A multi-proxy stalagmite record indicates a shift in forcing of 20th Century drought events in Normandy

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Supplementary data

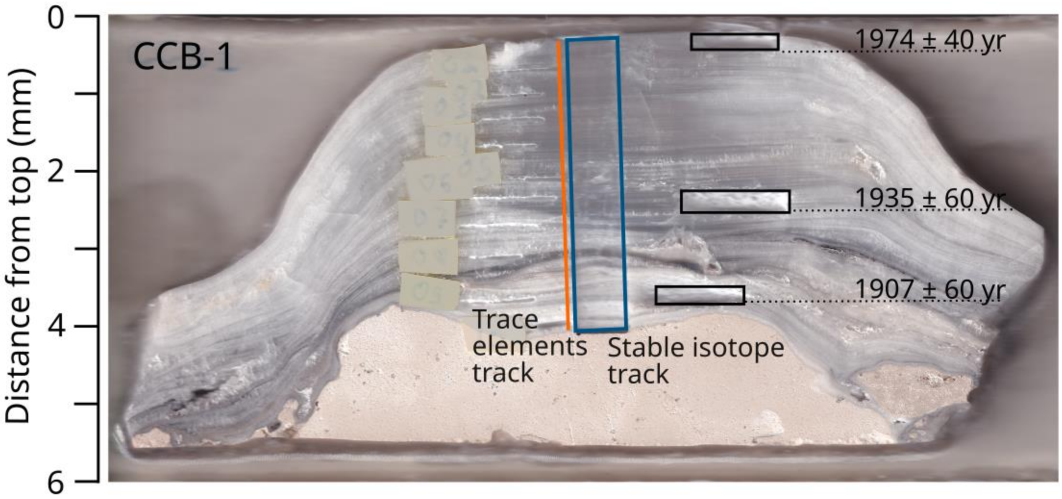

Figure S1. Image of CCB-1 stalagmite with the locations of the U/Th ages (black rectangles, numbers are in calendar years with 2σ errors), stable isotope (blue rectangle) and trace element laser ablation sampling track (orange line).

Table S1. U and Th content, isotopic activity ratios and U/Th ages from stalagmite CCB-1. $\delta^{234}U_M$ = {[($^{234}U/^{238}U)_{sample}/(^{234}U/^{238}U)_{eq}$]-1} x 1000, where $(^{234}U/^{238}U)_{sample}$ is the measured atomic ratio and $(^{234}U/^{238}U)_{eq}$ is the atomic ratio at secular equilibrium. $\delta^{234}U_{(T)}$ is the initial value and is calculated by the equation: $\delta^{234}U_{(T)} = \delta^{234}U_m \exp(\lambda^{234}t)$, where t is the corrected age in years and λ^{234} is the decay constant for ^{234}U. Raw ages are given in ka before year of measure (2019). Ages were corrected from detrital fraction using Strutage routine (Roy-Barman and Pons-Branchu, 2016) $^{230}Th/^{232}Th$ initial of the detrital fraction determined using STRUTages routine is 1.24 +/- 0.11. Corrected ages are given as years AD.

Sample ID	Depth (mm from top)	^{238}U (ppm)	Error (2s)	^{232}Th (ppb)	Error (2s)	$\delta^{234}U_M$ (%)	Error (2s)	$^{230}Th/^{238}U$	Error (2s)	$^{230}Th/^{232}Th$	Error (2s)	Age (raw ages)	Error (2s)	$\delta^{234}U_T$ (%)	Error (2s)	Age (ka before year of measure)	Error (2s)	Age (CE) (corrected)
CCB-1-01	1	0.22	0.002	0.32	0.003	101.50	1.20	0.00	0.00	2.93	1.61	0.14	0.074	101.50	1.20	0.09	0.09	1974 +55 -40
CCB-1-02	16	0.42	0.003	8.92	0.070	99.90	1.20	0.01	0.00	1.71	0.05	1.19	0.038	100.10	1.20	0.57	0.35	1935 +70 -59
CCB-1-03	34	0.41	0.003	2.82	0.020	107.30	3.20	0.00	0.00	1.90	0.10	0.43	0.025	107.40	3.20	0.23	0.12	1907 +67 -59

