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SISAL_monv1: a global database of cave monitoring observations

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Summary. Water dripping from cave ceilings is studied to understand how water moves from the surface to the cave. This has applications for palaeoclimate, groundwater and cave conservation studies. We present a new database containing water isotope measurements for drip water and rainfall at 75 cave locations globally. The database is a SISAL working group initiative (Speleothem Isotopes Synthesis and AnaLysis) and complements cave speleothem databases previously constructed by SISAL.

Abstract. Cave monitoring is the process of collecting observational data such as microclimate conditions, hydrogeochemistry and water movement in cave systems. The most common motivation is for speleothem science – the reconstruction of past climate and environmental variability from cave formations such as stalagmites. Applications also include the monitoring of potential recharge to aquifers, as well as cave conservation. PAGES-SISAL (Past Global Changes - Speleothem Isotope Synthesis and AnaLysis), an international working group focused on speleothem science, has created a new global database of cave monitoring data consisting of drip rates and drip water isotopes, and the modern carbonate precipitates that form from these drip waters (so called farmed carbonates, grown on artificial substrates). Moreover, we report meteoric precipitation amounts and water isotopes at or near to cave sites. The draft version of the database can be found at https://repo.researchdata.hu/privateurl.xhtml?token=43a43257-f06e-4dc5-9e96-6603eabe775f, which will be available under doi: 10.5158/ARP/29W5J3 upon publication. The database contains datasets from 75 caves, with summary information including meta-data on location, elevation, cave depth, lithology, measurement methods and citations for original publications. Speleothem records previously curated by SISAL in SISAL speleothem database versions and corresponding to monitored drip sites are also identified in the new SISAL monitoring database. To supplement observational data gaps and provide accessible and consistent climate data for users, surface climate (precipitation, evaporation, temperature) and meteoric water isotope data extracted from global climate model products are also included in the database.

1 Introduction

1.1 Background

Speleothems are secondary carbonate formations, such as stalagmites or flowstones, that form from the precipitation of calcium carbonate from drip water in caves in carbonate host rocks. Precise and accurate chronologies can be constructed for their growth intervals, while the stable isotopes of oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) as well as trace elements, can be readily measured. These geochemical data reflect the hydrochemistry of the parent drip water at the time of mineralisation (accounting for aqueous to solid phase isotopic fractionation factors) (e.g. Mattey et al., 2008; Pérez-Mejías et al., 2018) that can be related to past climatic conditions at the cave site. Hence speleothem records are considered powerful archives of past climate information (e.g. Cheng et al., 2016; Moseley et al., 2021).

Cave monitoring is the process of collecting data on cave systems, typically to understand hydrochemical and gas fluxes from the surface to the cave and their response to climatic and environmental forcing (Fairchild and Baker, 2012). The interpretation of speleothem proxies can be site specific, owing to local climate, vegetation, soil, host rock lithology and cave depth. The source of cave drip water is infiltration from meteoric precipitation (rainfall and/or snowmelt). The meteoric precipitation isotopic values may be generalised from isoscapes (Bowen et al, 2002; Terzer-Wassmuth et al., 2021) or simulated using isotope-enabled Earth System models (Haese et al., 2013; Brady et al., 2019). However, regional and local atmospheric circulation as well as altitude and distance from the coast, also influence the meteoric precipitation isotopic values. Hence local monitoring of the meteoric precipitation isotopes at the cave site is also often conducted and necessary for a correct interpretation of speleothem isotope records (e.g. Riechelmann et al., 2017; Zhang et al., 2025). The drip water oxygen isotopic value relative to the rainfall $\delta^{18}O$ value depends on recharge thresholds and infiltration flow path properties (i.e., antecedent soil moisture, karst water residence times, preferential/fast versus diffuse/slow flow, mixing, attenuation, partial re-evaporation; Bradley et al., 2010).

SISAL is an international working group of the Past Global Changes (PAGES) project SISAL | PAGES (pastglobalchanges.org) that is currently in Phase III (Hatvani et al., 2025). The first two phases focused on compiling speleothem data into a global databases to be used for paleoclimate and data-model comparison studies (Atsawawaranunt et al., 2018; Comas-Bru et al., 2020, 2019; Kaushal et al., 2024). Studies have used the SISAL speleothem database, currently SISALv3, to produce synthesis papers on regional speleothem-based paleoclimate interpretations (e.g., Burstyn et al., 2019; Lorrey et al., 2020); for data-model comparisons (Comas Bru et al., 2019; Parker et al., 2021; Bühler et al., 2021) and proxy evaluations (Treble et al., 2022; Skiba and Fohlmeister, 2023; Fohlmeister et al., 2020).

The SISAL community have created a new database (SISAL_monv1) of cave monitoring datasets to further support the goals of SISAL, i.e., to: i) increase accessibility and sharing of data; ii) enable data-model comparisons; and iii) constrain and/or quantify hydroclimate and hydrogeochemical processes related to speleothem and cave science. In addition to speleothem science, cave monitoring also has applications, for example, the monitoring of cave climate to preserve cultural artefacts (Bourges et al., 2014), and the monitoring of water movement through the vadose zone as an indicator of potential rainfall recharge to groundwater aquifers (Poulain et al., 2018) or supporting the protection of the cave environment (Cigna, 2016).

1.2 Potential applications

Monitoring cave drip waters for speleothem science began more than 50 years ago (e.g., Holland et al., 1963). The number of cave monitoring datasets has risen since and this has permitted the compilation of cave monitoring data and site metadata into global datasets (Baker et al., 2019; Treble et al., 2022). This elevates the utility of these datasets from informing studies at a particular location to informing studies on a regional or global scale. Potential applications of global compilations of cave monitoring data are to:

- Highlight the dominant controls on drip water hydrochemistry, hence speleothems, and identify, for example, climatic forcing versus local factors (Baker et al., 2019).
- Provide baseline data to inform repeat future measurements of cave data to assess long-term changes, e.g., responses to fire, land-use or climate change (Wong and Banner, 2010).
- Broaden the comparison of SISALv3 speleothem oxygen isotope data with monitoring data at sites overlapping (or in close proximity) to assist with local studies and better understand isotopic fractionation processes during carbonate precipitation in natural caves.
- Enable global and regional meta-analyses of the isotopic relationships between meteoric precipitation to drip water, and the drip water to farmed carbonates.

