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Caves provide early warning of unprecedented decrease in rainfall recharge of groundwater

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Abstract

Billions of people worldwide rely on groundwater. As rainfall in many regions in the future is projected to decrease, it is critical to understand the impacts of climate change on groundwater recharge. In this study, five caves record a consistent response to a sustained decrease in rainfall across southwest Australia that began in the late 1960s, characterised by a pronounced increase or 'uptick' in dripwater and speleothem oxygen isotopic composition (δ18O). It is demonstrated that the uptick is in response to the shallow karst aquifers becoming disconnected from recharge due to regional drying. Our findings imply that rainfall recharge to groundwater across this region is no longer reliably occurring. Examination of the longer speleothem record shows that this is unprecedented over at least the last 800 years. A global network of cave dripwater monitoring would serve as an early warning of reduced groundwater recharge elsewhere, while evidence for upticks in speleothem paleoclimate records would provide a longer-term context to evaluate if current groundwater recharge changes are outside the range of natural variability. This study also validates speleothems as recorders of past hydroclimate via amplification of the δ18O signal by karst hydrology highlighting that speleothem δ18O are records of recharge, rather than a direct proxy for rainfall.

Introduction

Groundwater use is accelerating globally due to population growth[1,2]. Further reductions in water availability in many regions due to climate change[3,4] are likely placing increasing pressure on groundwater resources and groundwater dependent ecosystems[5,6]. It is critical to understand how drying in the mid-latitudes will impact rainfall recharge to groundwater resources globally. Currently our understanding of the sensitivity of groundwater systems to climate change is limited[4,7,8]. This is because water table monitoring using direct methods such as bores can be complicated by groundwater extraction and land use change which can obscure the climate change signal[9], and the water table may be recharged by rivers or lakes[10] in addition to rainfall recharge. Furthermore, the hydraulic memory of fossil groundwater systems can delay a response to climate change by decades or longer[1]. These factors mean that attributing changes in groundwater recharge to the impacts of climate change on rainfall is difficult.

Caves offer a natural 'window' to observe the movement of water from the surface through the vadose zone and into groundwater aquifers, and can thus indicate rainfall recharge to groundwater[11,12]. Rainfall recharge may be focussed along fractures, fracture zones and conduits, or it can be diffuse porous flow where highly permeable host rock are present. In karst environments recharge is likely to be a mixture of the two flow types[11,13]. Similar to groundwater, the oxygen isotopic composition ($\delta^{18}O$) of cave dripwaters and consequently speleothems, is largely determined by the recharge-weighted $\delta^{18}O$, particularly in water-limited climates[14] where groundwater resources are increasingly under pressure.

Accordingly, speleothems offer a highly temporally-resolved record of rainfall recharge to groundwater. Modern speleothems formed since the early 20th century can be used to assess the response of rainfall recharge to groundwater during recently observed climate change, while older speleothem material can provide a longer-term context of the range of natural, pre-industrial variability of recharge to groundwater. As speleothems form in the vadose zone above the water table, they are not complicated by modern groundwater abstraction nor the longer term processes such as changes in hydraulic boundary conditions.

Rainfall in southwest Australia is highly seasonal and falls in the cooler months, typically from May to October, owing to the seasonal migration of the Southern Hemisphere westerly winds. The region has experienced a prolonged decline in annual rainfall attributed to changes in Southern Hemisphere atmospheric circulation systems with a significant contribution from anthropogenic forcing[15,16]. In response to anthropogenic changes in ozone and then greenhouse gases[16] rainfall has decreased by 10-25% overall across the region since the 1960s[17]. Several local studies have since recognised the effect of reduced rainfall and increased abstraction on water resources within southwest Australia, as direct rainfall recharge has generally been found to be the major recharge mechanism[18,19]. For example, the Rottnest Island freshwater lens (Fig. 1) has decreased in size by 40% primarily due to the rainfall decrease[18]. Likewise, water table decline within the Perth Basin has been identified as a result of decreasing rainfall[19,20]. However, quantifying the amount of water table decline attributable to decreased rainfall input is complicated by increasing groundwater extraction over the same time period[21]. Climate models indicate, with high confidence, that rainfall in this region is likely to decline further throughout the 21st century[16] which will continue to impact water availability in southwest Australia[19,20]. This will have a consequent impact on water-dependent ecosystems[22] and water security for this region that currently depends on groundwater to meet 75% of its water demand[19].

In this study we constructed a regional speleothem $\delta^{18}O$ record using eight speleothems from five caves across a 300 km transect in southwest Australia (Fig. 1). The stalagmites have all grown through the period of regional rainfall decline. The speleothem $\delta^{18}O$ records, along with cave dripwater monitoring, demonstrate a common rise, or 'uptick', in values beginning in the 1990s. This change is not driven by a change in the input source water (rainfall) $\delta^{18}O$ values but rather is demonstrated to be a shift in the hydraulic flow properties in the karst aquifer in response to reduced rainfall recharge. We argue that the declining rainfall has reduced rainfall recharge to groundwater along focussed flow paths. We also assess this in the context of the longer (paleo) speleothem record for the region and demonstrate that this reduction in recharge is unprecedented for the last 800 years. This is the first study to use speleothems from multiple caves to examine the response of reduced rainfall recharge due to climate change in the modern record. In doing so, it also confirms that 'upticks' in speleothem $\delta^{18}O$ values

primarily represent reduced water supply to the speleothem. This substantiates the interpretation of speleothem $\delta^{18}O$ datasets as a proxy for hydroclimate, and importantly validates the hydrological flow path response to rainfall changes control on recharging water $\delta^{18}O$ values.

