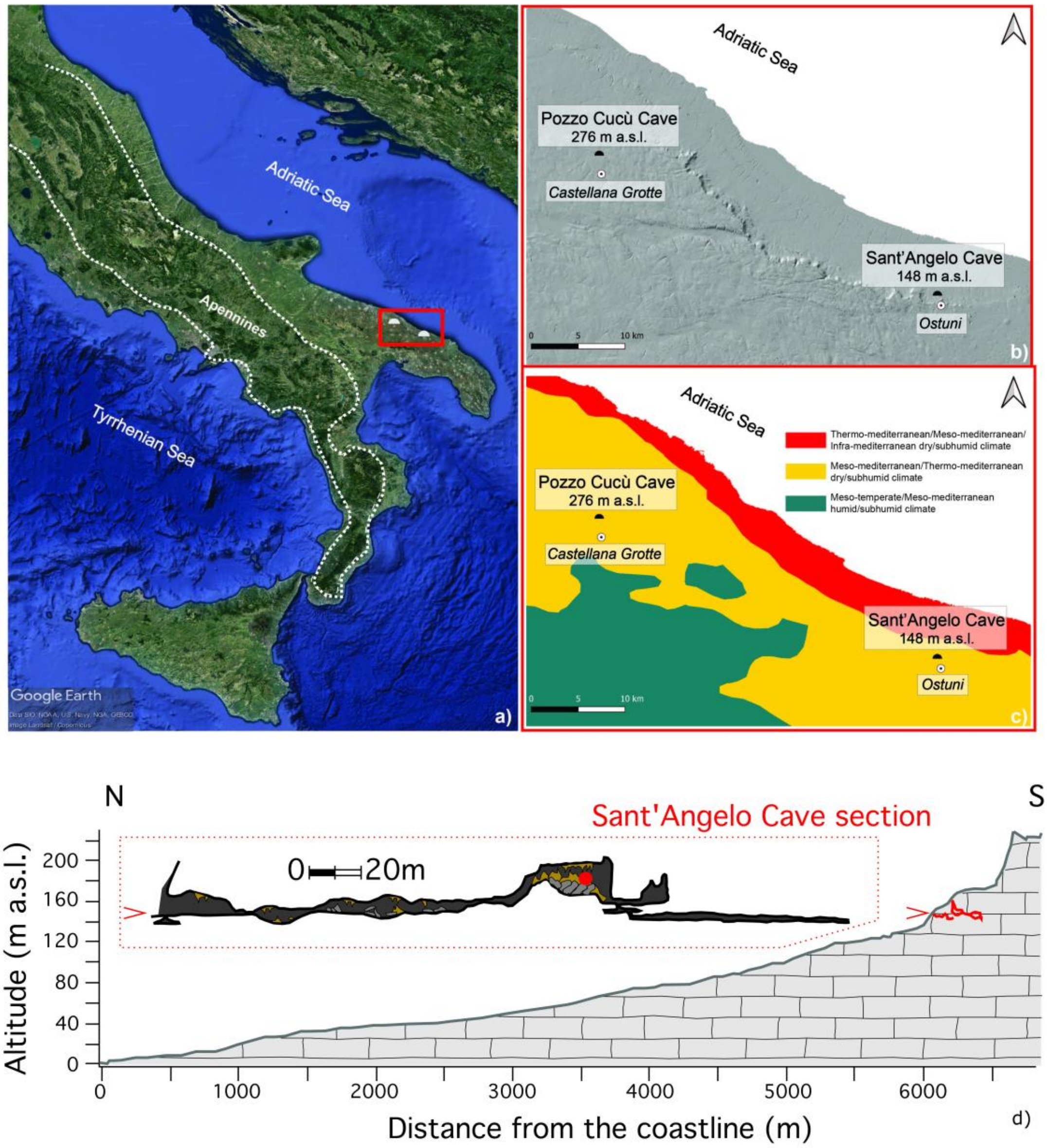
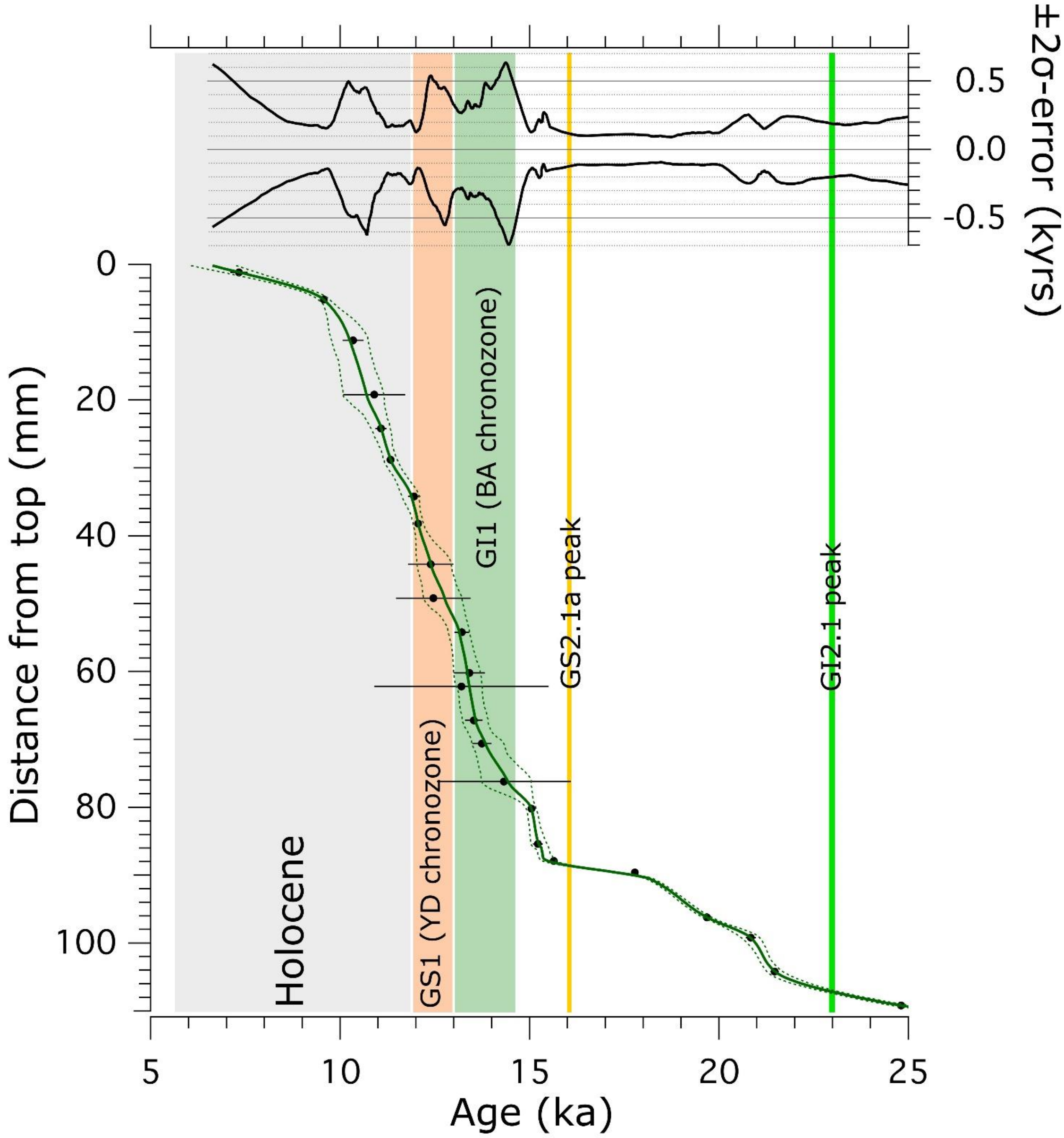
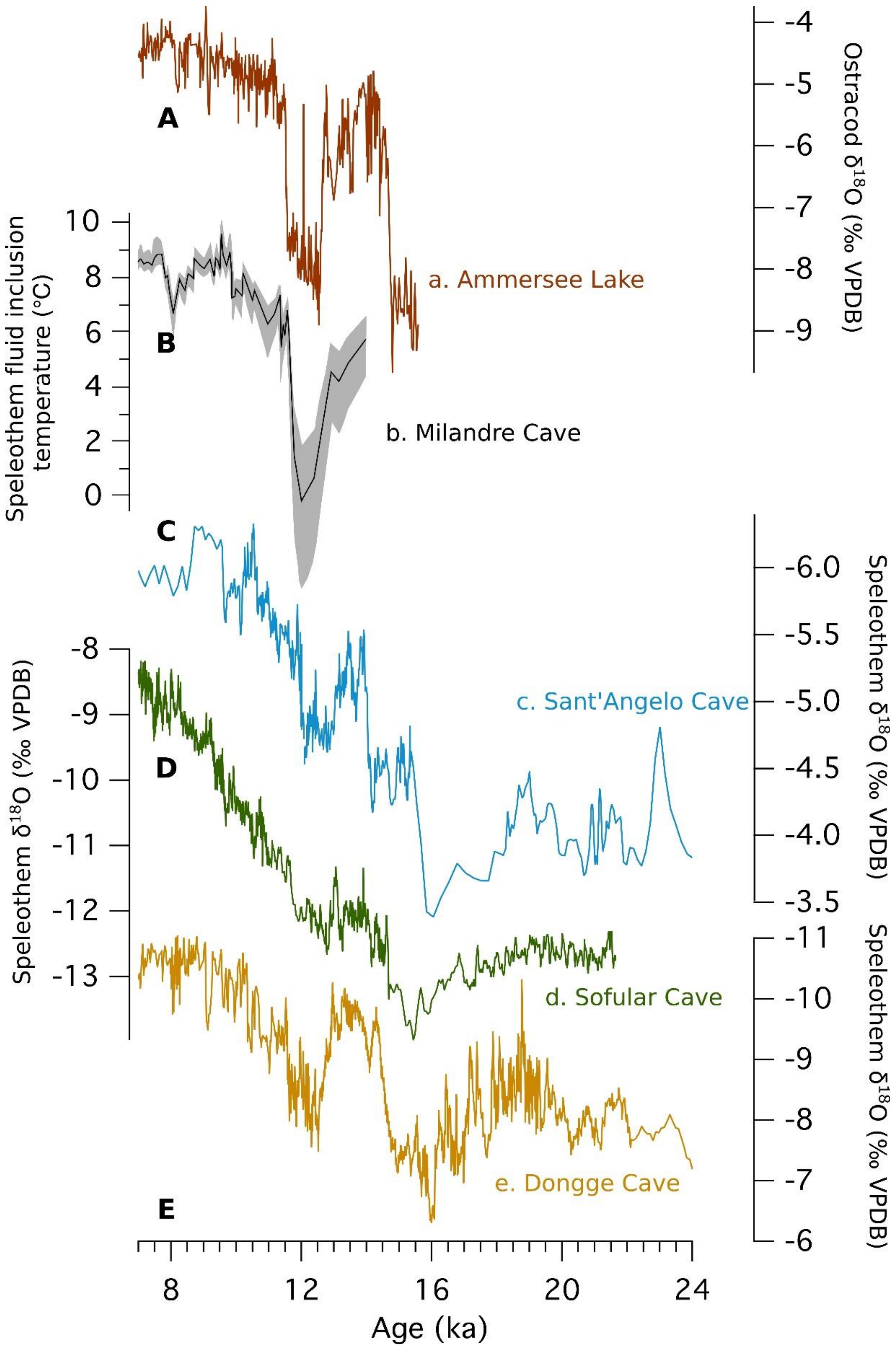
Supplementary



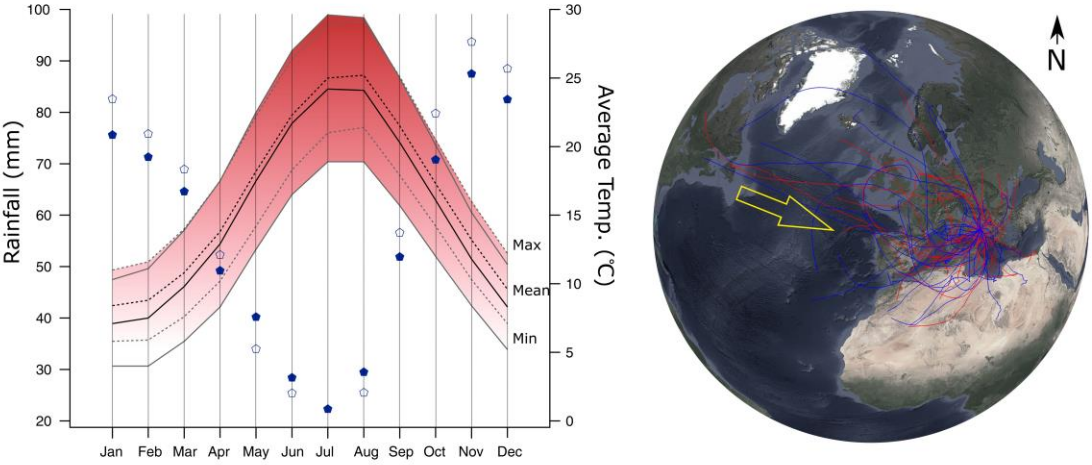
Supplementary figure 1. Study area. A) Study site (red rectangle) in Apulia, distant from the Apennine mountain range (dotted line). B) The red rectangle of (A) is enlarged here, showing the location of Sant'Angelo Cave (this study) and Pozzo Cucù[1]. The digital elevation model shows that the two caves are located in a similar topographic setting. C) The same as (B) but showing the climatic micro-zonation of the area. D) Sant'Angelo Cave profile. SA1 sampling location is highlighted by the red dot. Cave map and geological section are from D'Angeli et al (in prep.).



