Virginia (USA) showed that cave temperatures are not necessarily constant, but may vary widely (Cropley 1965).

In Postojna Cave, air circulation typical for winter or summer can be observed during the transition from one to another regime, such as during warm midday and cold night. In spring and autumn, air circulation is minimal due to the small difference between outside air and cave air temperatures, but there are always some exceptions as well. If the air coming into the cave during warmer seasons becomes cooler and denser, it moves to the deeper parts of the cave. If contrary during the colder seasons the air becomes warmer, it moves toward the upper parts of the cave. The intensity of mixing between outer and cave air depends on numerous conditions, such as the relation between cave entrance size and cave depth, and the air pressure (Gams 2003).

Studies of cave climate have been performed in other caves to understand the influence of tourist visits (Bourges et al. 2006; Pflitsch and Piasecki 2003; Milanolo and

S. Šebela (✉) · J. Turk
ZRC SAZU Karst Research Institute,
Titov trg 2,
6230 Postojna, Slovenia
e-mail: sebela@zrc-sazu.si

J. Turk
e-mail: janez.turk@zrc-sazu.si

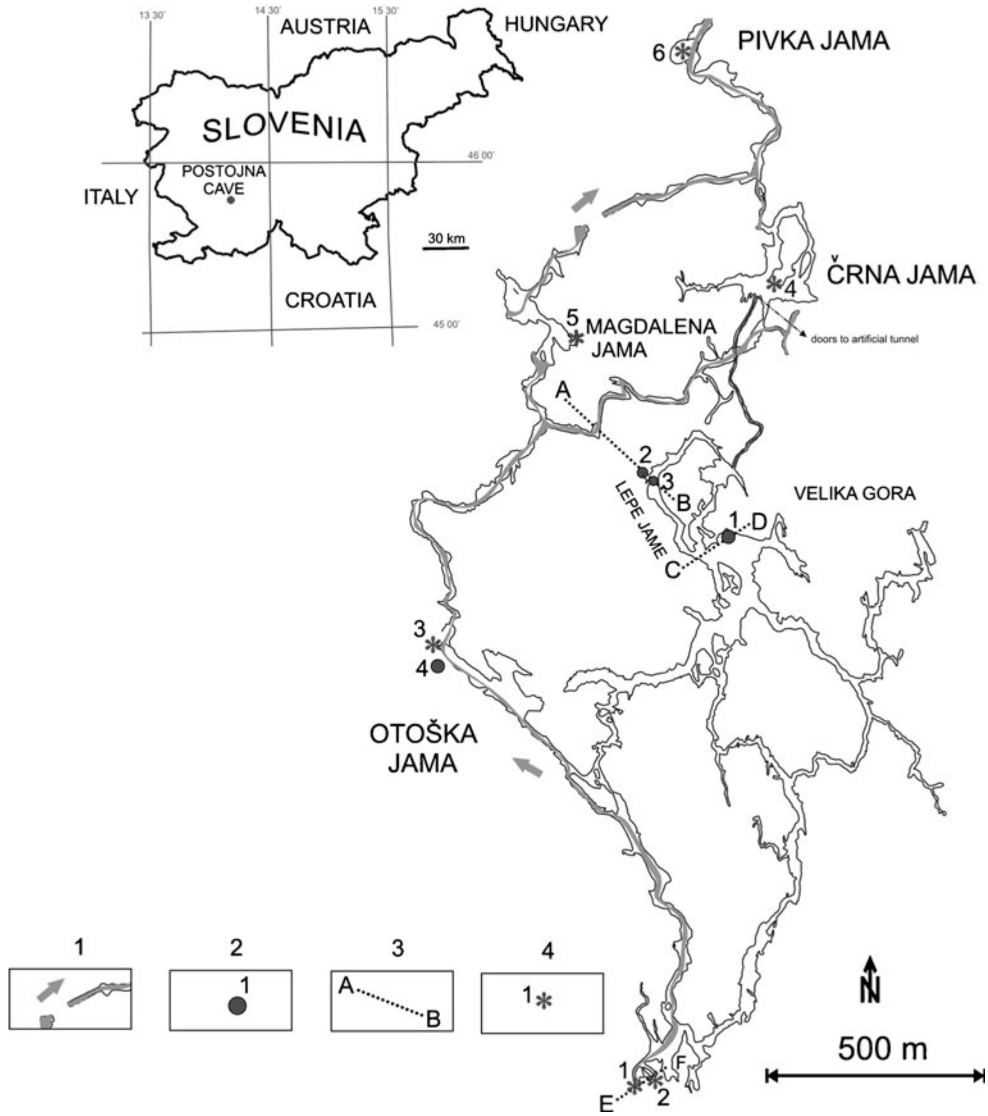


Fig. 1 Ground plan of Postojna Cave with air temperature and pressure monitoring sites. *1* underground Pivka River with flow direction, *2* monitoring sites (*1* Velika Gora, *2* Lepe Jame, *3* Lepe Jame, *4* outside Otoška Jama), *3* cross section, *4* cave entrances (*1* ponor entrance of River Pivka at 511 m, *2* entrance from the artificial platform at 529.50 m, *3* entrance to Otoška Jama at 531.70 m, *4* Črna Jama entrance at 531 m, *5* Magdalena Jama entrance at 562 m, *6* Pivka Jama entrance at 550 m)

Gabrovšek 2009), formation or solution of ice in ice caves (Luetscher and Jeannin 2004a; Perşoiu et al. 2006), understanding speleobiology and microbiology, and understanding climate changes in the cave environment (Badino 2004). In such sense, we want to give basic overview of selected publications, especially those related to cave air temperature and pressure studies. They were of a great assistance in understanding the climate situation in Postojna Cave.

In general, the temperature inside a cave is very close to the average annual temperature outside the cave. When compared to the outside climate, caves have high humidity, cooler temperatures in summer, warmer in winter, higher carbon dioxide levels, and very small seasonal and diurnal changes (Bourges et al. 2006). In the first hundred meters from the entrance into the cave, the cave temperature is still influenced by seasonal variations. This is the heterothermic zone, where highly ventilated conduits occur (Luetscher and Jeannin 2004b).

The period November to April is characterized by a good correlation (r^2=0.91) between Monlesi ice cave air temperature and negative outside air temperature. When the outside temperature is lower than that of the cave, the density difference between the two air masses leads to a chimney effect between the entrances. The period from May to October shows a stable temperature, close to 0°C. When outside temperature is higher than cave temperature, no significant air circulations can be observed (Luetscher and Jeannin 2004a).

During the summer regime, the cave air temperature is stable and does not correlate with the temperature outside. In contrast, during the winter regime, the cave temperature is characterized by large oscillations, more pronounced near the entrance, and correlated with the outside temperature (Bourges et al. 2006).

During the winter, the air entering the cave warms up, becomes less dense, ascends, and escapes through an upper opening. This loss in mass causes a very small amount of lower pressure inside the cave in comparison with the outer air pressure. During the summer, air entering the cave cools down, becomes denser, descends, and flows outside through a lower opening (Pflitsch and Piasecki 2003).

The temperature inside the Bear Cave in Poland is mainly governed by rock temperature, which in turn reflects the long-term mean annual air temperature of the outside atmosphere (Pflitsch and Piasecki 2003).

The modification of the air temperature and the situation of the air currents are partly short-lived, but long-term alterations also could be observed, and conditions only returned to normal after a quiescence period of at least 1 day (Pflitsch and Piasecki 2003).

The study of Perrier et al. (2001) showed that temperature variations in the atmosphere of an underground limestone quarry in France are associated with pressure variations. On the contrary, Bourges et al. (2006) described that natural karst caves exchange gases and water with the outside environment through various sized channels and thus might behave differently than quarries.

In the Salle Plane, a room situated more than 500 m away from the entrance, the air temperature is never controlled by the outside temperature but rather by the derivative of pressure, dP/dt (Bourges et al. 2006). Pressure-induced temperature changes relaxed in less than 1 h by thermal exchanges with a large volume whose temperature is assumed to be constant (Bourges et al. 2006).

An interesting study was performed by Stoeva et al. (2006). Climatic trends connected with short- and long-period variations of the solar activity occur as a reaction even in such conservative media as the air volumes of karst caves. The yearly mean air temperatures in the zone of constant temperatures (ZCT) of four show caves in Bulgaria were studied for a period of 36 years (1968–2003). It has been found that the correlation between ZCT temperature time series and sunspot number is better than that between the cave air temperature and Apmax indices (Stoeva et al. 2006).

Moreover, we deeply agree with Smithson (1991) that the study of cave climate (temperatures, air ventilation) is important not only for the understanding of cave flora and fauna but also for interpretation of carbon dioxide and radon levels, which can affect some karst processes underground and health underground (Smithson 1991).

Between numerous researches of cave climate, the abovementioned were of the best literature ideas to be related to the case of Postojna Cave climate study. The fact is that systematic continuous cave climate monitoring is taking place since 2008 and only at three monitoring sites. Recently, some additional underground meteorological stations were added.