Results and Discussion

Regional speleothem $\delta^{18}O$ record

Eight speleothem records from five caves, as well as cave dripwater $\delta^{18}O$ data from one of the caves (Fig. 2) were used to construct a regional speleothem $\delta^{18}O$ record (Fig. 3a). These records all demonstrate a consistently replicated rise in $\delta^{18}O$ values during the late 20th Century and early 21st Century. The beginning of this rise varies between speleothem records, with the rise beginning as early as the late 1960s in one speleothem record, i.e., MND-S1 (Fig. 2). The variability in the timing of the $\delta^{18}O$ response could be due to different hydraulic response times (i.e. cave flow properties) or speleothem age uncertainty. Nevertheless, the composite data indicate that the isotopic rise becomes a common signal by the 1990s. The speleothem records show that this rise is approximately 1‰, while our dripwater data confirm that this rising trend has continued to the present indicating an overall increase of 1.5‰ above the 1900-1968 mean speleothem $\delta^{18}O$ value (Fig. 3a).

Speleothem $\delta^{18}O$ is a function of multiple processes, including: i. cave temperature; ii. possible reaction processes that can result in speleothem $\delta^{18}O$ being precipitated 'out of isotopic equilibrium' with its source water; iii. rainfall $\delta^{18}O$; and iv. impacts of flow-path variability on dripwater $\delta^{18}O$[23,24]. Yet despite the possibility for multiple processes, the distinct and replicated large rise in speleothem $\delta^{18}O$ values indicates a common response to forcing that is occurring across the region (Fig. 3a). The regional uptick in speleothem $\delta^{18}O$ cannot be attributed to the temperature-dependent fractionation that occurs during calcite precipitation[23] as recent warming[16] would lower speleothem $\delta^{18}O$ by an estimated −0.27 ‰ below pre-1960 values rather than raise speleothem $\delta^{18}O$ values as observed (Fig. 3a). Enhanced 'out of isotopic equilibrium processes'[23,25] were shown not to be dominating $d^{18}O$ variability in the modern Golgotha Cave records (representing four of the eight stalagmites in our composite)[26]. Furthermore, neither temperature nor calcite precipitation disequilibrium could produce the rising trend observed in the dripwater $\delta^{18}O$ values. The rising dripwater $\delta^{18}O$ trend that is concurrent with and extends the speleothem $\delta^{18}O$ trend, confirms that the speleothem $\delta^{18}O$ values are recording a primary signal arising from the dripwater $\delta^{18}O$. This confirms that rainfall $\delta^{18}O$ and/or flow path variability must be the common driver of the regional uptick in $\delta^{18}O$ values.

Rainfall recharge and the speleothem $\delta^{18}O$ response

Rainfall $\delta^{18}O$ (the source of dripwater $\delta^{18}O$) is considered to be the primary driver of dripwater $\delta^{18}O$ variability[14]. Long-term monitoring of rainfall $\delta^{18}O$ in southwest Australia[27] can constrain the impact of climate change on rainfall $\delta^{18}O$ in the region. The decline in southwest Australian winter rainfall has occurred in two steps[17] occurring in 1968/1969 and 1999/2000 (Fig. 3b). This pattern of rainfall decline is also evident over the narrow coastal limestone belt where the caves are located (Fig. 3b). The rainfall decrease has been characterised as a reduction in total rainfall and heavy rainfall during winter, as well as a decrease in the total number of rain days[28]. Of these three factors, it is rainfall intensity that most impacts the $\delta^{18}O$ composition of southwest Australian rainfall[27]. However, using both measured and modelled rainfall $\delta^{18}O$ values, we can quantify that this accounts for between a −0.4 ‰ to +0.1 ‰ change in rainfall $\delta^{18}O$ over the period of rainfall decline (Table 1), whereas the rise in cave $\delta^{18}O$ data is fifteen times greater (Fig. 3a). Shallow groundwater extracted from the freshwater lens of Rottnest Island, for which mean $\delta^{18}O$ values are −4.0 ‰ (Fig. 3c) and generally reflect mean $\delta^{18}O$ composition of the recharging rainfall[18], further supports the relatively small change in rainfall $\delta^{18}O$. Thus, we argue that the overall rise of 1.5 ‰ in our regional $\delta^{18}O$ record reflects a rise in dripwater $\delta^{18}O$ despite little change in the $\delta^{18}O$ of annual rainfall supplying these drips.

A recent study identified that rainfall recharge through Golgotha Cave occurs via both diffuse flow through the matrix and focussed flow along fractures[26]. Importantly, it was also shown that dripwater from fracture dominated flow paths is up to 1 ‰ lower than the dripwater supplied by diffuse flow[26]. The isotopic distinction is due to activation of flow along fractures preferentially recharging karst stores with water that is relatively ^{18}O-depleted as it is sourced from higher intensity rainfall[26]. The isotopic distinction between flow types is seen in the distribution of $\delta^{18}O$ values for diffuse and fracture flow dripwaters (Fig. 4). The distributions of diffuse flow drips overlap with that for all daily rainfall events ≥ 2 mm, whereas fracture flow drip $\delta^{18}O$ values are lower and overlap with the distribution of daily rainfall when recalculated to only include daily totals for heavy (≥ 5 mm) rainfall events. This is characteristic of the typical recharge-bias response seen at a global scale in cave drips[14,26]. Figure 4 also shows that the distribution of fracture flow $\delta^{18}O$ values closely agrees with that of Holocene groundwater values supporting that rainfall recharge to groundwater beneath these caves occurs primarily via fracture flow.

The eight speleothems from five different caves in our composite record will each have unique flow path properties and length, yet all exhibit rising $d^{18}O$ values, suggesting a common hydrological response to the regional decline in rainfall. A reduction in the contribution of focused flow along fractures supplying

drips is the only mechanism that can explain the magnitude of the $\delta^{18}O$ uptick in the regional speleothem $\delta^{18}O$ record. A reduction in focussed flow will also led to a volumetric decline in rainfall recharge to groundwater and this is observed in the local water table beneath the cave systems (Fig. 3d). Three caves in the region have water table level measurements that span wholly or partially over the period of the rainfall decrease. The longest record that began in the 1950s confirms a decline in the volume of rainfall recharge to the local water table that began around 1980 (Fig. 3d), in agreement with the beginning of the speleothem $\delta^{18}O$ uptick. A further two records of cave water table measurements that commenced in the late 1990s also support further large drops in the water table below at least two other caves in the region (Fig. 3d).

