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Correspondence and requests for materials should be addressed to H.S.S. (hanna.sundqvist@natgeo.su.se)

Evidence of a large cooling between 1690 and 1740 AD in southern Africa

H. S. Sundqvist[1,2], K. Holmgren[1,2], J. Fohlmeister[3], Q. Zhang[1,2], M. Bar Matthews[4], C. Spötl[5] & H. Körnich[6]

[1]Department of Physical Geography and Quaternary Geology, Stockholm University, S-10691 Stockholm, Sweden, [2]Bolin Centre for Climate Research, Stockholm University, S-10691 Stockholm, Sweden, [3]Heidelberg Academy of Sciences, University of Heidelberg, Im Neuenheimer Feld 229 D-69120 Heidelberg, Germany, [4]Geological Survey of Israel, 30 Malchei Israel St, Jerusalem, Israel 95501, [5]Department of Geology and Paleontology, University of Innsbruck, Innrain 52, 6020 Innsbruck, Austria, [6]Swedish Meteorological and Hydrological Institute, SE-601 76 Norrköping, Sweden.

A 350-year-long, well-dated $\delta^{18}O$ stalagmite record from the summer rainfall region in South Africa is positively correlated with regional air surface temperatures at interannual time scales. The coldest period documented in this record occurred between 1690 and 1740, slightly lagging the Maunder Minimum (1645–1710). A temperature reconstruction, based on the correlation between regional surface temperatures and the stalagmite $\delta^{18}O$ variations, indicates that parts of this period could have been as much as 1.4°C colder than today. Significant cycles of 22, 11 and 4.8 years demonstrate that the solar magnetic and the El Niño-Southern Oscillation cycle could be important drivers of multidecadal to interannual climate variability in this region. The observation that the most important driver of stalagmite $\delta^{18}O$ on interannual time scales from this subtropical region is regional surface temperature cautions against deterministic interpretations of $\delta^{18}O$ variations in low-latitude stalagmites as mainly driven by the amount of precipitation.

Scenario projections of future climate change involve a number of uncertainties. This is especially true for the sub-tropical and tropical regions where, for example, different precipitation scenarios, as summarized by the IPCC[1], disagree not only in magnitude but also in the sign. Knowledge-based data of the patterns and causes (natural and anthropogenic) of past temperature and precipitation variability and changes are necessary to test and evaluate climate model results against empirical data[2]. In comparison to high- and mid-latitude regions, few high-resolution palaeoclimatic records are available from low latitudes. This imbalance in data availability hampers a clear understanding of the Earth system functioning[3]. The southern African sub-continent is one of the white spots in this respect, with a widespread lack of quantitative palaeoclimate records[4].

Rainfall and temperature patterns over southern Africa respond to a variety of coupled ocean-atmosphere processes[5]. The long-term precipitation pattern is characterized by interdecadal variability of 16 and 20 years[6], modulated by an El Niño-Southern Oscillation (ENSO)-like decadal variability[7–10], which influences southern Indian Ocean sea-surface temperatures (SST) and wind fields on multidecadal time scales. Improved knowledge of the spatio-temporal patterns of this variability is critical for understanding sub-continental climate patterns, such as the movement, displacement, and/or intensification of existing weather patterns, including the Intertropical Convergence Zone (ITCZ) and the circumpolar westerlies[11].

