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

Article Type: Research paper

Keywords: drip rate; infiltration; temperature; oxygen and hydrogen isotopes; NAO; cave microclimate monitoring

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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, western 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. 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 delta18O and deltaD values with atmospheric temperature data reveal water transfer times of 3 months for soilwater at site BW 2 (40 cm depth) 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. Variations in drip rate and thus, precipitation and infiltration are recorded by delta13C and Mg/Ca ratios in speleothem calcite. Speleothem delta18O 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).

Dear Dr. Böttcher,

Please find below our response to the reviewers. We would like to emphasize that we greatly appreciate the helpful and constructive comments of the two reviewers. Their work certainly led to an improved version of our paper. In the following, detailed answers to the individual comments are provided.

Reviewer #1: Overview - This study involves an analysis of oxygen and hydrogen isotopic values in precipitation, soil water, and cave dripwater, as well as calculations of infiltration systematics and measurements of dripwater activity. The overarching goal is to better understand the response time and degree of mixing/alteration of isotopic signals between the land surface and the cave. Once these processes are constrained, speleothems can then be used most effectively to reconstruct paleoenvironmental change and thereby linked to climatic phenomena such as the NAO.

Aside from the fact that paper too often reads as a laundry list of observations, I have two major concerns. The first, as I note below, might be due to my inexperience working with vadose zone hydraulics, but involves the calculation of infiltration RATES without knowing antecedent moisture conditions and hydraulic head. Perhaps I simply missed it, but I see only calculations of permeability. I am more than happy to have my mistake pointed out to me by the authors in the revision. In any case, this section must be more carefully and fully fleshed out before it can be considered for publication. In the hydro literature, entire manuscripts are devoted to calculating infiltration rates but here it seemingly appears out of thin air next to a permeability determination. Why not just let the isotopes speak for themselves? Forget the permeability calculations and just focus on what the geochemistry of the drips vs precip tells you. The paper would be more concise and would contain less arm-waiving.

Our reply: We thank the reviewer for this constructive comment. The calculation of the coefficient of permeability (k_f) is a very simplified approach to calculate the transfer time through the soil. This approach ignores many important factors, which influence the infiltration of water in the soil. Therefore, we follow the suggestion of the reviewer and focus on the isotopes. As a consequence all text sections regarding the k_f value and the transfer time calculated by it are deleted.

Second, I know that there are numerous studies showing offsets between d18O values of drips collected at the same time in the same room of the same cave. Likewise, variations in d13C in drips can be ascribed to PCP, but how do you substantially alter the d18O of infiltrating water by PCP? Evaporation could do it, but the dD/d18O relationships suggest no evap is occurring.

Our reply: Due to statistical artifacts, we were led on the wrong path. We re-calculated all correlations with the monthly data as suggested by the second reviewer and our original conclusion that PCP alters the $\delta^{18}O$ signal is thus invalid. We apologize for this. These parts were completely rewritten.

Line 32 - "dripwater were"

Our reply: Done (line 32).

35 - commas used incorrectly. Edit as follows: "…infiltration, and thus the annual precipitation, control …"

Our reply: Done (line 37).

39 - what is BW2? Is this a specific sample? A location? A depth? A soil classification (B horizon…?)

Our reply: We clarified this part (lines 40-43) and wrote: “Correlations of soil- and dripwater monthly $\delta^{18}O$ and δD values with atmospheric temperature data reveal water transfer times of 3 months for soilwater at site BW 2 (40 cm depth) and 4 months for 70 cm depth (soilwater at site BW 1). “

40 - am I interpreting this correctly? Your estimates are that water takes up to 6 months to infiltrate 40 cm into the soil?!? What sort of soil is this? If it's fine-grained, I would have thought that capillarity alone would draw water down much faster than this.

Our reply: This issue has been solved. See first main comment.

41 - this must mean that the water moves much, much faster once it enters the epikarst. How

deep is the cave below landsurface? Below soil/bedrock interface? This should be mentioned here. So far, the abstract has been a little jumpy and hard to follow.

Our reply: We added the information about the depth of the cave chambers below landsurface as suggested (line 43).

42 - is this a consistent offset? Is it worth mentioning the magnitude or nature of this offset here in the abstract?

Our reply: It is a consistent offset and we added the magnitude of it in the abstract (line 44).

44 - repeating the word "due" is awkward

Our reply: This sentence is deleted. See second main comment.

44 - I will be interested to read how you know that PCP is to blame; I think of PCP as influencing d13C but not necessarily O because the oxygen reservoir is so much larger than that of C.

Our reply: See second main comment.

45 - since O is affected by not H, it can't be evaporation, but I don't see (yet) how PCP can influence the d18O signal so profoundly.

Our reply: See second main comment.

49 - this abstract is a little choppy. Adding a little more information to tie the narrative together would help the reader understand the point of the study and would make for a more fluid discussion.

Our reply: Due to changes according to the first and second main comment and the main comments of the second reviewer, the abstract was partly rewritten.

53 - perhaps write "(for a summary, see Fairchild and Baker, 2012)"

Our reply: Done (lines 57-58).

54 - I suggest using either "Th/U" or "230Th/234U" but don't mix and match

Our reply: ^{230}Th/U is an established notation. See for example Scholz and Hoffmann (2008). We keep it as it is (line 59).

55 - "many, largely geochemical, parameters, " is awkwardly worded

Our reply: We replaced “many, largely” by “several, mostly” (line 60).

57 - use "major" rather than "main"

Our reply: Done (line 61).

60 - remove first use of "e.g."

Our reply: This part was rewritten and the e.g. was deleted.

73 - Do you mean to state that there have been studies on the elemental composition of rain water? I am surprised by this.

Our reply: We apologize for this confusing sentence. There are no studies on the elemental composition of rainwater in the study area. We rewrote the sentence to state this correctly (lines 69-72).

74 - this is the major raison d'etre for the study: to better understand cave carbonate-based paleoenvironmental reconstructions through analysis of cave hydraulics. Make that point more clear in this sentence.

Our reply: We rewrote the sentence as the reviewer suggested: “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" (lines 72-75).

79 - it may be preference only, but I suggest adding the word "values" after "d18O" or "dD".

Our reply: Done (line 80).

83 - is "whilst" the correct word here? Are you actually contrasting the Breitenbach study/interpretation with that of Riechelmann? The way it's written, it seems like both authors refer to the same cave system.

Our reply: We deleted "whilst" and included two sentences to clarify this matter (lines 83-86).

87 - "focused" is misspelled

Our reply: Corrected (line 88).

92 - don't use "relevant" twice in the same sentence

Our reply: We replaced the first "relevant" by "of significance" (line 93).

94 - "This paper"

Our reply: Done (line 95).

97 - "main goals of the present study"

Our reply: Done (line 98).

97 - longer than what? Be specific here. Multi-annual? Decadal?

Our reply: We added "multi-annual" after "longer-term" (line 99).

98 - what the "environmental parameters"? Temp? Precip? Be specific.

Our reply: We modified lines 95 to 96 to clarify this.

101 - delete this last sentence. It is redundant with (iv).

Our reply: Done.

103 - Here at the end of the Introduction, I think the first paragraph is a bit of a detour and suggest shortening it considerably and integrating it into the second paragraph.

Our reply: We shortened the first paragraph and put it together with the second one as suggested by the reviewer (lines 56-64).

106 - what does "fully humid" mean?

Our reply: Fully humid means there is no dry season, but equally distributed rainfall throughout the whole year. We used the Köppen-Geiger climate classification world map updated by Kottek et al. (2006). Nevertheless, we added a short explanation in brackets (lines 106-107).

109 - include 1 s.d. values of mean annual precip.

Our reply: Due to minor relevance of this information regarding the interpretation and discussion of our paper, we deleted the paragraph and Figure 2.

111 - include 1 s.d. values of MAAT

Our reply: Due to minor relevance of this information regarding the interpretation and discussion of our paper, we deleted the paragraph and Figure 2.

114 - you don't need to tell the reader it is colder in winter than in summer; delete this sentence

Our reply: Done.

120 - do we have any estimates of percent land surface covered by houses, roads, parking lots, sidewalks, etc? These are obviously important components of infiltration hydrology.

Our reply: The information was added as requested (lines 123-124).

123 - I am not sure "brown" is appropriate here. What about Munsell soil chart codes?
123 - I would write " loamy soil formed in loess"

Our reply: We added the colours of the soil according to the Munsell soil chart code and defined the soil according to USDA Soil Taxonomy (lines 115-118).

126 - "… and subordinate along bedding planes" sounds awkward. I think you are missing a word in this phrase.

Our reply: We deleted “subordinate along”.

138 - how was rainwater stored between (bi)monthly sample collection visits? What methods were utilized to minimize evaporation?

Our reply: We wrote “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.” to clarify this (lines 133-136).

145 - I suggest hyphenating TS-1, etc.

Our reply: In order to keep the consistency with all other Bunker Cave studies, which examined the same drip sites, we prefer not to change the labelling of the sample sites.

160 - since you are converting to volumetric discharge, write the equation in the standard form as volumetric discharge (ml/time) = drip rate (drips/time) x volume/drip (ml/drips)

Our reply: Done (line 158).

165 - what is an "instantaneous water sample" and how do you know the drip volume?

Our reply: An instantaneous water sample is collected during the monitoring tour, therefore the exact time of collection is known. The drip volume was determined as described in the previous sentence. In order to clarify this we added this information (lines 163-164).

176 - delete hyphen

Our reply: Done (lines 175 and 178).

176 - I assume this means ±0.09‰?

Our reply: We added "±" (lines 175 and 178).

183 - "(Fig. 1) - Hagen-Fley … and Hemen (…) - were used…"

Our reply: Done (lines 182-184).

191 - is 13:00 a time of day?

Our reply: We replaced it by "1 p.m." (lines 190 and 195).

194 - this equation needs to be referenced to its original author

Our reply: Done (line 191).

198 - "equation was used"

Our reply: Done (line 197).

203 - ok but weather station on top of the cave would have been better

Our reply: The reviewer is right. The perfect solution would be a weather station directly above the cave, where precipitation amount and temperature are measured. Unfortunately, we did not have this luxury and therefore use the temperature data being from the nearest meteorological station 15 km away. Precipitation was collected at the German Cave Museum only 1.5 km from Bunker Cave (subchapter 3.1 lines 131-133).

215 - how were the soil samples collected? Please include methodology. If soils were compacted during collection, then their permeability would have been decreased.

Our reply: This issue has been solved. See first main comment.

216 - is "loam" the formal particle size distribution (e.g., silty clay loam) or a more generic term?

Our reply: This issue has been solved. See first main comment.

223 - As I recall, permeability (k) is fluid-specific, whereas hydraulic conductivity (K) is permeability specifically dealing with water. Is there a reason that k is chosen over K here?

Our reply: This issue has been solved. See first main comment.

246 - combine some of the short, choppy sentences that begin this paragraph

Our reply: Done (line 246 ff.).

251 - is the negative supposed to be in front of 171? How do you have negative infiltration? Does this mean potential ET was greater than precip by that amount? That's a very dry year in Germany.

Our reply: Yes, the negative is supposed to be in front of 171, see also Figure 4. 2003 was an exceptional dry year. Mean annual ET was greater than the precipitation amount and thus resulted in a negative infiltration and a dry year in this part of Germany (lines 232-233).

252 - you have already defined the acronym MAAT so use it here rather than redefining it

Our reply: Done (line 235).

253 - I find the word "whilst" to be distracting. I suggest replacing it in all case with "while"

Our reply: Done.

299 - "akin" means "similar" but isn't really correctly used in this sentence. Replace with "similar"

Our reply: This sentence has been deleted.

311 - sections 4.1 - 4.3 involve a largely mundane play-by-play of observations. Perhaps it will read better when juxtaposed to the figures on the journal page, but as it stands now, it is difficult to follow (or care about) without knowing what the point of all this is. The paper needs to include a better introduction to each section (or at least each major section) to provide a road map to the reader about what information is about to learned and why it is important and how it fits into the overall narrative of the study. For example, it is interesting and important to note that the drip sites mostly show similar trends over time, but why is this important to the study?

Our reply: We apologize for the problems pointed out by the reviewer. We added information regarding why these results are of importance at the beginning of the results section (lines 217-222). Furthermore, the individual sections were shortened or rewritten (see also the second main comment of the second reviewer).

316 - the abbreviation "i.e." is overused in this manuscript and is inappropriate here.

Our reply: This section was deleted. See first main comment.

320 - I am missing something here, and I recognize that it is likely rooted in my own lack of understanding of this topic, but infiltration is not solely a function of permeability. This is just one of several factors that drive infiltration. The others are the depth of ponded water (that provides the head) and the antecedent moisture (saturation state) of the soil. It is unclear to me how these infiltration rate calculations were calculated.

Our reply: This section was deleted. See first main comment.

329 - I am not exactly sure what is meant by "hydrologically connected" but at least they have similar hydraulic properties (orientation, number and size of fractures, matrix hydraulic conductivity, etc.).

Our reply: We rewrote the sentence to “these sites are characterized by similar hydrological properties” (line 300).

330 - drips don't respond to a "pattern", but instead they respond to some type of forcing, most likely a climatic one. Please reword.

Our reply: We agree with the reviewer and rewrote the sentence: “…respond to the same environmental (climate) forcing.” (lines 301-302).

353 - or it might not…

Our reply: We agree with the reviewer. That is why we used the word “might”. The correlations are possibly affected but not necessarily. We rewrote the sentence slightly to “…, which might affect the correlation” (line 326).

453 - I would like to see a citation to a study in which PCP is shown to noticeably alter d18O values. It's effects should be concentrated in the d13C value given that the carbon reservoir in infiltrating fluids is much, much smaller than the oxygen reservoir.

Our reply: This part has been deleted. See second main comment and first main comment of the second reviewer.

Notes on Figures.

Figures, 4, 6, and 7 - I can't distinguish between errors bars for different points (triangles vs circles) in some portions of a few panels (TS5 and BW1, as examples).

Our reply: We changed colors to better distinguish the error bars.

Reviewer #2: This is a nice study that presents the synthesis of a seven years of monitoring in Bunker Cave, NW-Germany. Even if it is already published, I think that a complete figure with all the monthly data is necessary here so that we can appreciate the seasonality of the rainfall d18O and the more or less stability of the dripping cave water. This cave is a specific site that is covered by a thick soil which slows down the rainfall infiltration but this is not the main reason and the important result in this study is certainly the quite long time (up to 3 years) that meteoric water takes to reach the cave galleries. This is an important result that highlights the importance of a long monitoring in order to understand the infiltration processes and for this reason it merits publication.

However there are two major points that needs more explanations and/or different interpretations:

1) I am not convinced by the fact that prior calcite precipitation (PCP) changes the d18O composition of seepage water because the molecule quantity of water containing oxygen is much more important than HCO3- ions that are involved in the calcite precipitation. Moreover, that fact that there is no difference between instantaneous and monthly collected water is in contradiction of a PCP influence on the d18O. PCP which is likely seasonal in most sites, would then produce differences between summer and winter dripping waters (?). I suggest that the authors check this possibility by measuring Mg/Ca and Sr/Ca and doing Ca-Mg/Ca and Ca-Sr/Ca graphs. This is an important point on which all the work that is (and was) done on fluid inclusions depends;

Our reply: Statistical artifacts led to a misinterpretation of the data. We apologize for that. Thus, the original interpretation that PCP alters δ^{18}O is invalid. The respecting passages have been deleted and rewritten. See also second main comment by the first reviewer. Furthermore, we followed the suggestion by the reviewer and present the monthly data of δ^{18}O and δD of rain-, soil- and dripwater.