Movement of water focused along fractures will occur and be enhanced once overlying soils have become saturated[29], consistent with observations at Golgotha Cave[30]. A reduction in soil moisture and/or the length of the season of soil saturation will reduce the overall contribution of recharge from focused flow, and consequently impact the $\delta^{18}O$ values of the percolating water. We examined temporal variability in soil moisture by extracting modelled values for the five cave sites for 1911-2019[31] (see Methods and Supplementary Fig. 2). A decline in modelled soil moisture is evident over the same period as the $\delta^{18}O$ uptick (Fig. 3a,e). Prior to 1969, mean values across the region for the number of days/year when soils were saturated was 96 (Fig. 3e). This decreased to 67 days/year following 1969 and an overall decrease of 42% to 55 days/year after 1999 CE when the $\delta^{18}O$ uptick is also steepest (Fig. 3a,e). A long-term reduction in soil moisture further supports our interpretation that the mechanism of reduced focused flow is driving the uptick in the cave $\delta^{18}O$ record.

The rise in regional speleothem $\delta^{18}O$ values accelerates in the last two decades (Fig. 3a). Thus, it appears that the majority of the speleothem $\delta^{18}O$ increase is in response to the second rather than the first rainfall decrease. This likely reflects the cumulative impact of reduced rainfall on soil moisture, whereby reduced saturation in the soil layers reduces the likelihood of focussed flow along fractures occurring, and the duration that it occurs for each wet season. That is, we propose that fracture activation is still occurring but was reduced during the period of the first rainfall decrease (1969 to 1999), whilst fracture activation was further reduced to infrequent or no fracture activation from the commencement of the second rainfall decrease after 1999. A further consideration is the lag for karst stores to drain. For example, fracture activation evident at one site that was monitored in Golgotha Cave took at least three years for dripwater $\delta^{18}O$ to return to values equivalent to matrix-flow drips[26]. Thus the impact of a reduced water balance has decreased recharge along focussed flowpaths in the karst and led to the ‘disconnection’ of karst aquifers from rainfall recharge, resulting in the rise in dripwater and speleothem $\delta^{18}O$ values.

Implications for understanding rainfall-recharge to groundwater

The replication of the uptick signal across the southwest Australian region validates the interpretation that the contribution of diffuse versus focussed flow to dripwater dominates stalagmite $\delta^{18}O$[26], as no other mechanism could produce this common response across multiple caves. Our study offers a robustly constrained processed-based relationship between rising speleothem $\delta^{18}O$ values in response to a well-documented and sustained decrease in rainfall. Importantly, it has been shown that this is due to the impact of varying rainfall recharge to the soil and the karst rather than a shift in rainfall $d^{18}O$, highlighting that this response amplifies the speleothem $d^{18}O$ signal. In the global literature, there are examples of similar isotopic upticks in speleothem paleoclimate records, typically prior to a hiatus in speleothem growth[32,33]. Thus, identification of replicated upticks in speleothems can be used to identify past reductions in rainfall recharge to groundwater in a region.

The speleothem record from Golgotha Cave[26] provides a longer-term context to assess the recent $d^{18}O$ uptick against. Stalagmite GL-S4 grew continuously since 1200 CE with a robust chronology constructed from annual laminae counting (Fig. 5a). It is fed by diffuse dripwater supplied from the matrix but also by focused flow along fractures that activate during wetter years[26]. Speleothem $d^{18}O$ values for GL-S4 are −3.9 $‰_{VPDB}$ or lower, consistent with fracture flow for the entire record until the mid-1990s, when higher values indicate that diffuse flow dominates (Fig. 5a,b). Figure 5a,c compares the speleothem GL-S4 recharge $d^{18}O$ record with the Law Dome ice core accumulation-based rainfall reconstruction (see Fig. 1 for location) for southwest Western Australia[15,34]. The two records are in agreement in terms of the unprecedented nature for the last eight centuries of both the recent rainfall decrease depicted in the Law Dome record and the corresponding reduced rainfall recharge in the speleothem record. We confirm that no replicated uptick events are seen in the last 800 years in the stalagmite record from the southwest Australian region[26] suggesting that the current decoupling of rainfall to groundwater recharge is unprecedented for the last eight centuries. This has important implications for contextualising the threat to the biodiversity in groundwater dependent ecosystems and sustainable use of groundwater in a region heavily dependent on it for agriculture, and where future use is anticipated to increase[20].

In this study, caves located in the vadose zone and where recharge can be identified unambiguously from rainfall, have provided an early warning of decreased rainfall recharge to groundwater resources. The recent speleothem and dripwater dataset indicates that rainfall recharge to groundwater may no longer be reliably occurring, while the longer speleothem record demonstrates that this is unprecedented for at

least the last 800 years and highlights the immediate threat of climate change to water security in a region heavily dependent on groundwater. This is of relevance for future climate change as there is debate over the modelled increase in rainfall intensity and whether that would lead to increased hydrological responses. Runoff (i.e. flooding) has been the focus of research and adaptation planning so far[35], with little attention until now given to the implications of future climate change on groundwater recharge. This study shows that a network of monitored caves in other regions where groundwater is relied upon could serve as an early warning of reduced recharge, particularly in mid-latitude regions where widespread rainfall declines are expected this century as a result of human-caused climate change[36]. Monitoring also provides valuable data for ground-truthing speleothem paleoclimate records, while upticks in the speleothem paleoclimate records provide a longer-term context for evaluating the risks to groundwater resources from natural and human-caused climate changes.

