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Solar forced diurnal regulation of cave drip rates via phreatophyte evapotranspiration

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Abstract

We present results of a detailed study of drip rate variations at 12 drip discharge sites in Glory Hole Cave, New South Wales, Australia. Our novel time series analysis, using the synchrosqueeze transform, reveals pronounced oscillations at daily and sub-daily frequencies occurring in 8 out of the 12 monitored sites. These oscillations were not spatially or temporally homogenous, with different drip sites exhibiting such behaviour at different times of year in different parts of the cave. We test several hypotheses for the cause of the oscillations including variations in pressure gradients between karst and cave due to cave breathing effects or atmospheric and earth tides, variations in hydraulic conductivity due to changes in viscosity of water with daily temperature oscillations, and solar driven daily cycles of vegetative (phreatophytic) transpiration. We conclude that the only hypothesis consistent with the data and hydrologic theory is that daily oscillations are caused by solar driven pumping by phreatophytic trees which are abundant at the site. The daily oscillations are not continuous and occur sporadically in short bursts (2-14 days) throughout the year due to non-linear modification of the solar signal via complex karst architecture. This is the first observation of tree water use in cave drip water and has important implications for karst hydrology in regards to developing a new protocol to determine the relative importance of trends in drip rate at different timescales and to infer karst architecture. Our findings support a growing body of research exploring the impact of trees on speleothem paleoclimate proxies.

1. Introduction

Karst architecture determines the flow and storage of water from the surface to the underlying cave and is a major influence on drip discharge. Karst systems are characterised by three principle flow types. Primary flow occurs where the water travels through the primary porosity of the rock matrix, secondary flow pathways are characterised by water transported along fractures in the bedrock and tertiary flow pathways consist of conduits enlarged by dissolution. The dominance of a particular flow regime can be influenced by the age of the limestone, for example, older limestone tends to be more heavily karstified (more fractures and enlarged conduits) with a lower primary porosity due to marmorisation. The relationship between karst architecture and delivery of water to cave drip discharge sites has been studied to constrain uncertainty in paleoclimate studies (Bradley et al., 2010; Markowska et al., 2015), identify suitable speleothems as climate archives (McDonald and Drysdale, 2007) and in conjunction with drip water geochemistry to determine water residence times in karst aquifers (Fairchild et al., 2000; Tooth and Fairchild, 2003; Treble et al., 2013b). Recent research into drip hydrology and fluctuations in drip rate have used hydrological response to characterise flow paths. For example, Markowska et al., (2015) used statistical analysis of drip hydrology data to identify storage flow, in both the epikarst and overlying soil, to develop conceptual models of a karst system.

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Over a timescale of months to years, fluctuations in drip discharge are typically driven by seasonal variation in water availability (Hu et al., 2008; Sondag et al., 2003) and long-term climate forcings such as the North Atlantic Oscillation or El Niño-Southern Oscillation (McDonald, 2004; Proctor et al., 2000). On a daily to weekly timescale, drip rate responds to individual rainfall events (Baldini et al., 2012) and barometric changes (Genty and Deflandre, 1998; Jex et al., 2012; Tremaine and Froelich, 2013). Tremaine and Froelich (2013) found weekly and daily fluctuations at one drip site where an increase in barometric pressure decreased volumetric drip rate. This was attributed to atmospheric tides, the heating and cooling of the atmosphere, as the diurnal cycles occurred at two hours before the solar noon (S1) and solar midnight (S2) each day. The cave was situated in poorly to moderately indurated Oligocene limestone with a high likelihood of primary porosity (Scott, 2001). Jex et al. (2012) observed a negative correlation between weekly barometric pressure changes and drip rate at two out of forty drip sites monitored at the base of a paleokarst feature in the marmorised and fractured Devonian limestone at Cathedral Cave, NSW. One drip discharge site had a relatively strong anti-correlation (R=-0.52) after accounting for a 40 hr time lag. This relationship was attributed to a two-phase flow, where pressure fluctuations expanded and compressed air bubbles in the water held within the paleokarst in the unsaturated zone.

Non-linear and chaotic behaviour of drip discharge has been observed over very short (second to minutes) timescales. Chaotic drip regimes were first noted by Genty and Deflandre (1998) in the Devonian limestone of southern Belgium (Genty and Deflandre, 1998). Chaotic and non-linear drip responses were also observed at an event-scale in the fractured-rock limestone of Cathedral Cave, NSW (Mariethoz et al., 2012). These were attributed to the filling and draining of subsurface karst stores within a recharge event, with increasing homogenisation of flow with the filling of the stores. Baker and Brunsdon (2003) observed non-linear responses to rainfall in multi-year drip time series from a fractured rock (Carboniferous limestone) in Yorkshire, UK. With the exception of Tremaine and Froeclich (2013), daily fluctuations have not been observed in cave drip water hydrology.

In this paper we aim to increase our understanding of karst architecture by using a novel approach, the synchosqueeze transform, to analyse drip discharge time series from 12 drip discharge sites in Glory Hole Cave, SE Australia. This analysis allows us to characterise daily and sub-daily fluctuations in drip rate and identify the processes driving these oscillations.

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2. Field site and methods

2.1 Glory Hole Cave at Yarrangobilly Caves National Park

Glory Hole Cave is part of the Yarrangobilly Caves National Park located in the Snowy Mountains, New South Wales, Australia (35°43'29.3"S 148°29'14.9"E) at an elevation of 980 m AHD. The Snowy Mountains forms part of the Great Dividing Range, a mountainous region stretching along the eastern seaboard from Queensland to Victoria. The region is sub-alpine and the climate is classified as temperate montane with mild summers and no dry season (Köppen climate classification Cfb) (Peel et al., 2007; Stern et al., 2012).