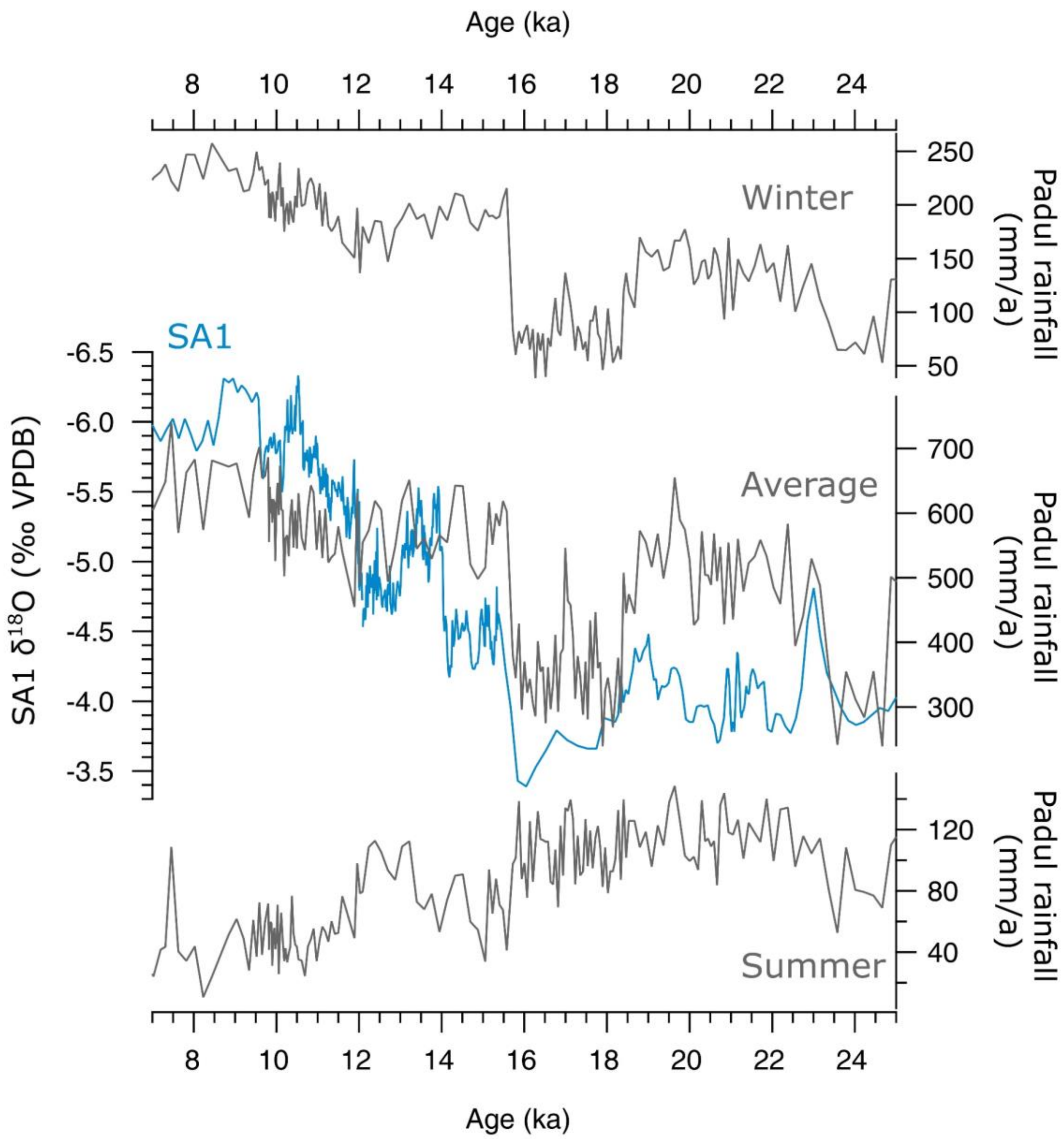
Supplementary figure 2. Age model for the period of interest of this study (~25-10 ka). Dots with error bars represent U-Th ages. The solid line is the mean age model, and the dotted lines mark the uncertainty envelope. The uncertainties are also shown on the graph above, where 2-σ errors are plotted against time.



