High-resolution monitoring of Yok Balum Cave, Belize: an investigation of seasonal ventilation regimes and the atmospheric and drip flow response to a local earthquake

Harriet E. Ridley[1*], James U.L. Baldini[1], Keith M. Prufer[2], Izabela W. Walczak[1], Sebastian F.M. Breitenbach[3].

[1]Department of Earth Sciences, University of Durham, Durham, DH1 3LE, UK.

[2]Department of Anthropology, University of New Mexico, Albuquerque, NM 87106, USA.

[3]Department of Earth Science, Eidgenössische Technische Hochschule (ETH), CH-8092 Zurich, Switzerland.

* Corresponding author . Telephone number +44 (0) 78529 26305

Abstract

The nature of cave ventilation is of interest to cavers, speleologists and paleoclimatologists working with stalagmites. Because cave ventilation systematics may change over the growth span of a stalagmite, understanding what factors affect them is critical for determining events that may have potentially affected climate proxies within the stalagmite. Similarly, understanding how the hydrologies of the drips feeding a stalagmite evolve through time is key to building robust records of paleoclimate, particularly because stalagmite records have become critical archives of climate change information of the last 500,000 years. Here we present data from an extensive, on-going monitoring effort at Yok Balum Cave, Belize, initiated in 2011, that characterises high-resolution ventilation dynamics at this site. Clear seasonal ventilation regimes exist, driven by thermally induced inside-outside air density differences. The winter regime is dominated by air inflow from the cave, decreased drawdown from the epikarst into the cave and a limited diurnal signal. Conversely, summer ventilation is dominated by air outflow from the cave, greater CO_2 drawdown and drip water degassing and a strong diurnal signal. Active monitoring during a large (M7.4) earthquake in November 2012 provides a unique opportunity to assess the response of cave atmosphere and hydrology to substantial seismic activity. Cave atmosphere and hydrology is found to be highly resilient to seismic activity, with no observable disturbance occurring around the earthquake, despite there being considerable evidence of physical disruption in the cave. Monitoring included different drip hydrologies, and the earthquake affected none of the monitored drip types. This suggests that stalagmite-derived paleoclimate records are not affected by seismic activity, except in extreme cases where the stalagmite or conjugate stalactite are damaged or reoriented.

1. Introduction

Characterising caves in terms of their unique ventilation processes is important as it has a first-order control on atmosphere composition, can potentially lead to seasonal bias in speleothem growth and consequently has significant implications when interpreting paleoclimate proxy signals from speleothems (Kowalczk and Froelich, 2010; Baldini, 2010; Sanchez-Canete et al., 2013). Real-time cave atmosphere data is also useful when characterising cave ecosystems (Oh and Kim, 2011; De Freitas et al., 1982) and assessing the suitability of caves for industry and tourism (De Freitas et al., 1982; Smithson, 1991; Dueñas et al., 1999; Dueñas et al., 2011; Virk et al., 1997). Estimation of cave ventilation is possible directly, via anemometers, indirectly via measurement of radon gas (^{222}Rn) levels (Kowalczk and Froelich, 2010; Hakl et al., 1997; Faimon et al., 2006; Oh and Kim, 2011) and other tracer gases (De Freitas et al., 1982) or by studies of air density contrasts and thermal patterns within the cave (Faimon et al., 2012; Smithson, 1991; Sanchez-Canete et al., 2013). The importance of understanding unique cave ventilation mechanisms have been well highlighted in recent studies (Kowalczk and Froelich, 2010; Cowan et al., 2013; Mattey et al., 2010; Baker et al., 2014) as the distinct nature of ventilation in individual caves can negate general assumptions regarding the seasonality of carbonate precipitation. For example, Mattey et al. (2010) identified unusual seasonal ventilation regimes in New St Michaels Cave, Gibraltar where the summer season was typified by low cave air pCO_2. This proved important when linking seasonal regimes to calcite fabric, paired annual laminae, stable isotope and trace element variability and highlighted the importance of understanding unique cave environments. Studies like this become increasingly important as speleothem-based paleoclimate research continues to develop higher resolution records that are resolved to a seasonal or sub-seasonal level.