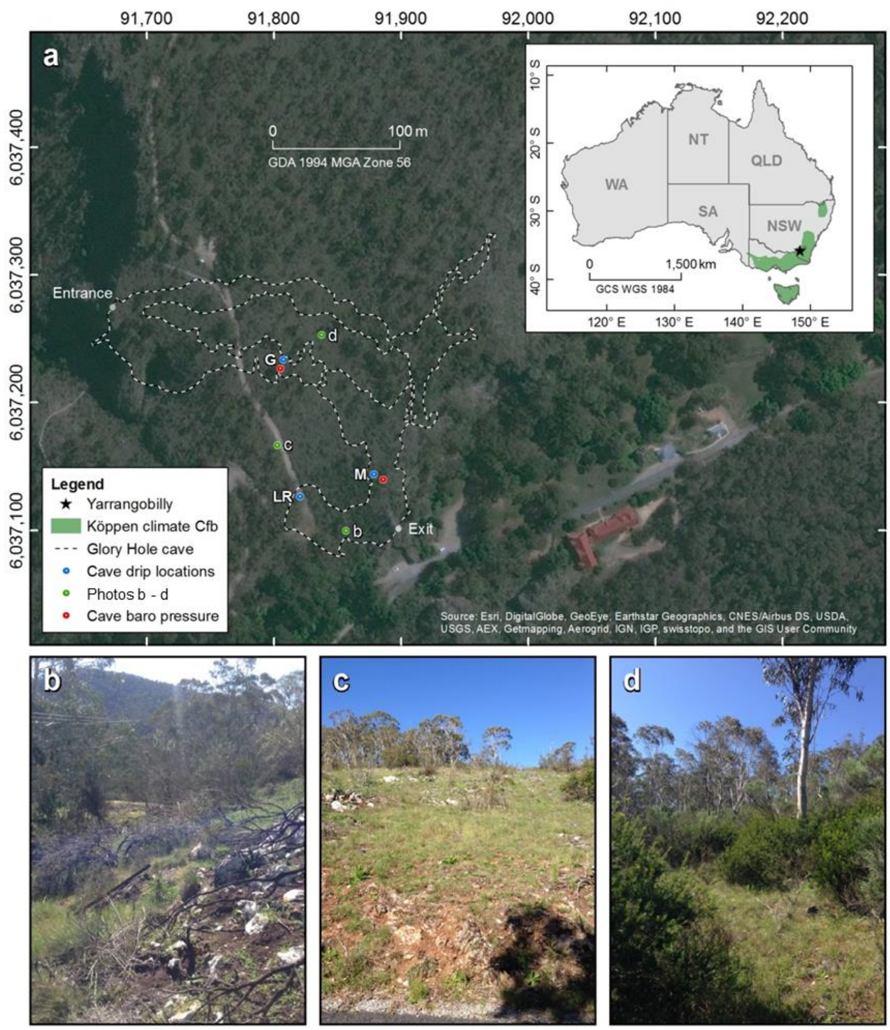

Figure 1 location of Yarrangobilly Caves in New South Wales, Australia with photos of surface vegetation b-d. Extent of Köppen climate zone is from Peel et al. (2007).

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Glory Hole Cave is formed of two main sections connected by a narrow constriction ~2 m x 6 m. It is ~243 m in length and is ~100 m at its widest point. The cave extends more than 40 m below the surface in an unsaturated zone of westward sloping limestone bedrock. The cave is situated within a formation of massive limestone approximately 12 km long and on average 1 km wide (Worboys, 1982). The limestone is typical of south-eastern Australian limestone; it is Silurian, highly fractured and marmorised with little primary porosity. The bedding planes of the limestone are generally obvious with a westward dip (Adamson and Loudon, 1966). It is likely that Glory Hole Cave was formed by water running off less permeable rocks to the east of the limestone, sinking to the water table and rising through large springs close to the Yarrangobilly River (Spate, 2002) which is situated in a gorge in <100 m west of the cave entrance.

The vegetation is classified as sub-alpine open snowgum (*Eucalyptus pauciflora subsp. pauciflora*) and black sallee (*E. stelullata*) woodland.

2.2 Cave and surface monitoring

Drip discharge rate was recorded at 12 drip sites in three locations (Fig. 1 and Table 1) within Glory Hole Cave using Stalagmate© drip loggers between December 2012 and September 2015, and monitoring is ongoing. Drip loggers recorded the frequency of drips falling onto the surface of the sealed box containing an acoustic sensor in 15 min intervals. The number of drips were converted to ml min^{-1}, assuming that 1 drip equals 0.19 ml (Collister and Mattey, 2008). Recently, automated drip loggers have been widely used in cave hydrology research (Cuthbert et al., 2014b; Hu et al., 2008; Mahmud et al., 2015; Rutlidge et al., 2014; Treble et al., 2013a) as they provide a more convenient and efficient way of recording higher temporal resolution data than traditional drip counting methods.

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Table 1 Summary of drip sites and location within cave as indicated in Fig. 1, the mean and standard deviation (std) of total flow volume and maximum and minimum drip rate in summer (December- February) and winter (June- August).

		Total flow volume (L)				Drip rate (ml min^{-1})			
		Summer		Winter		Summer		Winter	
Site	Location	mean	std	mean	std	Maximum	Minimum	Maximum	Minimum
G1	G	72.67	9.21	209.58	107.78	19.51	1.84	56.75	0.00
G3		23.76	10.13	115.44	8.37	7.00	0.00	34.43	0.00
G6		3.73	1.90	16.45	0.10	1.43	0.10	4.10	0.65
G8		6.36	0.49	5.81	0.16	1.11	0.00	0.96	0.34
G10		32.47	23.08	104.54	73.58	9.97	0.04	27.27	0.00
G12		6.57	5.71	9.74	4.39	1.68	0.00	2.04	0.43
LR1	LR	32.31	23.93	98.62	7.39	58.30	0.00	57.77	0.00
M1	M	0.29	0.18	0.47	0.00	0.13	0.00	0.11	0.00
M2		7.67	12.85	120.09	21.21	42.53	0.00	74.30	0.00
M4		0.88	1.47	33.95	5.17	4.02	0.00	28.45	0.00
M10		24.53	34.68	127.79	51.36	13.95	0.00	27.56	0.00
M13		7.33	5.05	67.03	6.60	12.40	0.09	41.80	0.92

Barometric pressure and air temperature were recorded at two locations within the cave (Fig. 1) using Solinst level loggers at 15 min intervals from January-September 2015. Precipitation (accuracy ± 4% of total), wind speed (accuracy ± 0.1 kph), relative humidity (accuracy ±2%), air temperature (accuracy ± 0.5 °C) and barometric pressure (accuracy: ±1.0 hPa/ mb) were measured with a Davis Vantage Pro 2 weather station <1 km from Glory Hole Cave at 15 min intervals and data stored using a Datataker DT80 data logger. Solar radiation was derived from satellite imagery processed by the Bureau of Meteorology from the Geostationary Meteorological Satellite and MTSAT series.

Daily evapotranspiration was estimated using ETo Calculator software developed by the Land and Water Division of the Food and Agriculture Organisation of the United Nations http://www.fao.org/nr/water/eto.html. The software is based on the Penman-Monteith equation and is a physically-based method with physiological and aerodynamic parameters. The climate parameters used were air temperature (mean, maximum and minimum), relative humidity (mean, maximum and minimum), wind speed and solar radiation. Daily evapotranspiration data was only available for the period 19/12/2012-03/07/2014 due to a malfunction in the weather station post-July 2014. Lag time analysis involved the manual calculation of the difference between the timing of minimum daily drip rate and the timing of maximum evapotranspiration during periods of daily drip rate oscillations. In the absence of sub-daily evapotranspiration data, the timing of maximum evapotranspiration was assumed to be 1 pm (Burgess, 2001).

2.3 Spectral analysis of cave drip discharge rates

Synchrosqueezing was used to analyse the frequency-time content of the cave drip discharge rate. Daubechies et al (2011) first presented the synchrosqueeze transform (SST) as an empirical mode decomposition like tool for disentangling a complex signal into approximately harmonic components. SST combines the advantages of the wavelet transform in regards to frequency resolution with the frequency reallocation method (Auger and Flandrin, 1995) in order to reduce smearing when mapping out the frequency-time content of a complex signal. Thakur et al (2013) adapted the transform to discretised data and developed a MATLAB Synchrosqueeze Toolbox (available for download: https://web.math.princeton.edu/~ebrevdo/synsq/) which efficiently implements the algorithm and offers a log2 frequency resolution. They further tested the robustness properties of SST and found that it precisely estimated key signal components, and that it was stable against errors and noise (Thakur et al., 2013).

