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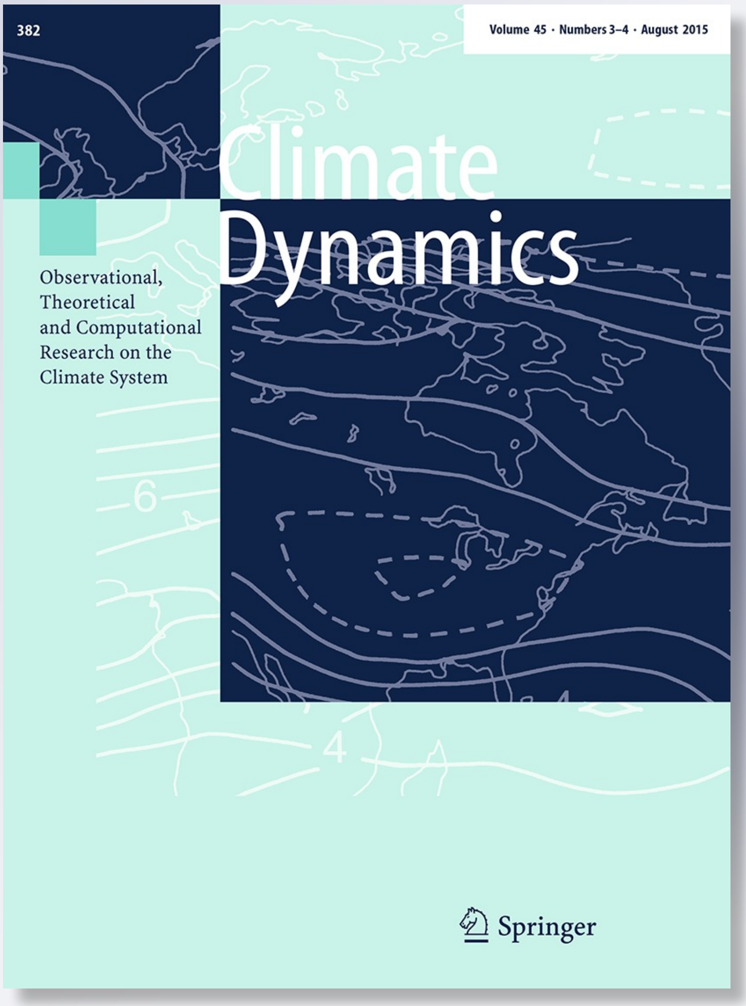

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Is global warming affecting cave temperatures? Experimental and model data from a paradigmatic case study

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Abstract This research focuses on the mechanisms that transfer the variations in surface atmospheric temperature into caves to evaluate whether they record the warming trend of recent decades. As a study case, we use the data from a hall in Postojna Cave (Slovenia), which was monitored from 2009 to 2013. The low-frequency thermal variability of this cave chamber is dominated by the conduction of heat from the surface through the bedrock. We implemented a thermal conduction model that reproduces low-frequency thermal gradients similar to those measured in the cave. At the 37 m depth of this chamber, the model confirms that the bedrock is already recording the local expression of global warming with a delay of 20–25 years, and predicts a cave warming during the coming decades with a mean rate of 0.015 ± 0.004 C year^{-1}. However, because of the transfer of surface atmosphere thermal variability depends on the duration of the oscillations, the thermal anomalies with periods 7–15 years in duration have delay times <10 years at the studied hall. The inter-annual variability of the surface atmospheric temperature is recorded in this cave hall, although due to the different delay and amplitude attenuation that depends on the duration of the anomalies, the cave temperature signal differs significantly from that at the surface. As the depth of the cave is a major factor in thermal conduction, this is a principal control on whether or not a cave has already recorded the onset of global warming.

Keywords Global warming · Cave · Temperature · Heat conduction · Postojna

D. Domínguez-Villar (✉)
Centro Nacional de Investigación sobre la Evolución Humana, Paseo Sierra de Atapuerca s/n, 09002 Burgos, Spain
e-mail: david.dominguez@cenieh.es

D. Domínguez-Villar · I. J. Fairchild
School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, B15 2TT Birmingham, UK

S. Lojen
Department of Environmental Sciences, Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia

K. Krklec
Department of Soil Science, Faculty of Agriculture, University of Zagreb, Svetošimunska 25, 10000 Zagreb, Croatia

A. Baker
Connected Waters Initiative Research Centre, University of New South Wales, 110 King St. Manly Vale, Sydney, NSW 2093, Australia

1 Introduction

Cave atmosphere temperature is frequently very stable, with an annual variability <1 °C when measured away from the entrance influence (e.g. Moore and Sullivan 1978). The direct interaction of external and underground atmospheres causes the cave temperature near the entrances to record a larger variability. However, after a certain relaxation length from the entrance, the cave temperature becomes much more stable (Wigley and Brown 1971). This relaxation length usually has an order of magnitude from 10^1 to 10^2 m depending on the differences between the properties of internal and external atmospheres as well as other cave specific physical parameters (Wigley and Brown 1976). For those caverns with stable temperatures in their interior, mean cave temperature has been related to the mean annual temperature at the surface of the cave (Moore 1964; Moore and Sullivan 1964; Palmer 2007). The

Table 1 Thermal diffusion coefficients used in the conduction model

Coefficient	$m^2\ s^{-1}$
κ_0^a	1.000×10^{-6}
κ_1	0.850×10^{-6}
κ_2^b	0.756×10^{-6}
κ_3	0.700×10^{-6}
κ_4	0.650×10^{-6}
κ_5	0.600×10^{-6}
κ_6	0.520×10^{-6}

[a] Cemak and Rybach (1982)
[b] Domínguez-Villar et al. (2013)

mechanism linking cave and exterior mean annual temperatures is the conduction of atmospheric thermal signal through the underground (Domínguez-Villar 2012), because aquifers from karst regions are thought to drain the geothermal heat flux (Bögli 1980; Luetscher and Jeannin 2004).

Direct correlation of cave and external temperatures have been previously reported (Smithson 1991). However, correlations were found only during periods with enhanced advection causing the entrance of external air into the cave. Additionally, the significance level of these correlations diminished with increasing distance from the cave entrance. On the other hand, the enhanced cave advection was found to depend on the difference between internal and external air temperature, but also on the wind regime. Thus, the temperature of caves dominated by the advection mechanism has a discontinuous link to external temperature which depends on several parameters. Therefore, these caves are not good candidates to accurately reflect the long-term temperature changes from the surface. Alternatively, caves with a thermal regime dominated by heat conduction from the surface represent better environments to record the temperature changes such as global warming, although a certain delay in the signal is expected (Badino 2004). Such delay depends on the underground thermal properties (e.g. Pollack and Huang 2000; Smerdon et al. 2006) and for shallow caves (i.e. <20 m) can be quantified based on the amplitude of the harmonic thermal signal at seasonal timescales (Domínguez-Villar et al. 2013).

Understanding cave temperature dynamics is of major importance for paleoclimate studies. Cave records obtained from speleothems are considered among the most valuable paleoclimate archives in continental regions (Fairchild et al. 2006; Fairchild and Baker 2012). Most of the proxies recorded in speleothems and used for paleoclimate reconstructions such as the isotope ratios, trace elements, growth rate or some biomarkers are affected by cave temperature (e.g. Lachniet 2009; Huang and Fairchild 2001; Baker et al. 1998; Schouten et al. 2007). Therefore, it is important to know whether long-term temperature changes in the surface above caves have an impact on cave temperature, its magnitude and the expected delay times. The temperature of cave atmosphere determines its density and consequently controls the air movements within the cave (de Freitas et al. 1982). Differences in the air density gradients among different galleries or chambers in a cave system could result in the modification of the ventilation regime within the cave. Additionally, changes in the ventilation regime can produce condensation of moisture on speleothems and cave walls causing the corrosion of carbonates (de Freitas and Schmekal 2003; Dreybrodt et al. 2005). Therefore, changes in cave temperature may have major implications in the management of tourist caves and the cave art conservation (Sanchez-Moral et al. 1999; Lario et al. 2006).