2) In the results part, you have to explain clearly, in the main text, how you calculate the d18O annual means : what limits did you take , month of beginning and month of end . Please explain how you choose these limits. Also, you have to precise the months during which the infiltration occurs (winter and spring? part of Fall or most of the year). But, the way used to calculate the mean d18O of rainwater is already an interpretation because it is calculated on ONE year. It could be actually much more or less; you may find this by doing weighted averaging from month to month (in the past) until reaching the d18O value of the dripping site. Finally, considering the surface air temperature as a proxy of the d18O seems hazardous unless you have strong correlations between T and rainwater d18O.

Our reply: At the beginning of the results section we added information on the calculation of the annual mean values. Furthermore, we added the time of main infiltration in lines 233-234. We followed the reviewer's suggestion to use the monthly values to calculate the water transfer time. However, since the GNIP stations are far away from the study site and δ^{18}O and δD values of rain water of the monitoring only cover the monitoring period, we used the atmospheric temperature of the close-by meteorological stations. The reviewer is correct by pointing out that this approach is only feasible, when δ^{18}O and δD of rainwater show a strong correlation with T. Since this is the case as we pointed out in section 4.1 lines 253-256 (citing Riechelmann et al., 2011) and section 5.2 lines 368-369, we consider this approach as valid. According to this new approach results (4.3) and interpretation and discussion (5.2) sections were rewritten.

Detailed comments:

About references: when speaking about generalities, I think that it would be better to refer to precise studies that marked the topics. For example, line 56 and elsewhere, instead of referring to the nice book of Fairchild and Baker 2012, it would be better to refer to Cheng et al. or Hellstrom et al. or other specialists in U-Th that really worked on the topics; the same for other subjects; otherwise the Fairchild and Baker book will be referred in all cases.

Our reply: We replaced the Fairchild and Baker citation by other studies.

Lines 58-59 : what drove this choice of references ? If it is a globally important like results on speleothem stable isotopes, you may cite Cheng et al. 2016 Nature which presents an unprecedented well dated 600ka speleothem record; you may also focus on more regional studies.

Our reply: The choice of references should be representative for the region. Therefore, we cite original studies from western central Europe. We feel that the Cheng et al. (2016) study, being focused on the Asian monsoon, is not appropriate here (lines 62-63).

Lines 90-91 : I do not entirely agree that nobody before detrended the seasonal signal. In their work on Villars and Chauvet caves, Genty et al. (GCA 2014) made rainfall averaging on several years (up to > 10 yrs) which is a real long term analysis.

Our reply: We corrected this (line 91).

Lines 101-102 : not necessary in an article

Our reply: This sentence was deleted.

Lines 153-155 : don't you think that the fact that there is no difference between instantaneous and monthly collected water is in contradiction of a PCP influence on the d18O ? PCP which is likely seasonal in most sites, would then produce differences between summer and winter dripping waters (?).

Our reply: The reviewer is right. PCP does not alter $\delta^{18}O$ in Bunker Cave. See also first main comment.

Line 194 : dealing with temperatures, I guess that it is 273 instead 237 (?)

Our reply: This value is correct (237; line 193).

Lines 293-295 : this sentence is not clear to me

Our reply: The sentence was rewritten (lines 282-283).

Lines 351-353 : I entirely agree with this. Do you have any idea of the duration, in the year, of the real infiltration ? Or, what are the months, in the year, during which the rainfall infiltrate ? You may find this by doing weighted averaging from month to month (in the past) until reaching the d18O of the dripping site.

Our reply: We added the information of infiltration time in this paragraph (lines 324-326).

In summary, these were constructive reviews, which provided helpful suggestions for improvement of this manuscript that we submit as a revised version.

Sincerely

Sylvia Riechelmann on behalf of the authors.

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

Sylvia Riechelmann[a,*], Andrea Schröder-Ritzrau[b], Christoph Spötl[c], Dana Felicitas Christine Riechelmann[d], Detlev Konrad Richter[a], Augusto Mangini[b], Norbert Frank[b], Sebastian F.M. Breitenbach[a] and Adrian Immenhauser[a]

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Chemical Geology

Keywords: drip rate, infiltration, temperature, oxygen and hydrogen isotopes, NAO, cave microclimate monitoring

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, western 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. 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 for soilwater at site BW 2 (40 cm depth) 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. 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 δ^{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 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 (> 5yrs) 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 reduces 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 were taken between 2012 and 2013. An exception is drip site TS 1, where sufficient water could be collected during each visit. Dripwater first dripped onto a drip counter placed in a plastic box and was then transferred into a closed bottle via tubing to minimize CO_2 degassing and potential evaporation. Comparison of instantaneous and monthly collected water revealed similar $\delta^{18}O$ values, confirming that fractionation processes due to evaporation are negligible (Riechelmann et al., 2011). For further details of the monitoring, the reader is referred to Riechelmann (2010) and Riechelmann et al. (2011; 2012a; 2013; 2014).

Drip rates were measured manually with a stopwatch. The following equation was used to convert drip rate into volumetric discharge (*z*):

$$z\ [\text{ml/time}] = \text{drip rate [drips/time]} * V\ [\text{ml/drips}] \qquad (1)$$

where *V* is the volume of each drip. The volume of a drip was determined by a defined collection time, the total amount of water and the drip rate (in drips per min). In some cases, the drip rate at site TS 8 was not quantified by means of a stopwatch, and was instead calculated via the amount of an instantaneous water sample (collected during the monitoring tour) and the known drip volume (determined as described above). Furthermore, drip rates were measured automatically by acoustic drip counters (Stalagmate; Mattey and Collister, 2008), which were placed under drip sites TS 2 (2009-2013), TS 3 (2010-2013), TS 5 (2007-2013) and TS 8 (2009-2013).

3.2 $\delta^{18}O$ and δD of rain-, soil- and dripwater

The oxygen and hydrogen isotopic compositions of all water samples were determined at the University of Innsbruck. Water samples were collected in small, airtight glass vials without headspace. The oxygen isotope composition was analysed using a ThermoFinnigan DELTA^{plus}XL mass spectrometer connected with a Gasbench II using the CO_2 equilibrium technique. The 1σ reproducibility of the $\delta^{18}O$ values is ±0.09 ‰ VSMOW (Spötl et al., 2005). The hydrogen isotope composition was measured using a ThermoFinnigan DELTA^{plus}Advantage equipped with a TC/EA high-temperature pyrolysis unit. The 1σ reproducibility is ±1 ‰ VSMOW.

3.3 Evapotranspiration and infiltration

Instrumental climate data of two nearby meteorological stations (Fig. 1) - Hagen-Fley (51°25'N, 07°29'E; 100 m asl; 2000-2007; www.dwd.de) and Hemer (51°23'N, 07°45'E; 200 m asl; 2008-2013; www.meteomedia.de) - were used to calculate the evapotranspiration after Haude (1955) using the following equation:

$$E_{pot}\ [\text{mm/day}] = x\ [\text{mm/day} * \text{hPa}] * P^{13}\ [\text{hPa}] * (1 - (F^{13}\ [\%] / 100)) \qquad (2)$$

where E_{pot} is the potential evaporation, x represents the monthly coefficient depending on vegetation, P^{13} is the saturation pressure at 1 p.m. and F^{13} is the relative humidity at 1 p.m.. The saturation pressure was calculated using the Magnus-formula:

$$P^{13}\ [\text{hPa}] = 6.107\ [\text{hPa}] * 10\text{^}((7.5 * T^{13}\ [°\text{C}]) / (237 + T^{13}\ [°\text{C}])) \qquad (3)$$

T^{13} is the air temperature at 1 p.m.. Equations 2 and 3 were used to calculate the amount of water which can potentially infiltrate (Inf_{pot}) into the soil and thus, into the cave. Therefore, the following equation was used:

$$Inf_{pot}\ [\text{mm/day}] = N\ [\text{mm/day}] - E_{pot}\ [\text{mm/day}] \qquad (4)$$

where *N* is precipitation. The amount of water infiltrating into the soil above Bunker Cave was determined using precipitation data from the German Cave Museum Iserlohn.

3.4 GNIP stations

Data of four nearby GNIP (Global Network of Isotopes in Precipitation; http://www-naweb.iaea.org/napc/ih/IHS_resources_gnip.html) stations were used for comparison with monitoring and meteorological data. These include Bad Salzuflen (52°06'N, 08°43'E; 100 m asl), Emmerich (51°49'N, 06°36'E; 43 m asl), Koblenz (50°21'N, 07°34'E; 97 m asl) and Wasserkuppe Rhön (50°30'N, 09° 57'E; 921 m asl).

4. Results

Seasonally resolved monitoring data of rain-, soil- and dripwater of Bunker Cave were partly published by Immenhauser et al. (2010), Kluge et al. (2010, 2013), Riechelmann et al. (2011, 2012a, b, 2013, 2014), Fohlmeister et al. (2012), Münsterer et al. (2012), and Wackerbarth et al. (2012). In this study, we present monthly data as well as annual mean values of the relevant parameters, which were calculated using the monthly or bimonthly values of the respective year to (i) examine long-term variability and (ii) compare these data with precipitation/infiltration and temperature data to determine the hydraulic response time and water transfer time. Annual means were obtained from monthly data (January to December).

4.1 Precipitation, infiltration, temperature and rainwater $\delta^{18}O$ and δD

For this study, the time period from 2000 to 2013 is considered. Annual mean values are shown for all years except 2013, since monitoring stopped in August of this year. Hence, all mean values for 2013 are related to this time interval. Furthermore, annual mean values for 2006 were not calculated, due to insufficient data. The lowest annual precipitation sum (720 mm) was recorded in 2003, without considering 2013 with the lowest precipitation sum of 447 mm. The highest annual rainfall (1202 mm) and the highest mean annual infiltration (546 mm) occurred in 2007 (Fig. 3A). The lowest annual mean infiltration was observed in 2003 (-171 mm). Infiltration at Bunker Cave is lower during summer months than during winter (Riechelmann et al., 2011). Monthly temperature data show low values in winter and high ones during summer. The lowest mean annual air temperature (7.1°C) was observed in 2010, while the highest (11.3°C) was observed twice, in 2000 and 2007 (Fig. 3A).

Oxygen and hydrogen isotope values of monthly rainwater samples display a seasonal variability with higher values during summer and lower ones during winter months (Fig. 3B). In the years 2010 and 2013, the lowest mean annual δ^{18}O and δD values of rainwater were observed (δ^{18}O: -9.20 and -9.01‰; δD: -66.2 and -62.5‰), while the highest mean annual values were observed in 2011 (δ^{18}O: -5.92‰; δD: -45.8‰; Fig. 3B). Monthly δ^{18}O and δD values of rainwater are highly correlated ($r = 0.98$, $p < 0.001$; $n = 65$; see also Fig. 4C).

Since monthly rainwater samples collected during the monitoring do not cover the same time period as the monthly samples from the GNIP stations, mean annual values are used here for comparison. Mean annual oxygen and hydrogen isotope values of rainwater collected at the German Cave Museum correlate well with those of nearby GNIP stations (Figs. 4A, B). The Local Meteoric Water Line (LMWL) of the rainwater (Fig. 4C) is close to that of the GNIP station Bad Salzuflen ($\delta D = 7.72 * \delta^{18}O + 5.7$; $r = 0.98$; Stumpp et al., 2014). Thus, rainwater collected during the monitoring period reflects the climate conditions of western Germany. The slope of 7.72 is close to that of the Global Meteoric Water Line (8), indicating insignificant evaporation of the collected samples (Gat et al., 2000). Since all dripwater data plot on the LMWL (Fig. 4C) evaporation in the soil, epikarst and cave generates no significant imprint on their corresponding isotope values. Furthermore, both isotope systems depend on the regional surface air temperature and the isotopic composition of Bunker Cave dripwater reflects the infiltration weighted mean annual $\delta^{18}O$ and δD values of rainwater (Riechelmann et al., 2011).

4.2 Drip rate

Due to different drip characteristics of the different drip sites (ranging from seepage flow to seasonal drip; Riechelmann et al., 2011; Appendix S1 and Fig. 8), annual mean drip rates were calculated and their long-term variability compared. Both manually and automatically obtained mean annual drip rates show the same trends (Fig. 5). Sites TS 1, TS 2 and TS 5 show a decreasing trend in mean drip rates over the monitoring period, which is also reflected in cross-correlations of mean annual drip rates at these sites (TS 1 vs. TS 2: $r = 0.82$; TS 1 vs. TS 5: $r = 0.85$; TS 2 vs. TS 5: $r = 0.88$; $p_{all} \leq 0.02$, $n_{all} = 7$). The annual mean drip rate at site TS 3 correlates only with the annual mean drip rate at site TS 2 within the 95% confidence level ($r = 0.81$) and with TS 1 ($r = 0.79$) and TS 5 ($r = 0.72$) just below the 95% confidence level ($n_{all} = 6$). However, it can be assumed that the annual mean drip rate at site TS 3 follows the same trend as sites TS 1, 2 and 5. At drip site TS 8 a similar annual mean drip rate was observed in 2008 and 2009 before drip rates increased until 2011, followed by a decreasing trend. Drip rate of drip site TS 8 does not show any significant correlation with any other drip rate.

4.3 $\delta^{18}O$ and δD of soil- and dripwater

Seasonal trends are difficult to identify for soilwater, because of lack of data (no water), especially summer months. An exception is soilwater at site BW 1 which yielded a complete time series from 2007 to 2008. There, higher $\delta^{18}O$ and δD values occur during summer/autumn months, while lower values are observed in winter/spring months (Fig. 6). The lowest mean annual $\delta^{18}O$ and δD values occurred in 2010 and 2011 for both soilwaters, while the highest values are shown in 2007 and 2008 (Fig. 6). Monthly $\delta^{18}O_{BW1}$ values are significantly correlated with $\delta^{18}O_{BW2}$ values (Table 1). The same can be observed for δD (Table 2).

Seasonal trends in $\delta^{18}O$ and δD of dripwaters are minor, but most pronounced for water at site TS 1. In general, lower isotope values occur in summer, while higher values are observed in winter (Fig. 6). Correlations between $\delta^{18}O$ and δD values of monthly samples of the same site are significant for all dripwaters and both soilwater samples ($r \geq 0.44$; $p < 0.001$; $n \geq 21$). All dripwaters share similarities in their oxygen and hydrogen isotopic composition as shown by positive cross-correlations (Tables 1 and 2). Mean annual values display the overall trend for $\delta^{18}O$ and δD, which is similar for all drip sites considering the errors (Fig. 6). Oxygen and hydrogen isotope values increased until 2009, reached a plateau and decreased around 2012. This trend is less distinct for dripwater at site TS 8 (Fig. 6).

