

Hydroclimatic instability during the late Roman Warm Period–early Dark Ages Cold Period transition in the eastern Mediterranean

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Text S1. Climatic interpretation of the BC-4 $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ data

Speleothem $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ ratios are valuable proxies for reconstructing past climatic and environmental conditions. Reliable paleoclimate interpretation requires calcite to precipitate in or close to isotopic equilibrium with cave drip water, which are influenced by multiple factors, including rainfall amount, moisture source, temperature, seasonality, latitude/altitude, continentality, geologic setting, and global ice volume (McDermott, 2004; Fairchild et al., 2006; Lachniet, 2009). In the eastern Mediterranean region, speleothem $\delta^{18}\text{O}$ primarily reflects changes in precipitation amount, moisture sources, and temperature, with lower values generally indicating wetter and warmer conditions and higher values corresponding to drier and colder periods (Bar-Matthews et al., 1997; Ünal-İmer et al., 2015; Baykara et al., 2026).

The isotopic composition of modern precipitation in the cave region exhibits a pronounced seasonal pattern (Fig. S1a). Winter precipitation, as the principal contributor to groundwater recharge and cave drip water, is characterized by low $\delta^{18}\text{O}$ (−6.2 to −5.4‰) and δD (−36 to −31‰) values. In contrast, isotope values become progressively high from spring through summer up to −3.2‰ for $\delta^{18}\text{O}$ and −22‰ for δD in response to rising temperature and declining precipitation. Seasonal temperature variations significantly influence the isotopic composition of precipitation, while evaporative processes may further elevate the precipitation isotopes prior to infiltration under warm and dry conditions (McDermott, 2004).

Modern precipitation in western Türkiye is sourced by moisture originating from both Mediterranean Sea and North Atlantic Ocean (Batibenz et al., 2020). The $\delta^{18}\text{O}$ (1.4 to 1.7‰ VSMOW) and δD (7.5 to 8.4‰) values of the eastern Mediterranean Sea surface water are isotopically more enriched than those of the upper North Atlantic Ocean ($\delta^{18}\text{O} = -0.1$ to 0.5 ‰; $\delta\text{D} = 1.0$ to 4.0 ‰) (Gat et al., 1996; Frew et al., 2000; Schrag et al., 2002). The $\delta^{18}\text{O}$ and δD compositions of meteoric waters from the İzmir station (38° 25' 50" N; 27° 09' 04" E) are close to the Global Meteoric Water Line (GMWL). It suggests that regional western Anatolian precipitation primarily derives from moisture sources transported by large-scale westerly circulation linked to the North Atlantic, rather than solely from strongly-evaporated Mediterranean Sea (Fig. S1c).

Stalagmite BC-4 $\delta^{18}\text{O}$ record is interpreted as a proxy for effective moisture (precipitation minus evaporation, P–E), which is largely controlled by the amount and isotopic composition of winter precipitation and modulated by large-scale westerly circulation patterns, whereas seasonal temperature and moisture-source variability exert less influences (Bar-Matthews et al., 1997; Ünal-İmer et al., 2015; Baykara et al., 2026). Accordingly, low (high) BC-4 $\delta^{18}\text{O}$ values reflect wet (dry) hydroclimatic conditions.

Speleothem $\delta^{13}\text{C}$ value is governed by multiple environmental and karst processes, including vegetation type (C_3 versus C_4 plants), soil biological activity, host rock-meteoric water interaction, host rock dissolution, degree of the CO_2 degassing, and prior calcite precipitation (PCP) (Fairchild and McMillan, 2006; Fohlmeister et al. 2020). Under relatively wet and warm conditions, enhanced vegetation productivity and increased soil respiration promote the incorporation of isotopically depleted biogenic CO_2 into infiltrating cave waters, resulting in low speleothem $\delta^{13}\text{C}$ value (Fohlmeister et al., 2020). Conversely, dry and cold conditions suppress soil biological activity, reduce infiltration, and possibly increase water residence time within the karst system. These conditions enhance water–rock interaction, CO_2 degassing, and PCP, which preferentially removes isotopically light ^{12}C from drip–waters before they reach the cave. Consequently, the remaining dissolved inorganic carbon becomes enriched in ^{13}C , leading to elevated speleothem $\delta^{13}\text{C}$ value (Fairchild and McMillan, 2006).