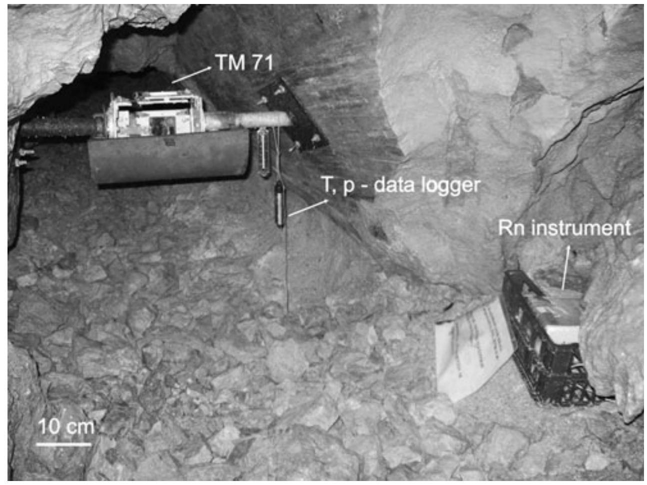


Fig. 3 Postojna 2 monitoring site, Lepe Jame (photo S. Šebela)

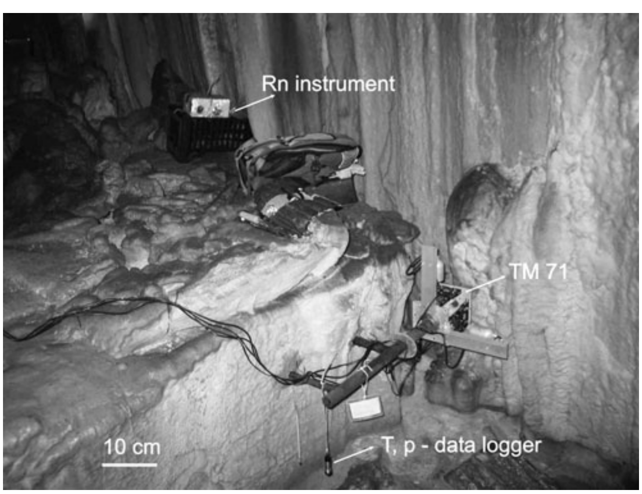


Fig. 2 Postojna 1 monitoring site, Velika Gora (photo S. Šebela)

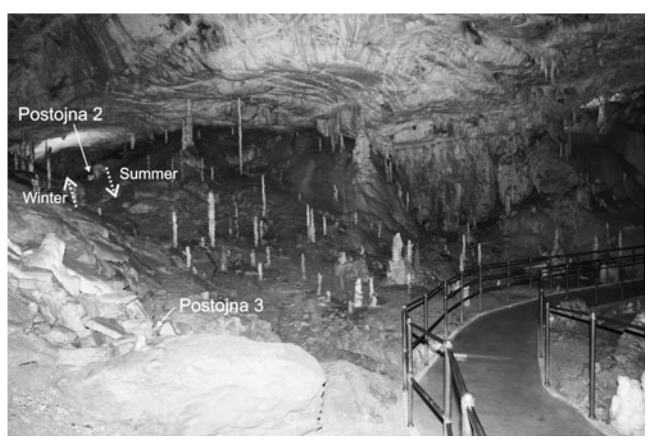


Fig. 4 Postojna 3 monitoring site, Lepe Jame, the view toward Postojna 2 site (photo S. Šebela)

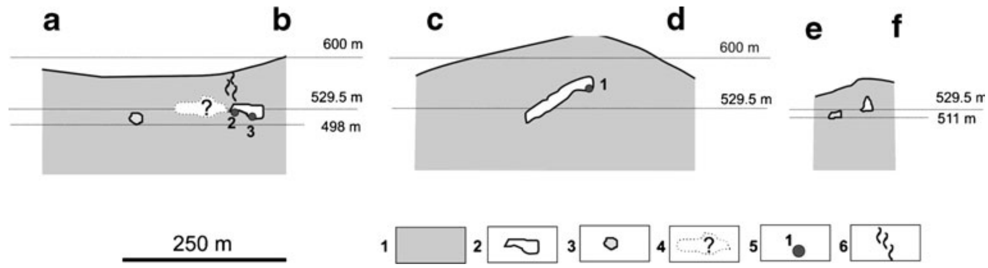


Fig. 5 Cross sections *AB*, *CD*, and *EF*. *1* upper Cretaceous limestone, *2* cross section of cave passage, *3* passage with underground Pivka River, *4* hypothesized unknown cave, *5* monitoring sites (*1* Postojna 1, Velika Gora; *2* Postojna 2, Lepe Jame; *3* Postojna 3, Lepe Jame), *6* tectonically fissured zone

2 Site description

Slovenia is a country where karst covers 43% of the area (8,700 km^2). Of 10,000 registered karst caves, Postojna Cave is the longest, with 20,570 m of known passages. In 2009, the cave received 500,000 visitors and is one of the most visited show caves in Europe.

The River Pivka sinks at the lower entrance to the cave (Fig. 1) at 511 m above sea level. The entrance to the main, currently dry, passage is situated at 526.5 m and is 10 m high and 6 m wide. Cave passages are mostly horizontal, dipping toward the north and northeast. Horizontal passages are connected with some vertical shafts, such as Magdalena Jama, which is 40 m deep, and with collapse dolines such as Pivka Jama (75 m deep). The cave has six known entrances (Fig. 1) and some less known or unknown connections to the surface, mostly corrosionally widened fissures. The thickest ceiling in the cave is about 110 m. Between Lepe Jame and Črna Jama (Fig. 1), an artificial tunnel is closed by doors that are only shortly opened during occasional tourist visits. The ventilation from Črna Jama to Lepe Jame does not have a significant impact on our monitoring sites.

Postojna 1 (Fig. 2) is located at the northern edge of the biggest collapse chamber in the cave at 561.4 m above sea level with 65 m of the limestone roof and 50 m from a well-used tourist route. Postojna 2 (Fig. 3) is located at 526 m above sea with 58 m of limestone roof and 15 m from the tourist route. This narrow fissure in Lepe Jame was due to the strong blowhole artificially enlarged about 50 years ago, because speleologists hoped that the passage will continue. Although a strong effort for continuation was undertaken, the passage ended in a narrow fissure. The location is 190 m south of and 28 m higher than the underground Pivka River. Monitoring site number 3 (Fig. 4) is located just a few meters SE of Postojna 2 at 524 m, and has 60 m of limestone roof (Fig. 5). It is 4 m away from the tourist route. The fourth monitoring site (Fig. 1) is on the surface, outside the cave, about 30 m southeast of the Otoška Jama entrance.

The fact is that the air and pressure temperature measurements started at Postojna 1 and 2 sites as parallel studies of microtectonic deformations connected with radon emanations and not primarily as cave climate studies. Finding out the different behavior in air temperature between Postojna 1 and 2 directed our research to study cave climate more in detail and to add Postojna 3 monitoring site inside the principal passage of Lepe Jame. In this sense, our idea that Postojna 2 has characteristics of local cave climate (not typical for the rest of the cave) become clearer due to the fact that Postojna 3 site is more similar to distant Postojna 1 site than to closer Postojna 2.

3 Methodology

Air temperature and air pressure were continuously measured using Divers™ Data loggers, produced by Van Essen. All major meteorological processes in the cave, which are associated with seasonal climatic changes at the surface,

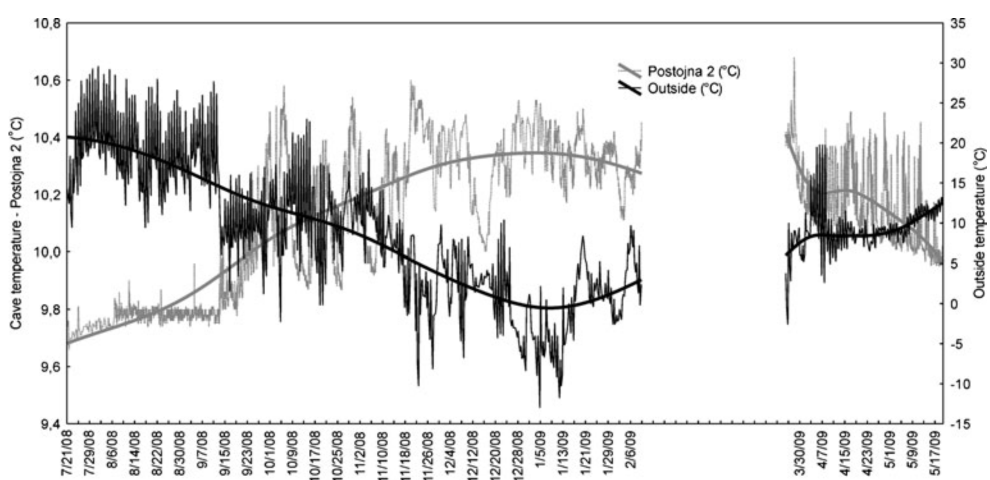


Fig. 6 Temperature time series (July 21, 2008 to May 17, 2009) for Postojna 2 and outside. Distance weighted fitting is depicted, to show seasonal trend