5. Interpretation and Discussion

5.1 Constraints on the hydraulic response time

The positive correlations of mean annual drip rates of all sites except TS 8 (Fig. 5) suggests that: (i) these sites are characterized by similar hydrological properties (Baker et al., 1997), and (ii) the drip rates of these sites most likely respond to the same environmental (climate) forcing. According to Riechelmann et al. (2011), no drip site showed a direct response to rainfall events, but rather a lagged response of up to several months due to slowly increasing hydrological pressure in the karst reservoir above the cave. Correlations between drip rates and precipitation and infiltration during the preceding years based on monitoring and meteorological data of the stations Hagen-Fley and Hemer were used to determine the response time of mean annual drip rates to mean annual precipitation and infiltration. The correlation coefficients (*r*) between drip rate and infiltration show that the mean annual drip rates at TS 1 and TS 3 are controlled by mean annual infiltration of the same year, as observed for other cave systems (Fig. 7A; Genty and Deflandre, 1998; Baker et al., 2000; Miorandi et al., 2010; Tremaine and Froelich, 2013). Correlation coefficients at drip sites TS 2 and 5 are close to the 95% confidence level. Since the infiltration amount is controlled by precipitation amount and temperature (water loss due to evapotranspiration), correlations between mean annual drip rate and annual precipitation amount were calculated (Fig. 7B). Positive correlations at the 95% confidence level were found for TS 2 and TS 3 for the same year interval, while correlation coefficients of TS 1 and 5 are just below the 95% confidence level. Several sources of error must be considered, however, which lead to a lack of correlation at the 95% confidence level. Lack of data (< 12 for annual means) may be the problem in case of drip site TS 5, since neither infiltration nor precipitation correlate at the 95% confidence level with drip rate. This might also be the case for sites TS 1 and 2. The calculated mean annual drip rate of the former might be biased, since it shows pronounced seasonal drip rate variability, with most changes not being covered by the monitoring (Figs. 5 and S1 in supplementary material). Finally, the calculated mean annual infiltration in the soil reflects the *potential* rather than *effective* infiltration. Furthermore, it must be kept in mind that effective infiltration is biased towards winter (Wackerbarth et al., 2010; Riechelmann et al., 2011), which might affect the correlation.

A decrease of the drip rate was already observed for two other drip sites and TS 2 in Bunker Cave for the first three years as reported in Riechelmann et al. (2011). As shown here, this trend continued (Fig. 5), i.e. the reservoir was drained further during the seven years. This might be due to relatively dry years with low infiltration at the beginning of the century. The following years (2007 to 2010) with higher infiltration most likely did not fill the reservoir sufficiently to stop the draining and afterwards infiltration decreased again (2011 to 2013; Fig. 3A).

The mean annual drip rate at site TS 8 shows a significant positive correlation with mean annual infiltration with a lag of three years, but no significant correlation near the 95% confidence level with precipitation. Drip site TS 8 is the only site, whose drip rate does not show the same trends as the other sites and also lacks a correlation with infiltration and precipitation for the interval recorded by the other drip sites. This absence of any correlation might be due to a change in drip behaviour during the monitoring period.

The drip characteristics of all drip sites, plotted according to Smart and Friederich (1987) and Baker et al. (1997; see Figs. 8 and S1 in supplementary material to this paper) highlight minor variability, with more or less the same drip characteristics over time. Drip behaviour changed drastically at TS 8 during the monitoring period (Fig. 8): while seasonal drip characteristics prevailed in 2008 and 2009, this drip shows seepage flow behaviour between 2010 and 2012. Possible reasons for this change in drip characteristics include: (i) the flow paths and the reservoir behaviour in the epikarst underwent changes as a result of strongly variable rainfall events (Tooth and Fairchild, 2003), (ii) the flow paths of percolating water changed or became blocked due to prior calcite precipitation (PCP; Fairchild et al.,

2006) occluding the flow paths of water; (iii) the overhanging stalactite was broken off (earthquake, human interference etc.) resulting in drip parameter changes (Baldini et al., 2006). Amongst these scenarios, it is conceivable that rainfall filled the reservoir feeding TS 8 to a threshold resulting in a more continuous water flow into the cave. PCP is a more likely explanation for the change in drip behaviour as documented for this site (Riechelmann et al., 2011). The stalactite was removed in June 2008, but the change in drip rate lagged by one year, suggesting that the drip pattern was not controlled by the stalactite and thus the third option mentioned above is considered unlikely. Concluding, the drip rate at site TS 8 is controlled by infiltration and hence rainfall, but the dripwater signal reflecting both of these parameters is strongly affected by prior calcite precipitation in the aquifer. Although the catchment of the cave is partly sealed, infiltration and thus the precipitation signal can still be recognized in the drip rate.

5.2 Constraints on the water transfer time

Water transfer times from the surface to the cave are highly variable and range from days to several years not only for different caves but also for different drip sites in a given cave (e.g., Kaufmann et al., 2003; Mattey et al., 2008b, Lambert and Aharon, 2010; Treble et al., 2013; Genty et al., 2014, Breitenbach et al., 2015). Here, the dependency of rainwater δ^{18}O and δD on temperature (δ^{18}O *versus* T: $r = 0.73$; δD *versus* T: $r = 0.68$; $n_{both} = 67$; $p_{both} < 0.001$; Riechelmann et al., 2011) is used to quantify the water transfer time. Correlation coefficients (*r*) between δ^{18}O and δD of soil- and dripwater with surface air temperature were calculated using data of the meteorological stations Hagen-Fley and Hemer. To this end, monitoring data were correlated with temperature data of preceding years. Since rainwater

$\delta^{18}O$ and δD values correlate positively with temperature, only positive correlations are relevant to determine the water transfer time.

Monthly $\delta^{18}O$ and δD values of soilwater site BW 1 at 70 cm correlate significantly with the atmospheric temperature with a lag of four months (Fig. 9). In case of soilwater site BW 2 a significant correlation was found using a three months lag (40 cm; Fig. 9). However, gaps in the monthly soilwater data during dry summer months limit the significance of these calculations and they should therefore be treated with caution. Thus, this is also resulting in other highly significant correlations at 63 months lag time in case of BW 2. Since $\delta^{18}O$ and δD values of soilwater correlate significantly with atmospheric temperature at both sites, and monthly $\delta^{18}O$ and δD values also correlate for both soilwater sites, we conclude that water isotopes are not or only slightly altered by processes in the soil zone such as evaporation and uptake of biogenic CO_2 into the water (e.g., Lachniet, 2009). Thus, the temperature dependency of rainwater is preserved in the $\delta^{18}O$ and δD values of soilwater above Bunker Cave.

Because dripwater at site TS 1 was collected as an instantaneous sample, the $\delta^{18}O$ and δD values are not representative for the whole month as is the case for the other dripwaters. Therefore, calculations with monthly data were only performed for all other drip sites resulting in a lag of 29 to 31 months (Fig. 10). Difficulties occurred for TS 2, TS 3, and TS 8 in case of correlations using $\delta^{18}O$. There, the highest correlations are found between 41 and 66 months and only slightly lower ones are observed for a lag of 29 to 31 months. Calculations using δD of all drip sites except TS 2 and $\delta^{18}O$ for TS 5 do not show these features, which are most likely due to different mixing of the younger and older water in the reservoir as a consequence of different transfer times. Variability in the transfer times between different drip sites may arise due to: (i) variable thickness of the soil layer above

Bunker Cave, and (ii) differential thickness of the host rock overlying the cave, as well as (iii) differential lengths and types of individual flow paths (e.g., Tooth and Fairchild, 2003). The water retention capacity of soil is another factor that may or may not lead to an admixture waters with different residence time in the soil and epikarst zone (Hölting and Coldewey, 2013). Following dry periods, the portion of older water in the soil increases (Kottek et al., 2006) and the opposite is found during more humid periods. Although, rainfall is equally distributed throughout the year, infiltration is not, as it is lower during summer than during winter months (Wackerbarth et al., 2010; Riechelmann et al., 2011). Thus, water retention capacity might have a small effect on water transfer times at Bunker Cave sulphate and nitrate data show that dripwaters at sites TS 1 and TS 5 have shorter residence times compared to sites TS 2, 3, and 8 (Riechelmann et al., 2011). This might explain why both δ^{18}O and δD correlations with temperature performed well for TS 5. Drip water at TS 2 appears to be the site with the longest and strongest buffering in the epikarst zone. In contrast to most others this site displays seepage flow characteristics (see Appendix S1) and the oldest age based on tritium data (Riechelmann et al., 2012a). This pattern might explain why the correlations at this site are weakest. However, the shift in correlations using δD compared to the other drip sites (Fig. 10) remains insufficiently explained. Since δ^{18}O and δD values of dripwater at site TS 1 correlate with those of all other drip sites it can be assumed that the TS 1 water has a similar transfer time of 29 to 31 months.

The results shown here suggest that the dripwater transfer time at all monitored drip sites in Bunker Cave ranges between 29 to 31 months (ca. 2.5 years). This is in good agreement with tritium data, suggesting a transfer time of 2-4 years (±1 year; Kluge et al., 2010). The tritium-based estimates, however, represent mixing ages of younger infiltrating water and older water of the epikarst reservoir (Kluge et al., 2010; Riechelmann et al., 2012a).

Based on the fact that all dripwaters plot on the LMWL, alteration of δ^{18}O and δD values are excluded and hence, both retain the temperature signal of rainwater.

Summing up, the multi-annual monitoring programme at Bunker Cave sheds light on the complex processes affecting water transfer times. Obviously, a short-term monitoring program would fail to resolve these patterns.

5.3 Influence of the North Atlantic Oscillation on the climate in western Germany

The North Atlantic Oscillation (NAO) regulates Northern Hemisphere climate variability and particularly so in western Europe and eastern North America (e.g., Marshall et al., 2001; Visbeck et al., 2001; Baldini et al., 2008; Hurrell and Deser, 2010; Langebroek et al., 2011; Pinto and Raible, 2012; Trouet et al., 2012; Wassenburg et al., 2013, 2016; Comas-Bru et al., 2013). The NAO index is defined as the difference of sea-level pressure between the Icelandic Low and the Azores High (Hurrell, 1995; Wanner et al., 2001). While the sea-level pressure pattern is present throughout the year, it is most pronounced during winter (Wanner et al., 2001; Pinto and Raible, 2012). Thus, most often the winter (December to March) NAO index is used when studying climatic variability in the North Atlantic realm (Proctor et al., 2000; Trouet et al., 2009; Baker et al., 2015). During a negative NAO mode, the winter in Europe is dominated by cold and dry conditions, while during a positive NAO mode, mild and humid conditions prevail (Fig. 11A; Hurrell and van Loon, 1997; Marshall et al., 2001). This NAO-temperature link is reflected in δ^{18}O of precipitation (Baldini et al., 2008; Mischel et al., 2015; Comas-Bru et al., 2016) and thus can be reconstructed using suitably sensitive speleothems.

To quantify the effect of the NAO on regional weather and climate, precipitation and temperature records of the GNIP stations Bad Salzuflen, Emmerich, Koblenz, Wasserkuppe

Rhön, and the meteorological stations Hagen-Fley and Hemer were averaged for the months December to March. December-March average NAO index values (NAO_{DJFM}) were calculated using data provided by the Koninklijk Nederlands Meteorologisch Instituut (KNMI; http://www.knmi.nl/). Both precipitation amount ($r \geq 0.36$, $p \leq 0.05$, $n \geq 19$, except Hemer) and temperature ($r \geq 0.58$, $p \leq 0.03$, $n \geq 5$; except Wasserkuppe/Rhön) correlate significantly with the NAO_{DJFM} for most stations (Fig. 11). Thus, precipitation amount and temperature above Bunker Cave are affected by the NAO during winter months. Since both parameters are imprinted on drip rate and the dripwater isotope composition, it is possible to reconstruct NAO variability using proxy time-series from speleothems of Bunker Cave. As the precipitation in this region is equally distributed throughout the year, substantial summer precipitation between April to November – despite evapotranspiration – may weaken the imprint of the winter NAO signal on speleothems (Mischel et al., 2015). However, studies by Baldini et al. (2008) and Comas-Bru et al. (2016) show that many Central European regions are sensitive to reconstruct NAO variability. A moderate connection between $\delta^{18}O$ and NAO variability has also been detected for Herbstlabyrinth-Adventshöhle in Central Germany (Mischel et al., 2015), supporting the notion that speleothems from these caves record NAO variability.

With short residence times of <3 years and limited signal smoothing in the overlying epikarst, Bunker Cave proves to be a sensitive site for high-resolution proxy reconstructions of past climate dynamics under the influence of North Atlantic atmospheric circulation. The links between Bunker Cave hydrology and the NAO found in this study are consistent with the interpretation brought forward by previous workers (Fohlmeister et al., 2012; Wassenburg et al., 2016).

5.4 Wider implications of the present data set for speleothem research in general

In case of Bunker Cave, Mg/Ca ratios as well as $\delta^{13}C$ values depend on drip rate and thus, on precipitation and infiltration amount (Riechelmann et al., 2011, 2013; Fohlmeister et al., 2012). Therefore, both proxies are well-suited for reconstructions of precipitation and NAO variability.

Disentangling air temperature based on speleothem $\delta^{18}O$ is a more complex task. There is a clear temperature signal in dripwater $\delta^{18}O$ of all drip sites. This temperature signal of speleothem $\delta^{18}O$, however, is altered by (drip rate-related) fractionation processes during calcite precipitation in the cave (Riechelmann et al., 2013). In the case of speleothem $\delta^{18}O$ in Bunker Cave, variations in both parameters (precipitation and temperature) are recorded (Fohlmeister et al., 2012). A proxy not recorded in speleothem calcite but in dripwater is δD showing a well-defined temperature signal. Fluid inclusions extracted from speleothems could be used to quantify δD and $\delta^{18}O$ of the original dripwater and to constrain past temperature changes (McGarry et al., 2004; van Breukelen et al., 2008; Affolter et al., 2015). Given that the temperature pattern is unaltered in dripwater $\delta^{18}O$, fluid inclusions $\delta^{18}O$ and δD analyses should allow for the reconstruction of past temperature variability from speleothems in Bunker Cave and thus, variations of NAO strength.

The most striking observation of the present study is the difference between hydraulic response time, i.e. immediate drip rate response (<1 year; Fig. 7), and the transfer time of water from the soil to the cave (ca. 2.5 years; Fig. 10). While drip rate response to annual precipitation occurs without significant lag on (sub-)annual basis, the temperature signal is delayed by up to 2.5 years. Thus, the precipitation and temperature signals recorded by different proxies in speleothems are not fully synchronous. In case of Bunker Cave this delay is negligible, because here speleothems record proxies on decadal rather than annual or seasonal scales (Riechelmann et al., 2011; Fohlmeister et al., 2012). Such proxy biases to either water transfer or hydraulic response time must be considered in (sub-)annual reconstructions, and where the signal transfer times for both parameters differ.

6. Conclusions

The seven year-long monitoring of hydrological parameters in and above Bunker Cave, NW Germany, provides unprecedented insights into processes influencing δ^{18}O and δD in dripwater and speleothems that cannot be resolved with shorter-term monitoring programmes. The results of this study aim at quantifying the most relevant processes that may alter isotope proxies in Bunker Cave speleothems over time scales of several years:

1. Inter-annual drip rate dynamics are controlled by annual infiltration and thus, annual precipitation. No lag of the hydraulic response time is observed at annual resolution.
2. Water transfer time is 3 months for a 40 cm-thick soil layer and 4 months for a 70 cm-thick soil. It takes approximately 2.5 years for meteoric water to reach the cave chambers.
3. Neither oxygen nor hydrogen isotopes of dripwaters are altered and hence, record the temperature signal of meteoric precipitation. As a consequence, δ^{18}O and δD from fluid inclusions in speleothems are genuine temperature proxies at this site.
4. Temperature and precipitation during winter months (December-March) are significantly influenced by the NAO. Hence, long-term NAO variations are recorded in speleothems from northwestern Germany.
5. Monitoring data reveal a difference between the hydraulic response time and the water transfer time. This, however, does not affect the proxy interpretation of speleothems from this cave, because of their slow growth rate. But, with regard to other caves, especially

with seasonally to annually resolved speleothems, this time offset may lead to difficulties regarding the interpretation of various proxy data.

6. This study provides insights into multi-annual processes operating in cave depositional environments that are of relevance in speleothem research and can serve as a template for other cave monitoring programmes.

