

The temperature variation in an epikarstic cave and its impact factors: a case from Velika Pasica Cave, Central Slovenia

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Abstract In order to reveal the temperature variation mechanism of a small and relatively closed cave, the surface temperature, the cave air temperature and the drip water temperatures were monitored with high-resolution recorders for a 7-year period. The results indicated that the cave temperature is mainly affected by the external seasonal oscillations. The temperature curve of the inner cave area (with standard deviation between 0.59 and 0.87) was much smoother in comparison with that of the surface (with SD as high as 8.46). However, the cave reacted to the temperature drifts with some delay, for example, at VP3 in 2006, the internal temperature increased for additional 49 days after the surface temperature dropped colder than inside of the cave. This seasonal variation and delayed response of the internal temperature were mainly affected by conduction from the epikarst rock mass. Air convection also occurred in the cave, especially when the surface temperature dropped lower than that of the inside cave (during the winter time) and in the outer section (close to the entrance), which caused an abrupt and irregular

variation of the outer section. In addition, the influence from the percolating water was ephemeral and depended on its supplementary amount and temperature difference, e.g., there were more apparent responses at VP1 and VP3 when the intensive rain fell. The percolating water temperature could be a good indicator for water flow in epikarst.

Keywords Epikarst · Temperature · Convection · Conduction

Introduction

Research on the thermal variations in karstic caves is asymptotically growing in importance (Jeannin et al. 1997; Sanderson and Bourne 2002; Badino 2004; Stoeva et al. 2006; Šebela and Turk 2011; Bourges et al. 2014). The “cave climate” was specifically discussed at the 17th International Karstological School “Classical Karst”, Postojna, Slovenia, in 2009.

Various cave climatology and cave meteorology were presented and studied from different cave research conducted globally. For palaeo-climatic research, the cave microclimate variation was monitored in order to interpret the formation of stalagmites in cave environments (Genty et al. 2001; Ford and Williams 2007; Genty 2008; Asrat et al. 2008). Furthermore, the global climate changes were also discussed through cave temperature analysis (Badino 2004). In addition, heat was also a significant tool for shallow ground water research, especially in relationship to shallow karst aquifer. In Bundschuh (1993), temperature was shown as a parameter in order to indicate the components of different aquifers in spring water. Genthon et al. (2005) used temperature as a marker for karstic water hydrodynamics in La Peyrere Cave (France). Potentially useful information for thermal patterns of karst cave streams was considered for aquifer morphology and recharge studies (Luhmann et al. 2011). However, fundamental studies on heat

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transport and temperature gradients for shallow subsurface karstic aquifers are still limited in the literature, especially for epikarst aquifers.

Based on the generally accepted model, the karst geological system can be divided into three main zones: heterothermic zone (near surface), transitional zone and constant temperature zone (Stoeva et al. 2006). Heat exchange is the dominant process to tend to equilibrium in each zone and is the most important factor for cave climate variation. Accordingly, heat enters into a cave in four ways: conduction from cave ceiling layer or from the floor layer, convection from air flow, or heat transfer from water flow. Regarding to different structures and locations in the cave, the dominant way for heat transmission is different (Badino 2004; Stoeva et al. 2006). In order to investigate and clarify the mechanism of thermal variation in a shallow cave, the air temperature on the surface, within the cave, and the temperature of the drip water were monitored for a 7-year period (2006–2013) in the Velika Pasica Cave. Generally, daily variations of temperature in the soil and rock diminished at 1 m below the surface, and the annual variations of temperature can be observed as deep as 20–24 m below surface, depending on the rock and soil types (Thakur and Momoh 1983). This cave is shallow with an average depth of 10–12 m below surface (in some places only 2–5 m), and the cave is relatively isolated thermally from the surface. Thus, it could be a good intermediate window for tracing subsurface temperature variation.

This task was one of the few detailed studies undertaken of a shallow karst aquifer in dolomitized limestone geology. The originality of the study lies in the fact that the data collected on the events in the epikarst zone over a long period of high-frequency measurements (at hourly intervals), provided a detailed insight into the dynamics in the cave thermal condition.

The Velika Pasica Cave

The Velika Pasica Cave is located 20 km south of Ljubljana (45° 55' 14" N, 14° 29' 41" E), near the village of Gornji Ig, with the cave entrance at an elevation of 662 m a.s.l. The geology is thinly bedded Norian-Retian dolomite from the Upper Triassic period (Pleničar 1970). Strata incline to the north at 10–15°. Three hundred meters south-west of the cave is a hill, known as Črtež (765 m a.s.l.), with approximately 30° slopes descending towards the cave.

The climate of Ljubljana area dominates with continental characteristics of warm summers and moderately cold winters. Average daily temperatures in July and August are 20.4 and 19.8 °C and in January -0.1 °C (www.arso.gov.si). The precipitation is relatively evenly distributed throughout the seasons, although winter and spring tend to be considerably drier than summer and autumn. Storm events are common from May to September and can occasionally fall as heavy precipitation. Snow is common from December to February.