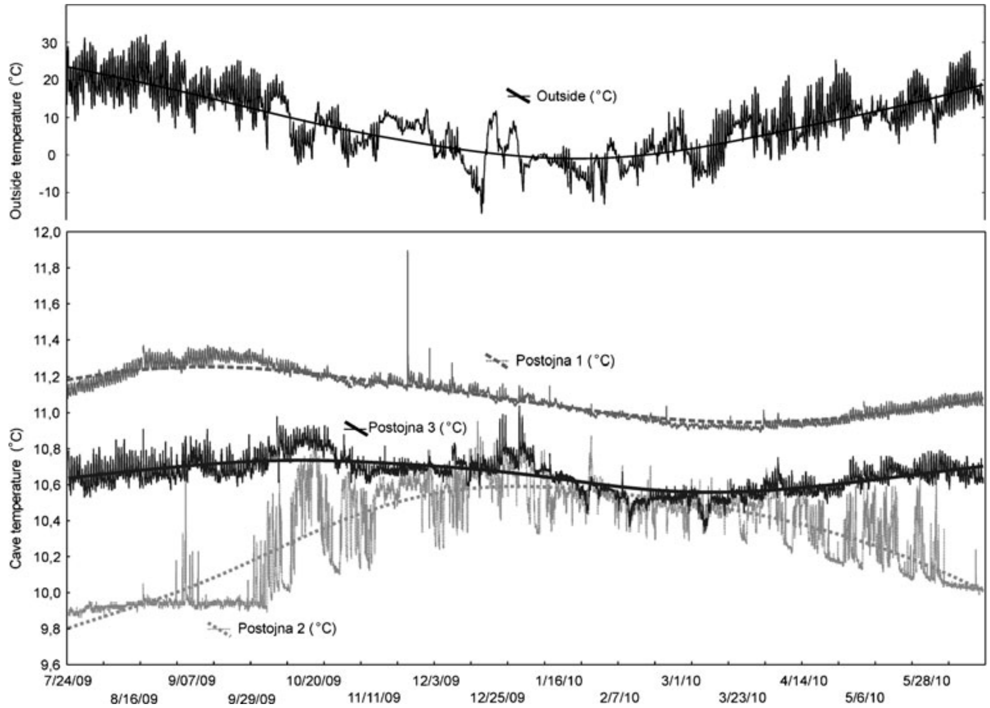


Fig. 7 Temperature time series (July 24, 2009 to June 18, 2010) for outside and three underground sites. Distance weighted fitting for all time series is depicted, to show seasonal trend

can be interpreted from the discussed dataset. Climatic characteristics of the cave are discussed for each of four seasons separately.

Air temperature and air pressure parameters were recorded hourly, and in some periods even at shorter intervals. Temperature accuracy of the data logger is ±0.1°C with a resolution of 0.01°C. Before the monitoring started, all data loggers were adjusted to the same temperature.

Measured air pressure data are relative, and values cannot be transformed to pressure units accurately. We were interested in outside and cave air pressure to find eventual differences or phase shifts between outside and cave air pressure. Hence, we compared trends and variation of air pressure at different locations.

The strongest air currents were observed at Postojna 2. For the period 2008–2010, only manual measurements of wind direction were performed by handheld anemometer. Measurements were performed occasionally (in average once per month) and always in the morning between 9 and 11 a.m. Velocities of wind are relatively slow (<1 m/s). The information, which we got in such mode, was additional to the automatic temperature measurements at Postojna 2 especially during the winter, when the highest temperature unrest was detected.

Data were processed with statistical methods. Basic statistics, linear correlation, cross-correlation, and spectral analysis were applied. Basic statistics such as mean, maximum value, minimum value, and standard deviation

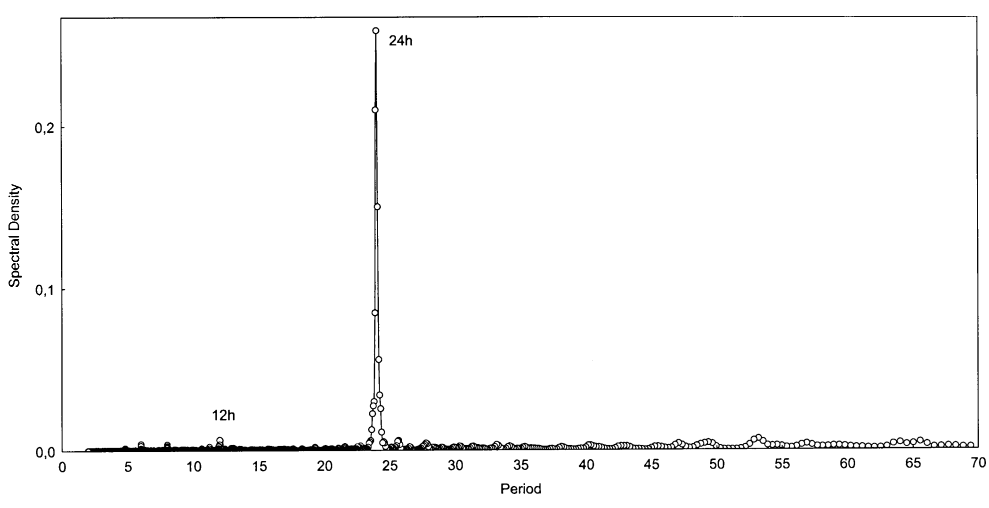


Fig. 8 Spectral analysis (July 24, 2009–June 18, 2010) of air temperature at Postojna 1 site

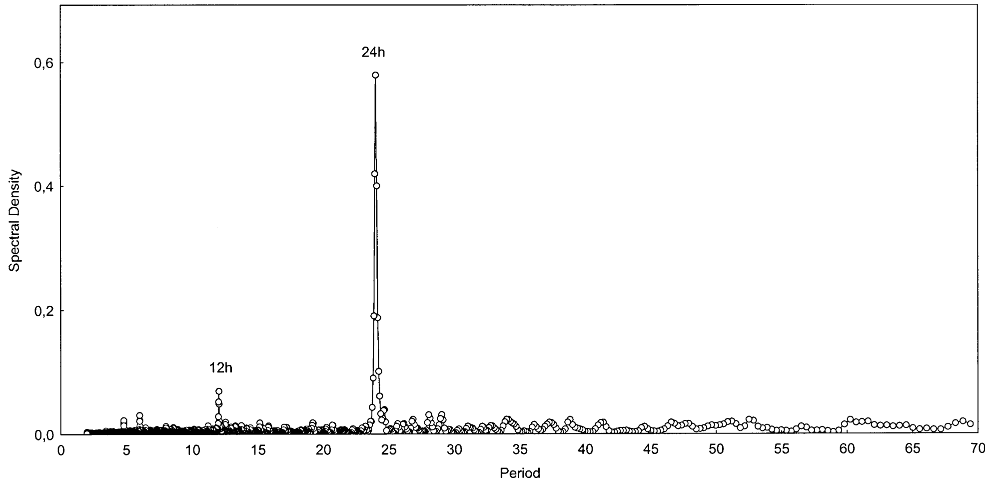


Fig. 9 Spectral analysis (July 24, 2009–June 18, 2010) of air temperature at Postojna 3 site

were applied to characterize the thermal properties of each underground location.

Spectral analysis is concerned with the exploration of cyclical patterns of data. The purpose of the analysis is to decompose a complex time series with cyclical components into a few underlying sinusoidal functions of particular wavelengths (Hill and Lewicki 2010). Spectral analysis is a measure of amplitude squared of the signal at a given frequency (Bourges et al. 2006). An example of spectral analysis is the cyclical variation of air temperature, due to solar radiation. Air is warmed during the day and cooled at night, resulting in a 24-h periodicity.

4 Results

4.1 Seasonal air temperature fluctuations

All three monitoring sites in the cave are situated relatively far away from known cave entrances (Fig. 1). Despite this, all of them exhibit diurnal variations of air temperature. But interestingly, they do not exhibit a similar seasonal trend. The expected seasonal trend is characteristic only for Postojna 1 and partly for Postojna 3 monitoring sites. The seasonal temperature trends at Postojna 1 and 3 are generally in accordance with the outside trend, but it is exactly opposite at the Postojna 2 site (Fig. 6). The seasonal trend at Postojna 3 is less pronounced than at Postojna 1 (Fig. 7).

Air temperature data at Postojna 1 show that temperature reaches a peak value in late summer or almost at the beginning of autumn (September), and a low value in early spring (March; Fig. 7). Hence, the peak and saddle values do not coincide exactly with seasonal temperature peak and saddle at the surface.

Postojna 2 exhibits a reverse temperature trend as compared to air temperature on the surface, but also contrary to temperature within the other two monitoring sites in the cave. Air temperature is stabilized at a consistently low temperature (temperature variations are of very small magnitude −0.05 °C) during summer months (June, July, and August) at the Postojna 2 site. Temperature

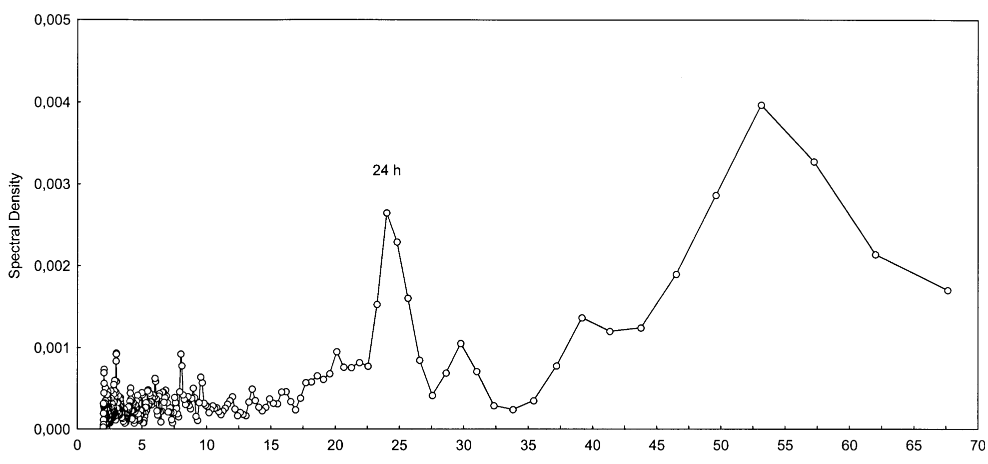


Fig. 10 Spectral analysis (August 1–18, 2009) of air temperature at Postojna 2 site