Vegetation type also influences speleothem $\delta^{13}\text{C}$ through differences in photosynthetic pathways. Speleothem carbonate formation typically has $\delta^{13}\text{C}$ values of approximately -14 to -6‰ under C_3 vegetation and from -6 to 2‰ under C_4 vegetation (McDermott, 2004). Stalagmite BC-4 $\delta^{13}\text{C}$ values, ranging from -8.9 to -5.6‰ , consistently fall within the isotopic range characteristic of C_3 vegetation, suggesting persistent dominance of C_3 plant communities within the cave catchment throughout the record interval. BC-4 $\delta^{13}\text{C}$ predominantly reflects changes in effective moisture, mediated through soil biological activity, vegetation productivity, and karst processes, rather than shifts in vegetation type (Ünal-İmer et al., 2015; Baykara et al., 2026). Thus, low (high) $\delta^{13}\text{C}$ values generally indicate enhanced (reduced) soil biological activity and vegetation productivity associated with relatively wet (dry) conditions.

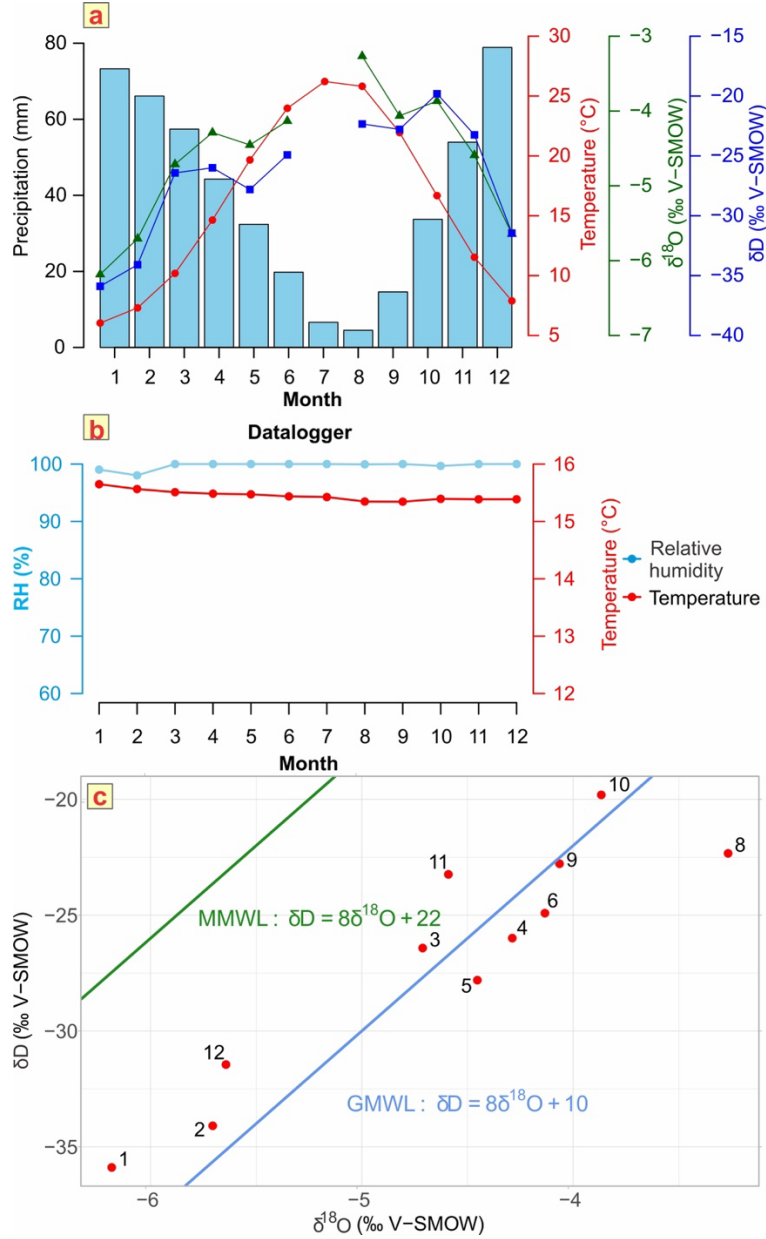
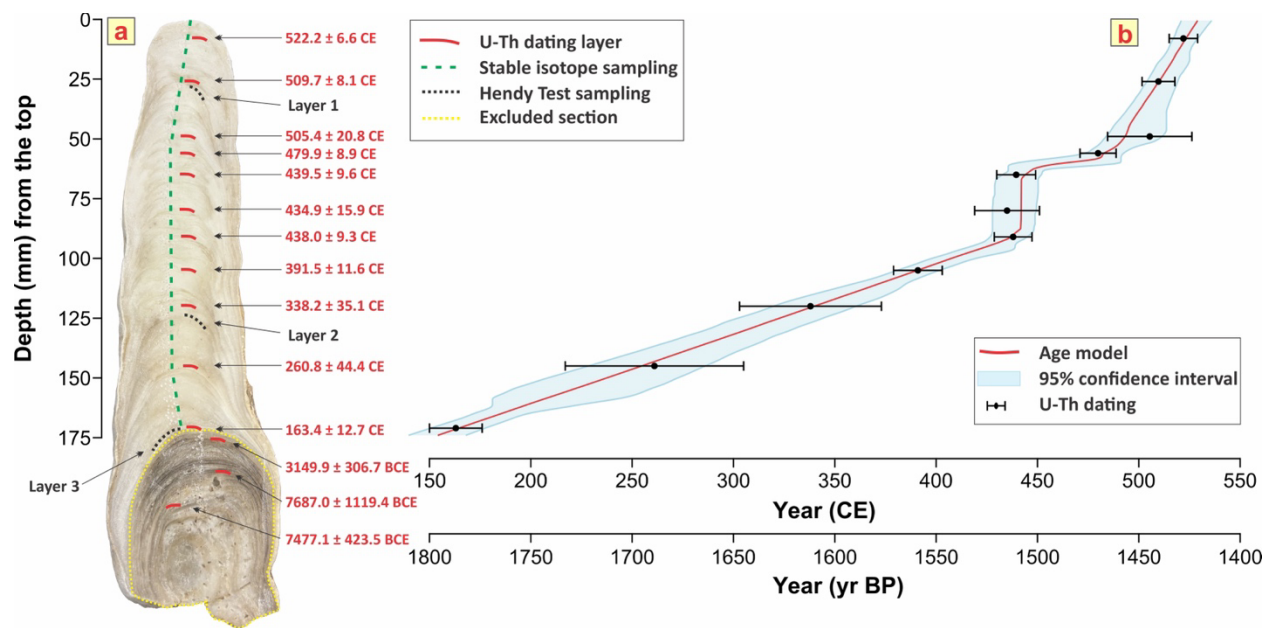