- Improve isoscapes by increasing the spatial coverage of precipitation water isotope monitored sites.
- Assist with data-model comparisons. Monitoring data can guide the level of complexity needed for proxy system forward models (e.g., Hu et al., 2021). This may be particularly important for global initiatives as site specific models may not be useful or practical.
- Calibrate groundwater recharge models (Baker et al., 2024).

2 Data and methods

2.1 Data types

The website https://cavemonitoringgroup.wordpress.com/ contains meta-data on cave monitoring studies. This information is not currently being updated, but was used as a starting point to identify monitored cave sites as well as identify the types of observations being made. The metadata mainly include the locations of caves, the variables being monitored, the length of time for which these variables have been monitored, and contact information. From this dataset (last accessed on 13-08-2019), we identified a total of 147 cave sites that have been monitored, of which 89 cave sites have drip water oxygen isotope measurements, 57 cave sites have meteoric precipitation oxygen isotope measurements and 58 cave sites have modern carbonate measurements. This information was recorded in a spreadsheet (Table S1) and confirmed that the most commonly measured variables were: precipitation $\delta^{18}O$ and $\delta^{2}H$ from above/nearby the cave, cave temperature, drip rate, cave drip $\delta^{18}O$ and $\delta^{2}H$. Table S1 lists many other types of observations that can capture a range of processes in the cave and its vicinity, and that were considered for inclusion in SISAL_monv1. However, after consultation and discussion with researchers in the SISAL community, it was decided to commit to compiling the following data:

- Precipitation amount, precipitation $\delta^{18}O$ and $\delta^{2}H$ from above/nearby the cave;
- Cave drip water $\delta^{18}O$, $\delta^{2}H$ and drip rate;
- Carbonate $\delta^{18}O$ and $\delta^{13}C$ of modern carbonates grown on substrates in cave experiments and/or active speleothem growth from monitored drips.

The consideration of the types of monitoring data to include was driven by the likely scientific value of the data in a global database, their ubiquity and also pragmatism. Speleothem $\delta^{18}O$ are the most common proxy measured in speleothems and drip water stable isotopes are the most commonly measured monitoring variable. Drip water stable isotopes and drip rate are also the primary variables for tracing water movement through the karst and ultimately are the basis for the climate proxy-speleothem relationship (Duan et al., 2016). Modern carbonates were also considered valuable for inclusion, also due to their relevance for the climate proxy-speleothem relationship (e.g, Tremaine et al., 2011; Riechelmann et al., 2013). Furthermore, the methods for the collection of drip water and carbonate isotopic data are relatively consistent across the community hence the precision and accuracy of these methods are generally well-understood. Similarly for meteoric precipitation amount and drip rate. However, this is not the case for many other observations, e.g., soil moisture, cave atmosphere parameters, etc., for which methods, hence precision and accuracy of such measurements, as well as the temporal resolution of their sampling, vary considerably. These data would have required greater amounts of pre-processing efforts to homogenise input to the database. s to be used for paleoclimate and data-model comparison studies.

2.2 Data collection

Using the initial survey as a starting point, a literature search for published papers and research theses containing these data was conducted. The literature search was then expanded to identify other published studies not listed on our initial survey. Corresponding authors were contacted, as well as a general call to our networks for data contribution. Corresponding authors were asked to supply data and these were transferred to a standardised workbook template by SISAL_monv1 working group members. If data were available as tables in papers or electronic attachments, these were input into the workbooks. In some cases where the original data were not readily available, authors consented to data being digitised from original publications. Additional information was compiled from publications, or direct communication with data contributors. Following Quality Checks (see subsection 2.4) workbooks were shared with corresponding authors for approval and consent.

All of the records in SISAL_monv1 are given in Table 1. Listed are the data contained for each cave and as well as any speleothem entities in SISAL that are also common to the cave. Spatial distribution is visualized on a global map (Fig. 1). Overall, there are 75 cave entities in SISAL_monv1 with 36 of these (53%) in common with entities (speleothem records) in SISALv3. An outline of the database structure and fields, the data and meta-data contained within these are presented in Sect. 2.3. The quality control (QC) process is outlined in Sect. 2.4. See also the ReadMe file accompanying the database.

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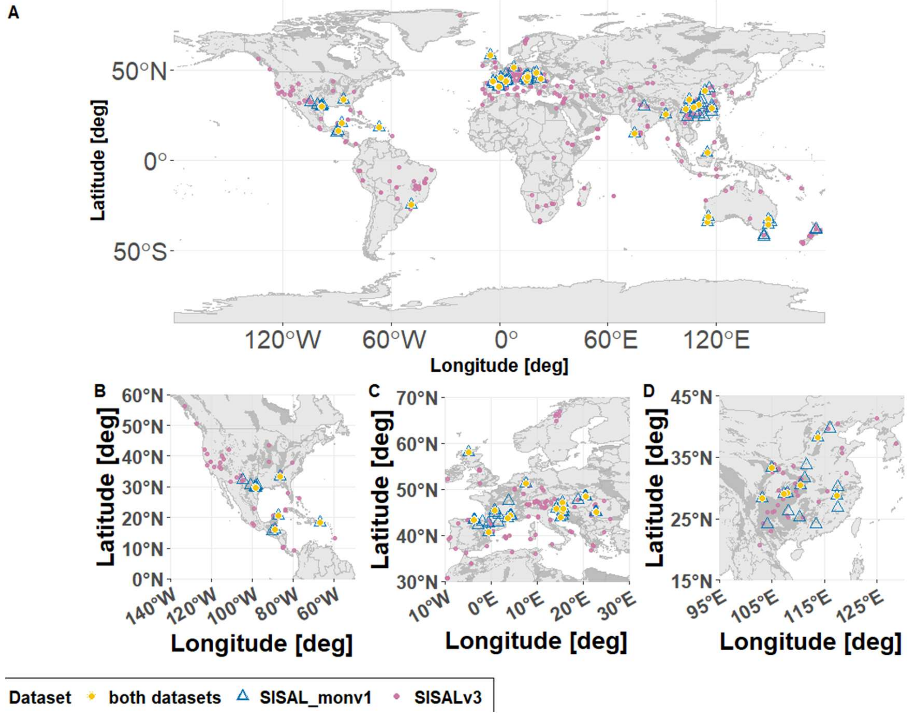

