

Northumbria Research Link

Citation: Riechelmann, Sylvia, Schröder-Ritzrau, Andrea, Spötl, Christoph, Riechelmann, Dana Felicitas Christine, Richter, Detlev Konrad, Mangini, Augusto, Frank, Norbert, Breitenbach, Sebastian and Immenhauser, Adrian (2017) Sensitivity of Bunker Cave to climatic forcings highlighted through multi-annual monitoring of rain-, soil-, and dripwaters. *Chemical Geology*, 449. pp. 194-205. ISSN 0009-2541

Published by: Elsevier

URL: <https://doi.org/10.1016/j.chemgeo.2016.12.015>
<<https://doi.org/10.1016/j.chemgeo.2016.12.015>>

This version was downloaded from Northumbria Research Link:
<http://nrl.northumbria.ac.uk/id/eprint/42406/>

Northumbria University has developed Northumbria Research Link (NRL) to enable users to access the University's research output. Copyright © and moral rights for items on NRL are retained by the individual author(s) and/or other copyright owners. Single copies of full items can be reproduced, displayed or performed, and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided the authors, title and full bibliographic details are given, as well as a hyperlink and/or URL to the original metadata page. The content must not be changed in any way. Full items must not be sold commercially in any format or medium without formal permission of the copyright holder. The full policy is available online: <http://nrl.northumbria.ac.uk/policies.html>

This document may differ from the final, published version of the research and has been made available online in accordance with publisher policies. To read and/or cite from the published version of the research, please visit the publisher's website (a subscription may be required.)

Manuscript Number: CHEMGE9714R1

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

Corresponding Author: Dr. Sylvia Riechelmann, D.Sc.

Corresponding Author's Institution: Institute of Geology, Mineralogy and Geophysics

First Author: Sylvia Riechelmann, D.Sc.

Order of Authors: Sylvia Riechelmann, D.Sc.; Andrea Schröder-Ritzrau; Christoph Spötl; Dana F. C Riechelmann; Detlev K Richter; Augusto Mangini; Norbert Frank; Sebastian F. M Breitenbach; Adrian Immenhauser

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 $\delta^{18}\text{O}$ 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 $\delta^{13}\text{C}$ and Mg/Ca ratios in speleothem calcite. Speleothem $\delta^{18}\text{O}$ 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).

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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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: ²³⁰Th/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 Kottke 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 $\pm 0.09\%$?

Our reply: We added " \pm " (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. Its 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ composition of seepage water because the molecule quantity of water containing oxygen is much more important than HCO_3^- 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 $\delta^{18}\text{O}$. 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$? 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 $\delta^{18}\text{O}$ 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.

26 **ABSTRACT**

27 The last two decades have seen a considerable increase in studies using speleothems as
28 archives of past climate variability. Caves under study are now monitored for a wide range of
29 environmental parameters and results placed in context with speleothem data. The present
30 study investigates trends from a seven year long monitoring of Bunker Cave, western
31 Germany, in order to assess the hydraulic response and transfer time of meteoric water from
32 the surface to the cave. Rain-, soil-, and dripwater were collected from August 2006 to August
33 2013 at a monthly to bimonthly resolution and their oxygen and hydrogen isotope
34 composition was measured. Furthermore, drip rates were quantified. Due to different drip
35 characteristics, annual mean values were calculated for the drip rates of each drip site.
36 Correlations of the annual mean drip rate of each site with precipitation and infiltration
37 demonstrate that the annual infiltration, and thus the annual precipitation control the inter-
38 annual drip-rate variability for all except one site. The hydraulic response is not delayed. All
39 drip sites display identical long-term trends, which suggests a draining of a common karst
40 reservoir over these seven years of monitoring. Correlations of soil- and dripwater monthly
41 $\delta^{18}\text{O}$ and δD values with atmospheric temperature data reveal water transfer times of 3
42 months for soilwater at site BW 2 (40 cm depth) and 4 months for 70 cm depth (soilwater at
43 site BW 1). Finally, the water reaches the cave chambers (15 to 30 m below land surface)
44 after ca. 2.5 years. Consequently, a temporal offset of 29 to 31 months (ca. 2.5 years) between
45 the hydraulic response time (no time lag on annual basis) and the water transfer time (time lag
46 of 29 to 31 months) was found, which is negligible with regard to Bunker Cave speleothems
47 because of their slow growth rates. Variations in drip rate and thus, precipitation and
48 infiltration are recorded by $\delta^{13}\text{C}$ and Mg/Ca ratios in speleothem calcite. Speleothem $\delta^{18}\text{O}$
49 values reflect both temperature and precipitation signals due to drip rate-related fractionation
50 processes. We document that long-term patterns in temperature and precipitation are recorded

51 in dripwater patterns of Bunker Cave and that these are linked to the North Atlantic
52 Oscillation (NAO).

53

54 **1. Introduction**

55

56 Palaeoclimate reconstructions based on speleothems, i.e. mostly carbonate deposits
57 formed in caves, have increased significantly during the last two decades (for a summary, see
58 Fairchild and Baker, 2012). The most important strengths of speleothems are the precise
59 $^{230}\text{Th}/\text{U}$ dating (e.g., Dorale et al., 2004; Scholz and Hoffmann, 2008; Cheng et al., 2013) and
60 the availability of several, mostly geochemical, parameters such as carbon and oxygen isotope
61 values, major and trace elemental abundances, and $\delta^{18}\text{O}$ and δD of fluid inclusions (e.g.,
62 Niggemann et al., 2003; Mangini et al., 2005; Vonhof et al., 2006; Fohlmeister et al., 2012;
63 Scholz et al., 2012; Luetscher et al., 2015). These can be used for single- or multi-proxy
64 approaches to reconstruct past climate dynamics.

65 In order to gain a better understanding of the processes influencing geochemical
66 proxies in the soil and epikarst zone, as well as processes acting during deposition of
67 speleothems, sophisticated monitoring programmes have been established (e.g., Spötl et al.,
68 2005; Matthey et al., 2008b, 2016; Riechelmann et al., 2011, Wassenburg et al., 2013; Genty et
69 al., 2014; van Rampelbergh et al., 2014, Breitenbach et al., 2015; Treble et al., 2016). In the
70 context of these efforts, cave air temperature, pCO_2 and humidity, drip rate, as well as the
71 isotopic composition of rain-, soil- and dripwater and the element concentrations of soil-, and
72 dripwater have been recorded. Furthermore, in order to link the dripwater with speleothems
73 used for palaeoclimate reconstructions, recent cave carbonate precipitates have been
74 investigated in combination with their respective dripwater composition and the hydraulic

75 regime in the cave (e.g., Miorandi et al., 2010; Tremaine et al., 2011; Riechelmann et al.,
76 2013, 2014).

77 Most monitoring studies focused on seasonal variations of the above-mentioned
78 parameters, whereby, for example, the drip rate was analysed to study the response to rainfall
79 events or the hydrological connection of the drip sites (Baker et al., 1997; Matthey et al.,
80 2008b; Riechelmann et al., 2011). The analysis of dripwater $\delta^{18}\text{O}$ and δD values shows either
81 seasonal variations (Matthey et al., 2008a, Breitenbach et al., 2015) or rather stable values
82 close to the annual mean of rainwater (Riechelmann et al., 2011; van Rampelbergh et al.,
83 2014). Seasonal variations in cave dripwater reflect a fast transfer of the water (e.g.,
84 Breitenbach et al., 2015). The lack of an intra-annual pattern points to strong mixing in the
85 epikarst and/or the vadose zone with transfer times between the soil and the cave drip site in
86 excess of one year (e.g., Riechelmann et al., 2011; van Rampelbergh et al., 2014). Financial
87 constraints, accessibility, or lack in manpower commonly limit monitoring studies to
88 durations of a few years or less. Thus far, only a very limited number of studies focused on
89 multi-annual trends of the monitored parameters and implications for speleothem research
90 (Genty and Deflandre, 1998; Treble et al., 2013; Genty et al., 2014, Breitenbach et al., 2015;
91 Matthey et al., 2016). To the knowledge of the authors, only the study by Genty et al. (2014)
92 detrended the seasonal signal in order to gain insights in potential longer-term (> 5yrs) trends.
93 This is of significance as particularly the longer-term trends are relevant for the assessment of
94 proxy data from speleothems recording decadal or longer variability only.

95 This paper documents and discusses observations of precipitation/infiltration and drip
96 rate as well as atmospheric temperature and the oxygen and hydrogen isotopic composition of
97 rain-, soil-, and cave dripwater from a seven year-long monitoring campaign in Bunker Cave
98 in northwestern Germany. The main goals of the present study are: (i) to quantify the longer-
99 term (multi-annual) variability of the environmental parameters; (ii) to assess the response

100 time of the carbonate precipitating drip sites to these parameters; (iii) to identify signal
101 smoothing and possible alteration processes during percolation through the epikarst; and (iv)
102 to draw, where possible, general implications for speleothem research.

103

104 2. Climate and cave parameters

105

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

113 The host rock consists of Middle to Upper Devonian massive limestone (von Kamp,
114 1972). The rock overburden of the cave is between 15 and 30 m (Grebe, 1993) and the host
115 rock is overlain by ca. 70 cm inceptisol to alfisol (USDA Soil Taxonomy). The colour varies
116 between dark and yellowish brown (10YR 3/3 and 10YR 5/6) for the upper soil layers and
117 bright reddish brown to bright brown (5YR 5/8 to 7.5YR 5/8) for the lower layer (Munsell
118 soil colour charts). The vegetation above the cave consists of deciduous forest (mainly ash
119 and beech trees) and scrubs (Riechelmann et al., 2011). Bedding dips to the North or
120 Northwest (von Kamp and Ribbert, 2005) and water percolates mainly along fractures and
121 bedding planes. This feature and the fact that Bunker Cave is located in a south-facing hill
122 reduces the effective catchment of the cave dripwater to a few hundred m². Furthermore, the
123 Dröscheder Emst karst plateau is partly used as a residential area and ca. 15 to 20% of the
124 catchment area is anthropogenically sealed. Furthermore, a railway route runs above the cave.

125

126 3. Materials and Methods

127

128 *3.1 Monitoring and sample collection of rain-, soil- and dripwater*

129

130 The monitoring programme performed in and above Bunker Cave ran from August
131 2006 to August 2013. Rainwater samples were collected with a rain gauge according to the
132 DIN 58666C norm on the roof of the German Cave Museum Iserlohn (51°22'N, 07°38'E; 175
133 m asl), located 1.5 km from Bunker Cave (Fig. 1). Rainfall amount was measured and
134 sampled daily and collected as monthly samples between 2007 and 2012. In 2013, rainwater
135 samples were collected only bimonthly. Rainwater samples were stored in PET bottles in a
136 fridge to minimize evaporation.

137 Two soilwater sampling sites were installed above Bunker Cave. The soilwater suction
138 probes were manufactured by Umwelt-Geräte-Technik GmbH (UGT, Germany). One probe
139 (BW 1) was installed at a depth of 70 cm and water was sampled monthly between 2007 and
140 2011. The second probe (BW 2) sampled water at 40 cm depth in monthly intervals between
141 2009 and 2011. In 2012 and 2013, both soilwater sites were sampled only bimonthly.

142 In total, five drip sites (TS 1, TS 2, TS 3, TS 5 and TS 8; Fig. 2) were monitored in
143 Bunker Cave from 2006 to 2013. Sampling at drip site TS 8 started in 2007. Drip sites TS 1
144 and TS 5 are located in chamber 1. All other sites are located in chamber 2 of Bunker Cave
145 (Fig. 2). Dripwater samples were integrated over one month in order to obtain sufficient
146 volumes of water for multi-proxy geochemical analyses. These monthly samples were taken
147 between 2006 and 2011, while bimonthly samples were taken between 2012 and 2013. An
148 exception is drip site TS 1, where sufficient water could be collected during each visit.
149 Dripwater first dripped onto a drip counter placed in a plastic box and was then transferred

150 into a closed bottle via tubing to minimize CO₂ degassing and potential evaporation.
151 Comparison of instantaneous and monthly collected water revealed similar δ¹⁸O values,
152 confirming that fractionation processes due to evaporation are negligible (Riechelmann et al.,
153 2011). For further details of the monitoring, the reader is referred to Riechelmann (2010) and
154 Riechelmann et al. (2011; 2012a; 2013; 2014).

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

157

$$158 \quad z \text{ [ml/time]} = \text{drip rate [drips/time]} * V \text{ [ml/drips]} \quad (1)$$

159

160 where V is the volume of each drip. The volume of a drip was determined by a defined
161 collection time, the total amount of water and the drip rate (in drips per min). In some cases,
162 the drip rate at site TS 8 was not quantified by means of a stopwatch, and was instead
163 calculated via the amount of an instantaneous water sample (collected during the monitoring
164 tour) and the known drip volume (determined as described above). Furthermore, drip rates
165 were measured automatically by acoustic drip counters (Stalagmate; Matthey and Collister,
166 2008), which were placed under drip sites TS 2 (2009-2013), TS 3 (2010-2013), TS 5 (2007-
167 2013) and TS 8 (2009-2013).

168

169 *3.2 δ¹⁸O and δD of rain-, soil- and dripwater*

170

171 The oxygen and hydrogen isotopic compositions of all water samples were determined
172 at the University of Innsbruck. Water samples were collected in small, airtight glass vials
173 without headspace. The oxygen isotope composition was analysed using a ThermoFinnigan
174 DELTA^{plus}XL mass spectrometer connected with a Gasbench II using the CO₂ equilibrium

175 technique. The 1σ reproducibility of the $\delta^{18}\text{O}$ values is ± 0.09 ‰ VSMOW (Spötl et al., 2005).
176 The hydrogen isotope composition was measured using a ThermoFinnigan
177 DELTA^{plus} Advantage equipped with a TC/EA high-temperature pyrolysis unit. The 1σ
178 reproducibility is ± 1 ‰ VSMOW.

179

180 3.3 Evapotranspiration and infiltration

181

182 Instrumental climate data of two nearby meteorological stations (Fig. 1) - Hagen-Fley
183 ($51^{\circ}25'\text{N}$, $07^{\circ}29'\text{E}$; 100 m asl; 2000-2007; www.dwd.de) and Hemer ($51^{\circ}23'\text{N}$, $07^{\circ}45'\text{E}$; 200
184 m asl; 2008-2013; www.meteo-media.de) - were used to calculate the evapotranspiration after
185 Haude (1955) using the following equation:

186

$$187 E_{pot} [\text{mm/day}] = x [\text{mm/day} * \text{hPa}] * P^{l3} [\text{hPa}] * (1 - (F^{l3} [\%] / 100)) \quad (2)$$

188

189 where E_{pot} is the potential evaporation, x represents the monthly coefficient depending on
190 vegetation, P^{l3} is the saturation pressure at 1 p.m. and F^{l3} is the relative humidity at 1 p.m..

191 The saturation pressure was calculated using the Magnus-formula:

192

$$193 P^{l3} [\text{hPa}] = 6.107 [\text{hPa}] * 10^{((7.5 * T^{l3} [^{\circ}\text{C}]) / (237 + T^{l3} [^{\circ}\text{C}]))} \quad (3)$$

194

195 T^{l3} is the air temperature at 1 p.m.. Equations 2 and 3 were used to calculate the amount of
196 water which can potentially infiltrate (Inf_{pot}) into the soil and thus, into the cave. Therefore,
197 the following equation was used:

198

$$199 Inf_{pot} [\text{mm/day}] = N [\text{mm/day}] - E_{pot} [\text{mm/day}] \quad (4)$$

200

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

203

204 *3.4 GNIP stations*

205

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

211

212 **4. Results**

213

214 Seasonally resolved monitoring [data](#) of rain-, soil- and dripwater of Bunker Cave were
215 [partly](#) published by Immenhauser et al. (2010), Kluge et al. (2010, 2013), Riechelmann et al.
216 (2011, 2012a, b, 2013, 2014), Fohlmeister et al. (2012), Münsterer et al. (2012), and
217 Wackerbarth et al. (2012). In this study, we [present monthly data as well as](#) annual mean
218 values of the relevant parameters, which were calculated using the monthly or bimonthly
219 values of the respective year [to \(i\) examine long-term variability and \(ii\) compare these data](#)
220 [with precipitation/infiltration and temperature data to determine the hydraulic response time](#)
221 [and water transfer time. Annual means were obtained from monthly data \(January to](#)
222 [December\).](#)

223

224 *4.1 Precipitation, infiltration, temperature and rainwater $\delta^{18}O$ and δD*

225

226 For this study, the time period from 2000 to 2013 is considered. Annual mean values
227 are shown for all years except 2013, since monitoring stopped in August of this year. Hence,
228 all mean values for 2013 are related to this time interval. Furthermore, annual mean values for
229 2006 were not calculated, due to insufficient data. The lowest annual precipitation sum (720
230 mm) was recorded in 2003, without considering 2013 with the lowest precipitation sum of
231 447 mm. The highest annual rainfall (1202 mm) and the highest mean annual infiltration (546
232 mm) occurred in 2007 (Fig. 3A). The lowest annual mean infiltration was observed in 2003 (-
233 171 mm). Infiltration at Bunker Cave is lower during summer months than during winter
234 (Riechelmann et al., 2011). Monthly temperature data show low values in winter and high
235 ones during summer. The lowest mean annual air temperature (7.1°C) was observed in 2010,
236 while the highest (11.3°C) was observed twice, in 2000 and 2007 (Fig. 3A).

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

243 Since monthly rainwater samples collected during the monitoring do not cover the
244 same time period as the monthly samples from the GNIP stations, mean annual values are
245 used here for comparison. Mean annual oxygen and hydrogen isotope values of rainwater
246 collected at the German Cave Museum correlate well with those of nearby GNIP stations
247 (Figs. 4A, B). The Local Meteoric Water Line (LMWL) of the rainwater (Fig. 4C) is close to
248 that of the GNIP station Bad Salzuflen ($\delta\text{D} = 7.72 * \delta^{18}\text{O} + 5.7$; $r = 0.98$; Stumpp et al.,
249 2014). Thus, rainwater collected during the monitoring period reflects the climate conditions

250 of western Germany. The slope of 7.72 is close to that of the Global Meteoric Water Line (8),
251 indicating insignificant evaporation of the collected samples (Gat et al., 2000). Since all
252 dripwater data plot on the LMWL (Fig. 4C) evaporation in the soil, epikarst and cave
253 generates no significant imprint on their corresponding isotope values. Furthermore, both
254 isotope systems depend on the regional surface air temperature and the isotopic composition
255 of Bunker Cave dripwater reflects the infiltration weighted mean annual $\delta^{18}\text{O}$ and δD values
256 of rainwater (Riechelmann et al., 2011).