Figure S1. Climate pattern around and in Börtlücke Cave. **a)** the nearest meteorological station data in Salihli District of Manisa Province with 30-year observation interval (1960-2020 CE), located 38 km southwest of the cave, obtained from Turkish State Meteorological Service and the modern precipitation isotope data from İzmir meteorological station between 2008 and 2022 CE. The meteoric isotope data was obtained from the International Atomic Energy Agency (<https://www.iaea.org/services/networks/gnip>). **b)** Temperature and relative humidity (RH) recorded by data logger inside the cave (Fig. 1c) from August 2023 to July 2024. **c)** δD versus $\delta^{18}\text{O}$ plot of monthly rainfall for the at the Global Network of Isotopes in Precipitation (GNIP) İzmir station for the period 2008-2022 CE. Numbers by red dots indicate the respective month in Northern Hemisphere. The Mediterranean Meteoric Water Line (MMWL; Gat and Carmi, 1970) and Global Meteoric Water Line (GMWL; Craig, 1961) are shown as references.



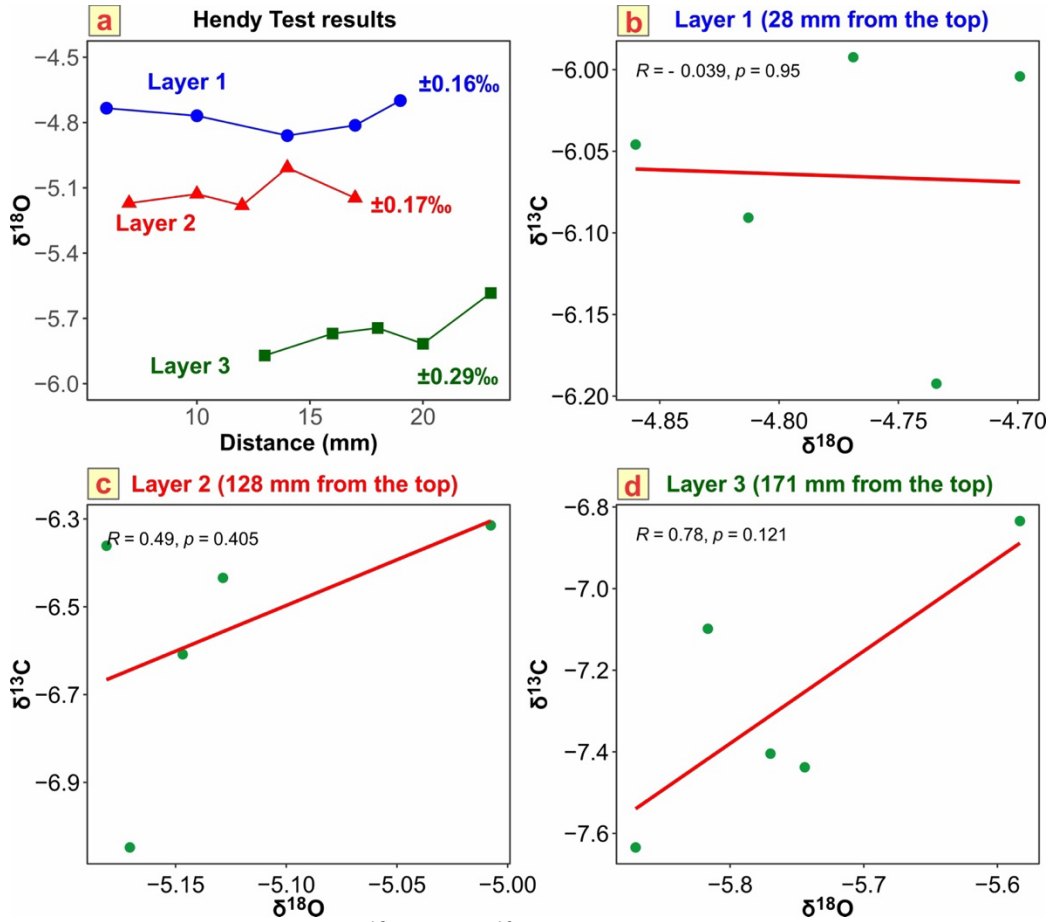


Figure S3. Hendy Test on coeval $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ data measured along three selected layers (28, 128, and 171 mm from the top of the BC-4 stalagmite (Fig. 2a). **a)** A plot of $\delta^{18}\text{O}$ variation with increasing distance from the central growth axis along individual growth laminae. **b-d)** Plots of $\delta^{18}\text{O}$ vs. $\delta^{13}\text{C}$ for three layers. Pearson correlation coefficients (r) and corresponding p -values are shown for each layer.