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Figure Captions

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).

Fig. 2 Plan view of Bunker Cave with the locations of drip sites TS 1 and TS 5 in chamber 1 and TS 2, TS 3 and TS 8 in chamber 2 (modified after Scheudoschi and Hasenkamp in Scheudoschi, 2007).

Fig. 3 Monthly values of temperature as well as rainwater oxygen and hydrogen isotope data and mean annual values of precipitation, infiltration, temperature as well as rainwater oxygen and hydrogen isotope data. A) Precipitation data from 2000 to 2006 of the meteorological station (MS) Hagen-Fley and data from 2007 to 2013 measured during this study at the German Cave Museum Iserlohn. Temperature data from 2000 to 2007 were provided by the MS Hagen-Fley and 2008 to 2013 by the MS Hemer. Infiltration data are calculated using data of both meteorological stations. B) Rainwater oxygen and hydrogen isotope data measured from the rain sampled at the German Cave Museum Iserlohn.

Fig. 4 A) Comparison of mean annual oxygen isotope data of four GNIP stations with rainwater data collected during this study. B) Comparison of mean annual hydrogen isotope data of four GNIP stations with rainwater data collected in this study. C) Local meteoric water line (LMWL) of the rainwater and position of the dripwaters on the LMWL (small box).

Fig. 5 Mean annual drip rates in Bunker Cave. Both manual and automatic drip rate data are shown.

Fig. 6 Monthly and mean annual oxygen and hydrogen isotope data of soil- and dripwaters.

Fig. 7 A) Correlation coefficients between mean annual drip rate and annual infiltration. B) Correlation coefficients of mean annual drip rate with annual precipitation. Note the offset to obtain the hydraulic response time of the reservoir to precipitation and infiltration.

Fig. 8 Drip characteristics of drip site TS 8 according to Smart and Friederich (1987) and Baker et al. (1997). Data from 2013 are not displayed as they do not cover the whole year.

Fig. 9 Correlation coefficients of monthly $\delta^{18}O$ and δD values with atmospheric temperature for both soilwater sites BW 1 and BW 2.

Fig. 10 Correlation coefficients between the monthly $\delta^{18}O$ and δD values of all dripwaters and atmospheric temperature.

Fig. 11 A) NAO index for December to March calculated for the period 1975-2013 (http://www.knmi.nl/). B) Precipitation data of the GNIP and meteorological stations for December to March for the period 1975-2013. C) Temperature data of the GNIP and meteorological stations for December to March for the period 1978-2013.

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

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Keywords: drip rate, infiltration, temperature, oxygen and hydrogen isotopes, NAO, cave microclimate monitoring

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, western 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. 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 for soilwater at site BW 2 (40 cm depth) 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. 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 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 (> 5yrs) 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 reduces 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 were taken between 2012 and 2013. An exception is drip site TS 1, where sufficient water could be collected during each visit. Dripwater first dripped onto a drip counter placed in a plastic box and was then transferred into a closed bottle via tubing to minimize CO_2 degassing and potential evaporation. Comparison of instantaneous and monthly collected water revealed similar $\delta^{18}O$ values, confirming that fractionation processes due to evaporation are negligible (Riechelmann et al., 2011). For further details of the monitoring, the reader is referred to Riechelmann (2010) and Riechelmann et al. (2011; 2012a; 2013; 2014).

Drip rates were measured manually with a stopwatch. The following equation was used to convert drip rate into volumetric discharge (z):

$$z \text{ [ml/time]} = \text{drip rate [drips/time]} * V \text{ [ml/drips]} \qquad (1)$$

where V is the volume of each drip. The volume of a drip was determined by a defined collection time, the total amount of water and the drip rate (in drips per min). In some cases, the drip rate at site TS 8 was not quantified by means of a stopwatch, and was instead calculated via the amount of an instantaneous water sample (collected during the monitoring tour) and the known drip volume (determined as described above). Furthermore, drip rates were measured automatically by acoustic drip counters (Stalagmate; Mattey and Collister, 2008), which were placed under drip sites TS 2 (2009-2013), TS 3 (2010-2013), TS 5 (2007-2013) and TS 8 (2009-2013).

3.2 $\delta^{18}O$ and δD of rain-, soil- and dripwater

The oxygen and hydrogen isotopic compositions of all water samples were determined at the University of Innsbruck. Water samples were collected in small, airtight glass vials without headspace. The oxygen isotope composition was analysed using a ThermoFinnigan DELTA^{plus}XL mass spectrometer connected with a Gasbench II using the CO_2 equilibrium technique. The 1σ reproducibility of the $\delta^{18}O$ values is ±0.09 ‰ VSMOW (Spötl et al., 2005). The hydrogen isotope composition was measured using a ThermoFinnigan DELTA^{plus}Advantage equipped with a TC/EA high-temperature pyrolysis unit. The 1σ reproducibility is ±1 ‰ VSMOW.

3.3 Evapotranspiration and infiltration

Instrumental climate data of two nearby meteorological stations (Fig. 1) - Hagen-Fley (51°25’N, 07°29’E; 100 m asl; 2000-2007; www.dwd.de) and Hemer (51°23’N, 07°45’E; 200 m asl; 2008-2013; www.meteomedia.de) - were used to calculate the evapotranspiration after Haude (1955) using the following equation:

$$E_{pot}\ [\text{mm/day}] = x\ [\text{mm/day * hPa}] * P^{13}\ [\text{hPa}] * (1 - (F^{13}\ [\%] / 100)) \qquad (2)$$

where E_{pot} is the potential evaporation, x represents the monthly coefficient depending on vegetation, P^{13} is the saturation pressure at 1 p.m. and F^{13} is the relative humidity at 1 p.m.. The saturation pressure was calculated using the Magnus-formula:

$$P^{13}\ [\text{hPa}] = 6.107\ [\text{hPa}] * 10\text{^}((7.5 * T^{13}\ [°\text{C}]) / (237 + T^{13}\ [°\text{C}])) \qquad (3)$$

T^{13} is the air temperature at 1 p.m.. Equations 2 and 3 were used to calculate the amount of water which can potentially infiltrate (Inf_{pot}) into the soil and thus, into the cave. Therefore, the following equation was used:

$$Inf_{pot}\ [\text{mm/day}] = N\ [\text{mm/day}] - E_{pot}\ [\text{mm/day}] \qquad (4)$$

where N is precipitation. The amount of water infiltrating into the soil above Bunker Cave was determined using precipitation data from the German Cave Museum Iserlohn.

3.4 GNIP stations

Data of four nearby GNIP (Global Network of Isotopes in Precipitation; http://www-naweb.iaea.org/napc/ih/IHS_resources_gnip.html) stations were used for comparison with monitoring and meteorological data. These include Bad Salzuflen (52°06'N, 08°43'E; 100 m asl), Emmerich (51°49'N, 06°36'E; 43 m asl), Koblenz (50°21'N, 07°34'E; 97 m asl) and Wasserkuppe Rhön (50°30'N, 09° 57'E; 921 m asl).

4. Results

Seasonally resolved monitoring data of rain-, soil- and dripwater of Bunker Cave were partly published by Immenhauser et al. (2010), Kluge et al. (2010, 2013), Riechelmann et al. (2011, 2012a, b, 2013, 2014), Fohlmeister et al. (2012), Münsterer et al. (2012), and Wackerbarth et al. (2012). In this study, we present monthly data as well as annual mean values of the relevant parameters, which were calculated using the monthly or bimonthly values of the respective year to (i) examine long-term variability and (ii) compare these data with precipitation/infiltration and temperature data to determine the hydraulic response time and water transfer time. Annual means were obtained from monthly data (January to December).

4.1 Precipitation, infiltration, temperature and rainwater $\delta^{18}O$ and δD

For this study, the time period from 2000 to 2013 is considered. Annual mean values are shown for all years except 2013, since monitoring stopped in August of this year. Hence, all mean values for 2013 are related to this time interval. Furthermore, annual mean values for 2006 were not calculated, due to insufficient data. The lowest annual precipitation sum (720 mm) was recorded in 2003, without considering 2013 with the lowest precipitation sum of 447 mm. The highest annual rainfall (1202 mm) and the highest mean annual infiltration (546 mm) occurred in 2007 (Fig. 3A). The lowest annual mean infiltration was observed in 2003 (-171 mm). Infiltration at Bunker Cave is lower during summer months than during winter (Riechelmann et al., 2011). Monthly temperature data show low values in winter and high ones during summer. The lowest mean annual air temperature (7.1°C) was observed in 2010, while the highest (11.3°C) was observed twice, in 2000 and 2007 (Fig. 3A).

Oxygen and hydrogen isotope values of monthly rainwater samples display a seasonal variability with higher values during summer and lower ones during winter months (Fig. 3B). In the years 2010 and 2013, the lowest mean annual δ^{18}O and δD values of rainwater were observed (δ^{18}O: -9.20 and -9.01‰; δD: -66.2 and -62.5‰), while the highest mean annual values were observed in 2011 (δ^{18}O: -5.92‰; δD: -45.8‰; Fig. 3B). Monthly δ^{18}O and δD values of rainwater are highly correlated ($r = 0.98$, $p < 0.001$; $n = 65$; see also Fig. 4C).

Since monthly rainwater samples collected during the monitoring do not cover the same time period as the monthly samples from the GNIP stations, mean annual values are used here for comparison. Mean annual oxygen and hydrogen isotope values of rainwater collected at the German Cave Museum correlate well with those of nearby GNIP stations (Figs. 4A, B). The Local Meteoric Water Line (LMWL) of the rainwater (Fig. 4C) is close to that of the GNIP station Bad Salzuflen ($\delta D = 7.72 * \delta^{18}O + 5.7$; $r = 0.98$; Stumpp et al., 2014). Thus, rainwater collected during the monitoring period reflects the climate conditions of western Germany. The slope of 7.72 is close to that of the Global Meteoric Water Line (8), indicating insignificant evaporation of the collected samples (Gat et al., 2000). Since all dripwater data plot on the LMWL (Fig. 4C) evaporation in the soil, epikarst and cave generates no significant imprint on their corresponding isotope values. Furthermore, both isotope systems depend on the regional surface air temperature and the isotopic composition of Bunker Cave dripwater reflects the infiltration weighted mean annual δ^{18}O and δD values of rainwater (Riechelmann et al., 2011).

4.2 Drip rate

Due to different drip characteristics of the different drip sites (ranging from seepage flow to seasonal drip; Riechelmann et al., 2011; Appendix S1 and Fig. 8), annual mean drip rates were calculated and their long-term variability compared. Both manually and automatically obtained mean annual drip rates show the same trends (Fig. 5). Sites TS 1, TS 2 and TS 5 show a decreasing trend in mean drip rates over the monitoring period, which is also reflected in cross-correlations of mean annual drip rates at these sites (TS 1 vs. TS 2: $r = 0.82$; TS 1 vs. TS 5: $r = 0.85$; TS 2 vs. TS 5: $r = 0.88$; $p_{all} \leq 0.02$, $n_{all} = 7$). The annual mean drip rate at site TS 3 correlates only with the annual mean drip rate at site TS 2 within the 95% confidence level ($r = 0.81$) and with TS 1 ($r = 0.79$) and TS 5 ($r = 0.72$) just below the 95% confidence level ($n_{all} = 6$). However, it can be assumed that the annual mean drip rate at site TS 3 follows the same trend as sites TS 1, 2 and 5. At drip site TS 8 a similar annual mean drip rate was observed in 2008 and 2009 before drip rates increased until 2011, followed by a decreasing trend. Drip rate of drip site TS 8 does not show any significant correlation with any other drip rate.

4.3 δ^{18}O and δD of soil- and dripwater

Seasonal trends are difficult to identify for soilwater, because of lack of data (no water), especially summer months. An exception is soilwater at site BW 1 which yielded a complete time series from 2007 to 2008. There, higher δ^{18}O and δD values occur during summer/autumn months, while lower values are observed in winter/spring months (Fig. 6). The lowest mean annual δ^{18}O and δD values occurred in 2010 and 2011 for both soilwaters, while the highest values are shown in 2007 and 2008 (Fig. 6). Monthly $\delta^{18}O_{BW1}$ values are significantly correlated with $\delta^{18}O_{BW2}$ values (Table 1). The same can be observed for δD (Table 2).

Seasonal trends in δ^{18}O and δD of dripwaters are minor, but most pronounced for water at site TS 1. In general, lower isotope values occur in summer, while higher values are observed in winter (Fig. 6). Correlations between δ^{18}O and δD values of monthly samples of the same site are significant for all dripwaters and both soilwater samples ($r \geq 0.44$; $p < 0.001$; $n \geq 21$). All dripwaters share similarities in their oxygen and hydrogen isotopic composition as shown by positive cross-correlations (Tables 1 and 2). Mean annual values display the overall trend for δ^{18}O and δD, which is similar for all drip sites considering the errors (Fig. 6). Oxygen and hydrogen isotope values increased until 2009, reached a plateau and decreased around 2012. This trend is less distinct for dripwater at site TS 8 (Fig. 6).

5. Interpretation and Discussion

5.1 Constraints on the hydraulic response time

The positive correlations of mean annual drip rates of all sites except TS 8 (Fig. 5) suggests that: (i) these sites are characterized by similar hydrological properties (Baker et al., 1997), and (ii) the drip rates of these sites most likely respond to the same environmental (climate) forcing. According to Riechelmann et al. (2011), no drip site showed a direct response to rainfall events, but rather a lagged response of up to several months due to slowly increasing hydrological pressure in the karst reservoir above the cave. Correlations between drip rates and precipitation and infiltration during the preceding years based on monitoring and meteorological data of the stations Hagen-Fley and Hemer were used to determine the response time of mean annual drip rates to mean annual precipitation and infiltration. The correlation coefficients (r) between drip rate and infiltration show that the mean annual drip rates at TS 1 and TS 3 are controlled by mean annual infiltration of the same year, as observed for other cave systems (Fig. 7A; Genty and Deflandre, 1998; Baker et al., 2000; Miorandi et al., 2010; Tremaine and Froelich, 2013). Correlation coefficients at drip sites TS 2 and 5 are close to the 95% confidence level. Since the infiltration amount is controlled by precipitation amount and temperature (water loss due to evapotranspiration), correlations between mean annual drip rate and annual precipitation amount were calculated (Fig. 7B). Positive correlations at the 95% confidence level were found for TS 2 and TS 3 for the same year interval, while correlation coefficients of TS 1 and 5 are just below the 95% confidence level. Several sources of error must be considered, however, which lead to a lack of correlation at the 95% confidence level. Lack of data (< 12 for annual means) may be the problem in case of drip site TS 5, since neither infiltration nor precipitation correlate at the 95% confidence level with drip rate. This might also be the case for sites TS 1 and 2. The calculated mean annual drip rate of the former might be biased, since it shows pronounced seasonal drip rate variability, with most changes not being covered by the monitoring (Figs. 5 and S1 in supplementary material). Finally, the calculated mean annual infiltration in the soil reflects the *potential* rather than *effective* infiltration. Furthermore, it must be kept in mind that effective infiltration is biased towards winter (Wackerbarth et al., 2010; Riechelmann et al., 2011), which might affect the correlation.

A decrease of the drip rate was already observed for two other drip sites and TS 2 in Bunker Cave for the first three years as reported in Riechelmann et al. (2011). As shown here, this trend continued (Fig. 5), i.e. the reservoir was drained further during the seven years. This might be due to relatively dry years with low infiltration at the beginning of the century. The following years (2007 to 2010) with higher infiltration most likely did not fill the reservoir sufficiently to stop the draining and afterwards infiltration decreased again (2011 to 2013; Fig. 3A).