257

258 *4.2 Drip rate*

259

260 Due to different drip characteristics of the different drip sites (ranging from seepage
261 flow to seasonal drip; Riechelmann et al., 2011; Appendix S1 and Fig. 8), annual mean drip
262 rates were calculated and their long-term variability compared. Both manually and
263 automatically obtained mean annual drip rates show the same trends (Fig. 5). Sites TS 1, TS 2
264 and TS 5 show a decreasing trend in mean drip rates over the monitoring period, which is also
265 reflected in cross-correlations of mean annual drip rates at these sites (TS 1 vs. TS 2: $r = 0.82$;
266 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
267 rate at site TS 3 correlates only with the annual mean drip rate at site TS 2 within the 95%
268 confidence level ($r = 0.81$) and with TS 1 ($r = 0.79$) and TS 5 ($r = 0.72$) just below the 95%
269 confidence level ($n_{all} = 6$). However, it can be assumed that the annual mean drip rate at site
270 TS 3 follows the same trend as sites TS 1, 2 and 5. At drip site TS 8 a similar annual mean
271 drip rate was observed in 2008 and 2009 before drip rates increased until 2011, followed by a
272 decreasing trend. Drip rate of drip site TS 8 does not show any significant correlation with
273 any other drip rate.

274

275 4.3 $\delta^{18}\text{O}$ and δD of soil- and dripwater

276

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

285 Seasonal trends in $\delta^{18}\text{O}$ and δD of dripwaters are minor, but most pronounced for
286 water at site TS 1. In general, lower isotope values occur in summer, while higher values are
287 observed in winter (Fig. 6). Correlations between $\delta^{18}\text{O}$ and δD values of monthly samples of
288 the same site are significant for all dripwaters and both soilwater samples ($r \geq 0.44$; $p < 0.001$;
289 $n \geq 21$). All dripwaters share similarities in their oxygen and hydrogen isotopic composition
290 as shown by positive cross-correlations (Tables 1 and 2). Mean annual values display the
291 overall trend for $\delta^{18}\text{O}$ and δD , which is similar for all drip sites considering the errors (Fig. 6).
292 Oxygen and hydrogen isotope values increased until 2009, reached a plateau and decreased
293 around 2012. This trend is less distinct for dripwater at site TS 8 (Fig. 6).

294

295 5. Interpretation and Discussion

296

297 5.1 Constraints on the hydraulic response time

298

299 The positive correlations of mean annual drip rates of all sites except TS 8 (Fig. 5)
300 suggests that: (i) these sites are characterized by similar hydrological properties (Baker et al.,
301 1997), and (ii) the drip rates of these sites most likely respond to the same environmental
302 (climate) forcing. According to Riechelmann et al. (2011), no drip site showed a direct
303 response to rainfall events, but rather a lagged response of up to several months due to slowly
304 increasing hydrological pressure in the karst reservoir above the cave. Correlations between
305 drip rates and precipitation and infiltration during the preceding years based on monitoring
306 and meteorological data of the stations Hagen-Fley and Hemer were used to determine the
307 response time of mean annual drip rates to mean annual precipitation and infiltration. The
308 correlation coefficients (r) between drip rate and infiltration show that the mean annual drip
309 rates at TS 1 and TS 3 are controlled by mean annual infiltration of the same year, as observed
310 for other cave systems (Fig. 7A; Genty and Deflandre, 1998; Baker et al., 2000; Miorandi et
311 al., 2010; Tremaine and Froelich, 2013). Correlation coefficients at drip sites TS 2 and 5 are
312 close to the 95% confidence level. Since the infiltration amount is controlled by precipitation
313 amount and temperature (water loss due to evapotranspiration), correlations between mean
314 annual drip rate and annual precipitation amount were calculated (Fig. 7B). Positive
315 correlations at the 95% confidence level were found for TS 2 and TS 3 for the same year
316 interval, while correlation coefficients of TS 1 and 5 are just below the 95% confidence level.
317 Several sources of error must be considered, however, which lead to a lack of correlation at
318 the 95% confidence level. Lack of data (< 12 for annual means) may be the problem in case of
319 drip site TS 5, since neither infiltration nor precipitation correlate at the 95% confidence level
320 with drip rate. This might also be the case for sites TS 1 and 2. The calculated mean annual
321 drip rate of the former might be biased, since it shows pronounced seasonal drip rate
322 variability, with most changes not being covered by the monitoring (Figs. 5 and S1 in
323 supplementary material). Finally, the calculated mean annual infiltration in the soil reflects

324 the *potential* rather than *effective* infiltration. Furthermore, it must be kept in mind that
325 effective infiltration is biased towards winter (Wackerbarth et al., 2010; Riechelmann et al.,
326 2011), which might affect the correlation.

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

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

340 The drip characteristics of all drip sites, plotted according to Smart and Friederich
341 (1987) and Baker et al. (1997; see Figs. 8 and S1 in supplementary material to this paper)
342 highlight minor variability, with more or less the same drip characteristics over time. Drip
343 behaviour changed drastically at TS 8 during the monitoring period (Fig. 8): while seasonal
344 drip characteristics prevailed in 2008 and 2009, this drip shows seepage flow behaviour
345 between 2010 and 2012. Possible reasons for this change in drip characteristics include: (i) the
346 flow paths and the reservoir behaviour in the epikarst underwent changes as a result of
347 strongly variable rainfall events (Tooth and Fairchild, 2003), (ii) the flow paths of percolating
348 water changed or became blocked due to prior calcite precipitation (PCP; Fairchild et al.,

349 2006) occluding the flow paths of water; (iii) the overhanging stalactite was broken off
350 (earthquake, human interference etc.) resulting in drip parameter changes (Baldini et al.,
351 2006). Amongst these scenarios, it is conceivable that rainfall filled the reservoir feeding TS 8
352 to a threshold resulting in a more continuous water flow into the cave. PCP is a more likely
353 explanation for the change in drip behaviour as documented for this site (Riechelmann et al.,
354 2011). The stalactite was removed in June 2008, but the change in drip rate lagged by one
355 year, suggesting that the drip pattern was not controlled by the stalactite and thus the third
356 option mentioned above is considered unlikely. Concluding, the drip rate at site TS 8 is
357 controlled by infiltration and hence rainfall, but the dripwater signal reflecting both of these
358 parameters is strongly affected by prior calcite precipitation in the aquifer. Although the
359 catchment of the cave is partly sealed, infiltration and thus the precipitation signal can still be
360 recognized in the drip rate.

361

362 *5.2 Constraints on the water transfer time*

363

364 Water transfer times from the surface to the cave are highly variable and range from
365 days to several years not only for different caves but also for different drip sites in a given
366 cave (e.g., Kaufmann et al., 2003; Matthey et al., 2008b, Lambert and Aharon, 2010; Treble et
367 al., 2013; Genty et al., 2014, Breitenbach et al., 2015). Here, the dependency of rainwater
368 $\delta^{18}\text{O}$ and δD on temperature ($\delta^{18}\text{O}$ versus T: $r = 0.73$; δD versus T: $r = 0.68$; $n_{\text{both}} = 67$; $p_{\text{both}} <$
369 0.001 ; Riechelmann et al., 2011) is used to quantify the water transfer time. Correlation
370 coefficients (r) between $\delta^{18}\text{O}$ and δD of soil- and dripwater with surface air temperature were
371 calculated using data of the meteorological stations Hagen-Fley and Hemer. To this end,
372 monitoring data were correlated with temperature data of preceding years. Since rainwater

373 $\delta^{18}\text{O}$ and δD values correlate positively with temperature, only positive correlations are
374 relevant to determine the water transfer time.

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

387 Because dripwater at site TS 1 was collected as an instantaneous sample, the $\delta^{18}\text{O}$ and
388 δD values are not representative for the whole month as is the case for the other dripwaters.
389 Therefore, calculations with monthly data were only performed for all other drip sites
390 resulting in a lag of 29 to 31 months (Fig. 10). Difficulties occurred for TS 2, TS 3, and TS 8
391 in case of correlations using $\delta^{18}\text{O}$. There, the highest correlations are found between 41 and
392 66 months and only slightly lower ones are observed for a lag of 29 to 31 months.
393 Calculations using δD of all drip sites except TS 2 and $\delta^{18}\text{O}$ for TS 5 do not show these
394 features, which are most likely due to different mixing of the younger and older water in the
395 reservoir as a consequence of different transfer times. Variability in the transfer times
396 between different drip sites may arise due to: (i) variable thickness of the soil layer above

397 Bunker Cave, and (ii) differential thickness of the host rock overlying the cave, as well as (iii)
398 differential lengths and types of individual flow paths (e.g., Tooth and Fairchild, 2003). The
399 water retention capacity of soil is another factor that may or may not lead to an admixture
400 waters with different residence time in the soil and epikarst zone (Hölting and Coldewey,
401 2013). Following dry periods, the portion of older water in the soil increases (Kottek et al.,
402 2006) and the opposite is found during more humid periods. Although, rainfall is equally
403 distributed throughout the year, infiltration is not, as it is lower during summer than during
404 winter months (Wackerbarth et al., 2010; Riechelmann et al., 2011). Thus, water retention
405 capacity might have a small effect on water transfer times at Bunker Cave sulphate and nitrate
406 data show that dripwaters at sites TS 1 and TS 5 have shorter residence times compared to
407 sites TS 2, 3, and 8 (Riechelmann et al., 2011). This might explain why both $\delta^{18}\text{O}$ and δD
408 correlations with temperature performed well for TS 5. Drip water at TS 2 appears to be the
409 site with the longest and strongest buffering in the epikarst zone. In contrast to most others
410 this site displays seepage flow characteristics (see Appendix S1) and the oldest age based on
411 tritium data (Riechelmann et al., 2012a). This pattern might explain why the correlations at
412 this site are weakest. However, the shift in correlations using δD compared to the other drip
413 sites (Fig. 10) remains insufficiently explained. Since $\delta^{18}\text{O}$ and δD values of dripwater at site
414 TS 1 correlate with those of all other drip sites it can be assumed that the TS 1 water has a
415 similar transfer time of 29 to 31 months.

416 The results shown here suggest that the dripwater transfer time at all monitored drip
417 sites in Bunker Cave ranges between 29 to 31 months (ca. 2.5 years). This is in good
418 agreement with tritium data, suggesting a transfer time of 2-4 years (± 1 year; Kluge et al.,
419 2010). The tritium-based estimates, however, represent mixing ages of younger infiltrating
420 water and older water of the epikarst reservoir (Kluge et al., 2010; Riechelmann et al., 2012a).

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

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

426

427 *5.3 Influence of the North Atlantic Oscillation on the climate in western Germany*

428

429 The North Atlantic Oscillation (NAO) regulates Northern Hemisphere climate
430 variability and particularly so in western Europe and eastern North America (e.g., Marshall et
431 al., 2001; Visbeck et al., 2001; Baldini et al., 2008; Hurrell and Deser, 2010; Langebroek et
432 al., 2011; Pinto and Raible, 2012; Trouet et al., 2012; Wassenburg et al., 2013, 2016; Comas-
433 Bru et al., 2013). The NAO index is defined as the difference of sea-level pressure between
434 the Icelandic Low and the Azores High (Hurrell, 1995; Wanner et al., 2001). While the sea-
435 level pressure pattern is present throughout the year, it is most pronounced during winter
436 (Wanner et al., 2001; Pinto and Raible, 2012). Thus, most often the winter (December to
437 March) NAO index is used when studying climatic variability in the North Atlantic realm
438 (Proctor et al., 2000; Trouet et al., 2009; Baker et al., 2015). During a negative NAO mode,
439 the winter in Europe is dominated by cold and dry conditions, while during a positive NAO
440 mode, mild and humid conditions prevail (Fig. 11A; Hurrell and van Loon, 1997; Marshall et
441 al., 2001). This NAO-temperature link is reflected in $\delta^{18}\text{O}$ of precipitation (Baldini et al.,
442 2008; Mischel et al., 2015; Comas-Bru et al., 2016) and thus can be reconstructed using
443 suitably sensitive speleothems.

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

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

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

469

470 *5.4 Wider implications of the present data set for speleothem research in general*

471

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

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

488 The most striking observation of the present study is the difference between hydraulic
489 response time, i.e. immediate drip rate response (<1 year; Fig. 7), and the transfer time of
490 water from the soil to the cave (ca. 2.5 years; Fig. 10). While drip rate response to annual
491 precipitation occurs without significant lag on (sub-)annual basis, the temperature signal is
492 delayed by up to 2.5 years. Thus, the precipitation and temperature signals recorded by
493 different proxies in speleothems are not fully synchronous. In case of Bunker Cave this delay
494 is negligible, because here speleothems record proxies on decadal rather than annual or

495 seasonal scales (Riechelmann et al., 2011; Fohlmeister et al., 2012). Such proxy biases to
496 either water transfer or hydraulic response time must be considered in (sub-)annual
497 reconstructions, and where the signal transfer times for both parameters differ.

498

499 **6. Conclusions**

500

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

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

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

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

524

525 **Acknowledgements**

526

527 This is a joint contribution of the collaborative research initiative DAPHNE (DFG
528 Forschergruppe 668) and CHARON (DFG Forschergruppe 1644), both financed by the
529 German Science Foundation (DFG). This study received funding from the European Union's
530 Horizon 2020 Research and Innovation programme under the Marie Skłodowska-Curie grant
531 agreement No 691037 (to S.F.M.B.). The Speleogroup Letmathe is thanked for their support
532 in monitoring Bunker Cave and the student assistants C. Kirchmann, T. Meyer and M. Lyhs
533 are thanked for their help during monitoring tours. We would also like to thank Y. Kocot and
534 S. Mischel for sampling rainwater in 2012. Y. Dublyansky and M. Wimmer are thanked for
535 measuring $\delta^{18}\text{O}$ and δD data. We are grateful to the IAEA and especially S. Terzer for
536 providing an updated GNIP dataset.

537

538 **References**

539 Affolter, S., Häuselmann, A.D., Fleitmann, D., Häuselmann, P. and Leuenberger, M., 2015.

540 Triple isotope (δD , $\delta^{17}\text{O}$, $\delta^{18}\text{O}$) study on precipitation, dripwater and speleothem fluid
541 inclusions for a Western Central European cave (NW Switzerland). Quaternary
542 Science Reviews, 127: 73-89.

543 Baker, A., Barnes, W.L. and Smart, P.L., 1997. Variations in the discharge and organic matter

544 content of stalagmite dripwaters in Lower Cave, Bristol. *Hydrological Processes*, 11:
545 1541-1555.

546 Baker, A., Genty, D. and Fairchild, I.J., 2000. Hydrological characterisation of stalagmite
547 dripwaters at Grotte de Villars, Dordogne, by the analysis of inorganic species and
548 luminescent organic matter. *Hydrology and Earth System Sciences*, 4(3): 439-449.

549 Baker, A., Hellstrom, J.C., Kelly, B.F.J., Mariethoz, G. and Trouet, V., 2015. A composite
550 annual-resolution stalagmite record of North Atlantic climate over the last three
551 millennia. *Scientific Reports*, 5: 8.

552 Baldini, L.M., McDermott, F., Foley, A.M. and Baldini, J.U.L., 2008. Spatial variability in
553 the European winter precipitation $\delta^{18}\text{O}$ -NAO relationship: Implications for
554 reconstructing NAO-mode climate variability in the Holocene. *Geophysical Research*
555 *Letters*, 35: L04709.

556 Baldini, J.U.L., McDermott, F. and Fairchild, I.J., 2006. Spatial variability in cave dripwater
557 hydrochemistry: Implications for stalagmite paleoclimate records. *Chemical Geology*,
558 235: 390-404.

559 Breitenbach, S.F.M., Lechleitner, F. A., Meyer, H., Diengdoh, G., Matthey, D., and Marwan,
560 N., 2015. Cave ventilation and rainfall signals in dripwater in a monsoonal setting - a
561 monitoring study from NE India. *Chemical Geology*, 402: 111-124.

562 Cheng, H., Edwards, R. L., Shen, C.-C., Polyak, V. J., Asmerom, Y., Woodhead, J.,
563 Hellstrom,
564 J., Wang, Y., Kong, X., Spötl, C., Wang, X., and Alexander Jr., E. C., 2013.
565 Improvement in ^{230}Th dating, ^{230}Th and ^{234}U half-life values, and U-Th isotopic
566 measurement by multi-collector inductively coupled plasma mass spectrometry. *Earth*
567 *and Planetary Science Letters*, 371-372: 82-91.

568 Comas-Bru, L., McDermott, F. and Werner, M., 2016. The effect of the East Atlantic pattern

569 on the precipitation $\delta^{18}\text{O}$ -NAO relationship in Europe. *Climate Dynamics*, doi:
570 10.1007/s00382-015-2950-1.

571 Dorale, J.A., Edwards, R. L., Alexander, E. C., Shen, C.-C., Richards, D. A., and Cheng, H.,
572 2004. Uranium-Series Dating of Speleothems: Current Techniques, Limits, &
573 Applications. In: I.D. Sasowsky and J. Myroie (Editors), *Studies of Cave Sediments:
574 Physical and Chemical Records of Paleoclimate*. Springer US, Boston, MA, pp. 177-
575 197.

576 Fairchild, I.J. and Baker, A., 2012. *Speleothem Science - From Process to Past Environments*.
577 Wiley-Blackwell, Chichester, 432 pp.

578 Fairchild, I.J., Tuckwell, G.W., Baker, A. and Tooth, A.F., 2006. Modelling of dripwater
579 hydrology and hydrogeochemistry in a weakly karstified aquifer (Bath, UK):
580 Implications for climate change studies *Journal of Hydrology*, 321: 213-231.

581 Fohlmeister, J., Schröder-Ritzrau, A., Scholz, D., Spötl, C., Riechelmann, D.F.C., Mudelsee,
582 M., Wackerbarth, A., Gerdes, A., Riechelmann, S., Immenhauser, A., Richter, D.K.,
583 and Mangini, A., 2012. Bunker Cave stalagmites: an archive for central European
584 Holocene climate variability. *Climate of the Past*, 8: 1751-1764.

