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Reconstruction of cave air temperature based on surface atmosphere temperature and vegetation changes: Implications for speleothem palaeoclimate records

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ABSTRACT

Cave temperature is a parameter of major importance for palaeoclimate studies based on speleothems since most proxies used are temperature-dependent. The general assumption that cave temperature reflects the mean annual surface atmosphere temperature (SAT) over the cave is based on a limited number of specific studies, and detailed mechanisms supporting this link are not properly described. Eagle Cave, in Spain, was used to understand the detailed mechanisms connecting SAT and cave temperature. A monitoring programme conducted from 2009 to 2011 allows the characterization of the thermal dynamics in the cave air. In the studied karstic environment thermal conduction is the main mechanism responsible for transferring the ground temperature signal to the cave. The calculated thermal diffusion coefficient is $0.756 \times 10^{-6} \pm 0.013$ m^2 s^{-1}. The SAT signal is recorded at the cave with a delay ranging from ~3 to 11 yr, depending on the thickness of the bedrock over the ceiling (5–18 m). A cave cooling of 2 °C has been recorded since mid-1970s, when cave temperature measurements were made. The application of a model exclusively based on thermal conduction of SAT does not reproduce the observed thermal changes. However, vegetation cover over the cave was modified dramatically during recent decades. This impacts ground temperature due to the changes in exposure to insolation and the modification of soil properties, which is eventually recorded in the cave. The incorporation of changes in vegetation cover in the model provides a realistic thermal reconstruction. The impact of vegetation cover was much more significant than SAT in order to explain the large thermal change in the cave over past decades. Thus, the cooling in Eagle Cave during past decades is mainly controlled by a variable decoupling from mean annual SAT as a result of the afforestation over the cave. The effect of this thermal decoupling on speleothem $\delta^{18}O$ records is potentially significant and should be considered when performing accurate palaeoclimate reconstructions.

1. Introduction

It is well known that many caves have a relatively stable temperature during the year in their sections away from the entrance (Moore, 1964). This cave air temperature has been related to the mean annual surface atmosphere temperature (SAT) at the exterior over the cave (Moore and Nicholas, 1964; Wigley and Brown, 1976; Moore and Sullivan, 1978). The implications of this link are of major importance for palaeoclimate studies on cave records since their archives have the potential to record low-frequency changes in SAT. Many proxies recorded in speleothems are dependent on cave temperature. This is the case for oxygen stable isotopes (Epstein et al., 1953), some trace elements (Huang and Fairchild, 2001; Fairchild and Treble, 2009), the growth rate (Dreybrodt, 1981; Baker et al., 1998), or some biomarkers, as the glycerol dialkyl glycerol tetraethers (Schouten et al., 2007). Thus, some speleothem records have been interpreted as affected by changes in cave temperature, and hence reflecting long term variations in SAT (e.g., Dorale et al., 1992; Lauritzen and Lundberg, 1999). The assumption of a connexion between SAT and cave

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temperature has also been incorporated in speleothem modelled proxies (e.g., Kaufmann, 2003; Oster et al., 2010). Additionally, the calibration of temperature-dependent proxies from speleothems with external climate has been conducted (e.g., Frisia et al., 2003; Treble et al., 2003; Mangini et al., 2005; Baker et al., 2007; Mattey et al., 2008; Cai et al., 2010; Jex et al., 2011). Regardless of whether the interpretation of a particular speleothem record is linked to SAT or any other climate/geochemical variable, thermally dependent proxies will be affected by the changes in cave temperature. Therefore, a decoupled and variable relation between mean annual SAT and cave temperature could affect the speleothem calibration and the proxy interpretation.

Despite the great importance of cave temperature for the interpretation of many speleothem proxies, there are a limited number of studies focused in the coupling of cave temperature and SAT (Perrier et al., 2005; Genty, 2008). Although there are some studies connecting cave temperature and SAT (e.g., Moore and Nicholas, 1964; Smithson, 1991), little attention has been paid to the mechanisms transferring the temperature signal to the cave, and the time that takes for the cave temperature to respond to changes in SAT. Lag times in the hydrology of the cave systems are already considered when transferring the external signals to the cave for calibration purposes (e.g., Jex et al., 2010) or in models (Baker and Bradley, 2010). However, the lag time between changes in SAT and its record in caves, as well as the impact that those changes would have on speleothem proxies, is still unexplored. Additionally, it is well known that ground temperature at the surface depends not only in SAT but on its vegetation cover (e.g., Munroe, 2012). Changes in vegetation cover over caves can be natural or anthropogenic in origin, and the process being gradual (e.g., afforestation) or rapid (e.g., fire). A decoupling of SAT and cave temperature as a result of changes in the vegetation cover was not previously identified.

In this paper we focus on Eagle Cave in central Spain. A decrease of cave air temperature of the order of ~2 °C since the mid-1970s allows us to investigate the causes of this temperature change and the transfer mechanisms into the cave. A thermal model was implemented to reconstruct the cave air temperature for the last decades accounting for SAT and vegetation cover changes, incorporating the lag times resulting for thermal transfer from the surface. Finally, a synthetic $\delta^{18}O$ speleothem record is presented to evaluate the impact of cave temperature changes related to variations in the vegetation cover.

