1. *CSIRO Mk3L Climate System Model:*

The CSIRO Mk3L climate system model is a reduced-resolution coupled general circulation model, designed primarily for millennial-scale climate simulation and palaeoclimate research [*Phipps et al.*, 2011; 2012]. It combines a stable and realistic control climatology with computational efficiency, making it particularly suitable for a study of this nature. Four simulations are used here: a 10,000-year pre-industrial control simulation, and a three-member ensemble of transient simulations of the past 1000 years. The transient simulations account for orbital, greenhouse gas, solar and volcanic forcing, and are described in detail by *Phipps et al.* [2013].

**Figure S1:** Boxplots of observed precipitation (A) and temperature (E) at Gümüşhane meteorological station (1969 to 2000 AD); and the CSIRO Mk3L transient simulations of P and T (last 1 ka) for each model simulation (M1 (B and F), M2 (C and D) and M3 (D and H). All model simulations for the last 1 ka are within the range of that for the observed meteorological record during the instrumental period, which gives confidence in the fidelity of the transient climate model simulations for this location.

**Figure S2:** Correlation between simulated cool season precipitation at Gumushane and 500mb geopotential height, diagnosed from a 10,000-year control simulation conducted using the CSIRO Mk3L model: 10, 30, 50 and 100-year running means respectively.

1. *KarstFOR Karst hydrology model:*

The KarstFOR model envisages five water stores: i. Soil; ii. Epikarst; iii. Karst Store 1; iv. Karst Store 2, and v. an Overflow Store, each of which drains monthly at a rate proportional to the volume of water stored. The sole hydrological input to the model is precipitation (*P*) (to Soil Store), and outputs are potential evapotranspiration (*PET*) (from Soil Store), drip-water flow within the cave and drainage. Model constraints include: i. no flow occurs from the Soil Store when surface temperatures (*T*) are lower than 0.0 °C; ii. flow from the Epikarst to Karst Store 2 (*F4*) occurs when Epikarst water storage exceeds threshold *Epicap*; and iii. flow from Karst Store 2 to the Overflow Store (*F7*) occurs when the former exceeds threshold *Ovcap*. The model assumes that fracture flow between stores is the dominant flow process, an acceptable assumption for mature limestones with low primary porosity.

The δ18O composition of each store is modelled as a function of precipitation (δ18Opttn) and store δ18O in the preceding time-step, allowing for evaporative fractionation in the Soil Store. Individual drip-water δ18O series are then produced by assuming that drip-waters are i. solely derived from a particular water store; ii. the product of mixing of waters draining from a selection of water stores; and iii. a combination of store drainage and recent precipitation δ18O (arising through preferential flow through the soil and limestone). Stalagmite δ18O series (*Stal\_1* to *Stal\_6* in Figure S3) are derived from each drip-water δ18O series after allowing for calcite fractionation; here we use the commonly applied equation of *Kim and O’Neil* [1997], using *T* calculated as the mean of the preceding 12-months.

As input data, we generated 1000-yr synthetic climate series of monthly *T*, *P*, *ET* and δ18Opttn, representative of the local climate. P and T were derived for this location from the transient CSIRO Mk3L model simulations (3 time series, referred to as m1 to m3 in Figures 5 and S5), and adjusted to a local series (a monthly correction factor was calculated based on monthly average values of instrumental observations vs. overlapping GCM data, and applied to all remaining GCM data). These adjusted series were used to estimate potential evapotranspiration (ET), following *Thornthwaite* [1948], as input to the KarstFor model. Input series for δ18O*pptn* were randomly generated using the mean and standard deviation of observed δ18O*pptn* obtained from the nearest GNIP station, Batumi in Georgia, 220 km East of Gümüşhane. Comparable data from other GNIP stations were considered and further details are provided in Figure S4. For one of the GCM input series (M3) two other alternative synthetic δ18Opttn were calculated (referred to as m3.1, m3.2 and m3.3 in Figure 5 and S5), following the same method as above. The karst model was set up with a –11.75 per mille initial store value (obtained from stalagmite fluid inclusions at 6ka [*Rowe et al.*, 2012]) and run for 1 ka, the last 500 years of which overlaps with the duration of growth of speleothem 2p.