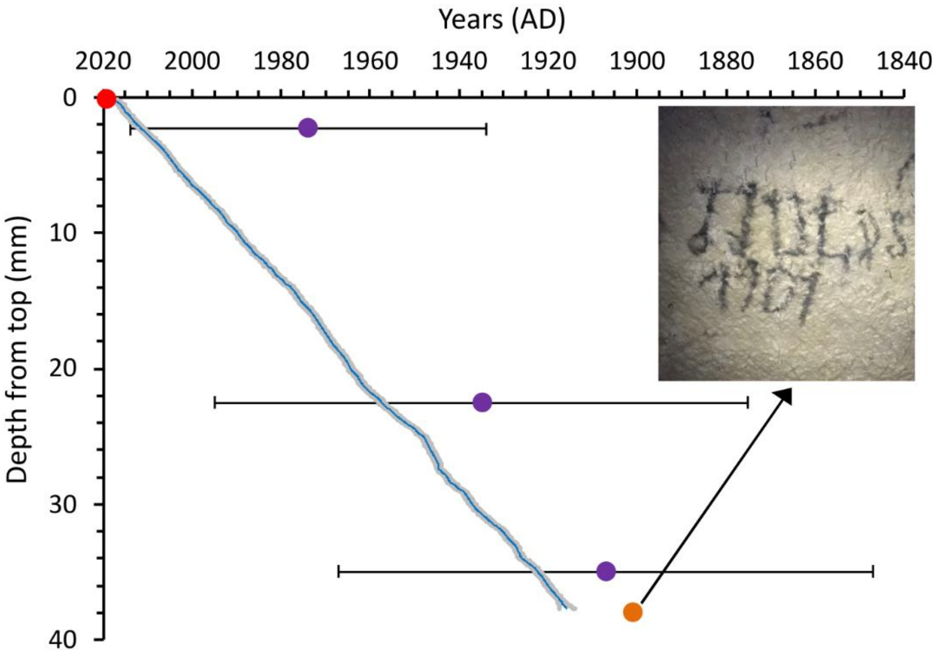

Figure S2. Age-depth model of CCB-1 stalagmite. The blue represents the age-model obtained from COPRA and the grey ones show the 95% confidence intervals, with 2σ = 2 years. The U-series ages used to build the age model are shown in purple, the stalagmite collection year in red and the year of the historical inscription in orange. Photo of the ceiling indicates the inscription "1901" as the year of opening of the gallery.

Table S2. Response of the instrumental data and speleothem CCB-1 multi-proxy records to the drought events of the 20th and 21st centuries, in Normandy, France. The drought events I-VI correspond to the events in Figure 3.

Drought events	Drought years	October SPEI6	Effective infiltration (mm)	Annual Temperature (°C)	Annual $\delta^{13}C$ (‰ VPDB)	Annual Mg (ppm)	Annual Sr (ppm)	Annual $\delta^{18}O$ (‰ VPDB)
I	1920	-0.31	460	10.60	-10.28	150.70	16.64	-4.92
	1921	-2.34	397	11.51	-9.11	196.62	15.64	-4.42
	1922	-0.03	731	10.02	-8.20	304.93	23.35	-4.58
	1923*	0.59	862	10.73	-8.32	352.10	22.43	-4.33
II	1934	-1.40	498	11.70	-11.45	102.84	9.97	-5.24
	1937*	-0.48	846	11.35	-8.54	245.67	16.20	-4.64
III	1947	-2.01	600	11.69	-10.22	177.56	15.84	-4.59
	1949	-1.36	524	11.95	-10.96	106.97	9.49	-5.22
	1952*	0.07	816	10.66	-9.69	181.67	21.12	-4.98
IV	1973*	0.04	592	9.79	-10.41	141.52	8.70	-4.78
	1976	-1.87	459	10.45	-10.66	115.81	6.23	-4.87
V	1989	-1.88	504	10.67	-11.52	98.02	7.90	-5.15
	1990	-1.71	611	10.84	-11.54	90.69	9.06	-5.05
	1995*	-1.43	829	11.03	-10.39	139.87	6.59	-5.07
VI	2001*	0.45	1039	10.77	-10.25	147.58	8.61	-4.78

2003	-1.12	655	11.30	-11.18	104.99	8.60	-5.09
Mean value	0.00	740	10.60	-10.80	125.39	9.33	-4.94

*Response peaks observed in offset with drought years.

