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Simulated European stalagmite record and its relation to a quasi-decadal climate mode

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Abstract

A synthetic stalagmite record for the Bunker cave is constructed using a combined climate-stalagmite modeling approach. The power spectrum of the simulated speleothem calcite δ^{18}O record has a pronounced peak at quasi-decadal time scale. Interestingly, mixing processes in the soil and karst above the cave represent a natural low-pass filter of the speleothem climate archive. We identify a quasi-decadal mode characterized by a "tripole pattern" of sea surface temperature affecting stalagmite δ^{18}O values. This pattern, which is well-known in literature as the quasi-decadal mode in the North Atlantic, propagates eastwards and affects western European temperature surrounding the cave. Stalagmite δ^{18}O values at Bunker Cave lag the regional surface temperature ($r = 0.4$) and soil moisture ($r = -0.4$) signal by 2–3 yr. Our modelling study suggests that stalagmite records from Bunker Cave are representative for large-scale teleconnections and can be used to obtain information about the North Atlantic and its decadal variability.

1 Introduction

Speleothems are a valuable archive of past climate variability since they allow precise dating (Richards and Dorale, 2003; Fairchild et al., 2006; Scholz and Hoffmann, 2008) and provide high-resolution climate proxy data. The most commonly used climate proxies in speleothems are stable carbon and oxygen isotope signals (δ^{13}C and δ^{18}O) (McDermott, 2004; Lachniet, 2009) as well as various trace elements such as magnesium or strontium (Fairchild and Treble, 2009). Their potential for paleoclimate research is related to the question whether they reflect local climate conditions above the cave or large-scale climate variability modes. Such modes show coherent spatial structures and were identified both in the tropical Pacific (Philander, 1990) and the North Atlantic (Deser and Blackmon, 1993). Part of the problem of understanding climate variability is linked to the question of identifying the corresponding spatial patterns (e.g. Rimbu et al., 2001; Felis et al., 2004; Lohmann et al., 2004; Langebroek et al., 2011). A climate-speleothem proxy relationship is postulated through a correspondence between a speleothem δ^{18}O record and large-scale surface temperature and/or rainfall amount (e.g. Fairchild and Treble, 2009; Drysdale et al., 2009). Baker et al. (2011) analyze the climate-proxy relationship for a high-resolution speleothem δ^{18}O and found little correspondence to instrumental data, although a clear relationship between local rainfall δ^{18}O and atmospheric circulation is observed.

Here, we follow their idea and trace the speleothem δ^{18}O which stems from the composition of infiltrated water in a simulated cave. We analyze the climate variability pattern related to variations in a simulated cave system in Central Europe, which is under the influence of maritime climate. Climate over the North Atlantic sector varies on quasi-decadal to multi-decadal timescales (Deser and Blackmon, 1993; Hurrell, 1995; Sutton and Allen, 1997). In this pattern, the atmospheric circulation, similar to the North Atlantic Oscillation (NAO)(Walker, 1924), generates a tripole pattern in sea surface temperature (SST) anomalies (Bjerknes, 1964; Deser and Blackmon, 1993; Kushnir, 1994). Modeling studies with atmospheric general circulation models (AGCMs) of different complexity forced by global SST variability over the last century show that the atmospheric circulation over the North Atlantic is predictable if global SST variability can be predicted (Rodwell et al., 1999; Latif et al., 2000; Robertson et al., 2000; Sutton and Hodson, 2003; Grosfeld et al., 2007). For instance, North Atlantic SST can be used as a predictor for the NAO pattern. However, it remains poorly understood how changing climatic boundary conditions affect the strength and dynamics of these natural oscillations in the North Atlantic realm on long time scales. Such information can be inferred from the past using climate proxy data.

Here, we elaborate the large-scale relation of the δ^{18}O signal recorded in a simulated stalagmite, for the location of Bunker Cave (51° N, 7° E). The cave is located in the Rhenish Slate Mountains in the western part of Germany (Riechelmann et al., 2011; Fohlmeister et al., 2012). Our model approach is based on an AGCM including water stable isotopes (Werner and Heimann, 2002) as well as a proxy model for the general processes influencing the $\delta^{18}O$ signal of cave drip water and speleothem calcite (Wackerbarth et al., 2010). This model was developed in order to better understand the influence of climate change on the $\delta^{18}O$ values of speleothem calcite. We examine the related large-scale variability on interannual to multi-decadal timescales in the North Atlantic realm. In addition, our approach helps to study the relationship between climate change and the recorded speleothem proxy signals.

2 Methods

2.1 Atmospheric model

The applied model was the Hamburg AGCM ECHAM4 (Roeckner et al., 1996) with both water stable isotopes $H_2^{18}O$ and HDO explicitly cycled through the water cycle of the model (Werner and Heimann, 2002). The simulation was performed in T30 resolution (3.75 by 3.75 spatial grid; 19 vertical levels). Observed monthly values of the global sea ice and sea surface temperature data set (GISST2.2) of the United Kingdom Meteorological Office were prescribed for the period 1908–1994 (Rayner et al., 1996). Atmospheric concentrations of greenhouse gases (CO_2, CH_4, N_2O) but no additional aerosol forcing were also prescribed according to the observations. With the same SST data and the same model, ensemble integration with three members were performed in order to study interannual to multi-decadal variability (Arpe et al., 2000; Grosfeld et al., 2007). Furthermore, the water isotope module has been applied for recent and past interglacial variability (Werner and Heimann, 2002; Herold and Lohmann, 2009; Cruz et al., 2009).

