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Sensitivity of Bunker Cave to climatic forcings highlighted through multi-annual monitoring of rain-, soil-, and dripwaters

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ABSTRACT

The last two decades have seen a considerable increase in studies using speleothems as archives of past climate variability. Caves under study are now monitored for a wide range of environmental parameters and results placed in context with speleothem data. The present study investigates trends from a seven year long monitoring of Bunker Cave, northwestern Germany, in order to assess the hydraulic response and transfer time of meteoric water from the surface to the cave. Rain-, soil-, and dripwater were collected from August 2006 to August 2013 at a monthly to bimonthly resolution and their oxygen and hydrogen isotope composition was measured. Furthermore, drip rates were quantified. Due to different drip characteristics, annual mean values were calculated for the drip rates of each drip site. Correlations of the annual mean drip rate of each site with precipitation and infiltration demonstrate that the annual infiltration, and thus the annual precipitation control the inter-annual drip-rate variability for all except one site. The hydraulic response is not delayed on an annual basis. All drip sites display identical long-term trends, which suggests a draining of a common karst reservoir over these seven years of monitoring. Correlations of soil- and dripwater monthly $\delta^{18}O$ and δD values with atmospheric temperature data reveal water transfer times of 3 months to reach a depth of 40 cm (soilwater at site BW 2) and 4 months for 70 cm depth (soilwater at site BW 1). Finally, the water reaches the cave chambers (15 to 30 m below land surface) after ca. 2.5 years. Consequently, a temporal offset of 29 to 31 months (ca. 2.5 years) between the hydraulic response time (no time lag on annual basis) and the water transfer time (time lag of 29 to 31 months) was found, which is negligible with regard to Bunker Cave speleothems because of their slow growth rates. Here, proxies recording precipitation/infiltration and temperature are registered on a decadal scale. Variations in drip rate and thus precipitation and infiltration are recorded by $\delta^{13}C$ and Mg/Ca ratios in speleothem calcite. Speleothem $\delta^{18}O$ values reflect both temperature and precipitation signals due to drip rate-related fractionation processes. We document that long-term patterns in temperature and precipitation are recorded in dripwater patterns of Bunker Cave and that these are linked to the North Atlantic Oscillation (NAO).

1. Introduction

Palaeoclimate reconstructions based on speleothems, i.e. mostly carbonate deposits formed in caves, have increased significantly during the last two decades (for a summary, see Fairchild and Baker, 2012). The most important strengths of speleothems are the precise $^{230}Th/U$ dating (e.g., Dorale et al., 2004; Scholz and Hoffmann, 2008; Cheng et al., 2013) and the availability of several, mostly geochemical, parameters such as carbon and oxygen isotope values, major and trace elemental abundances, and $\delta^{18}O$ and δD of fluid inclusions (e.g., Niggemann et al., 2003; Mangini et al., 2005; Vonhof et al., 2006; Fohlmeister et al., 2012; Scholz et al., 2012; Luetscher et al., 2015). These can be used for single- or multi-proxy approaches to reconstruct past climate dynamics.

In order to gain a better understanding of the processes influencing geochemical proxies in the soil and epikarst zone, as well as processes acting during deposition of speleothems, sophisticated monitoring programmes have been established (e.g., Spötl et al., 2005; Mattey et al., 2008b, 2016; Riechelmann et al., 2011, Wassenburg et al., 2013; Genty et al., 2014; van Rampelbergh et al., 2014, Breitenbach et al., 2015; Treble et al., 2016). In the context of these efforts, cave air temperature, pCO_2 and humidity, drip rate, as well as the isotopic

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composition of rain-, soil- and dripwater and the element concentrations of soil-, and dripwater have been recorded. Furthermore, in order to link the dripwater with speleothems used for palaeoclimate reconstructions, recent cave carbonate precipitates have been investigated in combination with their respective dripwater composition and the hydraulic regime in the cave (e.g., Miorandi et al., 2010; Tremaine et al., 2011; Riechelmann et al., 2013, 2014).

Most monitoring studies focused on seasonal variations of the above-mentioned parameters, whereby, for example, the drip rate was analysed to study the response to rainfall events or the hydrological connection of the drip sites (Baker et al., 1997; Mattey et al., 2008b; Riechelmann et al., 2011). The analysis of dripwater $\delta^{18}O$ and δD values shows either seasonal variations (Mattey et al., 2008a, Breitenbach et al., 2015) or rather stable values close to the annual mean of rainwater (Riechelmann et al., 2011; van Rampelbergh et al., 2014). Seasonal variations in cave dripwater reflect a fast transfer of the water (e.g., Breitenbach et al., 2015). The lack of an intra-annual pattern points to strong mixing in the epikarst and/or the vadose zone with transfer times between the soil and the cave drip site in excess of one year (e.g., Riechelmann et al., 2011; van Rampelbergh et al., 2014). Financial constraints, accessibility, or lack in manpower commonly limit monitoring studies to durations of a few years or less. Thus far, only a very limited number of studies focused on multi-annual trends of the monitored parameters and implications for speleothem research (Genty and Deflandre, 1998; Treble et al., 2013; Genty et al., 2014, Breitenbach et al., 2015; Mattey et al., 2016). To the knowledge of the authors, only the study by Genty et al. (2014) detrended the seasonal signal in order to gain insights in potential longer-term (>5 yrs) trends. This is of significance as particularly the longer-term trends are relevant for the assessment of proxy data from speleothems recording decadal or longer variability only.