Supplementary results – stable oxygen isotope

The $\delta^{18}O$ record presents lower amplitude variability compared to the $\delta^{13}C$ record, varying between -4.1 ‰ and -6 ‰. Elevated values, aligning with $\delta^{13}C$ excursions are also identifiable, especially in the early half of the 20th century (Figure 3). After 1954 CE, $\delta^{18}O$ excursions become less distinct, although a trend towards higher values exists after ~2003 CE, similarly to the $\delta^{13}C$ record.

The monitored modern calcite $\delta^{18}O$ record, from Caumont quarry and cave system, shows a clear bias towards the higher infiltration winter months (November to February) (Bejarano-Arias et al., 2024), which renders $\delta^{18}O$ less susceptible to infiltration changes.

The CCB-1 $\delta^{18}O$ record shows elevated values that coincide with the years of increased $\delta^{13}C$, Mg and Sr values. $\delta^{13}C$, Mg and Sr are enhanced by PCP, but the $\delta^{18}O$ record is influenced by additional factors such as precipitation amount, sometimes snowmelt and, potentially, cave ventilation, that result in higher variability and a less clear response to below-average infiltration.

The link between elevated $\delta^{18}O$ values and effective infiltration minima is noticeable in 1921, the 1940s, 1972-1974 and 1976 CE, but less evident during 1933-1937, 1987-1990 and 2003 CE. Moreover, some of the higher $\delta^{18}O$ peaks correspond with dry events from October SPEI6, more specifically for years 1921 and ~1972-1976 CE, although the relationship is less clear for the rest of the $\delta^{18}O$ peaks in the CCB-1 record.

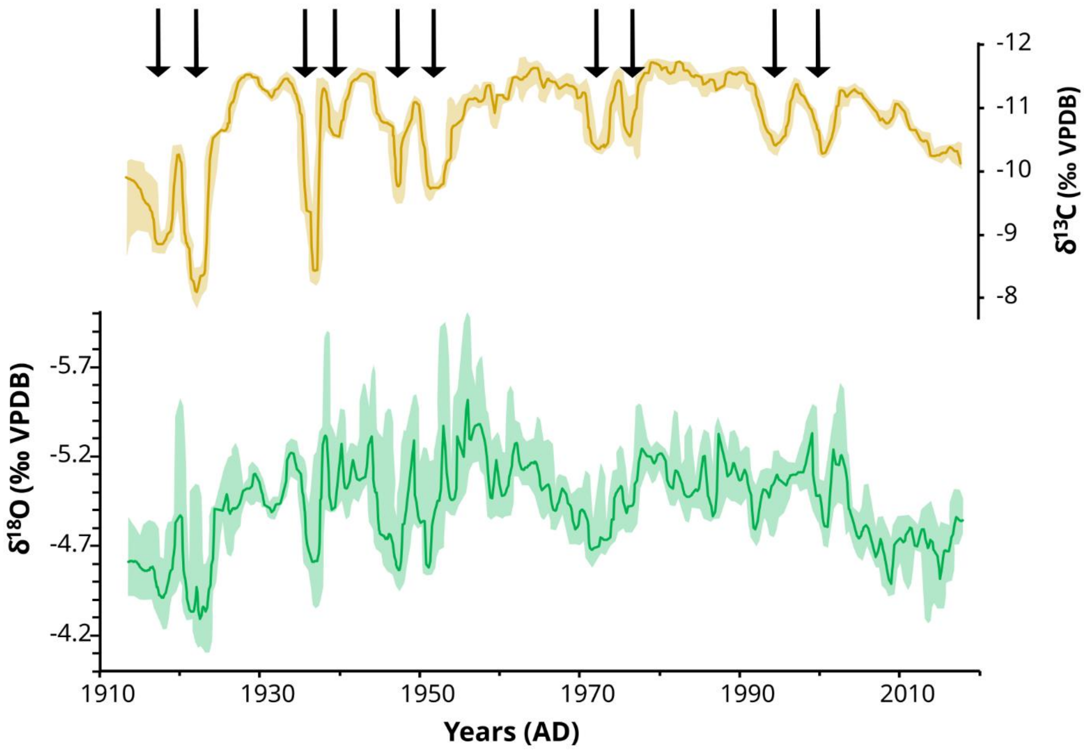

Figure S3. Speleothem CCB-1 stable isotope ($\delta^{13}C$ and $\delta^{18}O$) variability. $\delta^{13}C$ shows evident higher value peaks (arrows) which are less evident in $\delta^{18}O$, during the second half of the record.