Using SST, spectral plots were created from drip discharge rate time series as well as their surface weather related drivers (barometric pressure and air temperature). These plots allowed visual identification of key frequency components as well as chaos, i.e. lack of regular oscillations identified as signals with varying amplitude and frequency over time. Drip discharge rate oscillations could be defined as continuous periods of a) stable 1 cycle per day (cpd) frequency, b) stable 1 cpd and 2 cpd frequency, c) chaos. These spectral "fingerprints" were used to identify and mark periods of continuous occurrence in the drip discharge dataset.

Results

3.1 Drip discharge rate time series

The drip discharge time series are presented in Fig. 2. The drip discharge sites are spatially clustered in three groups within the cave (Fig. 1 and Table 1). Sites with the G prefix are located near the main entrance of the cave on the western side. The location is highly decorated with speleothems. M sites are located in the middle section of the cave in a large chamber with a high ceiling populated by soda straw formations. Location LR1 is situated near the cave exit at the top of a flow stone.

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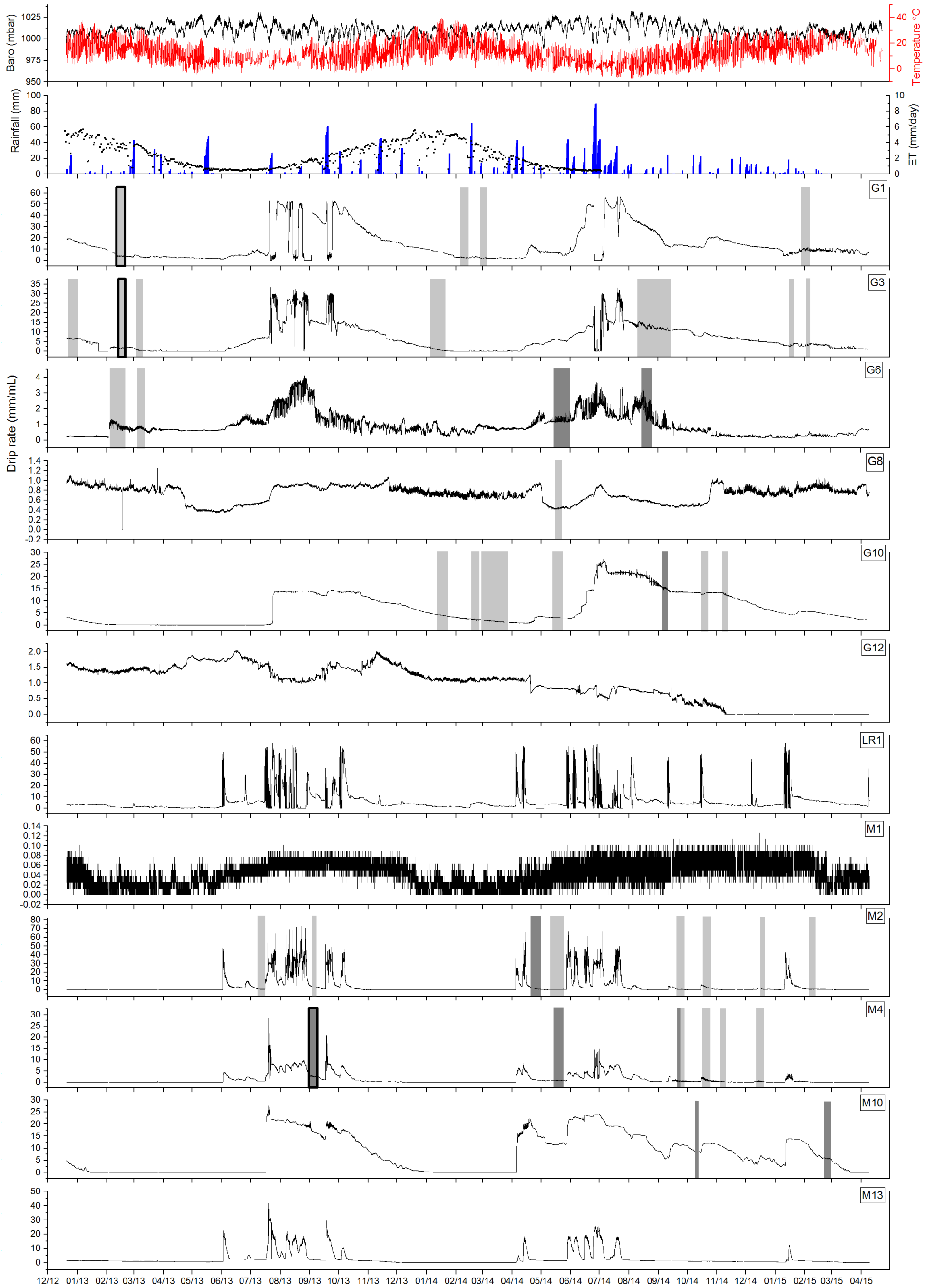

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Figure 2 Drip discharge rate time series for all drip sites in Glory Hole Cave with periods where daily fluctuations occur highlighted in light grey (1 cpd) and dark grey (1 cpd and 2 cpd). The time periods examined in more detail in Fig. 3, 4 and 5 are indicated by bolder outline. Daily evapotranspiration (19/12/2012- 03/07/2014), rainfall, barometric, air temperature and are also shown.

The drip discharge rate at G1 and G3 varies seasonally, with higher drip rates in winter, total flow volume of 133.37 L and 109.52 L, respectively, than summer (64.56 L and 14.1 L, respectively). Drip rate increases in response to rainfall events during the wet season and gradually decreases through the drier part of the year. Drip rate is lowest during April and May and highest during June and July. Similarly, G6 exhibits seasonal variation with a higher volume of discharge during the winter than summer. The drip rate at G10 increases sharply from 0.14 ml min^{-1} on 21/07/2013 to 13.75 ml min^{-1} on 29/07/2013, this drip rate is consistently sustained for 3 months indicated by the flat topped hydrograph (Fig. 2). From July 2013 onwards, the drip rate gradually decreases until June 2014 where it increases sharply again by an order of magnitude from 2.03 ml min^{-1} on 3/06/2014 to 24.96 ml min^{-1} on 4/07/2014. In May 2014, the drip rate again rapidly increases at G10 from 0.142 ml min^{-1} to 21.59 ml min^{-1} on 18/04/2014 and then proceeds to gradually decline until April 2015 where it reaches baseline conditions. M10 exhibits similar behaviour with a low baseline drip rate which increases sharply during July 2013 and is sustained for ~3 months, however, the elevated drip rate decreases more rapidly than G10, returning to baseline conditions in January 2014. M1 has a very low drip rate ranging from 0- 0.13 ml min^{-1} and is seasonally variable with higher drip rates during the winter. LR1, M2, M4 and M13 are very responsive to infiltration events and are characterised by a 'flashy' flow type, evidenced by the frequent spikes in drip rate. G12 has a low discharge rate which gradually decreases over the monitoring period until the site dries up completely in November 2014. There are small variations in drip rate that are not associated with rainfall events or seasonal drying. G8 is the only site which has a lower total flow volume during the winter (2013= 5.92 L; 2014= 5.7 L) than summer (2014= 6.39 L; 2015= 6.84 L).