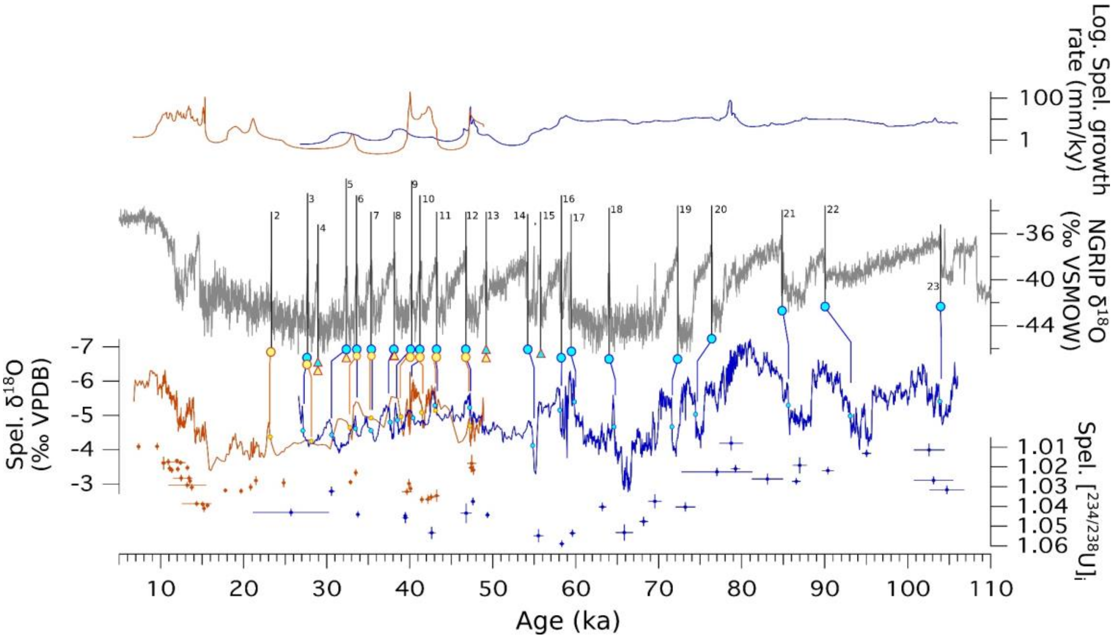
Supplementary figure 3. SA1 $\delta^{18}O$ time series compared to regional records. A) Ammersee Lake[2] (Germany); B) Milandre Cave[3] (Switzerland); C) this study; D) Sofular Cave[4] (Turkey); E) Dongge Cave[5] (China).