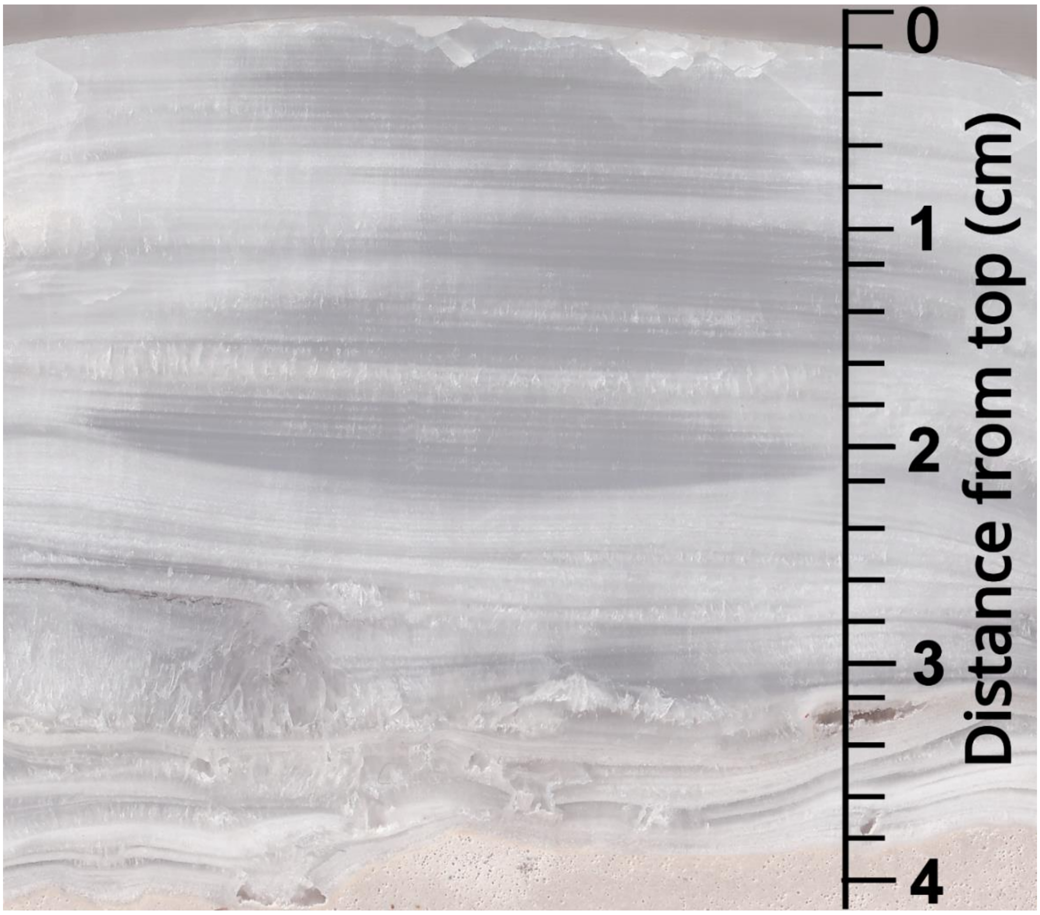

Figure S4. High-resolution scan of stalagmite CCB-1 depicting the lamination.

Supplementary methods

Instrumental data for drought index

For this study we used the monthly precipitation amount (P) and monthly mean air temperature (T) from the Rouen-Boos station, covering the period from 1970 - 2017. The precipitation data for 2018 were complemented with the record taken from Royal Netherlands Meteorological Institute (KNMI) Climate Explorer for Rouen. Air temperature data before 1970 was complemented using data from KNMI for the Paris-Le Bourget meteorological station, located ca. 105 km from Caumont. The record at this station dates back to the beginning of the 1900s.

List of References

Bejarano-Arias, I., Nehme, C., Breitenbach, S., Meyer, H., Modestou, S., Mouralis, D., 2024. Climate monitoring in the Caumont cave and quarry system (northern France) reveal near oxygen isotopic equilibrium conditions for carbonate deposition. Int. J. Speleol. 53, 13–23. https://doi.org/10.5038/1827-806X.53.1.2482

Roy-Barman, M., Pons-Branchu, E., 2016. Improved U–Th dating of carbonates with high initial ^{230}Th using stratigraphical and coevality constraints. Quat. Geochronol. 32, 29–39. https://doi.org/10.1016/j.quageo.2015.12.002