Figure 1: Global map of cave locations in SISAL_monv1 (SISAL cave monitoring database records) and SISALv3 (SISAL speleothem database records). Legend key distinguishes the sites as SISAL_monv1 data only, SISALv3 data only, or caves with both speleothem and monitoring datasets. Karst areas are shaded in darker grey and were extracted from the World Karst Aquifer Map (WOKAM, Goldscheider et al., 2020).

Table 1: List of all sites in the SISAL_monv1 database. Latitude and longitude are given in decimal degrees; measurements are primary data compiled for SISAL_monv1 (*indicates data digitised from original publications with consent from the corresponding author). Precip_amount is meteoric precipitation amount, precip_δ18O and/or d2H are meteoric precipitation water isotopes, drip_rate is cave drip rate, drip_iso is drip water δ^{18}O and/or δ^{2}H, mod_carb is modern carbonate). Speleothem entity (Y/N/unknown) indicates if speleothem records from the same cave are in the SISALv3 database. The 'Measurements' column indicates the presence of numeric values in the SISAL_monv1 database for a given site. The metadata tables in the database reflect all measurements that have been made by researchers rather than all measurements that are available in SISAL_monv1 database itself.

Site ID	Site name	Lat. (N+, S-)	Lon. (E+, W-)	Elev. (m asl)	Speleothem entity	Measurements	Citation

238	Akalagavi Cave	14.98	74.52	521	Y	mod_carb_d18O_measurement; mod_carb_d13C_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Kaushal (2017, 2020)
1000	Aranui Cave	-38.27	175.08	120	N	drip_iso_d18O_measurement; drip_rate_measurement; precip_amount; precip_d18O_measurement;	Williams and Fowler (2002)
1001	Arcy-sur-Cure Cave	47.59	3.77	130	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Zhang et al. (2025)
72	Ascunsa Cave	45.00	22.60	1050	Y	mod_carb_d18O_measurement; mod_carb_d13C_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_d18O_measurement; precip_d2H_measurement;	Drăgușin et al. (2017, 2020)

1002	Baojinggong Cave	24.12	113.35	610	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_d18O_measurement; precip_d2H_measurement;	Duan et al (2016)
71	Baradla Cave	48.48	20.50	336	Y	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Czuppon et al. (2018a, 2022)
276	Beke Cave	48.46	20.54	338	Y	mod_carb_d18O_measurement; mod_carb_d13C_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Czuppon et al. (2018a, 2022)
117	Bunker Cave	51.37	7.66	184	Y	mod_carb_d18O_measurement; mod_carb_d13C_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Riechelmann et al. (2011, 2013, 2017)

1003	Carlsbad Cave*	32.15	-104.57	1658	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_d18O_measurement; precip_d2H_measurement;	Chapman (1986), Chapman et al. (1992), Turin et al. (2022)
301	Cathedral Cave	-32.62	148.94	325.2	Y	drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Cuthbert et al. (2014)
75	Cave Without A Name	29.89	-98.62	382	Y	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Miller et al. (2021)
1004	Caverns of Sonora	30.55	-100.81	750	N	drip_iso_d18O_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Pape et al. (2010)

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77	Chauvet Cave	44.39	4.42	200	Y	drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Zhao et al. (2022)
108	Clamouse Cave	43.84	3.84	75	Y	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_d18O_measurement; precip_d2H_measurement;	Zhang et al. (2025)
67	Clearwater/Wind caves	4.1	114.83	174	Y	drip_iso_d18O_measurement_measurement; drip_iso_d2H_measurement_measurement; drip_rate_measurement_measurement; precip_amount; precip_d18O_measurement_measurement; precip_d2H_measurement_measurement	Moerman et al (2013), Ellis et al (2020)
179	Cloşani Cave	45.10	22.80	433	Y	mod_carb_d18O_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement;	Warken et al. (2018)

119	Cueva de Asiul	43.32	-3.59	285	unknown	drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_d18O_measurement; precip_d2H_measurement;	Smith et al. (2016)
1005	Cussac Cave	44.83	0.85	118	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_d18O_measurement; precip_d2H_measurement;	Zhang et al. (2025), Peyraube et al (2016)
37	DeSoto Caverns	33.31	-86.28	170	unknown	drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Lambert and Aharon (2010)
1006	Dharamjali Cave	29.52	80.21	2162	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement	Giesche et al. (2023a,b)

120	Ejulve Cave	40.76	-0.59	1269	Y	mod_carb_d18O_measurement; mod_carb_d13C_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Pérez-Mejías et al. (2018), Moreno et al. (2021)
1007	Frankcombe Cave	-42.53	146.45	400	N	mod_carb_d18O_measurement; mod_carb_d13C_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Goede et al. (1982)
80	Furong Cave	29.23	107.90	480	Y	mod_carb_d18O_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Duan et al. (2016), Qiu et al. (2016)
310	Golgotha Cave	-34.08	115.05	72	Y	mod_carb_d18O_measurement; mod_carb_d13C_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Treble et al. (2013, 2015, 2022), Griffiths et al. (2022)

1008	Gruta del Rey Marcos	15.42	-90.33	1350	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Bernal et al. (2023)
311	Harrie Wood Cave	-35.73	148.50	965	Y	mod_carb_d18O_measurement; mod_carb_d13C_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement;	Tadros (2018), Tadros et al. (2016, 2022)
122	Heshang Cave	30.45	110.42	294	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Duan et al. (2016)
1009	Inner Space Cavern	30.61	-97.69	182	N	mod_carb_d18O_measurement; drip_iso_d18O_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Pape et al. (2010), Feng et al (2012)
1010	Jiguan Cave	33.77	111.57	900	N	mod_carb_d18O_measurement; drip_iso_d18O_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Chen et al. (2023)