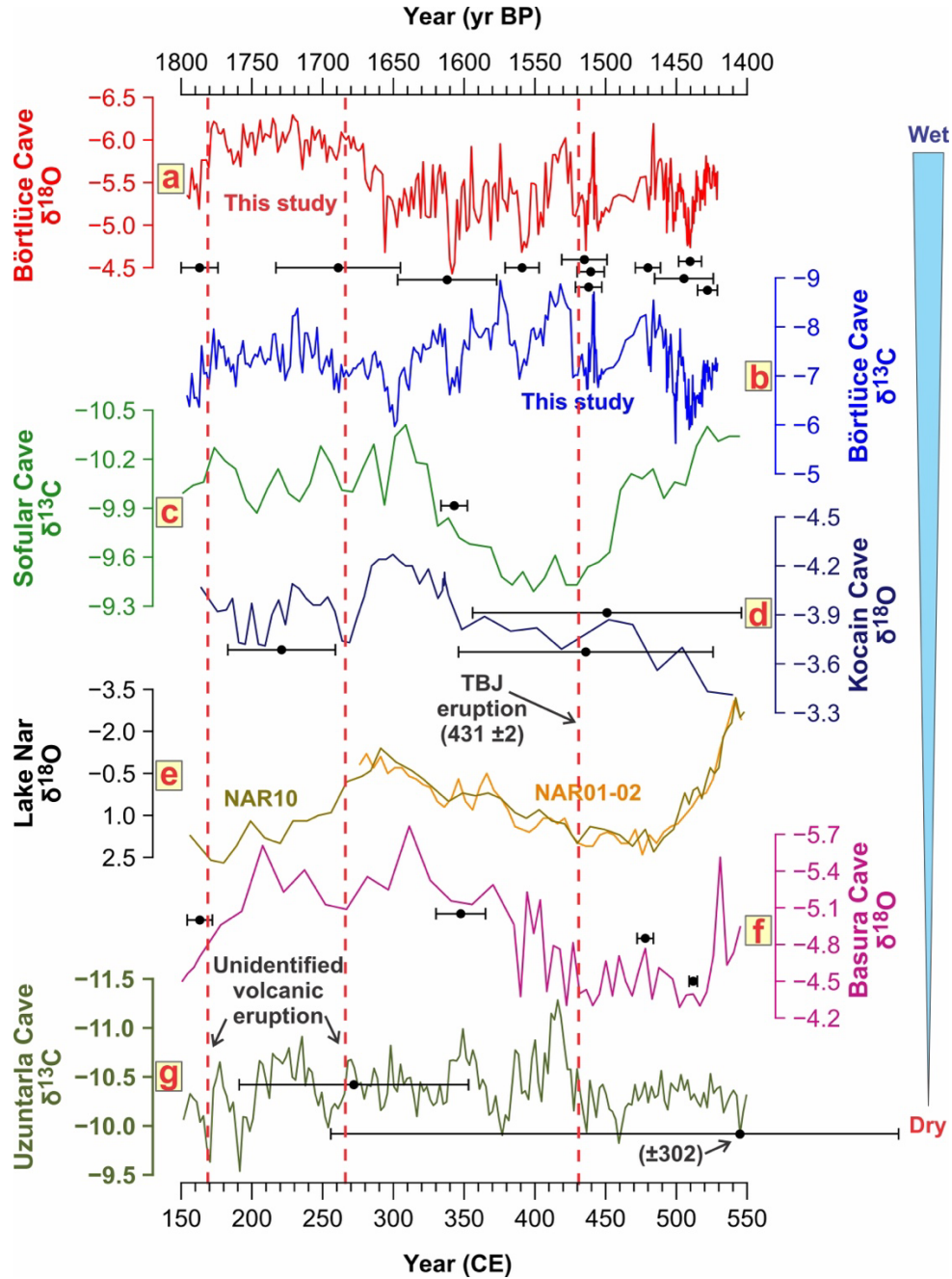


Figure S4. Comparison between Börtlüce Cave and regional proxy records **a)** Stalagmite BC-4 $\delta^{18}\text{O}$ and **b)** $\delta^{13}\text{C}$ records from Börtlüce Cave (this study). **c)** $\delta^{13}\text{C}$ records of Sofular Cave, northwestern Türkiye (Fleitmann et al., 2009; Göktürk et al., 2011). **d)** $\delta^{18}\text{O}$ record of Kocain Cave, southwestern Türkiye (Jacobson et al., 2021). **e)** Carbonate $\delta^{18}\text{O}$ records of core NAR10 (Dean et al., 2015) and core NAR01/02 (Jones et al., 2006) from Lake Nar, central Türkiye. **f)** Stalagmite $\delta^{18}\text{O}$ record of Bäsura Cave, northern Italy (Hu et al., 2022). **g)** Stalagmite $\delta^{13}\text{C}$ records of Uzuntarla Cave, northwestern Türkiye (Morgan et al., 2025). Horizontal black error bars indicate U-Th ages with errors (2σ). Vertical dashed red lines represent volcanic eruptions: the Tierra Blanca Joven eruption (TBJ) of Ilopango, El Salvador in 431 ± 2 CE (Smith et al. 2020) and unidentified volcanic eruptions in 169 and 266 CE (Sigl et al. 2015; Toohey and Sigl, 2017).