The interior of the cave is a 126-m-long horizontal gallery (Fig. 1). The entrance to the cave is located at the bottom of 10-m-deep circular depression with a maximum diameter of 15 m. The ceiling of the gallery has a maximum thickness of 10–12 m; however, at some points, it only has 2–5 m (Brancelj 2002). Thus the cave represents a typical, shallow cave formation (Jeannin et al. 2007). The cave is divided into two sections (Fig. 1): the outer section with two chambers and the inner section with an additional two chambers. The outer section and the inner section are connected by a 0.7 × 1.0-m-high passage. Four permanent drips, designated as VP1, VP2, VP3 and VP4, are distributed within the cave; drips VP1 and VP2 are located in the outer section and the other two are in the inner section of the cave. All water in the cave is exclusively percolating water, entering the cave as permanent or temporary drips from the ceiling or temporary flows (after heavy rain or intensive snow-melt) from the side. During the dry season (mostly summer time), only a few permanent dripping points remain active (Fig. 1).

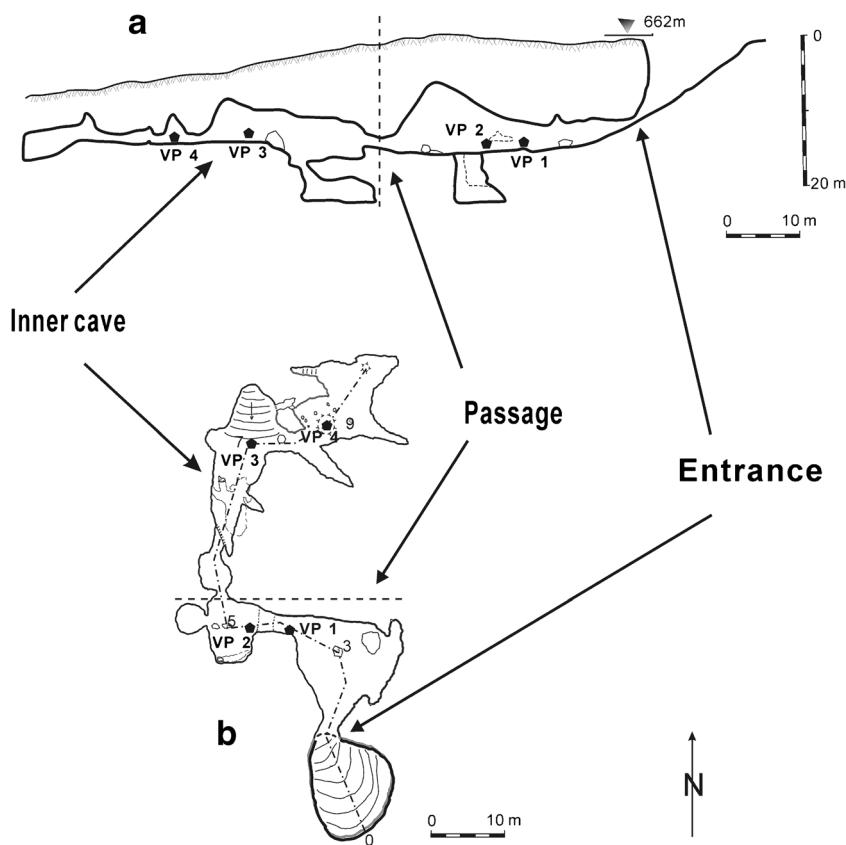
Method and material

Accuracy and frequency in data collection over a long period were essential parameters undertaken for this research. Systematic data were collected for 7 years—from May 2006 to April 2013, in order to interpret the climatic variation of the inner and outer cave environments, both temperatures on the surface and within the cave were monitored. Two data loggers (DL2e, Delta-T Device Company) equipped with several sensors were used for data collection. One Delta-T Data-Logger with sensors for air temperature and precipitation was set on the surface 100 m from the cave entrance. The other Delta-T Data-Logger with four sets of sensors and rain gauges for air and water temperature and drip water discharge were set at four drips in the cave (Fig. 1).

In the cave, the discharge of four permanent drips were measured as a volume of water percolated from the ceiling by four same type of rain gauges (RG1-UM-3, Delta-T Device Company). They were set under each drip in order to capture the percolation amount and thus recorded the volume in millimetre (mm) every hour, with an accuracy and resolution of ±0.2 mm. Due to the distance between the ceiling and the funnel of rain gauge (1–5 m), in order to collect dispersed jets of water, a plastic screen (2 m × 2 m) was placed to collect and direct drip discharge into the funnel of the rain gauge.

The drip water temperature (T_{water}) and the air temperature (T_{air}) of all the drips were recorded every hour by eight identical probes (ST1-05, Delta-T Device Company) (resistivity type with a range of measurement of -25.0 °C to +100.0 °C and a digital resolution of 0.1 °C). Probes for water temperature (T_{water}) were inserted into the lower section of each rain gauge where some water was always maintained, and probes for air temperature (T_{air}) were located 50 cm away from the rain gauges and 1 m above the cave floor. All these

Fig. 1 Cross-section (A) and ground plan (B) of the Velika Pasica Cave (Slovenia). VP1–VP4: permanent dripping points. The *arrowhead* points the cave entrance, the inner cave and the narrow passage for demarcation of the inner cave and the outer cave



temperature probes and the four rain gauges were connected to the data-logger within the cave. In order to determine the correlation and dissimilarity of temperature between the water at the epikarst discharge point and the drip water near the cave floor, two probes (at VP2 and VP3) were placed at different locations for 2 weeks in October 2012. Results showed that there was a insignificant difference in the water temperature between these locations.

On the surface, the amount of precipitation and the surface air temperature ($T_{outside}$) were recorded by the same type rain gauge and temperature probe, which were connected to the data-logger on the surface. Both of them recoded the results once an hour and were synchronised with the monitoring of drip water discharge and temperature within the cave.