Previous paleoclimatic studies of the southern Africa summer rainfall region, over the last millennium, are mainly based on qualitative records from different archives, such as documentary data[12], tree rings[13,14], speleothems[15–17], bones[18] and sediments[19–22]. Only a few attempts to quantitative temperature reconstructions exist[15,23,24]. Speleothem-based studies in southern Africa report significant relative changes in climate and environmental conditions over different time scales[15–17,24–27]. Conclusions are mainly based on the stable isotopic composition of the speleothems. The interpretation of these data, however, is not straight-forward. Several processes contribute to the isotopic composition and these may influence the signal differently at different spatial and temporal scales[28,29]. Most commonly, $\delta^{18}O$ in speleothems is interpreted as reflecting the $\delta^{18}O$ value of meteoric water, in turn interpreted to reflect surface temperatures (especially at high latitudes) and/or rain amount effect (tropical oceanic sites, monsoon regions). However, other processes also influence the $\delta^{18}O$ composition in precipitation, such as changing atmospheric circulation patterns and changing climate modes, leading to changing temperature/$\delta^{18}O$ relationships[30–32]. The speleothem $\delta^{18}O$ records from Makapansgat (or Cold Air Cave) in South Africa were previously interpreted as being generally determined by shifts in atmospheric circulation patterns, in turn related to temperature variations[16,17,25]. In order to test these assumptions and to obtain a high-resolution quantitative temperature reconstruction, we re-analyzed the last 350 years of growth of the stalagmite T7, from Cold Air Cave, by high-resolution sampling of stable isotopes in combination with an improved age model, based on U-series and ^{14}C-dating and trace-element lamina-counting (Supplementary Figs. S1–S3).

Cold Air Cave (24°0′S; 29°11′E, 1420 m above sea level) is situated in Makapansgat valley (Fig. 1), in the summer rainfall region of South Africa, where over 90% of the rain falls during summer (October-March) with the main moisture source being the Indian Ocean. Summer rainfall amounts in Makapansgat valley show a high correlation with the rest of the summer rainfall region of southern Africa and the temperature shows a high correlation with an even larger region demonstrating that this site is representative of the climate in the region (Fig. 1). The vegetation above the cave is patchy and consists mainly of C_4 grasses with scattered C_3 bushes. The soil cover is less than 30 cm thick and the bedrock thickness above the cave chamber, where T7 grew, is about 20 m. We therefore expect a short travel time of the water from the surface into the cave during the rainy season. Results from a semi-continuous monitoring study (2000–2002) show that the cave interior temperature is stable (18.8 ± 0.3°C) and close to the local annual mean and the relative humidity inside the cave is close to 100% all year around[25]. $\delta^{18}O$ of drip water samples near and at the stalagmite locations have a mean value of about -4‰ VSMOW, which is rather constant throughout the year in spite of large seasonal changes in drip discharge, and is close to the annually weighted average of $\delta^{18}O$ from the nearest Global Network of Isotopes in Precipitation (GNIP) station in Pretoria (~250 km south-west of Cold Air Cave) between 1997 and 2001[33].

Results

According to previous age models[17] stalagmite T7 started growing about 6000 years ago and was active when collected in 1996. The new high quality age model is based on 10 new U-series datings over the last 400 years (corresponding to the upper 8.5 cm of T7) and combined with observations of the ^{14}C bomb activity as a time marker and annual cycles in trace elements for the period 1926 to 1996.

$\delta^{18}O$ and $\delta^{13}C$ profiles of the upper ~8 cm of stalagmite T7 were obtained by micromilling 820 samples along the growth axis at 100 μm intervals, yielding a time resolution of 0.2 to 1.5 years, with an average of 0.4 years per sample (Supplementary Fig. S4). An earlier study showed no correlation between $\delta^{18}O$ and $\delta^{13}C$ in individual layers[16] indicating that the aragonitic stalagmite was precipitated in isotopic equilibrium and kinetic effects on the isotope values are negligible[34]. Both the $\delta^{18}O$ and $\delta^{13}C$ records along the growth axis show multidecadal variability and they fluctuate between ~−2 to −27 and~−3 to −5‰ VPDB respectively (Fig. S4). On top of that the $\delta^{18}O$ data follow a linear trend towards more enriched values during the 20th century and a distinct negative excursion between 1690 and 1740 (~−6 to −7‰), which encompasses parts of the Maunder Minimum (1645–1710).