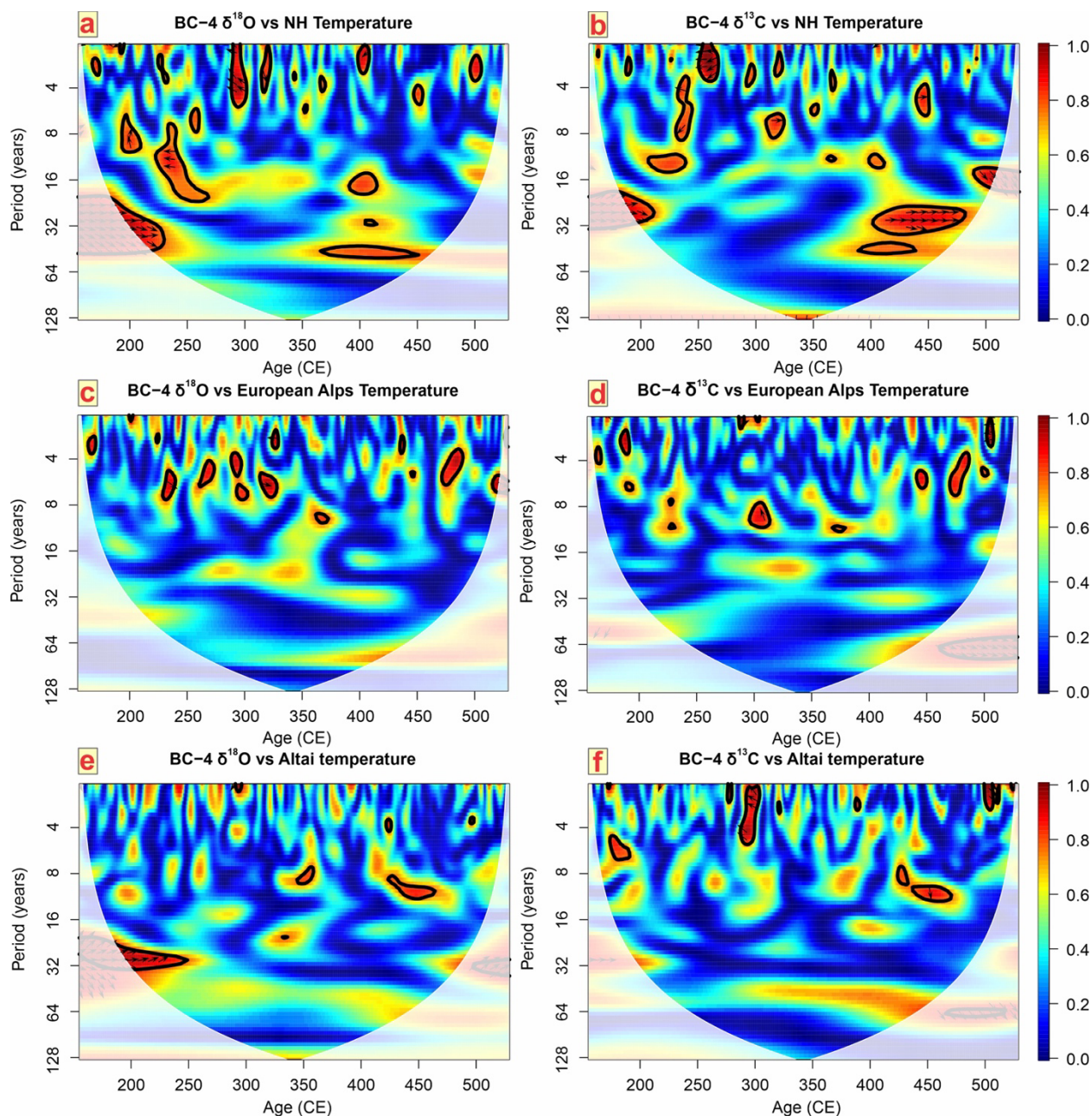


Figure S5. Wavelet coherence between BC-4 $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ records and the Northern Hemisphere (a-b), European Alps (c-d), and Russian Altai (e-f) temperature reconstructions. The x-axis represents time space, while the y-axis represents periodicity. Color coding indicates coherence, with blue and red representing low and high coherence, respectively. Statistically significant regions are enclosed by black contours at the 95% confidence level. Phase arrows indicate apparent phase relationships between the records, with rightward arrows (→) and leftward arrows (←) denoting in-phase and anti-phase behavior, respectively. Phase arrows indicate apparent relative phase relationships between the records. These relationships should be interpreted cautiously because of chronological uncertainties and differences in temporal resolution among the proxy records. The cone of influence (COI) delineates regions potentially affected by edge effects and should therefore be interpreted cautiously (Torrence and Compo, 1998; Grinsted et al., 2004).