All the sensors, especially the rain gauges, were regularly maintenance checked and all the data from these two data-loggers were transferred to a computer data base at approximately 1-month intervals.

Results

The general variation of temperature in the cave

Seasonal microclimates apparently varied in the cave area (Fig. 2), which have been monitored since 2006. During the

observation period, from 20th June, 2006 to 31st December, 2011, July and August were the hottest months and the highest temperature outside was 32.0 °C on 26th August 2008. December and January were the coldest months and the lowest temperature recorded was on December 20th, 2009, at -13.2 °C (Table 1).

On the surface, the temperature differences between day and night were frequently over 10.0 °C, shown as the SD (standard deviation) as high as 8.46 (Table 1). On 23rd July, 2006, the difference was over 13.0 °C. The intensity of the rainfall in spring (April and May) was not high, but it was frequent; while in summer, the frequency of rain events decreased but several heavy storms occurred; the strongest one on 20th June, 2010 (44 mm of rain in 24 h).

Compared with the surface, the temperature in the cave was more constant (Fig. 2). The variation range and the standard deviation were much lower (Table 1). The temperature inside the cave (both of air and dripping water) showed a similar trend with distinct seasonal variations: increasing during summer and autumn and decreasing in winter and spring (Fig. 2).

The variation of temperature in the cave

There was some time lag in the temperature variation between the surface and inside the cave. In order to interpret it, the air temperature near the site VP3 was selected in order to provide

Fig. 2 The temperature (°C), precipitation (mm/h) from outside the cave, the water temperatures of four drips (°C) and adjacent air temperature of each drip (°C) recorded from 20th June, 2006 to 31st December, 2011. The number of the legend indicates the drip site number; “A” indicates the air temperature; “W” is for the water temperature; “O” is for the outer section of the cave and “I” is for the inner section of the cave due to some technical problems. Some data were missed, e.g., the surface temperature data from August 2008 to December 2009

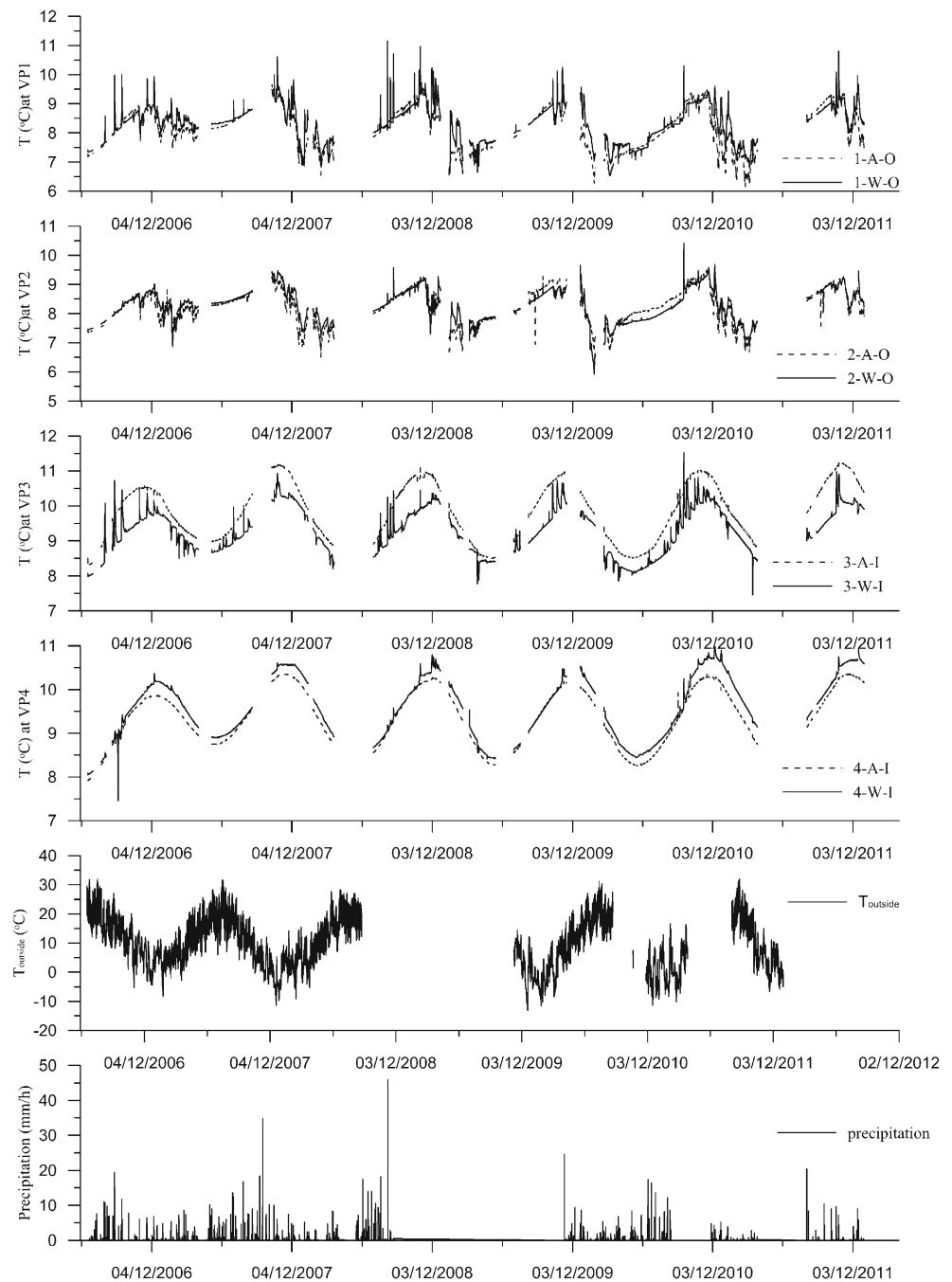


Table 1 The variation range and average air and water temperatures inside and outside the Velika Pasica Cave (Slovenia) from 20th June, 2006 to 31st December, 2011. X-A/W-O/I indicates: the air/water temperature near drip X from outer or inner section of the cave. $T_{outside}$ the surface air temperature, SD standard deviation