Methods

Speleothem chronologies. Chronologies for all speleothems were published previously. Briefly, all stalagmites had been actively forming at the time that they were removed from the caves and the date of removal from the cave is used as the youngest age. The chronologies for CRY-S1[37], YD-S2[38] GL-S3 and GL-S4[26] were determined from annual laminae counting of 2D maps of Sr concentration and/or visible layering formed from fabric/colloidal matter in thin section; MND-S1 from annual laminae counting of Ba concentration from duplicate transects[39]; LAB-S1 from the peak fitting method of ref. [40] utilising principal components analysis of duplicate transects of Ba, Sr and U concentrations; while GL-S1 and GL-S2 chronologies were determined from 'bomb pulse' detection using radiocarbon analyses[41] and U/Th disequilibrium dating[26] for details of chronologies for Golgotha Cave stalagmites.

Speleothem $\delta^{18}O$. Data were previously published for all records[26,38,42] with the exception of CRY-S1 and LAB-S1. Milling and isotope ratio mass spectrometry methods are as described in ref. [26]. CRY-S1 $d^{18}O$ measurements were made at the Mark Wainwright Analytical Centre at UNSW Sydney using a MAT-253 isotope ratio mass spectrometer with Kiel carbonate device (25–50 µg samples). LAB-S1 $d^{18}O$ measurements were made at the Research School of Earth Sciences, ANU, using a Thermo MAT-253 isotope ratio mass spectrometer coupled to a Kiel IV carbonate device (110–130 µg samples). Data in both laboratories are normalised to the Vienna Pee Dee Belemnite (VPDB) scale using NBS19 ($\delta^{18}O$ = −2.20 ‰ and $\delta^{13}C$ = +1.95 ‰) and NBS-18 ($\delta^{18}O$ = −23.0 ‰ and $\delta^{13}C$ = −5.0 ‰).

Golgotha Cave dripwater and farmed calcite $\delta^{18}O$. Dripwater data, sampled at 4-6 weekly intervals; and farmed calcites, in situ for 9-31 months, were previously published in ref. [26]. Data and method for converting dripwaters from the VSMOW scale to a calcite equivalent on the VPDB scale were also previously published[26] using mean annual cave temperature measured at Golgotha Cave (14.6 ±0.1°C) and the bulk empirical fractionation factor for Golgotha Cave (1.0318 ±0.0004) determined therein.

Composite speleothem record. Speleothem, and dripwater $\delta^{18}O$ data (as calcite equivalent values) were interpolated to be annually resolved to construct the composite record. For Golgotha Cave speleothem records this represented a 3-5x increase in resolution, for YD-S2 a 1.2x increase in resolution; and for records CRY-S1 and LAB-S1, this represented a 2-3x decrease in resolution relative to the original data. Alternative methods were investigated such as maintaining the sampled resolution and weighting each data point according to the time interval that it represents, and the uptick in $\delta^{18}O$ values is still robust i.e., the choice of method for compositing the data did not affect the interpretation. We considered uncertainty in the age-depth models but this is least at the youngest end. i.e., 0% at the year of collection and still small at 1900 CE (range ±3 to 12%). It was not necessary to account for analytical uncertainty in $\delta^{18}O$ as these are small (0.05 ‰ for carbonates and 0.1 ‰ for water)[26].

Rainfall $\delta^{18}O$ data. Annual rainfall amount for southwest Australia (line joining 30°S, 115°E and 35°S, 120°E) and the extent of the Tamala Limestone (Fig. 1) was extracted from Bureau of Meteorology gridded spatial data[31].

Annual and monthly amount weighted $\delta^{18}O$ was measured at the Perth Global Network of Isotopes in Precipitation (GNIP) site[43] and Calgradup[27].

Predicted amount weighted annual $\delta^{18}O$ calculated from an empirical relationship between daily $\delta^{18}O$ and daily precipitation, Eq. (3) in ref. [27], applied to Bureau of Meteorology rainfall observations from the 'high quality'[44] sites Boyanup and Cape Naturaliste.

Soil moisture data. Modelled soil moisture data were extracted for each cave site from the Australian Bureau of Meteorology's Australian Water Resources Assessment Landscape model: AWRA-L version 6[45]. Briefly, AWRA-L is a continent-wide water balance model with 0.05° gridded outputs of soil moisture, runoff, evapotranspiration and drainage. We utilised daily soil moisture in the lower (0.1-1 m; term 'Ss') and deep soil store (1-6 m; term 'Sd'), as well as rainfall (term P_g) and actual evapotranspiration (term E_{tot})[45]. Model output (Ss) is validated against field measurements of soil moisture at Golgotha Cave[46] (see Supplementary Figure 2) and the Sd output, corresponding to the observed depth of seasonal wetting prior to initiation of percolation into the host rock[30], is used to calculate the number of days per year when soil is saturated. The best match between observed and modelled soil moisture data is 66%; however, observed recharge at Golgotha suggests a higher percentile (78th) would be representative of fracture activation necessary for recharge and we apply this to all 5 sites. See Supplementary Figure 2 for further details.

Declarations

ONLINE SUPPORTING MATERIAL

Supporting figures, tables, text and associated references, are contained in the Supplementary Information.

DATA AND CODE AVAILABILITY STATEMENT

The Golgotha speleothem and drip water time series data may be found on the PANGEA paleoclimate data repository (PDI-30276 and PDI-30277). The authors agree to archive the LAB-S1, CRY-S1 and YD-S2 records on the PANGEA paleoclimate data repository upon the manuscript being accepted for publication (https://www.pangaea.de/).

Weather station and gridded climate data are available from the Australian Bureau of Meteorology, http://www.bom.gov.au.

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AUTHOR CONTRIBUTING STATEMENT

This manuscript was devised by PCT, AB and SCP. SCP, PCT and ADG collated data and prepared the figures. PCT, NJA, and KTM conducted analyses and provided data. SCP wrote the manuscript with input from all co-authors.

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Tables

Table 1: A comparison of annual rainfall $\delta^{18}O$ values before and after southwest Australian rainfall decreased. 1968/1969 was used for the timing of the decrease following the analysis of ref. [17].