2. Cave air and ground temperature: theoretical background

Temperature is an easily measurable parameter of cave microclimate (Cigna, 1961; Eraso, 1962; Moore, 1964). For most studied caves, the air temperature far from the entrance is relatively stable during the year (e.g., Moore and Sullivan, 1978). In the cave entrance, the external and inner cave temperatures interact along a certain relaxation length, whose extension depends on local cave factors as the dimensions of galleries, air velocity and flow regime (Wigley and Brown, 1971, 1976). For those caves in which sections far away from the entrance record non-stable temperatures during the year (e.g., annual variability >1 °C), the causes are usually related to the forced cave ventilation (e.g., Cropley, 1965; De Freitas and Littlejohn, 1987; Smithson, 1991; Pflitsch and Piasecki, 2003) or the thermal anomalies driven by water streams crossing the cave (Kranjc and Opara, 2002). It has been assumed that the stable temperature in caves is close to the mean annual SAT over the cave (Moore and Nicholas, 1964; Wigley and Brown, 1976; Moore and Sullivan, 1978). Thus, caves located at higher elevation and/or latitudes are normally cooler, in accordance with their mean annual SAT (Moore and Nicholas, 1964; Buecher, 1999). However, there are many exceptions to this general assumption, and caves out of thermal equilibrium with their relative mean annual SAT are common, having differences of several degrees, with the caves either cooler (Myers, 1962) or warmer than the mean annual SAT (Atkinson et al., 1983; Buecher, 1999). Causes for the thermal differences between cave and mean annual SAT are not very well understood, since complete thermal evaluation of cave systems are scarce (Luetscher et al., 2008). However, underground temperatures in karst and non-karst areas are also studied in anthropological cavities such as mines, quarries, tunnels, wine cellars (Perrier et al., 2001; Salve et al., 2008; Mazarrón and Cañas, 2009), or in borehole and soil temperature depth-logs (e.g., Pollack and Huang, 2000; Smerdon et al., 2006), providing further general knowledge about the underground thermal dynamics.

The underground temperature depends on the heat transferred. Apart from rare cases with a local radioactive heat source, for most sites the underground heat sources in the upper crust are the geothermal energy and the heat provided from the atmosphere at the surface (Pollack and Huang, 2000). In the case of caves, human or other organisms can provide additional sources of heat (e.g., Cigna, 1993). Additionally, due to the high humidity levels in caves, latent heat effects during phase changes modify the energy balance impacting cave temperature (De Freitas and Schmekal, 2003; Luetscher et al., 2008). The study of deep borehole and soil thermal profiles has demonstrated that the transfer of heat within the subsurface is mostly due to conduction (e.g., Pollack and Huang, 2000; Smerdon et al., 2006). The geothermal gradients are relatively constant for a specific region and typical values range from 2.5 to 5 °C/100 m (Anderson, 2005). Above a certain depth, generally ranging from 150 to 50 m (e.g., Stevens et al., 2008), the geothermal gradients are modified because of the progressive importance of the atmosphere at the surface as a heat source/sink. However, due to the high permeability of the limestone rocks, the karst terrains present a different thermal pattern. The geothermal heat is drained by the aquifers due to lateral advection, and unless in those aquifers with stagnant water or limited flow, has little or no impact on the unsaturated zone of the karst (Bögli, 1980; Anderson, 2005). Thus, the thermal gradient in the deep vadose sector of karst terrains reflects the impact of water percolation through the high permeability of the rock. Because of the friction of water along the flow path, the rock is progressively warmed with depth and the thermal gradient is typically 0.2–0.4 °C/100 m (Badino, 1995; Luetscher and Jeannin, 2004). This gradient is slightly lower than the range of adiabatic gradients on the atmosphere at the surface, and the temperature measured deep in the vadose zone of a karst massif is often cooler than that found in the surface at the same elevation (Badino, 2005).

Many caves record seasonality in their temperature records due to advection or conduction of the SAT signal (e.g., Sánchez-Moral, et al., 1999; Spötl et al., 2005; Boch et al., 2011). Seasonality due to advection normally causes sudden and sharp thermal changes which are related to cave ventilation that responds quickly to meteorological changes at the surface (e.g., Smithson, 1991; Pflitsch and Piasecki, 2003; Bourges et al., 2006). The contrasting air-density between the cave and the exterior due to thermal difference of the atmosphere environments may produce a dynamic ventilation regime in some caves, which imprints a thermal seasonality due to heat advection (e.g., De Freitas and Littlejohn, 1987). In these cases, high-frequency oscillations in temperature accompany the seasonal signature. The seasonal cycles that transport the external temperature signal through the rock by conduction have a very regular sinusoidal signal (e.g., Sánchez-Moral, et al., 1999; Buecher, 1999). The amplitude of the thermal seasonality is muted with depth and there is a phase shift in relation with the SAT, the deeper the site the larger is the signal delay (Labs, 1982;