From the model run, we extract the local climate and oxygen isotope signature for the region 7.5–8.5° E, 51–52° N. This information is then used as the input for the stalagmite model (Wackerbarth et al., 2010, 2012).

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2.2 Stalagmite model

Cave drip water inherits the δ^{18}O value from the meteoric precipitation above the cave modified in the soil-karst system before it enters the cave and feeds the stalagmite. The parameters influencing the δ^{18}O signal can, in principle, be divided into four groups: the atmosphere, the bio- and pedosphere, the karst system and the cave environment. In the biosphere, pedosphere and the karst system, the signal is influenced by various processes, such as evapotranspiration, mixing of water of different age and host rock dissolution, which in turn depend on different parameters such as temperature, the properties of the soil and karst layer, the $p\mathrm{CO}_2$ of soil air and the type and seasonal state of vegetation (Dreybrodt and Scholz, 2011). Isotope fractionation between the δ^{18}O value of the drip water and the precipitated speleothem calcite also depends on several conditions inside the cave, such as cave temperature, drip interval and supersaturation of the drip water with respect to calcite (e.g. Dreybrodt, 2008; Mühlinghaus et al., 2009; O'Neil et al., 1969; Scholz et al., 2009). The model establishes a weighting function and calculates the resulting δ^{18}O value of the drip water. Wackerbarth et al. (2012) have evaluated the modelled $\delta^{18}\mathrm{O}_{\mathrm{drip}}$ and $\delta^{18}\mathrm{O}_{\mathrm{calcite}}$ values for seven European caves supplying extensive data from cave monitoring programs.

The Oxygen isotope Drip water and Stalagmite Model (ODSM) (Wackerbarth et al., 2010) simulates the modification of the δ^{18}O value of precipitation ($\delta^{18}\mathrm{O}_{\mathrm{prec}}$) by processes occurring in the soil and karst (e.g. evapotranspiration, calcite dissolution, the residence time of the infiltrating water and mixing of water parcels of different age) in order to calculate the δ^{18}O value of cave drip water ($\delta^{18}\mathrm{O}_{\mathrm{drip}}$). Furthermore, calcite precipitation at the stalagmite's surface (either kinetic or equilibrium stable isotope fractionation during calcite precipitation) is considered in order to compute the δ^{18}O value of speleothem calcite ($\delta^{18}\mathrm{O}_{\mathrm{calcite}}$). A detailed description of the model can be found in Wackerbarth et al. (2010) and Wackerbarth (2012).

For this application, the ODSM is forced with the climate and rainfall δ^{18}O values simulated by ECHAM4. Cave- and drip site-specific parameters were appropriately

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adjusted for Bunker Cave (Riechelmann et al., 2011). The mixing of water parcels in the soil and karst matrix is assumed to be 48 months (Wackerbarth, 2012), the mean value of the infiltration related drip interval is 3600s, and the mixing parameter is set to 1 (the latter two parameters are needed for calculating kinetic isotope fractionation according to the Mühlinghaus et al. (2009) model). The extent of mixing of water parcels in the aquifer only affects the degree of smoothing of the $\delta^{18}O$ signal. The mean $\delta^{18}O$ value remains unchanged.

It should be noted that the simulated stalagmite $\delta^{18}O$ values are given in monthly resolution and, therefore, show a higher variability than corresponding natural stalagmites from Bunker Cave. These normally have a temporal resolution of about 8–10 yr (Riechelmann, 2010; Fohlmeister et al, 2012).

3 Results

We start with local temperature and the hydrological cycle in the AGCM. Figure 1 shows the temporal evolution of the simulated surface temperature (panel a), local precipitation minus evaporation (panel b), and the $\delta^{18}O$ value of precipitation at the cave site. The panels indicate pronounced seasonal, interannual, and decadal climate variability. Figure 2 shows the relation between the simulated monthly $\delta^{18}O$ values and surface temperature, indicating a positive correlation between the $\delta^{18}O$ value of local precipitation and temperature. The climate information is used as an input for the ODSM stalagmite proxy model. Figure 3 displays the cave temperature, which is calculated from the running-mean over the past 12 months (panel a) and predicted speleothem calcite $\delta^{18}O$ values at Bunker Cave (panel b). The temperature data indicate pronounced interannual variations, whereas the calcite $\delta^{18}O$ values exhibit decadal oscillation (Fig. 3). Figure 4 displays the corresponding spectra of the cave temperature and speleothem calcite $\delta^{18}O$ values in Bunker cave. Interestingly, the interannual variability in calcite $\delta^{18}O$ is suppressed (Fig. 4b), and the power spectrum shows a significant peak at about 14 yr ($p = 0.002$).

In order to relate the recorded δ^{18}O signal to the large-scale temperature, the correlation of simulated speleothem calcite δ^{18}O in the Bunker cave and SST is evaluated (Fig. 5). Areas showing a significant correlation (95 % confidence level, t-test) are colored. The correlation map with SST is characterized by zonal bands of SST stacked in the meridional direction.

