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ORIGINAL PAPER

# Črna Jama as a cold air trap cave within Postojna Cave, Slovenia

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**Abstract** Črna Jama is the coldest section of cave within the Postojna Cave System. Mean annual air temperatures at the Črna Jama 2 site are 5.6 °C (2015) and 5.7 °C (2016), and at the Črna Jama 3 site 7.1 °C (2015) and 7.2 (2016), whereas the mean external air temperature was 10.3 °C (2015) and 10.0 °C (2016). In Lepe Jame, the passage most heavily visited by tourists, the mean cave-air temperature is 10.7 °C (2014–2017). Črna Jama exhibits winter and summer temperature regimes. During warm periods ($T_{cave} < T_{out}$), it acts as a cold air trap, exchanging no air with the outside atmosphere. Under such conditions the cave-air temperature shows no short-term diurnal temperature oscillations. Cave-air temperature is significantly stable and affected only by elevation of the groundwater table, which is associated with precipitation. During cold periods ($T_{cave} > T_{out}$), ventilation takes place and dense, cold, outside air sinks into Črna Jama because of the favourable cave entrance morphology. Recent Črna Jama air temperature data (2014–2017) indicate a < 0.5 °C higher temperature than that recorded in historical data since 1933. Črna Jama is the most appropriate place within the Postojna Cave System to study long-term climatic changes. There are hardly any tourist visits to the cave, and human impacts on the cave climate are essentially reduced.

Article deals with meteorological studies in the coldest part of Postojna Cave, Slovenia. Regarding air temperature data set, meteorological characteristics of Črna Jama are described. Being the most visited show cave in Slovenia, Postojna Cave (environment and climate) is under strong human impact, but part of the system (Črna Jama) is mostly eliminated from human impact and is the best place for long-term climatic studies.

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## 1 Introduction

In recent years, the microclimate of the Postojna Cave System has been the subject of intensive investigations (Šebela and Turk 2011, Šebela et al. 2013, Gregorič et al. 2013, Gregorič et al. 2014, Šebela and Turk 2014, Šebela et al. 2015), reflecting the obligation of the cave management (the Postojnska jama d.d. company) to organise climatic monitoring and expert control within the heavily visited show cave. Being the second longest cave and the most visited of the show caves in Slovenia, Postojna Cave exhibits complex meteorological conditions. There are side passages and some remote parts that show different patterns of cave climate (Gregorič et al. 2013) to those met in the most visited passages used for tourism (Šebela et al. 2015). There are also some parts of the cave where meteorological studies pointed to possible correlations with global warming, which thus seems to be affecting not only external, but also cave temperatures (Domínguez-Villar et al. 2015, Šebela et al. 2015). In 2014, alongside climatic monitoring of the heavily visited Postojna Cave passages, studies were extended to Črna Jama, which is a less visited part of the cave system. To help determine anthropogenic impacts (Mulec and Kosi 2009, Mulec et al. 2012, Muri et al. 2013, Mulec 2014) upon cave climate, it is necessary to compare meteorological conditions in heavily visited passages with those in rarely visited passages.

The mean annual air temperature in Črna Jama is significantly lower than the mean annual temperature of outside air in the Postojna region. In this respect, Črna Jama is more closely related to ice caves, but there are no permanent ice deposits in the cave. In terms of cave entrance morphology, the cave is similar to Županova jama (Ravbar and Košutnik, 2014), the entrance of which is situated at 440 m, whereas Črna Jama sits at 533 m above sea level. During the cold part of the year, the freezing of dripping water can be observed in the entrance zone of Županova jama, forming ephemeral ice stalagmites. The ice is neither deposited in layers nor does it form a build-up of ice (Ravbar and Košutnik 2014). The same situation is also typical of Črna Jama.

Not many meteorological studies relate to cold caves that lack permanent ice, but studies have been performed in ice caves worldwide (Holmgren and Pflitsch, 2014; Luscher and Jeannin, 2004; Luscher et al. 2008; Williams and McKay 2015; Obleitner and Spötl, 2011; etc.). Ice caves are fairly common and have even been found, perhaps surprisingly, in areas with warm and arid climates, including New Mexico, California and Southern Idaho (USA) (Williams and McKay 2015). Ice caves can be seen as providing indicators for short- and long-term changes within the climates of their respective regions (Holmgren and Pflitsch 2014, Kern and Per oiu 2013). For example, the thickness of the ice in Monlesi ice cave (Swiss Jura Mountains) decreased by nearly 10 cm during the 2002–2003 annual cycles (Luscher et al. 2008). Moreover, massive ice loss in recent years has been reported from the Mauna Loa ice cave in Hawaii (Pflitsch et al. 2016).

Evaluation of historical photographs taken in the Eisriesenwelt cave (Austria) shows that 10–20 cm of ice has been lost since the 1920s (Obleitner and Spötl, 2011). The annual mass balance of ice depends strongly upon the late summer temperatures and the availability of seepage water in spring (Obleitner and Spötl, 2011).

In Central Pennsylvania (USA), meteorological studies have been carried out in the Trough Creek Ice Mine cave, which is considered to be a simple cold air trap. In winter, dense cold air sinks into the cave, cooling the interior rock surface. This site can be considered as an apparently static cave that behaves seasonally in a manner consistent with other simple cold air traps, having open and closed periods of cave-air circulation and stratification (Edenborn et al. 2012).

Cold air traps are commonly of particular ecological interest because they can provide climatic refuges or habitat islands (Edenborn et al. 2012); this is also the case for bats in Črna Jama. It was reported that Indian bats and grey bats hibernate in the near freezing zone of certain North American caves that have deep or large entrances and which function as cold air traps (Elliot 2012).

In the oldest recorded studies, Schmidl (1854) ascertained that Črna Jama is the coldest part of the Postojna Cave System. In the period from 17 February 1933 to 25 August 1936, Crestani and Anelli (1939) performed occasional measurements of cave-air temperature at Črna Jama. They found that air ventilation in the cave exists only when the external air temperature is lower than the cave-air temperature. In the neighbouring Pivka Jama, there is an additional effect from the underground river Pivka, raising the temperature of the cave air, which is then higher than in Črna Jama (Crestani and Anelli 1939). Occasional measurements of air temperature and $CO_2$ concentration at Črna Jama were carried out by Gams (1970, 1974).

The entrance to Črna Jama (533 m above sea level) sits in the southern slope of a 45-m deep collapse doline. The morphology of the cave entrance is favourable, such that cold winter air can readily descend deep inside the cave.

The aims of this study were to seek an explanation of the local cave meteorology (Črna Jama) within the complex Postojna Cave System and to produce a scientifically supported foundation for long-term climatic monitoring in part of the cave that is not subject to a heavy visitor load.