	1-A-O (°C)	1-W-O (°C)	2-A-O (°C)	2-W-O (°C)	3-A-I (°C)	3-W-I (°C)	4-A-I (°C)	4-W-I (°C)	$T_{outside}$ (°C)
Max	9.7	11.2	9.5	10.4	11.3	11.5	10.4	11.0	32.0
Min	6.2	6.6	6.5	5.9	7.5	7.2	7.3	7.4	-13.2
Average	8.2	8.3	8.2	8.3	9.8	9.3	9.4	9.6	9.2
SD	0.72	0.66	0.62	0.59	0.87	0.71	0.70	0.75	8.46

a comparison with the surface temperature, during the period from 20th June, 2006 to 22nd March, 2008 (Fig. 3).

On the surface of the cave, the temperature increased from the end of December 2006, at the lowest point, $-4.4\text{ }^{\circ}\text{C}$. It reached the highest temperature of $31.7\text{ }^{\circ}\text{C}$ in the middle of July 2007. Within the cave, it is divided into two sections: the outer section and the inner section (Fig. 1). The temperature of inner section decreased from the highest point $10.5\text{ }^{\circ}\text{C}$ in November 2006 (the average value of air temperature at VP3 and VP4) and $9.5\text{ }^{\circ}\text{C}$ of the outer section (the average value of air temperature at VP1 and VP2). Until the beginning of May 2007, the temperature in the cave dropped to the lowest point (Fig. 3). Overall, the temperature inside the cave varied between 6.5 and $11.0\text{ }^{\circ}\text{C}$, although there was more intensive variation outside the cave. This variation lag was presented in Fig. 3 obviously. In addition, at VP3 in 2006, the internal temperature still increased for additional 49 days, after the surface temperature dropped colder than that of the inside cave.

Comparing with the temperature variation between two sections within the cave, there were considerable differences. Although there were apparent similar seasonal climate variation patterns in both sections, the outer section was generally more than $1.0\text{ }^{\circ}\text{C}$ (the average value) cooler than the inner section (Fig. 2; Table 1). In addition, due to the entrance morphology, the outer section immediately connected with the surface, and the temperature in it varied abruptly and irregularly, especially when the surface was colder. Generally, this abnormal variation commenced from late August.

The impacts from rain events

In the Velika Pasica Cave area, the rainfall is the only replenishment source for the cave hydrology and it can carry different temperature values from outside, which may affect cave environment. Here, two periods in different seasons were

observed for detailed temperature variation: one was from 20th January to 28th February, 2007 during a winter season; and the other was from 3rd July to 23rd August, 2008 during a summer season (Figs. 4 and 5). In winter, the rain fell gently but lasted long, while in summer, it came intensively but of short duration.

During the selected winter period, the average air temperature on the surface was $3.4\text{ }^{\circ}\text{C}$, which was lower than inside the cave (the average temperature of inner section was $9.2\text{--}9.8\text{ }^{\circ}\text{C}$; the outer section was $7.9\text{--}8.4\text{ }^{\circ}\text{C}$). On the overall trend, the temperatures inside the cave decreased gradually.

Additionally, the amount of percolation also affected the temperature variation of drip water apparently in winter period (Fig. 4). Both VP1 and VP3 discharged more intensively and the temperature of drip water of them responded more apparently to the rain events. While for the drips VP2 and VP4, they represented smaller temperature variation of the drip water to the percolation events. In addition, the temperature at the outer drips VP1 and VP2 which were close to the entrance varied dramatically, compared with the inner drips.

Comparatively, during the selected summer period, the average air temperature on the surface was $18.2\text{ }^{\circ}\text{C}$, which was hotter than inside the cave (the average temperature of inner section was $8.9\text{ }^{\circ}\text{C}$; the outer section was $8.3\text{ }^{\circ}\text{C}$). Considering the overall trend, the temperatures inside the cave increased gradually. Similarly, the water temperature of the higher discharge drips (VP1 and VP3) varied more obviously than the other two drips in the summer period (Fig. 5). This supplement with a different temperature carried some heat from the surface, which affected the temperature temporally.

Discussion

Cave temperature is affected by the external climate directly and indirectly, especially for the shallow caves (Badino 2004).