Due to the delay between the infiltration of a water parcel and its inflow into the cave (i.e. a lag of 2 yr for Bunker Cave, Kluge et al., 2010) and the propagation of the climate pattern, we also calculate the lag-correlation and lag-composite maps. To extract the patterns that coincide with a maximum index, we applied a Composite Map Analysis (von Storch and Zwiers, 2003) between the δ^{18}O calcite (Fig. 3b) and different horizontal quantities (SSTs and precipitation). For the calculation we use all time slices that are above −5.2 ‰. We apply composite analysis for different lags prior to the maxima in δ^{18}O calcite (Fig. 6). The results are not sensitive to the exact choice of the threshold (not shown). The SST anomalies develop around the Gulf Stream area south of Newfoundland (Fig. 6a) and propagate 1 yr (Fig. 6b) and 2 yr (Fig. 6c) further downstream.

Of interest is also the hydrological budget and its spatial extension. Figure 7 displays the composite map of the δ^{18}O value of precipitation (‰) with respect to speleothem calcite δ^{18}O (Fig. 3b), indicating a regional coherence in Central Europe. Because the surface signal is transported within ∼ 2 yr, we again calculate a lagged composite map.

4 Discussion

Instrumental surface temperature data over the last century depict strong variability at interannual to multidecadal time scales. There is evidence that the global climate system contains modes of climatic variability operating on decadal to multidecadal time scales involving temperature and atmospheric circulation (e.g. Mann et al., 1995; Delworth and Mann, 2000; Dima and Lohmann, 2004; Deser and Blackmon, 1993; Kushnir, 1994; Liu, 2012). Here, we want to elaborate the temporal behaviour of the speleothem climate archive for a specific cave site in western Germany where large-scale patterns may play a role. We combine two models, one AGCM and a speleothem proxy model for Bunker cave. We build pseudo proxy data by calculating the local speleothem calcite δ^{18}O values in Bunker Cave (Fig. 3b). This allows attributing dominant signals of variability in observed and proxy data of the North Atlantic realm to changes in SST forcing.

The decadal SST-signature is characterized by a remote North Atlantic tripolar pattern (Figs. 5 and 6) and has a quasi-decadal time scale (Fig. 4). Due to the lagged response, this also projects to a European regional pattern. It has been proposed that this mode with a time period of 12–14 yr results from ocean-atmosphere and tropics-midlatitudes interactions in the North Atlantic basin (Deser and Blackmon, 1993; Dima et al., 2001; Dima and Lohmann, 2004). The clear distinction of peaks in the climate spectra suggests that other than random processes may be responsible for the Atlantic quasi-decadal mode (Deser and Blackmon, 1993).

An important question is the mechanism of the filtering through the speleothem climate archive. Due to mixing processes in the soil and karst matrix, the $\delta^{18}O_{prec}$ signal is smoothed to an infiltration weighted mean δ^{18}O value. The extent of mixing determines the variance of the simulated $\delta^{18}O_{drip}$. We find that the spectrum of the calcite δ^{18}O value in Bunker Cave is dampened for interannual time scales providing for a natural filter. We emphasize that this parameter is location-dependent and can be calibrated to agree with the observed natural variance in the particular cave system (Wackerbarth et al., 2010). However, for the interpretation of stalagmite proxy records, the smoothing of the signal may be an advantage. Werner and Heimann (2002) found that simulated δ^{18}O records at ice core sites indicate year-to-year variations masked by internal atmospheric variability. Indeed, one can interpret ice core proxy data in terms of the frequency of weather patterns (Rimbu and Lohmann, 2010). If a proxy filters out the inherent noise of the climate system, it may be easier to detect a deterministic response to a large-scale SST pattern (Rodwell et al., 1999; Grosfeld et al., 2007; Latif et al., 2000; Sutton and Hodson, 2003; Robertson et al., 2000). The smoothing,

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of course, makes it more difficult to detect the corresponding mechanism, especially when dealing with relatively short periods as done in Baker et al. (2011). We admit that the actual mixing process in the real caves are more complex than in our ODSM model (Wackerbarth et al., 2010) and might be climate dependent.

The mode indicates the propagation of SST anomalies from the Gulf Stream region along the gyre circulation (Dima and Lohmann, 2004, cf. Fig. 5). Evidence for the Gulf Stream SST anomalies to be transferred from mid-latitudes into the tropics through surface advection is further supported by a lag composite analysis between speleothem calcite δ^{18}O and the SST field (Fig. 6). Local surface temperature is largely determined by the surrounding SST. The moderate correlation (0.4) with temperature indicates that other processes than SST affect the calcite δ^{18}O. Besides the effect through the modulation of δ^{18}O via temperature, the hydrological cycle shows a spatially coherent pattern (Fig. 7). Thus, we would expect a similar temporal behaviour in the areas showing a positive correlation in Fig. 7.

5 Conclusions

Several attempts to reconstruct reliable climate information from stalagmites over the last few centuries have been made to reconstruct large-scale climate patterns for the last millennium (see, for instance, the review papers by McDermott (2004) and Lachniet (2009)). At present, the modes of climate variability and their modulation through longer-term background climate, and how this has varied in the past, is not well known. Accordingly, climate models used to assess potential changes of these climate modes in the future are only poorly constrained.