## 2 Methodology

Hourly cave-air temperature data for the period 2014–2017 were collected at four cave locations (Fig. 1), three sites in Črna Jama (Črna Jama 1, Črna Jama 2 and Črna Jama 3) and one in Pivka Jama (Črna Jama 1-Pivka Jama or PJ). The Črna Jama 1 site was situated at the entrance to Črna Jama near to the wire net door, 1.5 m above the floor at 533 m above sea level (ceiling thickness 26 m). Črna Jama 2 site was at the bottom of entrance chamber, at 517 m above sea level and 1 m above the floor (ceiling thickness 38 m). Črna Jama 3 site was placed 1.2 m above the floor at 513 m above sea level (ceiling thickness 40 m). The fourth site in Pivka Jama was at 498 m above sea level and 1.2 m above the floor (ceiling thickness 59 m). Baro-Diver® (Schlumberger Water Services) data loggers with an accuracy of ± 0.1 °C and resolution 0.01 °C were used to measure air temperature. To compare cave-air temperature data with conditions outside the cave, additional air temperature measurements were performed in the forest above Črna Jama. The data set was divided according to the different seasons for periodic statistical analyses performed by Statistica software (Statistica StatSoft. Inc.).

The Črna Jama monitoring sites (1–3) are separated from the rest of Postojna Cave System by two full metal doors (Fig. 1), which make it impossible for Črna Jama air masses to mix with air from other parts of the cave. The metal doors preserve the original Črna Jama cave conditions, because artificial tunnels were constructed in the 1920s to connect Črna Jama with the other passages. The only natural connection between Črna Jama and the rest of the Postojna Cave System is by way of water-filled phreatic loops.

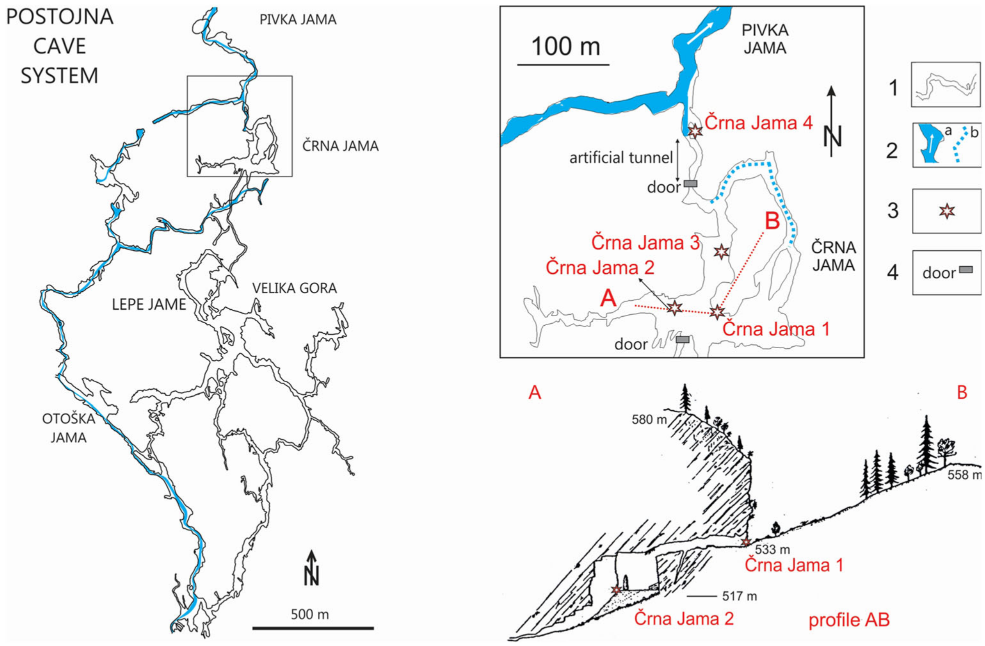



**Fig. 1** Črna Jama air temperature monitoring sites. 1—dry passages, 2a—water passage, 2b—intermittent water passage, 3—air temperature monitoring site, 4—solid metal door

## 3 Results and discussions

The air temperature data series for the period 16 January 2014 to 28 August 2017 are presented in Fig. 2. Characteristic annual temperature cycle data for the studied monitoring locations are provided for 3.6 successive years. There are no big differences in seasonal temperature trend at four monitoring sites during this period. Even summer of 2017 with high outside air temperatures (up to 37 °C) did not change Črna Jama air temperature. Črna Jama 2 site shows similar temperature curve for each year during 2014–2017. Summer 2017 temperature curve for Črna Jama 3 site is like the one in summer 2015, but both curves are lower as the one in summer 2016 (for almost 1 °C). The reason is that in winter 2015/2016, intrusion of outside cold air into the cave was not significant as much as in winter 2016/2017.

At the Črna Jama 2 and 3 sites, the air temperature is particularly stable during the summer, with no daily oscillations. In contrast, intrusions of cold outside air are detected at the Črna Jama 2 and 3 sites during the winter. Hence, the cave-air temperature data were divided into three seasonal periods: warm period (20 April–20 October 2015), cold period (16

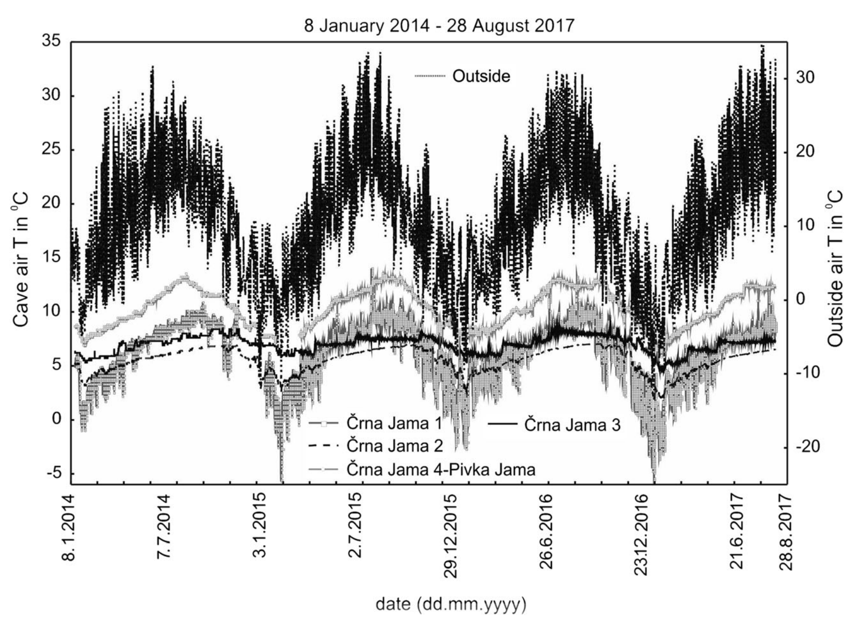



**Fig. 2** Hourly air temperature data set inside and outside Črna Jama for the period 16 January 2014 to 28 August 2017 (°C)

October 2015–17 March 2016, autumn–winter) and spring period (17 March–23 April 2015).