3.2 Characterisation of oscillations in the drip discharge rate

Daily fluctuations in drip discharge rate were identified in eight out of twelve sites using SST. There was no connection between the sites that did not exhibit the fluctuations with respect to spatial location, flow volume or flow regime type. The temporal and spatial pattern of daily oscillations are shown by the grey shaded areas in Fig. 2. The length of time the signal is present varied temporally for each drip site. For example, there was a strong 1 cpd signal in the drip water at G1 for 10 days in February 2013 whereas in January 2014 1 cpd fluctuations only lasted 5 days. The timing of when the signal occurs on an annual scale varied within and between drip sites. For example, a 1 cpd signal only occurred during the first 3 months of the year for G1, whereas a 1 cpd signal occurred sporadically at G3 throughout the calendar year (December 2012, February and March 2013, January 2014, September 2014, January 2015).

The daily timing of minimum and maximum drip rates varied within and between individual drip sites. At G3 the 1 cpd minimum and maximum drip rate generally appeared between 12- 9 am and 3pm-12am, respectively. The minimum drip rate lagged 11-20 hours behind the timing of maximum evapotranspiration, which Burgess et al (2001) estimated to be 1 pm. Daily oscillations were only observed once at G8 between 14-21/05/2014 with minimum drip rate appearing 3-9 am and maximum drip rate appearing between 12-9 pm. G6 exhibited a similar pattern with the exception of May and August 2014 where an additional 2 cpd signal was observed with the second peak following 3-6 hours later. Similar patterns of minimum drip rate lagging 11-20 hours behind the maximum daily evapotranspiration were exhibited at G10 (with weak 2 cpd between 5-16/10/2013) and M2 (with weak 2 cpd between 20-28/04/2014). Both 1 cpd and 2 cpd signals were observed at M10 for all the periods of drip rate oscillation with the larger peak occurring in the afternoon between 3-6 pm and the smaller peak between 12-3 am, minimum drip rate appeared consistently between 6-9 am. In contrast, minimum drip rate at G1 was observed between 12-9 pm and maximum drip rate between 6-9 am indicating a lag time of ≤9 hours behind peak evapotranspiration. M4 was unique in that minimum drip rate are recorded between 6-9 am until October 2014 when it switches to 12-9 pm.

1 cpd and 2 cpd signals can occur concurrently, for example, at M4 between 1-9/9/2013 (Fig. 4). This trend, where the 2 cpd is weaker than the 1 cpd is consistent across all sites where the two signals coincide. The 2 cpd signal can be visually determined in the raw drip rate data by a second smaller peak (Fig.4). Examples of characteristic SST plots alongside the corresponding raw drip rate and surface temperature data will be discussed in greater detail below. All SST analyses have been plotted in the SI.

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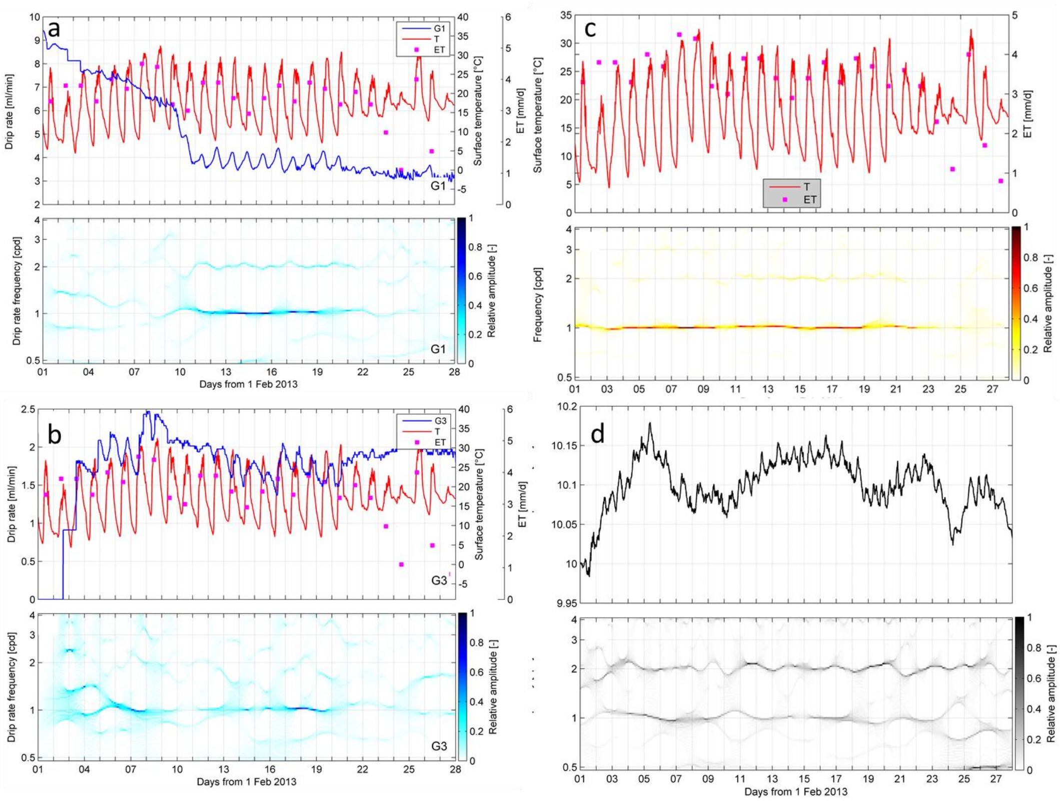

Figure 3 shows the raw drip rate, evapotranspiration and surface temperature data with the corresponding drip rate synchrosqueezing plot for time periods where a 1 cpd signal is present for sites a) G1 and b) G3 c) surface air temperature and evapotranspiration and d) barometric pressure for period February 2013.

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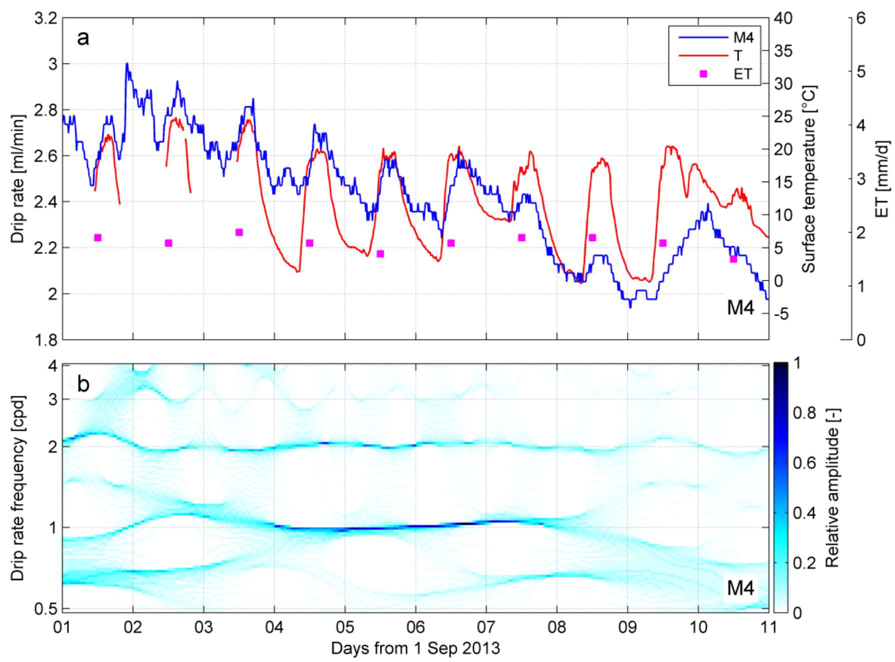