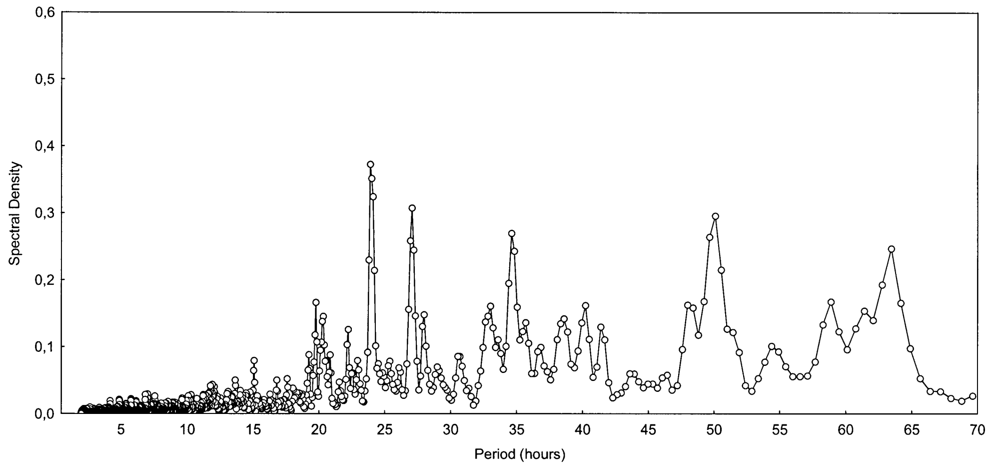


Fig. 11 Spectral analysis (July 24, 2009–June 18, 2010) of air temperature at Postojna 2

suddenly rises and begins to fluctuate significantly with magnitude of up to 0.5°C in the cooler part of the year. In this period, even the minimal temperatures remain above the temperature, which is characteristic for summer time (Fig. 7).

4.2 Diurnal air temperature fluctuations

Detailed spectral analysis of short-term, diurnal temperature fluctuations at the Postojna 1 site exhibits clear dependence on outside temperature. It shows clear 24-h and also 12-h periodicity (Fig. 8), caused by forced and density-induced advection of external air to the cave. Similar can be said for the Postojna 3 site (Fig. 9), while the dependence with outside temperature is not uniform for Postojna 2 (Figs. 10 and 11). Diurnal fluctuations may be in relatively good accordance with outside temperature fluctuations in the summer (Fig. 10); however, relationship is mainly reverse in the autumn and spring (Fig. 12). Moreover, there is no relation or small relation in the winter time.

4.3 Air pressure variation

A comparison of air pressure between the four monitoring sites shows simultaneous pressure variations at the surface and in the underground (Fig. 13). Air pressure in the cave fluctuates synchronically with outside air pressure.

4.4 Temperature statistics

According to Fig. 7, it is obvious that the air temperature is the highest at the Postojna 1 site on average, where the maximum recorded temperature was 11.89°C. The minimum temperature at Postojna 1 (10.89°C) is very close to the maximum temperature at the Postojna 2 and 3 sites (10.99°C and 11.04°C). The minimum temperature at Postojna 2 was 9.86°C and 10.34°C at Postojna 3 (Table 1).

There is a relatively large temperature contrast between Postojna 1 and Postojna 2 sites, while Postojna 3 is somewhere in between. Mean annual temperature of Postojna 1 is 11.09°C, while it is 10.32°C at Postojna 2.

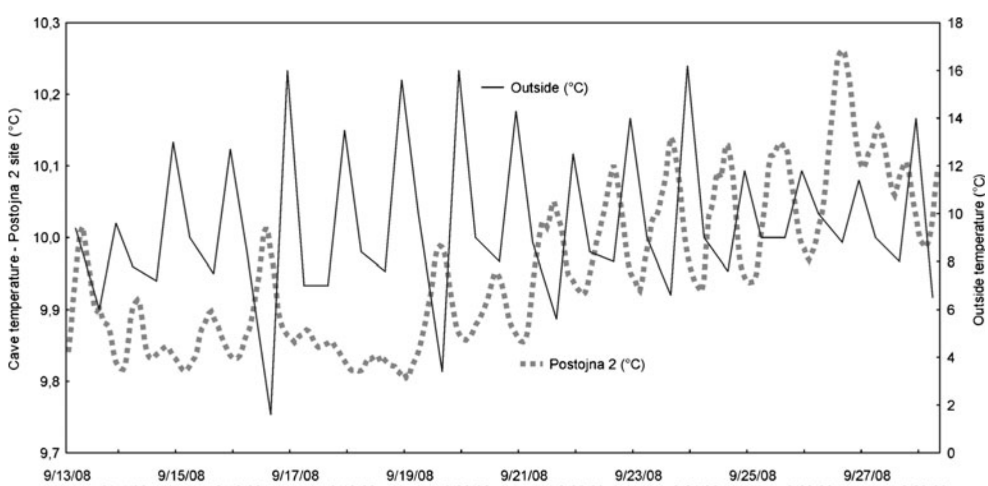


Fig. 12 Temperature time series (September 13–28, 2008) for Postojna 2 and outside

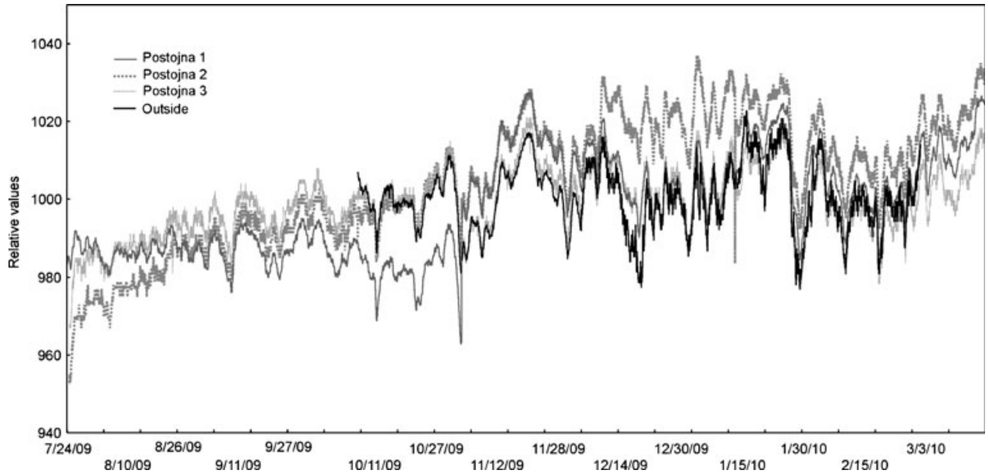


Fig. 13 Air pressure time series (July 24, 2009 to March 19, 2010) for all four monitoring locations (one at the surface and three in the cave)

5 Discussion

5.1 Comparison of air pressure time series

Variations of air pressure in the cave and outside the cave seem simultaneous (Fig. 13). One could argue that the reason might be a sampling interval that is too long. For 1 month (October 2009), we increased the frequency of measurements from 1 per hour to 30 per hour (i.e., measuring interval was 2 min), but still no phase shift between cave pressure and external pressure was revealed, which results in simultaneous changes of air pressure. Instant air pressure equalization between the cave and outside atmosphere occurs. This process takes place due to the fact that the cave presents well-ventilated system with several entrances, which are relatively big in comparison to the entire cave volume.

5.2 Comparison of air temperature time series

The air temperature characteristics of monitoring sites can be attributed to ventilation within the cave. They were interpreted for each season separately, because ventilation regimes alternate seasonally.

5.2.1 Summer 2009

The initial process in summer is outflow of the cold dense air from the cave to the outside atmosphere. When the outside temperature is much higher than the cave temperature, warm air enters the cave system through known and unknown higher entrances and leaves the cave through lower entrances.

Due to high porosity of the ceiling, we presume that in the summer, external air flows down into the cave also through subvertical fissures that induce climate characteristics at Postojna 1. This location is on the top of collapse blocks within the collapse chamber, where the thickness of the ceiling is 65 m. Main cave passage is situated a few 10 m below this monitoring location. Relatively high diurnal variations occur at this station (around 0.1°C).