This research uses the study case from a gallery in Postojna Cave (Slovenia) to investigate the impact of the external atmosphere temperature in the cave. The Postojna region has experienced a long-term warming trend since early 1980s that results in a temperature increase >1.5 °C in relation to the mean temperature recorded during the previous decades. The temperature at the studied cave site is very stable and the mechanism transferring the external temperature signal to the cave is dominated by conduction. The regional climate that captures the global warming trend during recent decades, and the particular cave dynamic in the studied gallery, makes this site ideal to observe and model the transfer of external thermal anomalies to a cave.

2 Regional setting

Postojna Cave is located in the northern sector of the Dinarides (45.78°N;14.20°E) in a hilly terrain of Cretaceous limestones (Mihevc et al. 2010). The site is only 35 km from the Adriatic Sea and there is no major topographic barrier between the cave and the sea. The region has a continental climate with a mean annual temperature of 8.68 °C during the period 1971–2000 AD, with mean monthly temperatures of the warmest and coolest months of 18.05 °C (July) and 0.05 °C (January) respectively. Postojna recorded a mean annual precipitation of 1,590 mm during the same period. The precipitation lacks a dry season or any clear seasonality, although precipitation is often more abundant in autumn. Above the cave there is a dense mixed forest (i.e. conifers-beeches). According to the archives of the Slovenian Forest Service and local witnesses, the forest cover over the cave site has not been modified for over 50 years. This implies that variable coupling between mean ground and atmosphere temperature due to this factor (Domínguez-Villar et al. 2013), may be discarded as an effect on our cave site for the time period of interest.

Postojna Cave is among the largest caves in Slovenia with over 20 km of known passages (Fig. 1). Several

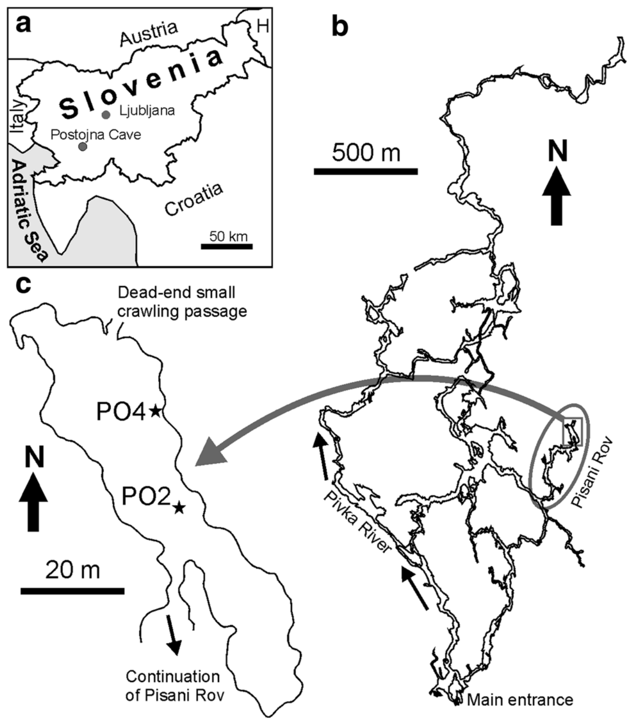

Fig. 1 Location of the study site. **a** Location map of Postojna Cave **b** Sketch of Postojna Cave. The *ellipse marks* the location of Pisani Rov, whereas the *rectangle frames* the Bela in Rdeča hall **c** Detailed sketch of Bela in Rdeča hall (after Glažar and Domínguez-Villar 2013) with the location of the two monitoring locations

galleries of the cave are open to tourists and over 500,000 people visit the cave every year. The cave has six known entrances and the river Pivka flows trough the lower gallery at the western sector of the cave system. The microclimate of most of the cave is characterized by an active ventilation, more dynamic during the winter season, which records daily fluctuations during most of the year (Šebela and Turk 2011; Gregorič et al. 2013a, 2013b). The large size of entrances and principal passages facilitates the influence of external conditions on the cave microclimate. We performed our study in Pisani Rov, a gallery closed to tourists and with a different ventilation regime compared to the rest of the cave, which is characterized with limited advection, especially during the summer period (Gregorič et al. 2013a). The gallery of Pisani is over ~1.5 km away from the nearest entrance to Postojna Cave and is connected to the principal passage by a small entrance ~1 × 1.5 m located in the higher part of the principal corridor. Pisani Rov is ~0.6 km long and consists of a series of big halls and narrow passages by which a person has to lean over in order to cross them. We studied the Bela in Rdeča hall (hereafter BiR hall) of Pisani Rov, which is a 70 m long room with average width and height of 12 and 4.5 m respectively (Glažar and Domínguez-Villar 2013). This chamber is the last large room of Pisani Rov and represents the dead-end of the gallery. The hall has a very limited advection dynamic compared to the rest of the cave (Gregorič et al. 2013a), and air flow is not perceptible at any period during the year. Above this hall, the surface has a mean altitude of 571 m above sea level. In this research two monitoring stations were considered inside the studied room: PO2 and PO4, both at an elevation of 529 masl. The hall is amply decorated with speleothems and we are developing at this site a wider cave research that includes hydrochemical monitoring of several drips and construction of paleoclimate records from speleothems. The PO2 and PO4 monitoring sites are related to the location of speleothems and drip sites with ongoing research lines.

3 Methods

The thermometers used in this research are thermistors from Gemini Loggers Ltd. The instruments are TGP-4500 and TGP-4017 (Tinytag Plus 2), although a waterproof device TG-4100 (Tinytag Aquatic 2) was also used. All loggers have an accuracy of 0.5 °C and a precision of 0.001 °C. Additionally, drip rates were studied with Stalagmate loggers (Collister and Mattey 2008). Temperature data were acquired every 20 min. The variability of the recorded thermal signal related to internal noise of each instrument is from 0.002 to 0.006 °C (Fig. 2). Daily averages were used in this paper in order to filter this high-frequency variability. The loggers were deployed at different times. In January 2009 two loggers were deployed at PO2 and PO4 sites directly over the cave floor (Fig. 1), and one additional logger was deployed outside the cave just over the study site. The location of this external logger is at ground level and among rocks that prevent direct insolation. In June 2010 a new logger was deployed in the cave at PO2 site on a tripod 10 cm from the cave floor. Finally, in November 2010 the waterproof logger was deployed in a plastic beaker with 100 ml of cave water. Although the beaker rested over the cave floor, the logger had a minimum contact with its base to minimize the buffering effect of cave ground on atmospheric temperature. The low volume of water in the beaker favours its fast thermal equilibration (i.e. <3 h) with the cave atmosphere (Fig. 2). Thus, we use the record of this logger as a reliable record of cave atmosphere temperature at daily timescales. The non waterproof loggers inside the cave have recorded occasional temperature drifts due to humidity affecting the interior of the instruments. The deployment of devices at different dates was a strategy to identify signal drift. The waterproof logger was used as an additional test to confirm possible bias of the temperature records, and it was submerged in water to be completely sure that moisture would