Visual comparison between the $\delta^{18}O$ and $\delta^{13}C$ records with meteorological data for the 20th century reveals strong similarities between stalagmite $\delta^{18}O$ and the mean annual air temperature outside the cave (Fig. 2), except for the period 1956–1976. This period has the highest $\delta^{18}O$ and $\delta^{13}C$ values of the 20th century (Supplementary Fig. S4). Such a positive offset in both isotopes suggests that the climate signal was overprinted by another process, causing disequilibrium fractionation conditions. The annual mean temperature and $\delta^{18}O$ are positively correlated at the 95% level with $R = 0.42$ for the period 1901–1995 and $R = 0.57$ if the period 1956–76 is excluded. Rainfall amounts and $\delta^{13}C$ and $\delta^{18}O$ show a weak anti-correlation with $R = -0.21$ for the same period.

To further examine the signal of the $\delta^{18}O$ record, annually averaged stalagmite $\delta^{18}O$ values were compared to annual and seasonal (October-March) temperatures, both against the corresponding temperature for the same year, as well as against temperature data averaged over up to five previous years (Supplementary Table S3). Smoothing the data takes into account that the transfer time of the water through the karst aquifer may be longer than one year. The highest significant correlations occur between temperature and stalagmite $\delta^{18}O$ if the anomalous period 1956–76 is excluded and the data are averaged over the year of deposition plus the four previous ones.

One of the very few other high resolution temperature reconstructions covering almost the same time period from this region is a SST reconstruction based on $\delta^{18}O$ in a coral from the Agulhas Straight off the southwest coast of Madagascar[35] (Fig. 1). The coral $\delta^{18}O$ values show a strong resemblance with our stalagmite $\delta^{18}O$ record (Fig. 3). Indian Ocean SSTs change in concert with ENSO and the Indian Ocean Dipole (IOD)[10]. IOD and El Niño episodes are significantly correlated, particularly during the IOD mature phase

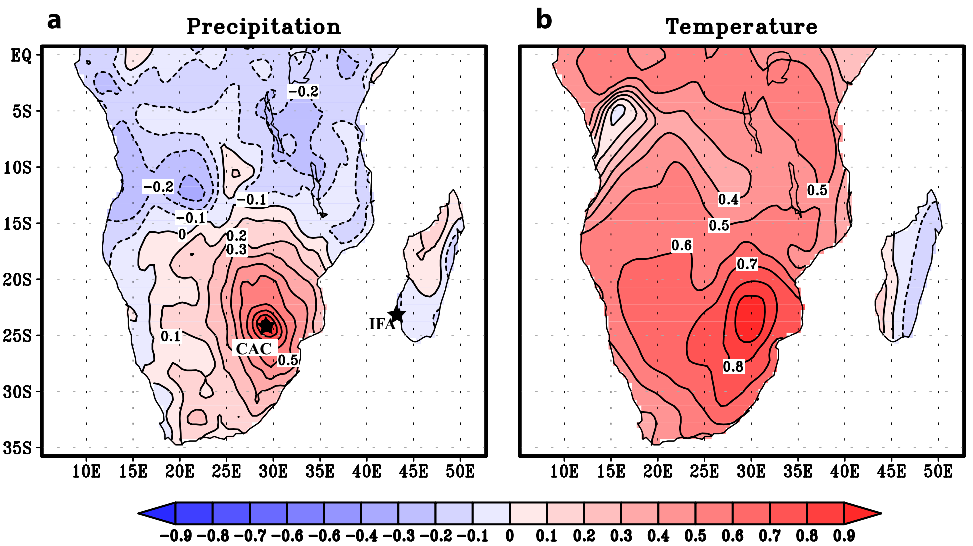

Figure 1 | One-point correlation pattern for precipitation (A) and temperature (B) between the closest grid to the cave site (24°E, 29°S) and the southern African region using CRU TS3.1 1901–2009 annual mean data[51]. The Cold Air Cave (CAC) and the Ifaty coral (IFA) sites are indicated by asterisks. These maps have been generated used Grid Analysis and Display System (GrADS) Version 2.0.a3.