In the summer, there is frequent and strong ventilation from Postojna 2 toward the main passage (Postojna 3; Table 2, Figs. 5 and 14). Behind the Postojna 2 site, the subvertical corrosionally widened fissures are probably after 58 m connected with the surface, from where wind enters to the Postojna 2 site in the summer (Fig. 15). Whether the connection is direct through subvertical fissures or possibly through some unknown cave chamber

Table 1 Basic statistics of underground temperature (in °C) and outside temperatures

	Mean	Standard deviation	Minimum	Maximum	25%	75%
Outside[a]	8.40	8.725	−15.61	32.10	1.38	14.59
Postojna 1—Velika Gora	11.09	0.128	10.89	11.89	10.89	11.20
Postojna 2—Lepe Jame	10.32	0.271	9.86	10.99	10.03	10.55
Postojna 3—Lepe Jame	10.65	0.095	10.34	11.04	10.58	10.71

Statistics are for the period July 24, 2009–June 18, 2010

[a] Outside temperature data from July to October 2009 were obtained from Environmental Agency of Slovenia for the town of Postojna and from October 2009 to June 18, 2010 from our monitoring data loggers at Postojna 4

Table 2 Postojna 2 air temperature, outer air temperature, and wind direction at Postojna 2

Date (dd.mm.yy)	T (°C) cave	Wind	T (°C) at 7 a.m.—Postojna	T (°C) at 10 a.m.—Postojna	T (°C) at 2 p.m.—Postojna
3.3.2008	11	Weak wind	2.4		11
10.4.2008	10	No wind	9		11
21.4.2008	**10**	**In the cave**	**5.2**		**10**
5.6.2008	*9.5*	*In the cave*	*15*		*16*
26.6.2008	*10*	*In the cave*	*22*		*25.5*
21.7.2008	*10*	*In the cave*	*15.4*		*14.2*
24.7.2008	10	No wind	16		24
25.7.2008	9.5	No wind	13		25
27.7.2008	10	No wind			
29.7.2008	*10*	*In the cave*	*19.5*		*28.5*
31.7.2008	*10*	*In the cave*	*19.3*		*28*
3.8.2008	10	No wind			.
5.8.2008	*9.5*	*Strongly in the cave*	*19*		*29*
7.8.2008	*9.5*	*In the cave*	*18*		*28.5*
9.8.2008	10	No wind			
12.8.2008	*9.5*	*In the cave*	*14.8*		*25.6*
14.8.2008	*9.5*	*Strongly in the cave*	*19*		*26*
17.8.2008	10	No wind			
25.8.2008	10	No wind	12.6		21.5
10.9.2008	*9.5*	*Strongly in the cave*	*11.8*		*26.4*
3.10.2008	10	No wind	11.7		17.3
21.10.2008	10	No wind	2.4		10.3
29.10.2008	**10**	**From the cave**	**14.2**		**16.5**
11.11.2008	***10***	***From the cave***	***4.6***		***8.3***
20.11.2008	***10.5***	***From the cave***	***3***		***8.4***
11.12.2008	10	No wind			
7.1.2009	**10**	**In the cave**	**−5.7**		**0.5**
10.2.2009	***10.5***	***From the cave***	***2.4***		***4.2***
10.3.2009	***10***	***From the cave***	***−6.2***		***10.2***
6.4.2009	*10*	*In the cave*	*8*		*19.8*
21.4.2009	10	No wind	10.7		12
28.4.2009	*10*	*In the cave*	*10.3*		*14*
20.5.2009	*10*	*In the cave*	*17.3*	*21.08*	*23.6*
16.6.2009	*9.5*	*In the cave*	*17.9*	*24.3*	*26.7*
10.7.2009	*10*	*In the cave strongly*	*12.9*	*14*	*15.7*
24.7.2009	10	No wind	16	25.7	28.3
20.8.2009	*10*	*In the cave strongly*	*19.6*	*23.1*	*29.5*
2.10.2009	*9.5*	*In the cave*	*12.7*	*15.5*	*13*
12.10.2009	**10**	**From the cave**	**11.3**	**11.18**	**5.9**
3.11.2009	**10**	**In the cave**	**0.1**	**0**	**3**
23.11.2009	***10***	***From the cave***	***8.9***	***9.31***	***9***
1.12.2009	10	No wind	6.5	6.48	6.6
9.12.2009	10	No wind	1.4	1.47	6.2
13.1.2010	10	No wind	−2.2	−1.81	−0.6
19.1.2010	10	Almost no wind	−4.6	−4.07	1.5
27.1.2010	***10***	***From the cave***	***−9***	***−7.88***	***−3***
28.1.2010	***10***	***From the cave***	***−9***	***−7.78***	***−1.4***
15.2.2010	***10***	***From the cave***	***−3.5***	***−1.23***	***1.3***
24.2.2010	10	No wind	0.7	3.26	5.5

Table 2 (continued)

Date (dd.mm.yy)	T (°C) cave	Wind	T (°C) at 7a.m.—Postojna	T (°C) at 10a.m.—Postojna	T (°C) at 2p.m.—Postojna
1.3.2010	10	No wind	5.6	7.2	11.2
19.3.2010	***10***	***From the cave***	***3.4***	***8.53***	***12.9***
31.3.2010	***10***	***From the cave***	***5.9***	***7.53***	***8.5***
9.4.2010	*9.5*	*In the cave*	*3*	*12.71*	*20.5*
6.5.2010	**10**	**From the cave**	**9.8**	**11**	**9.11**
24.5.2010	*10*	*In the cave*	*8.3*	*15.24*	*22.1*
18.6.2010	*10*	*In the cave*		*15.9*	

Manual measurements of cave temperature and wind direction in the cave were taken between 9 and 11 a.m. In italics are T outside > T cave (flowing in the cave from surface). In italics and bold are T outside < T cave (flowing from the cave to the surface). In bold are exceptions

situated behind the Postojna 2 site, we do not know. The direction of ventilation can also be reversed (Table 2, Fig. 14).

Diurnal fluctuations of air temperature at Postojna 2 can be attributed to such ventilation coming whether from unknown cave behind or directly from the surface. Descending air is warmer during the day then during the night. However, diurnal fluctuations are of slight magnitude within the data logger accuracy at Postojna 2. We may presume that wind, which penetrates to this location from the surface, gains greatly the temperature of the rock and that diurnal fluctuations are highly dampened here (in contrast with Postojna 1). Or if we presume the possibility that the wind comes from some unknown cave behind, then the wind at Postojna 2 can be a mixture of fresh air and cave air, which is equilibrated with the cave environment.

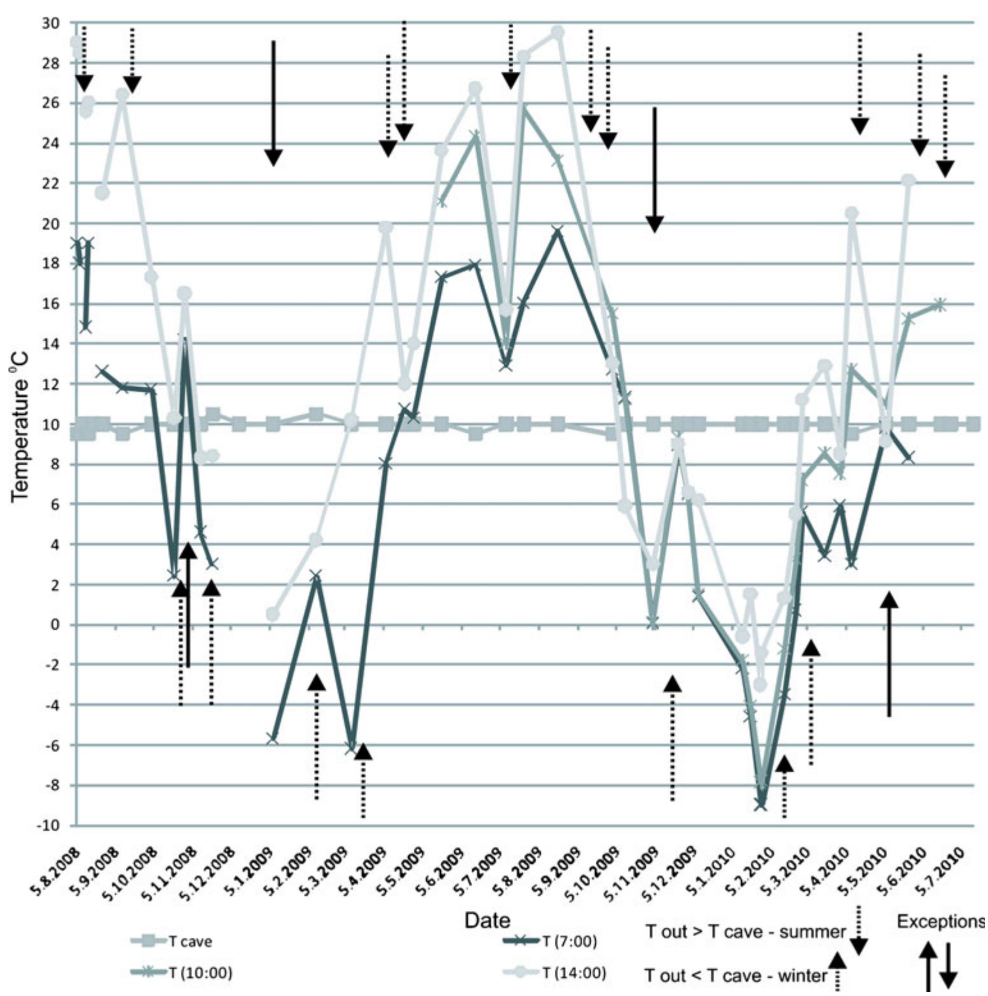


Fig. 14 Air temperature and wind direction at Postojna 2 site measured manually (9:00–11:00) in the relation to outside temperature (at 7:00, 10:00, and 14:00) for 2008–2010

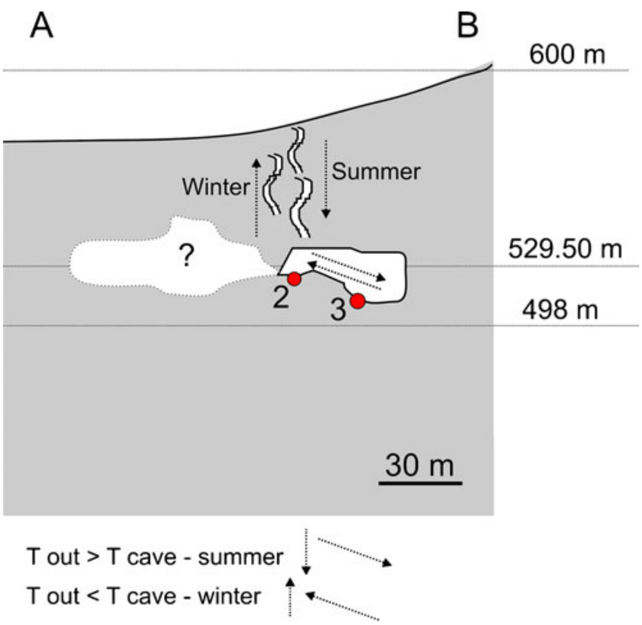


Fig. 15 Cross section *AB* with Postojna 2 and 3 sites and wind directions

The latter hypothesis can also explain the extremely low magnitude of diurnal fluctuations.