In the Dobšinskà ice cave (Korzystka et al. 2011) in Slovakia, a similar threefold pattern of air temperature changes was distinguished: (1) winter, (2) spring and the warmer part of winter and (3) summer. There are two distinct types of air exchange: the winter type and the summer type. Seasonal changes in the air exchange regime between Dobšinskà ice cave and its surroundings, along with in-cave air exchanges, are the main climatological factors affecting the cave climate system (Korzystka et al. 2011).

Relatively lower cave entrances experience a strong winter cooling and relatively higher entrances suffer a strong summer warming (Luscher et al. 2008). Depending upon the cave morphology, this is due to accumulation of cold and dry air or unidirectional advection of cold air into the cave during winter (Ford and Williams, 1989; Luscher and Jeannin, 2004). Most of the ice caves in the Swiss Jura Mountains act as cold air traps (Luetscher et al. 2005). In winter, because of the density differences between cave and outside air, significant air circulation (up to 20 $m^3/s$) takes place throughout the cave (Luetscher et al. 2005).

### 3.1 Warm period: 20 April–20 October 2015

During the warm part of the year (Fig. 3a), Črna Jama acts as a cold air trap. Warm outside air is lighter than cold cave air and cannot enter the cave, which is at lower level. Because of the lack of significant air exchange with the external atmosphere during the summer season, in most caves that are cold air traps, seasonal snow melting is generally related to water infiltration (e.g. related to thunderstorms). Summer air temperature appears to play only a minor role in the annual energy balance (Luetscher et al. 2005).

Temperatures at the Črna Jama 2 and 3 sites do not show daily oscillations but display a noticeably gradual rise (Fig. 4). Significant daily air temperature oscillations occur only at the Črna Jama 1 site, which is at the cave entrance.

During the warm period of the year, air temperature at Črna Jama 2 gradually increases from 5 to 7 °C (Fig. 4). Warm outside air does not come through the cave entrance by convection in this period, and thus the slight cave-air temperature increase could be attributed to the heating of the karst massif by conduction.

The air temperature at Črna Jama 3 in warm periods is very stable (Fig. 4). An exception was on 27 June 2015 (A on Fig. 4), when a rise of 1 °C was detected. This was probably connected to precedent surface precipitation, with water filling a horizontal epiphreatic passage (Fig. 1) that is 50 m away from the Črna Jama 3 monitoring site. On 24 June 2015, heavy precipitation (65 mm) in Postojna town raised the underground water level and also filled some generally dry epiphreatic passages. In Črna Jama, the groundwater temperature is higher than the air temperature, and an increase in

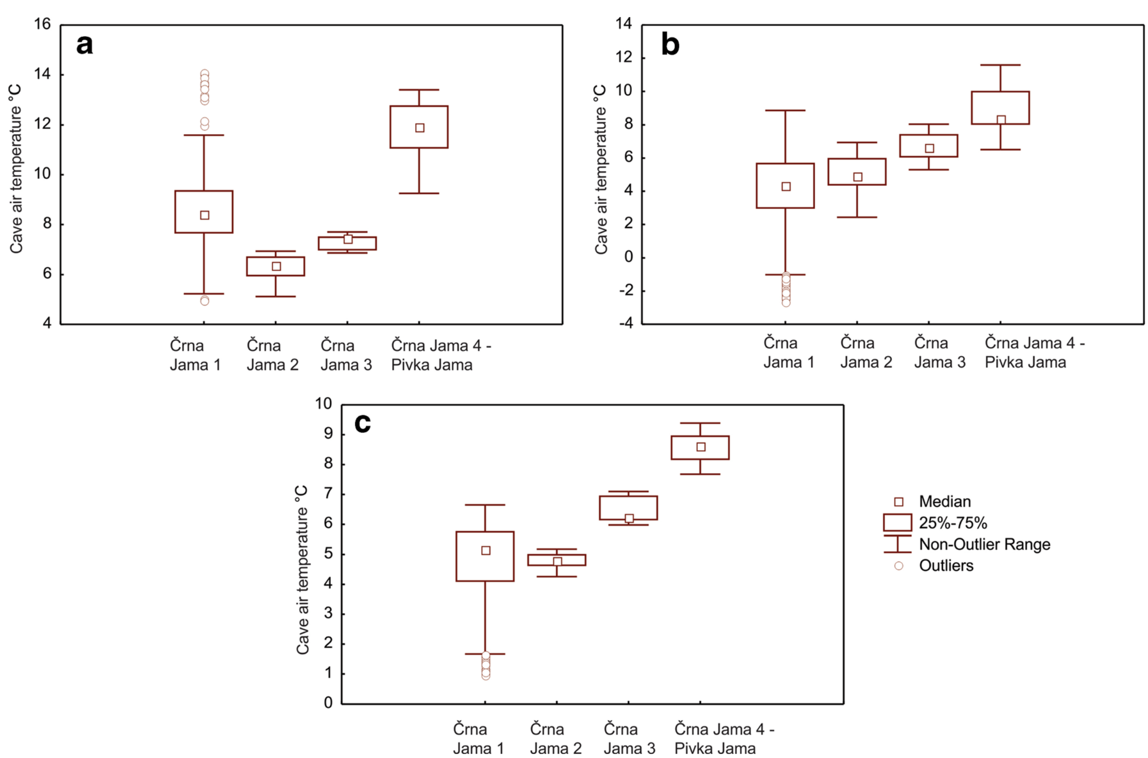



**Fig. 3** Box diagram of Črna Jama air temperature (°C). **a** 20 April 2015–20 October 2015 warm period. **b** 16 October 2015–17 March 2016 cold period. **c** 17 March 2015–23 April 2015 early spring period