100	Katerloch Cave	47.08	15.55	900	Y	drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement	Boch (2008), Boch et al. (2011)
286	La Garma Cave	43.43	-3.67	85	Y	drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement	Baldini et al. (2015, 2019), Baker et al. (2019)
1011	La Paz Cave*	42.18	-2.70	1100	N	mod_carb_d18O_measurement; drip_iso_d18O_measurement; drip_rate_measurement	Osácar et al. (2014)
1012	La Vina Cave*	42.18	-2.70	1080	N	mod_carb_d18O_measurement drip_iso_d18O_measurement; drip_rate_measurement	Osácar et al. (2014)

325	Larga Cave	18.32	-66.80	350	Y	mod_carb_d18O_measurement; mod_carb_d13C_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Vieten et al. (2018a,b, 2023, 2024), Warken et al. (2022)
1032	Las Guixas Cave	42.68	-0.53	957	N	precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Giménez et al. (2021)
1013	Liangfeng Cave	26.27	108.05	600	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Duan et al. (2016)
1014	Little Trimmer Cave	-41.56	146.25	400	N	mod_carb_d18O_measurement; mod_carb_d13C_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Goede et al. (1982)

1015	Lokvarka Cave	45.82	15.67	780	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Surić et al. (2018)
1016	Lower Barać Cave	44.98	15.72	309.5	N	mod_carb_d18O_measurement; mod_carb_d13C_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_d18O_measurement; precip_d2H_measurement;	Czuppon et al. (2018b)
327	Manita Peć Cave	44.30	15.47	570	Y	mod_carb_d18O_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Surić et al. (2017, 2021)
1033	Maomaotou Cave	25.30	110.27	209	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement	Yin et al. (2020)

12	Mawmluh Cave	25.26	91.88	1160	Y	drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_amount;	Breitenbach et al (2015)
1034	Mendukilo Cave	42.97	-1.90	750	N	mod_carb_d18O_measurement; mod_carb_d13C_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement	Bernal-Wormull et al. (2023)
86	Modrič Cave	44.26	15.54	32	N	mod_carb_d18O_measurement; mod_carb_d13C_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Rudzka et al. (2012), Surić et al. (2010, 2018, 2020, 2025)
109	Molinos Cave	40.79	-0.45	1050	Y	mod_carb_d18O_measurement; mod_carb_d13C_measurement; drip_iso_d18O_measurement; drip_rate_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Moreno et al. (2014, 2021), Pérez-Mejías et al. (2018)
51	Natural Bridge Caverns	29.69	-98.34	306	Y	mod_carb_d18O_measurement; drip_iso_d18O_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Musgrove (2000), Pape et al. (2010), Feng et al. (2012)

1017	Niaux Cave	42.82	1.59	681	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_d18O_measurement; precip_d2H_measurement;	Zhang et al. (2025)
334	Nova Grgosova Cave	45.82	15.68	239	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Surić et al. (2018)
1018	Obir Caves	46.51	14.55	1090	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Spötl et al. (2005)
1019	Orgnac Cave	44.32	4.41	200	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Zhang et al. (2025), Bourges et al. (2001)

1020	Pech-Merle Cave	44.51	1.64	292	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Zhang et al. (2025), Bourges et al. (2001)
1021	Penglaixian Cave	30.23	117.53	170	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Duan et al. (2016)
88	Postojna Cave	45.77	14.20	529	Y	drip_iso_d18O_measurement; precip_amount; precip_d18O_measurement;	Dominguez-Villar et al. (2018)
232	Rio Secreto Cave	20.59	-87.13	20	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Lases-Hernández et al. (2020)

234	Santana Cave	-24.53	-48.73	250	Y	mod_carb_d18O_measurement; mod_carb_d13C_measurement; drip_iso_d18O_measurement; drip_rate_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Cruz et al. (2005)
219	Shennong Cave	28.70	117.25	383	Y	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Tian et al. (2021)
248	Shenqi Cave	28.93	103.10	1407	unknown	precip_d18O_measurement; precip_d2H_measurement;	Tan et al. (2020), Zhao et al. (2022)
1023	Shihua Cave	39.74	115.93	251	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Duan et al. (2016)
1035	South Glory Cave	-35.70	148.50	980	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement;	Coleborn et al. (2016, 2018)

1024	Spilja U Zubu Buljme Cave	44.35	15.45	1250	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Surić et al. (2017)
264	Strašna Peć Cave	44.00	15.03	74	Y	mod_carb_d18O_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Surić et al. (2017)
21	Uamh An Tartair	58.14	-4.93	220	Y	drip_iso_d18O_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Fuller (2007), Fuller et al. (2008)
1025	Vacska Cave	47.70	18.84	504	Y	drip_iso_d18O_measurement; drip_iso_d2H_measurement	Czuppon et al. (2022)

4	Villars Cave	45.43	0.78	175	Y	precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Genty et al. (2014)
1026	Waipuna Cave	-38.32	175.02	395	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement	Nava-Fernandez et al. (2020)
223	Wanxiang Cave	33.32	105.00	1200	Y	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Duan et al. (2016)
1036	West Cave Preserve	30.34	-98.14	250	N	mod_carb_d18O_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Feng et al. (2012), Pape et al (2010)

1028	Wombeyan Cave	-34.31	149.97	560	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Hughes and Crawford (2013), Bian et al. (2019)
1029	Xianren Cave	24.13	104.13	1443	N	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Duan et al. (2016)
5	Yangkou Cave	29.03	107.18	2140	Y	drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_amount; precip_d18O_measurement; precip_d2H_measurement;	Chen and Li (2018)
107	Yok Balum Cave	16.21	-89.07	336	Y	drip_iso_d18O_measurement; drip_rate_measurement;	Kennett et al. (2012), Ridley et al. (2015)