585 Gat, J.R., Mook, W.G. and Meijer, H.A.J., 2000. *Environmental Isotopes in the Hydrological
586 Cycle. Principles and Applications Ch. vol. II: Atmospheric Water*, IAEA, Vienna.

587 Genty, D. and Deflandre, G., 1998. Drip flow variations under a stalactite of Père Noël cave
588 (Belgium). Evidence of seasonal variations and air pressure constraints *Journal of
589 Hydrology*, 211: 208-232.

590 Genty, D., Labuhn, I., Hoffmann, G., Danis, P.A., Mestre, O., Bourges, F., Wainer, K.,
591 Massault, M., Van Exter, S., Régnier, E., Orengo, P., Falourd, S., and Minster, B.,
592 2014. Rainfall and cave water isotopic relationships in two South-France sites.
593 *Geochimica et Cosmochimica Acta*, 131: 323-343.

594 Grebe, W., 1993. Die Bunkerhöhle in Iserlohn-Letmathe (Sauerland). Mitt. Verb. dt. Höhlen-
595 und Karstforsch., 39(2): 22-23.

596 Hammerschmidt, E., Niggemann, S., Grebe, W., Oelze, R., Brix, M.R., and Richter, D.K.,
597 1995. Höhlen in Iserlohn. Schriften zur Karst- und Höhlenkunde in Westfalen, 1: 153.

598 Haude, W., 1955. Zur Bestimmung der Verdunstung auf möglichst einfache Weise.
599 Mitteilungen des Deutschen Wetterdienstes, 2: 1-24.

600 Hölting, B. and Coldewey, W.G., 2013. Hydrogeologie - Einführung in die Allgemeine und
601 Angewandte Hydrogeologie. Spektrum Akademischer Verlag, Heidelberg, 438 pp.

602 Hurrell, J.W., 1995. Decadal trends in the North Atlantic Oscillation: Regional temperatures
603 and precipitation. Science, 269: 676-679.

604 Hurrell, J.W. and Deser, C., 2010. North Atlantic climate variability: The role of the North
605 Atlantic Oscillation. Journal of Marine Systems, 79: 231-244.

606 Hurrell, J.W. and van Loon, H., 1997. Decadal variations in climate associated with the North
607 Atlantic oscillation. Climatic Change, 36(3-4): 301-326.

608 Immenhauser, A., Buhl, D., Richter, D.K., Niedermayr, A., Riechelmann, D., Dietzel, M. and
609 Schulte, U., 2010. Magnesium-isotope fractionation during low-Mg calcite
610 precipitation in a limestone cave - field study and experiments. Geochimica et
611 Cosmochimica Acta, 74(15): 4346-4364.

612 Kaufman, A., Bar-Matthews, M., Ayalon, A. and Carmi, I., 2003. The vadose flow above
613 Soreq Cave, Israel: a tritium study of the cave waters. Journal of Hydrology, 273: 155-
614 163.

615 Kluge, T., Riechelmann, D.F.C., Wieser, M., Spötl, C., Sültenfuß, J., Schröder-Ritzrau, A.,
616 Niggemann, S., and Aeschbach-Hertig, W., 2010. Dating cave dripwater by tritium.
617 Journal of Hydrology, 394(3-4): 396-406.

618 Kluge, T., Affek, H.P., Marx, T., Aeschbach-Hertig, W., Riechelmann, D.F.C., Scholz, D.,

619 Riechelmann, S., Immenhauser, A., Richter, D.K., Fohlmeister, J., Wackerbarth, A.,
620 Mangini, A., and Spötl, C., 2013. Reconstruction of drip-water $\delta^{18}\text{O}$ based on calcite
621 oxygen and clumped isotopes of speleothems from Bunker Cave (Germany). *Climate*
622 *of the Past*, 9: 377-391.

623 Kottek, M., Grieser, J., Beck, C., Rudolf, B. and Rubel, F., 2006. World map of the Köppen-
624 Geiger climate classification updated. *Meteorologische Zeitschrift*, 15(3): 259-263.

625 Lachniet, M.S., 2009. Climatic and environmental controls on speleothem oxygen-isotope
626 values. *Quaternary Science Reviews*, 28: 412-432.

627 Lambert, W.J. and Aharon, P., 2010. Oxygen and hydrogen isotopes of rainfall and dripwater
628 at DeSoto Caverns (Alabama, USA): Key to understanding past variability of moisture
629 transport from the Gulf of Mexico. *Geochimica et Cosmochimica Acta*, 74(3): 846-
630 861.

631 Langebroek, P.M., Werner, M. and Lohmann, G., 2011. Climate information imprinted in
632 oxygen-isotopic composition of precipitation in Europe. *Earth and Planetary Science*
633 *Letters*, 311: 144-154.

634 [Luetscher, M., Boch, R., Sodemann, H., Spötl, C., Cheng, H., Edwards, R. L., Frisia, S., Hof,](#)
635 [F., and Muller, W., 2015. North Atlantic storm track changes during the Last Glacial](#)
636 [Maximum recorded by Alpine speleothems. *Nature Communications*, 6: 6.](#)

637 [Mangini, A., Spötl, C. and Verdes, P., 2005. Reconstruction of temperature in the Central](#)
638 [Alps](#)
639 [during the past 2000 yr from a \$\delta^{18}\text{O}\$ stalagmite record. *Earth and Planetary Science*](#)
640 [Letters](#), 235: 741-751.

641 Marshall, J., Kushner, Y., Battisti, D., Chang, P., Czaja, A., Dickson, R., Hurrell, J.,

642 McCartney, M., Saravanan, R., and Visbeck, M., 2001. North Atlantic climate
643 variability: Phenomena, impacts and mechanisms. *International Journal of*
644 *Climatology*, 21(15): 1863-1898.

645 Matthey, D. and Collister, C., 2008. Acoustic drip counters for environmental monitoring.
646 *BCRA Cave Radio & Electronics Group Journal*, 70: 14-17.

647 Matthey, D., Latin, J.P. and Ainsworth, M., 2008b. Cave monitoring and calibration of a $\delta^{18}\text{O}$ -
648 climate transfer function for a Gibraltar speleothem. *PAGES News*, 16(3): 15-17.

649 Matthey, D., Lowry, D., Duffet, J., Fisher, R., Hodge, E. and Frisia, S., 2008a. A 53 year
650 seasonally resolved oxygen and carbon isotope record from a modern Gibraltar
651 speleothem: Reconstructed dripwater and relationship to local precipitation. *Earth and*
652 *Planetary Science Letters*, 269: 80-95.

653 [Matthey, D.P., Atkinson, T. C., Barker, J. A., Fisher, R., Latin, J. P., Durrell, R., and](#)
654 [Ainsworth,](#)
655 [M., 2016. Carbon dioxide, ground air and carbon cycling in Gibraltar karst.](#)
656 [Geochimica et Cosmochimica Acta](#), 184: 88-113.

657 McGarry, S., Bar-Matthews, M., Matthews, A., Vaks, A., Schilman, B., and Ayalon, A.,
658 2004. Constraints on hydrological and paleotemperature variations in the Eastern
659 Mediterranean region in the last 140 ka given by the δD values of speleothem fluid
660 inclusions. *Quaternary Science Reviews*, 23(7-8): 919-934.

661 Miorandi, R., Borsato, A., Frisia, S., Fairchild, I.J. and Richter, D.K., 2010. Epikarst
662 hydrology and implications for stalagmite capture of climate changes at Grotta di
663 Ernesto (N.E. Italy): results from long-term monitoring. *Hydrological Processes*, 24:
664 3101-3114.

665 Mischel, S.A., Scholz, D. and Spötl, C., 2015. $\delta^{18}\text{O}$ values of cave dripwater: a promising

666 proxy for the reconstruction of the North Atlantic Oscillation? *Climate Dynamics*, 45:
667 3035-3050.

668 Münsterer, C., Fohlmeister, J., Christl, M., Schröder-Ritzrau, A., Alfimov, V., Ivy-Ochs, S.,
669 Wackerbarth, A., and Mangini, A., 2012. Cosmogenic ^{36}Cl in karst waters from
670 Bunker Cave North Western Germany - A tool to derive local evapotranspiration?
671 *Geochimica et Cosmochimica Acta*, 86: 138-149.

672 [Niggemann, S., Mangini, A., Mudelsee, M., Richter, D.K. and Wurth, G., 2003. Sub-](#)
673 [Milankovitch climatic cycles in Holocene stalagmites from Sauerland, Germany. *Earth*](#)
674 [and *Planetary Science Letters*, 216: 539-547.](#)

675 Pinto, J.G. and Raible, C.C., 2012. Past and recent changes in the North Atlantic Oscillation.
676 *Wiley Interdisciplinary Reviews-Climate Change*, 3(1): 79-90.

677 Proctor, J.C., Baker, A., Barnes, L.W. and Gilmour, A.M., 2000. A thousand year speleothem
678 proxy record of North Atlantic climate from Scotland. *Climate Dynamics*, 16(10):
679 815-820.

680 Riechelmann, D.F.C., 2010. Aktuospeläologische Untersuchungen in der Bunkerhöhle des
681 Iserlohner Massenkalks (NRW/Deutschland): Signifikanz für kontinentale
682 Klimaarchive. PhD thesis, Ruhr-Universität Bochum, 199 pp.

683 Riechelmann, D.F.C., Schröder-Ritzrau, A., Scholz, D., Fohlmeister, J., Spötl, C., Richter,
684 D.K., and Mangini, A., 2011. Monitoring Bunker Cave (NW Germany): A prerequisite
685 to interpret geochemical proxy data of speleothems from this site. *Journal of*
686 *Hydrology*, 409(3-4): 682-695.

687 Riechelmann, D.F.C., Deininger, M., Scholz, D., Riechelmann, S., Schröder-Ritzrau, A.,
688 Spötl, C., Richter, D.K., Mangini, A., and Immenhauser, A., 2013. Disequilibrium
689 carbon and oxygen isotope fractionation in recent cave calcite: Comparison of cave
690 precipitates and model data. *Geochimica et Cosmochimica Acta*, 103: 232-244.

691 Riechelmann, S., Buhl, D., Schröder-Ritzrau, A., Spötl, C., Riechelmann, D.F.C., Richter,
692 D.K., Kluge, T., Marx, T., and Immenhauser, A., 2012a. Hydrogeochemistry and
693 fractionation pathways of Mg isotopes in a continental weathering system: Lessons
694 from field experiments. *Chemical Geology*, 300-301: 109-122.

695 Riechelmann, S., Buhl, D., Schröder-Ritzrau, A., Riechelmann, D.F.C., Richter, D.K.,
696 Vonhof, H.B., Wassenburg, J.A., Geske, A., Spötl, C., and Immenhauser, A., 2012b.
697 The magnesium isotope record of cave carbonate archives. *Climate of the Past*, 8:
698 1849-1867.

699 Riechelmann, S., Schröder-Ritzrau, A., Wassenburg, J.A., Schreuer, J., Richter, D.K.,
700 Riechelmann, D.F.C., Terente, M., Constantin, S., Mangini, A., and Immenhauser, A.,
701 2014. Physicochemical characteristics of dripwaters: Influence on mineralogy and
702 crystal morphology of recent cave carbonate precipitates. *Geochimica et*
703 *Cosmochimica Acta*, 145: 13-29.

704 Scheudoschi, M., 2007. Geologische Kartierung der Bunkerhöhle im Massenkalk bei Iserlohn,
705 Unpublished report Ruhr-Universität Bochum, 67 pp.

706 [Scholz, D. and Hoffmann, D.L., 2008. ²³⁰Th/U-dating of fossil reef corals and speleothems.](#)
707 [Journal of Quaternary Science \(Eiszeitalter und Gegenwart\), 57\(1-2\): 52-76.](#)

708 [Scholz, D., Frisia, S., Borsato, A., Spötl, C., Fohlmeister, J., Mudelsee, M., Miorandi, R., and](#)
709 [Mangini, A., 2012. Holocene climate variability in north-eastern Italy: potential](#)
710 [influence of the NAO and solar activity recorded by speleothem data. *Climate of the*](#)
711 [Past, 8: 1367-1383.](#)

712 Smart, P.L. and Friederich, H., 1987. Water movement and storage in the unsaturated zone of
713 a maturely karstified carbonate aquifer, Mendip Hills, England, Proceedings of the
714 Environmental Problems in Karst Terranes and their Solutions Conference, Bowling
715 Green, Kentucky, USA, pp. 57-87.

716 Spötl, C., Fairchild, I.J. and Tooth, A.F., 2005. Cave air control on dripwater geochemistry,
717 Obir Caves (Austria): Implications for speleothem deposition in dynamically
718 ventilated caves. *Geochimica et Cosmochimica Acta*, 69(10): 2451 - 2468.

719 Stumpp, C., Klaus, J. and Stichler, W., 2014. Analysis of long-term stable isotopic
720 composition in German precipitation. *Journal of Hydrology*, 517: 351-361.

721 Tooth, A.F. and Fairchild, I.J., 2003. Soil and karst aquifer hydrological controls on the
722 geochemical evolution of speleothem-forming dripwaters, Crag Cave, southwest
723 Ireland. *Journal of Hydrology*, 273: 51-68.

724 Treble, P.C., Bradley, C., Wood, A., Baker, A., Jex, C.N., Fairchild, I.J., Gagan, M.K.,
725 Cowley, J., and Azcurra, C., 2013. An isotopic and modelling study of flow paths and
726 storage in Quaternary calcarenite, SW Australia: implications for speleothem
727 paleoclimate records. *Quaternary Science Reviews*, 64: 90-103.

728 Treble, P.C., Fairchild, I. J., Baker, A., Meredith, K. T., Andersen, M. S., Salmon, S. U.,
729 Bradley, C., Wynn, P. M., Hankin, S. I., Wood, A., and McGuire, E., 2016. Roles of
730 forest bioproductivity, transpiration and fire in a nine-year record of cave dripwater
731 chemistry from southwest Australia. *Geochimica et Cosmochimica Acta*, 184: 132-
732 150.

733 Tremaine, D.M. and Froelich, P.N., 2013. Speleothem trace element signatures: A hydrologic
734 geochemical study of modern cave dripwaters and farmed calcite. *Geochimica et*
735 *Cosmochimica Acta*, 121: 522-545.

736 Tremaine, D.M., Froelich, P.N. and Wang, Y., 2011. Speleothem calcite farmed *in situ*:
737 Modern calibration of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ paleoclimate proxies in a continuously-monitored
738 natural cave system. *Geochimica et Cosmochimica Acta*, 75: 4929-4950.

739 Trouet, V., Scourse, J.D. and Raible, C.C., 2012. North Atlantic storminess and Atlantic

740 Meridional Overturning Circulation during the last millenium: Reconciling
741 contradictory proxy records of NAO variability. *Global and Planetary Change*, 84-85:
742 48-55.

743 [Trouet, V., Esper, J., Graham, N. E., Baker, A., Scourse, J. D., and Frank, D. C., 2009.](#)
744 [Persistent](#)
745 [positive North Atlantic Oscillation Mode dominated the Medieval Climate Anomaly.](#)
746 [Science, 324\(78\): 78-80.](#)

747 van Breukelen, M.R., Vonhof, H.B., Hellstrom, J.C., Wester, W.C.G. and Kroon, D., 2008.
748 Fossil dripwater in stalagmites reveals Holocene temperature and rainfall variation in
749 Amazonia. *Earth and Planetary Science Letters*, 275: 54-60.

750 van Rangelbergh, M., Verheyden, S., Allan, M., Quinif, Y., Keppens, E., and Claeys, P.,
751 2014. Monitoring of a fast-growing speleothem site from the Han-sur-Lesse cave,
752 Belgium, indicates equilibrium deposition of the seasonal $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signals in
753 calcite. *Climate of the Past*, 10: 1871-1885.

754 Visbeck, M.H., Hurrell, J.W., Polvani, L. and Cullen, H.M., 2001. The North Atlantic
755 Oscillation: Past, present, and future. *Proceedings of the National Academy of*
756 *Sciences*, 98(23): 12876-12877.

757 Vonhof, H. B., van Breukelen, M. R., Postma, O., Rowe, P. J., Atkinson, T. C., and Kroon,
758 D., 2006. A continuous-flow crushing device for on-line $\delta^2\text{H}$ analysis of fluid
759 inclusion water in speleothems. *Rapid Commun. Mass Spectrom.*, 20: 2553–2558.

760 von Kamp, H., 1972. *Geologische Karte von Nordrhein-Westfalen 1:25.000. Erläuterungen zu*
761 *Blatt 4611 Hohenlimburg. Geologisches Landesamt Nordrhein-Westfalen, Krefeld,*
762 *182 pp.*

763 von Kamp, H., and Ribbert, K.-H., 2005. *Geologische Karte von Nordrhein-Westfalen*
764 *1:25.000. Erläuterungen zu Blatt 4611 Hagen-Hohenlimburg, Krefeld, 156 pp.*

765 Wackerbarth, A., Scholz, D., Fohlmeister, J. and Mangini, A., 2010. Modelling the $\delta^{18}\text{O}$ value
766 of cave drip water and speleothem calcite. *Earth and Planetary Science Letters*, 299:
767 387-397.

768 Wackerbarth, A., Langebroek, P.M., Werner, M., Lohmann, G., Riechelmann, S., Borsato, A.,
769 and Mangini, A., 2012. Simulated oxygen isotopes in cave dripwater and speleothem
770 calcite in European caves. *Climate of the Past*, 8: 1781-1799.

771 Wanner, H., Brönnimann, S., Casty, C., Gyalistras, D., Luterbacher, J., Schmutz, C.,
772 Stephenson, D.B., and Xoplaki, E., 2001. North Atlantic Oscillation - Concepts and
773 studies. *Surveys in Geophysics*, 22(4): 321-382.

774 Wassenburg, J.A., Immenhauser, A., Richter, D.K., Niedermayr, A., Riechelmann, S.,
775 Fietzke, J., Scholz, D., Jochum, K.P., Fohlmeister, J., Schröder-Ritzrau, A., Sabaoui,
776 A., Riechelmann, D.F.C., Schneider, L., and Esper, J., 2013. Moroccan speleothem
777 and tree ring records suggest a variable positive state of the North Atlantic Oscillation
778 during the Medieval Warm Period. *Earth and Planetary Science Letters*, 375: 291-302.