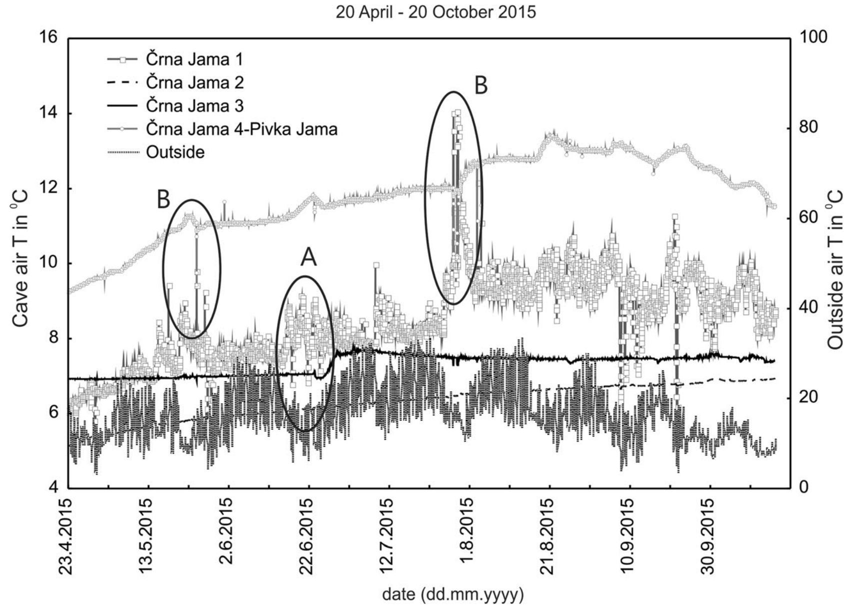



**Fig. 4** Details of the cave air and outside air temperature (°C) during the warm period between 20 April and 20 October 2015

groundwater level can also influence the temperature of the cave air.

At the Črna Jama 2 site, the air temperature probably reflects the temperature of the rock massif; this is about 8 °C, which is the value of the mean air temperature outside the cave in the period 1961–1990 (Šebela and Turk, 2011).

Values recorded at Črna Jama 4 (PJ) show a strong dependence of cave-air temperature upon underground Pivka water temperature described by Kaufmann et al. (2016), which can be 7 °C higher than the air temperature at the Črna Jama 2 and 3 sites. In summer, the underground river Pivka, flowing from the surface into the cave, keeps water temperatures higher deep into the karst system.

On 25 May 2015 and on 28 July 2015 (B on Fig. 4), two similar short-duration events took place. The outside air temperature dropped from about 30 °C to about 10 °C, and there was also a temperature drop of about 2 °C at Črna Jama 4. In contrast, at the Črna Jama 1 site, there was a cave-air temperature increase of 1–3 °C. The two events were not detected at the Črna Jama 2 and 3 sites, which remained beyond the influence of the summer weather conditions, with their temperatures remaining below 8 °C.

During the warm part of the year, there is no typical correlation ($r = 0.16$) between the outside air temperature and the temperature at Črna Jama 2 (Fig. 5). Warm air currents do not penetrate as far as the Črna Jama 2 site during the warm period, and this causes the trapping of cold air in the cave. A key morphology for such trapping of cold air is a wide cave entrance with downward sloping passages connected to closed, or partially closed lower chambers (Kite 2014), as is typified at Črna Jama too.

### 3.2 Cold period: 16 October 2015–17 March 2016 (autumn–winter)

Outside air has a strong impact on the Črna Jama air temperature during the cold part of the year because winter ventilation causes dense cold air to sink into the cave along the lower part of the cave entrance. The cooling effect declines with distance from the cave entrance, as is demonstrated by the median values of cave-air temperature (Fig. 3b), which increase from Črna Jama site 1 to site 3, and also by air temperature oscillations, which decrease from Črna Jama site 1 to site 3. At the Pivka Jama site, the situation is different because the

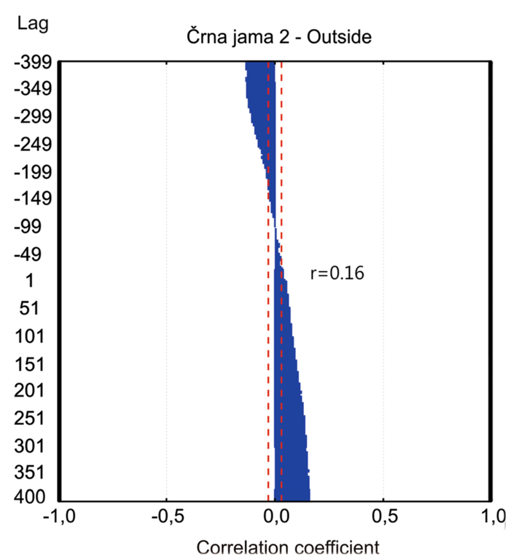



**Fig. 5** Cross correlation diagrams with cross correlation coefficients for warm period 20 April–20 October 2015 (Črna Jama 2–outside)

karst massif and also, indirectly, the cave air is thermally influenced by the underground river Pivka.

Between 02 and 08 December 2015 and 08 and 11 January 2016 (A on Fig. 6), two temperature events were recorded at the Črna Jama 3 and 4 sites. A cave-air temperature drop of 1–2 °C at the Črna Jama 4 site coincided with a temperature rise at Črna Jama site 3. During the same periods, the outside temperature was slightly higher than 10 °C.

Between 27 January and 03 February 2016 (B on Fig. 6), the outside air was constantly at about 8 °C, which is close to the temperature of the karst massif. During this period, the air temperature at the cave entrance site (Črna Jama 1) and the cave site (Črna Jama 2) increased logarithmically towards the temperature of the massif. It can be argued that under such conditions, there is no significant ventilation in Črna Jama.

A decrease of cave-air temperature in winter has been noted at all the monitoring sites in Črna Jama (Fig. 6). Črna Jama site 3 shows at least three events (C on Fig. 6) when the air temperature has risen due to surface precipitation filling up the water channel close to the site. Because of winter ventilation and intrusion of cold outside air, cave temperatures were elevated for only a short time. For example, a similar situation is described from the Monlesi ice cave (Swiss Jura Mountains) through the period 2001–2006. Here, the recorded values of air, rock, water and ice temperature, airflow, water discharge and cave humidity demonstrated that forced convection, controlled by the temperature difference between the cave air and the external atmosphere, is a driving force for the heat exchange between the cave and the surrounding environment (Luscher et al. 2008).

The correlation between cave-air temperature at Črna Jama 1 and the outside air temperature (Fig. 7a) is statistically significant, with $r = 0.89$. Other statistically significant correlations are those between Črna Jama site 2 and site 1 (Fig. 7b) ($r = 0.77$); Črna Jama site 2 and site 3 (Fig. 7c) ($r = 0.91$) and Črna Jama site 2 and site 4 (Pivka Jama) (Fig. 7d) ($r = 0.89$).

In contrast, the correlation between Črna Jama site 2 and the outside atmosphere (Fig. 7e) is relatively low ($r = 0.57$). Also, the correlation between Črna Jama site 4 (Pivka Jama) and outside air temperature (Fig. 7f) is not significant, with a low correlation coefficient ($r = 0.46$). This shows that during the winter, the temperature of the underground Pivka river has a stronger impact on the cave-air temperature in Pivka Jama (Črna Jama site 4) than does intrusion of cold outside air and/or the temperature of the rock massif. Warming and cooling of the karst massif by underground water flow depend strongly upon the discharge of the Pivka river (Kaufman et al. 2016).