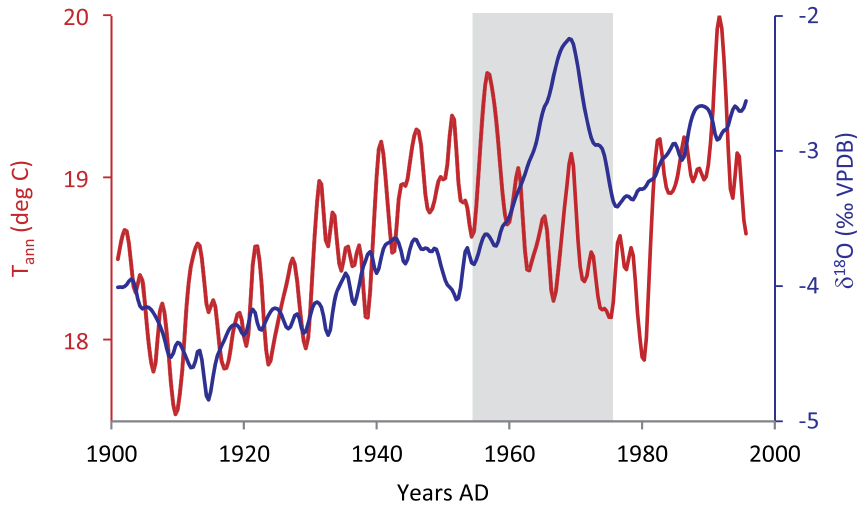

Figure 2 | Stalagmite $\delta^{18}O$ compared with annual mean temperature (T_{ann}) (CRU TS3.1) for the period 1901–1995. Due to the varying time resolution (0.2–1.5 years) between the stable isotope data points we interpolated the isotopes into 1/7 years resolution and then averaged over a year to obtain a mean annual value. The time interval with low correlation, 1956–76, is shaded.

(September-November). A 19th century winter severity record from Lesotho show similarities in the pattern with the stalagmite $\delta^{18}O$ record, however the timing of an interval with cold temperatures in both records is slightly out of phase. The explanation for this is most likely dating uncertainties in the T7-stalagmite during this century. Further than these records not much high resolution information about temperature variations in the region beyond the instrumental record is available.

Spectrum analysis of stalagmite $\delta^{18}O$ using the Multi Taper Method (MTM) shows significant peaks at 22, 11 and 4.7 years (Supplementary Fig. S5). The 4.8 year cycle is also highly significant in the regional annual precipitation (Fig. S5), indicating a strong coherence between the two records and also to ENSO and IOD. On the interdecadal time scale, the 22-year solar magnetic cycle is clearly present in our speleothem $\delta^{18}O$ record and most likely corresponds to the observed quasi-18-year climate oscillation in the southern Africa summer rainfall region[6,11] and the 16–20 year cycle identified in the Madagascar coral[36]. Instrumental data from the cave and coral locations show significant positive correlations between temperature and SSTs on annual to decadal timescales (0.64–0.77 at 95% confidence level). We found no significant correlation between SSTs and precipitation amounts on these time scales.

Discussion

Given the good correlation between stalagmite $\delta^{18}O$ and local annual mean temperatures and the strong agreement with the SST record from the Agulhas Straight, we calibrated the speleothem record (excluding the anomalous period 1956–76) against a 5-year smoothed annual mean temperature record, using linear regression (Supplementary Fig. S6). The reconstruction shows that the coldest period of the record, 1690–1740, was on average 0.9°C colder than today (1961–90 mean) and the coldest interval, at around 1720, could