779 Wassenburg, J.A. Dietrich, S., Fietzke, J., Fohlmeister, J., Jochum, K.P., Scholz, D., Richter,
780 D.K., Sabaoui, A., Spötl, C., Lohmann, G., Andreae, M.O., and Immenhauser, A.,
781 2016. Reorganization of the North Atlantic Oscillation during early Holocene
782 deglaciation. *Nature Geoscience*, 9(8): 602-+.

783

784 **Figure Captions**

785

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

789

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

793

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

802

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

807

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

810

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

812

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

816

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

819

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

822

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

825

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

26 **ABSTRACT**

27 The last two decades have seen a considerable increase in studies using speleothems as
28 archives of past climate variability. Caves under study are now monitored for a wide range of
29 environmental parameters and results placed in context with speleothem data. The present
30 study investigates trends from a seven year long monitoring of Bunker Cave, western
31 Germany, in order to assess the hydraulic response and transfer time of meteoric water from
32 the surface to the cave. Rain-, soil-, and dripwater were collected from August 2006 to August
33 2013 at a monthly to bimonthly resolution and their oxygen and hydrogen isotope
34 composition was measured. Furthermore, drip rates were quantified. Due to different drip
35 characteristics, annual mean values were calculated for the drip rates of each drip site.
36 Correlations of the annual mean drip rate of each site with precipitation and infiltration
37 demonstrate that the annual infiltration, and thus the annual precipitation control the inter-
38 annual drip-rate variability for all except one site. The hydraulic response is not delayed. All
39 drip sites display identical long-term trends, which suggests a draining of a common karst
40 reservoir over these seven years of monitoring. Correlations of soil- and dripwater monthly
41 $\delta^{18}\text{O}$ and δD values with atmospheric temperature data reveal water transfer times of 3
42 months for soilwater at site BW 2 (40 cm depth) and 4 months for 70 cm depth (soilwater at
43 site BW 1). Finally, the water reaches the cave chambers (15 to 30 m below land surface)
44 after ca. 2.5 years. Consequently, a temporal offset of 29 to 31 months (ca. 2.5 years) between
45 the hydraulic response time (no time lag on annual basis) and the water transfer time (time lag
46 of 29 to 31 months) was found, which is negligible with regard to Bunker Cave speleothems
47 because of their slow growth rates. Variations in drip rate and thus, precipitation and
48 infiltration are recorded by $\delta^{13}\text{C}$ and Mg/Ca ratios in speleothem calcite. Speleothem $\delta^{18}\text{O}$
49 values reflect both temperature and precipitation signals due to drip rate-related fractionation
50 processes. We document that long-term patterns in temperature and precipitation are recorded

51 in dripwater patterns of Bunker Cave and that these are linked to the North Atlantic
52 Oscillation (NAO).

53

54 **1. Introduction**

55

56 Palaeoclimate reconstructions based on speleothems, i.e. mostly carbonate deposits
57 formed in caves, have increased significantly during the last two decades (for a summary, see
58 Fairchild and Baker, 2012). The most important strengths of speleothems are the precise
59 $^{230}\text{Th}/\text{U}$ dating (e.g., Dorale et al., 2004; Scholz and Hoffmann, 2008; Cheng et al., 2013) and
60 the availability of several, mostly geochemical, parameters such as carbon and oxygen isotope
61 values, major and trace elemental abundances, and $\delta^{18}\text{O}$ and δD of fluid inclusions (e.g.,
62 Niggemann et al., 2003; Mangini et al., 2005; Vonhof et al., 2006; Fohlmeister et al., 2012;
63 Scholz et al., 2012; Luetscher et al., 2015). These can be used for single- or multi-proxy
64 approaches to reconstruct past climate dynamics.

65 In order to gain a better understanding of the processes influencing geochemical
66 proxies in the soil and epikarst zone, as well as processes acting during deposition of
67 speleothems, sophisticated monitoring programmes have been established (e.g., Spötl et al.,
68 2005; Matthey et al., 2008b, 2016; Riechelmann et al., 2011, Wassenburg et al., 2013; Genty et
69 al., 2014; van Rampelbergh et al., 2014, Breitenbach et al., 2015; Treble et al., 2016). In the
70 context of these efforts, cave air temperature, pCO_2 and humidity, drip rate, as well as the
71 isotopic composition of rain-, soil- and dripwater and the element concentrations of soil-, and
72 dripwater have been recorded. Furthermore, in order to link the dripwater with speleothems
73 used for palaeoclimate reconstructions, recent cave carbonate precipitates have been
74 investigated in combination with their respective dripwater composition and the hydraulic

75 regime in the cave (e.g., Miorandi et al., 2010; Tremaine et al., 2011; Riechelmann et al.,
76 2013, 2014).

77 Most monitoring studies focused on seasonal variations of the above-mentioned
78 parameters, whereby, for example, the drip rate was analysed to study the response to rainfall
79 events or the hydrological connection of the drip sites (Baker et al., 1997; Matthey et al.,
80 2008b; Riechelmann et al., 2011). The analysis of dripwater $\delta^{18}\text{O}$ and δD values shows either
81 seasonal variations (Matthey et al., 2008a, Breitenbach et al., 2015) or rather stable values
82 close to the annual mean of rainwater (Riechelmann et al., 2011; van Rampelbergh et al.,
83 2014). Seasonal variations in cave dripwater reflect a fast transfer of the water (e.g.,
84 Breitenbach et al., 2015). The lack of an intra-annual pattern points to strong mixing in the
85 epikarst and/or the vadose zone with transfer times between the soil and the cave drip site in
86 excess of one year (e.g., Riechelmann et al., 2011; van Rampelbergh et al., 2014). Financial
87 constraints, accessibility, or lack in manpower commonly limit monitoring studies to
88 durations of a few years or less. Thus far, only a very limited number of studies focused on
89 multi-annual trends of the monitored parameters and implications for speleothem research
90 (Genty and Deflandre, 1998; Treble et al., 2013; Genty et al., 2014, Breitenbach et al., 2015;
91 Matthey et al., 2016). To the knowledge of the authors, only the study by Genty et al. (2014)
92 detrended the seasonal signal in order to gain insights in potential longer-term (> 5yrs) trends.
93 This is of significance as particularly the longer-term trends are relevant for the assessment of
94 proxy data from speleothems recording decadal or longer variability only.

95 This paper documents and discusses observations of precipitation/infiltration and drip
96 rate as well as atmospheric temperature and the oxygen and hydrogen isotopic composition of
97 rain-, soil-, and cave dripwater from a seven year-long monitoring campaign in Bunker Cave
98 in northwestern Germany. The main goals of the present study are: (i) to quantify the longer-
99 term (multi-annual) variability of the environmental parameters; (ii) to assess the response

100 time of the carbonate precipitating drip sites to these parameters; (iii) to identify signal
101 smoothing and possible alteration processes during percolation through the epikarst; and (iv)
102 to draw, where possible, general implications for speleothem research.

103

104 **2. Climate and cave parameters**

105

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

113 The host rock consists of Middle to Upper Devonian massive limestone (von Kamp,
114 1972). The rock overburden of the cave is between 15 and 30 m (Grebe, 1993) and the host
115 rock is overlain by ca. 70 cm inceptisol to alfisol (USDA Soil Taxonomy). The colour varies
116 between dark and yellowish brown (10YR 3/3 and 10YR 5/6) for the upper soil layers and
117 bright reddish brown to bright brown (5YR 5/8 to 7.5YR 5/8) for the lower layer (Munsell
118 soil colour charts). The vegetation above the cave consists of deciduous forest (mainly ash
119 and beech trees) and scrubs (Riechelmann et al., 2011). Bedding dips to the North or
120 Northwest (von Kamp and Ribbert, 2005) and water percolates mainly along fractures and
121 bedding planes. This feature and the fact that Bunker Cave is located in a south-facing hill
122 reduces the effective catchment of the cave dripwater to a few hundred m². Furthermore, the
123 Dröscheder Emst karst plateau is partly used as a residential area and ca. 15 to 20% of the
124 catchment area is anthropogenically sealed. Furthermore, a railway route runs above the cave.

125

126 **3. Materials and Methods**

127

128 *3.1 Monitoring and sample collection of rain-, soil- and dripwater*

129

130 The monitoring programme performed in and above Bunker Cave ran from August
131 2006 to August 2013. Rainwater samples were collected with a rain gauge according to the
132 DIN 58666C norm on the roof of the German Cave Museum Iserlohn (51°22'N, 07°38'E; 175
133 m asl), located 1.5 km from Bunker Cave (Fig. 1). Rainfall amount was measured and
134 sampled daily and collected as monthly samples between 2007 and 2012. In 2013, rainwater
135 samples were collected only bimonthly. Rainwater samples were stored in PET bottles in a
136 fridge to minimize evaporation.

137 Two soilwater sampling sites were installed above Bunker Cave. The soilwater suction
138 probes were manufactured by Umwelt-Geräte-Technik GmbH (UGT, Germany). One probe
139 (BW 1) was installed at a depth of 70 cm and water was sampled monthly between 2007 and
140 2011. The second probe (BW 2) sampled water at 40 cm depth in monthly intervals between
141 2009 and 2011. In 2012 and 2013, both soilwater sites were sampled only bimonthly.

142 In total, five drip sites (TS 1, TS 2, TS 3, TS 5 and TS 8; Fig. 2) were monitored in
143 Bunker Cave from 2006 to 2013. Sampling at drip site TS 8 started in 2007. Drip sites TS 1
144 and TS 5 are located in chamber 1. All other sites are located in chamber 2 of Bunker Cave
145 (Fig. 2). Dripwater samples were integrated over one month in order to obtain sufficient
146 volumes of water for multi-proxy geochemical analyses. These monthly samples were taken
147 between 2006 and 2011, while bimonthly samples were taken between 2012 and 2013. An
148 exception is drip site TS 1, where sufficient water could be collected during each visit.
149 Dripwater first dripped onto a drip counter placed in a plastic box and was then transferred

150 into a closed bottle via tubing to minimize CO₂ degassing and potential evaporation.
151 Comparison of instantaneous and monthly collected water revealed similar δ¹⁸O values,
152 confirming that fractionation processes due to evaporation are negligible (Riechelmann et al.,
153 2011). For further details of the monitoring, the reader is referred to Riechelmann (2010) and
154 Riechelmann et al. (2011; 2012a; 2013; 2014).

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

157

$$158 \quad z \text{ [ml/time]} = \text{drip rate [drips/time]} * V \text{ [ml/drips]} \quad (1)$$

159

160 where V is the volume of each drip. The volume of a drip was determined by a defined
161 collection time, the total amount of water and the drip rate (in drips per min). In some cases,
162 the drip rate at site TS 8 was not quantified by means of a stopwatch, and was instead
163 calculated via the amount of an instantaneous water sample (collected during the monitoring
164 tour) and the known drip volume (determined as described above). Furthermore, drip rates
165 were measured automatically by acoustic drip counters (Stalagmate; Matthey and Collister,
166 2008), which were placed under drip sites TS 2 (2009-2013), TS 3 (2010-2013), TS 5 (2007-
167 2013) and TS 8 (2009-2013).

168

169 *3.2 δ¹⁸O and δD of rain-, soil- and dripwater*

170

171 The oxygen and hydrogen isotopic compositions of all water samples were determined
172 at the University of Innsbruck. Water samples were collected in small, airtight glass vials
173 without headspace. The oxygen isotope composition was analysed using a ThermoFinnigan
174 DELTA^{plus}XL mass spectrometer connected with a Gasbench II using the CO₂ equilibrium

175 technique. The 1σ reproducibility of the $\delta^{18}\text{O}$ values is $\pm 0.09\text{‰}$ VSMOW (Spötl et al., 2005).
176 The hydrogen isotope composition was measured using a ThermoFinnigan
177 DELTA^{plus} Advantage equipped with a TC/EA high-temperature pyrolysis unit. The 1σ
178 reproducibility is $\pm 1\text{‰}$ VSMOW.

179

180 *3.3 Evapotranspiration and infiltration*

181

182 Instrumental climate data of two nearby meteorological stations (Fig. 1) - Hagen-Fley
183 ($51^{\circ}25'\text{N}$, $07^{\circ}29'\text{E}$; 100 m asl; 2000-2007; www.dwd.de) and Hemer ($51^{\circ}23'\text{N}$, $07^{\circ}45'\text{E}$; 200
184 m asl; 2008-2013; www.meteo-media.de) - were used to calculate the evapotranspiration after
185 Haude (1955) using the following equation:

186

$$187 \quad E_{pot} [\text{mm/day}] = x [\text{mm/day} * \text{hPa}] * P^{13} [\text{hPa}] * (1 - (F^{13} [\%] / 100)) \quad (2)$$

188

189 where E_{pot} is the potential evaporation, x represents the monthly coefficient depending on
190 vegetation, P^{13} is the saturation pressure at 1 p.m. and F^{13} is the relative humidity at 1 p.m..

191 The saturation pressure was calculated using the Magnus-formula:

192

$$193 \quad P^{13} [\text{hPa}] = 6.107 [\text{hPa}] * 10^{((7.5 * T^{13} [^{\circ}\text{C}]) / (237 + T^{13} [^{\circ}\text{C}]))} \quad (3)$$

194

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

198

$$199 \quad Inf_{pot} [\text{mm/day}] = N [\text{mm/day}] - E_{pot} [\text{mm/day}] \quad (4)$$

200

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

203

204 *3.4 GNIP stations*

205

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

211

212 **4. Results**

213

214 Seasonally resolved monitoring data of rain-, soil- and dripwater of Bunker Cave were
215 partly published by Immenhauser et al. (2010), Kluge et al. (2010, 2013), Riechelmann et al.
216 (2011, 2012a, b, 2013, 2014), Fohlmeister et al. (2012), Münsterer et al. (2012), and
217 Wackerbarth et al. (2012). In this study, we present monthly data as well as annual mean
218 values of the relevant parameters, which were calculated using the monthly or bimonthly
219 values of the respective year to (i) examine long-term variability and (ii) compare these data
220 with precipitation/infiltration and temperature data to determine the hydraulic response time
221 and water transfer time. Annual means were obtained from monthly data (January to
222 December).

223

224 *4.1 Precipitation, infiltration, temperature and rainwater $\delta^{18}O$ and δD*

225

226 For this study, the time period from 2000 to 2013 is considered. Annual mean values
227 are shown for all years except 2013, since monitoring stopped in August of this year. Hence,
228 all mean values for 2013 are related to this time interval. Furthermore, annual mean values for
229 2006 were not calculated, due to insufficient data. The lowest annual precipitation sum (720
230 mm) was recorded in 2003, without considering 2013 with the lowest precipitation sum of
231 447 mm. The highest annual rainfall (1202 mm) and the highest mean annual infiltration (546
232 mm) occurred in 2007 (Fig. 3A). The lowest annual mean infiltration was observed in 2003 (-
233 171 mm). Infiltration at Bunker Cave is lower during summer months than during winter
234 (Riechelmann et al., 2011). Monthly temperature data show low values in winter and high
235 ones during summer. The lowest mean annual air temperature (7.1°C) was observed in 2010,
236 while the highest (11.3°C) was observed twice, in 2000 and 2007 (Fig. 3A).

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

243 Since monthly rainwater samples collected during the monitoring do not cover the
244 same time period as the monthly samples from the GNIP stations, mean annual values are
245 used here for comparison. Mean annual oxygen and hydrogen isotope values of rainwater
246 collected at the German Cave Museum correlate well with those of nearby GNIP stations
247 (Figs. 4A, B). The Local Meteoric Water Line (LMWL) of the rainwater (Fig. 4C) is close to
248 that of the GNIP station Bad Salzflun ($\delta\text{D} = 7.72 * \delta^{18}\text{O} + 5.7$; $r = 0.98$; Stumpp et al.,
249 2014). Thus, rainwater collected during the monitoring period reflects the climate conditions

250 of western Germany. The slope of 7.72 is close to that of the Global Meteoric Water Line (8),
251 indicating insignificant evaporation of the collected samples (Gat et al., 2000). Since all
252 dripwater data plot on the LMWL (Fig. 4C) evaporation in the soil, epikarst and cave
253 generates no significant imprint on their corresponding isotope values. Furthermore, both
254 isotope systems depend on the regional surface air temperature and the isotopic composition
255 of Bunker Cave dripwater reflects the infiltration weighted mean annual $\delta^{18}\text{O}$ and δD values
256 of rainwater (Riechelmann et al., 2011).

257

258 *4.2 Drip rate*

259

260 Due to different drip characteristics of the different drip sites (ranging from seepage
261 flow to seasonal drip; Riechelmann et al., 2011; Appendix S1 and Fig. 8), annual mean drip
262 rates were calculated and their long-term variability compared. Both manually and
263 automatically obtained mean annual drip rates show the same trends (Fig. 5). Sites TS 1, TS 2
264 and TS 5 show a decreasing trend in mean drip rates over the monitoring period, which is also
265 reflected in cross-correlations of mean annual drip rates at these sites (TS 1 vs. TS 2: $r = 0.82$;
266 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
267 rate at site TS 3 correlates only with the annual mean drip rate at site TS 2 within the 95%
268 confidence level ($r = 0.81$) and with TS 1 ($r = 0.79$) and TS 5 ($r = 0.72$) just below the 95%
269 confidence level ($n_{all} = 6$). However, it can be assumed that the annual mean drip rate at site
270 TS 3 follows the same trend as sites TS 1, 2 and 5. At drip site TS 8 a similar annual mean
271 drip rate was observed in 2008 and 2009 before drip rates increased until 2011, followed by a
272 decreasing trend. Drip rate of drip site TS 8 does not show any significant correlation with
273 any other drip rate.