This paper documents and discusses observations of precipitation/infiltration and drip rate as well as atmospheric temperature and the oxygen and hydrogen isotopic composition of rain-, soil-, and cave dripwater from a seven year-long monitoring campaign in Bunker Cave in northwestern Germany. The main goals of the present study are: (i) to quantify the longer-term (multi-annual) variability of the environmental parameters; (ii) to assess the response time of the carbonate precipitating drip sites to these parameters; (iii) to identify signal smoothing and possible alteration processes during percolation through the epikarst; and (iv) to draw, where possible, general implications for speleothem research.

2. Climate and cave parameters

The climate of northwestern Germany is warm-temperate, i.e. fully humid (equally distributed rainfall amount throughout the year) with warm summers (Kottek et al., 2006). Bunker Cave is located between the villages of Iserlohn and Letmathe in the Rhenish Slate Mountains in the NW part of the Sauerland, Germany (Fig. 1). It is part of the Bunker-Emst-Cave system (3.5 km long) with the Bunker Cave entrance (51°22′N, 07°40′E) being located at 184 m above sea level (asl) on a south-facing hill slope of the Dröscheder Emst karst plateau (Grebe, 1993; Hammerschmidt et al., 1995).

The host rock consists of Middle to Upper Devonian massive limestone (von Kamp, 1972). The rock overburden of the cave is between 15 and 30 m (Grebe, 1993) and the host rock is overlain by ca. 70 cm inceptisol to alfisol (USDA Soil Taxonomy). The colour varies between dark and yellowish brown (10YR 3/3 and 10YR 5/6) for the upper soil layers and bright reddish brown to bright brown (5YR 5/8 to 7.5YR 5/8) for the lower layer (Munsell soil colour charts). The vegetation above the cave consists of deciduous forest (mainly ash and beech trees) and scrubs (Riechelmann et al., 2011). Bedding dips to the north or northwest (von Kamp and Ribbert, 2005) and water percolates mainly along fractures and bedding planes. This feature and the fact that Bunker Cave is located in a south-facing hill reduce the effective catchment of the cave dripwater to a few hundred m^2. Furthermore, the Dröscheder Emst karst plateau is partly used as a residential area and ca. 15 to 20% of the catchment area is anthropogenically sealed. Furthermore, a railway route runs above the cave.

3. Materials and methods

3.1. Monitoring and sample collection of rain-, soil- and dripwater

The monitoring programme performed in and above Bunker Cave ran from August 2006 to August 2013. Rainwater samples were collected with a rain gauge according to the DIN 58666C norm on the roof of the German Cave Museum Iserlohn (51°22′N, 07°38′E; 175 m asl), located 1.5 km from Bunker Cave (Fig. 1). Rainfall amount was measured and sampled daily and collected as monthly samples between 2007 and 2012. In 2013, rainwater samples were collected only bimonthly. Rainwater samples were stored in PET bottles in a fridge to minimize evaporation.

Two soilwater sampling sites were installed above Bunker Cave. The soilwater suction probes were manufactured by Umwelt-Geräte-Technik GmbH (UGT, Germany). One probe (BW 1) was installed at a depth of 70 cm and water was sampled monthly between 2007 and 2011. The second probe (BW 2) sampled water at 40 cm depth in monthly intervals between 2009 and 2011. In 2012 and 2013, both soilwater sites were sampled only bimonthly.

In total, five drip sites (TS 1, TS 2, TS 3, TS 5 and TS 8; Fig. 2) were monitored in Bunker Cave from 2006 to 2013. Sampling at drip site TS 8 started in 2007. Drip sites TS 1 and TS 5 are located in chamber 1. All other sites are located in chamber 2 of Bunker Cave (Fig. 2). Dripwater samples were integrated over one month in order to obtain sufficient volumes of water for multi-proxy geochemical analyses. These monthly samples were taken between 2006 and 2011, while bimonthly samples

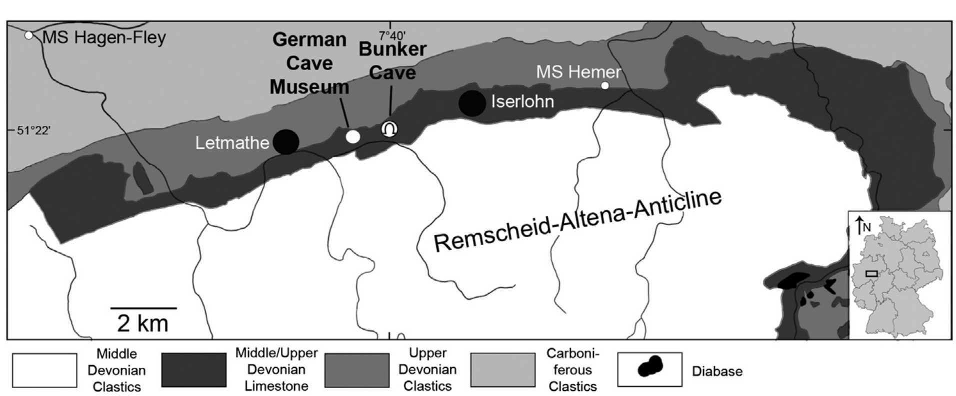

Fig. 1. Geological map of the northern Rhenish Slate Mountains in northwestern Germany. Locations of Bunker Cave, German Cave Museum Iserlohn and the meteorological stations (MS) Hagen-Fley and Hemer are shown (modified after Riechelmann et al., 2011).

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