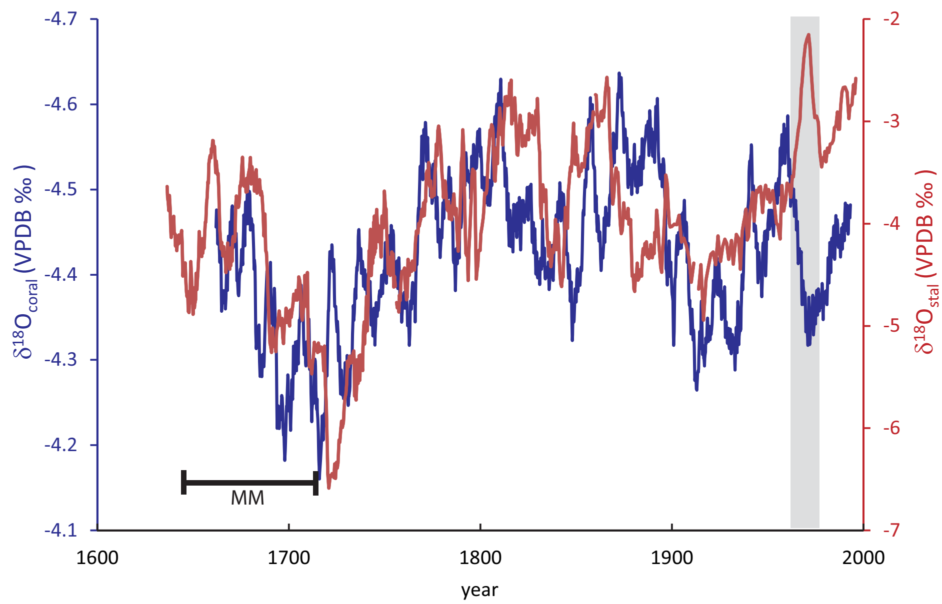

Figure 3 | The T7 $\delta^{18}O$ record compared to the Ifaty-4 coral $\delta^{18}O$ dataset (ref. 35). The coral record is smoothed to represent ~3-year running mean. Interval of reduced solar magnetic activity during Maunder Minimum (MM) is indicated. As in fig. 2, the time interval with low correlation to surface temperatures is shaded.

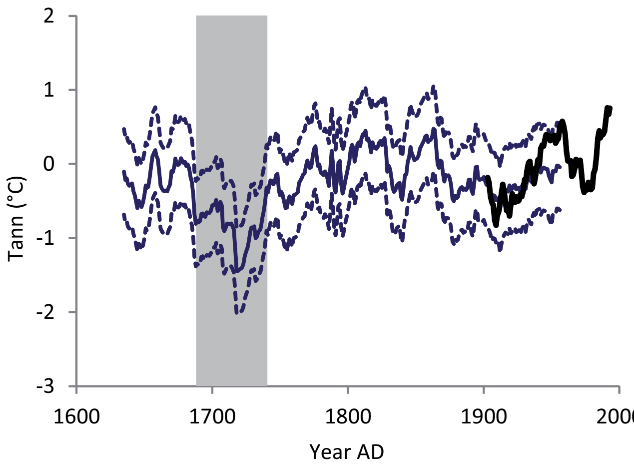

Figure 4 | Stalagmite $\delta^{18}O$-based temperature reconstruction. The reconstruction is based on linear regression of 5-year smoothed annual mean temperature (T_{ann}) and annual $\delta^{18}O$ between 1635 and 1995, using linear regression (blue solid line). Dotted lines illustrate an uncertainty of 0.65°C (2 standard errors of the regression). The black line represents the 5 year smoothed instrumental annual mean temperature. The shaded area indicates the cold period between 1690 and 1740 AD.

have been 1.4°C colder (Fig. 4). The lack of a verification point outside of the calibration period, or additional stalagmite data from the summer rainfall region of southern Africa, hampers a validation of our inferred annual mean surface temperature record. We note, however, that a preliminary local temperature reconstruction, using the correlation between temperature and colour variations in stalagmite T7 during the 20th century, shows similar trends for the period 1500–1800 (around 1°C colder than today[24]), but differed in amplitudes. The SST reconstruction, using the Madagascar coral $\delta^{18}O$, Sr/Ca ratios and instrumental SST data[35], suggests 0.3–0.5°C cooler SSTs of the southwestern Indian Ocean than today between 1675 and 1760. A recent surface water temperature reconstruction from Lake Malawi[37] show similar features with our temperature reconstruction (Fig. S7) and a cooling of more than 3°C between 1670–1700 and another study from Ross Sea, Antarctica, identified 2°C colder SSTs between 1300 and 1800[38]. All these records show evidence that the Little Ice Age, originally identified in the Northern Hemisphere, had a counterpart of similar magnitude and sign also in the Southern Hemisphere.