357	Yonderup Cave	-31.55	115.69	100	Y	drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement	Nagra et al. (2016)
1030	Yongxing Cave	31.58	111.23	800	N	mod_carb_d18O_measurement; mod_carb_d13C_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; precip_d18O_measurement; precip_d2H_measurement;	Wang et al. (2018)
1031	Yuhua Cave	26.83	117.43	0	N	mod_carb_d18O_measurement; drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_d18O_measurement; precip_d2H_measurement;	Qiu et al. (2023)
251	Zhenzhu Cave	38.25	113.70	990	Y	drip_iso_d18O_measurement; drip_iso_d2H_measurement; drip_rate_measurement; precip_d18O_measurement; precip_d2H_measurement;	Li et al. (2019)

2.3 Description of database structure and fields

The structure of the SISAL_monv1 database follows the well-established logic of the original SISAL speleothem databases (Atsawawaranunt et al., 2018; Comas-Bru et al., 2020; Kaushal et al., 2024). The data are stored in a relational database (MySQL), which consists of 12 linked tables, specifically cave_entity, drip_entity, drip_iso_sample, drip_rate_sample,

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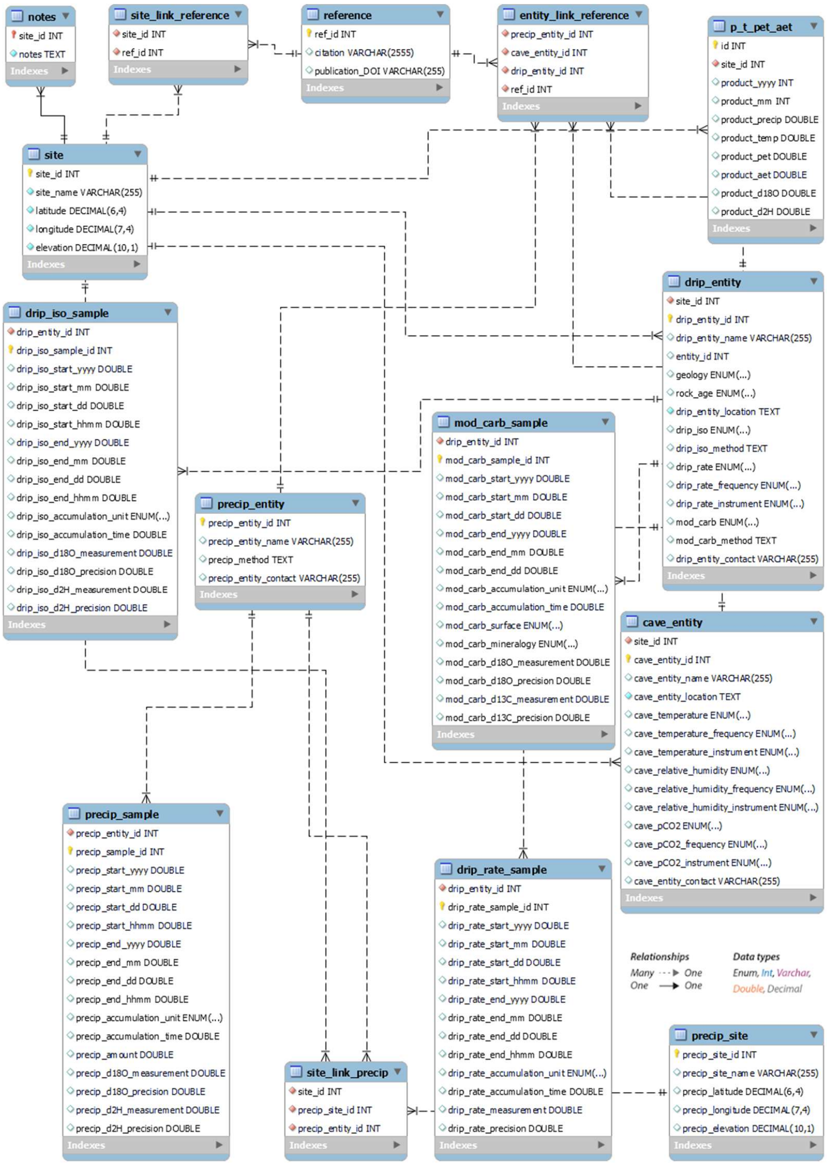
entity_link_reference, site_link_precip, site_link_reference, mod_carb_sample, precip_sample, precip_entity, precip_site, p_t_pet_aet, reference, site and notes (Fig. 2). A description of the structure and content of each of the tables is given below.

- **site:** provides information about the cave site. It provides the site_name, geographic coordinates (latitude and longitude in decimal degrees, and elevation in meters above sea level). If a site is included in both SISAL_monv1 and SISALv3, then the same site_id is used for both databases.
- **reference:** contains the DOI and bibliographic details of the original publication(s) with source information on the monitoring data, descriptions, literature, reports, and datasets related to the cave monitoring dataset.
- **notes:** is a flexible sheet for recording observations, comments, or additional details not captured in other structured fields. This allows for contextual or qualitative information to be included, such as field notes, anomalies, or unresolved questions.
- **p_t_pet_aet**: Includes monthly gridded climate variables at each cave site, derived from global models. These include precipitation from MSWEP, air temperature from ERA5, actual and potential evapotranspiration (AET and PET), and the stable isotopes of precipitation ($\delta^{18}O$ and δ^2H) from the IsoGSM model.
- **precip_site**: contains metadata specific to the precipitation monitoring sites (site_name, precip_entity_name) including geographic coordinates (latitude and longitude) and distance from the cave entrance (precip_distance_cave_entrance). It establishes the context for interpreting precipitation measurements.
- **precip_entity**: provides the name of the precipitation dataset, same name as in precip_site sheet, the monitoring methods, and the name of the person filling in this workbook.
- **precip_sample**: lists the actual precipitation data, including isotopic measurements $\delta^{18}O$ and δ^2H with precision values, precipitation amount, and timing of sample collection.
- **cave_entity**: provides information on the availability, frequency, instrumentation of cave_temperature, cave_relative_humidity and cave_pCO2 measurements for each cave_entity, as well as the name of the person filling in this workbook. These meta-data were included to direct the user to the original publications for these data.
- **drip_entity**: provides information on the availability of data describing drip rates (drip_rate), isotopic measurements (drip_iso), modern carbonate (mod_carb) from the dripping waters with data on the instrumentation, analytical methodology and frequency of sample collection. The entity_id of any speleothem record currently in SISALv3 that corresponds to a drip entity is given. The table also includes metadata such as geology, rock age, free-text regarding a description of the drip site or each cave_entity, as well as the name of the person filling in this workbook.
- **drip_iso_sample**: lists the actual dripping waters sample data, including isotopic measurements $\delta^{18}O$ and δ^2H with precision values, the period of time for which the drip water sample was collected (drip_iso_accumulation_time) and its unit (drip_iso_accumulation_unit), and timing of sample collection.
- **drip_rate_sample**: documents the drip rate (drip_rate_measurement) with precision values, drip rate accumulation time (drip_rate_accumulation_time) and its unit (drip_rate_accumulation_unit), and timing of sample collection. If