The mean annual drip rate at site TS 8 shows a significant positive correlation with mean annual infiltration with a lag of three years, but no significant correlation near the 95% confidence level with precipitation. Drip site TS 8 is the only site, whose drip rate does not show the same trends as the other sites and also lacks a correlation with infiltration and precipitation for the interval recorded by the other drip sites. This absence of any correlation might be due to a change in drip behaviour during the monitoring period.

The drip characteristics of all drip sites, plotted according to Smart and Friederich (1987) and Baker et al. (1997; see Figs. 8 and S1 in supplementary material to this paper) highlight minor variability, with more or less the same drip characteristics over time. Drip behaviour changed drastically at TS 8 during the monitoring period (Fig. 8): while seasonal drip characteristics prevailed in 2008 and 2009, this drip shows seepage flow behaviour between 2010 and 2012. Possible reasons for this change in drip characteristics include: (i) the flow paths and the reservoir behaviour in the epikarst underwent changes as a result of strongly variable rainfall events (Tooth and Fairchild, 2003), (ii) the flow paths of percolating water changed or became blocked due to prior calcite precipitation (PCP; Fairchild et al.,

2006) occluding the flow paths of water; (iii) the overhanging stalactite was broken off (earthquake, human interference etc.) resulting in drip parameter changes (Baldini et al., 2006). Amongst these scenarios, it is conceivable that rainfall filled the reservoir feeding TS 8 to a threshold resulting in a more continuous water flow into the cave. PCP is a more likely explanation for the change in drip behaviour as documented for this site (Riechelmann et al., 2011). The stalactite was removed in June 2008, but the change in drip rate lagged by one year, suggesting that the drip pattern was not controlled by the stalactite and thus the third option mentioned above is considered unlikely. Concluding, the drip rate at site TS 8 is controlled by infiltration and hence rainfall, but the dripwater signal reflecting both of these parameters is strongly affected by prior calcite precipitation in the aquifer. Although the catchment of the cave is partly sealed, infiltration and thus the precipitation signal can still be recognized in the drip rate.

5.2 Constraints on the water transfer time

Water transfer times from the surface to the cave are highly variable and range from days to several years not only for different caves but also for different drip sites in a given cave (e.g., Kaufmann et al., 2003; Mattey et al., 2008b, Lambert and Aharon, 2010; Treble et al., 2013; Genty et al., 2014, Breitenbach et al., 2015). Here, the dependency of rainwater δ^{18}O and δD on temperature (δ^{18}O *versus* T: $r = 0.73$; δD *versus* T: $r = 0.68$; $n_{both} = 67$; $p_{both} < 0.001$; Riechelmann et al., 2011) is used to quantify the water transfer time. Correlation coefficients (r) between δ^{18}O and δD of soil- and dripwater with surface air temperature were calculated using data of the meteorological stations Hagen-Fley and Hemer. To this end, monitoring data were correlated with temperature data of preceding years. Since rainwater

$\delta^{18}O$ and δD values correlate positively with temperature, only positive correlations are relevant to determine the water transfer time.

Monthly $\delta^{18}O$ and δD values of soilwater site BW 1 at 70 cm correlate significantly with the atmospheric temperature with a lag of four months (Fig. 9). In case of soilwater site BW 2 a significant correlation was found using a three months lag (40 cm; Fig. 9). However, gaps in the monthly soilwater data during dry summer months limit the significance of these calculations and they should therefore be treated with caution. Thus, this is also resulting in other highly significant correlations at 63 months lag time in case of BW 2. Since $\delta^{18}O$ and δD values of soilwater correlate significantly with atmospheric temperature at both sites, and monthly $\delta^{18}O$ and δD values also correlate for both soilwater sites, we conclude that water isotopes are not or only slightly altered by processes in the soil zone such as evaporation and uptake of biogenic CO_2 into the water (e.g., Lachniet, 2009). Thus, the temperature dependency of rainwater is preserved in the $\delta^{18}O$ and δD values of soilwater above Bunker Cave.

Because dripwater at site TS 1 was collected as an instantaneous sample, the $\delta^{18}O$ and δD values are not representative for the whole month as is the case for the other dripwaters. Therefore, calculations with monthly data were only performed for all other drip sites resulting in a lag of 29 to 31 months (Fig. 10). Difficulties occurred for TS 2, TS 3, and TS 8 in case of correlations using $\delta^{18}O$. There, the highest correlations are found between 41 and 66 months and only slightly lower ones are observed for a lag of 29 to 31 months. Calculations using δD of all drip sites except TS 2 and $\delta^{18}O$ for TS 5 do not show these features, which are most likely due to different mixing of the younger and older water in the reservoir as a consequence of different transfer times. Variability in the transfer times between different drip sites may arise due to: (i) variable thickness of the soil layer above

Bunker Cave, and (ii) differential thickness of the host rock overlying the cave, as well as (iii) differential lengths and types of individual flow paths (e.g., Tooth and Fairchild, 2003). The water retention capacity of soil is another factor that may or may not lead to an admixture waters with different residence time in the soil and epikarst zone (Hölting and Coldewey, 2013). Following dry periods, the portion of older water in the soil increases (Kottek et al., 2006) and the opposite is found during more humid periods. Although, rainfall is equally distributed throughout the year, infiltration is not, as it is lower during summer than during winter months (Wackerbarth et al., 2010; Riechelmann et al., 2011). Thus, water retention capacity might have a small effect on water transfer times at Bunker Cave sulphate and nitrate data show that dripwaters at sites TS 1 and TS 5 have shorter residence times compared to sites TS 2, 3, and 8 (Riechelmann et al., 2011). This might explain why both δ^{18}O and δD correlations with temperature performed well for TS 5. Drip water at TS 2 appears to be the site with the longest and strongest buffering in the epikarst zone. In contrast to most others this site displays seepage flow characteristics (see Appendix S1) and the oldest age based on tritium data (Riechelmann et al., 2012a). This pattern might explain why the correlations at this site are weakest. However, the shift in correlations using δD compared to the other drip sites (Fig. 10) remains insufficiently explained. Since δ^{18}O and δD values of dripwater at site TS 1 correlate with those of all other drip sites it can be assumed that the TS 1 water has a similar transfer time of 29 to 31 months.

The results shown here suggest that the dripwater transfer time at all monitored drip sites in Bunker Cave ranges between 29 to 31 months (ca. 2.5 years). This is in good agreement with tritium data, suggesting a transfer time of 2-4 years (±1 year; Kluge et al., 2010). The tritium-based estimates, however, represent mixing ages of younger infiltrating water and older water of the epikarst reservoir (Kluge et al., 2010; Riechelmann et al., 2012a).

Based on the fact that all dripwaters plot on the LMWL, alteration of δ^{18}O and δD values are excluded and hence, both retain the temperature signal of rainwater.

Summing up, the multi-annual monitoring programme at Bunker Cave sheds light on the complex processes affecting water transfer times. Obviously, a short-term monitoring program would fail to resolve these patterns.

5.3 Influence of the North Atlantic Oscillation on the climate in western Germany

The North Atlantic Oscillation (NAO) regulates Northern Hemisphere climate variability and particularly so in western Europe and eastern North America (e.g., Marshall et al., 2001; Visbeck et al., 2001; Baldini et al., 2008; Hurrell and Deser, 2010; Langebroek et al., 2011; Pinto and Raible, 2012; Trouet et al., 2012; Wassenburg et al., 2013, 2016; Comas-Bru et al., 2013). The NAO index is defined as the difference of sea-level pressure between the Icelandic Low and the Azores High (Hurrell, 1995; Wanner et al., 2001). While the sea-level pressure pattern is present throughout the year, it is most pronounced during winter (Wanner et al., 2001; Pinto and Raible, 2012). Thus, most often the winter (December to March) NAO index is used when studying climatic variability in the North Atlantic realm (Proctor et al., 2000; Trouet et al., 2009; Baker et al., 2015). During a negative NAO mode, the winter in Europe is dominated by cold and dry conditions, while during a positive NAO mode, mild and humid conditions prevail (Fig. 11A; Hurrell and van Loon, 1997; Marshall et al., 2001). This NAO-temperature link is reflected in δ^{18}O of precipitation (Baldini et al., 2008; Mischel et al., 2015; Comas-Bru et al., 2016) and thus can be reconstructed using suitably sensitive speleothems.

To quantify the effect of the NAO on regional weather and climate, precipitation and temperature records of the GNIP stations Bad Salzuflen, Emmerich, Koblenz, Wasserkuppe

Rhön, and the meteorological stations Hagen-Fley and Hemer were averaged for the months December to March. December-March average NAO index values (NAO_{DJFM}) were calculated using data provided by the Koninklijk Nederlands Meteorologisch Instituut (KNMI; http://www.knmi.nl/). Both precipitation amount ($r \geq 0.36$, $p \leq 0.05$, $n \geq 19$, except Hemer) and temperature ($r \geq 0.58$, $p \leq 0.03$, $n \geq 5$; except Wasserkuppe/Rhön) correlate significantly with the NAO_{DJFM} for most stations (Fig. 11). Thus, precipitation amount and temperature above Bunker Cave are affected by the NAO during winter months. Since both parameters are imprinted on drip rate and the dripwater isotope composition, it is possible to reconstruct NAO variability using proxy time-series from speleothems of Bunker Cave. As the precipitation in this region is equally distributed throughout the year, substantial summer precipitation between April to November – despite evapotranspiration – may weaken the imprint of the winter NAO signal on speleothems (Mischel et al., 2015). However, studies by Baldini et al. (2008) and Comas-Bru et al. (2016) show that many Central European regions are sensitive to reconstruct NAO variability. A moderate connection between $\delta^{18}O$ and NAO variability has also been detected for Herbstlabyrinth-Adventshöhle in Central Germany (Mischel et al., 2015), supporting the notion that speleothems from these caves record NAO variability.

With short residence times of <3 years and limited signal smoothing in the overlying epikarst, Bunker Cave proves to be a sensitive site for high-resolution proxy reconstructions of past climate dynamics under the influence of North Atlantic atmospheric circulation. The links between Bunker Cave hydrology and the NAO found in this study are consistent with the interpretation brought forward by previous workers (Fohlmeister et al., 2012; Wassenburg et al., 2016).

5.4 Wider implications of the present data set for speleothem research in general

In case of Bunker Cave, Mg/Ca ratios as well as $\delta^{13}C$ values depend on drip rate and thus, on precipitation and infiltration amount (Riechelmann et al., 2011, 2013; Fohlmeister et al., 2012). Therefore, both proxies are well-suited for reconstructions of precipitation and NAO variability.

Disentangling air temperature based on speleothem $\delta^{18}O$ is a more complex task. There is a clear temperature signal in dripwater $\delta^{18}O$ of all drip sites. This temperature signal of speleothem $\delta^{18}O$, however, is altered by (drip rate-related) fractionation processes during calcite precipitation in the cave (Riechelmann et al., 2013). In the case of speleothem $\delta^{18}O$ in Bunker Cave, variations in both parameters (precipitation and temperature) are recorded (Fohlmeister et al., 2012). A proxy not recorded in speleothem calcite but in dripwater is δD showing a well-defined temperature signal. Fluid inclusions extracted from speleothems could be used to quantify δD and $\delta^{18}O$ of the original dripwater and to constrain past temperature changes (McGarry et al., 2004; van Breukelen et al., 2008; Affolter et al., 2015). Given that the temperature pattern is unaltered in dripwater $\delta^{18}O$, fluid inclusions $\delta^{18}O$ and δD analyses should allow for the reconstruction of past temperature variability from speleothems in Bunker Cave and thus, variations of NAO strength.

The most striking observation of the present study is the difference between hydraulic response time, i.e. immediate drip rate response (<1 year; Fig. 7), and the transfer time of water from the soil to the cave (ca. 2.5 years; Fig. 10). While drip rate response to annual precipitation occurs without significant lag on (sub-)annual basis, the temperature signal is delayed by up to 2.5 years. Thus, the precipitation and temperature signals recorded by different proxies in speleothems are not fully synchronous. In case of Bunker Cave this delay is negligible, because here speleothems record proxies on decadal rather than annual or seasonal scales (Riechelmann et al., 2011; Fohlmeister et al., 2012). Such proxy biases to either water transfer or hydraulic response time must be considered in (sub-)annual reconstructions, and where the signal transfer times for both parameters differ.

6. Conclusions

The seven year-long monitoring of hydrological parameters in and above Bunker Cave, NW Germany, provides unprecedented insights into processes influencing δ^{18}O and δD in dripwater and speleothems that cannot be resolved with shorter-term monitoring programmes. The results of this study aim at quantifying the most relevant processes that may alter isotope proxies in Bunker Cave speleothems over time scales of several years:

1. Inter-annual drip rate dynamics are controlled by annual infiltration and thus, annual precipitation. No lag of the hydraulic response time is observed at annual resolution.
2. Water transfer time is 3 months for a 40 cm-thick soil layer and 4 months for a 70 cm-thick soil. It takes approximately 2.5 years for meteoric water to reach the cave chambers.
3. Neither oxygen nor hydrogen isotopes of dripwaters are altered and hence, record the temperature signal of meteoric precipitation. As a consequence, δ^{18}O and δD from fluid inclusions in speleothems are genuine temperature proxies at this site.
4. Temperature and precipitation during winter months (December-March) are significantly influenced by the NAO. Hence, long-term NAO variations are recorded in speleothems from northwestern Germany.
5. Monitoring data reveal a difference between the hydraulic response time and the water transfer time. This, however, does not affect the proxy interpretation of speleothems from this cave, because of their slow growth rate. But, with regard to other caves, especially

with seasonally to annually resolved speleothems, this time offset may lead to difficulties regarding the interpretation of various proxy data.

6. This study provides insights into multi-annual processes operating in cave depositional environments that are of relevance in speleothem research and can serve as a template for other cave monitoring programmes.

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Figure Captions

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).

Fig. 2 Plan view of Bunker Cave with the locations of drip sites TS 1 and TS 5 in chamber 1 and TS 2, TS 3 and TS 8 in chamber 2 (modified after Scheudoschi and Hasenkamp in Scheudoschi, 2007).

Fig. 3 Monthly values of temperature as well as rainwater oxygen and hydrogen isotope data and mean annual values of precipitation, infiltration, temperature as well as rainwater oxygen and hydrogen isotope data. A) Precipitation data from 2000 to 2006 of the meteorological station (MS) Hagen-Fley and data from 2007 to 2013 measured during this study at the German Cave Museum Iserlohn. Temperature data from 2000 to 2007 were provided by the MS Hagen-Fley and 2008 to 2013 by the MS Hemer. Infiltration data are calculated using data of both meteorological stations. B) Rainwater oxygen and hydrogen isotope data measured from the rain sampled at the German Cave Museum Iserlohn.

Fig. 4 A) Comparison of mean annual oxygen isotope data of four GNIP stations with rainwater data collected during this study. B) Comparison of mean annual hydrogen isotope data of four GNIP stations with rainwater data collected in this study. C) Local meteoric water line (LMWL) of the rainwater and position of the dripwaters on the LMWL (small box).

Fig. 5 Mean annual drip rates in Bunker Cave. Both manual and automatic drip rate data are shown.

Fig. 6 Monthly and mean annual oxygen and hydrogen isotope data of soil- and dripwaters.

Fig. 7 A) Correlation coefficients between mean annual drip rate and annual infiltration. B) Correlation coefficients of mean annual drip rate with annual precipitation. Note the offset to obtain the hydraulic response time of the reservoir to precipitation and infiltration.