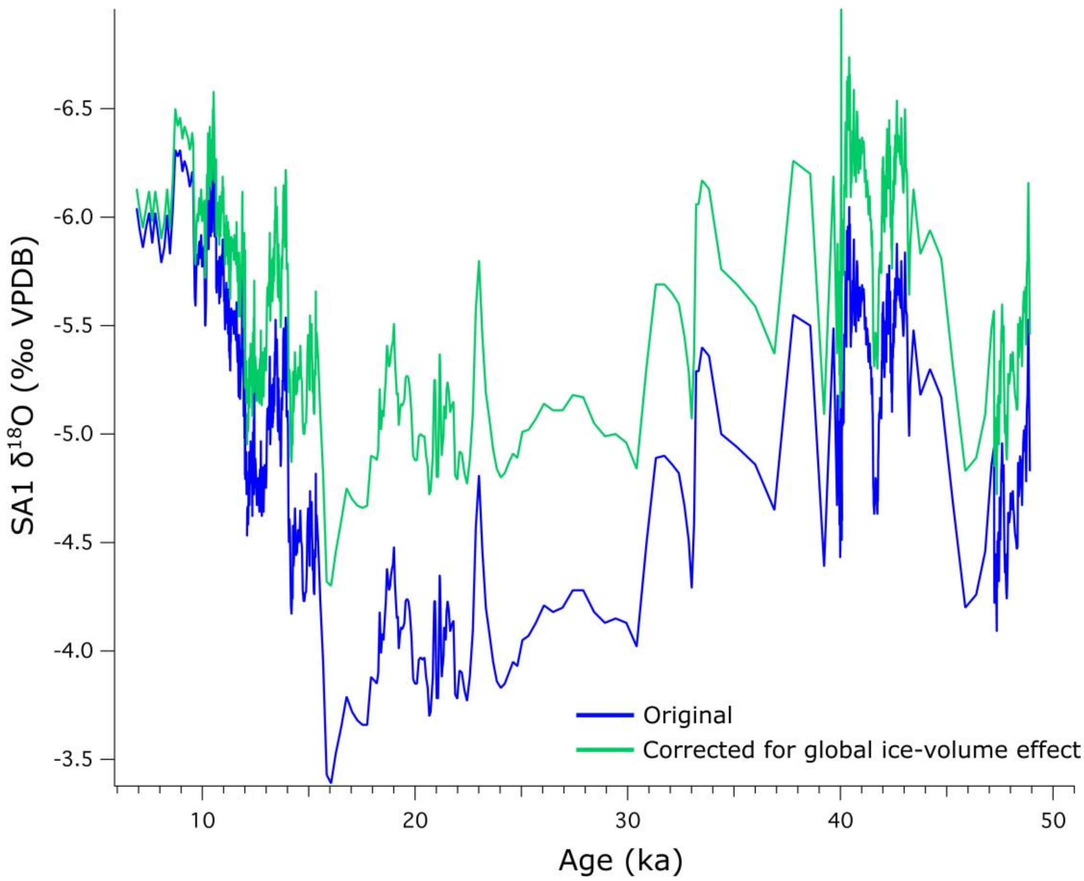
Supplementary figure 4. Average rainfall and temperature over the last 50 years (left) based on data from the meteorological station of Ostuni (the nearest with respect to Sant'Angelo Cave) and Castellana Grotte (the nearest with respect to Pozzo Cucù Cave). Diamonds represent average monthly rainfall, while lines indicate minimum, average and maximum monthly temperatures. Open diamonds and dotted lines are for Castellana, while Ostuni is represented by full diamonds and full lines, On the right, air mass back trajectories were reconstructed using the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT, www.arl.noaa.gov). Simulations were obtained for all 34 rainfall events in 2019. The current main moisture source of the study area is the Atlantic Ocean (yellow arrow). Blue and red lines mark air masses at 3015 m and 1500 m a.s.l., respectively. Globe map from Google Earth.