data were supplied as drip volume, these were converted to drips per minute and the conversion is reported in the notes sheet. The conversion was performed either by using the site drip volume if reported in the original source or otherwise an assumed drip volume of 0.2 ml was applied. Collister and Mattey (2008) show that drip volume can vary as a function of stalactite width, morphology, drip interval, drip height, although it was not possible nor practical to account for these factors so a uniform conversion was applied. This conversion is common in the reported Methods of drip monitoring studies, e.g., Surić et al. (2017).

- **mod_carb_sample**: lists the isotopic measurements $\delta^{18}O$ and $\delta^{13}C$ from modern carbonate with precision values, modern carbonate accumulation time (mod_carb_accumulation_time) and its unit (mod_carb_accumulation_unit), and timing of sample collection. In addition it provides information on which surface did the modern carbonate grow (mod_carb_surface) and what was its mineralogy (mod_carb_mineralogy). Here modern carbonates refer to carbonates grown on substrates during an in cave experiment and further details on these and other data types are given in Sect. 2.3. Here modern carbonates refer to so called ‘farmed’ carbonates grown on substrates during an in cave experiment. It does not include modern speleothem entities which appear in SISALv3 and are now linked by entity ID in SISAL_monv1.
- **junction tables:** lists the link between the named tables, site_link_precip, site_link_reference, entity_link_reference tables.



225 **Figure 2: The structure of the SISAL_monv1 database showing individual tables (and their contents) and the nature of the relationships between them where "many to one linkages" indicate that it is possible to have several entries in one table linked to a single entry in another table). The colours of the format of the particular field.**

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2.4 Quality control

An automated quality control procedure was developed and scripted in R (R Core Team, 2024) and is summarised below (see also the Supplement. The quality control procedure were performed on the cave monitoring datasets to ensure data integrity and consistency across the Excel worksheets containing the information for individual sites.

General metadata checks included verifying that site names were unique and uniform across the worksheets, ensuring that latitude and longitude values fell within valid ranges, and confirming that elevation data consisted of numeric entries in all site metadata tables (site, precip_site). Next, the references were validated and checks were done for proper formatting, no duplicates and presence of proper doi-s and at least one reference. Quality control in the entity metadata tables (precip_entity, cave_entity, drip_entity) included verification that drop-down menu cells were filled in with predefined options.

Sample tables (precip_sample, drip_iso_sample, drip_rate_sample, mod_carb_sample) were uniformly checked that dates were correctly formatted and fell within a logical range and the measurements and corresponding precision values fell within plausible ranges. It was verified in all tables that all the drop-down menu cells were filled in with predefined options. In the precipitation_sample worksheet additional checks were performed ensuring precipitation_amount and accumulation_time are numeric.

Consistency checks were conducted across tables to ensure that all site names listed in the metadata were also present in related sample sheets and that entities in dependent tables, such as drip or cave data, correspond correctly to the sites they referenced. The script also identified missing or null values in critical columns across all tables, flagging incomplete rows for manual review. The results of these checks were summarized in a pass/fail format for each table, highlighting areas that required attention before further analysis. A series of plots were generated for visual inspection and to identify data entry errors across various tables. Spatial coordinates for "site" and "precip_site" were displayed on a map to verify geographic accuracy. Temporal relationships were explored through scatter and bar plots, with specific variables plotted against date and time ranges. Precipitation-related data, including "precip_amount" versus "precip_accumulation_time" and isotopic measurements (e.g., "precip_d18O_measurement" and "precip_d2H_measurement"), were examined for consistency in units and values. Similar scatter and bar plots were used for cave and drip data, including isotopic and drip rate measurements such as "drip_iso_d18O", "drip_iso_d2H", "drip_rate_measurement", "mod_carb_d18O" and “mod_carb_d13C”. These plots effectively highlighted anomalies, such as mismatched units, implausible numeric values, or incorrect date-time entries, across all data types, enabling targeted corrections.

Flags raised by the automated quality control procedure were followed by manual checks by the database team and contributing authors. As a final step, during database compilation water isotope data were trimmed to two decimal places, and drip rate data to two significant figures (or three significant figures for values in the hundreds). Nevertheless, users should be guided by the precision reported in the data source (also listed in the precision column if reported).

2.5 Synthesized climate and precipitation isotope data

The SISAL_monv1 database provides monthly climate and precipitation-isotope inputs for each cave entity from four global products (Table 2): MSWEP v2.8 (precipitation), GLEAM 4.1a (actual and potential evaporation), ERA5 (air temperature), and IsoGSM (precipitation water isotopes, $\delta^{18}O$).