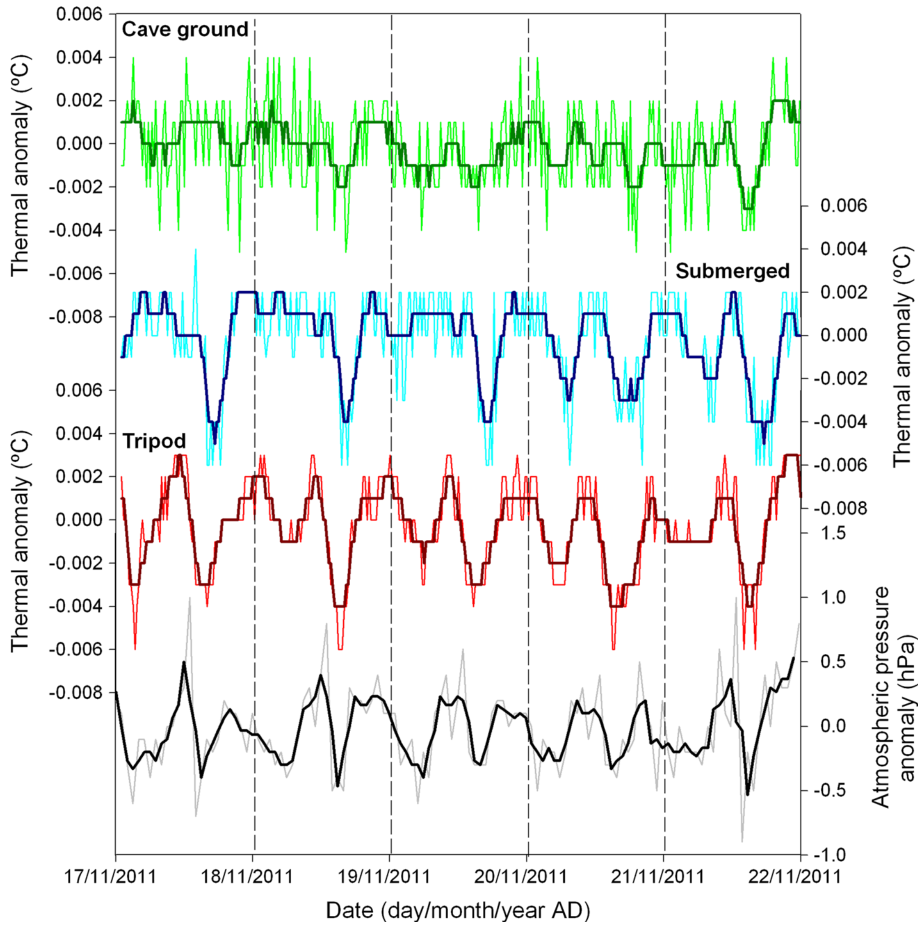

Fig. 2 Daily variability of temperature in the Bela in Rdeča hall. The thermal anomalies are calculated by normalizing the series in relation to the average value of the represented period. At daily timescales, during periods of limited atmospheric pressure variability outside the cave, advection related to barometric tides can be identified with 12 and 24 h periods affecting the cave temperature. The logger on the tripod better records these thermal oscillations, whereas the buffering effect of the rock on cave atmosphere is obvious in the loggers resting on the cave floor. The high frequency variability superimposed on these cycles is considered to be internal noise of each thermometer. Note that the waterproof thermometer submerged in water shows a negligible or very minor delay in relation to the other loggers. Pressure record is from Gregorič et al. (2013a)

not affect its record. In the case of temperature drift in the non-waterproof loggers, the record after the last data collection was discarded and the thermometer was taken off the cave, dried and deployed in its original position later on. The reproducibility of the thermal signal of the loggers was tested inside the cave providing a variability of ±0.1 °C, which is within the reported accuracy of the instruments. The absolute temperature provided in this paper is based on a calibration of the different thermometers that correct the bias of each logger relative to the mean of the four instruments during the test period. Finally, a composite cave temperature record was constructed by overlapping the calibrated series of different loggers.

Densities of cave and external atmospheres were calculated using the barometric pressure (P), universal gas constant (R_d) and virtual temperature (T_v) according to Eq. 1. In order to calculate the virtual temperature, air temperature (T), dew point (T_d) and barometric pressure were incorporated into Eq. 2 according to (Kowalczk and Froelinch 2010). Daily meteorological data from Postojna and Ljubljana stations are from the National Meteorological Service of the Slovenian Environment Agency (http://www.meteo.si).

$$\rho_{air} = \frac{P}{R_d \cdot T_v} \quad (1)$$

$$T_v = (T + 273.15) / \left(1 - \left(0.379 \cdot \left(\frac{6.11 \cdot 10^{(7.5 \cdot T_d / 237.7 + T_d)}}{P}\right)\right)\right) \quad (2)$$

A one-dimensional conduction thermal model considering a homogeneous half space was developed in order to transfer the annual surface temperature signal from Postojna meteorological station to the depth of the cave. The expected amplitude of thermal anomalies (T_a) recorded at a certain depth (z) were calculated according to.

$$T_a = erfc\left(\frac{z}{2\sqrt{\kappa \cdot t}}\right) \quad (3)$$

where $erfc$ is the complementary error function, κ is the thermal diffusivity coefficient and t is the time. The mean annual surface atmosphere temperature record from Postojna was decomposed in harmonic signals. Periods that produce thermal anomalies at the cave depth lower than the instrumental noise were not considered. Wavelet analysis showed that periodicity of the mean annual surface atmosphere temperature is not maintained through time, so, the filtered temperature series is the result of the sum of the harmonic segments during different periods that better fit the observed temperatures. According to Smerdon and Stieglitz (2006), the harmonic signals are transferred to depth with a phase shift (Φ) and an attenuation of the amplitude (A_r) which can be calculated for particular depths from

$$\Phi = k \cdot z \quad (4)$$

$$A_r = e^{-k \cdot z} \quad (5)$$

$$k = \sqrt{\frac{\pi}{\tau \cdot \kappa}} \quad (6)$$

where k is the wave vector and τ is the period. It is worth noting that the phase shift of all the harmonics would be the same for a particular depth according to the Eq. 4. However, because of each harmonic has different periods, the same phase shift implies variable delay times. Thus, harmonics having longer periods take more time to be recorded at the cave depth and vice versa. Therefore, the record of temperature variability in the external atmosphere would be transmitted to the cave with certain modifications and the signal of thermal anomalies of external and cave air would differ. Finally, the model of cave temperature at a particular depth (T_z) is obtained from

$$T_z = \sum A_z \cdot \sin\left(\frac{2 \cdot \pi \cdot t}{\tau} + \varepsilon - \Phi\right) \quad (7)$$

where the expected amplitude at a particular depth (A_z) is the result of multiplying A_r by the amplitude of the harmonics at the surface.

The cave is deep enough to completely mute the external atmosphere seasonality signal, precluding the calculation of κ based on the seasonal period for this site, and as a first approximation we use the κ value from a similar cave setting (Domínguez-Villar et al. 2013). However, we assume that Postojna κ would likely differ and the model was run using a wide range of κ values. The thickness of bedrock cover is an important parameter of the model. The depth of the centre of the gallery was calculated from the difference between the Lidar based topography from Postojna and the relative altitude of the topography by Glažar and Domínguez-Villar (2013) georeferenced to the topography by Gallino (1924/28). Due to the tubular shape of the room, the depth of the centre of the hall was considered as a realistic measure of thickness of bedrock cover. This criterion averages the depth of ceiling and walls allowing the evaluation of lateral heat flow (Ferguson and Beltrami 2006). Due to the reduced dimensions of the studied hall, the model assumes that the cave atmosphere buffers any possible temperature variability between different sectors of the hall walls. Therefore, an areal weighted average of the cave centre depth was used as an estimation of the cave bedrock cover. Thus, the bedrock cover considered for the model was 37 m.

4 Results

4.1 Surface and cave temperature

Surface atmospheric temperature has been measured continuously in Postojna since 1962 by the national meteorological service at 2 m above ground level. This station is located 3.5 km away from the surface projection of our study cave site and is 30 m lower in elevation. Despite the inter-annual variability, a warming trend is observed in this meteorological station since the early 1980s (Fig. 3). The relevance of this warming trend in relation to other anomalies becomes evident when comparing Postojna with Ljubljana temperature records, because the latter has a similar variability but longer record (see Fig. 1 for Ljubljana location). The correlation coefficient (r^2) of Postojna and Ljubljana mean annual temperature series is 0.95 (p value < 0.001). The mean annual atmosphere temperature during the years 2009–2012 was 9.96 °C at Postojna meteorological station, while we measured 8.74 °C during the same period at the ground level over the cave site. Despite the absolute difference, the variability on both records is highly correlated at daily timescale ($r^2 = 0.96$; p value < 0.001). The temperature difference between these two records is likely related to local microclimate conditions and the ground thermal effect of the logger resting on the ground over Pisani Rov. The thermal insolation of the ground from atmosphere during periods of significant snow cover should have an impact on ground mean annual temperature (Yazaki et al. 2013), although considering the duration of the snow cover in Postojna during the studied period, this factor should account for <0.3 °C of the offset with the atmosphere temperature. Although the absolute atmospheric temperature is important to evaluate the thermal equilibrium of the cave with the external thermal signature, the focus in this paper relies on the thermal anomalies. Therefore, we use the Postojna meteorological station record as a reliable record of the temperature variability over our study cave site.