Dataset	Measured and modelled mean annual rainfall $\delta^{18}O$ values (‰)		
	1908-1968	1969-2018	Difference
Perth measured[43]	−3.7 ±0.3 (1962-1966)	−4.1 ±0.5 (1973-1976, 1984-1995, 1998-1999, 2006-2014)	−0.4
Calgardup measured[27]	-	−4.4 ±0.5 (2006-2018)	-
Boyanup simulated[27]	−4.5 ±0.2	−4.4 ±0.2	+0.1
Cape Naturaliste simulated[27]	−4.1 ±0.2	−4.1 ±0.2	0
IsoGSM[47]	-	−4.2 ±0.3 (1979-2018)	-

Figures

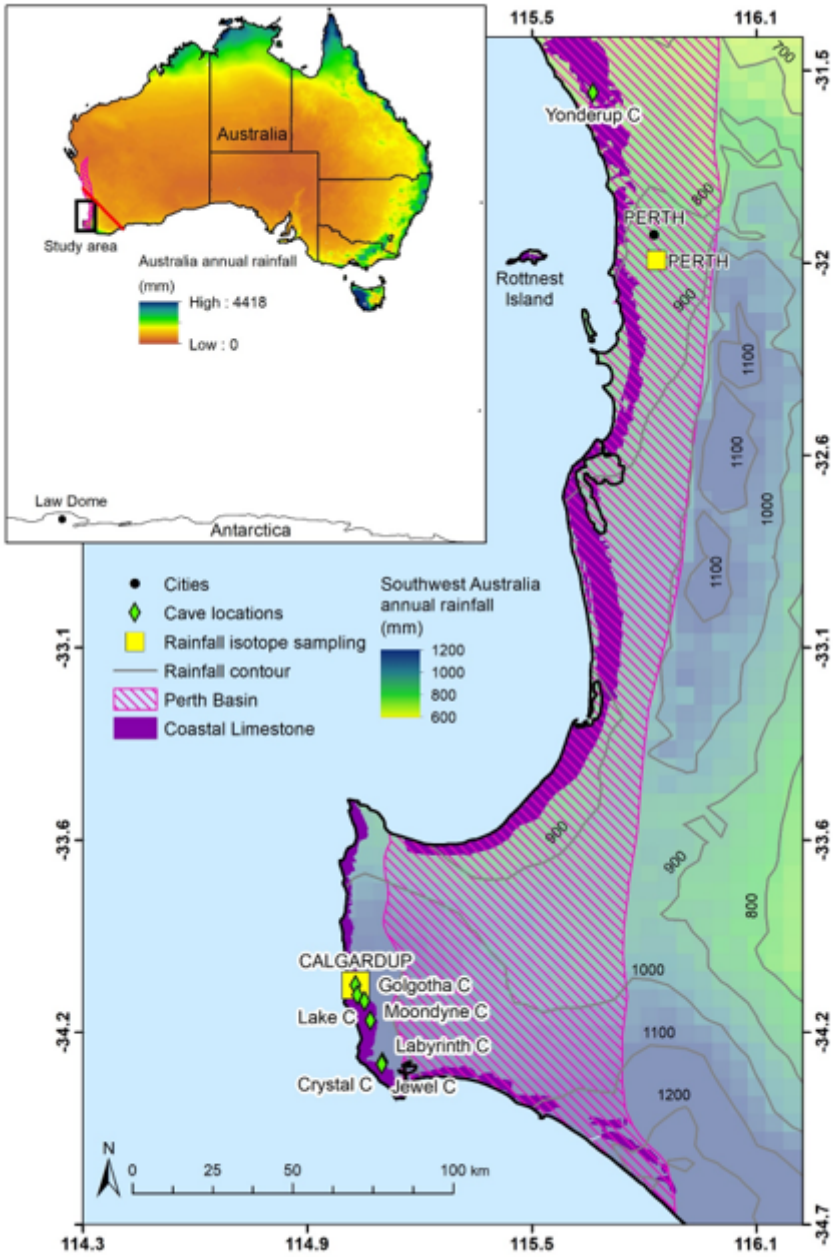


Figure 1

Location of speleothems and rainfall amount contours[31]. Shading on inset shows full extent of groundwater in the Perth Basin and the study area location and extent of southwest Australia region (shown by red line joining 30°S, 115°E and 35°S, 120°E). Annual rainfall shown on the inset map shows that the study area is in an important rainfall area of the southern Australian region. See supplementary note for description of field sites stalagmite samples.