274

275 4.3 $\delta^{18}\text{O}$ and δD of soil- and dripwater

276

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

285 Seasonal trends in $\delta^{18}\text{O}$ and δD of dripwaters are minor, but most pronounced for
286 water at site TS 1. In general, lower isotope values occur in summer, while higher values are
287 observed in winter (Fig. 6). Correlations between $\delta^{18}\text{O}$ and δD values of monthly samples of
288 the same site are significant for all dripwaters and both soilwater samples ($r \geq 0.44$; $p < 0.001$;
289 $n \geq 21$). All dripwaters share similarities in their oxygen and hydrogen isotopic composition
290 as shown by positive cross-correlations (Tables 1 and 2). Mean annual values display the
291 overall trend for $\delta^{18}\text{O}$ and δD , which is similar for all drip sites considering the errors (Fig. 6).
292 Oxygen and hydrogen isotope values increased until 2009, reached a plateau and decreased
293 around 2012. This trend is less distinct for dripwater at site TS 8 (Fig. 6).

294

295 5. Interpretation and Discussion

296

297 5.1 Constraints on the hydraulic response time

298

299 The positive correlations of mean annual drip rates of all sites except TS 8 (Fig. 5)
300 suggests that: (i) these sites are characterized by similar hydrological properties (Baker et al.,
301 1997), and (ii) the drip rates of these sites most likely respond to the same environmental
302 (climate) forcing. According to Riechelmann et al. (2011), no drip site showed a direct
303 response to rainfall events, but rather a lagged response of up to several months due to slowly
304 increasing hydrological pressure in the karst reservoir above the cave. Correlations between
305 drip rates and precipitation and infiltration during the preceding years based on monitoring
306 and meteorological data of the stations Hagen-Fley and Hemer were used to determine the
307 response time of mean annual drip rates to mean annual precipitation and infiltration. The
308 correlation coefficients (r) between drip rate and infiltration show that the mean annual drip
309 rates at TS 1 and TS 3 are controlled by mean annual infiltration of the same year, as observed
310 for other cave systems (Fig. 7A; Genty and Deflandre, 1998; Baker et al., 2000; Miorandi et
311 al., 2010; Tremaine and Froelich, 2013). Correlation coefficients at drip sites TS 2 and 5 are
312 close to the 95% confidence level. Since the infiltration amount is controlled by precipitation
313 amount and temperature (water loss due to evapotranspiration), correlations between mean
314 annual drip rate and annual precipitation amount were calculated (Fig. 7B). Positive
315 correlations at the 95% confidence level were found for TS 2 and TS 3 for the same year
316 interval, while correlation coefficients of TS 1 and 5 are just below the 95% confidence level.
317 Several sources of error must be considered, however, which lead to a lack of correlation at
318 the 95% confidence level. Lack of data (< 12 for annual means) may be the problem in case of
319 drip site TS 5, since neither infiltration nor precipitation correlate at the 95% confidence level
320 with drip rate. This might also be the case for sites TS 1 and 2. The calculated mean annual
321 drip rate of the former might be biased, since it shows pronounced seasonal drip rate
322 variability, with most changes not being covered by the monitoring (Figs. 5 and S1 in
323 supplementary material). Finally, the calculated mean annual infiltration in the soil reflects

324 the *potential* rather than *effective* infiltration. Furthermore, it must be kept in mind that
325 effective infiltration is biased towards winter (Wackerbarth et al., 2010; Riechelmann et al.,
326 2011), which might affect the correlation.

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

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

340 The drip characteristics of all drip sites, plotted according to Smart and Friederich
341 (1987) and Baker et al. (1997; see Figs. 8 and S1 in supplementary material to this paper)
342 highlight minor variability, with more or less the same drip characteristics over time. Drip
343 behaviour changed drastically at TS 8 during the monitoring period (Fig. 8): while seasonal
344 drip characteristics prevailed in 2008 and 2009, this drip shows seepage flow behaviour
345 between 2010 and 2012. Possible reasons for this change in drip characteristics include: (i) the
346 flow paths and the reservoir behaviour in the epikarst underwent changes as a result of
347 strongly variable rainfall events (Tooth and Fairchild, 2003), (ii) the flow paths of percolating
348 water changed or became blocked due to prior calcite precipitation (PCP; Fairchild et al.,

349 2006) occluding the flow paths of water; (iii) the overhanging stalactite was broken off
350 (earthquake, human interference etc.) resulting in drip parameter changes (Baldini et al.,
351 2006). Amongst these scenarios, it is conceivable that rainfall filled the reservoir feeding TS 8
352 to a threshold resulting in a more continuous water flow into the cave. PCP is a more likely
353 explanation for the change in drip behaviour as documented for this site (Riechelmann et al.,
354 2011). The stalactite was removed in June 2008, but the change in drip rate lagged by one
355 year, suggesting that the drip pattern was not controlled by the stalactite and thus the third
356 option mentioned above is considered unlikely. Concluding, the drip rate at site TS 8 is
357 controlled by infiltration and hence rainfall, but the dripwater signal reflecting both of these
358 parameters is strongly affected by prior calcite precipitation in the aquifer. Although the
359 catchment of the cave is partly sealed, infiltration and thus the precipitation signal can still be
360 recognized in the drip rate.

361

362 *5.2 Constraints on the water transfer time*

363

364 Water transfer times from the surface to the cave are highly variable and range from
365 days to several years not only for different caves but also for different drip sites in a given
366 cave (e.g., Kaufmann et al., 2003; Matthey et al., 2008b, Lambert and Aharon, 2010; Treble et
367 al., 2013; Genty et al., 2014, Breitenbach et al., 2015). Here, the dependency of rainwater
368 $\delta^{18}\text{O}$ and δD on temperature ($\delta^{18}\text{O}$ versus T: $r = 0.73$; δD versus T: $r = 0.68$; $n_{\text{both}} = 67$; $p_{\text{both}} <$
369 0.001 ; Riechelmann et al., 2011) is used to quantify the water transfer time. Correlation
370 coefficients (r) between $\delta^{18}\text{O}$ and δD of soil- and dripwater with surface air temperature were
371 calculated using data of the meteorological stations Hagen-Fley and Hemer. To this end,
372 monitoring data were correlated with temperature data of preceding years. Since rainwater

373 $\delta^{18}\text{O}$ and δD values correlate positively with temperature, only positive correlations are
374 relevant to determine the water transfer time.

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

387 Because dripwater at site TS 1 was collected as an instantaneous sample, the $\delta^{18}\text{O}$ and
388 δD values are not representative for the whole month as is the case for the other dripwaters.
389 Therefore, calculations with monthly data were only performed for all other drip sites
390 resulting in a lag of 29 to 31 months (Fig. 10). Difficulties occurred for TS 2, TS 3, and TS 8
391 in case of correlations using $\delta^{18}\text{O}$. There, the highest correlations are found between 41 and
392 66 months and only slightly lower ones are observed for a lag of 29 to 31 months.
393 Calculations using δD of all drip sites except TS 2 and $\delta^{18}\text{O}$ for TS 5 do not show these
394 features, which are most likely due to different mixing of the younger and older water in the
395 reservoir as a consequence of different transfer times. Variability in the transfer times
396 between different drip sites may arise due to: (i) variable thickness of the soil layer above

397 Bunker Cave, and (ii) differential thickness of the host rock overlying the cave, as well as (iii)
398 differential lengths and types of individual flow paths (e.g., Tooth and Fairchild, 2003). The
399 water retention capacity of soil is another factor that may or may not lead to an admixture
400 waters with different residence time in the soil and epikarst zone (Hölting and Coldewey,
401 2013). Following dry periods, the portion of older water in the soil increases (Kottek et al.,
402 2006) and the opposite is found during more humid periods. Although, rainfall is equally
403 distributed throughout the year, infiltration is not, as it is lower during summer than during
404 winter months (Wackerbarth et al., 2010; Riechelmann et al., 2011). Thus, water retention
405 capacity might have a small effect on water transfer times at Bunker Cave sulphate and nitrate
406 data show that dripwaters at sites TS 1 and TS 5 have shorter residence times compared to
407 sites TS 2, 3, and 8 (Riechelmann et al., 2011). This might explain why both $\delta^{18}\text{O}$ and δD
408 correlations with temperature performed well for TS 5. Drip water at TS 2 appears to be the
409 site with the longest and strongest buffering in the epikarst zone. In contrast to most others
410 this site displays seepage flow characteristics (see Appendix S1) and the oldest age based on
411 tritium data (Riechelmann et al., 2012a). This pattern might explain why the correlations at
412 this site are weakest. However, the shift in correlations using δD compared to the other drip
413 sites (Fig. 10) remains insufficiently explained. Since $\delta^{18}\text{O}$ and δD values of dripwater at site
414 TS 1 correlate with those of all other drip sites it can be assumed that the TS 1 water has a
415 similar transfer time of 29 to 31 months.

416 The results shown here suggest that the dripwater transfer time at all monitored drip
417 sites in Bunker Cave ranges between 29 to 31 months (ca. 2.5 years). This is in good
418 agreement with tritium data, suggesting a transfer time of 2-4 years (± 1 year; Kluge et al.,
419 2010). The tritium-based estimates, however, represent mixing ages of younger infiltrating
420 water and older water of the epikarst reservoir (Kluge et al., 2010; Riechelmann et al., 2012a).

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

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

426

427 *5.3 Influence of the North Atlantic Oscillation on the climate in western Germany*

428

429 The North Atlantic Oscillation (NAO) regulates Northern Hemisphere climate
430 variability and particularly so in western Europe and eastern North America (e.g., Marshall et
431 al., 2001; Visbeck et al., 2001; Baldini et al., 2008; Hurrell and Deser, 2010; Langebroek et
432 al., 2011; Pinto and Raible, 2012; Trouet et al., 2012; Wassenburg et al., 2013, 2016; Comas-
433 Bru et al., 2013). The NAO index is defined as the difference of sea-level pressure between
434 the Icelandic Low and the Azores High (Hurrell, 1995; Wanner et al., 2001). While the sea-
435 level pressure pattern is present throughout the year, it is most pronounced during winter
436 (Wanner et al., 2001; Pinto and Raible, 2012). Thus, most often the winter (December to
437 March) NAO index is used when studying climatic variability in the North Atlantic realm
438 (Proctor et al., 2000; Trouet et al., 2009; Baker et al., 2015). During a negative NAO mode,
439 the winter in Europe is dominated by cold and dry conditions, while during a positive NAO
440 mode, mild and humid conditions prevail (Fig. 11A; Hurrell and van Loon, 1997; Marshall et
441 al., 2001). This NAO-temperature link is reflected in $\delta^{18}\text{O}$ of precipitation (Baldini et al.,
442 2008; Mischel et al., 2015; Comas-Bru et al., 2016) and thus can be reconstructed using
443 suitably sensitive speleothems.

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

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

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

469

470 *5.4 Wider implications of the present data set for speleothem research in general*

471

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

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

488 The most striking observation of the present study is the difference between hydraulic
489 response time, i.e. immediate drip rate response (<1 year; Fig. 7), and the transfer time of
490 water from the soil to the cave (ca. 2.5 years; Fig. 10). While drip rate response to annual
491 precipitation occurs without significant lag on (sub-)annual basis, the temperature signal is
492 delayed by up to 2.5 years. Thus, the precipitation and temperature signals recorded by
493 different proxies in speleothems are not fully synchronous. In case of Bunker Cave this delay
494 is negligible, because here speleothems record proxies on decadal rather than annual or

495 seasonal scales (Riechelmann et al., 2011; Fohlmeister et al., 2012). Such proxy biases to
496 either water transfer or hydraulic response time must be considered in (sub-)annual
497 reconstructions, and where the signal transfer times for both parameters differ.

498

499 **6. Conclusions**

500

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

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

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

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

524

525 **Acknowledgements**

526

527 This is a joint contribution of the collaborative research initiative DAPHNE (DFG
528 Forschergruppe 668) and CHARON (DFG Forschergruppe 1644), both financed by the
529 German Science Foundation (DFG). This study received funding from the European Union's
530 Horizon 2020 Research and Innovation programme under the Marie Skłodowska-Curie grant
531 agreement No 691037 (to S.F.M.B.). The Speleogroup Letmathe is thanked for their support
532 in monitoring Bunker Cave and the student assistants C. Kirchmann, T. Meyer and M. Lyhs
533 are thanked for their help during monitoring tours. We would also like to thank Y. Kocot and
534 S. Mischel for sampling rainwater in 2012. Y. Dublyansky and M. Wimmer are thanked for
535 measuring $\delta^{18}\text{O}$ and δD data. We are grateful to the IAEA and especially S. Terzer for
536 providing an updated GNIP dataset.

537

538 **References**

539 Affolter, S., Häuselmann, A.D., Fleitmann, D., Häuselmann, P. and Leuenberger, M., 2015.

540 Triple isotope (δD , $\delta^{17}\text{O}$, $\delta^{18}\text{O}$) study on precipitation, dripwater and speleothem fluid
541 inclusions for a Western Central European cave (NW Switzerland). *Quaternary*
542 *Science Reviews*, 127: 73-89.

543 Baker, A., Barnes, W.L. and Smart, P.L., 1997. Variations in the discharge and organic matter

544 content of stalagmite dripwaters in Lower Cave, Bristol. *Hydrological Processes*, 11:
545 1541-1555.

546 Baker, A., Genty, D. and Fairchild, I.J., 2000. Hydrological characterisation of stalagmite
547 dripwaters at Grotte de Villars, Dordogne, by the analysis of inorganic species and
548 luminescent organic matter. *Hydrology and Earth System Sciences*, 4(3): 439-449.

549 Baker, A., Hellstrom, J.C., Kelly, B.F.J., Mariethoz, G. and Trouet, V., 2015. A composite
550 annual-resolution stalagmite record of North Atlantic climate over the last three
551 millennia. *Scientific Reports*, 5: 8.

552 Baldini, L.M., McDermott, F., Foley, A.M. and Baldini, J.U.L., 2008. Spatial variability in
553 the European winter precipitation $\delta^{18}\text{O}$ -NAO relationship: Implications for
554 reconstructing NAO-mode climate variability in the Holocene. *Geophysical Research*
555 *Letters*, 35: L04709.

556 Baldini, J.U.L., McDermott, F. and Fairchild, I.J., 2006. Spatial variability in cave dripwater
557 hydrochemistry: Implications for stalagmite paleoclimate records. *Chemical Geology*,
558 235: 390-404.

559 Breitenbach, S.F.M., Lechleitner, F. A., Meyer, H., Diengdoh, G., Matthey, D., and Marwan,
560 N., 2015. Cave ventilation and rainfall signals in dripwater in a monsoonal setting - a
561 monitoring study from NE India. *Chemical Geology*, 402: 111-124.

562 Cheng, H., Edwards, R. L., Shen, C.-C., Polyak, V. J., Asmerom, Y., Woodhead, J.,
563 Hellstrom,
564 J., Wang, Y., Kong, X., Spötl, C., Wang, X., and Alexander Jr., E. C., 2013.
565 Improvement in ^{230}Th dating, ^{230}Th and ^{234}U half-life values, and U-Th isotopic
566 measurement by multi-collector inductively coupled plasma mass spectrometry. *Earth*
567 *and Planetary Science Letters*, 371-372: 82-91.

568 Comas-Bru, L., McDermott, F. and Werner, M., 2016. The effect of the East Atlantic pattern

569 on the precipitation $\delta^{18}\text{O}$ -NAO relationship in Europe. *Climate Dynamics*, doi:
570 10.1007/s00382-015-2950-1.

571 Dorale, J.A., Edwards, R. L., Alexander, E. C., Shen, C.-C., Richards, D. A., and Cheng, H.,
572 2004. Uranium-Series Dating of Speleothems: Current Techniques, Limits, &
573 Applications. In: I.D. Sasowsky and J. Mylroie (Editors), *Studies of Cave Sediments:
574 Physical and Chemical Records of Paleoclimate*. Springer US, Boston, MA, pp. 177-
575 197.

576 Fairchild, I.J. and Baker, A., 2012. *Speleothem Science - From Process to Past Environments*.
577 Wiley-Blackwell, Chichester, 432 pp.

578 Fairchild, I.J., Tuckwell, G.W., Baker, A. and Tooth, A.F., 2006. Modelling of dripwater
579 hydrology and hydrogeochemistry in a weakly karstified aquifer (Bath, UK):
580 Implications for climate change studies *Journal of Hydrology*, 321: 213-231.

581 Fohlmeister, J., Schröder-Ritzrau, A., Scholz, D., Spötl, C., Riechelmann, D.F.C., Mudelsee,
582 M., Wackerbarth, A., Gerdes, A., Riechelmann, S., Immenhauser, A., Richter, D.K.,
583 and Mangini, A., 2012. Bunker Cave stalagmites: an archive for central European
584 Holocene climate variability. *Climate of the Past*, 8: 1751-1764.

585 Gat, J.R., Mook, W.G. and Meijer, H.A.J., 2000. *Environmental Isotopes in the Hydrological
586 Cycle. Principles and Applications Ch. vol. II: Atmospheric Water*, IAEA, Vienna.

587 Genty, D. and Deflandre, G., 1998. Drip flow variations under a stalactite of Père Noël cave
588 (Belgium). Evidence of seasonal variations and air pressure constraints *Journal of
589 Hydrology*, 211: 208-232.

590 Genty, D., Labuhn, I., Hoffmann, G., Danis, P.A., Mestre, O., Bourges, F., Wainer, K.,
591 Massault, M., Van Exter, S., Régnier, E., Orengo, P., Falourd, S., and Minster, B.,
592 2014. Rainfall and cave water isotopic relationships in two South-France sites.
593 *Geochimica et Cosmochimica Acta*, 131: 323-343.

594 Grebe, W., 1993. Die Bunkerhöhle in Iserlohn-Letmathe (Sauerland). Mitt. Verb. dt. Höhlen-
595 und Karstforsch., 39(2): 22-23.

596 Hammerschmidt, E., Niggemann, S., Grebe, W., Oelze, R., Brix, M.R., and Richter, D.K.,
597 1995. Höhlen in Iserlohn. Schriften zur Karst- und Höhlenkunde in Westfalen, 1: 153.

598 Haude, W., 1955. Zur Bestimmung der Verdunstung auf möglichst einfache Weise.
599 Mitteilungen des Deutschen Wetterdienstes, 2: 1-24.

600 Hölting, B. and Coldewey, W.G., 2013. Hydrogeologie - Einführung in die Allgemeine und
601 Angewandte Hydrogeologie. Spektrum Akademischer Verlag, Heidelberg, 438 pp.

602 Hurrell, J.W., 1995. Decadal trends in the North Atlantic Oscillation: Regional temperatures
603 and precipitation. Science, 269: 676-679.