The preparation of these datasets for all cave monitoring sites and evaluation of the IsoGSM precipitation-isotope datasets against alternative isotope products were carried out by Zang et al. (submitted) when preparing their global dataset for karst system characterisation and modeling (WoKaS-Iso). There, local observations of precipitation isotopic compositions at selected cave sites and karst springs were used to benchmark multiple isotope products. Based on performance across 55 sites (lowest median RMSE and highest median R^2), IsoGSM was identified as the most reliable product. Users are referred to Zang et al. (submitted) for full methodological detail.

Although the original temporal resolutions of the selected products vary (hourly to daily), all variables are provided at monthly resolution to align with the cadence of most cave monitoring datasets and to facilitate cross-site comparison. Precipitation is obtained from MSWEP v2.8 (0.1°, 1979–2020), a gauge–satellite–reanalysis blend (Beck et al., 2017; Beck et al., 2019). Evaporation is derived from GLEAM 4.1a (0.1°, 1980–2023), providing actual and potential evaporation derived from satellite/reanalysis (Miralles et al., 2011; Martens et al., 2017; Miralles et al., 2024). ERA5 provided air temperature (~31 km, 1940–2024) (Hersbach et al., 2020). As stated above, precipitation water isotopes are from IsoGSM (~200 km, 1979–2021) (Yoshimura et al., 2008; Zang et al., submitted). Together, these gridded products provide consistent, gap-filling inputs where cave-site observations are unavailable; key spatial and temporal characteristics are summarized in Table 2.

Table 2: Summary of global products for precipitation, evaporation, air temperature and precipitation isotopes.

Name	Data Source	Variable	Spatial Resolution	Temporal Resolution	Time Coverage	References
MSWEP v2.8	Gauge, Satellite, Reanalysis	Precipitation	0.1°	Monthly	1979-2020	Beck et al., (2017)
GLEAM 4.1a	Satellite, Reanalysis	Actual and potential evaporation	0.1°	Monthly	1980-2023	Miralles et al., (2024a)

ERA 5	Reanalysis	Air temperature	31 km	Monthly	1940-2024	Hersbach et al., (2020)
IsoGSM	Reanalysis	Precipitation $\delta^{18}O$ and $\delta^{2}H$	200 km	Monthly	1979-2021	Yoshimura et al., (2008)

3 Data summary and recommendations for use

The SISAL_monv1 is a standardised, quality-checked global database of surface meteoric precipitation amount and water isotopes at or near to cave sites, as well as the drip rates and water isotopes of drip waters and the modern carbonates that form from these drip water. Metadata including cave site location, elevation, cave depth, lithology, location of drip entities within the cave and links to original source publication are provided. Cave site identification codes, site names and latitude-longitude data for caves that appear in SISALv3 were carried into SISAL_monv1 in order to easily identify if monitoring data and speleothem records are from the same cave. Furthermore, if a drip entity corresponds to a speleothem entity, these are also identified in SISAL_monv1. Thus the creation of SISAL_monv1 greatly improves the identification and accessibility of the extent of data types available at cave sites. This will enable and enhance future studies using data from cave systems.

Figure 3 shows the number of SISAL_monv1 sites by region and by the generalized climate classification scheme for Global-Aridity values (UNEP 1997). The highest number of monitored cave sites in SISAL_monv1 database are from Europe and Asia, followed by North and Central America, with the least in the African, Middle East and South American regions. Drip water isotopes are the most common measurement in the database. By climate classification, monitored sites are dominated by humid regions. This representation in the database likely reflects relative accessibility to sites and also water availability for long-term monitoring.

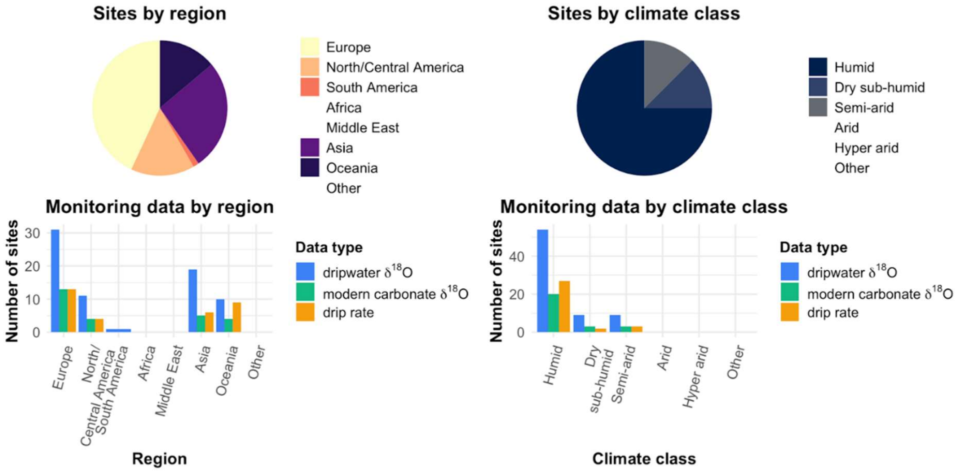

Figure 3: Number of SISAL_monv1 sites by region (left column), and by the generalized climate classification scheme for Global-Aridity values (UNEP 1997) (right column). The numbers reflect the sites with numeric values for a given variable in SISAL_monv1.

More than half (52 %) of the sites appearing in the SISAL_monv1 database also have speleothem data in the SISALv3 database. If considering a wider proximity, 65% SISAL_monv1 sites are within 25 km of a SISALv3 site, and ~69 % are within 50 km. Depending on the location, these monitoring sites may be sufficiently close in proximity that they may be representative of the SISALv3 sites. For speleothem science, the access to monitoring and speleothem data from the same or nearby drip sites, or karst areas, will enable further refinement of the interpretation of the speleothem record. Previously, these data may have appeared in separate publications and may have lacked clarity whether drip sites were common to speleothem records. The inclusion of climate data products from global models will also assist with monitoring - speleothem data comparisons. Moreover, the significant gain here is that such investigations could now be performed on a regional scale, rather than on single cave locations for which almost all published studies were based on.