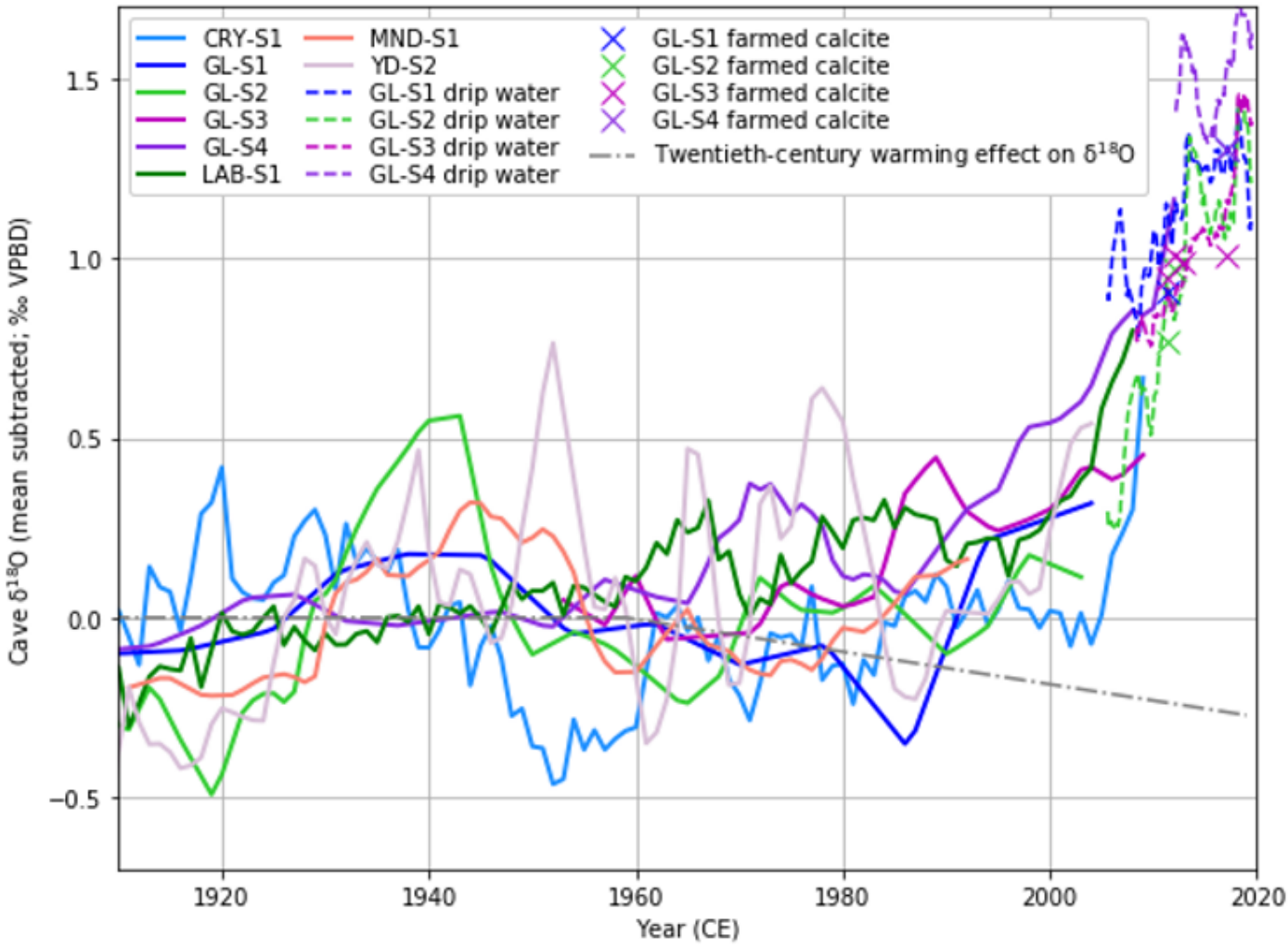


Figure 2

Individual speleothem (stalagmite) $\delta^{18}O$ records from Crystal Cave (CRY-S1), Golgotha Cave (GL-S2 and GL-S4), Labyrinth Cave (LAB-S1), Moondyne Cave (MND-S1) and Yonderup Cave (YD-S2), dripwater predicted $\delta^{18}O$ and farmed calcite $\delta^{18}O$ from the Golgotha speleothem locations all normalised by subtracting 1900-1968 mean speleothem $\delta^{18}O$ values, twentieth-century warming effect on $\delta^{18}O$ values.