There is no ice deposition in Črna Jama, even though winter cave-air temperature can be low. During the winter, ice stalagmites form on the floor only at the cave's entrance (Fig. 8). The main source for ice stalagmites is percolating water travelling through the 26-m thick limestone ceiling, entering the cave, where an air temperature below 0 °C is causing freezing. Ice accumulation in Trough Creek Ice Mine (USA) consisted solely of endogenous congelation ice that formed as drip or flowstone ice and as ponded ice on the floor, produced by the freezing of infiltration water. The greatest accumulation of ice inside the mine was observed to derive mainly from the infiltration of small volumes of water via snowmelt and early spring rains (Edenborn et al. 2012).

### 3.3 Early spring period: 17 March–23 April 2015

During the early spring period (Fig. 9), the situation is similar to that in the autumn–winter (i.e. cold period). In terms of median values, the air temperature at Črna Jama 2 is at its lowest, in

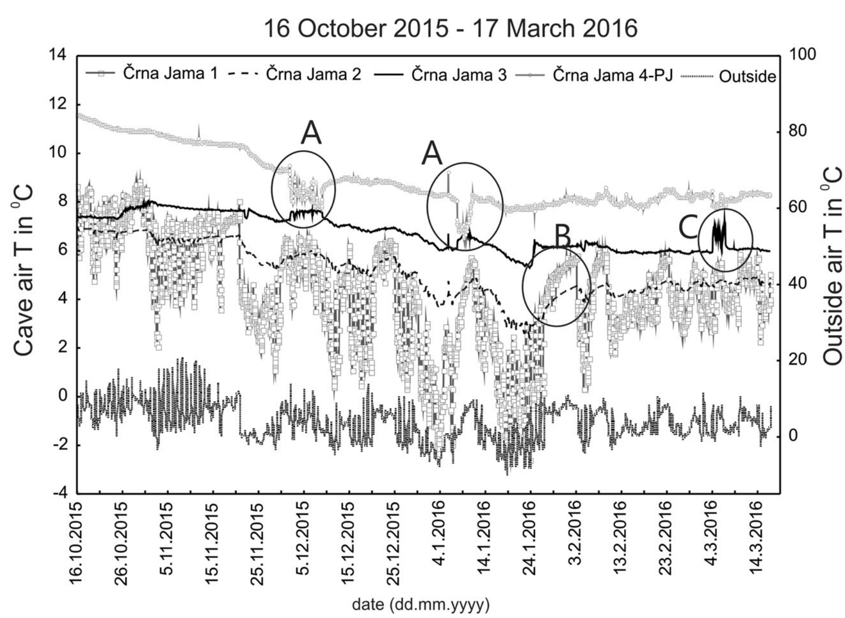



**Fig. 6** Cave air and outside air temperature (°C) during the 16 October 2015–17 March 2016 cold period

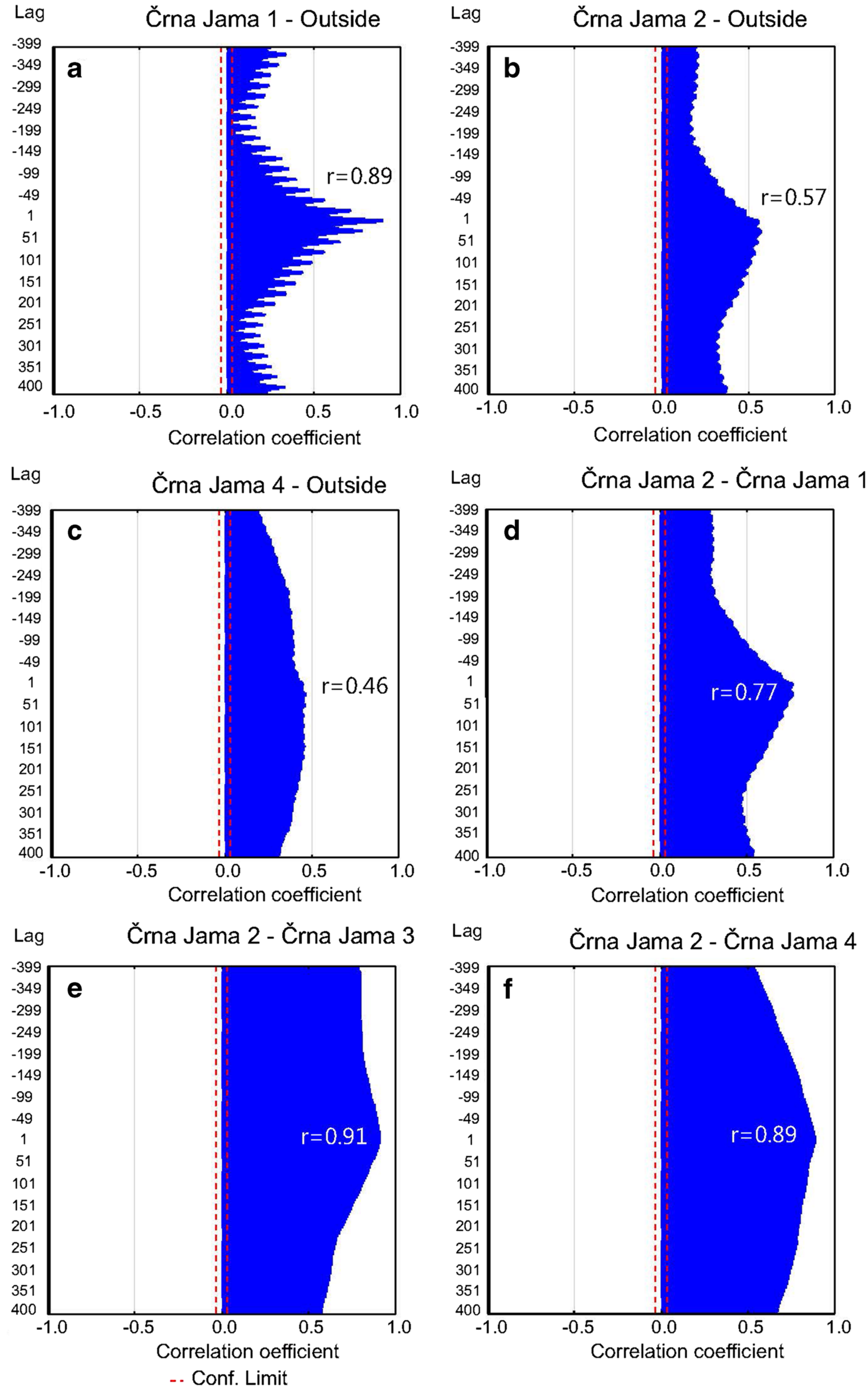



**Fig. 7** Cross correlation diagrams with cross correlation coefficients for cold period 16 October 2015–17 March 2016. **a** (Črna Jama 1–outside). **b** (Črna Jama 2–Črna Jama 1). **c** (Črna Jama 2–Črna Jama 3). **d** (Črna Jama 2–Črna Jama 4-Pivka Jama). **e** (Črna Jama 2–outside). **f** (Črna Jama 4-Pivka Jama–outside)

parallel with changes that occur during the warm period (Fig. 3a). In the period 12 April (1 a.m.) to 13 April 2015 (6 a.m.), there was a 1 °C temperature increase at Črna Jama site 3 (A on Fig. 9) due to the effects of a precipitation event.