Our finding of a clear relationship between T7 stalagmite $\delta^{18}O$ and mean annual air temperatures, but a less distinct one with rainfall, warrants an explanation. If carbonate is precipitated in isotopic equilibrium with the parent drip water[34], the $\delta^{18}O$ composition of the carbonate is governed by the cave air temperature (~mean annual surface temperature) and the $\delta^{18}O$ composition of the feeding drip water, which in turn is determined largely by isotope effects in precipitation, including moisture sources, air temperatures and storm tracks. We conclude that $\delta^{18}O$ changes in rainfall overprinted the temperature-dependent fractionation effect, because we found a positive relationship between the two, despite the fact that the temperature-dependent fractionation factor between water and carbonate has a negative slope. The $\delta^{18}O$ composition of precipitation in tropical and subtropical areas is often related to the amount of precipitation falling at a given location, the 'amount effect'[39] and $\delta^{18}O$ palaeorecords from these regions are often interpreted accordingly[40–42]. Depending on the travel time and degree of mixing, the water reaching the cave chamber can represent a seasonally, annually or even a decadally weighted average of $\delta^{18}O$ in precipitation. On a seasonal cycle, the amount of precipitation and $\delta^{18}O$ in precipitation at the GNIP station in Pretoria are anti-phased (Supplementary Fig. S8). The $\delta^{18}O$ composition of precipitation is the highest during the winter (dry season) and the lowest during the summer (wet season). Monthly average $\delta^{18}O$ values of precipitation have a significant negative correlation with the monthly amount of precipitation ($r = -0.50$) indicating the presence of an amount effect (Supplementary Table S4). However, when removing the seasonal cycle, the correlation breaks down ($r = 0$, Supplementary Table S4). When studying palaeoclimate records correlations with annual, or longer time averages are often more important, than monthly values. We find significant correlations with amount-weighted $\delta^{18}O$ values of precipitation and in situ temperatures at the 95% confidence levels ($r = 0.44$ for 12-months averages, and $r = 0.66$ for 24-months averages). Thus, the result from the analysis of the available modern isotope data provides a plausible explanation for the relationship between regional air temperatures and $\delta^{18}O$ in precipitation at annual to interannual time scales recorded in the T7 stalagmite. This cautions against always interpreting $\delta^{18}O$ variations in low-latitude stalagmites to mainly be governed by the amount of precipitation.

Several processes may explain the observed relationship, at interannual to decadal time scales, between regional air temperatures and isotopic composition in precipitation in the summer rainfall region of southern Africa. We rule out changes in *moisture sources* since it is unlikely that there were significant changes in ocean $\delta^{18}O$ over the last 350 years. It is most likely that precipitation falling at the study site only originates from the Indian Ocean. The storm tracks, determined from 6-hour reanalysis data, show that during the rainy season in eastern South Africa moisture is transported from the tropical Indian Ocean along the South Indian convergence zone[43]. A shift in *atmospheric circulation* due to SST variations in the south western Indian Ocean could affect the isotopic composition of precipitation. A warmer ocean would lead to a strengthening of the south easterly trade winds, which in turn would lead to more moisture coming directly from the ocean, having a shorter transport route, less rainout and therefore less depleted $\delta^{18}O$ values. A colder Indian Ocean would lead to enhanced transport of moisture overland - hence more recycling - and more depleted $\delta^{18}O$ values in precipitation. A shift in atmospheric circulation may also affect the *rain type,* whereby warmer conditions favour the formation of calm, relatively disorganized mid-altitude rain that is less depleted in $\delta^{18}O$ in comparison to more organized precipitation, or hail, from convective high-altitude storms[44] that characterize the atmospheric circulation during colder periods[11,45]. Finally, a change in the *duration of the rainy season* could also affect the isotope signal. At present the rainy season normally lasts from October to March. If the ITCZ was situated further south, the rainy season would most likely be longer. Since rainfall during neighbouring months (September and April) is isotopically enriched, the annually weighted mean $\delta^{18}O$ of precipitation would be more positive. Forthcoming modelling experiments of the isotopic composition of atmospheric water will aid in assessing the effect of the different processes that affect the meteoric isotope signal.