604 Hurrell, J.W. and Deser, C., 2010. North Atlantic climate variability: The role of the North
605 Atlantic Oscillation. Journal of Marine Systems, 79: 231-244.

606 Hurrell, J.W. and van Loon, H., 1997. Decadal variations in climate associated with the North
607 Atlantic oscillation. Climatic Change, 36(3-4): 301-326.

608 Immenhauser, A., Buhl, D., Richter, D.K., Niedermayr, A., Riechelmann, D., Dietzel, M. and
609 Schulte, U., 2010. Magnesium-isotope fractionation during low-Mg calcite
610 precipitation in a limestone cave - field study and experiments. Geochimica et
611 Cosmochimica Acta, 74(15): 4346-4364.

612 Kaufman, A., Bar-Matthews, M., Ayalon, A. and Carmi, I., 2003. The vadose flow above
613 Soreq Cave, Israel: a tritium study of the cave waters. Journal of Hydrology, 273: 155-
614 163.

615 Kluge, T., Riechelmann, D.F.C., Wieser, M., Spötl, C., Sültenfuß, J., Schröder-Ritzrau, A.,
616 Niggemann, S., and Aeschbach-Hertig, W., 2010. Dating cave dripwater by tritium.
617 Journal of Hydrology, 394(3-4): 396-406.

618 Kluge, T., Affek, H.P., Marx, T., Aeschbach-Hertig, W., Riechelmann, D.F.C., Scholz, D.,

619 Riechelmann, S., Immenhauser, A., Richter, D.K., Fohlmeister, J., Wackerbarth, A.,
620 Mangini, A., and Spötl, C., 2013. Reconstruction of drip-water $\delta^{18}\text{O}$ based on calcite
621 oxygen and clumped isotopes of speleothems from Bunker Cave (Germany). *Climate*
622 *of the Past*, 9: 377-391.

623 Kottek, M., Grieser, J., Beck, C., Rudolf, B. and Rubel, F., 2006. World map of the Köppen-
624 Geiger climate classification updated. *Meteorologische Zeitschrift*, 15(3): 259-263.

625 Lachniet, M.S., 2009. Climatic and environmental controls on speleothem oxygen-isotope
626 values. *Quaternary Science Reviews*, 28: 412-432.

627 Lambert, W.J. and Aharon, P., 2010. Oxygen and hydrogen isotopes of rainfall and dripwater
628 at DeSoto Caverns (Alabama, USA): Key to understanding past variability of moisture
629 transport from the Gulf of Mexico. *Geochimica et Cosmochimica Acta*, 74(3): 846-
630 861.

631 Langebroek, P.M., Werner, M. and Lohmann, G., 2011. Climate information imprinted in
632 oxygen-isotopic composition of precipitation in Europe. *Earth and Planetary Science*
633 *Letters*, 311: 144-154.

634 Luetscher, M., Boch, R., Sodemann, H., Spötl, C., Cheng, H., Edwards, R. L., Frisia, S., Hof,
635 F., and Muller, W., 2015. North Atlantic storm track changes during the Last Glacial
636 Maximum recorded by Alpine speleothems. *Nature Communications*, 6: 6.

637 Mangini, A., Spötl, C. and Verdes, P., 2005. Reconstruction of temperature in the Central
638 Alps
639 during the past 2000 yr from a $\delta^{18}\text{O}$ stalagmite record. *Earth and Planetary Science*
640 *Letters*, 235: 741-751.

641 Marshall, J., Kushner, Y., Battisti, D., Chang, P., Czaja, A., Dickson, R., Hurrell, J.,

642 McCartney, M., Saravanan, R., and Visbeck, M., 2001. North Atlantic climate
643 variability: Phenomena, impacts and mechanisms. *International Journal of*
644 *Climatology*, 21(15): 1863-1898.

645 Matthey, D. and Collister, C., 2008. Acoustic drip counters for environmental monitoring.
646 *BCRA Cave Radio & Electronics Group Journal*, 70: 14-17.

647 Matthey, D., Latin, J.P. and Ainsworth, M., 2008b. Cave monitoring and calibration of a $\delta^{18}\text{O}$ -
648 climate transfer function for a Gibraltar speleothem. *PAGES News*, 16(3): 15-17.

649 Matthey, D., Lowry, D., Duffet, J., Fisher, R., Hodge, E. and Frisia, S., 2008a. A 53 year
650 seasonally resolved oxygen and carbon isotope record from a modern Gibraltar
651 speleothem: Reconstructed dripwater and relationship to local precipitation. *Earth and*
652 *Planetary Science Letters*, 269: 80-95.

653 Matthey, D.P., Atkinson, T. C., Barker, J. A., Fisher, R., Latin, J. P., Durrell, R., and
654 Ainsworth,
655 M., 2016. Carbon dioxide, ground air and carbon cycling in Gibraltar karst.
656 *Geochimica et Cosmochimica Acta*, 184: 88-113.

657 McGarry, S., Bar-Matthews, M., Matthews, A., Vaks, A., Schilman, B., and Ayalon, A.,
658 2004. Constraints on hydrological and paleotemperature variations in the Eastern
659 Mediterranean region in the last 140 ka given by the δD values of speleothem fluid
660 inclusions. *Quaternary Science Reviews*, 23(7-8): 919-934.

661 Miorandi, R., Borsato, A., Frisia, S., Fairchild, I.J. and Richter, D.K., 2010. Epikarst
662 hydrology and implications for stalagmite capture of climate changes at Grotta di
663 Ernesto (N.E. Italy): results from long-term monitoring. *Hydrological Processes*, 24:
664 3101-3114.

665 Mischel, S.A., Scholz, D. and Spötl, C., 2015. $\delta^{18}\text{O}$ values of cave dripwater: a promising

666 proxy for the reconstruction of the North Atlantic Oscillation? *Climate Dynamics*, 45:
667 3035-3050.

668 Münsterer, C., Fohlmeister, J., Christl, M., Schröder-Ritzrau, A., Alfimov, V., Ivy-Ochs, S.,
669 Wackerbarth, A., and Mangini, A., 2012. Cosmogenic ^{36}Cl in karst waters from
670 Bunker Cave North Western Germany - A tool to derive local evapotranspiration?
671 *Geochimica et Cosmochimica Acta*, 86: 138-149.

672 Niggemann, S., Mangini, A., Mudelsee, M., Richter, D.K. and Wurth, G., 2003. Sub-
673 Milankovitch climatic cycles in Holocene stalagmites from Sauerland, Germany. *Earth*
674 *and Planetary Science Letters*, 216: 539-547.

675 Pinto, J.G. and Raible, C.C., 2012. Past and recent changes in the North Atlantic Oscillation.
676 *Wiley Interdisciplinary Reviews-Climate Change*, 3(1): 79-90.

677 Proctor, J.C., Baker, A., Barnes, L.W. and Gilmour, A.M., 2000. A thousand year speleothem
678 proxy record of North Atlantic climate from Scotland. *Climate Dynamics*, 16(10):
679 815-820.

680 Riechelmann, D.F.C., 2010. Aktuospeläologische Untersuchungen in der Bunkerhöhle des
681 Iserlohner Massenkalks (NRW/Deutschland): Signifikanz für kontinentale
682 Klimaarchive. PhD thesis, Ruhr-Universität Bochum, 199 pp.

683 Riechelmann, D.F.C., Schröder-Ritzrau, A., Scholz, D., Fohlmeister, J., Spötl, C., Richter,
684 D.K., and Mangini, A., 2011. Monitoring Bunker Cave (NW Germany): A prerequisite
685 to interpret geochemical proxy data of speleothems from this site. *Journal of*
686 *Hydrology*, 409(3-4): 682-695.

687 Riechelmann, D.F.C., Deininger, M., Scholz, D., Riechelmann, S., Schröder-Ritzrau, A.,
688 Spötl, C., Richter, D.K., Mangini, A., and Immenhauser, A., 2013. Disequilibrium
689 carbon and oxygen isotope fractionation in recent cave calcite: Comparison of cave
690 precipitates and model data. *Geochimica et Cosmochimica Acta*, 103: 232-244.

691 Riechelmann, S., Buhl, D., Schröder-Ritzrau, A., Spötl, C., Riechelmann, D.F.C., Richter,
692 D.K., Kluge, T., Marx, T., and Immenhauser, A., 2012a. Hydrogeochemistry and
693 fractionation pathways of Mg isotopes in a continental weathering system: Lessons
694 from field experiments. *Chemical Geology*, 300-301: 109-122.

695 Riechelmann, S., Buhl, D., Schröder-Ritzrau, A., Riechelmann, D.F.C., Richter, D.K.,
696 Vonhof, H.B., Wassenburg, J.A., Geske, A., Spötl, C., and Immenhauser, A., 2012b.
697 The magnesium isotope record of cave carbonate archives. *Climate of the Past*, 8:
698 1849-1867.

699 Riechelmann, S., Schröder-Ritzrau, A., Wassenburg, J.A., Schreuer, J., Richter, D.K.,
700 Riechelmann, D.F.C., Terente, M., Constantin, S., Mangini, A., and Immenhauser, A.,
701 2014. Physicochemical characteristics of dripwaters: Influence on mineralogy and
702 crystal morphology of recent cave carbonate precipitates. *Geochimica et*
703 *Cosmochimica Acta*, 145: 13-29.

704 Scheudoschi, M., 2007. Geologische Kartierung der Bunkerhöhle im Massenkalk bei Iserlohn,
705 Unpublished report Ruhr-Universität Bochum, 67 pp.

706 Scholz, D. and Hoffmann, D.L., 2008. $^{230}\text{Th}/\text{U}$ -dating of fossil reef corals and speleothems.
707 *Journal of Quaternary Science (Eiszeitalter und Gegenwart)*, 57(1-2): 52-76.

708 Scholz, D., Frisia, S., Borsato, A., Spötl, C., Fohlmeister, J., Mudelsee, M., Miorandi, R., and
709 Mangini, A., 2012. Holocene climate variability in north-eastern Italy: potential
710 influence of the NAO and solar activity recorded by speleothem data. *Climate of the*
711 *Past*, 8: 1367-1383.

712 Smart, P.L. and Friederich, H., 1987. Water movement and storage in the unsaturated zone of
713 a maturely karstified carbonate aquifer, Mendip Hills, England, *Proceedings of the*
714 *Environmental Problems in Karst Terranes and their Solutions Conference*, Bowling
715 Green, Kentucky, USA, pp. 57-87.

716 Spötl, C., Fairchild, I.J. and Tooth, A.F., 2005. Cave air control on dripwater geochemistry,
717 Obir Caves (Austria): Implications for speleothem deposition in dynamically
718 ventilated caves. *Geochimica et Cosmochimica Acta*, 69(10): 2451 - 2468.

719 Stumpp, C., Klaus, J. and Stichler, W., 2014. Analysis of long-term stable isotopic
720 composition in German precipitation. *Journal of Hydrology*, 517: 351-361.

721 Tooth, A.F. and Fairchild, I.J., 2003. Soil and karst aquifer hydrological controls on the
722 geochemical evolution of speleothem-forming dripwaters, Crag Cave, southwest
723 Ireland. *Journal of Hydrology*, 273: 51-68.

724 Treble, P.C., Bradley, C., Wood, A., Baker, A., Jex, C.N., Fairchild, I.J., Gagan, M.K.,
725 Cowley, J., and Azcurra, C., 2013. An isotopic and modelling study of flow paths and
726 storage in Quaternary calcarenite, SW Australia: implications for speleothem
727 paleoclimate records. *Quaternary Science Reviews*, 64: 90-103.

728 Treble, P.C., Fairchild, I. J., Baker, A., Meredith, K. T., Andersen, M. S., Salmon, S. U.,
729 Bradley, C., Wynn, P. M., Hankin, S. I., Wood, A., and McGuire, E., 2016. Roles of
730 forest bioproductivity, transpiration and fire in a nine-year record of cave dripwater
731 chemistry from southwest Australia. *Geochimica et Cosmochimica Acta*, 184: 132-
732 150.

733 Tremaine, D.M. and Froelich, P.N., 2013. Speleothem trace element signatures: A hydrologic
734 geochemical study of modern cave dripwaters and farmed calcite. *Geochimica et*
735 *Cosmochimica Acta*, 121: 522-545.

736 Tremaine, D.M., Froelich, P.N. and Wang, Y., 2011. Speleothem calcite farmed *in situ*:
737 Modern calibration of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ paleoclimate proxies in a continuously-monitored
738 natural cave system. *Geochimica et Cosmochimica Acta*, 75: 4929-4950.

739 Trouet, V., Scourse, J.D. and Raible, C.C., 2012. North Atlantic storminess and Atlantic

740 Meridional Overturning Circulation during the last millenium: Reconciling
741 contradictory proxy records of NAO variability. *Global and Planetary Change*, 84-85:
742 48-55.

743 Trouet, V., Esper, J., Graham, N. E., Baker, A., Scourse, J. D., and Frank, D. C., 2009.
744 Persistent
745 positive North Atlantic Oscillation Mode dominated the Medieval Climate Anomaly.
746 *Science*, 324(78): 78-80.

747 van Breukelen, M.R., Vonhof, H.B., Hellstrom, J.C., Wester, W.C.G. and Kroon, D., 2008.
748 Fossil dripwater in stalagmites reveals Holocene temperature and rainfall variation in
749 Amazonia. *Earth and Planetary Science Letters*, 275: 54-60.

750 van Rangelbergh, M., Verheyden, S., Allan, M., Quinif, Y., Keppens, E., and Claeys, P.,
751 2014. Monitoring of a fast-growing speleothem site from the Han-sur-Lesse cave,
752 Belgium, indicates equilibrium deposition of the seasonal $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signals in
753 calcite. *Climate of the Past*, 10: 1871-1885.

754 Visbeck, M.H., Hurrell, J.W., Polvani, L. and Cullen, H.M., 2001. The North Atlantic
755 Oscillation: Past, present, and future. *Proceedings of the National Academy of*
756 *Sciences*, 98(23): 12876-12877.

757 Vonhof, H. B., van Breukelen, M. R., Postma, O., Rowe, P. J., Atkinson, T. C., and Kroon,
758 D., 2006. A continuous-flow crushing device for on-line $\delta^2\text{H}$ analysis of fluid
759 inclusion water in speleothems. *Rapid Commun. Mass Spectrom.*, 20: 2553–2558.

760 von Kamp, H., 1972. *Geologische Karte von Nordrhein-Westfalen 1:25.000. Erläuterungen zu*
761 *Blatt 4611 Hohenlimburg. Geologisches Landesamt Nordrhein-Westfalen, Krefeld,*
762 *182 pp.*

763 von Kamp, H., and Ribbert, K.-H., 2005. *Geologische Karte von Nordrhein-Westfalen*
764 *1:25.000. Erläuterungen zu Blatt 4611 Hagen-Hohenlimburg, Krefeld, 156 pp.*

765 Wackerbarth, A., Scholz, D., Fohlmeister, J. and Mangini, A., 2010. Modelling the $\delta^{18}\text{O}$ value
766 of cave drip water and speleothem calcite. *Earth and Planetary Science Letters*, 299:
767 387-397.

768 Wackerbarth, A., Langebroek, P.M., Werner, M., Lohmann, G., Riechelmann, S., Borsato, A.,
769 and Mangini, A., 2012. Simulated oxygen isotopes in cave dripwater and speleothem
770 calcite in European caves. *Climate of the Past*, 8: 1781-1799.

771 Wanner, H., Brönnimann, S., Casty, C., Gyalistras, D., Luterbacher, J., Schmutz, C.,
772 Stephenson, D.B., and Xoplaki, E., 2001. North Atlantic Oscillation - Concepts and
773 studies. *Surveys in Geophysics*, 22(4): 321-382.

774 Wassenburg, J.A., Immenhauser, A., Richter, D.K., Niedermayr, A., Riechelmann, S.,
775 Fietzke, J., Scholz, D., Jochum, K.P., Fohlmeister, J., Schröder-Ritzrau, A., Sabaoui,
776 A., Riechelmann, D.F.C., Schneider, L., and Esper, J., 2013. Moroccan speleothem
777 and tree ring records suggest a variable positive state of the North Atlantic Oscillation
778 during the Medieval Warm Period. *Earth and Planetary Science Letters*, 375: 291-302.

779 Wassenburg, J.A. Dietrich, S., Fietzke, J., Fohlmeister, J., Jochum, K.P., Scholz, D., Richter,
780 D.K., Sabaoui, A., Spötl, C., Lohmann, G., Andreae, M.O., and Immenhauser, A.,
781 2016. Reorganization of the North Atlantic Oscillation during early Holocene
782 deglaciation. *Nature Geoscience*, 9(8): 602-+.