Caves in seismically active regions can display considerable evidence of past seismic activity, such as: broken speleothems, speleothem growth anomalies and deformation, displacement and rock fall events (Becker et al., 2006; Gilli, 1999; Gilli and Serface, 1999; Gilli and Delange, 2001). A limited number of studies have attempted to quantify the effect seismic activity may have on karst-cave atmosphere (Sebela et al., 2010; Virk et al., 1997), particularly with regards to CO_2 variability. Such information is pertinent when interpreting paleoclimate proxy evidence from speleothems in caves which may have been subject to substantial tectonic activity as seismic activity affects cave ^{222}Rn and CO_2 levels through pro-/co-seismic degassing and increased influx to the cave (Sebela et al., 2010; Wu et al., 2003; Virk et al., 1997; Menichetti, 2013). Crushing of material during seismic activity increases the rock permeability for ^{222}Rn gas and CO_2 leading to higher within cave concentrations. Cave air pCO_2 levels exert a strong control on carbonate precipitation rates (Baldini, 2010; Kowalczk et al., 2008; Palmer, 2007; Banner et al., 2007) and therefore substantial crustal degassing has the potential to stagnate speleothem growth, particularly in deep, poorly ventilated passages. This can complicate paleoclimate proxy interpretations from speleothems for weeks to years depending on site-specific ventilation regimes. ^{222}Rn is a radioactive yet inert tracer gas frequently used to assess cave ventilation (Kowalczk and Froelich, 2010; Oh and Kim, 2011) but can also pose a health risk in confined, poorly ventilated caves (Field, 2007; Virk et al., 1997) and therefore its relation to seismic activity warrants assessment, particularly caves used for commercial or tourism purposes. It is also largely unknown how seismic activity may affect karst hydrology and stalagmite drip regimes. Changes in the hydrological regime feeding a stalagmite can affect speleothem growth rates and the transmission of geochemical signals from overlying climate to the speleothem carbonate; consequently, changes in hydrology can have important implications when interpreting paleoclimate proxy data in speleothems.

This study presents high-resolution cave monitoring data from Yok Balum Cave, Belize. These data provide detailed information regarding seasonal cave ventilation mechanisms by understanding cave pCO_2 and air density relationships and via examination of thermal gradients as evidence of internal-external air exchange. An understanding of the subtle seasonally variable fluxes of cave air CO_2 allows improved interpretations from not only Yok Balum, but other tropical sites as well. Additionally, active monitoring during a large (M7.4) earthquake in November 2012 provides a unique opportunity to assess the response of cave atmosphere and hydrology to substantial seismic activity.

2. Study Site

Yok Balum Cave (Mopan Maya for ‘Jaguar Paw Cave’) is located in the Toledo District of southern Belize, approximately 3km south of the modern Mopan Maya village of Santa Cruz

(16^{o} 12’ 30” N, 89^{o} 4 24” W; 366 m above sea level) (Fig. 1a). The cave is developed within the tectonically uplifted Cretaceous Campur Limestone formation that originates from massive limestone deposition around the granite intrusions composing the Maya Mountains to the north (Miller, 1996; Kennett et al., 2012). The cave is one of several which occur in a SW-to-NE trending limestone karst ridge (Fig. 1b) whose formation is likely associated with the vertical flow of chemically aggressive allogenic water originating on the highlands of the Maya Mountains (Miller, 1996), although no stream exits within the cave today. Yok Balum extends as a main trunk passage approximately 540m from a small opening in the west (main entrance) to a larger, more elevated opening to the south (second entrance) (Fig. 1c). The second entrance resulted from cave collapse probably associated with tectonic activity. U-series dating of the base of a stalagmite growing on a breakdown block associated with the creation of the second entrance dates the collapse at a minimum of 44,000 ± 3300 years BP. There is also considerable evidence of seismic activity within the cave including large faulted flowstones and displaced speleothems. U-series dating of carbonate precipitated within a faulted flowstone provided a date of 26,400 ± 170 years BP.

The western coast of Central America displays relatively high seismic hazard potential due to the subduction of the Cocos Plate beneath the North American and Caribbean Plates (Fig. 1a). A divergent boundary exists between the North American and Caribbean Plates approximately 100km south of the southern Belize border. The dominant source of seismic activity felt in southern Belize, however will result from intermediate-depth earthquakes occurring within the subducted Cocos Plate.

3. Monitoring Instrumentation

Tropical environments provide a challenging environment for electronic monitoring instrumentation, especially for long term monitoring studies in remote areas. In this study the threat of malfunction due to high humidity and water was minimised by keeping non-waterproof equipment in airtight boxes and sealed plastic bags with a silica desiccant where applicable. Above cave soil temperature was recorded hourly using a Tinytag temperature logger buried at a 0.4m depth. Cave air CO_2 was monitored every three hours between April 2011 and January 2013 (with a four-month break from June 2012 to October 2012 due to equipment failure) using a Vaisala CARBOCAP Carbon Dioxide GMP343 Probe (± 3 ppmv + 1% of reading) linked to a Vaisala MI70 Indicator and powered by two Duracell MN918 Lantern batteries. A Radon Scout Plus, powered by two D-cell batteries and a four × D-cell external battery pack was set up next to the within-cave CO_2 logger to detect radon fluctuations every three hours for the same time interval. The Radon Scout, being extremely sensitive to moisture, was kept in a watertight box. This resulted in a muted radon measurement as fewer α particles reached the alpha counter. For qualitative assessment of ^{222}Rn fluctuations this was not considered an issue. However, ^{222}Rn values peaked during data download when the logger was removed from the box. To account for this, ten days of data were removed after data download to allow ^{222}Rn values to return to normal levels. Combined Barotroll pressure and temperature logger were installed both inside and above the length of the cave to measure hourly barometric pressure and temperature (precision ± 0.1% and ± 0.1^{o}C). Tinytag temperature loggers were placed in transect along the cave to measure hourly temperature. Stalagmate automated drip loggers recorded hourly drip rates feeding three stalagmites of potential paleoclimate interest. Data were downloaded and the equipment maintained every four months. A summary of all monitoring equipment is shown in Table 1. The location of all equipment and monitored stalagmites is shown in Figure 1c.