On the other hand, cave monitoring programs are not in a stage that they could cover decades to study the environmental processes relevant for climate reconstructions. Using a pseudo-proxy approach extracted from AGCM simulations and a proxy module, we analyze the (modelled) reconstructions in the light of variability modes. We find that the regional response in speleothem calcite δ^{18}O is sensitive to environmental

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changes in terms of temperature and the hydrological cycle. We find a clear signature of the Atlantic quasi-decadal mode (Deser and Blackmon, 1993; Dima et al., 2001; Dima and Lohmann, 2004; Liu, 2012).

Furthermore, we show that the speleothem climate archive may reduce the interannual variability through natural low-pass filtering. This feature is distinct from the random error represented by reconstruction uncertainty ranges. We admit that our analysis might depend on the choice of the speleothem calcite model and the climate model simulation used to provide the pseudo-proxies. As a next step, several other locations will be studied and compared to each other in order to study the underlying physics for different regions. Figure 7 suggests that other Central European caves should show a similar temporal behaviour. Furthermore, we will extend our approach to multi-centennial timescales by using long-term Holocene numerical experiments in combination with our proxy modules. Such experiments can help to interpret long-term $\delta^{18}O$ variability in stalagmites.

References

Arpe, K., Bengtsson, L., Golitsyn, G. S., Mokhov, I. I., Semenov, V. A., and Sporyshev, P. V.: Connection between Caspian Sea level variability and ENSO, Geophys. Res. Lett., 27, 2693–2697, 2000.

Baker, A. Wilson, R., Fairchild, I. J., Franke, J., Spötl, Ch., Mattey, D., Trouet, V., and Fuller, L.: High resolution $\delta^{18}O$ and δ13C records from an annually laminated Scottish stalagmite and relationship with last millennium climate, Global Planet. Change, 79, 303–311, doi:10.1016/j.gloplacha.2010.12.007, 2011.

Bjerknes, J.: Atlantic air–sea interaction, Adv. Geophys. 10, 1–82, 1964.

Bjerknes, J.: Atmospheric teleconections from the equatorial Pacific, Mon. Weather Rev. 97, 163–172, 1969.

Cruz, F. W., Vuille, M., Burns, S. J., Wang, X. F., Cheng, H., Werner, M., Edwards, R. L., Karmann, I., Auler, A. S., and Nguyen, H.: Orbitally driven east-west antiphasing of South American precipitation, Nat. Geosci., 2, 210–214, doi:10.1038/Ngeo444, 2009.

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Delworth, T. L. and Mann, M. E.: Observed and simulated multidecadal variability in the Northern Hemisphere, Clim. Dynam., 16, 661–676, 2000.
Deser, C. and Blackmon, M.: Surface climate variations over the North Atlantic ocean during winter: 1900–1989, J. Climate, 6, 1743–1753, 1993.
Dima, M. and Lohmann, G.: Fundamental and derived modes of climate variability: concept and application to interannual time-scales, Tellus A, 56, 229–249, 2004.
Dima, M., Rimbu, N., Stefan, S., and Dima, I.: Quasi-decadal variability in the Atlantic Basin involving tropics-midlatitudes and ocean-atmosphere interactions, J. Climate, 14, 823–832, 2001.
Dreybrodt, W.: Evolution of the isotopic composition of carbon and oxygen in a calcite H_2O-CO_2-$CaCO_3$ solution and the related isotopic composition of calcite in stalagmites, Geochim. Cosmochim. Acta, 72, 4712–4724, 2008.
Dreybrodt, W. and Scholz, D.: Climatic dependence of stable carbon and oxygen isotope signals recorded in speleothems: From soil water to speleothem calcite, Geochim. Cosmochim. Acta, 75, 734–752, 2011.
Drysdale, R. N., Hellstrom, J. C., Zanchetta, G., Fallick, A. E., Sánchez Gõni, M. F., Couchoud, I., McDonald, J., Maas, R., Lohmann, G., and Isola, I.: Evidence for obliquity forcing of glacial Termination II, Science, 325, 1527–1531, doi:10.1126/science.1170371, 2009.
Fairchild, I. J. and Treble, P. C.: Trace elements in speleothems as recorders of environmental change, Quaternary Sci. Rev., 28, 449–468, 2009.
Fairchild, I. J., Smith, C. L., Baker, A., Fuller, L., Spötl, C., Mattey, D., McDermott, F., and E. I. M. F.: Modification a preservation of environmental signals in speleothems, Earth-Sci. Rev., 75, 105–153, 2006.
Felis, T., Lohmann, G., Kuhnert, H., Lorenz, S., Scholz, D., Pätzold, J., Al-Rousan, S. A., and Al-Moghrabi, S. M.: Increased seasonality in Middle East temperatures during the last interglacial period, Nature, 429, 164–168, 2004.
Fohlmeister, J., Schröder-Ritzrau, A., Scholz, D., Spötl, C., Riechelmann, D. F. C., Mudelsee, M., Wackerbarth, A., Gerdes, A., Riechelmann, S., Immenhauser, A., Richter, D. K., and Mangini, A.: Bunker Cave stalagmites: an archive for central European Holocene climate variability, Clim. Past Discuss., 8, 1687–1720, doi:10.5194/cpd-8-1687-2012, 2012.
Grosfeld, K., Lohmann, G., Rimbu, N., Fraedrich, K., and Lunkeit, F.: Atmospheric multidecadal variations in the North Atlantic realm: proxy data, observations, and atmospheric circulation model studies, Clim. Past, 3, 39–50, doi:10.5194/cp-3-39-2007, 2007.