In summer, the air temperature at Postojna 3 more resembles temperature at Postojna 1 than Postojna 2, despite the fact that wind moves from Postojna 2 site directly to the passage, where the Postojna 3 site is located (Figs. 1, 4, and 15). Diurnal temperature variations are the highest at Postojna 3 site (around 0.2°C), which is characteristic for the summer mainly. This location is quite close to the touristic pathway; hence, massive tourism may theoretically have some influence on the high magnitude of diurnal fluctuations. Air temperature at Postojna 3 is constantly lower than at Postojna 1, but also higher than Postojna 2. It is obvious that confluence of at least two different air currents takes place at the Postojna 3 location.

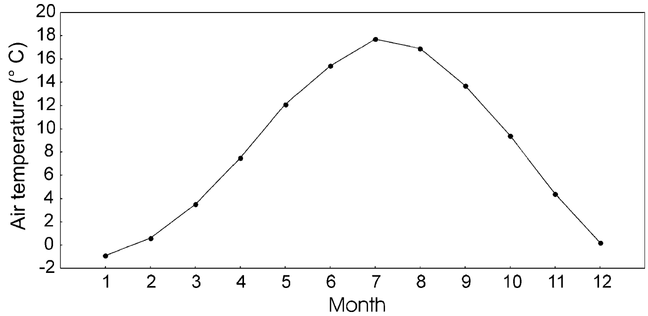


Fig. 17 Average monthly air temperatures in Postojna for the period 1960–1990 (Environmental Agency of Slovenia)

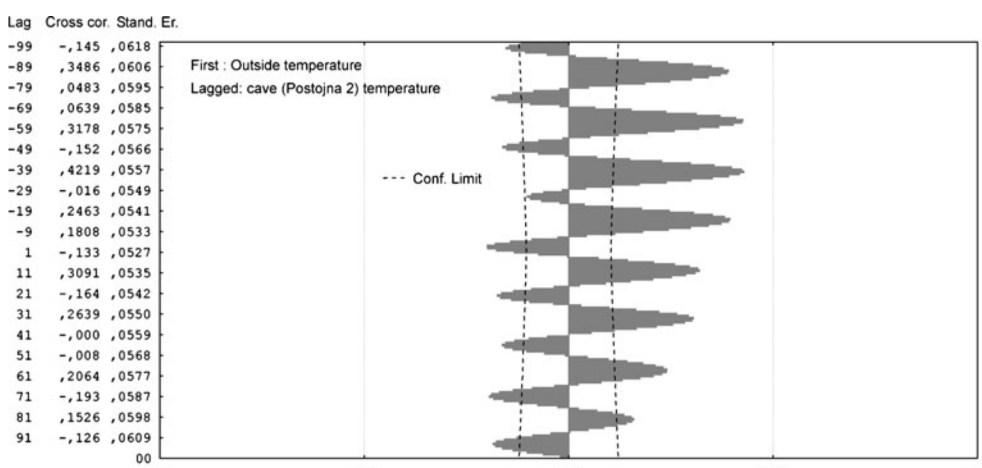
One air flux reflects a more general ventilation regime within the cave system (see also Postojna 1, especially its seasonal trend), and another one is more local, arriving from Postojna 2, representing microlocation particular from the air temperature point of view. The former air flux is prevailing at Postojna 3. As these two reverse trends tend to balance each other in the annual cycle, the seasonal trend is slight at Postojna 3. Moreover, occurrence of seasonal peak (and also saddle) at Postojna 3 site is not necessarily synchronous with the Postojna 1 site (Fig. 7).

5.2.2 Autumn 2008 and 2009

The summer ventilation regime, which is driven by forced convection, stops when outside temperature drops to around 10°C, which is the mean cave temperature. Moreover, the ventilation regime alters when outside temperature drops below 10°C. Such temperatures around 10°C are characteristic for autumn.

We presume that when outside temperature drops below that within the cave (September 13–28, 2008, Fig. 12), the cold air enters the cave from the main entrances (cross section EF on Fig. 5). Inflow of cold air sweeps through the cave near the bottom, and it displaces the warmer air

Fig. 16 Cross-correlation of surface air temperature versus underground air temperature (Postojna 2) for time period September 13–28, 2008



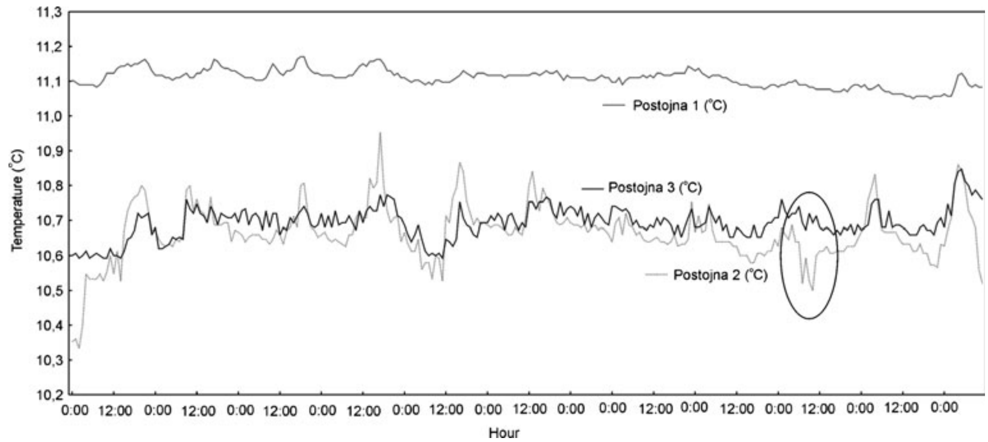


Fig. 18 Temperature time series (December 15–25, 2009) for Postojna 1, Postojna 2, and Postojna 3 sites. *Circle* shows the most significant temperature discrepancy between Postojna 2 and Postojna 3 sites

(Smithson 1991; Pflitch et al. 2006). The displaced warm air leaves the cave through secondary shafts or fissures, which penetrate to the surface, or it moves backward toward the cave entrance below the ceiling. The described ventilation regime is of the winter type.

Ventilation alters on a 12-h rhythm in the autumn and spring, when outside temperature increases above cave temperature (10°C) during the daytime (summer-type ventilation regime), and it decreases below cave temperature (10°C) at the nighttime (winter-type ventilation regime; Pflitch et al. 2006).

At the nighttime in autumn, when the winter ventilation regime occurs, relatively cool air displaces the warm air within the main cave passages. Such warm air is first displaced further in to the cave, and it tends to leave the cave also through solutionally enlarged vertical fissures in the cave ceiling. We presume that this displaced warm air passes the Postojna 3 site (in the main passage) and is partly sucked from this main passage (Postojna 3) to the back into unknown cave behind Postojna 2, from where it presumably penetrates to the surface or behind it into the unknown passages (Fig. 5). Consequently, the temperature at Postojna 2 increases in the nighttime, and tends to approach the temperature of Postojna 3 (from where the air fluxes arrive in such a case). In the daytime, the ventilation regime changes to the summer type, and temperature at Postojna 2 tends to drop to a value, which is characteristic for summer −9.9°C (Fig. 12).

The 12-h rhythm of alternation of the two ventilation regimes causes a reverse relation between outside and cave air temperature at Postojna 2. The outside maximum coincides with cave minimum and outside minimum with cave maximum (Figs. 12 and 16).