Fig. 3 The temperature ($^{\circ}\text{C}$) outside the cave and the air temperatures near drip VP3 ($^{\circ}\text{C}$) recorded from 20th June, 2006 to 22nd March, 2008 at the Velika Pasica Cave (Slovenia). The equation represents the fitted line for the outside temperature variation

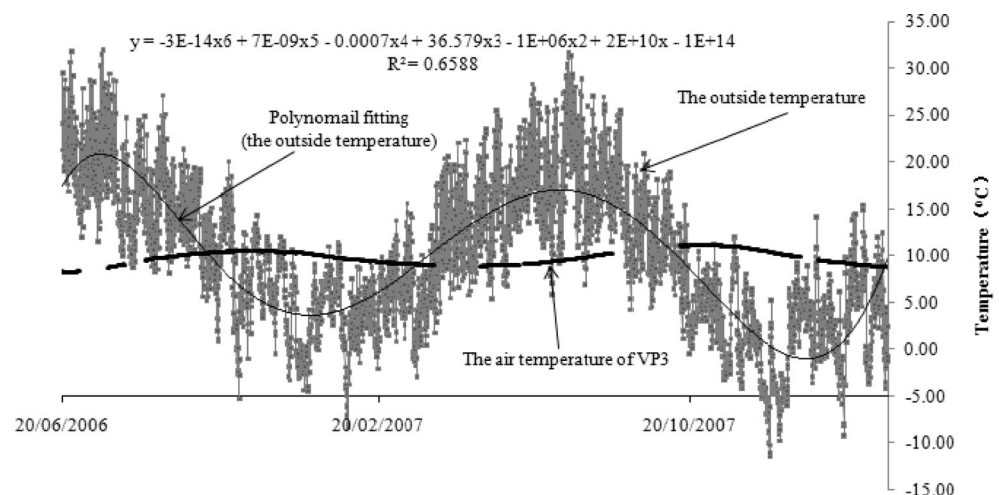
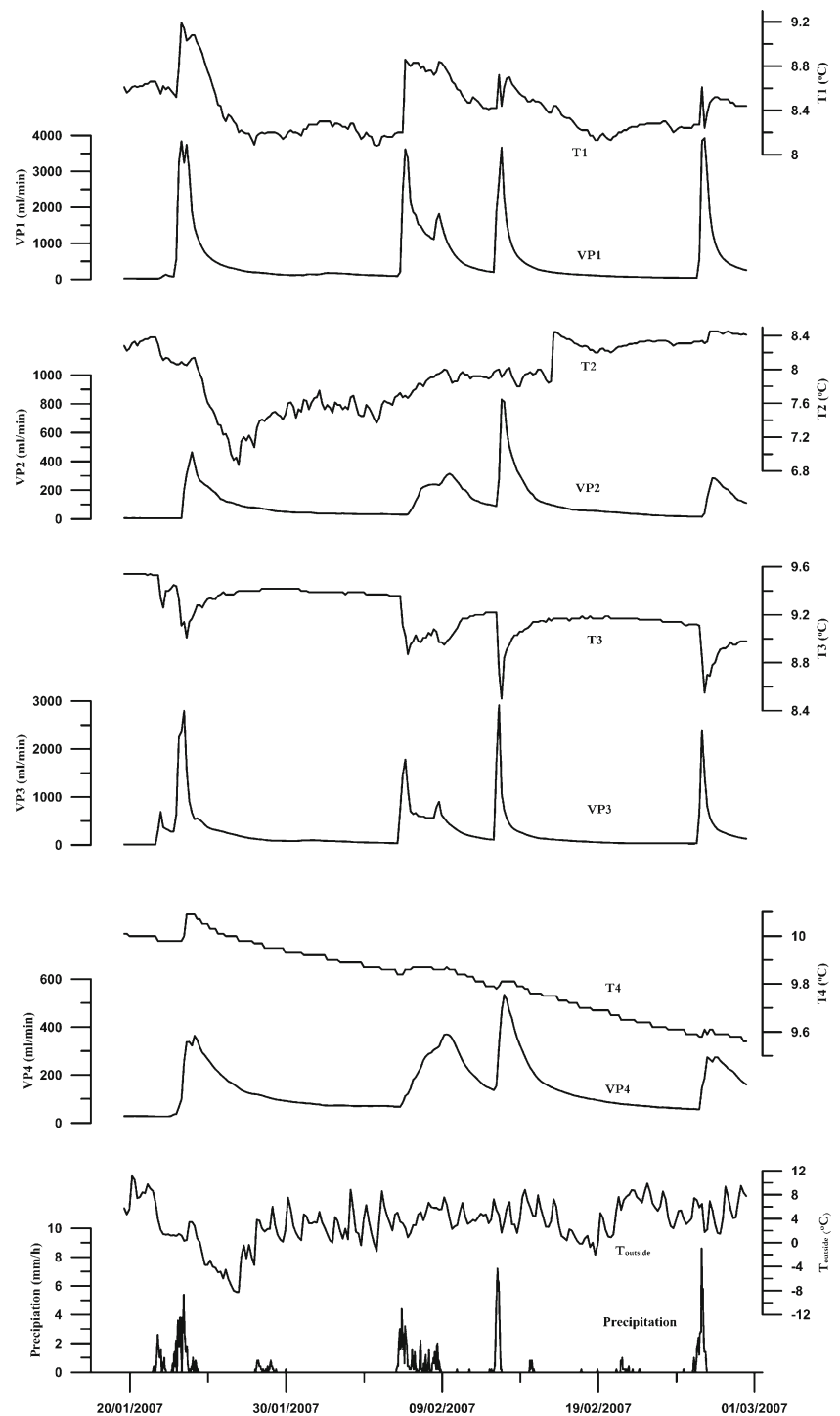