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8, 3513–3533, 2012

Herold, M. and Lohmann, G.: Eemian tropical and subtropical African moisture transport: an isotope modelling study, Clim. Dynam, 33, 1075–1088, doi:10.1007/s00382-008-0515-2, 2009.
Hurrell, J. W.: Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation, Science, 269, 676–679, 1995.
Kluge, T., Riechelmann, D. F. C, Wieser, M., Spötl, C., Sültenfuss, J., Schröder-Ritzrau, A., Niggemann, S., and Aeschbach-Hertig, W.: Dating cave drip water by tritium, J. Hydrol., 394, 396–406, 2010.
Kushnir, Y.: Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions, J. Climate, 7, 141–157, 1994.
Lachniet, M. S.: Climatic and environmental controls on speleothem oxygen-isotope values, Quaternary Sci. Rev., 28, 412–432, 2009.
Langebroek, P., Werner, M., and Lohmann, G.: Climate information imprinted in oxygen-isotopic composition of precipitation in Europe, Earth Planet. Sci. Lett., 311, 144–154, doi:10.1016/j.epsl.2011.08.049, 2011.
Latif, M., Arpe, K., and Roeckner, E.: Oceanic control of decadal North Atlantic sea level pressure variability in winter, Geophys. Res. Lett., 27, 727–730, 2000.
Liu, Z.: Dynamics of Interdecadal Climate Variability: A Historical Perspective, J. Climate, 25, 1963–1995, doi:10.1175/2011JCLI3980.1, 2012.
Lohmann, G., Rimbu, N., and Dima, M.: Climate signature of solar irradiance variations: Analysis of long-term instrumental and historical data, Int. J. Clim., 24, 1045–1056, doi:10.1002/joc.1054, 2004.
Mann, M. E., Park, J., and Bradley, R. S.: Global interdecadal and century-scale climate oscillations during the past five centuries, Nature, 378, 266–270, 1995.
McDermott, F.: Palaeo-climate reconstruction from stable isotope variations in speleothems: a review, Quaternary Sci. Rev., 23, 901–918, 2004.
Mühlinghaus, C., Scholz, D., and Mangini, A.: Modelling fractionation of stable isotopes in stalagmites, Geochim. Cosmochim. Acta, 73, 7275–7289, 2009.
O'Neil, J., Clayton, R., and Mayeda, T.: Oxygen isotope fractionation in divalent metal carbonates, J. Chem. Phys. 51, 5547–5558, 1969.
Philander, S. G.: El Nio, La Ni˜na, and the Southern Oscillation, Academic Press, New York, 293 pp., 1990.

Rayner, N. A., Horton, E. B., Parker, D. E., Folland, C., and Hackett, R. B.: Version 2.2 of the Global sea-Ice and Sea Surface Temperature data set, 1903–1994, Clim. Res. Tech. Note. 74, Hadley Centre, UK Meteorol. Off., Bracknell, England, 1996.
Richards, D. A. and Dorale, J. A.: Uranium-series chronology and environmental applications of speleothems, in: Uranium-series Geochemistry, edited by: Bourdon, B., Henderson, G. M., Lundstrom, C. C., and Turner, S. P., Reviews in Mineralogy & Geochemistry, Mineralogical Society of America, Washington, DC, 656, 2003.
Riechelmann, D. F. C.: Aktuospeläologische Untersuchungen in der Bunkerhöhle des Iserlohner Massenkalks (NRW/Deutschland): Signifikanz für kontinentale Klimaarchive, Ruhr-University Bochum, Ph.D. thesis, 2010.
Riechelmann, D. F. C., Schröder-Ritzrau, A., Scholz, D., Fohlmeister, J., Spötl, C., Richter, D. K., and Mangini, A.: Monitoring Bunker Cave (NW Germany): A prerequisite to interpret geochemical proxy data of speleothems from this site, J. Hydrol., 409, 682–695, 2011.
Rimbu, N. and Lohmann, G.: Decadal variability in a central Greenland high-resolution deuterium record and its relationship to the frequency of daily atmospheric circulation patterns from the North Atlantic Region. J. Climate, 23, 4608–4618, doi:10.1175/2010JCLI3556.1, 2010.
Rimbu, N., Lohmann, G., Felis, T., and Pätzold, J.: Arctic Oscillation signature in a Red Sea coral, Geophys. Res. Lett., 28, 2959–2962, 2001.
Robertson, A. W., Mechoso, C. R., and Kim, Y.-J.: The influence of Atlantic sea surface temperature anomalies on the North Atlantic Oscillation, J. Climate, 13, 122–138, 2000.
Rodwell, M. J., Rowell, D. P., and Folland, C. K.: Oceanic forcing of the wintertime North Atlantic Oscillation and European climate, Nature, 398, 320–323, 1999.
Roeckner, E., Arpe, K., Bengtsson, L., Christoph, M., Claussen, M., Dümenil, L., Esch, M., Giorgetta, M., Schlese, U., and Schulzweida, U.: The atmospheric general circulation model ECHAM4: Model description and simulation of present-day climate, MPI Report 218, Max-Planck-Institute for Meteorology, Hamburg, Germany, 90 pp., 1996.
Scholz, D. and Hoffmann, D. L.: 230Th/U-dating of fossil reef corals and speleothems, Quaternary Science Journal (Eiszeitalter und Gegenwart), 57, 52–77, 2008.
Scholz, D., Mühlinghaus, C., and Mangini, A.: Modelling the evolution of _13C and _18O in the solution layer on stalagmite surfaces, Geochim. Cosmochim. Acta 73, 2592–2602, doi:10.1016/j.gca.2009.02.015, 2009.