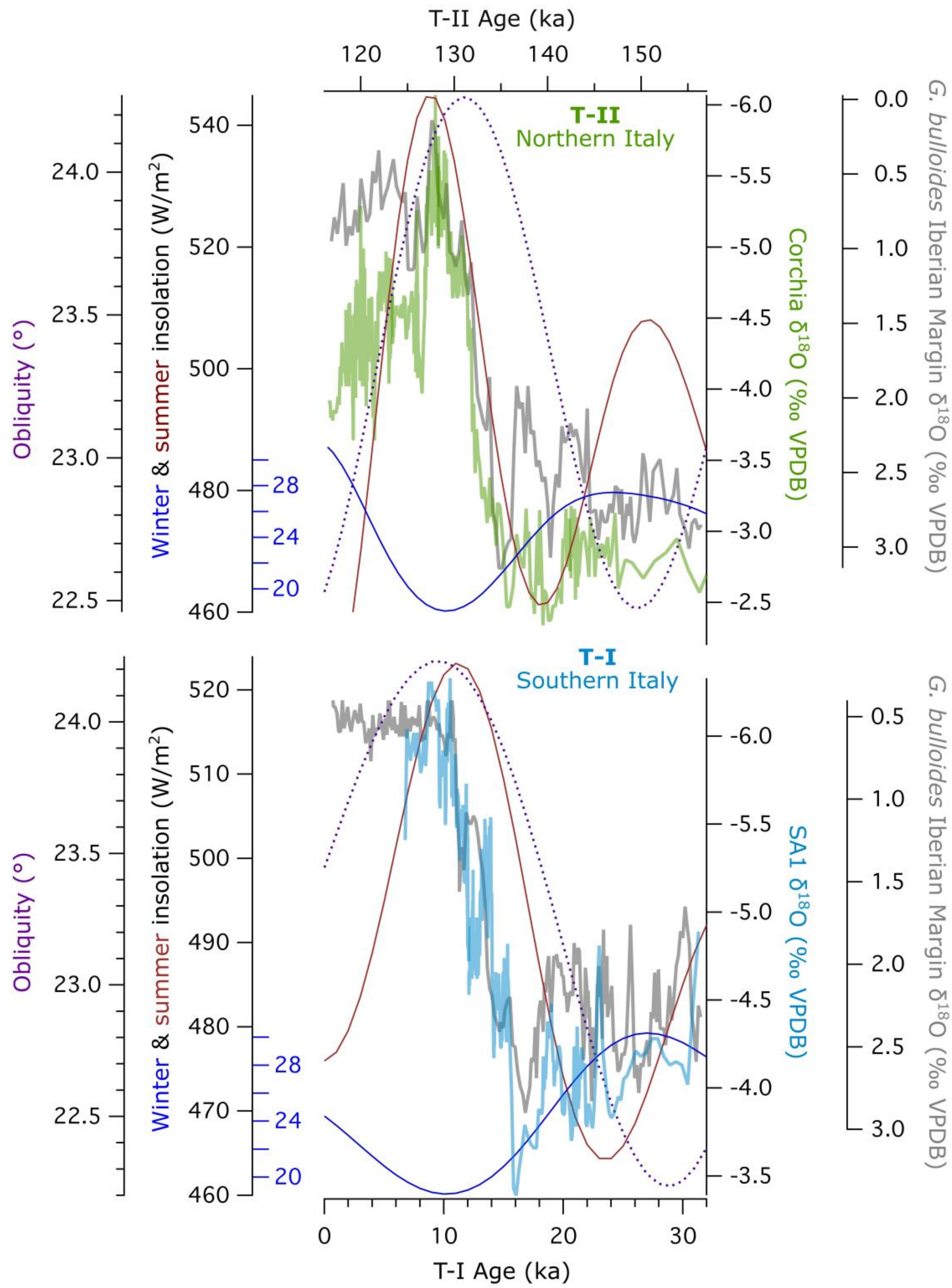
Supplementary figure 5. Comparison between SA1 rainfall proxy and reconstructed summer, winter and average rainfall amount from Padul wetland, southern Iberia[6].



Supplementary figure 6. Replication test considering SA1-$\delta^{18}O$ (orange) and PC-$\delta^{18}O$ (blue)[1]. Numbered black lines in the Greenland $\delta^{18}O$ curve (grey[7]) represent the start of interstadials related to DO cyclicity[8]. Circles mark DOs identified in SA1-$\delta^{18}O$ (yellow) and PC-$\delta^{18}O$ (light blue) using the detection algorithm (*methods*); orange and blue lines point to the detected DO in SA1-$\delta^{18}O$ and PC-$\delta^{18}O$, respectively. Triangles mark DOs not detected by the algorithm. The graph also shows growth rates of SA1 and PC (upper portion) and $[^{234/238}U]_i$.



Supplementary figure 7. SA1-$\delta^{18}O$ original data (blue) and corrected for the ice-volume effect (green, following ref[9]).



Supplementary figure 8. Comparison between T-I in southern Italy (this study, light blue line) and T-II in northern Italy (Corchia Cave[10]) (green line). Both records are compared to planktonic foraminifera (*G. bulloides*) data from the Iberian Margin[11], as well as obliquity (dotted lines) and winter (blue lines) and summer (brown lines) orbital parameters[12].

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