Fig. 4 The response of the discharge and the water temperature of the four drip waters to the rain events in the Velika Pasica Cave (Slovenia) in the winter 2007 (from 20th January to 28th February). $T_{outside}$ the air temperature on the surface, $VP1$ the discharge of drip site $VP1$, $T1$ the drip water temperature of the drip site $VP1$

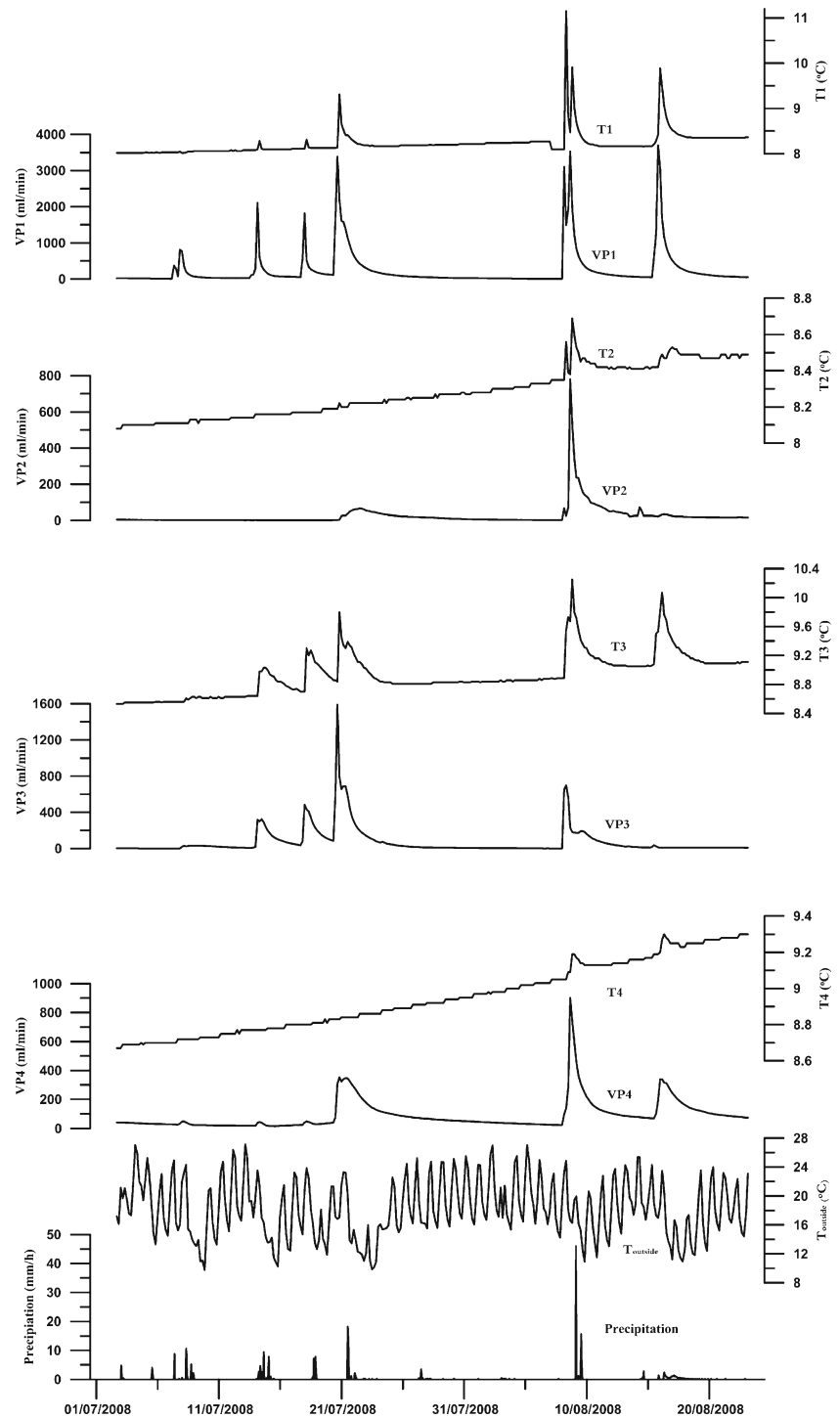


The average thickness of the cover layer of the Velika Pasica Cave is 10–12 m (Brancelj 2002), which is a typical shallow cave (Jeannin et al. 2007). The cave meteorology responds apparently and intensively with the external conditions.

Actually, there was a time difference in the variation trend between the external and internal cave conditions. These lags were a result of heat conduction which determined the thermal condition within the cave system (Covington et al. 2011). As

shown in Fig. 3, when the surface temperature dropped lower than the temperature of the inner cave, the internal temperature still kept rising for a while. On the contrary, when the surface temperature increased higher than the temperature of the inner cave, the internal temperature had certain time to decrease to its lowest point. It could be explained as the mass of the epikarst has an ability to store some heat (Fig. 6). When the surface was warmer than both the epikarst and the interior of

Fig. 5 The response of the discharge and the water temperature of the four drip waters to the rain events in the Velika Pasica Cave (Slovenia) in the summer 2008 (from 3rd July to 23rd August). $T_{outside}$ the air temperature on the surface, $VP1$ the discharge of drip site VP1, $T1$ the drip water temperature of drip site VP1



the cave, heat was transferred down through the epikarst into the cave (Fig. 6(I)). When the surface cooled down, even when the external surface was colder than the interior, and the epikarst was still warmer than the cave, it maintained heat transferred into the cave (Fig. 6(II)). The direction of heat conduction could not change, until the matrix cooled down and became colder than the cave interior (Fig. 6(III)). When the surface became warmer again, the matrix could retain

absorbed heat from both the surface and the deeper ground until it was warmer than the cave (Fig. 6(VI)). This shows that the direction of heat conduction was, therefore, driven by the temperature difference between the surface, epikarst and the cave system.