Sutton, R. T. and Allen, R. M.: Decadal predictability in North Atlantic sea surface temperature and climate, Nature, 388, 563–567, 1997.
Sutton, R. T. and Hodson, D. L. R.: Influence of the ocean on North Atlantic climate variability 1871–1999, J. Climate, 16, 3296–3313, doi:10.1175/1520-0442(2003)016<3296:IOTOON>2.0.CO;2, ISSN 1520-0442, 2003.
von Storch, H. V. and Zwiers, F.W.: Statistical Analysis in Climate Research. Cambridge University Press, Cambridge, 484 pp., 1999.
Wackerbarth, A.: Towards a better understanding of climate proxies in stalagmites – modelling processes from surface to cave, Dissertation, Ruprecht-Karls-Universität, 2780, 2781, 2012.
Wackerbarth, A., Scholz, D., Fohlmeister, J., and Mangini, A.: Modelling the _18O value of cave drip water and speleothem calcite, Earth Planet. Sci. Lett., 299, 387–397, 2779, 2780, 2781, 2010.
Wackerbarth, A., Langebroek, P. M., Werner, M., Lohmann, G., Riechelmann, S., and Mangini, A.: Simulated oxygen isotopes in cave drip water and speleothem calcite in European caves, Clim. Past Discuss., 8, 2777–2817, doi:10.5194/cpd-8-2777-2012, 2012.
Walker, G. T.: Correlation in seasonal variations of weather, IX. Mem. India Meteor. Dept., 24, 275–332, 1924.
Werner, M. and Heimann, M.: Modeling interannual variability of water isotopes in Greenland and Antarctica, J. Geophys. Res.-Atmos., 107, 4001, doi:10.1029/2001JD900253, 2002.

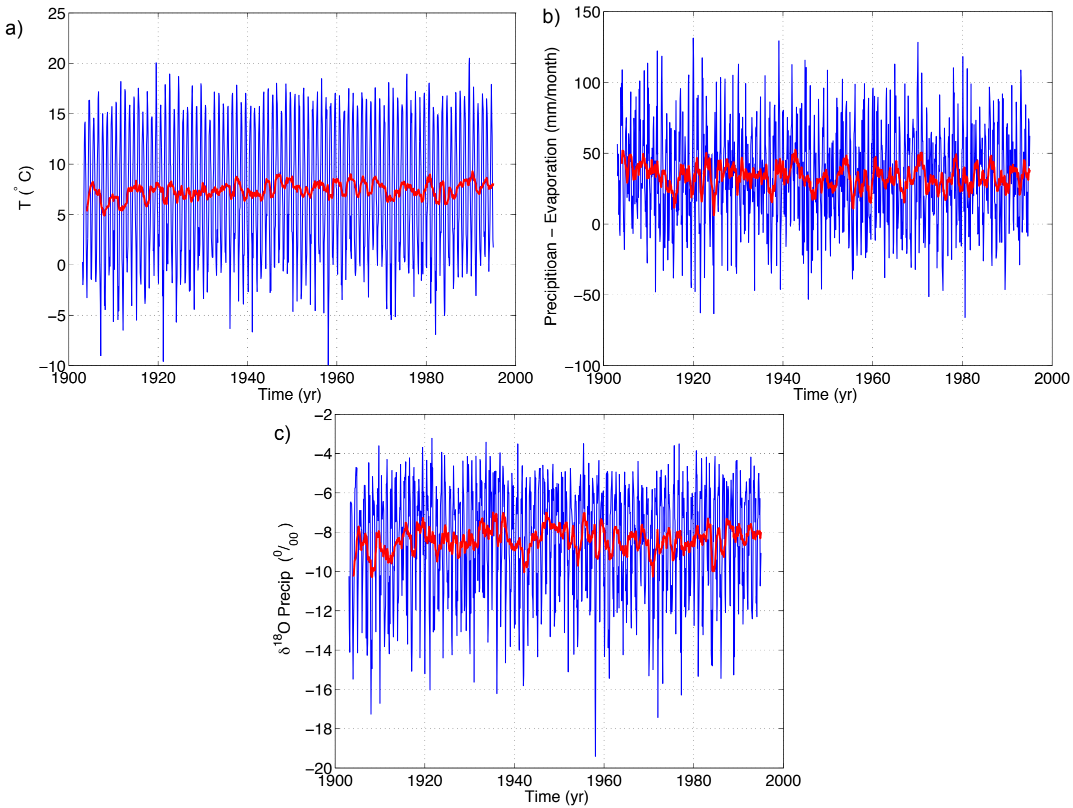

Fig. 1. (a) Time series of local annual mean surface temperature at the cave site (°C), **(b)** local net precipitation minus evaporation (mm/month), **(c)** simulated precipitation $\delta^{18}O$ values at Bunker cave (‰). The red lines indicate the 12-month running-mean values, respectively.