Figure 4 shows the raw drip discharge data, evapotranspirationsurface temperature and synchrosqueeze transform (SST) plot of the drip discharge for site M4 from 1-11/09/2013.SST identified a 1 cpd oscillation in drip rate between 08/02/2013 and 21/02/2013 at G1 and G3 (Fig. 3a, b). At G1 (Fig. 3a), the signal was initially chaotic, but from 08/02/13- 21/02/13 the drip rate oscillates sharply at 1 cpd. The maximum drip rate ranging from 4.03-3.75 ml min-^{1} occurred between 9:18 and 10:27 and the minimum drip rate ranging from 3.34 -3.75 ml min^{-1} occurred between 18:39 and 21:27. The signal was chaotic from 21/02/2013.

The drip rate at G3 (Fig. 3b) oscillated at 1cpd for 8 days from 12/02/13-20/02/13. In contrast to G1, the maximum drip rate appeared in the evening and the minimum drip rate occurred in the morning. The maximum drip rate ranging from 1.63 -2.01 ml min^{-1} occurred between 20:21 and 00:40 and the minimum drip rate ranging from 0.36-0.48 ml min^{-1} occurred between 9:03 and 11.36 with the exception of 15/02/13 and 18/02/13 where it appeared at 14:06 and 12:57, respectively. Similarly to G1, the 1 cpd trend descended into chaos from 20/02/13 onwards. The maximum drip rate occurs between 14:23 and 22:45 and ranged from 0.53 to 1.14 ml min^{-1}. The minimum drip rate occurred between 01:18 and 11:32 and ranged from 0.228 to 0.95 ml min^{-1}.

From 01-27/02/13, daily barometric pressure peaked between 8:30-9:00 with a magnitude of ~1-5 mbar with a smaller second peak between 20:00-22:00 with a magnitude of 1-3 mbar (Fig. 3c). There were larger changes in air pressure on a mesoscale with peaks in air pressure on 16/02/13, 22/02/13, 26/02/13 and minimum air pressure on 19/02/13, 24/02/13 and 28/02/13. The air pressure changes in these cycles were as much as 15-20 mbar. The drip rate at G1 and G3 did not appear to be affected by the daily or weekly changes in air pressure. For example, when air pressure decreased dramatically on 27/02/13 (Fig. 3c) there was no substantial change in drip rate at either G1 or G3.

Insolation drives daily cycles in surface air temperature with maximum temperatures recorded between 11:30-16:00 and minimum temperatures recorded between 4:00-8:00 (Fig. 3d). The difference in daily minimum and maximum air temperature varied greatly. For example, between 12- 20/02/2013 the difference was 17.05-22.2 °C whereas between 21-27/02/2013, the temperature difference was as little as 4.5 °C. Evapotranspiration ranged from 0.8- 4.5 mm/day and was relatively high from 1-23/02/2013 with a slight downward trend which then decreased sharply on 23/02/2013 and 24/02/2013 to 2.3 mm/day and 1.1 mm/day, respectively. Evapotranspiration had a strong correlation with maximum daily air temperature (R^2= 0.59, p-value <0.05).

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4. Discussion

4.1 Cave drip rate and karst architecture

The complexity of the Glory Hole Cave karst system is evident in the variety of drip regimes. For example, the drip rate at G1, G6 and G3 is seasonally driven with high discharge rates during the wettest period of the year. In contrast, drip discharge at G10 and M10 is likely driven by a storage component which discharges via a permeable pathway which limits the store at a particular level during wet periods. The drip site is fed via the main water store rather than the overflow pathway itself (Baker et al., 2012; Bradley et al., 2010). Sites LR1, M4, M13 and M2 behave similarly in that they are all very responsive to rainfall events and have low base flows during periods of low rainfall. The response to rainfall events occur within 24 hours across these sites. Calculated flow volumes indicate the storage capacity of the stores feeding the discharge sites. For example, there was an infiltration event on 01/06/2013 which caused a dramatic increase in drip rate for sites LR1, M2, M4 and M13. The flow volumes for each site from the start of the event to the point where the discharge returns to a constant rate are as follows LR1 (1.60 L), M4 (2.99 L), M13 (8.09 L) and M2 (11.30 L). The length of the recession limb is indicative of the speed at which the store drains. For example, the decay in drip rate is 12 days for site M2 compared to 4 days for M13. The time it takes for the store to drain is not dependent on flow volume, as M13 has a flow volume of more than 5 times that of site LR1 but they both have drainage periods of 5 days. The discrepancy in drainage time could indicate variation in flow pathway length between sites. G8 is the only site with a relatively lower total flow volume during winter than summer. M1 has a low drip rate that shows a small seasonal fluctuation but does not visibly respond to individual events. This site is likely being fed by a store that is large enough to assimilate short term inputs from the surface without impacting drip rate. This type of store has been described in a karst hydrological model by Markowska et al. (2015).

4.2 Daily oscillations in drip rate

Constant frequency oscillations in drip discharge (1 cpd and 2 cpd) occur sporadically throughout the monitoring period December 2012- April 2015 at 8 out of 12 monitored drip sites. This phenomenon could be explained by a number of daily drivers including variations in pressure gradients between karst and cave due to cave ventilation effects, atmospheric and earth tides, or variations in hydraulic conductivity (due to changes in viscosity of water with daily temperature oscillations), and solar driven daily cycles of vegetative (phreatophytic) transpiration. These drivers are now considered in turn.

4.2.1. Cave ventilation effects

A student's t-test showed that there was no significant difference between surface air pressure and cave air pressure for the monitoring period 19/01/2015-08/09/2015 (p-value=

3.95 10^{-6}, n=8939). This indicates that cave air exchange ("breathing" or ventilation) is very efficient and consequently that variations in air pressure between the cave and surface can be ruled out as driving the fluctuations in drip rate.

4.2.2. Barometric loading

Atmospheric tides are caused by changes in air pressure due to the heating and cooling of air masses during the day and night. Correlations between atmospheric tides and drip rates can occur since increases (decreases) in atmospheric pressure at the ground surface are partitioned into stress increase (decrease) in the soil/rock mass and pore pressure increase (decrease) within the formation (Acworth et al., 2015). Drip rates could be affected if this changes the pressure gradient between the groundwater in karst stores and the cave (Tremaine and Froelich, 2013). Such a pressure imbalance is dependent on the hydromechanical properties and karst architecture as well as the degree of pneumatic connection between both the surface and the water table, and the surface and the cave at the location of the drip. Maximum and minimum atmospheric pressure occur at the same time each day (Fig. 3c).