For the temperature difference between two sections of the cave, it is mainly affected by the convective airflows in the outer section, which also is a significant factor for the

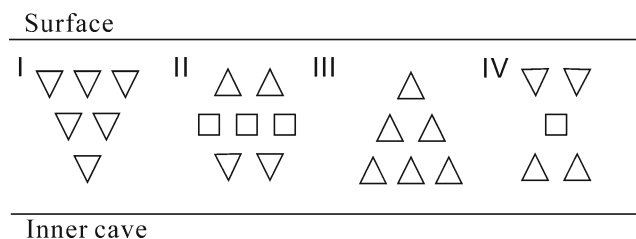


Fig. 6 A schematic diagram of the process of the annual heat conduction through the epikarst in the cave. The top row of triangles indicate the direction of the heat transference, the square represent the stored heat. *I*: the period when surface is warmer than inner cave is generally in summer time; *II*: the period when surface is cooling down but epikarst is still warm indicates autumn time; *III*: the period when the inner cave is warmer than surface is the winter time; and *IV*: the period when surface is warming up and the coldest time of epikarst represents the spring time

microclimate change in other caves (Stoeva et al. 2006; Faimon et al. 2012). In the outer section, due to the geomorphology of the Velika Pasica Cave, the cold air can flow into the outer section through the lower part of the entrance passage during winter, while the lighter and warmer air can be pulled out along the upper part of the entrance. However, the hot air from the surface is hard to flow into the cave during the summer time, which is indicated in Fig. 2 and the temperature variation is affected by conduction from the cover layer gradually. On the contrary, the temperature oscillation of the inner section is relatively slighter and smoother, which is constricted and prevented sufficiently by the narrow passage between the inner and outer sections. The inner section is indicated as a relatively close system and its temperature variation is mainly affected by the heat conduction, comparing with the outer section.

The cave temperature principally varied as the general trend of surface climate (Badino 2004). It can be indicated from the cave drip water which percolates from the fissures and conduits of epikarst. Due to the climate feature of the cave area, the rain patterns performed as short but intensive in summer, while long but gentle in winter (Liu et al. 2014, 2016). During winter time (Fig. 4), the surface was colder than inside cave, though the cold rain water was heated some by the epikarst before it percolated out at VP3, the rapid discharge drip water still colder than the inner cave temperature. But due to the slow flow at VP4, the percolated water was heated enough by epikarst which represented as the increase of the temperature of drip water. However, in the outer section, the air temperature was impacted dramatically by the surface air convection. Thus, after heating by epikarst, the percolated water was warmer than the outer cave. The influence of the percolation of VP2 was too limited, comparing with the cold air convection. During the summer time (Fig. 5), without convection, the heat conduction from the cover layer affected the principle trend of the variation, but also the rain water supplement was an important parameter which briefly impacted on the temperature variations in the cave. Difference in the temperature of drip water at different drips depended on the

temperature difference between the surface and inside the cave and also on the amount of discharge. The fast flow, which ran quickly, did not exchange heat adequately within the soil and the epikarstic zone. It was reflected in the apparent temperature peaks during the rain events. When the rain ceased and the drip flow slowed down and run as the base flow from fissures, the drip water, air and rock surrounding the cave chambers gained equilibrium (Liu et al. 2016). Cronaton and Perrochet (2002) and Liedl et al. (2003) described this feature as a result of the dual media system. Thus, heat also could be the tracer for the hydrodynamic of ground flow (Anderson 2005).

Conclusion

Microclimate monitoring with high resolution was conducted for 7 years in the Velika Pasica Cave, and the thermal condition of the cave was revealed. It can be concluded:

1. The cave temperature variation principally follows the surface climate oscillation, which is mainly affected by conduction of heat by the overlying rock. There was some apparent temperature variation lag between the surface and inside the cave, for example, at VP3 in 2006, after the surface temperature decreased lower than that of the inside cave, the internal temperature kept increasing for additional 49 days before it started to decrease, which was mainly the result of the heat absorption and release by the epikarst rock mass.
2. In addition, the air convection is also significant in the outer section of the cave, especially when the ground surface was colder than the inside the cave (the winter time), but the inner section of the cave is a relative insulated part of the cave and its condition is relatively stable all year around.
3. The percolating water can affect the cave water temperature conditions briefly and depends on the temperature difference between the surface and inside the cave, the amount of percolation and the patterns of discharge, which relates to the seasonal recharge. In other words, the temperature of cave drip water can act as a tracer for hydrodynamic process in the epikarst.