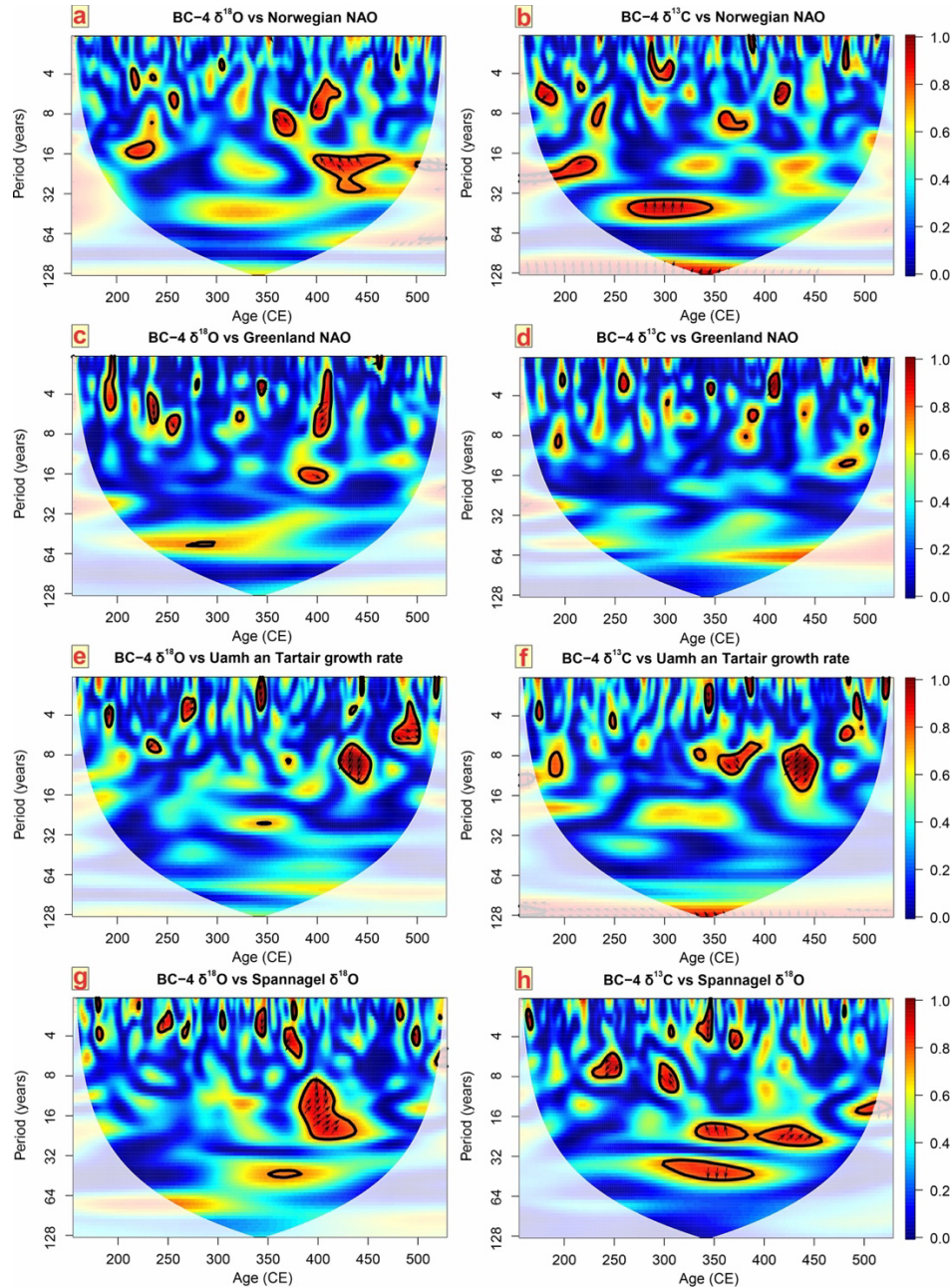


Figure S6. . Wavelet coherence between BC-4 $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ records and Norwegian NAO Index (**a-b**), Greenland NAO Index (**c-d**), and Uamh an Tartair growth rate (**e-f**) and Spannagel Cave $\delta^{18}\text{O}$ (**g-h**) records. The x-axis represents time and the y-axis represents periodicity. Color coding indicates coherence, with blue and red representing low and high coherence, respectively. Statistically significant regions are enclosed by black contours at the 95% confidence level. Phase arrows denote the relationship between the records, with rightward arrows (→) and leftward arrows (←) representing in-phase and anti-phase behavior, respectively, and upward (↑) or downward (↓) arrows indicating phase offsets. Because of chronological uncertainties and differences in temporal resolution among the proxy records, these phase relationships should be interpreted cautiously and are not used to infer precise synchronicity or lead-lag relationships. The cone of influence (COI) delineates regions potentially affected by edge effects and should therefore be interpreted cautiously (Torrence and Compo, 1998; Grinsted et al., 2004).

Table S1. Uranium and Thorium isotopic compositions and ages for subsamples of stalagmite BC-4 from Börtlüce Cave.