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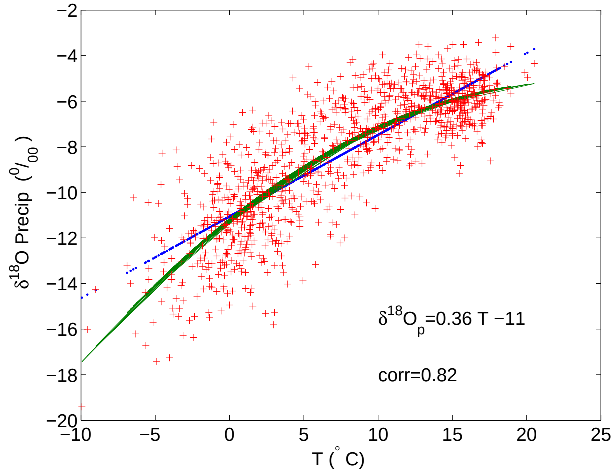

Fig. 2. Relation between local surface temperature at the cave site with simulated precipitation δ^{18}O values at Bunker Cave (monthly values as in Fig. 1a and c). The linear regression line is shown in blue with a correlation coefficient of 0.82. The green line indicates a polynomial fit emphasizing more negative δ^{18}O values for low temperatures.

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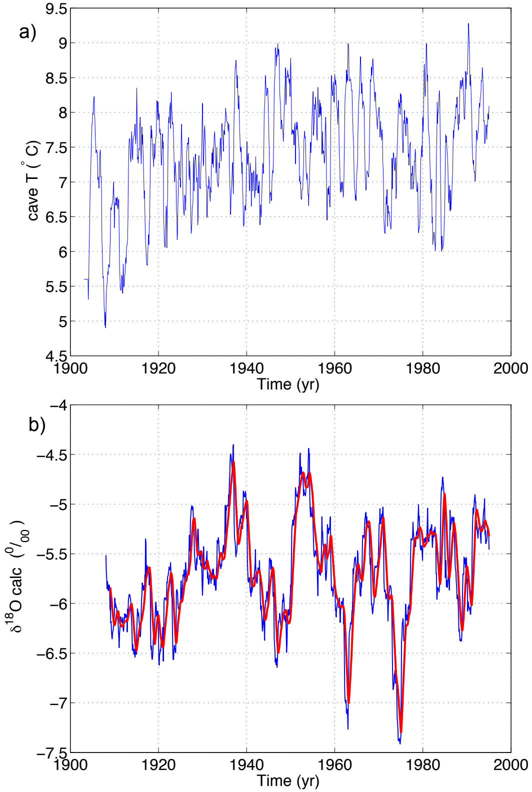

Fig. 3. Time series of the simulated **(a)** cave temperature (°C) and **(b)** speleothem calcite $\delta^{18}O$ values at Bunker Cave (‰) using the method of Wackerbarth et al. (2010, 2012). The red line in panel **(b)** shows the 12-month running mean.

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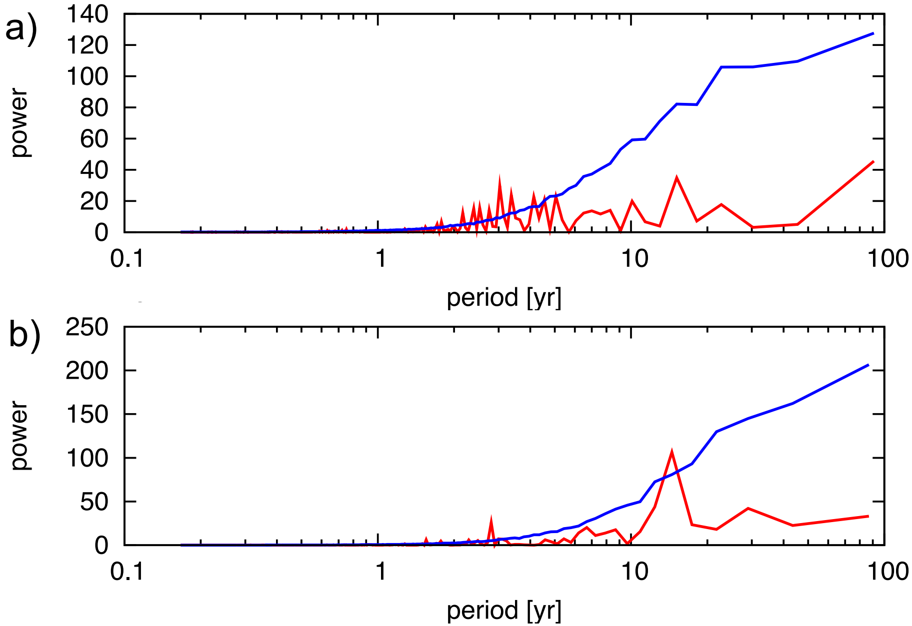

Fig. 4. Power spectrum of the simulated **(a)** cave temperature (°C) and **(b)** speleothem calcite δ^{18}O values in Bunker Cave. The blue line denotes the 95 % highest spectrum of 5000 AR(1) processes with the same autocorrelation. In **(b)**, a pronounced peak at quasi-decadal time scale (˜14 yr) is detected.