Atmospheric tides were eliminated as a process to explain the daily oscillation phenomenon for several reasons. Firstly, there was no relationship between drip discharge rate and the longer term barometric changes caused by synoptic weather patterns (Fig. 4c). The mesoscale fluctuations in pressure caused by synoptic weather patterns are an order of magnitude higher than those caused by daily atmospheric tides. Since the drip rate did not respond to pressure changes of this size, they will not respond significantly to changes of a smaller magnitude at a higher frequency because higher frequency signals will be more highly damped and lagged. Secondly, the timing of the daily maximum and minimum drip rates in Glory Hole Cave varied within each drip site over time. For example, the peak discharge time for site G6 varied between 13:24 and 19:48 for the period 11/08/2013-25/08/2015. This finding contrasts with previous studies where drip rate is negatively correlated with barometric pressure and responds to daily pressure changes linearly (Tremaine and Froelich, 2013). However, this could indicate that the daily drip water variations in Glory Hole Cave are being driven by a non-linear process and this is discussed further below. Thirdly, the karst architecture of Glory Hole Cave is well-developed, has little to no primary porosity and is unconfined. Hence, it is unlikely to exhibit barometric responses such as seen in confined systems (Merritt, 2004), whereby pore pressure changes due to barometric loading are substantially lower than the change of cave air pressure.

4.2.3. Earth tides

Earth tides are solid deformations of the Earth's surface caused by the gravitational pull of the moon and sun (Merritt, 2004). It has been previously shown that earth tides can cause regular oscillations in groundwater level if the aquifer is sufficiently confined (Acworth et al., 2015). However, at Glory Hole Cave this process can be ruled out due to the unconfined conditions, the fact that the compressibility of limestone is smaller than that of water, and because fluctuations in pressure caused by earth tides are so small.

4.2.4. Temperature driven viscosity influences on hydraulic conductivity

The study site has large surface temperature variations, particularly in summer where day time and night time temperatures can vary up to 31.1 °C. Consequently, the dynamic viscosity of water could range from 0.8- 1.79 x 10^{-3} Pa s (based on a temperature range from 30-0 °C, respectively). However, the conductive propagation in diel temperature variations are expected to be highly attenuated with depth (Rau et al., 2015) resulting in almost complete damping by 1 m bgl. Furthermore, the daily temperature range within the cave itself is just 0.08-1.53 °C, primarily due to air exchange moderated by conductive equilibrium with the cave walls. The variation of water viscosity (which is inversely proportional to hydraulic conductivity) is approximately 2 to 3 % per degree in the range 10 to 30 °C. Considering that the amplitude of a 1 cpd drip rate fluctuation can be as much as 75 % of the maximum drip rate, the greatest anticipated change in hydraulic conductivity, and therefore the drip rate (proportional to the hydraulic conductivity by Darcy's law), on a daily cycle, is likely to be 2-3 orders of magnitude lower than the observed variation in drip rate on a daily basis. We therefore conclude that the daily fluctuations in drip rate are unlikely to be caused by variations in hydraulic conductivity due to changes in viscosity of water.

4.2.5. Solar driven daily cycles of vegetative (phreatophytic) evapotranspiration

The timing of the daily drip rate signal appears to be associated with the difference in maximum and minimum surface temperature. In the examples examined in more depth in Fig. 3a-b, when the difference between the maximum and minimum temperature was high (17.05-22 °C) and the evapotranspiration was relatively high (mean 3.6 mm/day) the 1cpd signal was strong. Conversely, when the temperature difference was small (4.5-12.7 °C) and the evapotranspiration was relatively lower (mean 2.2 mm/day), the 1 cpd signal dissolved into chaos.

During periods when there are 1 cpd oscillations in drip rate, there is a relationship between drip rate and surface temperature on a weekly timescale. For example, in Fig. 5 there is a negative relationship between the daily moving averages for surface air temperature and drip rate at G1 from 01-19/02/2014. We have demonstrated above that it cannot be air

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temperature driving the signal through either atmospheric tides or water viscosity changes. However, the relationship between surface temperature variability and 1 cpd drip rate oscillations could be explained if the association with diurnal temperature variability is due to variations in solar radiation received at the surface, as it is solar radiation which primarily drives photosynthesis and thus transpiration in vegetation. This is confirmed by the strong positive relationship between daily solar radiation and evapotranspiration (R^2= 0.59, p-value <0.05). Daytime solar radiation receipt is highest in the absence of cloud cover, because there is no barrier to incoming long wave and short wave radiation which leads to the heating of the earth's surface and atmosphere, resulting in higher air temperature. Due to the lack of cloud cover, night-time cooling occurs because of the loss of heat through outgoing long wave radiation, therefore periods of high daytime solar radiation are characterised by large air temperature amplitudes. In comparison, solar radiation received at the earth's surface is low in the presence of cloud cover. In this case, there is a smaller temperature amplitude because clouds reduce the amount of incoming short wave and longwave radiation during the day, reducing daytime temperatures and reduce the amount of outgoing longwave radiation and effectively "insulating" the air at night leading to relatively warmer temperatures at night.

During periods of high solar radiation, plants photosynthesise more and therefore use more water. We hypothesise that firstly, tree water use was driving the intermittent daily oscillations in drip discharge demonstrated by the relationship between daily to weekly variations in surface air temperature and drip discharge and secondly, the sporadic nature of the oscillations was driven by complexities in the karst architecture. It has been widely accepted that tree water use causes fluctuations of the water table (Gribovszki et al 2010; Acworth et al 2015). However, this is the first study that shows tree water use affecting cave drip water.

The area above the cave and in the small uphill catchment is dominated by *E. pauciflora* and *E. stelullata* (Fig. 1). Eucalypt species have a bimodal root systems with shallow lateral roots and vertically descending roots which penetrate into the profile to depths of up to 18 m, with depth depending on soil characteristics and the degree to which the bedrock is fractured/conduits developed (Crombie, 1992; Farrington et al., 1996). Hence, these trees have the mechanism to abstract water from karst stores at depth which supports our theory that tree water use causes daily oscillations in cave drip rate.