783

784 **Figure Captions**

785

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

789

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

793

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

802

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

807

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

810

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

812

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

816

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

819

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

822

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

825

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

Figure 1
[Click here to download high resolution image](#)

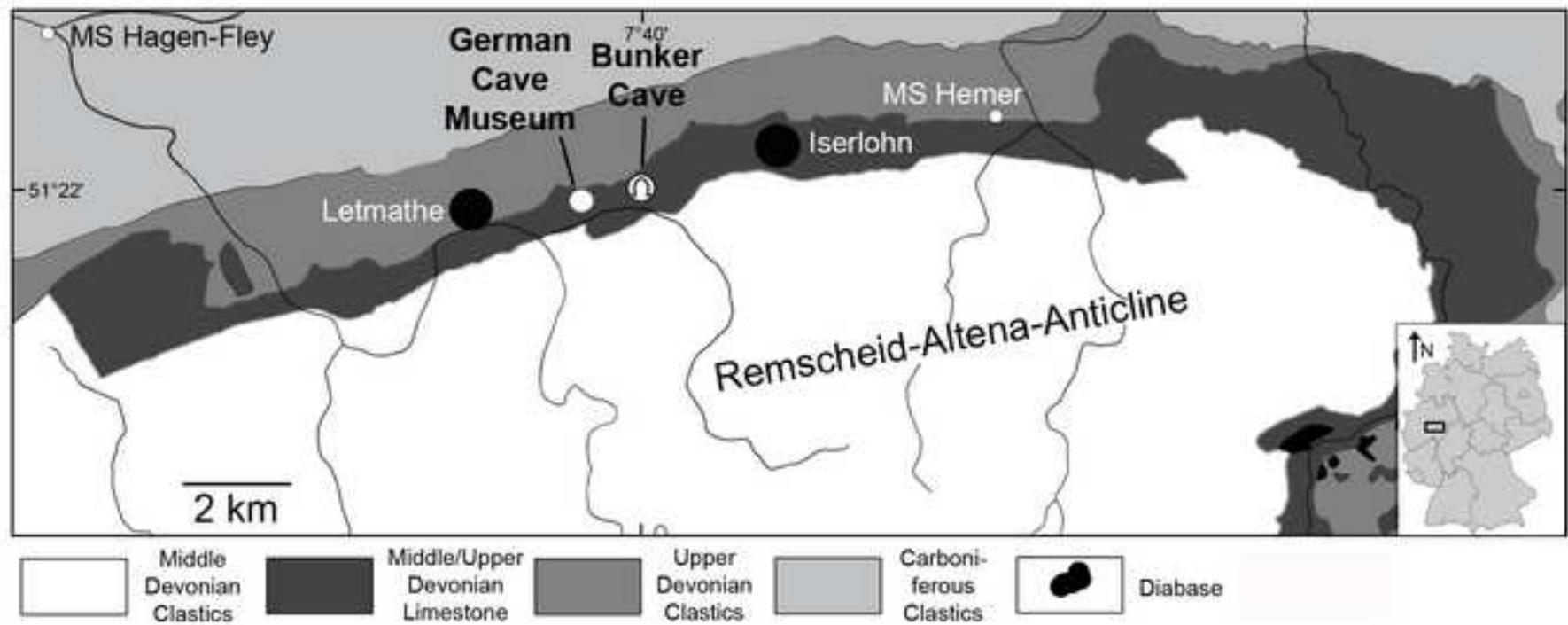


Figure 2

[Click here to download high resolution image](#)

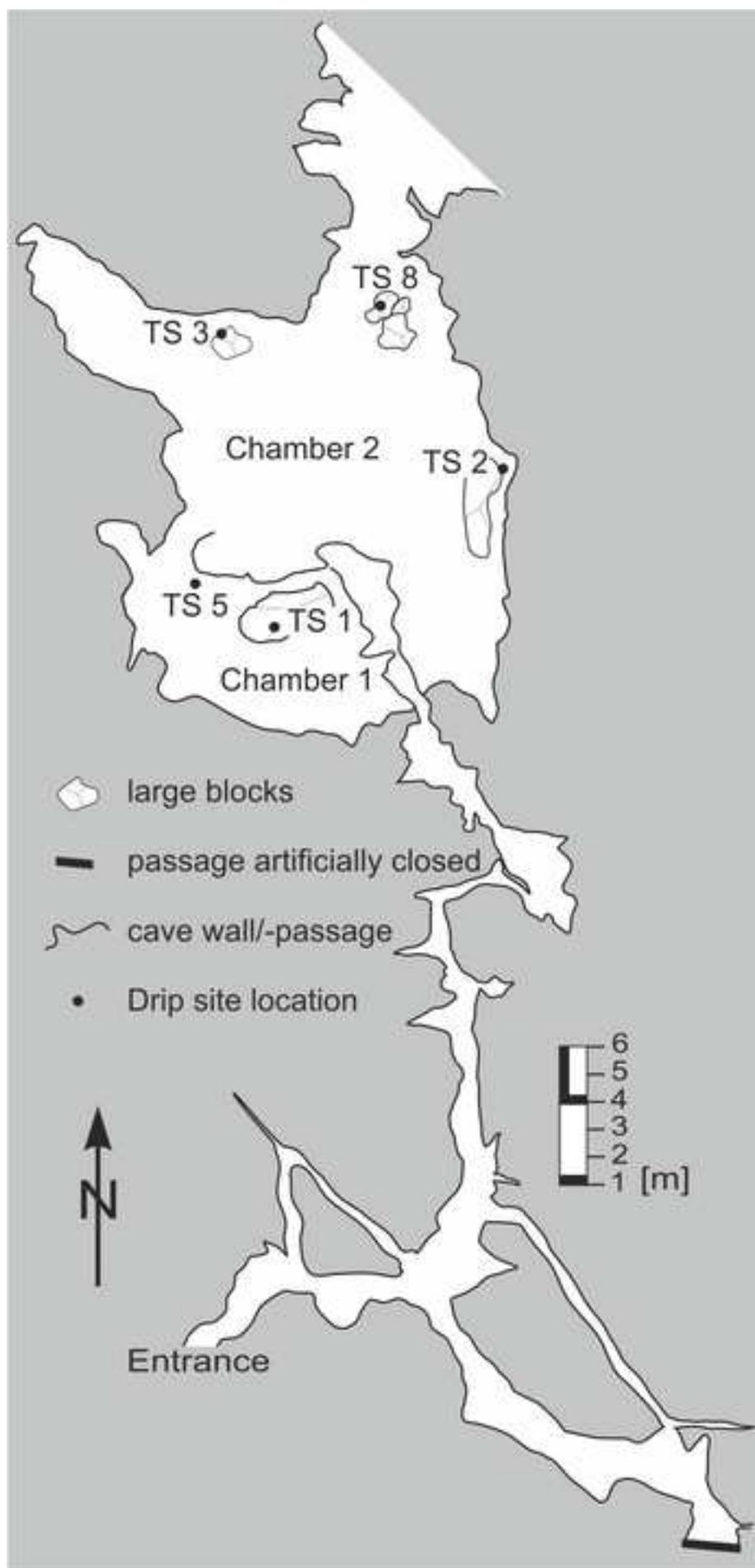


Figure 3
[Click here to download high resolution image](#)

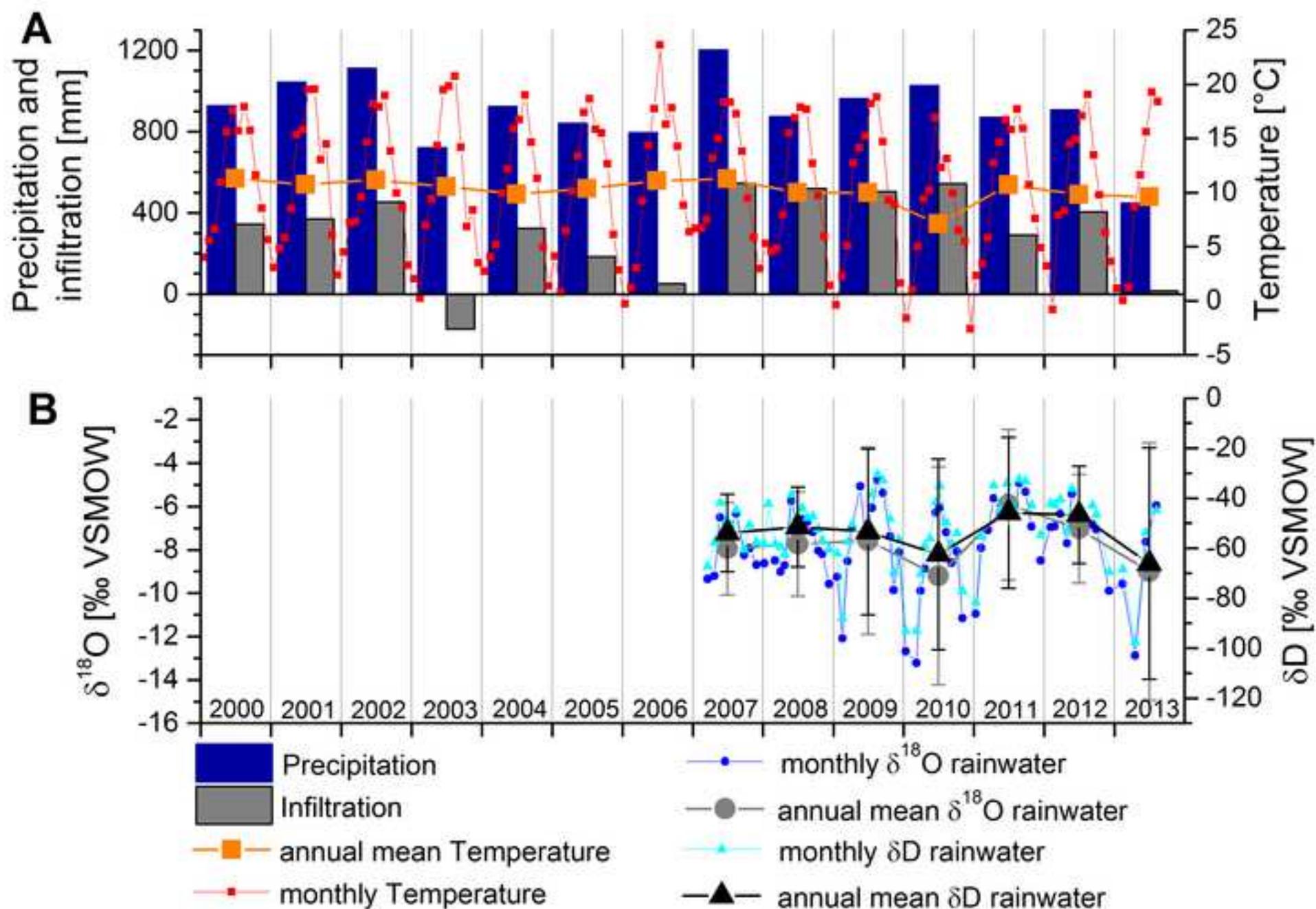


Figure 4

[Click here to download high resolution image](#)

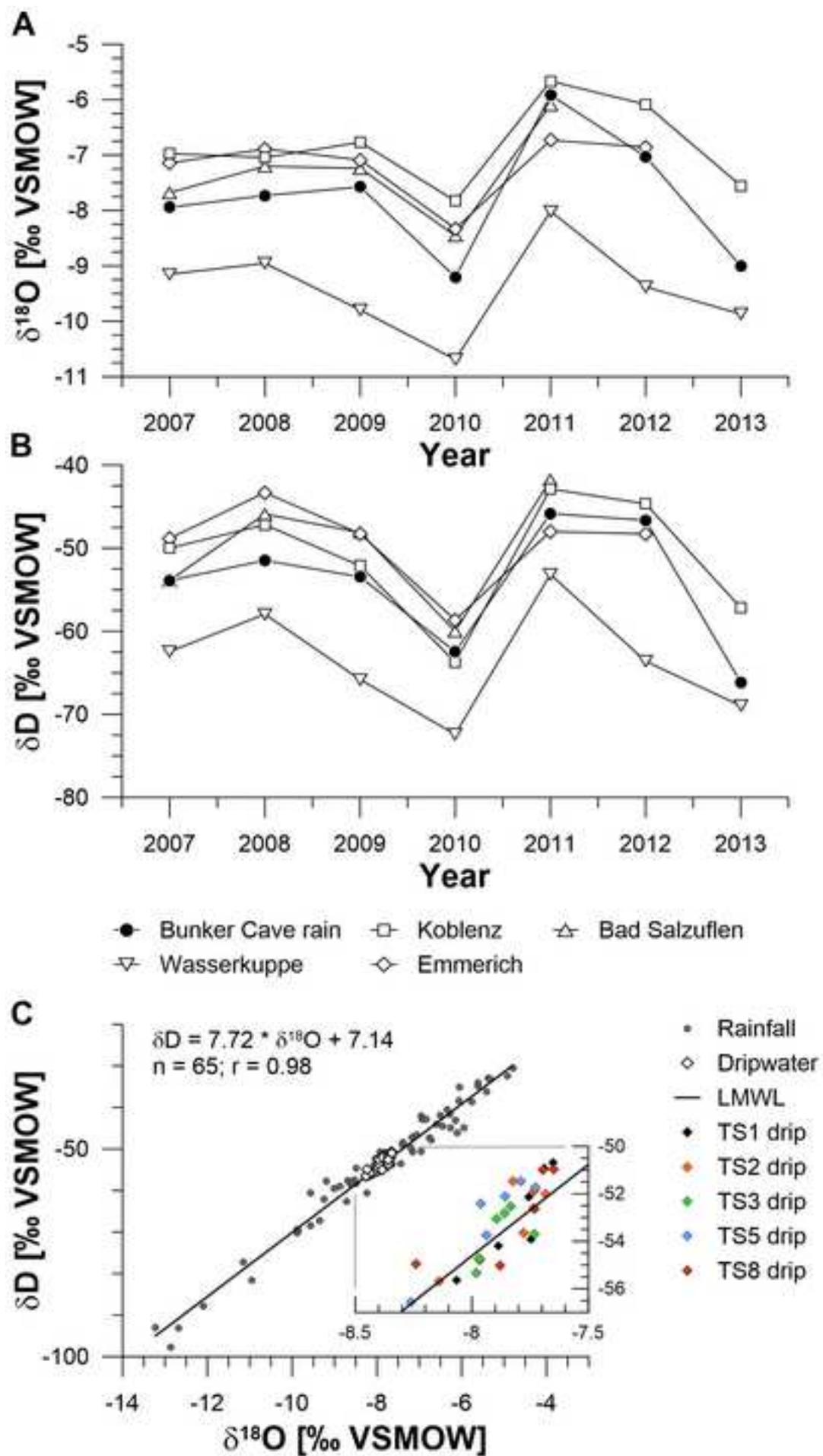


Figure 5
[Click here to download high resolution image](#)

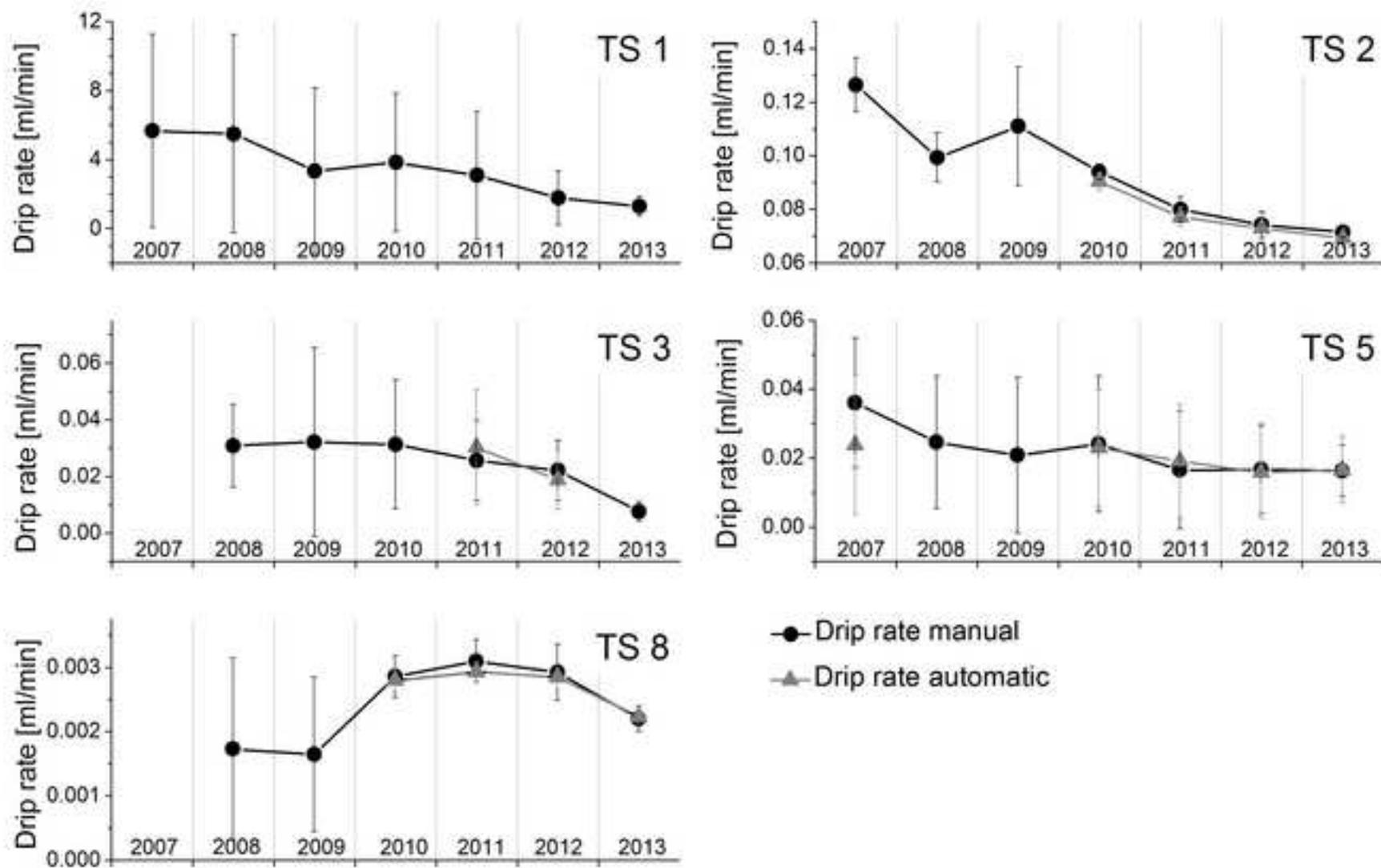


Figure 6

[Click here to download high resolution image](#)