The cave temperature recorded at PO2 and PO4 sites is within the accuracy range of the thermometers and therefore, we consider that all thermometers record the same mean temperature. This is expected since both sites are located at the same elevation: 529 m above sea level. The

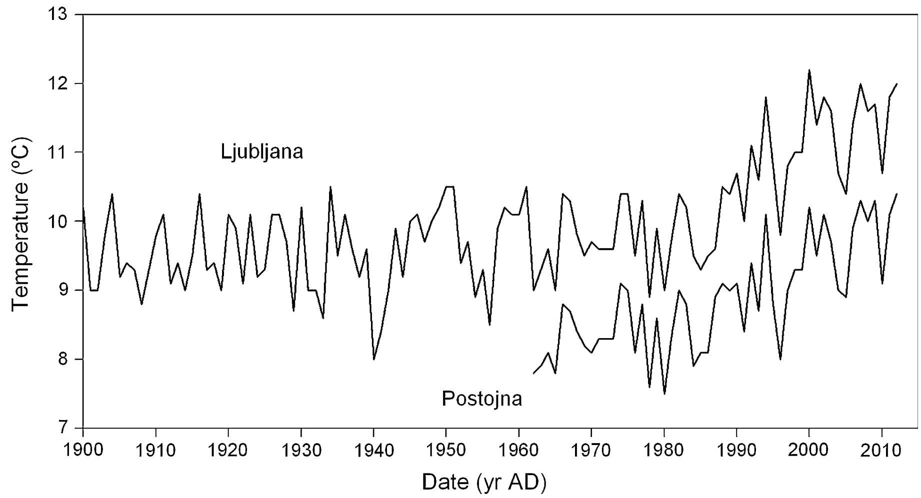

Fig. 3 Temperature records from Postojna and Ljubljana meteorological stations. The accumulated mean warming since the early 1980s in Postojna is >1.5 °C. Data from National Meteorological Service of the Slovenian Environment Agency (http://www.meteo.si)

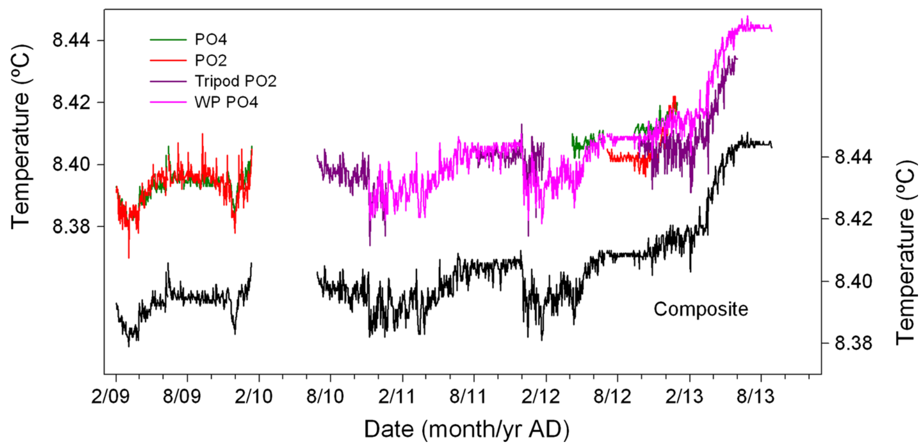

Fig. 4 Cave temperature records. The *upper panel* shows the records of the four loggers and the composite record is plotted in the *lower panel*. The data gap is due to the filter of inaccurate data recorded after the instruments were affected by cave moisture

cave had an average temperature of 8.40 °C during the studied period (Fig. 4). The measured cave temperature is very stable, with <0.07 °C thermal change in five years and a high-frequency variability on the daily temperatures of <0.02 °C. The composite cave temperature record shows that there is a seasonal pattern, with relatively stable temperatures during the summer months and more variable temperature during winter. The background or low-frequency signal of the cave temperature record shows a statistically significant warming trend (i.e. >99.9 %) of 0.004 °Cyr^{-1} from 2009 to 2012. However, during the first months of 2013, the cave temperature increased 0.03 °C, clearly disrupting the previous trend.

4.2 Causes of cave temperature variability

The temperature in BiR hall is controlled by advection and conduction transferring mechanisms. The movement of air in this room is caused by gradients in both, air density and atmospheric pressure. Caves with ventilation related to air density differences are known as "thermal caves" because of temperature is the main control on the air density, whereas caves with changes in atmospheric pressure causing the advection are known as "barometric caves", being possible the coexistence of both ventilation mechanisms within a same cave (Pflitsch et al. 2010). Thus, BiR hall functions as a thermal and barometric cave. On the other hand, the stable temperature in the hall and the background temperature values are the result of the dominant role of heat conduction through the rock in relation to the weaker impact of heat transported by advection. This is due to the limited ventilation of BiR hall (Gregorič et al. 2013a) and the much larger heat contained in the rock compared to the atmosphere (Pflitsch and Piasecki 2003). The advection effects on cave temperature are evaluated by comparing meteorological and other cave monitoring data with the recorded thermal signal, whereas the role of conduction would be tested by models in the next section.

We calculated the air density difference between exterior and cave atmospheres considering a 99 % relative humidity in BiR hall, which is a typical value for similar caves (e.g. Bourges et al. 2006). An estimated uncertainty

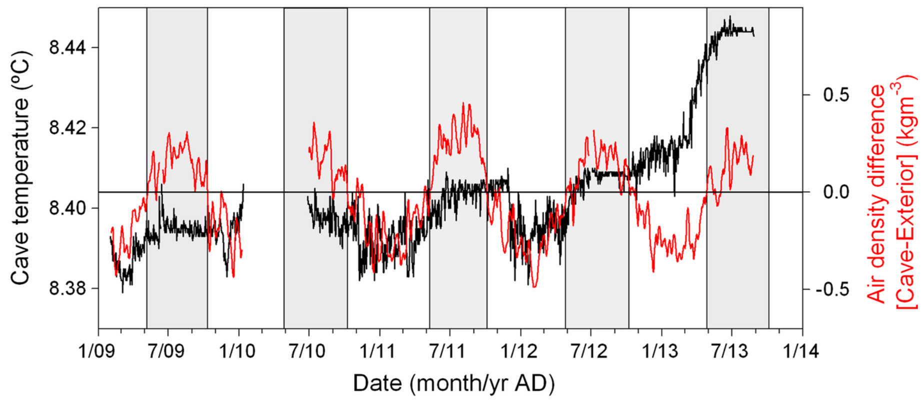

Fig. 5 Comparison of composite cave temperature and differences in cave air density (cave air-external air). The main periods of summer ventilation mode (*grey vertical bars*) and winter ventilation mode (*white vertical bars*) are also plotted. Notice that during transition periods alternation of both ventilation modes occurs

in cave relative humidity of ±1 % produces a cave air density uncertainty of ±0.005 kg m^{-3}, which is negligible compared with the variability of exterior air density (i.e. two orders of magnitude larger). The gradient of air density between the cave and the external atmosphere controls most of the divergence of the cave temperature record in relation to the background values by enhancing cave air advection (Fig. 5). Air density is greatly controlled by temperature, so the calculated record of density difference between the cave and exterior atmospheres resembles the record of temperature differences between atmospheres. When the air is denser outside than inside BiR hall, external air enters this room. A larger gradient implies more dynamic ventilation, which usually takes place during winter. However, when cave air is denser than external air, no air moves into the cave due to the density differences. In this case, the lack of cave air advection due to density difference with external air is independent to the magnitude of the gradient. We refer to the ventilation during the period with cave air less dense than external air as the "winter ventilation mode", whereas the reverse situation is called "summer ventilation mode", regardless both periods extend over part of the autumn and spring. Figure 5 shows how the winter ventilation mode affects the variability of temperature in BiR hall, whereas during the summer ventilation mode period the temperature is much more stable. There is a weak correlation between daily thermal anomalies in this hall and daily density anomalies during the period of winter ventilation mode ($r^2 = 0.16$; p value < 0.01), where the anomalies are measured as the change in each parameter since the previous value in the time series. It is worth noting, that these time series do not show auto-correlation and the parametric test shows a real relationship between both parameters. During the summer ventilation mode period there is an even weaker correlation ($r^2 = 0.04$; p value < 0.01), suggesting that some air advection takes place with other cave rooms having a denser atmosphere. This inter-rooms advection is also expected to occur during the winter ventilation mode period. Additionally, some atmosphere advection is expected within the hall due to likely thermal variability introduced from the bedrock due to variable thickness of rock cover along different sectors of the gallery, as observed in other caves (Domínguez-Villar et al. 2013). This air convection within the hall would tend to homogenize air temperature in the room.