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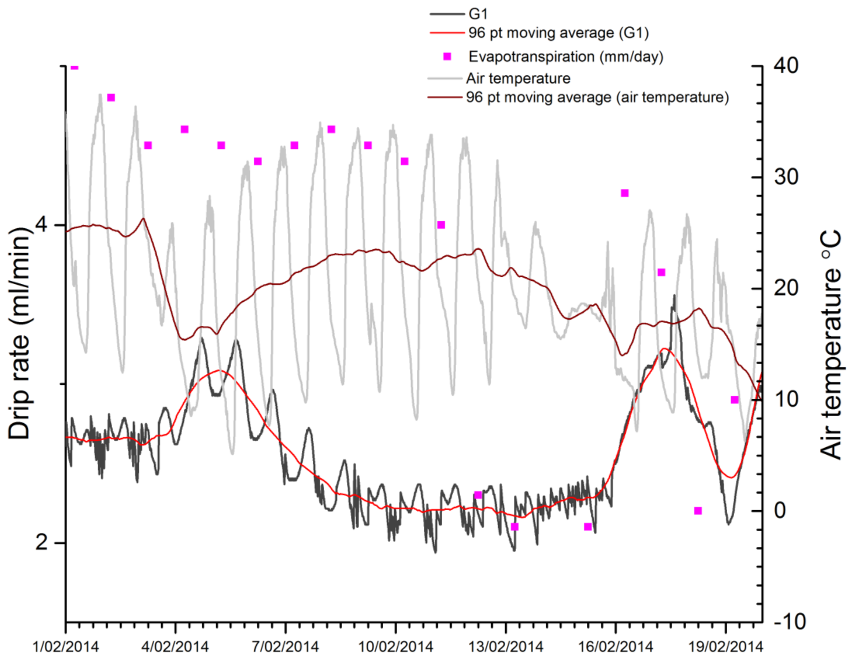

Figure 5 shows the surface air temperature, evapotranspiration and drip discharge rate with the corresponding daily moving average for site G1 01/02/2014-19/02/2014.

Tree water use from deep roots increases with the need for the tree to obtain water, and this will increase with increasing transpiration and solar radiation (O'Grady et al., 1999). Maximum tree water use by the roots is therefore expected in the afternoon during the period of maximum solar radiation, possibly lagged due to the time taken to hydraulically lift the water. Conversely, minimum tree water use is expected at the end of night around 6am. Burgess et al (2001) measured sap flow in Eucalypt tap roots, finding positive hydraulic lift peaked around 1 pm and a negative hydraulic lift between 7pm- 7am. In consideration of this, drip water that comes from fractures and stores which contain tree roots would be expected to have a minimum drip discharge in the afternoon and maximum around sunrise. In reality, we observe more complex daily drip oscillations, with peak drip rate occurring at different times of the day and different times of the year. This is to be expected from a karstified system with flow routed through a varied and complex fractured network. Different scenarios driving daily oscillations in a karst system will be discussed in detail below.

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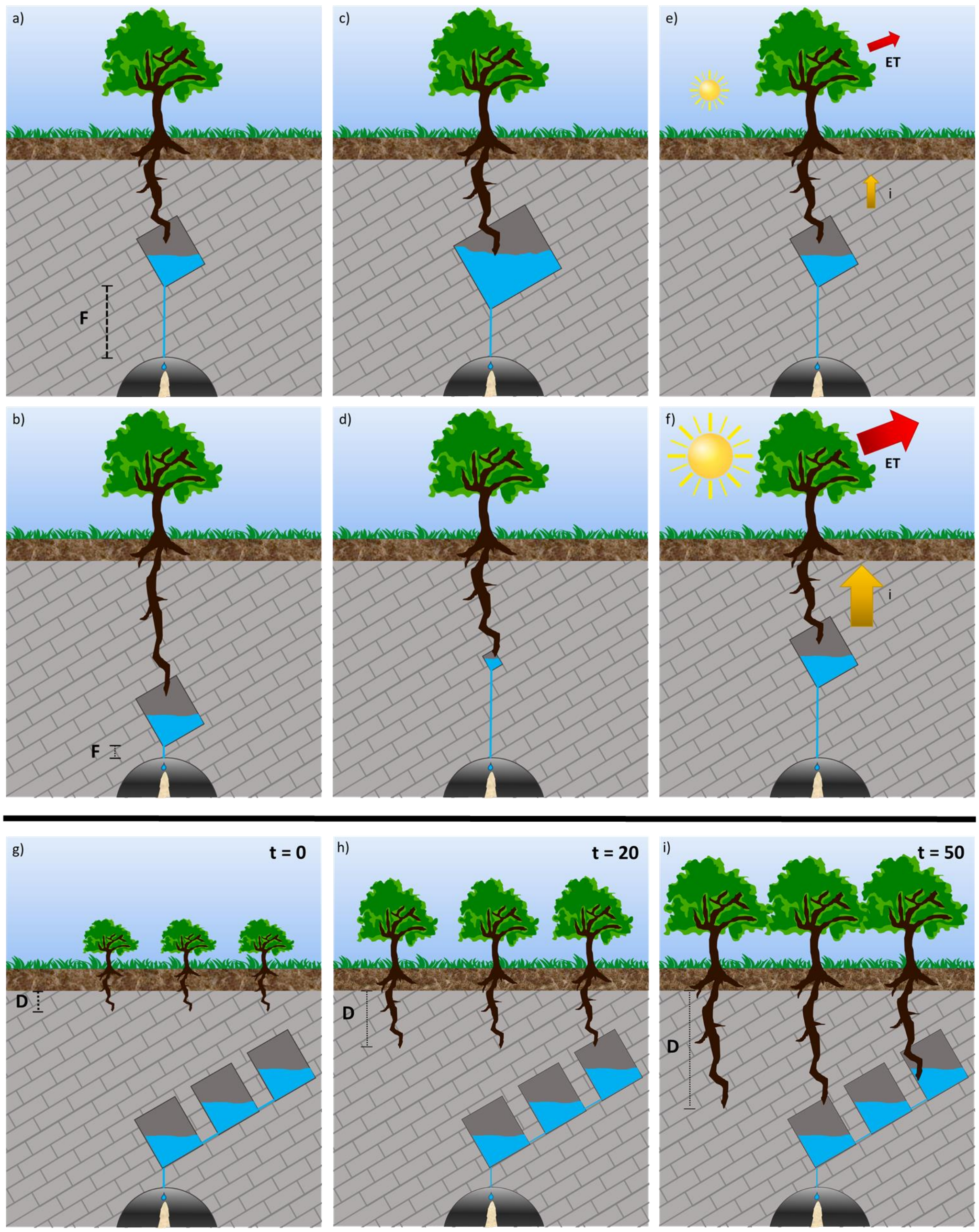

Figure 6 shows a conceptual representation of tree water use from karst stores under different circumstances. a) and b) show different karst store-drip site flow path lengths (F) as the tree roots access karst stores at different depths; c) and d) show tree roots accessing karst stores with different volumes; the influence of annual insolation on evapotranspiration

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(ET) and hydraulic lift (i) during winter and summer is shown in e) and f) respectively. Finally, the increase in rooting depth (L) and access to deeper karst stores over time in years (t) is explored in g-i.

The depth of a store could affect the timing of daily drip rate oscillations due to the delay in tree water transport. For example, consider the hypothetical, identical trees with roots intercepting identical karst stores or fractures at *different* depths in Fig. 6a and 6b. There is likely to be a greater lag in drip response in Fig. 6a than Fig. 6b because of the longer flow path-length (F) from the tree root to the cave drip site. Given that eucalypt tap roots can penetrate to depths ranging from 5-20 m with tap root length depending on the depth of accessible water (Carbon et al., 1980; Dawson and Pate, 1996) and the drip sites at Glory Hole Cave are located 30-50 m below the surface, we can speculate that the minimum flow path length between a taproot accessing the karst store and the drip site below could vary from 10-45 m. In reality, it is difficult to calculate exact flow path length because of the prevalence of lateral flow in heavily karstified systems. This has been demonstrated by Markowska et al (2016) in a study where water spiked with a tracer was used to irrigate the surface above a cave resulting in a response at discharge sites located 7 m laterally from the irrigation location. At all drip discharge sites the minimum drip discharge rate is lagged by 12-18 hours from when we would expect the peak transpiration to occur at 1pm. The exception is G1 where the minimum discharge rate occurs between 12-9 pm indicating a lag time of ≤9 hours. We can hypothesise that G1 has a shorter path length from tree root accessed store to cave discharge site than the other drip sites. This process could also explain the unique case of M4 where the timing of minimum and maximum drip rate during a 1 cpd oscillation switches in October 2014 (Fig. 2). We hypothesise that the change is due to a shortening of the path length from root accessed store to cave discharge site as the tree grows and increases its rooting depth, thus accessing a deeper water store.