Subsample ID	Depth mm	Weight g	²³⁸ U 10 ⁻⁹ g/g ^a	²³² Th 10 ⁻⁹ g/g	δ ²³⁴ U measured ^a	[²³⁰ Th/ ²³⁸ U] activity ^c	²³⁰ Th/ ²³² Th atomic (x 10 ⁻⁶)	Age (kyr ago) uncorrected	Age (kyr ago) corrected ^{c,d}	δ ²³⁴ U _{initial} corrected ^b
BC-4-A1	8	0.0545	2.1882 ± 0.0022	0.461 ± 0.009	1.6 ± 1.3	0.013080 ± 0.000050	1024 ± 19	1.4333 ± 0.0060	1.4278 ± 0.0066	1.6 ± 1.3
BC-4-A2	26	0.0240	2.8500 ± 0.0024	0.594 ± 0.019	4.7 ± 1.2	0.013927 ± 0.000067	1102 ± 36	1.5222 ± 0.0076	1.4403 ± 0.0081	4.7 ± 1.2
BC-4-A3	49	0.0283	2.8428 ± 0.0024	3.823 ± 0.019	4.6 ± 1.3	0.01424 ± 0.00010	174.6 ± 1.5	1.556 ± 0.011	1.445 ± 0.021	4.6 ± 1.3
BC-4-A4	56	0.0222	4.2543 ± 0.0035	1.688 ± 0.021	-1.9 ± 1.0	0.014151 ± 0.000063	588.1 ± 7.8	1.5571 ± 0.0072	1.4701 ± 0.0089	-1.9 ± 1.0
BC-4-A5	65	0.0213	3.9545 ± 0.0030	1.774 ± 0.021	-0.4 ± 1.0	0.014549 ± 0.000067	534.8 ± 6.9	1.5989 ± 0.0076	1.5105 ± 0.0096	-0.4 ± 1.0
BC-4-A6	80	0.0291	4.0621 ± 0.0030	4.479 ± 0.022	-2.28 ± 0.87	0.014719 ± 0.000056	220.1 ± 1.4	1.6207 ± 0.0064	1.515 ± 0.016	-2.29 ± 0.88
BC-4-A7	91	0.0178	3.6629 ± 0.0038	1.146 ± 0.026	8.4 ± 1.2	0.014658 ± 0.000074	772 ± 18	1.5967 ± 0.0084	1.5120 ± 0.0093	8.5 ± 1.2
BC-4-A8	105	0.0185	3.6456 ± 0.0035	1.182 ± 0.026	9.1 ± 1.1	0.01510 ± 0.00010	768 ± 17	1.643 ± 0.011	1.559 ± 0.012	9.2 ± 1.1
BC-4-A9	120	0.0144	3.8324 ± 0.0036	9.744 ± 0.052	8.9 ± 1.1	0.01611 ± 0.00010	104.45 ± 0.84	1.755 ± 0.011	1.612 ± 0.035	9.0 ± 1.1
BC-4-A10	145	0.0240	2.0838 ± 0.0017	6.828 ± 0.034	8.0 ± 1.0	0.01697 ± 0.00010	85.40 ± 0.65	1.852 ± 0.011	1.689 ± 0.044	8.1 ± 1.0
BC-4-A11	171	0.0584	1.4764 ± 0.0014	1.033 ± 0.008	6.2 ± 1.3	0.016518 ± 0.000077	389.3 ± 3.5	1.8050 ± 0.0088	1.787 ± 0.013	6.2 ± 1.3
BC-4-A12*	175	0.0209	1.2169 ± 0.0012	28.15 ± 0.26	8.0 ± 1.6	0.05208 ± 0.00025	37.12 ± 0.39	5.785 ± 0.030	5.10 ± 0.31	8.1 ± 1.7
BC-4-A13*	185	0.0200	1.3652 ± 0.0013	114.03 ± 0.92	8.2 ± 1.6	0.10447 ± 0.00041	20.62 ± 0.18	11.927 ± 0.053	9.6 ± 1.1	8.4 ± 1.7
BC-4-A14*	195	0.0213	1.6459 ± 0.0017	52.71 ± 0.42	14.9 ± 1.7	0.09184 ± 0.00040	47.28 ± 0.43	10.341 ± 0.051	9.43 ± 0.42	15.3 ± 1.7

* Ages were excluded for the age-depth model.

Analytical errors are 2s of the mean.

^a[²³⁸U] = [²³⁵U] x 137.818 (±0.65‰) (Hiess et al., 2012); δ²³⁴U = ([²³⁴U/²³⁸U]_{activity} - 1) x 1000.

^bδ²³⁴U_{initial} corrected was calculated based on ²³⁰Th age (*T*), i.e., δ²³⁴U_{initial} = δ²³⁴U_{measured} × e^{λ₂₃₄×*T*}, and *T* is corrected age.

^c[²³⁰Th/²³⁸U]_{activity} = 1 - e^{-λ₂₃₀*T*} + (δ²³⁴U_{measured}/1000)[λ₂₃₀/(λ₂₃₀ - λ₂₃₄)](1 - e^{-(λ₂₃₀ - λ₂₃₄) *T*}), where *T* is the age.

Decay constants used are 2.8215 x 10⁻⁶ yr⁻¹ for ²³⁴U from Hu et al. (2025) and others available in Cheng et al. (2013).

^dAge corrections, **relative to 1950 CE**, were calculated using an assumed initial ²³⁰Th/²³²Th atomic ratio of 4 (± 2) x 10⁻⁶.

Those are the values for a material at secular equilibrium, with the crustal ²³²Th/²³⁸U value of 3.8. The errors are arbitrarily assumed to be 50%.

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