The advection of air from the surface to the cave takes place by the network of fissures and connected porosity of the epikarst (Wigley 1967). The air uses the same conduits that feed some of the drip sites under study. Thus, some drip sites show faster drip rates during the winter ventilation mode period, suggesting that the advection of air enhances a faster water flow (Fig. 6). The opposite is also recorded and some drip sites have a limited drip rate during the winter ventilation mode period, suggesting that dynamic advection of air prevents the usual water flow along some conduits. Finally, other drip sites do not seem to be affected by the advection of the cave. The different response of drips to advection likely results from the complexity of the conduit networks in the epikarst. Thus, it is expected that the changes in pressure driven by the enhanced inflow of air in the interconnected or isolated conduit networks would differ depending on the geometry of conduits and their water saturation. Despite the complex response of drips to advection, drip rates in BiR hall are clear evidence of air advection from the surface to the cave during the winter ventilation mode period. This advection takes place independently of the existence of snow cover, freezing temperatures outside the cave or rain events that could saturate the soil porosity with water, because no correlation was found between cave temperature and these parameters (p values > 0.1). This is confirmed by the lack of correlation between precipitation and the concentrations of radon and CO_2 gases measured in this chamber (Gregorič et al. 2013a).

The cave air temperature is not affected by the water discharge variability. This is expected since although the drips response within a day to large precipitation events due to the piston effect, the residence time of water in the epikarst is larger than a year (Domínguez-Villar et al. 2011) and water temperature should be equilibrated with the bedrock temperature. A pilot study to determine the drip water temperature was conducted under PO4F drip site during several months in 2010, including the period of fast drip rate in this site. The drip water was collected in a beaker of 100 ml and its temperature record showed no difference in relation to the cave atmosphere temperature record, supporting that the drip water temperature is in equilibrium or near equilibrium with the bedrock and the cave atmosphere temperature. The discharge of different drip sites is largely variable. Assuming an average drop volume of 0.15 ml (Collister and Mattey 2008), the estimated annual discharge of PO4F drip site was >1,000 L during the studied period, whereas the flow of PO2 was <50 L per year. These discharge rates indicate that the dense network of drip sites in this gallery is able to drain the recharge water on top of the cave. Although the recharge water would introduce an additional seasonal temperature component to the ground temperature, the advection of heat between recharge water and the rock/soil is normally muted within the first 20 m of depth (Anderson 2005). Therefore, heat advection of the recharge water would be relevant only for the upper sector of the epikarst above the BiR hall, since the relatively low transmissivity of the aquifer on top of the cave favours the equilibration of the recharge water with the host rock before reaching the cave. Precipitation variability, as well as snow cover, has some potential to modify ground temperatures affecting the surface atmosphere and ground temperature coupling (Pollack et al. 2005). Although the recharge water does not cause direct advection in BiR hall atmosphere, the initial temperature at the time of infiltration has a limited but potentially significant impact to modify the ground temperature that would be transmitted underground by conduction.

The temperature in BiR hall is also controlled by atmospheric pressure. The thermal signal records 12 and 24 h periodicities related to atmospheric pressure during days with relatively stable atmospheric pressure (Fig. 2), when the atmospheric tides contribute to most of the pressure variability. On a larger scale, the atmospheric pressure also impacts the variability of the daily cave temperature record. Thus, significant correlation exists between the atmospheric pressure anomalies and the cave temperature anomalies during the winter ventilation mode period ($r^2 = 0.42$; p value < 0.001) and also during the summer ventilation mode period ($r^2 = 0.27$; p value < 0.001). The larger atmospheric pressure anomalies are recorded during the cooler months of the year, which could explain the difference in correlation factors during both ventilation mode periods. This phenomena of barometric advection is also found in other caves and underground environments (Wigley 1967; Perrier et al. 2001; Bourges et al. 2006), and is characteristic of caves with small openings to the surface in comparison with the volume of underground galleries (Pflitsch et al. 2010).

Based on the obtained correlation factors of the daily anomalies, the advection due to barometric changes has a larger control on cave temperature anomalies than the advection due to air density changes. However, the air density has a seasonal cycle that makes its daily anomalies to be cumulative during the winter ventilation mode period, whereas the atmospheric pressure has a larger daily variability but similar mean values at different seasons. As a result, the cumulative effect of air density has a larger impact on cave temperature, especially during the winter ventilation mode periods (Fig. 5). In contrast, during the summer ventilation mode periods the high-frequency thermal variability is reduced to typically less than ±0.01 °C. This variability is superimposed to low-frequency thermal changes, which are thought to be related to the temperature signal transferred by the rock (Domínguez-Villar 2012). The net temperature variability of the cave atmosphere produced by the bedrock is difficult to measure since air advection also affects the surface of cave bedrock to depths which could exceed 0.5 m from the cave walls/ceiling (Luetscher et al. 2008). Therefore, in order to evaluate the bedrock temperature in the cave, we opted to develop a model that would exemplify the physical principles of heat conduction.

4.3 Cave temperature model

There is no empirical value of the thermal diffusion coefficient (κ) for Postojna Cave bedrock, which is an essential parameter to constrain the heat conduction. As a first approximation we use the κ calculated for a different cave (Domínguez-Villar et al. 2013), to roughly evaluate the order of magnitude of the cave atmosphere temperature variability at the studied depth in response to external thermal oscillations. Considering the thickness of bedrock over BiR hall, the anomalies of atmosphere temperature outside the cave have to be at least 5 years in duration to be recorded at the cave depth considering the instrumental noise of the loggers (Fig. 7). The uncertainty related to the use of different realistic κ values is <1 year. In order to transfer the temperature signal from the external atmosphere, recorded at the Postojna meteorological station, to the cave depth, the time series was decomposed into its most significant harmonics with periods >5 ± 1 years. As the periodicity of harmonics is not constant through time, different intervals of the harmonic signals are chosen to produce the better fit to the observed temperature record at the meteorological station. Four harmonic signals with

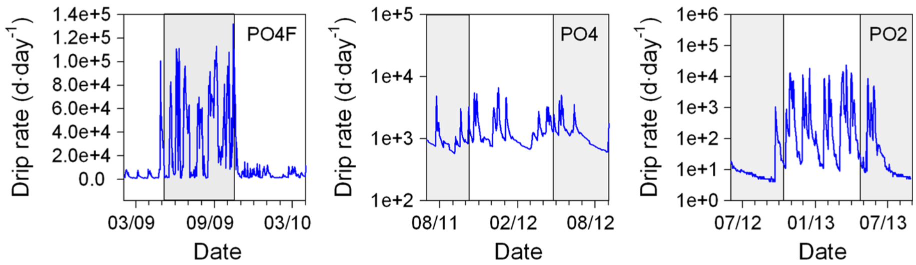

Fig. 6 Drip rates of sites PO4F, PO4 and PO2 during different periods. The main summer ventilation mode periods (*grey vertical bars*) and winter ventilation mode periods (*white vertical bars*) are as in Fig. 5. High drip rates in PO4F and PO2 are sometimes outside of the main ventilation modes that controls the dripping and depicted by the simplified *grey and white bars*. This is due to the alternation of summer and winter ventilation modes during transitional periods; see Fig. 5 for details of ventilation mode during transitional periods

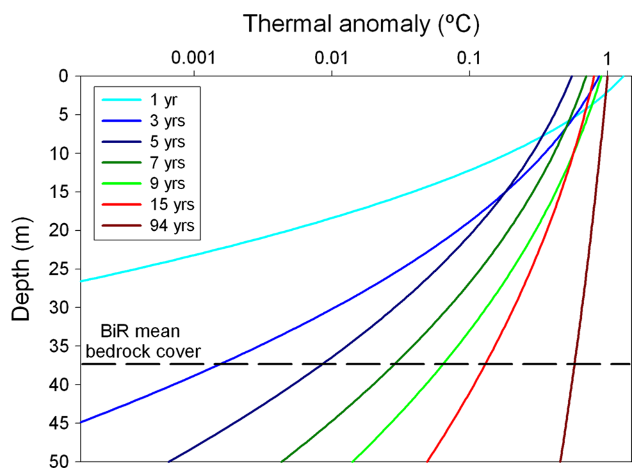

Fig. 7 Magnitude of thermal anomalies expected at the Bela in Rdeča hall depth for oscillations with different periods in the external atmosphere temperature. The thermal anomalies at the surface correspond to the amplitude for each period in the external atmosphere as recorded in the Postojna meteorological station. The model uses values of κ_2 (thermal diffusion coefficient) given in Table 1

periods of 7, 9, 15 and 94 years produced the best fit (Fig. 8).