The size of the karst store, or volume of water within the store, could determine whether the daily oscillation is observable or not. Consider the conceptual Fig. 6c and 6d, where identical trees have roots intercepting different karst stores at the *same* depth. We hypothesise that a daily oscillation will only be observed when the tree water use is a significant part of the total water store so a daily oscillation is more likely to be observed in the smaller store (Fig. 6d) than a store with a larger volume (Fig. 6c). This is supported by the fact that, generally, the daily oscillations are not exhibited during periods of high rainfall, and consequently high drip discharge, as the tree use signal is more likely to be a smaller fraction of the total water volume. Sites G1, G3 M2 and M4 have high seasonal discharge rates during June-September as indicated by the multiple hydrograph peaks for the corresponding sites in Fig. 2. There are no daily oscillations during these periods of peak discharge at any of these sites. Daily oscillations coincide with the receding limb of the peak at sites M4 (July and September 2013) and M4 (September 2013) as the drip rate decreases. The influence of store volume on the presence of daily oscillations could also explain why phenomenon is not observed at M1. In section 3.1 we discuss how the low, consistent drip

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rate at M1 responds to seasonal drying but does not respond to individual rainfall events. We propose that this site is fed by a store large enough to assimilate individual rainfall events and the same line of reasoning could explain the lack of response to tree water use, the volume of water extracted by tree roots is insignificant in relation to the large volume of water in the store. The non-observance of daily oscillations during periods of high rainfall could also be attributed to the redistribution of water by the roots from the saturated soil to the unsaturated subsurface (Burgess et al., 2001)

Tree water use responds to annual variation in insolation. Consider Fig. 6e and Fig. 6f where one tree root intercepts the same karst store over the course of a year. During winter (Fig 6e), there is less insolation than the summer (Fig 6f) therefore the rate of evapotranspiration is lower. This means that in winter the hydraulic lift (i) is low or negative and daily oscillations in drip discharge could be dampened or absent. Our analysis reveals that only 2 out of 41 periods of 1 cpd oscillation occur during winter months June-August (G6 between 14-24/8/13 and M2 between 8-13/7/2013).

In reality, there are multiple trees of different ages above the cave, further complicating the flow variability. Figure 6g-i presents a conceptual representation of tree tap root length increasing (L) as the tree grows and accesses deeper karst stores over 0-50 yr timescale (t). This response to annual insolation and the interaction of multiple trees of varying ages could explain why daily oscillations at an individual drip site occur one year and not the next, for example at M10 there is a 1 cpd in December 2012 however, this oscillation does not occur at the same time in 2013 or 2014. The mechanism in Fig. 6i could also explain why 2 cpd signals are also observed, whereby multiple tree roots are accessing interconnected water stores at different depths resulting in two separate cycles with differing lag times. The occurrence of 2 cpd signals in drip rate could also be related to signal processing where if the signal is not strictly sinusoidal there may be harmonics in the spectrum. This finding and the interpretation is an area for further research.

4.6 Implications for karst architecture and climate proxy modelling research

Karst architecture controls flow regimes and drip discharge rates of water exfiltrating into caves (e.g., Markowska et al., 2015). Flow rate influences speleothem climate proxies, such as the $\delta^{18}O$ and concentration of solutes in drip water, through the dilution and mixing of percolation waters prior to reaching the cave. It is important to distinguish between the influence of karst architecture and climate-driven processes, such as drought, on discharge so that paleoclimate proxy records from associated speleothems can be appropriately constrained. This study has increased our understanding of karst architecture, information which can be utilised in proxy-system models or forward models, approaches that are increasingly used to understand cave drip rate variability and to model speleothem proxies such as $\delta^{18}O$ (Bradley et al., 2010; Cuthbert et al., 2014a). Additionally, we propose that an important part of any protocol for inferring karst architecture is 1) the incorporation of cave drip rate monitoring with a minimum 15 min interval at multiple discharge sites for at least a

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year and 2) the systematic investigation of daily, weekly and monthly timescales using frequency analysis capable of showing frequency-time changes, such as the synchrosqueeze transform (Daubechies et al., 2011) to infer karst flow processes and their relative importance.

This is the first volumetric observation of tree water use in cave drip water. This supports a growing number of studies examining the impact of trees on karst processes and paleoclimate proxies. For example, tree root respiration provides a source of CO_2 for the dissolution of limestone that is additional to that from soil and vadose zone microbial respiration. Coleborn et al (2016) found that vegetation regeneration determined post-fire soil CO_2 in a study investigating post-fire impacts on karst processes. Direct observations of tree water use within the karst unsaturated zone implies the presence of root respiration, a process which in turn affects drip water and speleothem ^{14}C and $\delta^{13}C$ composition (Fairchild and Baker, 2012; Meyer et al., 2014; Noronha et al., 2015). Trees have been demonstrated to have long-term effects on cave drip-water solute concentrations. Treble et al. (2015, submitted) demonstrate long-term trends in drip water calcium and trace element concentration, which they attribute to increasing solute concentration due to forest regrowth and increased post-fire tree water use. Baldini et al (2005) infer an effect on speleothem $\delta^{18}O$ due to secondary forest regrowth after mining and Wong and Banner (2010) found clearing surface vegetation changed drip water Mg/Ca and Sr/Ca. The findings and suggested protocol in this study will inform the selection of speleothem specimens for further research into the impact of tree water use on speleothem paleoclimate proxies.

5. Conclusions

We demonstrated a novel method of analysing recurring patterns in cave water drip rate using the synchrosqueezing transform (SST). Our analysis revealed daily and sub-daily oscillations with variable temporal and spatial signatures. We tested competing hypotheses for causes of daily oscillations using drip rate, barometric and temperature data. The only hypothesis which all the data and hydrodrologic theory were consistent, was that daily fluctuations in drip rate were driven by tree water use. We proposed that the complexity of flow pathways in the karst system accounted for the spatial and temporal variation in the daily fluctuations of drip rate. This was explored in detail using conceptual models. The results have wider implications for karst research including providing a new protocol for inferring karst architecture and informing selection of speleothem specimens for tree water use paleoclimate studies.

Author contribution

KC, MOC, GCR and AB w rote the manuscript, discussed the results and implications and commented on the manuscript at all stages. KC, AB and ON collected data. GCR performed the SST analysis and generated the SST figures. GCR and ON created the location map. KC generated other graphs and conceptual figures.

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