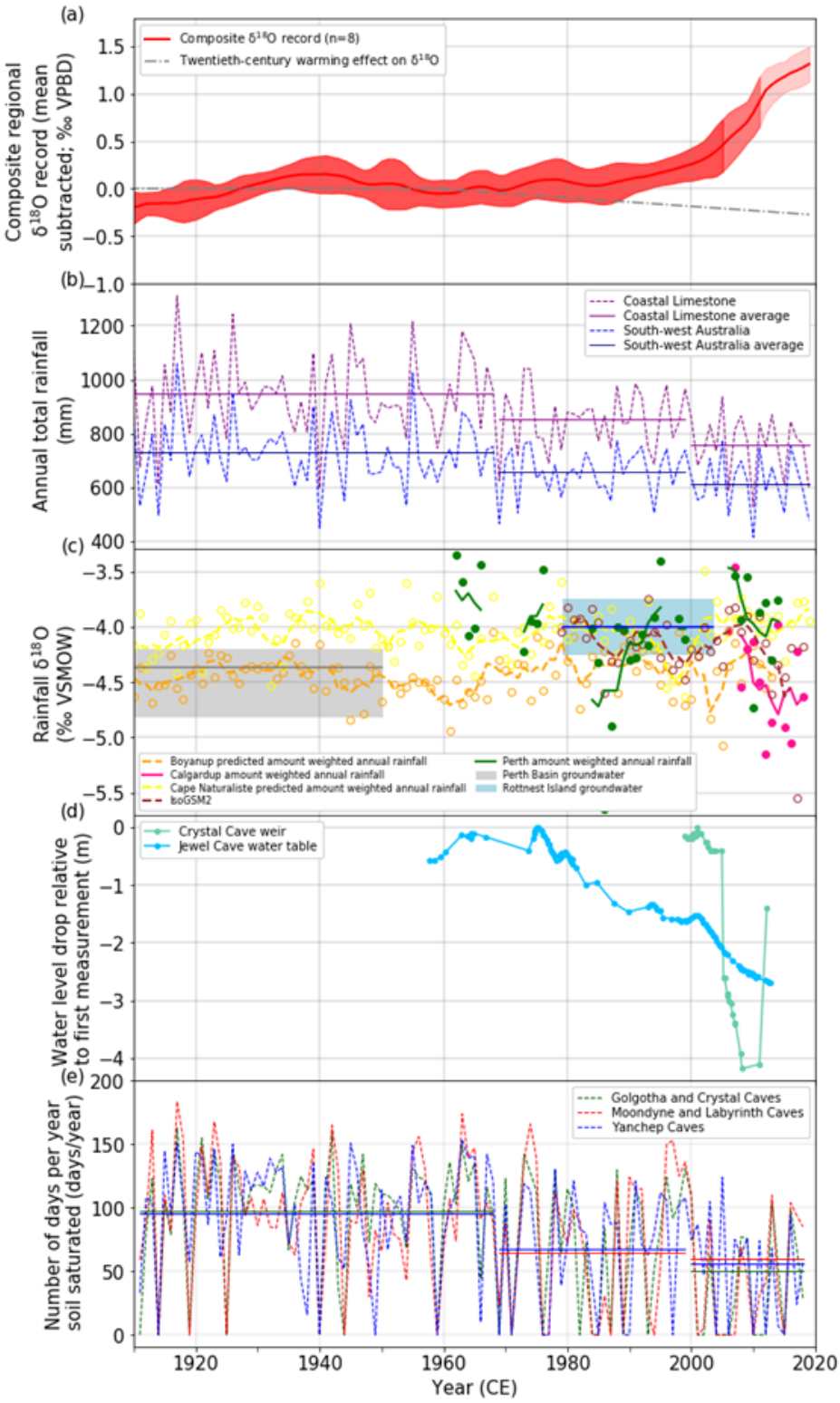


Figure 3

The regional uptick in cave $\delta^{18}O$ data is too large to be driven by rainfall $\delta^{18}O$ and is interpreted to be a reduction in focused flowpaths recharging groundwater. (a) Composite cave $\delta^{18}O$ record that is the 5-year rolling average of the 1900-1968 mean subtracted composite speleothem and dripwater records. Shaded area represents one standard deviation. Also, calculated twentieth-century warming effect on $\delta^{18}O$

values. (b) Rainfall amount for southwest Australia (region southwest of a line joining 30°S, 115°E and 35°S, 120°E; Fig.1) and the coastal Limestone extent (shown in Fig. 1). Means for the periods 1910–1968, 1969–1999, and 2000–2020 are represented by horizontal lines. (c) Five-year rolling average precipitation amount-weighted annual rainfall $\delta^{18}O$: measured at Calgardup and Perth; predicted from high quality long-term rainfall records at Boyanup and Cape Naturaliste; and predicted from IsoGSM2[47]. Circles of the same colour correspond to the monthly amount-weighted rainfall $\delta^{18}O$. Also, range of average $\delta^{18}O$ measured in groundwater from the Leederville and Yarragadee aquifers of the Perth Basin[48] and groundwater from Rottnest Island[18]. (d) Cave water level drop relative to the first measurement for local groundwater level in Jewel Cave. Measurements at another cave, Crystal Cave, began in 1998 and has since fallen 4 m. (e) Number of days per year soil is saturated with horizontal bars indicating the average values across all of the cave sites for the periods 1910–1968, 1969–1999, and 2000–2020. Three model estimates were determined corresponding to the three 0.05° gridded cells covering the five cave sites in the AWRA-L model[45].