The model shows a clear response to the warming trend observed in Postojna meteorological station since the early 1980s, although the response of this particular harmonic signal is delayed by >20 years. The magnitude of thermal response expected at the cave highly depends on the κ value, but in any case, all simulations predict less than half the anomaly recorded at the surface during the next decade. The thermal oscillations of short-term periods (i.e. 7, 9 and 15 years) produce at the cave high-frequency oscillations with thermal anomalies <0.05 °C superimposed onto the long-term trends. The shorter the period, the faster the signal would be transmitted to the cave. According to Eq. 4, all the harmonics have the same period delay at a particular depth, but because the periods have different durations, their signals reach the cave at different times. Therefore, the thermal anomalies related to these short-term periods have delay times at the cave depth ranging between 5 and 8 years. Some of these high-frequency anomalies extend over a decade and show warming or cooling trends. This has important implications for cave studies since monitoring periods rarely exceed 5–10 years (Stoeva et al. 2006), preventing the extraction of conclusions regarding long-term cave temperature gradients based on observational data.

5 Discussion

5.1 Potential of BiR hall to record long-term temperature changes from the surface

The temperature signal in BiR hall is quite different from the rest of the cave where advection processes are much more dynamic (Gregorič et al. 2013a). The main corridors in Postojna Cave have mean temperature values >2 °C warmer than in BiR hall, and even the lowest temperature recorded in other sectors of the cave is >1 °C warmer than in this chamber (Šebela and Turk 2011). Assuming that relative humidity is close to saturation in all corridors aside from main entrances, this implies that BiR atmosphere density is always higher than in galleries others than Pisani Rov. As a consequence, there is no air flow from the main corridors towards BiR hall at any moment during the year due to density differences, and the potential airflow caused by this mechanism always moves out of Pisani Rov, with the inflow of external air driven by pressure gradients compensating the mass balance. This situation significantly reduces the advection influence on temperature in the studied chamber. However, during the winter ventilation mode period, the higher density of the external atmosphere favours the entrance of air through conduits, cracks and connected porosity of the bedrock over the cave to BiR hall. When the external air finally reaches BiR hall after crossing the bedrock cover, its temperature is only slightly

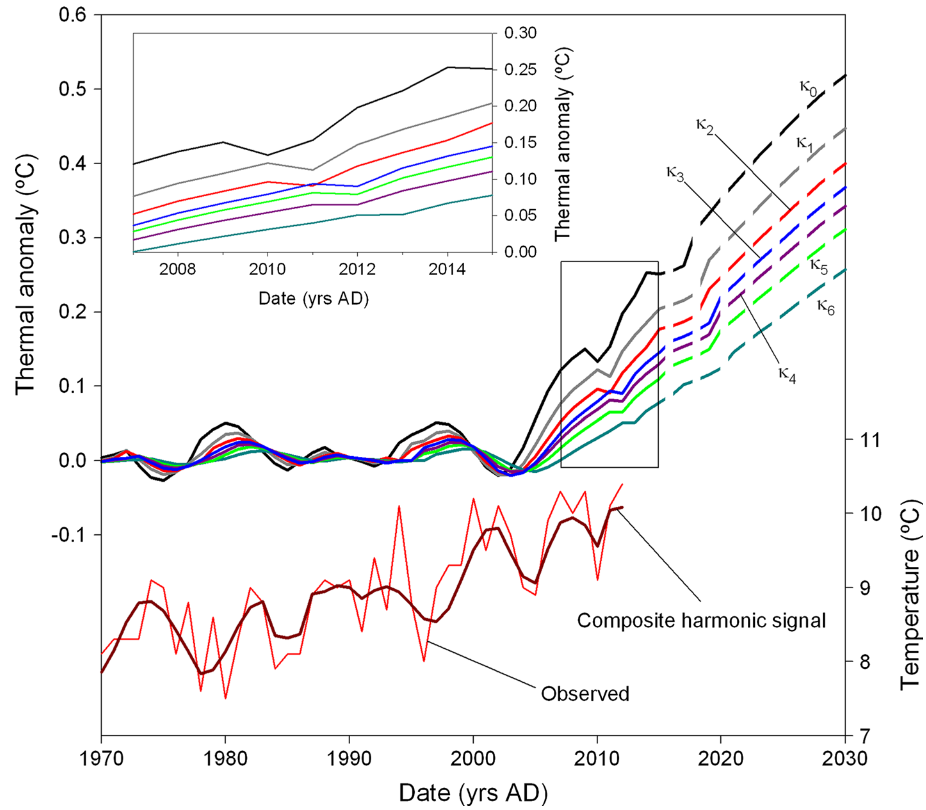

Fig. 8 Thermal conduction model for Bela in Rdeča hall. The *lower panel* shows the temperature recorded at Postojna meteorological station and the composite signal that includes the 7, 9, 15 and 94 years harmonics, which was used to implement the model. In the *upper panel* seven different simulations considering different κ values are plotted. Discontinuous lines indicate the period of the model considering just the larger period anomalies. Future temperature anomalies related to the inter-annual variability recorded in the external atmosphere would cause small scale oscillations to the general warming trend presented by these discontinuous lines. The results of the model for the 2007–2015 period are framed and enlarged in the *inset graph*

cooler than the cave temperature without the advection perturbances. The initial thermal difference is muted by a series of processes that include the friction of air with the cave walls (Atkinson et al. 1983), the transformation of sensible to latent heat (Wigley and Brown 1971; Luetscher et al. 2008) and the equilibration of the air with the bedrock (Domínguez-Villar et al. 2013). Advection is also possible in Pisani Rov due to barometric fluctuations. Depending on the barometric gradient, this process allows the air movement in or out from this chamber. This air flow connects BiR hall with the external atmosphere, but potentially, also allows the flow with other corridors from the cave. However, the impact of barometric fluctuations on the temperature from this chamber is small (i.e. ±0.01 °C), indicating a limited advection dynamic.

The thermal stability recorded in the BiR hall atmosphere is related to the buffering effect of the heat accumulated in the bedrock. In shallow caves (e.g. <20 m from surface) where advection is negligible, the temperature signal should exhibit sinusoidal oscillations with an annual period and without any high-frequency perturbation (e.g. Buecher 1999). In the case of deeper caves that prevent the recognition of seasonal variations, the temperature record simply shows long-term thermal changes (Domínguez-Villar 2012). At the depth of BiR hall (i.e. 37 m), there is no seasonal component related to the conduction of heat from the external seasonal temperature, and only thermal harmonics with periods >5 ± 1 years would be recorded with the precision of our loggers. Thus, the background temperature value of BiR hall captures long-term changes recorded at the cave surface. However, advection processes takes place in this chamber, with high-frequency fluctuations that accounts for <0.02 °C and seasonal anomalies during the winter ventilation mode period that cools the cave air ∼0.01 °C. These thermal variations of small amplitude do not prevent the observation of the long-term trend recorded in the cave, which is especially well preserved during the summer ventilation mode periods. Therefore, despite some advection takes place in this chamber, the thermal signal measured in the atmosphere of BiR hall is dominated by the bedrock temperature. Thus, this hall is a suitable location to evaluate the transfer of long-term climate changes underground.