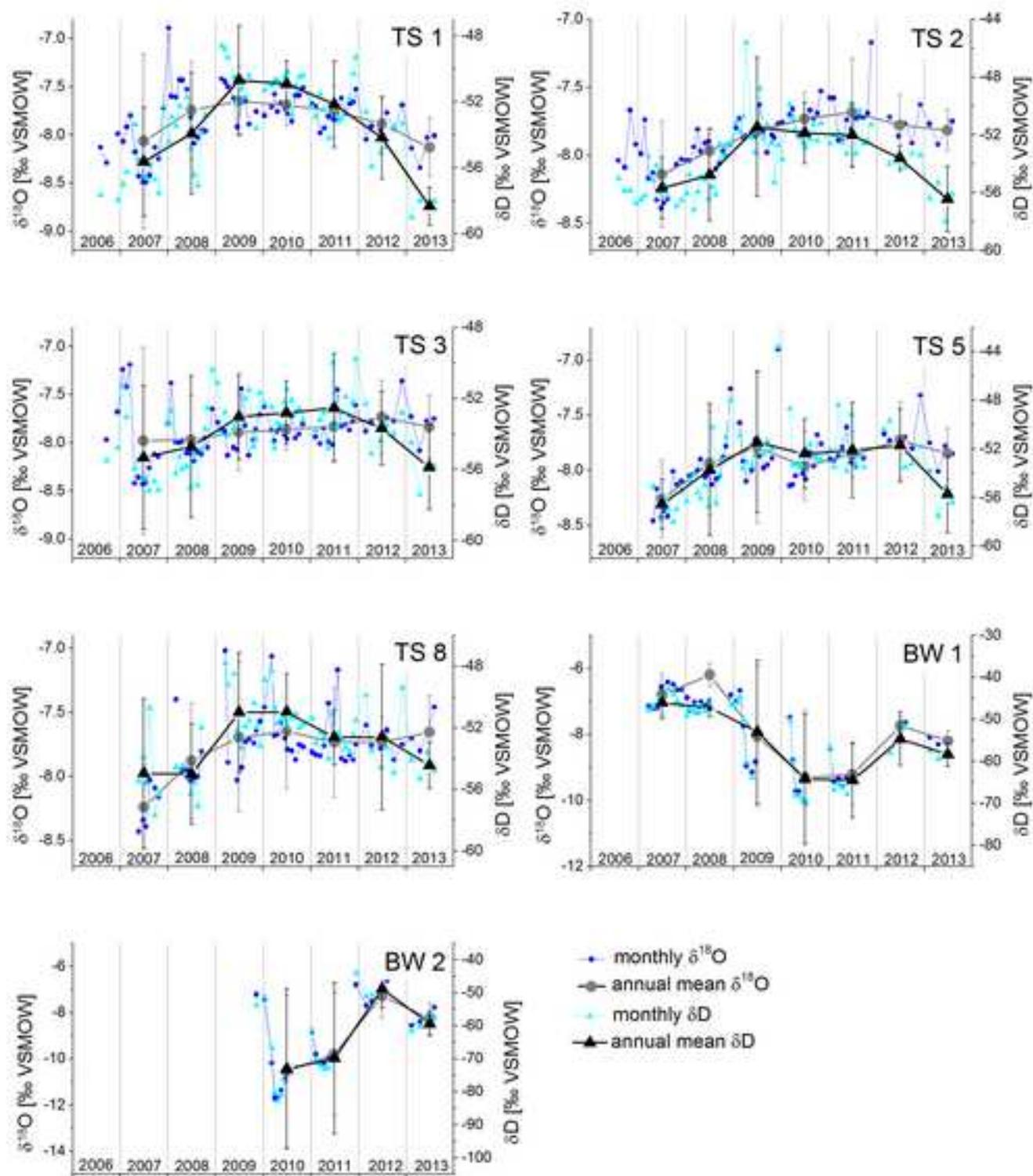


Figure 7
[Click here to download high resolution image](#)

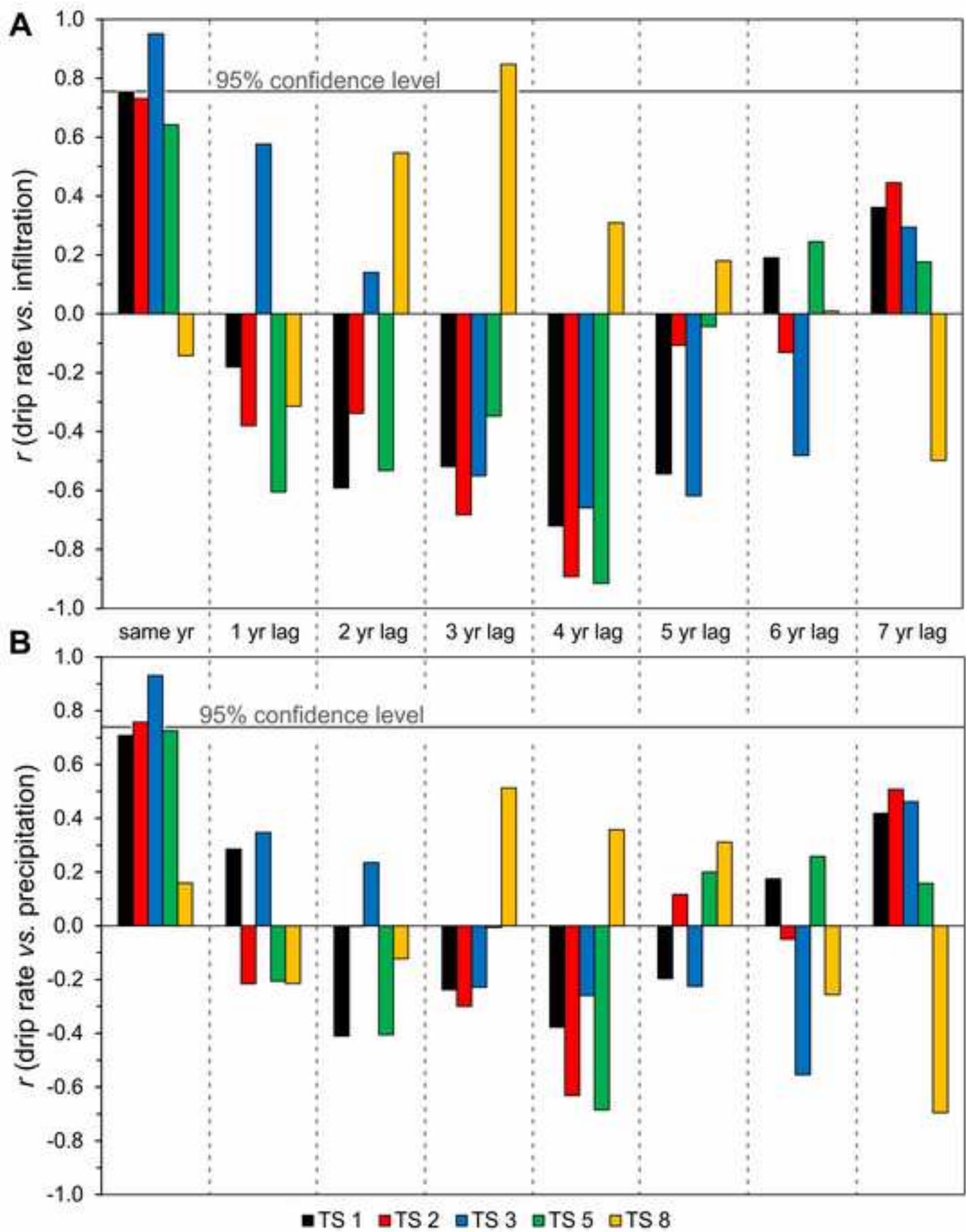


Figure 8
[Click here to download high resolution image](#)

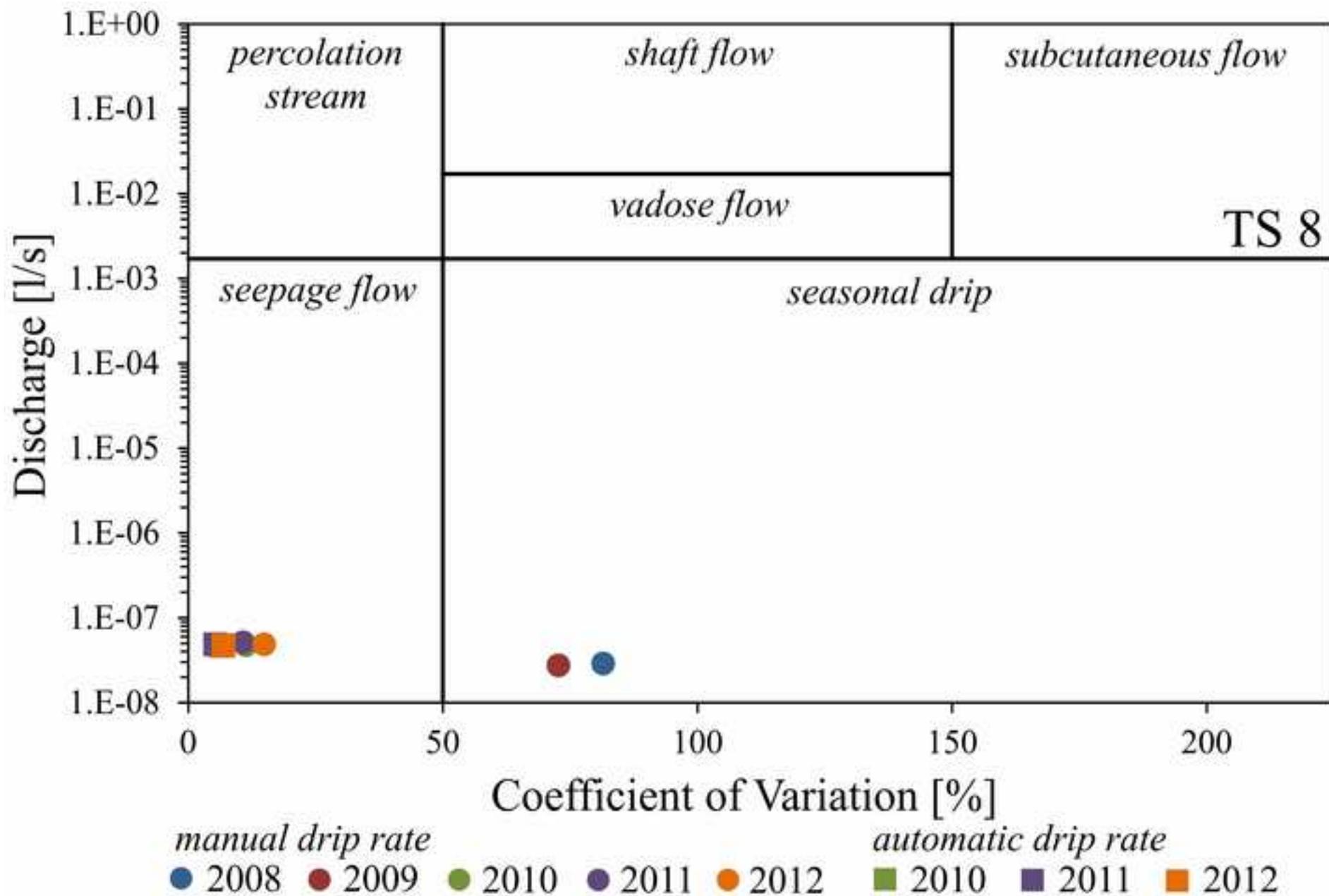


Figure 9

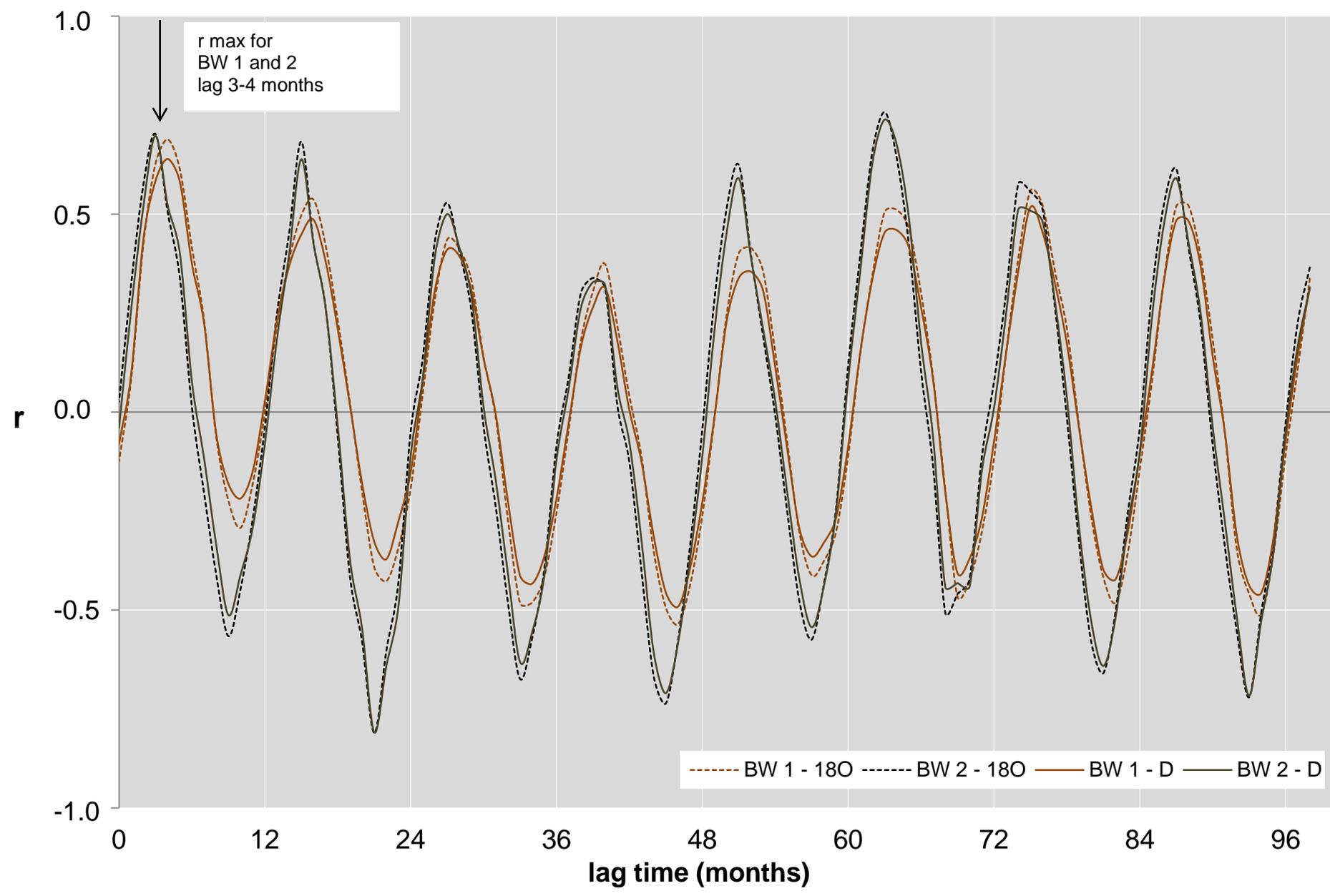


Figure 11
[Click here to download high resolution image](#)

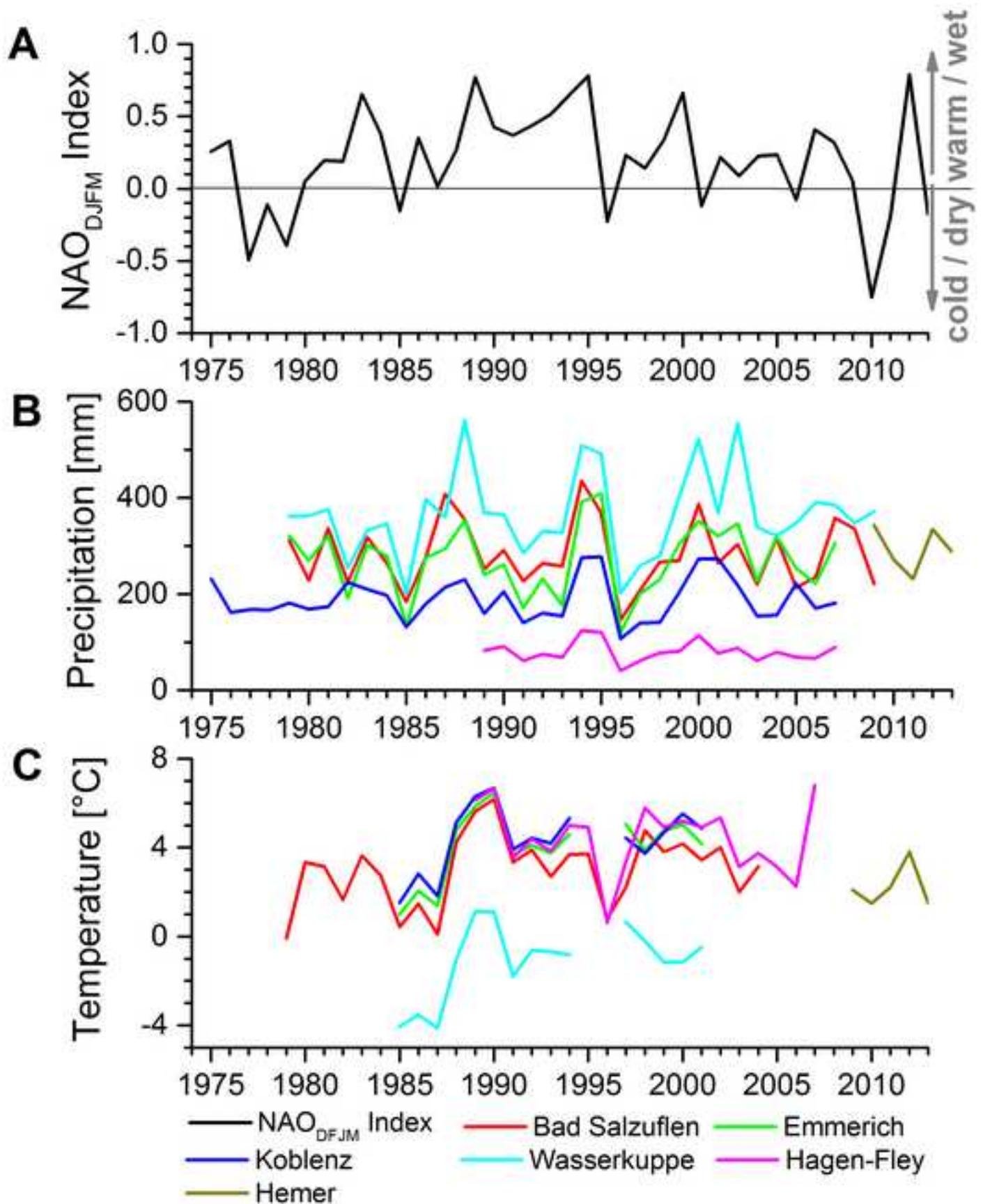


Table 1. Correlations between monthly $\delta^{18}\text{O}$ values of the different drip- and soilwaters. Significant correlation coefficients (r ; $p \leq 0.05$) are printed bold. Data points used for statistics vary between 14 and 65.

$\delta^{18}\text{O}$	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[Click here to download Table: Table 2.docx](#)

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

Background dataset for online publication only

[Click here to download Background dataset for online publication only: Supplementary material.docx](#)