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References

- Anderson MP (2005) Heat as a ground water tracer. *Groundwater* 43(6): 951–968. doi:10.1111/j.1745-6584.2005.00052.x
- Asrat A, Baker A, Leng MJ, Gunn J, Umer M (2008) Environmental monitoring in the Mechara caves, Southeastern Ethiopia: implications for speleothem palaeoclimate studies. *Int J Speleol* 37(3):207–220. doi:10.5038/1827-806X.37.3.5

- Badino G (2004) Cave temperatures and global climatic change. *Int J Speleol* 33(1/4):103–114. doi:[10.5038/1827-806X.33.1.10](https://doi.org/10.5038/1827-806X.33.1.10)
- Bourges F, Genthon P, Genty D, Lorblanchet M, Mauduit E, D'Hulst D (2014) Conservation of prehistoric caves and stability of their inner climate: lessons from Chauvet and other French caves. *Sci Total Environ* 493:79–91. doi:[10.1016/j.scitotenv.2014.05.137](https://doi.org/10.1016/j.scitotenv.2014.05.137)
- Brancelj A (2002) Microdistribution and high diversity of copepoda (Crustacea) in a small cave in central Slovenia. *Hydrobiologia* 477(1–3):59–72. doi:[10.1023/A:1021043014879](https://doi.org/10.1023/A:1021043014879)
- Bundschuh J (1993) Modeling heat transport from the earth's surface through aquifers to springs: theoretical examples and case studies. *Proceedings of the Yokohama Symposium*, IAHS Publish, pp 212
- Covington MD, Luhmann AJ, Gabrovšek F, Saar MO, Wicks CM (2011) Mechanisms of heat exchange between water and rock in karst conduits. *Water Resour Res* 47(10):1–18. doi:[10.1029/2011WR010683](https://doi.org/10.1029/2011WR010683)
- Cronatou F, Perrochet P (2002) Analytical 1D dual-porosity equivalent solutions to 3D discrete single-continuum models. *J Hydrol* 262(1–4):165–176. doi:[10.1016/S0022-1694\(02\)00033-1](https://doi.org/10.1016/S0022-1694(02)00033-1)
- Faimon J, Troppova D, Baldik V, Novotny R (2012) Air circulation and its impact on microclimatic variables in the C'isarska Cave (Moravian Karst, Czech Republic). *Int J Climatol* 32:599–623. doi:[10.1002/joc.2298](https://doi.org/10.1002/joc.2298)
- Ford D, Williams P (2007) *Karst hydrogeology and geomorphology*. Wiley, New York
- Genthon P, Bataille A, Fromant A, Dhulst D, Bourges F (2005) Temperature as a marker for karstic waters hydrodynamics. Inferences from 1 year recording at La Peyrère cave (Ariège, France). *J Hydrol* 311(1–4):157–171. doi:[10.1016/j.jhydrol.2005.01.015](https://doi.org/10.1016/j.jhydrol.2005.01.015)
- Genty D (2008) Palaeoclimate research in Villars Cave (Dordogne, SW-France). *Int J Speleol* 37:173–191. doi:[10.5038/1827-806X.37.3.3](https://doi.org/10.5038/1827-806X.37.3.3)
- Genty D, Baker A, Vokal B (2001) Intra- and inter-annual growth rate of modern stalagmites. *Chem Geol* 176:191–212. doi:[10.1016/S0009-2541\(00\)00399-5](https://doi.org/10.1016/S0009-2541(00)00399-5)
- Jeannin PY, Liedl R, Sauter M (1997) Some concepts about heat transfer in karstic systems. *Proceedings of the 12th International Congress of Speleology* 1: 195–198
- Jeannin PY, Groves C, Hauselmann P (2007) Speleological investigations. In: Goldscheider N, Drew D (eds) *Methods in karst hydrogeology*. Taylor & Francis, Leiden, pp. 25–44
- Liedl R, Sauter M, Huckinghaus D, Clemens T, Teutsch G (2003) Simulation of the development of karst aquifers using a coupled continuum pipe flow model. *Water Resour Res* 39(3):1057–1062. doi:[10.1029/2001WR001206](https://doi.org/10.1029/2001WR001206)
- Liu WA, Brancelj A, Brencic M (2014) The hydrochemical response of cave drip waters to different rain patterns (a case study from Velika Pasica Cave, central Slovenia). *Carpath J Earth Env* 9(1):189–197
- Liu WA, Brancelj A, Ellis Burnet J (2016) Interpretation of cave drip water recession curves, a case study from Velika Pasica Cave, central Slovenia. *Hydrolog Sci J*. doi:[10.1080/02626667.2016.1154150](https://doi.org/10.1080/02626667.2016.1154150)
- Luhmann AJ, Covington M, Peters AJ, Alexander SC, Anger CT, Green JA, Runkel AC, Alexander EC Jr (2011) Classification of thermal patterns at karst springs and cave streams. *Groundwater* 49(3):324–335. doi:[10.1111/j.1745-6584.2010.00737.x](https://doi.org/10.1111/j.1745-6584.2010.00737.x)
- Pleničar M (1970) Tolmač k Osnovni geološki karti SFRJ, List Postojna. Zvezni geološki zavod Beograd. (= Basic geological survey; section Postojna)
- Sanderson K, Bourne S (2002) Cave temperatures at Naracoorte caves. *Helictite* 38(1):7–10
- Šebela S, Turk J (2011) Local characteristics of Postojna Cave climate, air temperature, and pressure monitoring. *Theor Appl Climatol* 105: 371–386. doi:[10.1007/s00704-011-0397-9](https://doi.org/10.1007/s00704-011-0397-9)
- 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](https://doi.org/10.1016/j.pce.2005.05.001)
- Thakur AKS, Momoh MM (1983) Temperature variation in upper earth crust due to periodic nature of solar insolation. *Energ Convers Manage* 23(3):131–134. doi:[10.1016/0196-8904\(83\)90054-7](https://doi.org/10.1016/0196-8904(83)90054-7)