The metadata (e.g., location, elevation, cave depth and lithology) will also help in the exploration of cave drip water and climate versus non-climate relationships. Understanding these and their relationship to water infiltrating to caves are relevant for calibrating forward models of paleoclimate proxies and groundwater recharge studies. Similarly, this global compilation of modern farmed carbonates and their drip waters, as well as the linking of drip water and modern stalagmites between SISAL databases, will also greatly assist the characterisation and understanding of isotopic fractionation factors for speleothems and their drip waters in natural rather than laboratory settings.

The database permits spatial and temporal analysis of stable water isotopes in meteoric precipitation and drip waters at cave sites globally. These data are visualised on Fig. 4. Fifty-nine of SISAL_monv1 sites (79 %) contain precipitation water isotope data and IsoGSM simulated precipitation stable water isotopes are provided for all cave sites. The precipitation water isotope observations from cave sites in SISAL_monv1 are outside of the GNIP network and as such, may also be used to improve data gaps in isoscape studies. These precipitation water isotopes (measured and/or simulated) are a rich source for future studies investigating cave drip water isotopes, such as surface infiltration factors which may be investigated with the compiled climate and site meta-data, as well as karst flowpath variability and rainfall recharge to groundwater studies.

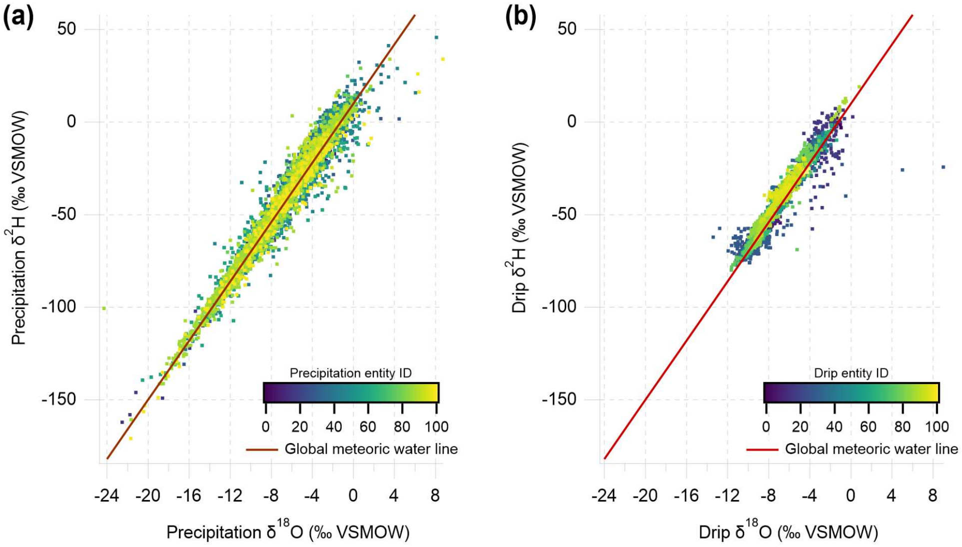

Figure 4: Scatter plot of $\delta^{18}O$ vs δ^2H for all the meteoric precipitation observation data in SISAL_monv1 (A) and drip water observation data in SISAL_monv1 (B). Both plots are shown with the Global Meteoric Water Line ($\delta^2H = 8x\delta^{18}O+10$). Precipitation entity ID and drip entity ID refer to the unique codes in SISAL_monv1 database assigned for meteoric precipitation measurement sites and drip measurement sites, respectively (see schematic in Fig. 2).

3.1 Code and data availability

The database is available in CSV and SQL format in a repository at https://repo.researchdata.hu/privateurl.xhtml?token=43a43257-f06e-4dc5-9e96-6603eabe775f (Treble et al., 2026). This dataset is licensed by the rights holder(s) under a Creative Commons Attribution 4.0 International licence: https://creativecommons.org/licenses/by/4.0/ (last access: 17 December 2025). The codes that can help to connect to and use the database are described in the README file. The code used to derive the figures 1-3 in this paper can be found here: https://github.com/istvan60/SISAL_monv1/blob/main/MS%20figures.

The SISAL_monv1 database, as is standard SISAL Working group practice, lists the original references, and users are encouraged to consult original authors for interpretative details.

The structure of the SISAL_monv1 database requires use of codes (SQL, R, Python, MATLAB) which may make it difficult to access the database for everyday research. Thus, the "SISAL webApp" (http://geochem.hu/SISAL_webApp; Hatvani et al., 2024) - a GUI for exploring the SISAL databases - has been extended with an option to also query the cave monitoring database, based on site name, SISAL site_id and geographical location (Hatvani et al., 2025). This complements the existing SISAL speleothem database of speleothem data and serves to develop a more robust understanding of the speleothem oxygen isotope records, by far the most ubiquitously measured and applied speleothem proxy.

3.2 How to cite the database

The SISAL_monv1 database is a community-driven effort to synthesize and standardize cave monitoring data and make them available to the wider palaeoclimate community. In agreement with the FAIR principles for scientific data management and stewardship, the database itself should be cited (available at 10.5158/ARP/29W5J3; (Treble et al., 2026), along with this publication. If individual records are extracted from the database, the original publications should also be listed. More details on the terms of use are provided in the repository.

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Author contributions

NK and LC-B designed the original database structure. NK, FL, AB, DR and PCT tested the initial database structure and refined the primary data entry worksheets. PCT, NK, and YZ contacted and liaised with the community for data contributions. PCT, YZ, NK, AB, ZK, IGH, BB, BD, WC performed workbook data entry, consulted original sources and communicated with data contributors. YZ, AH and KY extracted global product data for each site. PT wrote the code and compiled the ultimate version of the database with inputs from IGH and NK. IGH, PT, ZK, and NK wrote auto-quality control scripts, ran quality control and created the SQL version of the database. András H incorporated the database into the SISAL webApp. PCT wrote the original draft with inputs from YZ, AB, ZK, NK, IGH, PT, BB, DR and FL. FL IGH and PCT created the figures. "SISAL working group members" contributed published and/or unpublished data and all authors contributed to the final version.

Competing interests

The authors declare that they have no conflict of interest.

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