**Fig. 8** Ice stalagmites at the Črna Jama site 1 monitoring location during winter (photo S. Šebela)

During the early spring period, the correlation between the air temperature at Črna Jama site 2 and the outside air (Fig. 10a) is relatively significant ($r$ = 0.47). Correlation is also significant ($r$ = 0.59) between Črna Jama sites 2 and 1 (Fig. 10b) for cave-air temperature during the early spring period and is especially significant ($r$ = 0.80) for the Črna Jama site 1 and outside air temperatures (Fig. 10c).

The Črna Jama meteorology records point to the fact that this part of the Postojna Cave System displays the characteristics of a static cave. A static cave is idealised as being a pit or a subterranean room with no air drainage potential, where relatively cold air settles into the cave by gravity during the winter months, whereas the outside ambient air is too warm to sink into the cave during the warm summer months (Williams and McKay 2015). Static caves should have air currents only at certain times of year. Condensation resulting from warm moist air flowing by cooler cave walls has also been noted (Williams and McKay 2015).

### 3.4 Historical cave air temperatures in Črna Jama

Periodic historical air temperature measurements at Črna Jama show similar conditions to the recent cave meteorological data. Even though there is not a large enough set of historical air temperature records to conduct statistical analysis as done for recent temperature measurements, it appears that the actual Črna Jama air temperature increase has been < 0.5 °C since 1933. Parts of the Postojna Cave System that receive more tourist visits have shown temperature increases of about 2 °C since 1852 (Šebela et al. 2015).

Comparison of mean annual air temperature (2015–2016) with historical data (Tables 1 and 2) shows that Črna Jama (especially Črna Jama sites 2 and 3) is probably the most suitable place within the Postojna Cave System to carry out long-term climatic change monitoring. Caves where thermal stratification of the air in summer prevent convectional mixing of cold cave air and warm outside air might serve as valuable indicators of future global climate change (Edenborn et al. 2012).

### 3.5 Future perspectives of climate monitoring in Črna Jama

Actual visitor numbers (there were 3500 visitors per year in 2002–2008) do not obviously influence the cave microclimate. Any future increase in the number of visitors at Črna Jama could have a strong impact on the cave microclimate. In view of this, it is important to continue with climatic monitoring in Črna Jama. Additionally, we do not support the idea that

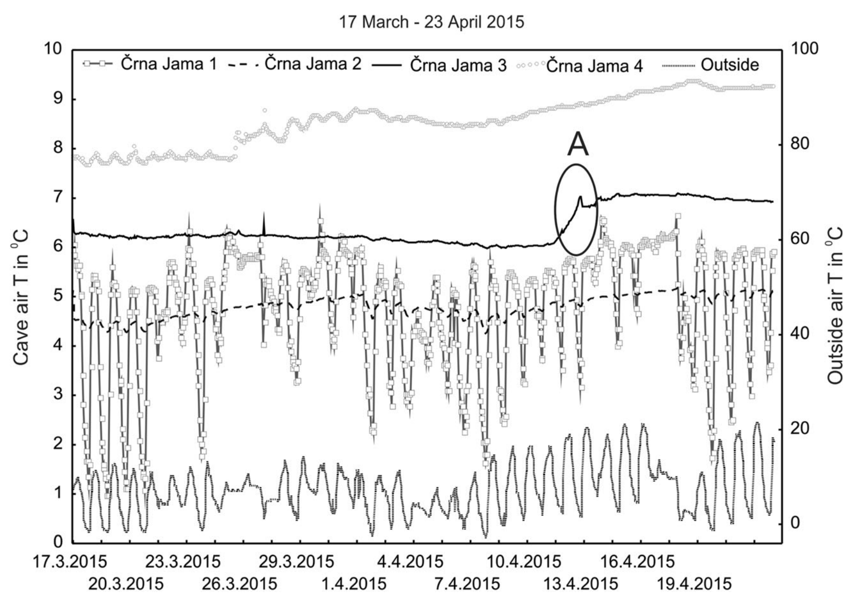
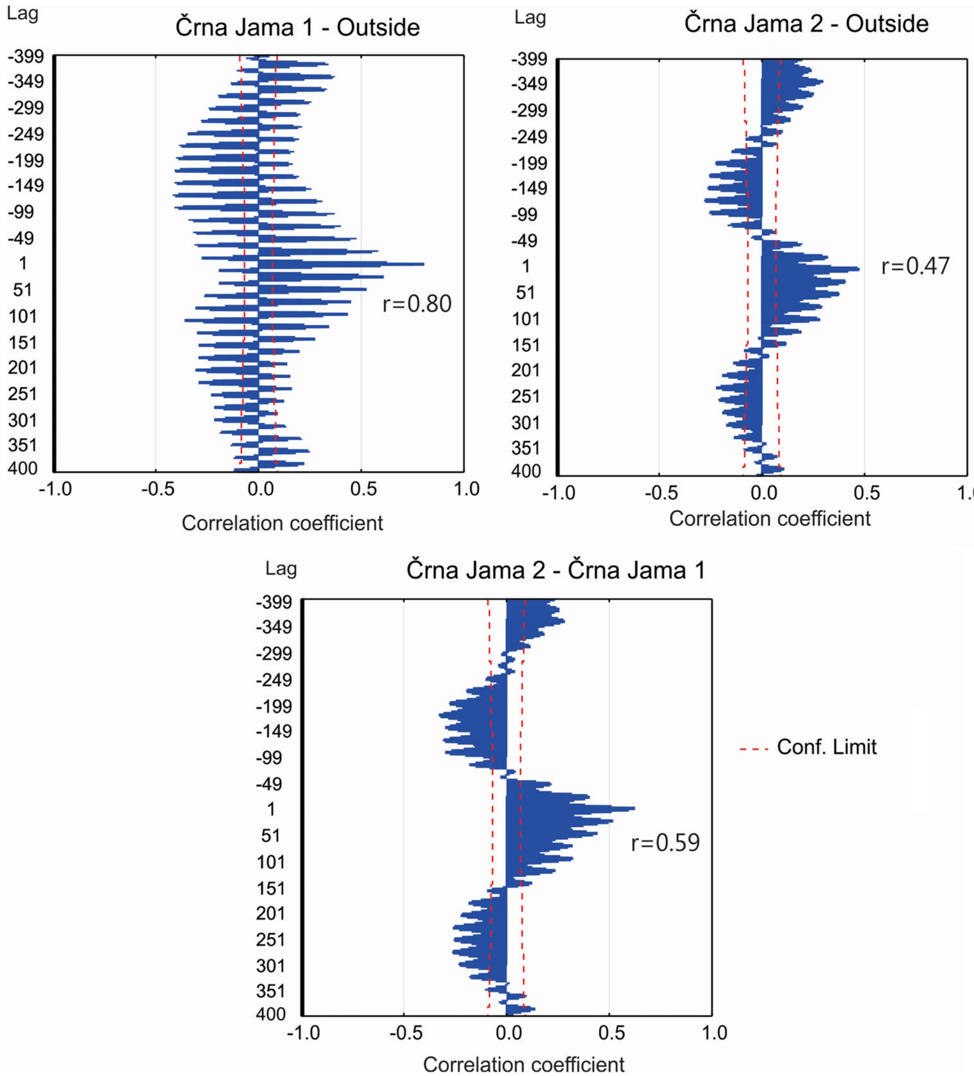