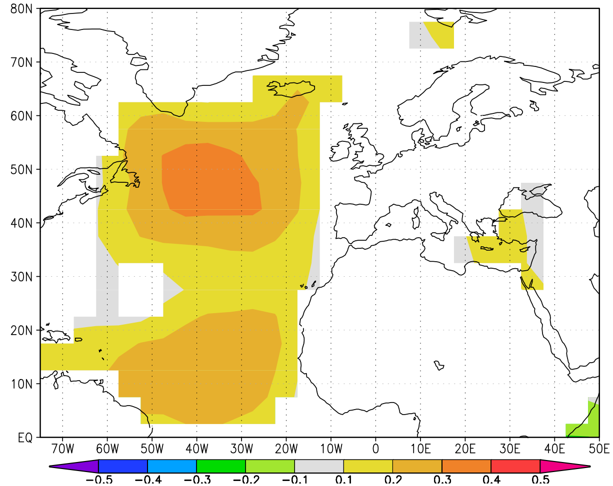

Fig. 5. In-phase significant correlations of simulated speleothem calcite $\delta^{18}O$ values in Bunker Cave and annual mean SST.

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Simulated European stalagmite record

G. Lohmann et al.

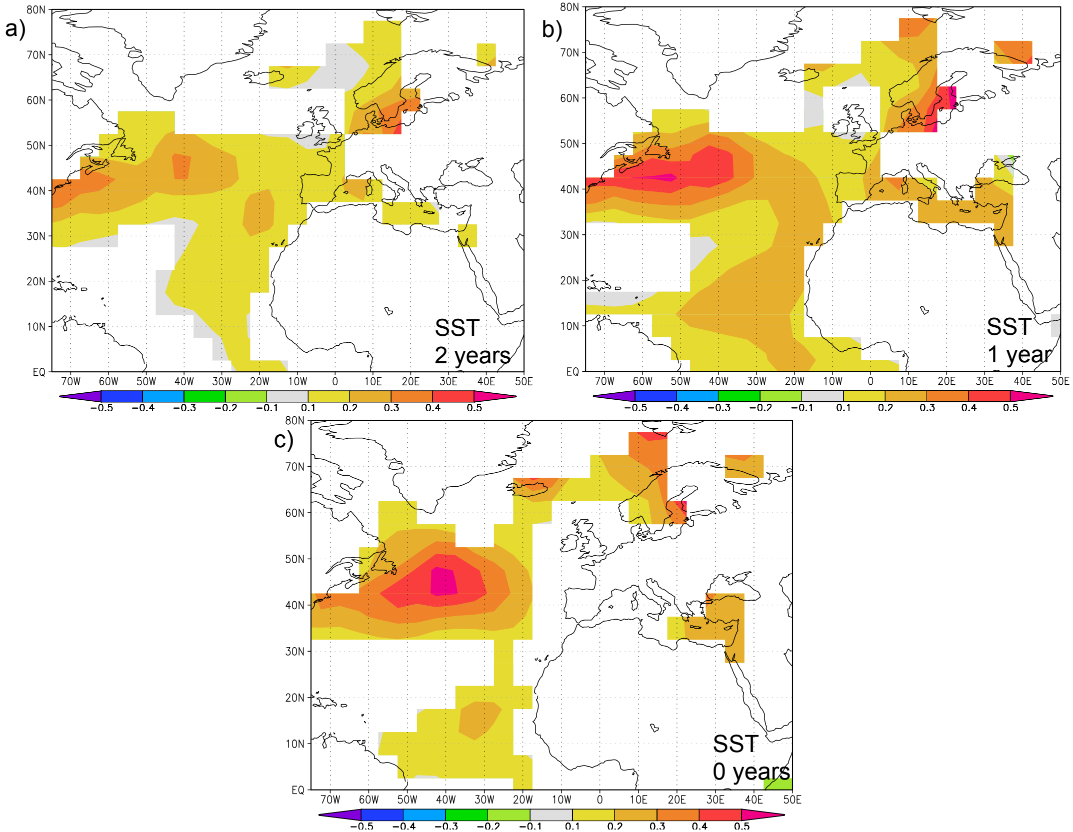

Fig. 6. SST Composite maps (°C) prior to high values (>−5.2 ‰) in speleothem calcite δ^{18}O values: **(a)** for 2 yr prior to speleothem calcite δ^{18}O, **(b)** 1 yr, **(c)** in-phase with speleothem calcite δ^{18}O. All values are based on annual means.

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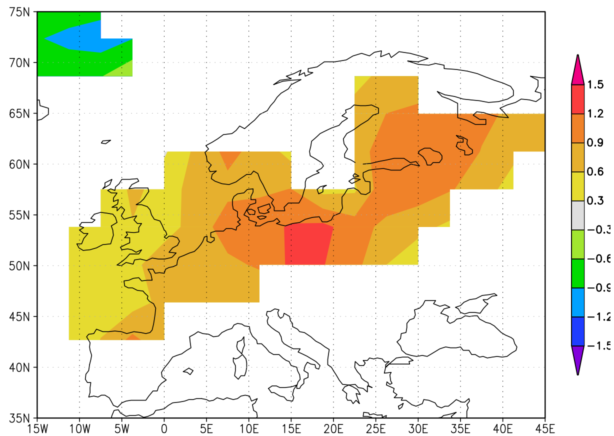

Fig. 7. Composite map 1 yr prior to high values (>−5.2 ‰) in speleothem calcite $\delta^{18}O$ for O-18 in precipitation (‰).

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