Alternation of the two ventilation regimes also affects the Postojna 3 site. Warm cave air is pushed along the Postojna 3 site in the nighttime, when cool air enters the cave from the cave entrances (cross section EF on Fig. 5). Because of this, the diurnal temperature minimum increases at Postojna 3, and a seasonal peak is reached on the annual scale (second half of October on Fig. 7). However, as soon as alternation of the 12-h rhythm of two ventilation regimes ceases, and the winter regime prevails also during the daytime (T outside < T cave in 24-h cycle), the cool air penetrates to the Postojna 3 site, and the decrease of seasonal trend begins (end of October on Fig. 7). The distance from the cave entrance to the Postojna 3 site is 1.5 km, and because of only when the outside temperature

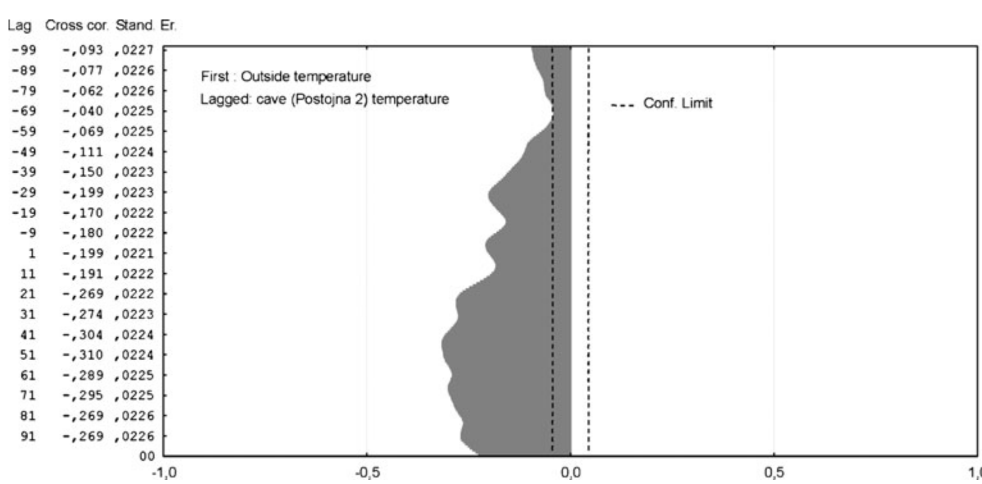


Fig. 19 Cross-correlation between outside and Postojna 2 for winter 2008–2009

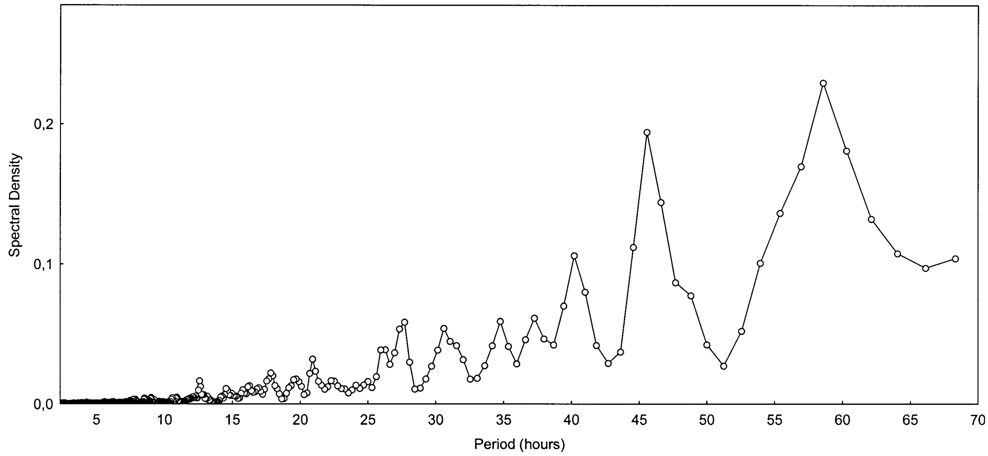


Fig. 20 Spectral analysis (winter 2008–2009) of air temperature at Postojna 2

decreases below cave temperature for a longer period (winter-type ventilation regime takes place continuously for at least a few days), cool air penetrates to this area.

In contrast, the warm air is pushed through Postojna 3 (and also Postojna 2) when the winter type of ventilation regime occurs only with periodicity of 12 h (during nighttime) and there is not time enough that cool air reaches the Postojna 3 site situated far from the entrance. Before it happens, ventilation regime alters to summer type during the daytime.

In autumn, the change of seasonal trend appears also at the Postojna 1 site. Air temperature at this specific location does not seem to be dependent on the type of ventilation regime, but rather on seasonal climatic conditions.

According to outside meteorological data for the period 1960–1990 (Environmental Agency of Slovenia 2010), the inversion of seasonal trend should occur in August, but it occurred with a 1-month phase delay (in September). The highest average annual temperature of the surface area above the cave occurs in July (17.7°C). August is usually slightly cooler (16.9°C), while there is typically a decline in September (13.7°C; Fig. 17).

The seasonal trend does not invert at Postojna 1, till mean monthly temperature at the surface does not exceed or decrease below cave temperature and the ventilation regime alters from summer type to winter type (peak in the seasonal trend) or vice versa (saddle in the seasonal trend).

5.2.3 Winter 2009–2010

In winter time, exclusively one type of ventilation regime takes place. Inflow of cold air is sweeping through the cave near the bottom, while warmer cave air is displaced below the ceiling (Smithson 1991; Pflitch et al. 2006).

The displaced warmer cave air rises up and influences the air temperature at Postojna 1, which is situated on the top of collapse chamber, a few tens of meters above the main passages. The slow negative temperature trend may be attributed to constant cooling of the entire underground system (including rock-mass) by cool airflows, which arrive mainly from the principal entrances (cross section EF on Fig. 5). Diurnal variations are relatively low in comparison with summer time. However, such variations are lower also at the surface in the winter.

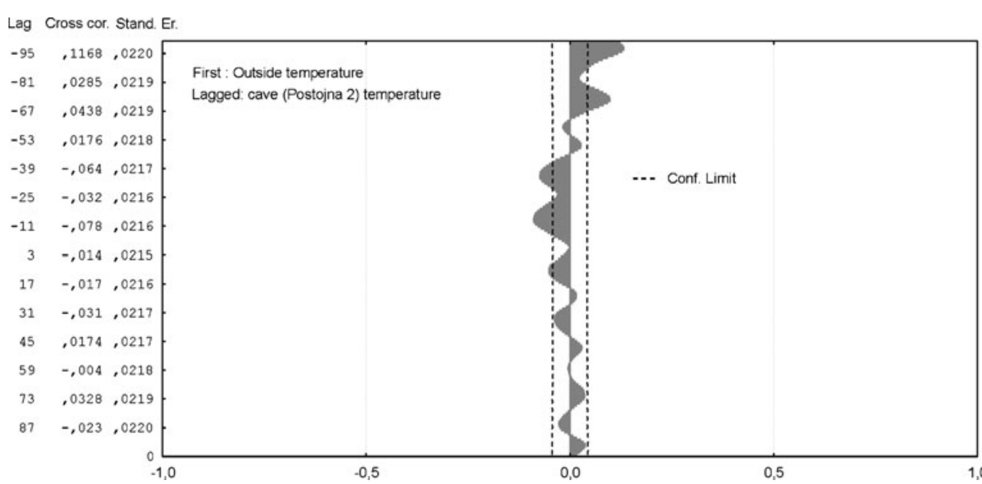


Fig. 21 Cross-correlation between outside and Postojna 2 temperature for winter 2009–2010

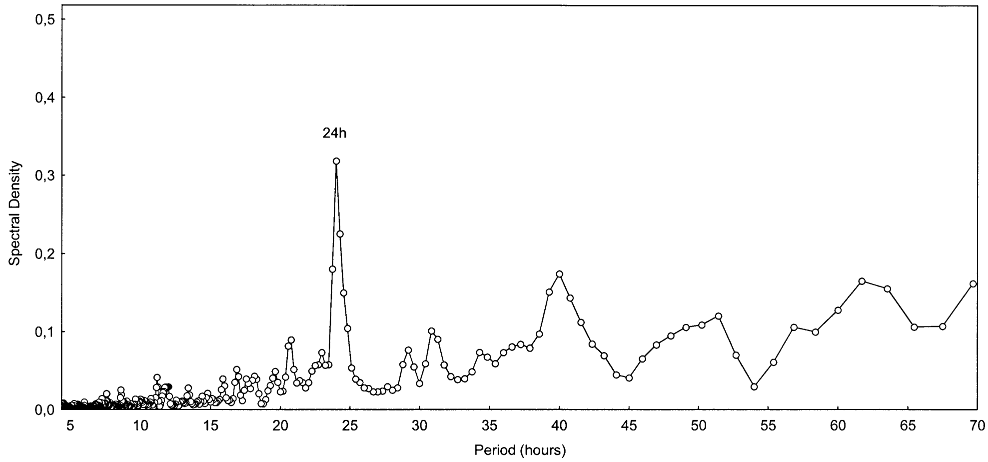


Fig. 22 Spectral analysis (winter 2009–2010) of air temperature at Postojna 2

It would be expected that the air should constantly blow from Postojna 3 situated in the main passage, toward Postojna 2 situated within small side passage. The temperature of Postojna 2 partly confirms this hypothesis, as it does not always resemble the temperature of Postojna 3. Occasionally, we manually measured the direction of wind at Postojna 2 (Table 2, Fig. 14). Usually, the wind is really directed from Postojna 3 to Postojna 2 site in the winter. But the wind is weak in comparison with summer time, when the ventilation regime is mostly reversed. Sometimes, there is also no detectable wind, or the direction of wind is not as expected in the winter. Such inversion cannot be explained by changes of general ventilation regime within the cave. Outside temperature is constantly lower than cave temperature in the winter.

As can be seen from Fig. 18, the air temperature at Postojna 2 may deviate from temperature at Postojna 3. The only reliable explanation is that different winds interact with each other at the Postojna 2 site. It seems that there are periods when additional airflow must be coming from "unknown cave" passages in the back (Fig. 15).