**Fig. 9** Cave air and outside air temperature (°C) during the 17 March 2015–23 April 2015 early spring period

**Fig. 10** Cross correlation diagrams with cross correlation coefficients for early spring period 17 March–23 April 2015. **a** (Črna Jama 2–outside). **b** (Črna Jama 2–Črna Jama 1). **c** (Črna Jama 1–outside)




during times of heavy tourist traffic elsewhere in the Postojna Cave System, opening metal doors in the southern part of Črna Jama can help to reduce the summer temperature in the touristic part of the cave. Such opening can also artificially elevate the relatively low summer air temperatures in Črna Jama. Every attempt to open metal doors for 'longer' period must be controlled by additional monitoring sites.

In the south-east of West Virginia (USA), some caves that trap cold air appear to be remnant palaeo-passages, separate from active systems. It is highly likely that the cold passages were perennial ice caves throughout most of the Pleistocene glacial periods (Kite 2014). For Črna Jama cave, the age of black deposits that cover flowstone deposits is 8394 ± 35 cal year BP (Šebela et al. 2017), which indicates that at least in the

**Table 1** Mean annual cave-air temperature (°C) for Črna Jama 2015 and 2016

| | Črna Jama 1 | Črna Jama 2 | Črna Jama 3 | Črna Jama 4-Pivka Jama | Outside |
|---|---|---|---|---|---|
| $T_{mean}$ 2015 | – | 5.6 | 7.1 | – | 10.3 |
| $T_{max}$ | – | 6.9 | 8.0 | – | 33.6 |
| $T_{min}$ | – | 2.6 | 5.9 | – | −10.9 |
| span | – | 4.3 | 2.1 | – | 44.5 |
| $T_{mean}$ 2016 | 6.2 | 5.7 | 7.2 | 10.4 | 10.0 |
| $T_{max}$ | 13.3 | 7.1 | 8.9 | 13.1 | 31.3 |
| $T_{min}$ | − 2.6 | 2.4 | 5.3 | 6.5 | − 9.7 |
| Span | 15.8 | 4.6 | 3.6 | 6.6 | 41 |

**Table 2** Historical air temperature measurements at Črna Jama (°C). 1933–1936, after Crestani and Anelli (1939), 1972 (Gams 1974)

| | Črna Jama 1 (°C) | Črna Jama 2 (°C) | Črna Jama 4-Pivka Jama (°C) |
|---|---|---|---|
| 15 March 1933 | − 1.5 | 2.5 | 7 |
| 28 April 1933 | 5.5 | 4.5 | 7.5 |
| 23 August 1933 | – | 7 | 9.4 |
| 28 August 1933 | – | 6.7 | – |
| 15 April 1935 | – | 3.9 | 7.7 |
| 16 April 1935 | 5 | 3.9 | – |
| 25 August 1936 | 8.8 | 7 | – |
| 26 August 1936 | 9.2 | 6.7 | – |
| 8 April 1972 | – | 4.2 | – |

early Holocene, Črna Jama probably had a similar meteorology and cave entrance morphology to those now displayed. In this sense, long-term microclimatic monitoring in connection with palaeo-environmental studies is important for Črna Jama.

## 4 Conclusions

Climatic monitoring in the coldest part of the Postojna Cave System—Črna Jama started in January 2014. During the period 2014–2017, the mean annual cave-air temperature at the Črna Jama 2 site was 5.7 °C and at Črna Jama 3, it was 7.1 °C. During the same period, the mean annual cave-air temperature for the more heavily visited Lepe Jame passage was 10.7 °C. Črna Jama is due to far fewer visitors than the touristic part of the Postojna Cave System, the most suitable place to study long-term cave microclimate without significant additional human impact and to observe the impact of external climatic changes upon the cave environment.

In the warm part of the year ($T_{cave} < T_{out}$), Črna Jama acts as a cold air trap with no air exchange with the external atmosphere. The Črna Jama 2 site is especially stable, without daily air temperature oscillations and with maximum air temperature of 7.1 °C (in 2016). Precipitation has a strong influence upon cave-air temperature at the Črna Jama 3 site, because in such situations, a nearby dry water passage is invaded by the underground Pivka river, which results in a 1 °C cave-air temperature increase.

In the cold part of the year ($T_{cave} > T_{out}$), dense cold outside air sinks into Črna Jama due to the favourable morphology of the cave entrance on the southern edge of a collapse doline. At the Črna Jama 2 site, cave-air temperature can drop to 2.4 °C (in 2016) and at the Črna Jama 3 site to 5.3 °C (in 2016).

Results of a 3.6 year-long (2014–2017) meteorological monitoring study at Črna Jama and data from periodic historical air temperature measurements (Table 2) show similar conditions. The actual air temperature increase at Črna Jama has been < 0.5 °C since 1933, which is more stable than in parts of the Postojna Cave System that experience higher tourist traffic.