Fig. 8 Drip characteristics of drip site TS 8 according to Smart and Friederich (1987) and Baker et al. (1997). Data from 2013 are not displayed as they do not cover the whole year.

Fig. 9 Correlation coefficients of monthly $\delta^{18}O$ and δD values with atmospheric temperature for both soilwater sites BW 1 and BW 2.

Fig. 10 Correlation coefficients between the monthly $\delta^{18}O$ and δD values of all dripwaters and atmospheric temperature.

Fig. 11 A) NAO index for December to March calculated for the period 1975-2013 (http://www.knmi.nl/). B) Precipitation data of the GNIP and meteorological stations for December to March for the period 1975-2013. C) Temperature data of the GNIP and meteorological stations for December to March for the period 1978-2013.

Figure 1

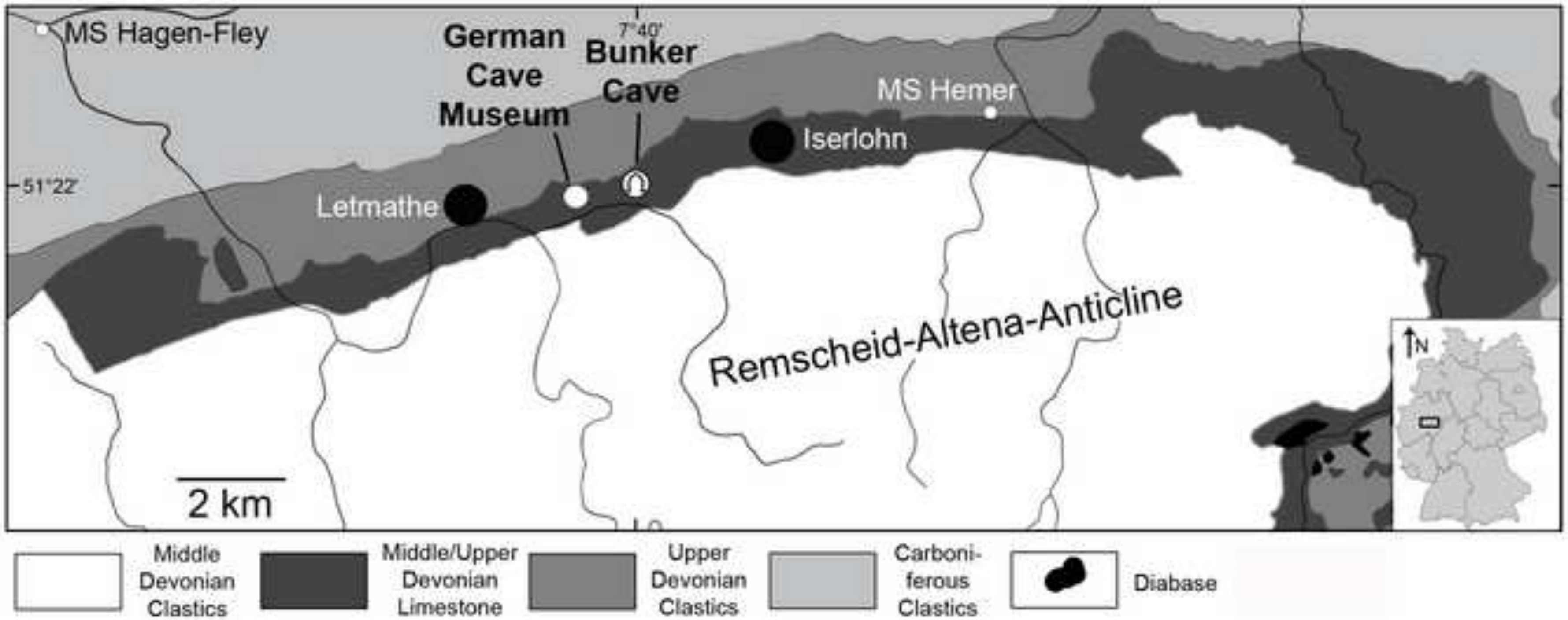
MS Hagen-Fley
German Cave Museum
7°40'
Bunker Cave
MS Hemer
Iserlohn
51°22'
Letmathe
Remscheid-Altena-Anticline
2 km
N
Middle Devonian Clastics
Middle/Upper Devonian Limestone
Upper Devonian Clastics
Carboniferous Clastics
Diabase

Figure 2

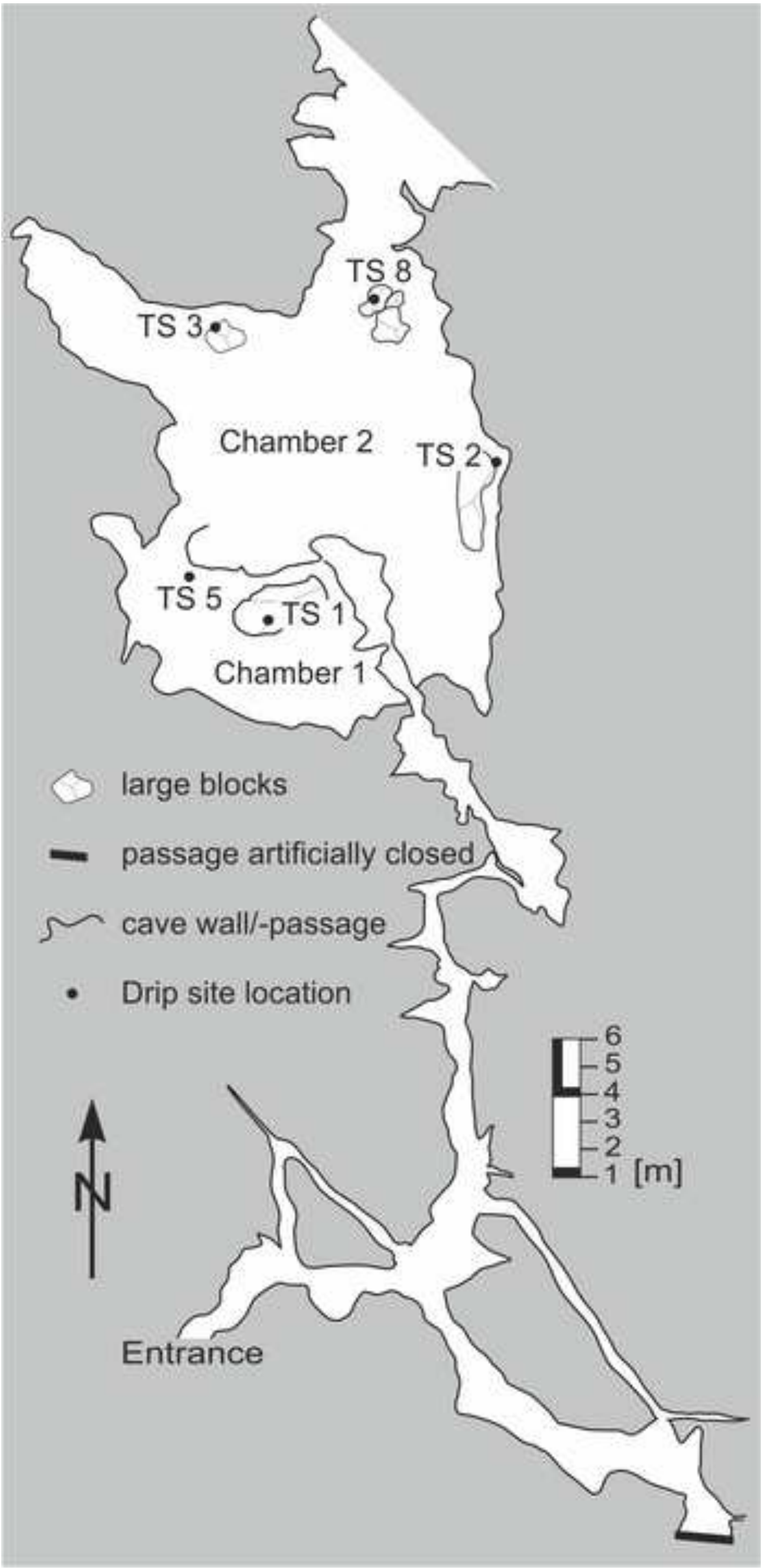
TS 8
TS 3
Chamber 2
TS 2
TS 5
TS 1
Chamber 1
large blocks
passage artificially closed
cave wall/-passage
Drip site location
N
6
5
4
3
2
1 [m]
Entrance

Figure 3

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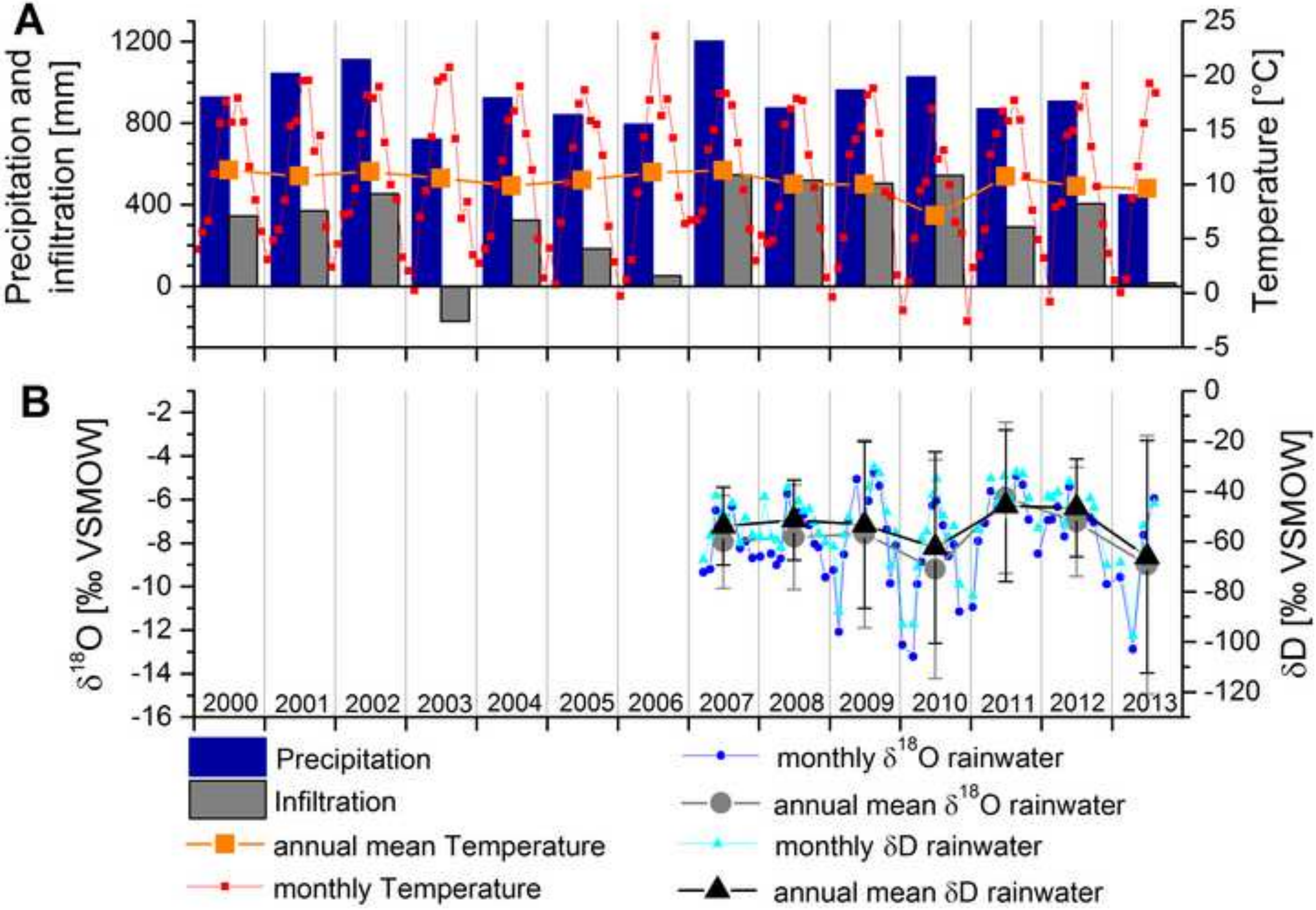

Figure 4

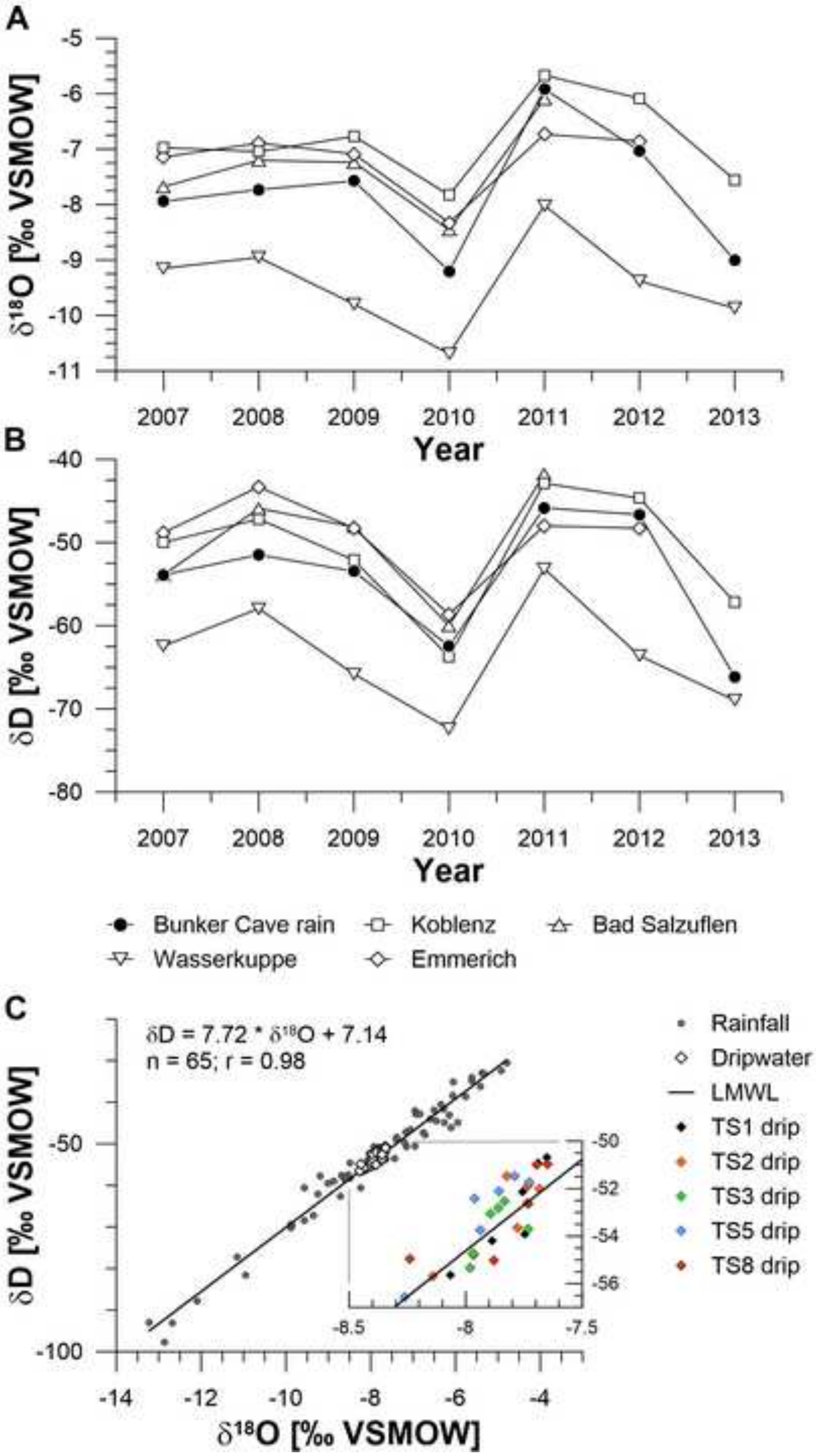
A
δ18O [‰ VSMOW]
-5
-6
-7
-8
-9
-10
-11
2007
2008
2009
2010
2011
2012
2013
Year
B
δD [‰ VSMOW]
-40
-50
-60
-70
-80
2007
2008
2009
2010
2011
2012
2013
Year
● Bunker Cave rain
□ Koblenz
△ Bad Salzuflen
▽ Wasserkuppe
◇ Emmerich
C
δD = 7.72 * δ18O + 7.14
n = 65; r = 0.98
δD [‰ VSMOW]
-50
-100
-14
-12
-10
-8
-6
-4
δ18O [‰ VSMOW]
-50
-52
-54
-56
-8.5
-8
-7.5
Rainfall
Dripwater
LMWL
TS1 drip
TS2 drip
TS3 drip
TS5 drip
TS8 drip