Methods

U-series isotope measurements were performed using MC-ICP-MS[46] at the Geological Survey of Israel. 10 subsamples were drilled using 0.5 mm diameter drill bits along the growth axis of the upper 8.5 cm of stalagmite T7. All samples were totally dissolved, in a combination of 7 M HNO_3 and HF, and spiked with a mixed $^{229}Th/^{236}U$ spike. The reproducibility of $^{234}U/^{238}U$ ratio was 0.11% (2σ). The samples were loaded onto mini-columns containing 2 ml Bio-Rad AG 1 × 8 200–400 mesh resin. U was eluted by 1 M HBr and Th with 6 M HCl. U and Th solutions were evaporated to dryness and the residue dissolved in 2 ml and 5 ml of 0.1 M HNO_3, respectively. Analyses of the isotope ratios were performed using a Nu Instruments Ltd (UK) MC-ICP-MS equipped with 12 Faraday cups and 3 ion counters. Each sample was introduced to the MC-ICP-MS through an Aridus® micro-concentric desolvating nebuliser sample introducing system. The instrumental mass bias was corrected (using the exponential equation) by measuring the $^{235}U/^{238}U$ ratio and correcting with the natural $^{235}U/^{238}U$ ratio. Calibration of ion-counters relative to Faraday cups was performed using several cycles of measurement with different collector configurations in each particular analysis[46]. Isotope ratios are given in Table S1 as activity ratios with 2 sigma uncertainties. The errors are propagated from the in-run precision errors, weighing errors and uncertainties in spike concentrations and their isotopic compositions. Uncertainties in the half-lives of the U-series isotopes are not included in the error propagation. The U-Th method assumes that all ^{230}Th present in the calcite speleothems is formed in situ by radioactive decay of uranium that co-precipitated with the calcite. However, this component is often present in detrital material such as clays, oxides and hydroxides[47,48]. For this correction, a ^{232}Th/^{238}U atomic ratio of 3.8 in the detrital components was used.

18 subsamples of calcite powder for ^{14}C measurements were micromilled along the upper 7 mm of stalagmite T7. Samples were milled continuously along the growth axis at a resolution of 400 μm and each sample contains between 6 to 8 mg of carbonate powder. The $CaCO_3$ was acidified with HCl *in vacuo* and the evolving CO_2 was combusted at 575°C to C under H_2 using an Fe catalyst. The Fe-C mixture was then measured with the MICADAS[49] at the Klaus-Tschirra Laboratory, Mannheim. Radiocarbon measurements were corrected to δ^{13}C values of −25‰ to account for fractionation effects. Marble background samples were prepared and measured under similar conditions as the stalagmite samples.

Samples for stable carbon and oxygen isotope analysis were micromilled continuously along the upper ~8.5 cm of the growth axis of stalagmite T7 at 100 μm intervals in a 2.5 mm wide and 100 μm deep track. They were measured using an on-line, automated carbonate preparation system linked to a triple collector gas source mass spectrometer at the University of Innsbruck. Values are reported in the δ-notation relative to the VPDB standard, in ‰ with a precision better than 0.08‰[50]. Due to the varying time resolution (0.2–1.5 years) we interpolated the stable isotope into 1/7 years resolution and then averaged over a year to obtain a mean annual value. This "annual" record of stalagmite δ^{18}O and δ^{13}C was then compared to instrumental climate parameters: precipitation (annual, seasonal totals) and temperature (annual, seasonal means).

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Author contributions

H.S.S. designed the study with input from K.H., J.F. performed the ^{14}C dating and the trace elemental lamina counting together with input from H.S.S., Q.Z. performed the MTM analysis. M.B.M. performed the U/Th datings. C.S. perfomed the stable isotope analysis. H.S.S. and K.H. wrote the paper with input from J.F., Q.Z., M.B.M., C.S. and H.K.

Additional information

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