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## References

Crestani G, Anelli F (1939) Ricerche di meteorologia ipogea delle grotte di Postumia. Istituto polografico dello stato Libreria, Roma

Domínguez-Villar D, Lojen S, Krklec K, Baker A, Fairchild IJ (2015) Is global warming affecting cave temperatures? Experimental and model data from a paradigmatic case study. Clim Dyn 45:569–681. https://doi.org/10.1007/s00382-014-2226-1

Edenborn HM, Sams JI, Kite JS (2012) Thermal regime of a cold air trap in Central Pennsylvania, USA: the Trough Creek Ice Mine. Permafr Periglac Process 23:187–195. https://doi.org/10.1002/ppp.1742

Elliot WR (2012) Protecting caves and cave life. In: White WB, Culver DC (eds) Encyclopedia of caves. Academic Press, Amsterdam, pp 624–633

Ford DC, Williams P (1989) Karst geomorphology and hydrology. Chapman and Hall, London

Gams I (1970) Luftzirulation als bestandteil de höhlenmilieus am beispiel der höhle von Postojna. In: Karamani Z, Manaković D (eds) Congrès Yougoslave de spèlèologie, Cinquiéme session. Prirodno-matematički fakultet, Skopje – Ohrid, pp 99–111

Gams I (1974) Concentration of $CO_2$ in the caves in relation to the air circulation (in the case of the Postojna Cave). Acta Carsol 6:183–192

Gregorič A, Vaupotič J, Gabrovšek F (2013) Reasons for large fluctuation of radon and $CO_2$ levels in a dead-end passage of karst cave (Postojna Cave, Slovenia). Nat Hazards Earth Syst Sci 13:287–297. https://doi.org/10.5194/nhess-13-287-2013

Gregorič A, Vaupotič J, Šebela S (2014) The role of cave ventilation in governing cave air temperature and radon levels (Postojna Cave, Slovenia). Int J Climatol 34:1488–1500. https://doi.org/10.1002/joc.3778

Holmgren D, Pflitsch A (2014) Analysis of selected climatological observations of Talus & Gorge ice caves in New England. In: International Workshop on Ice Caves VI. Idaho Falls, pp 68–71

Kaufmann G, Gabrovšek F, Turk J (2016) Modelling flow of subterranean Pivka river in Postojnska jama, Slovenia. Acta Carsol 45:57–70

Kern Z, Perşoiu A (2013) Cave ice—the imminent loss of untapped mid-latitude cryospheric palaeoenvironmental archives. Quat Sci Rev 67:1–7. https://doi.org/10.1016/j.quascirev.2013.01.008

Kite JS (2014) Cold-air trapping cave passages and algific talus slopes in the central Appalachians: similar thermal regimes point to similar Balch refrigeration mechanism. In: GSA Annual Meeting, Vancouver, British Columbia (19–22 October 2014), paper no. 155–9. https://gsa.confex.com/gsa/2014AM/finalprogram/abstract_249838.htm. Accessed 14 February 2017

Korzystka M, Piasecki J, Sawiński T, Zelinka J (2011) Climatic system of the Dobšinskà ice cave. In: Bella P, Gazik P (eds) 6th ISCA Congress. SNC of Slovak Republic, Slovak Caves Administration, pp 85–97

Luscher M, Jeannin PY (2004) A process-based classification of alpine ice caves. Theoretical Appl Karstol 17:61–66

Luscher M, Jeannin PY, Haeberli W (2005) Ice caves as an indicator of winter climate evolution: a case study from the Jura Mountains. The Holocene 17:982–993

Luscher M, Lismonde B, Jeannin PY (2008) Heat exchange in the heterothermic zone of a karst system: Monlesi cave, Swiss Jura Mountains. J Geophys Res 113:1–13. https://doi.org/10.1029/2007JF000892

Mulec J, Kosi G (2009) Lampenflora algae and methods of growth control. J Cave Karst Stud 71:109–115

Mulec J, Vaupotič J, Walonchik J (2012) Prokaryotic and eukaryotic airborne microorganisms as tracers of microclimatic changes in the underground (Postojna Cave, Slovenia). Microbial Ecol 64:654–667. https://doi.org/10.1007/s00248-012-0059-1

Mulec J (2014) Human impact on underground cultural and natural heritage sites, biological parameters of monitoring and remediation actions for insensitive surfaces: case of Slovenian show caves. J Nat Conserv 22:132–141. https://doi.org/10.1016/j.jnc.2013.10.001

Muri G, Jovičić A, Mihevc A (2013) Source assessment of deposited particles in a Slovenian show cave (Postojnska jama): evidence of long-lasting anthropogenic impact. Int J Speleol 42:225–233. https://doi.org/10.5038/1827-806X.42.3.6

Obleitner F, Spötl C (2011) The mass and energy balance of ice within the Eisriesenwelt cave, Austria. Cryosphere 5:245–257. https://doi.org/10.5194/tc-5-245-2011

Pflitsch A, Schörghofer N, Smith SM, Holmgren D (2016) Massive ice loss from the Mauna Loa Ice cave, Hawaii. Arctic Antarct Alpine Res 48:33–43. https://doi.org/10.1657/AAAR0014-095

Ravbar N, Košutnik J (2014) Variations of karst underground air temperature induced by various factors (cave of Županova jama, Central Slovenia). Theoretical Appl Climatol 116:327–341. https://doi.org/10.1007/s00704-013-0955-4

Schmidl A (1854) Die Grotten und Höhlen von Adelsberg, Lueg, Planina und Laas. Akademie der Wissenschaften, Wien

Šebela S, Prelovšek M, Turk J (2013) Impact of peak period visits on the Postojna Cave (Slovenia) microclimate. Theoretical Appl Climatol 111:51–64. https://doi.org/10.1007/s00704-012-0644-8

Šebela S, Turk J (2011) Local characteristics of Postojna Cave climate, air temperature, and pressure monitoring. Theoretical Appl Climatol 105:371–386. https://doi.org/10.1007/s00704-011-0397-9

Šebela S, Turk J (2014) Natural and anthropogenic influences on the year-round temperature dynamics of air and water in Postojna show cave, Slovenia. Tourism Manag 40:233–243. https://doi.org/10.1016/j.tourman.2013.06.011

Šebela S, Turk J, Pipan T (2015) Cave micro-climate and tourism: towards 200 years (1819–2015) at Postojnska jama (Slovenia). Cave Karst Sci 42:78–85

Šebela S, Zupančič N, Miler M, Grčman H, Jarc S (2017) Evidence of Holocene surface and near-surface palaeofires in karst caves and soils. Palaeogeography Palaeoclimatol Palaeoecol 485:224–235. https://doi.org/10.1016/j.palaeo.2017.06.015

Williams KE, McKay CP (2015) Comparing flow-through and static ice cave models for Shoshone Ice Cave. Int J Speleol 44:115–123. https://doi.org/10.5038/1827-806X.44.2.2