Figure 5

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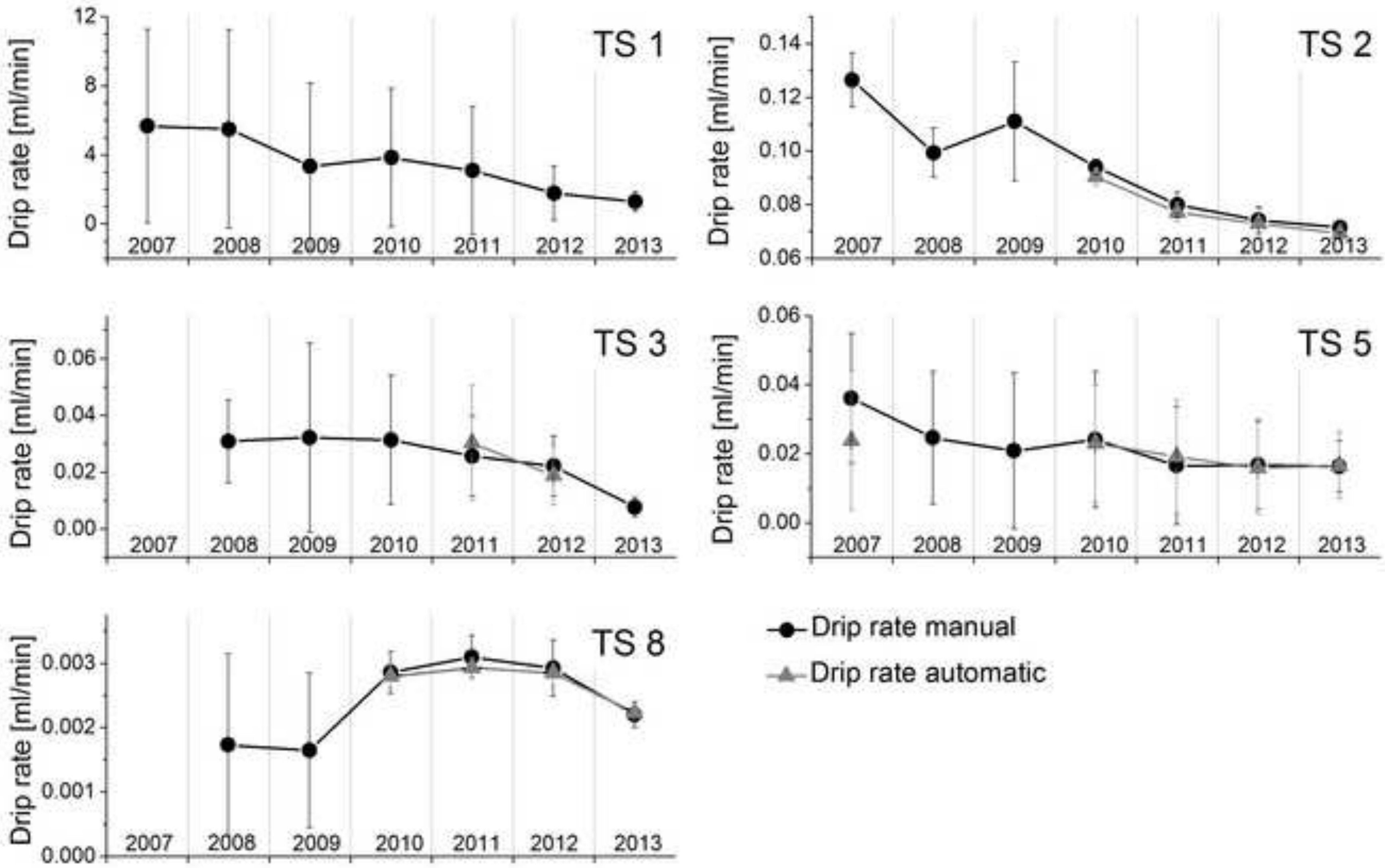

Figure 6

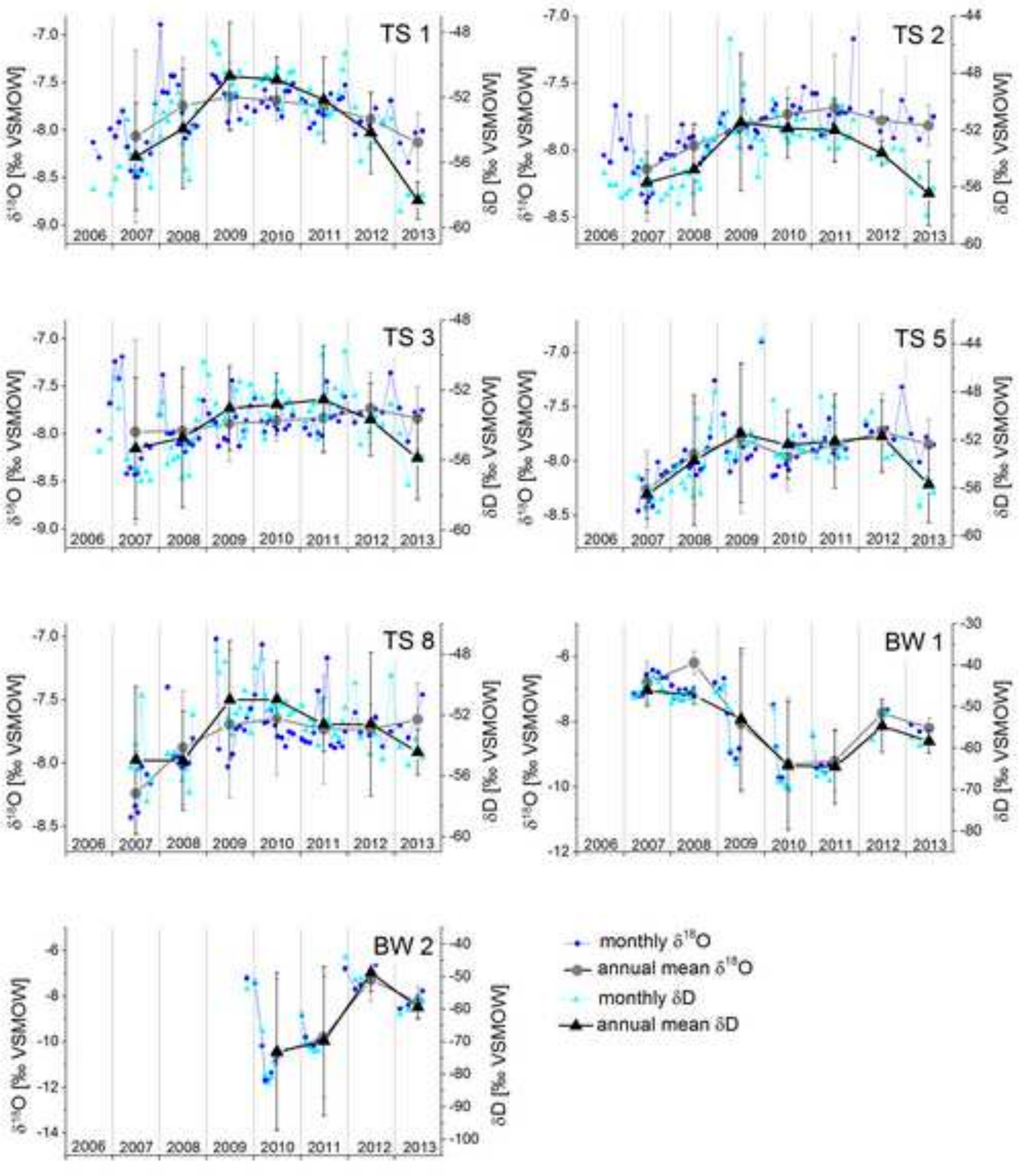
TS 1
δ18O [‰ VSMOW]
-7.0
-7.5
-8.0
-8.5
-9.0
δD [‰ VSMOW]
-48
-52
-56
-60
TS 2
-7.0
-7.5
-8.0
-8.5
-44
-48
-52
-56
-60
TS 3
-7.0
-7.5
-8.0
-8.5
-9.0
-48
-52
-56
-60
TS 5
-7.0
-7.5
-8.0
-8.5
-44
-48
-52
-56
-60
TS 8
-7.0
-7.5
-8.0
-8.5
-48
-52
-56
-60
BW 1
-6
-8
-10
-12
-30
-40
-50
-60
-70
-80
BW 2
-6
-8
-10
-12
-14
-40
-50
-60
-70
-80
-90
-100
2006
2007
2008
2009
2010
2011
2012
2013
monthly δ18O
annual mean δ18O
monthly δD
annual mean δD

Figure 7

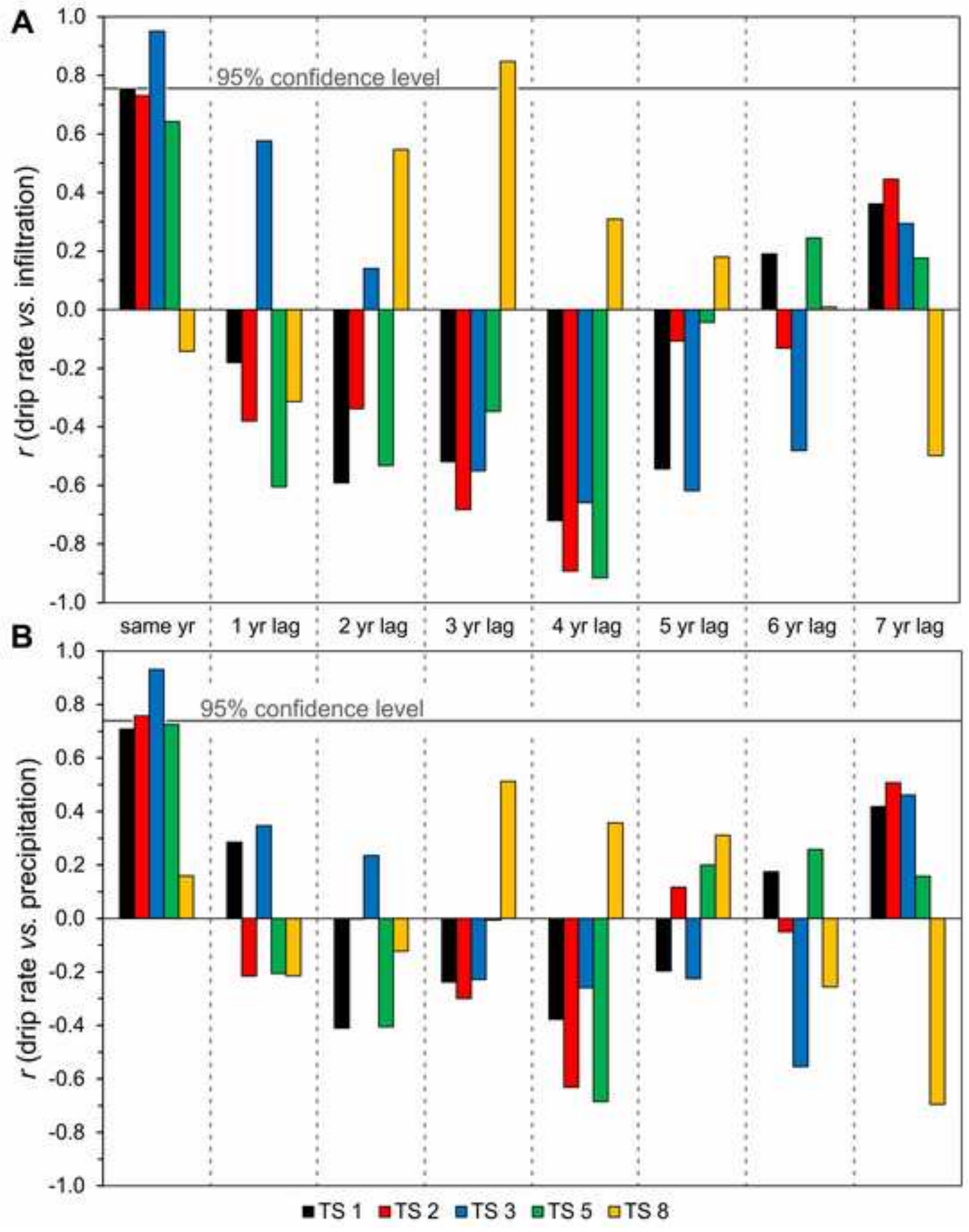
A
B
95% confidence level
95% confidence level
r (drip rate vs. infiltration)
r (drip rate vs. precipitation)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
same yr
1 yr lag
2 yr lag
3 yr lag
4 yr lag
5 yr lag
6 yr lag
7 yr lag
TS 1
TS 2
TS 3
TS 5
TS 8