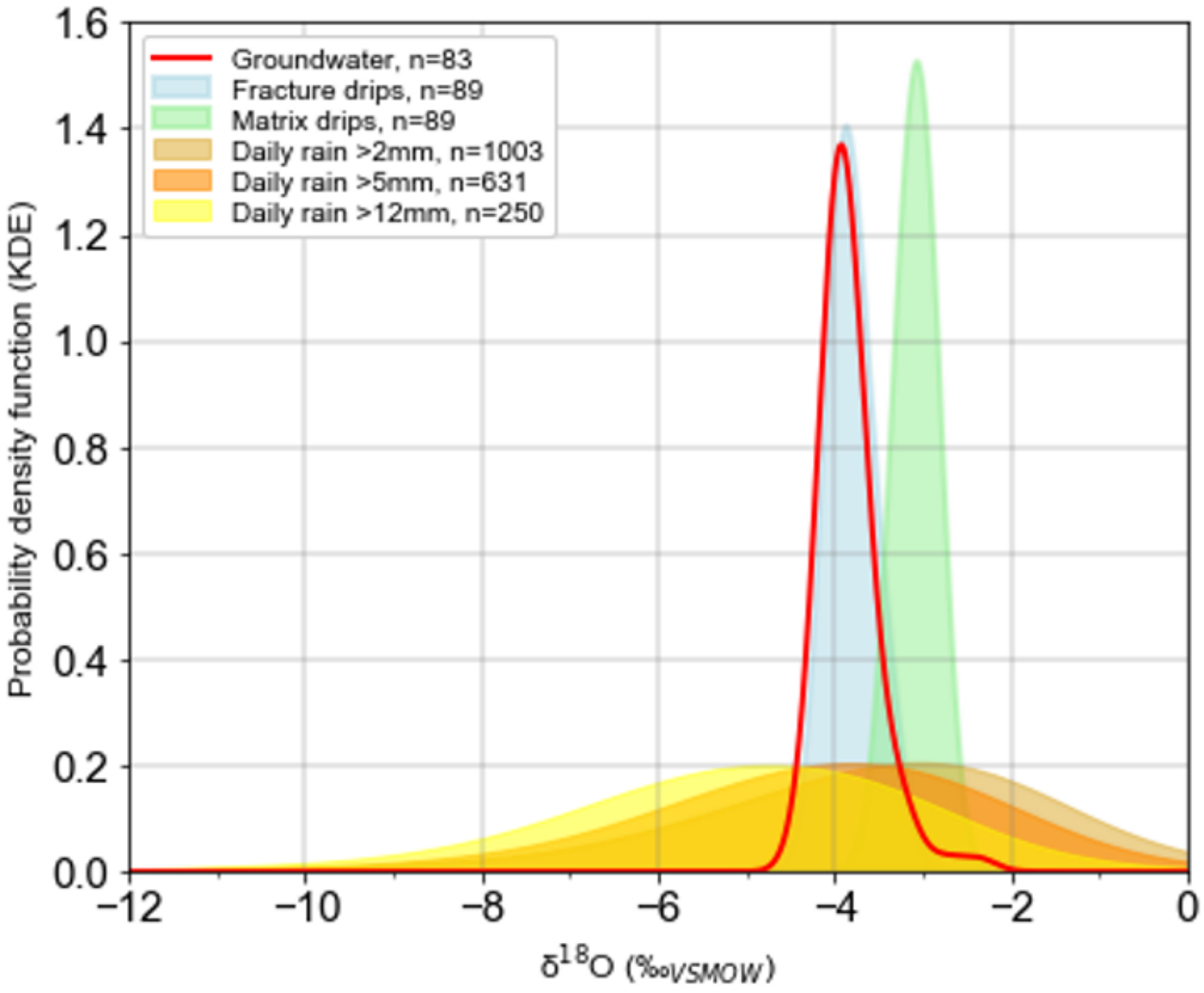


Figure 4

Distributions of $\delta^{18}O$ values for Calgardup daily rainfall, Golgotha dripwater and groundwater. Fracture flow dripwater are isotopically lower than matrix flow drips and the mean value of daily rainfall owing to recharge bias towards rainfall with higher daily totals. Fracture flow and groundwater $\delta^{18}O$ values closely agree indicating that infiltration to groundwater similarly has a recharge bias towards higher intensity rainfall. The kernel density estimate method was used to calculate the distributions using a band width (a generalisation of bin size) of 1 ‰ for daily rainfall and 0.2 ‰ for dripwater and groundwater. Matrix flow and fracture flow dripwaters are values from sites 1A and 2E, respectively in ref. [26]. Groundwater data are Holocene age data for the Southern Perth Basin (Leederville and Yarragadee aquifers) taken from ref. [48].

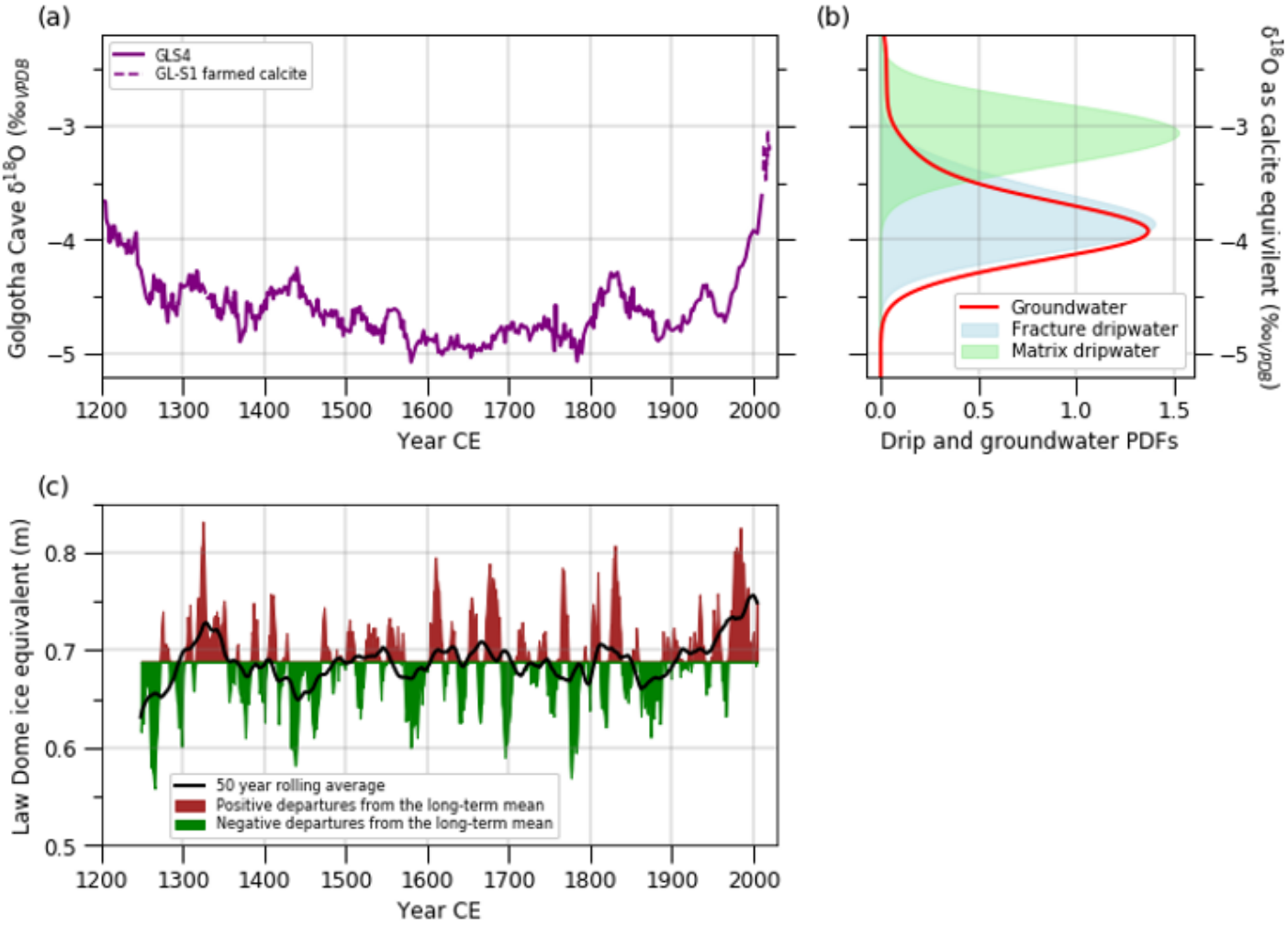


Figure 5

Golgotha Cave record compared with Law Dome-based reconstruction of southwest Australian rainfall. The recent uptick in $\delta^{18}O$ values indicates a disconnection in rainfall recharge (reduced focused

flow along fractures) to groundwater that is unprecedented in the last 800 years. (a) Golgotha Cave $\delta^{18}O$ record: speleothem GL-S4[26] (solid line) plus dripwater to this speleothem (dashed line). (b) Distributions of dripwater and Holocene groundwater $\delta^{18}O$ values on the calcite equivalent (VPDB) scale for comparison with the speleothem record. (c) Southwest Australian precipitation reconstructed from snow accumulation rates at Law Dome, Antarctica, where higher ice accumulation is related to reduced rainfall in southwest Australia[34]. Black line represents 50- year running average. See Supplementary Figure 4 for a comparison with other data for this region.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

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