Temperature characteristics at the Postojna 2 site are the most complex, especially in winter. In winter 2008–2009, there was no statistically significant correlation (neither normal, neither reverse) between outside temperature and Postojna 2 temperature (Fig. 19). Moreover, even spectral analysis shows no significant periodicity for Postojna 2 in contrast with other seasons, which all have significant 24-h periodicity (Fig. 20). But on the contrary, temperature at Postojna 2 can be correlated with outside temperature in winter 2009–2010 (Fig. 21). Characteristic 24-h periodicity occurs in this period (Fig. 22).

5.2.4 Spring 2010

The relation between outside and cave air temperature in spring 2010 is similar as in the autumn for all three stations within the cave. The alternation of summer- and winter-type ventilation regimes may occur with 12-h rhythm, as was described in autumn 2009.

The air temperature at the Postojna 2 site fluctuates with clear 12-h periodicity until June (Fig. 23), when it reaches

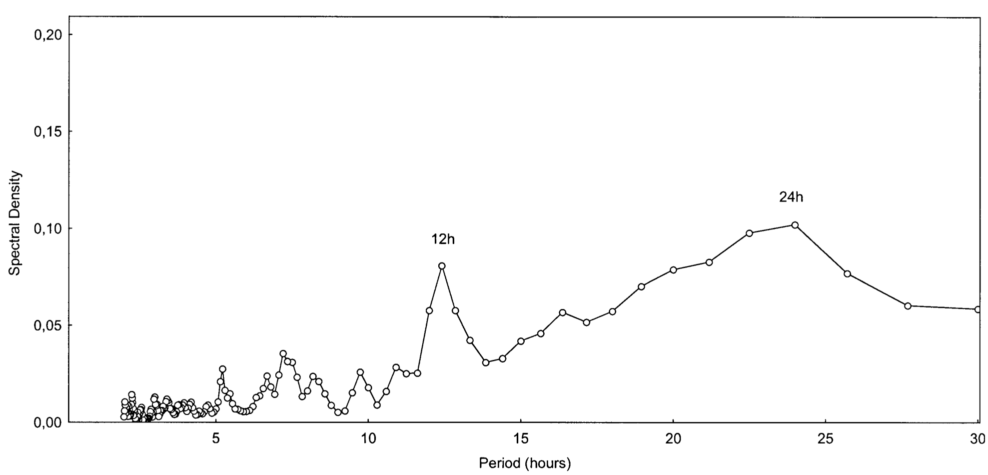


Fig. 23 Spectral analysis (May 5–19, 2010) of air temperature at Postojna 2

low temperature and is stabilized. Such low temperature is characteristic for the entire summer time, as was previously discussed.

The summer type of ventilation regime, which occurs during daytime, brings warm air from the surface, and the seasonal trend inverts at Postojna 3.

The seasonal trend at the Postojna 1 site inverts not before the end of March/the beginning of April, despite the fact that according to the surface data, there is already a significant rise of temperature in March (3.5°C) regarding the typical winter months (average January air temperature is −0.9°C; Fig. 16). As discussed for autumn, inversion of the seasonal trend at Postojna 1 occurs when the outside temperature increases above the cave temperature (10°C) and heat is brought to the cave by advection (air circulation) almost exclusively.

6 Conclusions

In Postojna Cave, the systematic studies of modern climate started only 2 years ago. First basic results are presented in this article. The study is proceeding with additional underground meteorological stations that employ a number of sensors for temperature, a sensor for water temperature in a pool, an ultrasonic wind speed monitor, a sensor for measuring the concentration of carbon dioxide in the air, and a sensor for measuring relative humidity.

Even if we systematically measured only the air temperature and air pressure at three locations in the cave, the data are interesting and represent the basis for future studies, especially to ensure the sustainable development of cave system and to develop guidelines for the use of cave system as natural asset.

The comparison between air pressure of three monitoring sites in the cave with the one on the surface above the cave shows simultaneous pressure variations at the surface and in the underground (Fig. 13). Air pressure in the cave fluctuates synchronically with outside air pressure.

Temperature data for Velika Gora (Postojna 1) and Lepe jame (Postojna 3) show good correlation with outside climate conditions for the studied time period (2009–2010). The 12-h periodicity (Postojna 1 and 3) proves that surface influences do penetrate deep in the cave and they are significant. According to results of spectral analysis, the Postojna 1 and 3 sites both represent general climatic characteristics of the cave system. Postojna 3 exhibits a relatively slighter seasonal trend. In the warmer part of the year, it seems to reflect the same trend as Postojna 1, but in the cooler part of the year, temperature at Postojna 3 tends to adjust with temperature at the neighboring Postojna 2 site (Fig. 7).

The temperature at Postojna 1 was increasing constantly from March to May 2009, while at Postojna 2, it was decreasing. Postojna 1 has a seasonal trend in accordance with the outside trend, while the seasonal trend at Postojna 2 is just opposite to the outside trend. Postojna 2 shows strong locally limited microclimate conditions. The most interesting data are for Postojna 2 in the winter (Figs. 19 and 21). The interaction between different airflows is the strongest in winter. Microclimate studies in this passage (Postojna 2) are showing local variability that can be due to unknown passages in the back (Fig. 15).

On the other hand, heavy precipitation, entering the cave as percolation water, can influence local cave temperature, but in our case, the data of snow cover and rain precipitation in the period January–March 2009 did not give any good correlation with temperature at Postojna 2.

According to Bourges et al. (2006), during the winter regime, the cave temperature is characterized by large oscillations, more pronounced near the entrance and correlated with the outside temperature. The winter temperature oscillations at Postojna 2 site do not show only the winter regime, but regarding Table 2 and Fig. 14, there must be a source of additional wind not only from subvertical fissures from the surface but also from unknown cave passages behind.

The study showed that Postojna 2 site is an interesting microclimate location, within a generally well-ventilated cave system, and is interesting for additional speleological and biological studies.

Acknowledgments The study was performed within the projects *Expert control and recommendations for management of cave systems* and *Climatic and biologic monitoring of cave systems* financed by Turizem KRAS Destinacijski management d.d. It is also part of *Karst Research Programme* (P6-0119) and project *Monitoring and analysis of selected climatic parameters in karst caves: The case of Postojna Cave system* (L6-2156) both financed by Slovenian Research Agency. Ira D. Sasowsky (University of Akron, OH, USA) is thanked for comments of the manuscript. Suggestions of reviewers significantly improved the original manuscript.

References

Badino G (2004) Cave temperatures and global climatic change. Int J Speleol 33(1/4):103–114

Bourges F, Genthon P, Mangin A, D'Hulst D (2006) Microclimates of l'aven d'Orgnac and other French limestone caves (Chauvet, Esparros, Marsoulas). Int J Climatol 26(12):1651–1670. doi:10.1002/joc.1327

Cropley JB (1965) Influence of surface conditions on temperatures in large cave systems. NSS Bull 27:1–10

Environmental Agency of Slovenia http://www.arso.gov.si/vreme/napovedi%20in%20podatki/postojna.html. Accessed 15 July 2010

Gams I (2003) Kras v Sloveniji v prostoru in času. ZRC Publishing, Ljubljana

Gosar A, Šebela S, Košťák B, Stemberk J (2009) Surface versus underground measurements of active tectonic displacements detected with TM 71 extensometers in Western Slovenia. Acta Carsologica 38(2–3):213–226

Hill T, Lewicki P (2010) Electronic statistics textbook. Tulsa, OK: StatSoft. http://www.statsoft.com/textbook/. Accessed 15 July 2010

Luetscher M, Jeannin PY (2004a) The role of winter air circulation for the presence of subsurface ice accumulations: an example from Monlesi ice cave (Switzerland). Theor Appl Karstol 17:19–25

Luetscher M, Jeannin PY (2004b) Temperature distribution in karst systems: the role of air and water fluxes. Terra Nova 16:344–350. doi:10.1111/j.1365-3121.2004.00572.x

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

Perrier F, Morat P, Le Mouël JL (2001) Pressure induced temperature variations in an underground quarry. Earth Planet Sci Lett 191:145–156

Perşoiu A, Feier I, Citterio M, Turri S, Maggi W (2006) Preliminary data on air temperature in Focul Viu ice cave (Bihor Mts, Romania). Proc 2nd Int Workshop on ice caves, pp. 62–64

Pflitch A, Piasecki J, Sawinski T, Strug K, Zelinka J (2006) Development and degradation of ice crystals sediment in Dobšinskà ice cave (Slovakia). Proc 2nd Int Workshop on ice caves, pp. 38–49

Pflitsch A, Piasecki J (2003) Detection of an airflow system in Niedzwiedzia (Bear) Cave, Kletno, Poland. J Cave Karst Stud 65 (3):160–173

Šebela S, Vaupotič J, Košťák B, Stemberk J (2010) Direct measurement of present-day tectonic movement and associated radon flux in Postojna Cave, Slovenia. J Cave Karst Stud 72(1):21–34. doi:10.4311/jcks2009es0077

Smithson PA (1991) Inter-relationships between cave and outside air temperatures. Theor Appl Climatol 44:65–73

Stoeva P, Stoev A, Kiskinova N (2006) Long-term changes in the cave atmosphere air temperature as a result of periodic heliophysical processes. Phys Chem Earth 31:123–128. doi:10.1016/j.pce.2005.05.001