5.2 Conduction as mechanism transferring the external atmosphere temperature signal to the cave

The cave atmosphere temperature and cave walls' temperature tend to equilibrate to each other. Since the heat content in the rock is much higher than in the air (Pflitsch and Piasecki 2003), and the advection of air is relatively limited in BiR hall, the air tends to equilibrate with cave wall temperature. However, during the periods of winter ventilation mode, the prolonged contact of cooler air with the cave walls affects the temperature of cave wall surfaces. The application of the conduction model to the cave walls suggest that these walls would have a maximum thermal anomaly of 0.01 °C at the surface, and this anomaly would penetrate in the bedrock 9 ± 1 m before this amplitude becomes <0.001 °C (uncertainty accounts for different realistic κ values). This surficial change in cave walls temperature due to advection is obvious at the onset of the summer ventilation mode period (Fig. 5), when the enhanced ventilation ceased. After the change of ventilation mode, there are some weeks in which the cave atmosphere temperature progressively gets warmer until the deeper cave wall temperature equilibrates with the cave wall surface. At the end of the summer ventilation mode periods, the opposite occurs and thermal stability of cave atmosphere is maintained because of the buffering effect of cave walls on the heat removed by advection.

These detailed processes are additional evidence that the conduction of the temperature signal stored in the bedrock of the cave is the main driver of cave background temperature values and its reduced variability. Because the soil temperature tends to be coupled with external atmosphere temperature (Pollack et al. 2005; Smerdon et al. 2006) and transferred underground by conduction (Pollack and Huang 2000), the temperature changes from the surface should be recorded in the cave following the principles of thermal conduction as implemented in our model. The heat to a cave could arise from origins other than the external atmosphere, such as the geothermal source, large water currents or the biotic/touristic influence (Palmer 2007). In the case of BiR hall, there are no streams or cave biota that would impact the cave temperature. The hall is only visited occasionally by scientists. Their thermal impact is clearly identified and removed before processing temperature series. The geothermal heat is thought to be removed by the aquifer, and in any case its influence is thought to be constant (Luetscher and Jeannin 2004). Therefore, it is reasonable to consider that the cave temperature variability should be derived exclusively from the external temperature, as accounted in our model.

According to all the simulated scenarios in Fig. 8, BiR hall is already recording the global warming trend observed in the surface since the 1980s, although with 20–25 years of delay. It is worth noting that the delay of the outside thermal signal depends on the period of the harmonic, and shorter periods are recorded earlier in the cave. Thus, during the monitoring period that runs from early 2009 until mid 2013, the cave atmosphere is recording the cooler temperature fluctuation recorded during the years 2004–2005 outside the cave. Although at BiR hall the cave atmosphere temperature shows a warming trend in agreement with predicted signal due to the local expression of global warming, high frequency anomalies with durations longer than the monitoring period are expected in relation to temperature changes in the external atmosphere of shorter periods. So, in order to extract conclusions of long-term temperature changes based on monitoring data, longer term records are recommended (e.g. Genty 2008).

In BiR hall there are five years of temperature record to evaluate the fit of model data to observations (Fig. 9). The comparison of model and monitoring data relies in the κ value used. The best fit of a simulation to the measured data

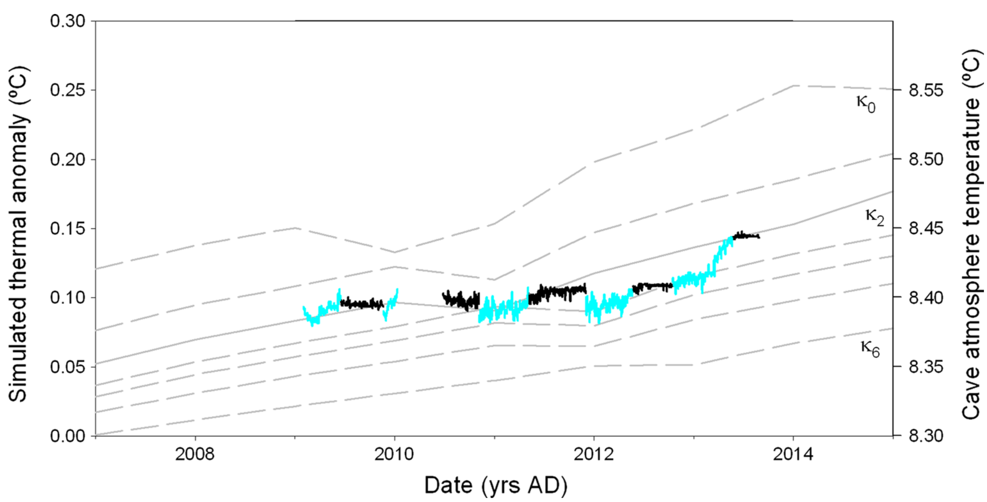

Fig. 9 Comparison of Bela in Rdeča hall atmosphere temperature record compared to model outputs. The mean values during the summer ventilation mode periods (*black lines*) are considered the background temperature that should be closer to model predictions. The temperature record during the winter ventilation mode periods (*clear blue lines*) is less indicative of the mean external signal due to accumulated impact of advection on the cave walls. The κ_2 value (*solid grey line*) represents the best fit to the long-term observed temperature. Other simulations are also represented (*dashed grey lines*)

is obtained using κ_2; the empirical value calculated in a different cave (Domínguez-Villar et al. 2013). Therefore, based on available data we can speculate that Postojna Cave κ has a value close to $0.756 \times 10^{-6}\ m^2\ s^{-1}$. However, although the overall warming trend is nicely picked up by this simulation, there are outstanding disagreements to capture some details of the thermal evolution. The largest discrepancy between model and observational data occurs during the year 2012, when the model predicts a mean thermal signal 0.03 °C warmer than measured. These discrepancies are likely the result of variability of the κ value or partial decoupling between external atmosphere and soil temperatures. Variable factors such as the snow cover, vegetation cover, soil organic matter, soil moisture, soil latent heat or solar radiation have been suggested to affect thermal coupling of ground and atmosphere temperatures (Beltrami and Kellman 2003; Nitoiu and Beltrami 2005). Additionally, in karst regions, the potential variable saturation of water in the epikarst could be a significant factor affecting the diffusion of temperature by conduction due to the different diffusion coefficients of water and air. Diffusion coefficient values measured empirically, that represent natural conditions, integrate not just the bedrock/soil properties but also those from the air and water contained. Due to the difficulty to evaluate many of these parameters, it should be assumed that details in the simulated thermal signal could be obscured by uncertainties.

6 Conclusion

The temperature recorded in the BiR hall from Postojna Cave is dominated by the bedrock heat. Advection of air due to density and barometric gradients was identified in this chamber, but its influence does not disturb much the cave temperature. Caves with significant heat advection have thermal signals whose mean values do not necessarily relate to external atmosphere temperature, but to the intensity and continuity of the advection processes. Therefore, caves with limited advection, where the external atmosphere temperature signal is transferred to the cave by conduction through the underground, are better candidates to accurately record long-term temperature changes from the surface.

We applied a thermal conduction model to transfer the external atmosphere temperature to the Postojna Cave. At the depth of 37 m, BiR hall is already recording the global warming trend observed over the cave since early 1980s, although with a delay of >20 years. The delay and the magnitude of this thermal anomaly depends on the depth, so deeper bedrock sectors of the cave are likely not to be affected yet by this warming trend. Therefore, whether global warming is impacting the temperature of other caves or not, depends on the particular features of each cave. The predicted cave atmosphere temperature increase until the year 2030 in BiR hall is <0.5 °C. Although a temperature change of this magnitude could seem small, it could be enough to change the ventilation dynamic among different chambers of some caves by affecting air density gradients. These changes have potential implications for speleothem growth, seasonal ventilation rates or condensation corrosion processes. Therefore, changes in external atmosphere temperature could have more relevance than previously thought for paleoclimate studies, cave tourism management and cave art preservation.