**Figure S3:** KarstFor karst hydrology model schematic. Details of each of the stores, fluxes and Stal output series are presented in Table S1.

**Table 1:** Summary of modelled water reservoirs, fluxes and resultant δ18O*dw*. Stal 2 represents drip water that is a mixture of 75% Epikarst Store δ18O, with preferential flow represented by 25% δ18O*pptn* of that same month. Stal 3 drip water is sourced from 50% Epikarst Store δ18O and a preferential flow of 25% δ18O*pptn* of that month, and 25% δ18O*pptn* of the previous month.

|  |  |
| --- | --- |
| **Water Reservoirs** | |
| *Soil Store (SOILSTOR)* | Inflow is hydrologically-effective precipitation (Precipitation minus Evapotranspiration); Outflows are Evapotranspiration, F1. Initial water storage: 12mm. |
| *Epikarst Store*  *(EPXSTOR)* | Receives inflow from SOILSTOR via F1, outflows are F3 and F4. The initial storage volume is 200mm. |
| *Karst Store 1*  *(KSTOR1)* | Receives inflow from EPXSTOR via F3. Initial storage volume: 250mm. Drained by F5 (F5 = KSTOR1 x 0.05) |
| *Karst Store 2*  *(KSTOR2)* | Receives inflow from EPXSTOR via F4. Initial storage volume: 100mm. Drained by F6 (F6 = KSTOR2 x 0.005). |
| *Overflow Store (OVSTOR)* | Receives inflow from Karst Store 2 via F7. The store has a defined capacity of 110 mm (OVCAP) |
| **Water Fluxes** | |
| F1 | Drainage from SOILSTOR to EPXSTOR. Flow is estimated as a function of store volume: SOILSTOR x 0.2. |
| F3 | Outflow from EPXSTOR that occurs every month (EPXSTOR x 0.08). |
| F4 | Overflow from EPXSTOR that occurs whenever EPXSTOR > 225 (i.e. F4 = EPXSTOR – 225). |
| F7 | Overflow from Karst Store 2 (when store exceeds OVCAP). |
| **Drip-water δ18O Series** | |
| Stal\_1 | Equivalent to KSTOR218O |
| Stal\_2 | 75% EPXSTOR18O; 25% Precipt18O |
| Stal\_3 | 50% EPXSTOR18O; 25% Precipt18O; 25% Precipt-118O |
| Stal\_4 | Equivalent to EPXSTOR18O |
| Stal\_5 | Equivalent to KSTOR118O |

**Figure S4:** Local meteoric water lines for two GNIP stations and for ISO-GSM reanalysis δ18Opptn data for this location. The closest GNIP station is Batumi in Georgia, 222 km to the East of the study site and at sea level. Data are discontinuous from 1980 to 1990 AD. The second closest (and most extensive and complete record in this region) is at Ankara, some 570 km to the west of the study site, data is available discontinuously from 1963 to 2009 AD. Re-analysis data from the IsoGSM model for this location is also available continuously from 1970 to 2007 (Data accessed through the IsoGSM website (hydro.iis.u-tokyo.ac.jp/~kei/?IsoGSM1), accessed 2012) [*Yoshimura et al.*, 2008]. LMWLs of these data were corrected for altitude to match that of the study site (–0.2 ‰/100m for δ18O*pptn* and –1.5 ‰/100 m for δ2H*pptn*) [*Lachniet*, 2009] and plotted alongside available isotope data from cave water, groundwater, surface water samples surrounding Akçakale cave, as well as a snow pack sample. All cave and ground waters plotted within range of cool season weighted monthly mean values of both isotopes at both the Georgian (November, December, January, February and March) and Turkish (December, January and February) GNIP stations, but there was no improvement using the reanalysis data. The δ18O*dw* model output series when using the Ankara δ18O*pptn* data resulted in model run outputs 2 to 3 per mille to heavy and as such only the model runs only using Batumi GNIP δ18O*pptn* as input data are presented in this paper.

**Figure S5:** All model outputs and drainage/store size scenarios smoothed by 6 years (*stal\_*1: A; *stal\_*2: C; *stal\_*3: E; *stal\_*4: G; *stal\_*5: I) and 1 year (*stal\_*1: B; *stal\_*2: D; *stal\_*3: F; *stal\_*4: H; *stal\_*5: J).

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