Figure 8

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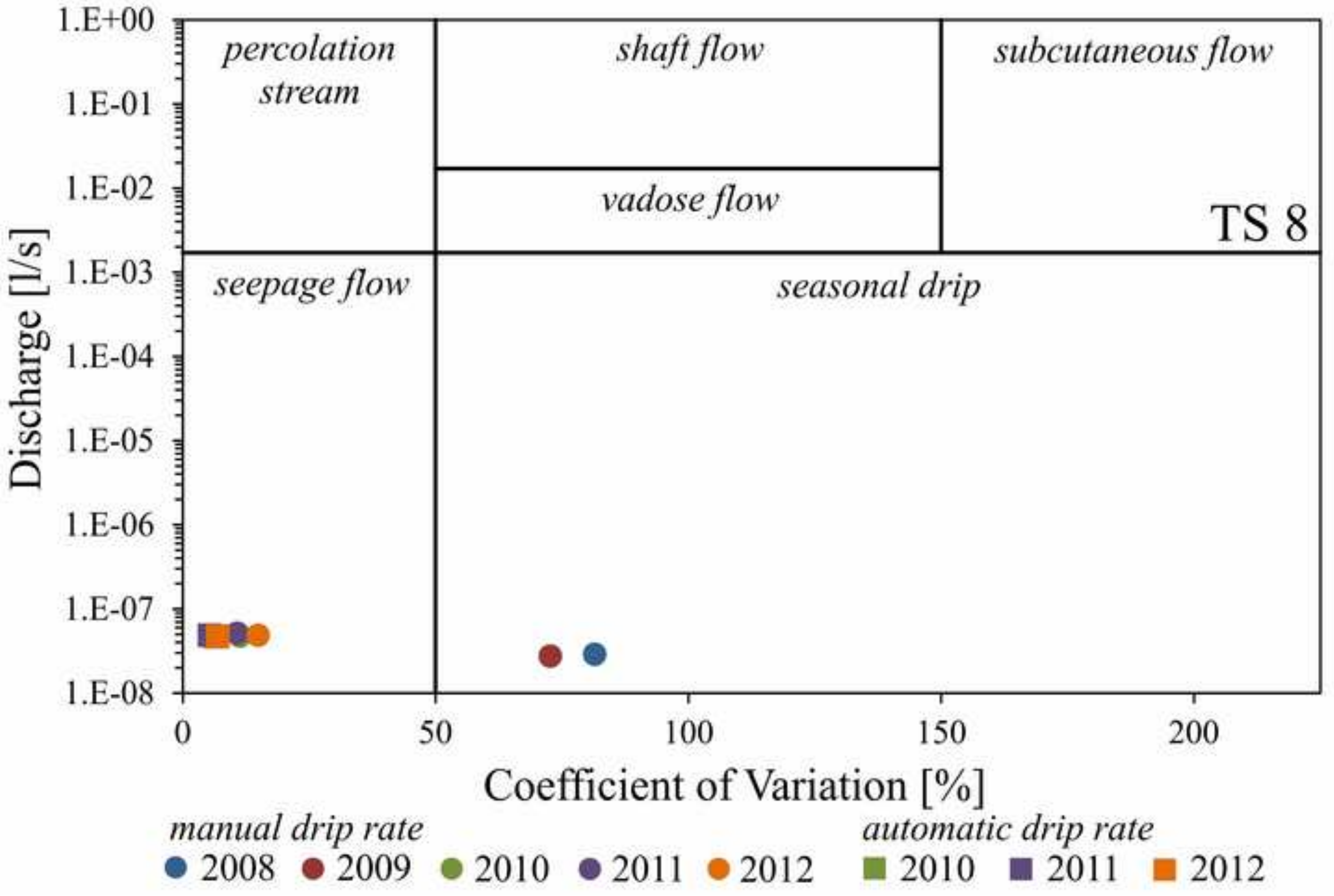

Figure 9

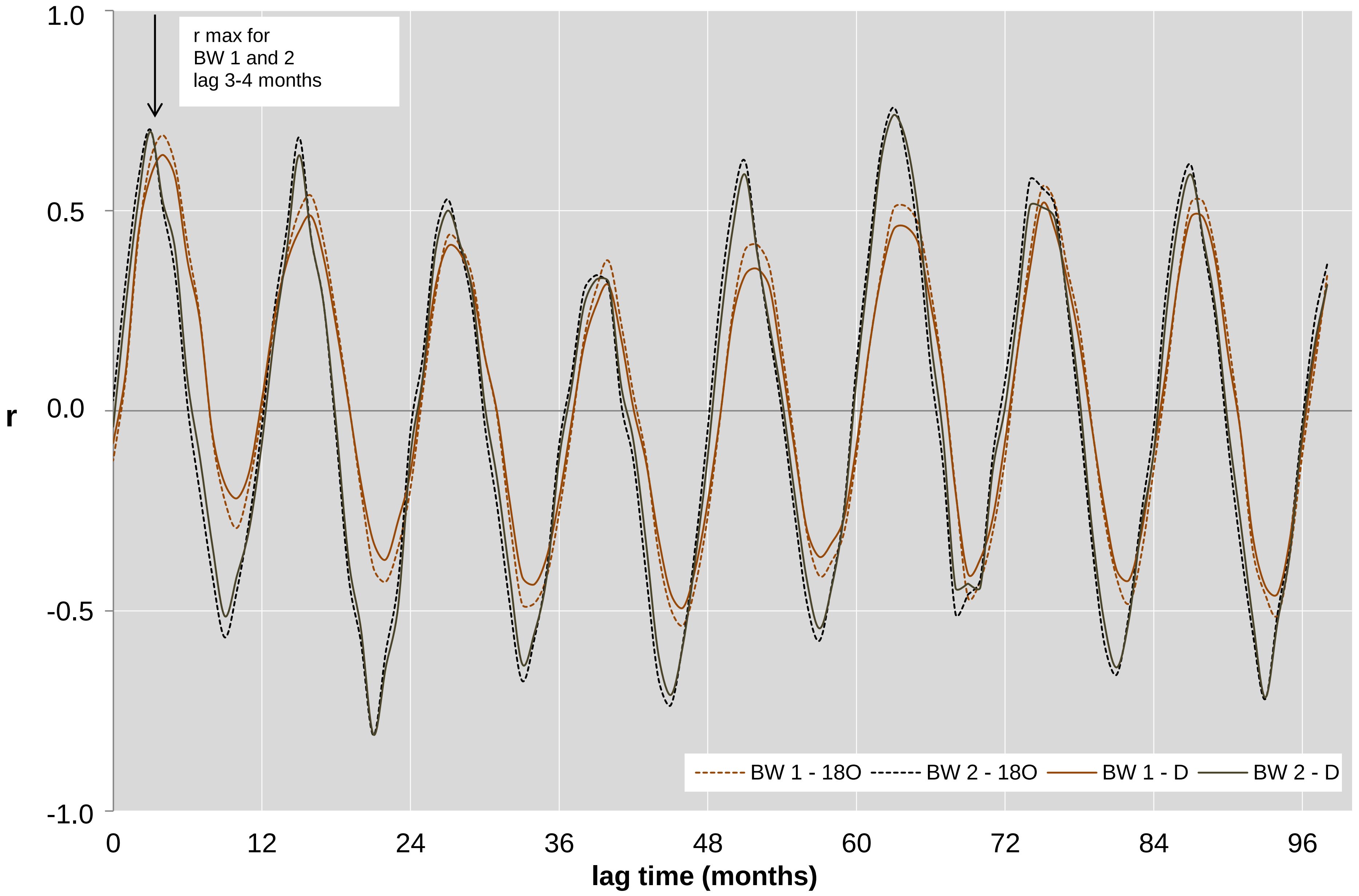
r max for
BW 1 and 2
lag 3-4 months
1.0
0.5
0.0
-0.5
-1.0
r
0
12
24
36
48
60
72
84
96
lag time (months)
BW 1 - 18O
BW 2 - 18O
BW 1 - D
BW 2 - D

Figure 10

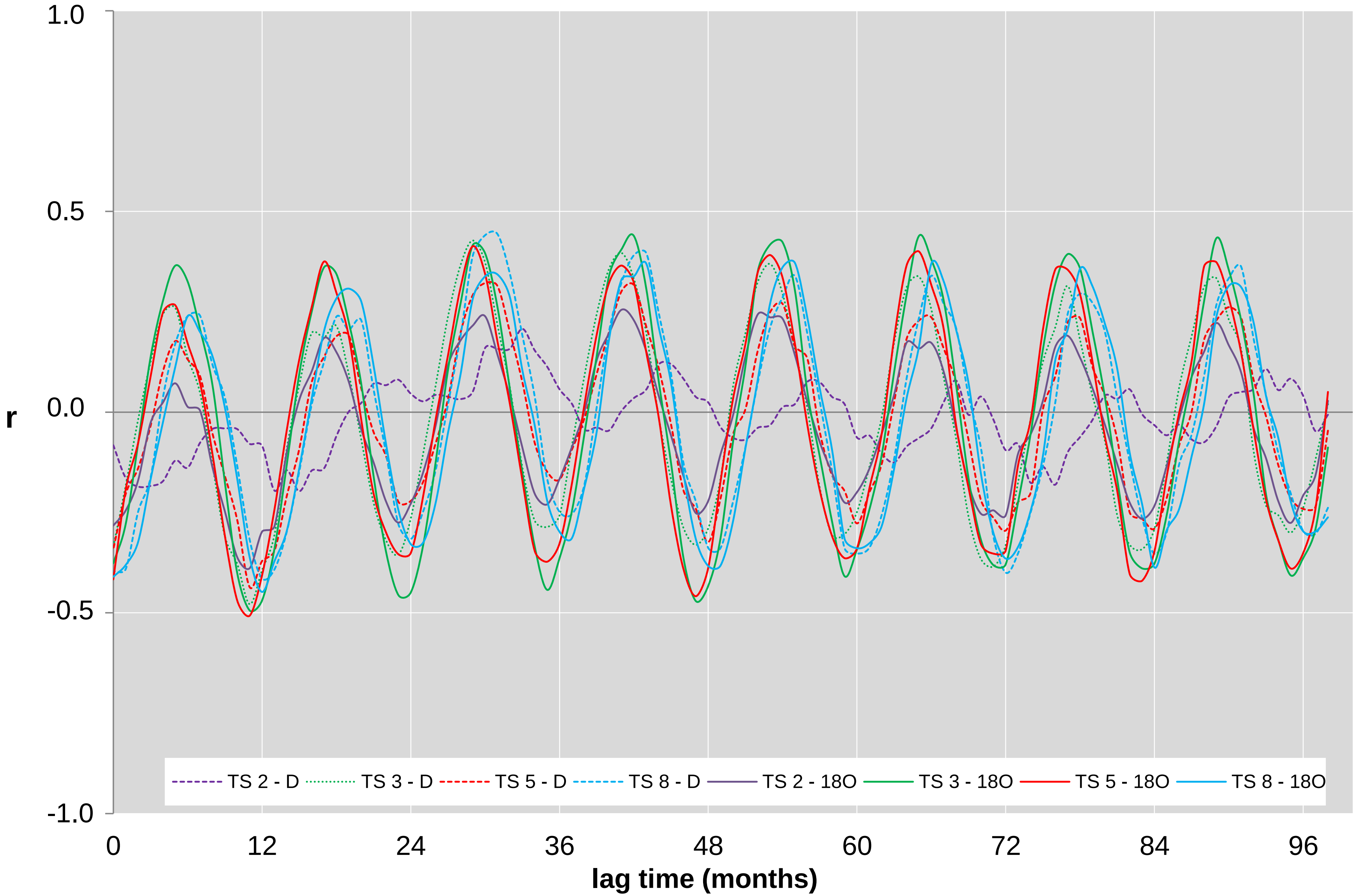
1.0
0.5
0.0
-0.5
-1.0
r
0
12
24
36
48
60
72
84
96
lag time (months)
TS 2 - D
TS 3 - D
TS 5 - D
TS 8 - D
TS 2 - 18O
TS 3 - 18O
TS 5 - 18O
TS 8 - 18O

Figure 11
Click here to download high resolution image

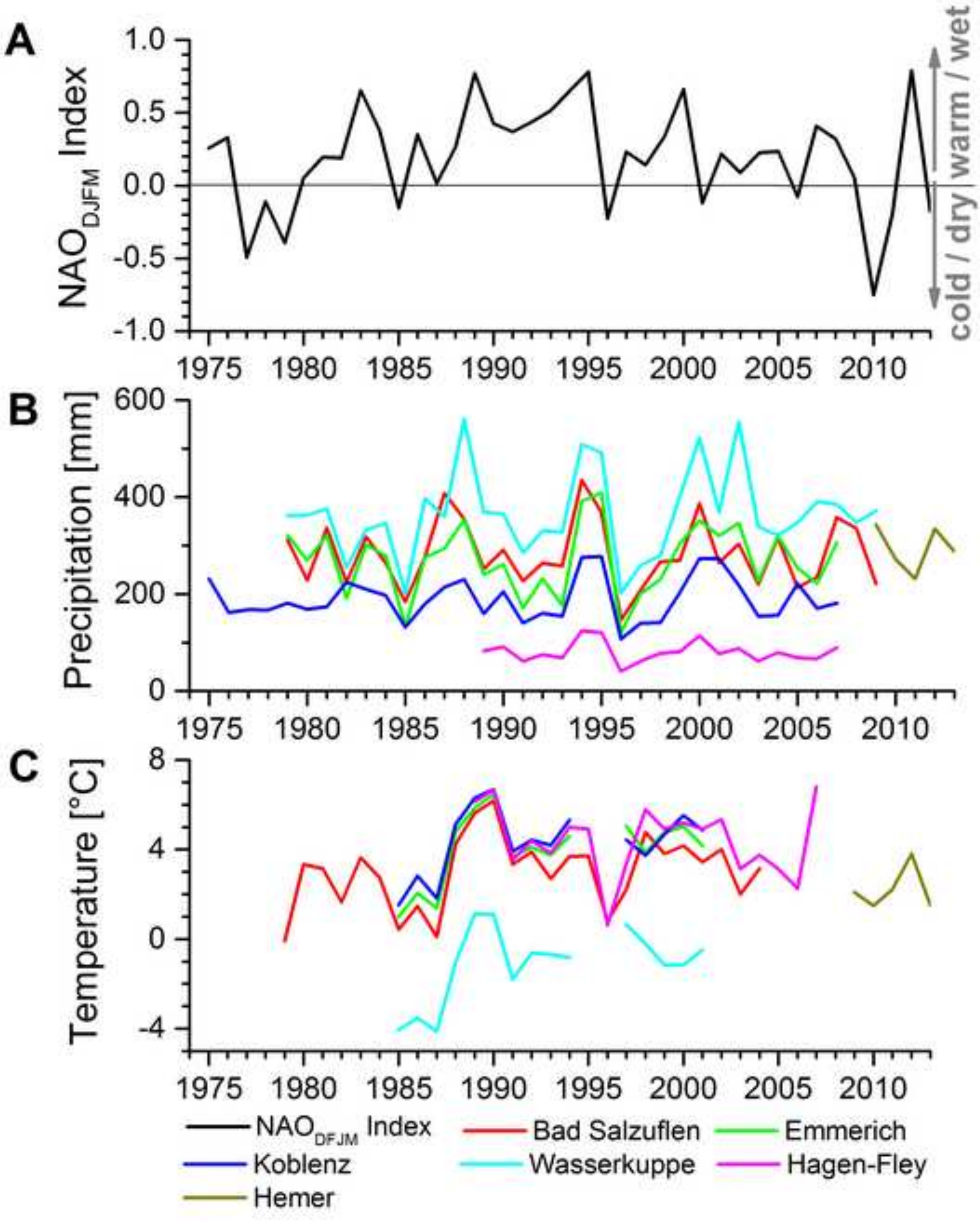

Table 1. Correlations between monthly $\delta^{18}O$ values of the different drip- and soilwaters. Significant correlation coefficients (*r*; $p \leq 0.05$) are printed bold. Data points used for statistics vary between 14 and 65.

$\delta^{18}O$	TS 1	TS 2	TS 3	TS 5	TS 8	BW 1
TS 2	**0.53**					
TS 3	**0.36**	**0.43**				
TS 5	**0.41**	**0.55**	**0.63**			
TS 8	**0.50**	**0.47**	**0.58**	**0.37**		
BW 1	-0.11	**-0.53**	-0.07	-0.17	-0.31	
BW 2	-0.27	-0.05	**0.57**	**0.66**	-0.07	**0.72**

Table 2. Correlations between monthly δD values of the different drip- and soilwaters. Significant correlation coefficients (r; $p \leq 0.05$) are printed bold. Data points used for statistics vary between 15 and 65.

δD	TS 1	TS 2	TS 3	TS 5	TS 8	BW 1
TS 2	**0.74**					
TS 3	**0.61**	**0.59**				
TS 5	**0.51**	**0.55**	**0.73**			
TS 8	**0.72**	**0.63**	**0.61**	**0.45**		
BW 1	-0.34	**-0.45**	**-0.38**	**-0.37**	**-0.38**	
BW 2	-0.34	**-0.58**	0.07	0.04	-0.14	**0.76**