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References

Anderson MP (2005) Heat as a ground water tracer. Gr Water 43:951–968

Atkinson TC, Smart PL, Wigley TML (1983) Climate and natural radon levels in Casteguard cave, Columbia icefields, Alberta, Canada. Artic Alp Res 15:487–502

Badino G (2004) Cave temperature and global climatic changes. Int J Speleol 33:103–114

Baker A, Genty D, Dreybrodt W, Barnes WL, Mockler NJ, Grapes J (1998) Testing theoretically predicted stalagmite growth rate with recent annually laminated samples: implications for past stalagmite deposition. Geochim Cosmochim Acta 62:393–404

Beltrami H, Kellman L (2003) An examination of short- and long-term air-ground temperature coupling. Global Planet Change 38:291–303

Bögli A (1980) Karst hydrology and physical speleolology. Springer, Berlin

Bourges F, Genthon P, Mangin A, D'Hulst D (2006) Microclimates of L'Aven D'Orgnac and other French limestone caves (Chaveaut, Esparros, Marsoulas). Int J Climatol 26:1651–1670

Buecher RH (1999) Microclimate study of Kartchner caverns, Arizona. J Cave Karst Stud 6:108–120

Cermak V, Rybach L (1982) Thermal conductivity and specific heat of minerals and rocks. In: Angenheister G (ed) Landolt-Börnstein: Zahlenwerte und Funktionen aus Naturwissenschaften und technik. Springer, Berlin, pp 305–343

Collister C, Mattey D (2008) Controls on water drop volume at speleothem drip sites: an experimental study. J Hydrol 358:259–267 de Freitas CR, Schmekal A (2003) Condensation as a microclimate process: measurement, numerical simulation and prediction in the Glowworm cave, New Zealand. Int J Climatol 23:557–575

de Freitas CR, Littlejhon RN, Clarkson TS, Kristament IS (1982) Cave climate: assessment of airflow and ventilation. J Climatol 2:383–397

Domínguez-Villar D (2012) Heat flux. In: Fairchild IJ, Baker A (eds) Speleothem science: from processes to past environments. Wiley-Blackwell, Chichester, pp 137–145

Domínguez-Villar D, Lojen S, Fairchild IJ (2011) Controls in stable isotopes of drip water from Postojna Cave (Slovenia). In: Fairchild IJ, Baker A, Gunn J, Henderson G (eds) Proceedings of the Climate Change - The Karst Record 6. University of Birmigham/British Cave Research Association, Birmingham, p 37

Domínguez-Villar D, Fairchild IJ, Baker A, Carrasco RM, Pedraza J (2013) Reconstruction of cave temperature based on surface atmosphere temperature and vegetation changes: implications of speleothem palaeoclimate records. Earth Planet Sci Lett 369–370:158–168

Dreybrodt W, Gabrovšek F, Perne M (2005) Condensation corrosion: a theoretical approach. Acta Carsologica 34:148–317

Fairchild IJ, Baker A (2012) Speleothem science: from processes to past environments. Wiley-Blackwell, Chichester

Fairchild IJ, Smith CL, Baker A, Fuller L, Spötl C, Mattey D, McDermott EIMF F (2006) Modification and preservation of environmental signals in speleothems. Earth Sci Rev 75:105–153

Ferguson G, Beltrami H (2006) Transient lateral heat flow due to land-use changes. Earth Planet Sci Lett 242:217–222

Gallino L (1924/28) Tavole del Rilievo delle R.R. Grotte di Postumia 1:500. Karst Research Institute ZRC SAZU, Postojna (Slovenia)

Genty D (2008) Paleoclimate research in Villars cave (Dordogne, SW-France). Int J Speleol 37:173–191

Glažar S, Domínguez-Villar D (2013) Topography of Bela in Rdeča hall from Pisani Rov (Postojna Cave). Technical report, unpublished

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

Gregorič A, Vaupotič J, Šebela S (2013b) The role of cave ventilation in governing cave air temperature and radon levels (Postojna Cave, Slovenia). Int J Climatol (in press)

Huang Y, Fairchild IJ (2001) Partitioning of Sr^{2+} and Mg^{2+} into calcite under karst analogue experimental conditions. Geochim Cosmochim Acta 65:47–62

Kowalczk A, Froelinch PN (2010) Cave air ventilation and CO_2 outgassing by radon-222 modeling: how fast caves breathe? Earth Planet Sci Lett 289:209–219

Lachniet MS (2009) Climatic and environmental controls on speleothem oxygen-isotope values. Quat Sci Rev 28:412–432

Lario J, Sánchez-Moral S, Cuezva S, Taborda M, Soler V (2006) High ^{222}Rn levels in a show cave (Castañar de Ibor, Spain): Proposal and application of management measures to minimize the effects on guides and visitors. Atmos Environ 40:7395–7400

Luetscher M, Jeannin PY (2004) Temperature distribution in karst systems: the role of air and water fluxes. Terra Nova 16:344–350

Luetscher M, Lismonde B, Jeannin PY (2008) Heat exchanges in the heterometric zone of a karst system: Monlesi cave, Swiss Jura Mountains. J Geophys Res 113:F02025

Moore GW (1964) Cave temperature. Natl Speleol Soc News 22:57–60

Moore GW, Sullivan GN (1964) Out of phase seasonal temperature fluctuations in Cathedral Cave, Kentucky. Geol Soc Am Spec Pap 76:313

Nitoiu D, Beltrami H (2005) Subsurface thermal effecs of land use changes. J Geophys Res 110:F01005

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

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

Pflitsch A, Wiles M, Horrocks R, Piasecki J, Ringeis J (2010) Dynamic climatologic processes of barometric cave systems using the example of jewel cave and wind cave in South Dakota, USA. Acta Carsol 39:449–462

Pollack HN, Huang S (2000) Climate reconstruction from subsurface temperatures. Annu Rev Earth Planet Sci 28:339–365

Pollack HN, Smerdon JE, van Keken PE (2005) Variable seasonal coupling between air and ground temperatures: A simple representation in terms of subsurface thermal diffusivity. Geophys Res Lett 32:L15405

Sánchez-Moral S, Soler V, Cañaveras JC, Sanz-Rubio E, van Grieten R, Gysels K (1999) Inorganic deterioration affecting the Altamira cave, N. Spain: quantitative approach to wall-corrosion (solutional etching) processes induced by visitors. Sci Total Environ 244:67–84

Schouten S, Huguet C, Hopmans E, Kienhuis MVM, Sinninghe Damsté JS (2007) Analytical methodology for TEX(86) paleothermometry by high-performance liquid chromatograhy/atmospheric pressure chemical ionization-mass spectrometry. Anal Chem 79:2940–2944

Šebela S, Turk J (2011) Local characteristics of Postojna cave climate, air temperature, and pressure monitoring. Theoret Appl Climatol 105:371–386

Smerdon JE, Stieglitz M (2006) Simulated heat transport of harmonic temperature signals in the Earth's shallow subsurface: lower-boundary sensitivities. Geophys Res Lett 33:L14402

Smerdon JE, Pollack HN, Cermak V, Enz JW, Krel M, Safanda J, Wehmiller JF (2006) Daily, seasonal, and annual relationships between air and subsurface temperatures. J Geophys Res 111:D07101

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

Wigley TML (1967) Non-steady flow through a porous medium and cave breathing. J Geophys Res 72:3199–3205

Wigley TML, Brown MC (1971) Geophysical applications of heat and mass transfer in turbulent pipe flow. Bound Layer Meteorol 1:300–320

Wigley TML, Brown MC (1976) The physics of caves. In: Ford TD, Cullingford CHD (eds) The science of speleology. Academic Press, London, pp 329–358

Mihevc A, Prelovšek M, Zupan Haina N (2010) Introduction to the Dinaric Karst. Karst Research Institute ZRC SAZU, Postojna (Slovenia)

Moore GW, Sullivan GN (1978) Speleology: the study of caves. Zephyrus Press, Teaneck NJ (USA)

Palmer AN (2007) Cave geology. Cave books, Dayton OH (USA)

Yazaki T, Iwata Y, Hirota T, Kominami Y, Kawakata T, Yoshida T, Yania Y, Inoue S (2013) Influences of winter climatic conditions on the relation between annual mean soil temperature and air temperatures from central to northern Japan. Cold Reg Sci Technol 85:217–224