4. Cave Ventilation

Cave ventilation (air exchange with the outside atmosphere) has a first order control on cave atmosphere composition and is dependent on a number of factors, including fluctuations in temperature and pressure, cave geometry and susceptibility to external winds (Cowan et al., 2013; Bourges et al., 2001; Spötl et al., 2005; Baldini et al., 2006; Denis et al., 2005; Kowalczk and Froelich, 2010). Pflitsch and Piasecki (2003) classify cave passages in terms of air movement as being dynamic, transitional or static. However, the static state is very rarely observed, aside from in deep passages (Pflitsch and Piaseki, 2003; Przylibski and Ciezkowski, 1999). Convective air circulation, driven by internal versus external air density differences, is a dominant ventilation mechanism in caves with more than one entrance at different elevations (Gregoric et al., 2013; Kowalczk and Froelich, 2010; Wigley, 1967; Badino, 2010). In tropical caves, where cave air temperatures do not vary significantly on seasonal timescales, air density difference will be predominantly controlled by surface temperature and barometric pressure variations (Fairchild et al., 2006). Air density responds primarily to temperature (Faimon et al., 2012; Gregoric et al., 2013; Gregoric et al., 2011) and to a lesser extent pressure and humidity as expressed in equation (1) below (after Kowalczk (2009)):

$$\rho_{air} = \frac{P}{R_d \bullet T_v} \quad (1)$$

Where R_d is the universal gas constant and P is barometric pressure. T_v is virtual temperature, calculated via equation (2), in which T_d is dew point.

$$T_v = (T + 273.15)/(1 - (0.379 \bullet \frac{6.11 \bullet 10^{\frac{7.5 \bullet T_d}{237.7 + T_d}}}{P})) \qquad (2)$$

If cave pCO_2 is more than an order of magnitude greater than that of the free atmosphere, T_v is affected. This can lead to errors of up to 9°C when calculating cave T_v (Sanchez-Canete et al., 2013) and subsequent error in air density calculations. At Yok Balum maximum recorded pCO_2 is 770ppm and the summertime mean is ~500ppm. This is less than an order of magnitude grater than the free atmosphere and therefore this CO_2 exerts a negligible effect on cave air density.

Typically, during the winter months, external air temperature will be cooler than that of the cave and a positive air density difference will dominate i.e. internal air will be denser, although a diurnal signal will also exist. Alternatively, during the summer, typically warmer external temperatures will result in largely negative air density difference. Local weather may result in short lived reversals in cave-atmosphere air density differences. The particular ventilation influence of seasonal air density differences between cave and free atmosphere is governed by the cave geometry (e.g passage orientation and size), the distance from cave entrances and total cave volume (Batiot-Guilhe et al., 2007; Cowan et al., 2013).

5. Results and Discussion of Ventilation

The diurnal and seasonal patterns of airflow at Yok Balum are a direct response to a thermally induced disequilibrium in air density between the cave and outside air, similar to other caves (De Freitas et al., 1982; Kowalczk and Froelich, 2010). Within cave temperature is nearly constant at 22.4°C (± 0.5°C) year round, although a low amplitude diurnal signal is present. Within cave temperature is equivalent to the average yearly external temperature (Fig. 2) and is likely a result of moderation of outside temperatures by the epikarst. External air temperature can affect cave air pCO_2 by both inducing density driven ventilation associated with inside-outside air density differences (De Freitas et al., 1982) (Fig. 3a) and by promoting higher soil pCO_2 stimulating biological activity in the soil zone (Baldini et al., 2008; Bond-Lamberty and Thomson, 2010; Hess and White, 1993; Murthy et al., 2003; Sherwin and Baldini, 2011).

The simple structure of Yok Balum Cave, with two entrances at either end of a single main trunk passage results in a well-ventilated dynamic cave system, evidenced by the low annual mean CO_2 values (461ppm) (Fig. 3b). However, CO_2 displays clear seasonal trends in both mean concentration and variability. Summer (April - October) is characterised by higher mean pCO_2 (~500ppm) and high temporal variability (standard deviation of 72.5ppmv) whereas winter (November – March) has lower pCO_2 (~420ppm) and displays lower temporal variability (standard deviation 24.3ppmv). Here, we use the theory of entropy of curves to highlight the differences between summer and winter ventilation. Entropy (E) is a measure of variance within a dataset. It is described as the mean cumulative sum of absolute first differences of a time or spatial derivative (Denis et al., 2005; Denis and Crémoux, 2002), or specifically, in this case, the average change in pCO_2 values at 3-hourly intervals. Therefore, higher entropy values indicate a greater change in subsequent pCO_2 measurements and therefore an indication of variance within subsets of the dataset. CO_2 displays entropy of approximately 430 during the summer and 150 during the winter (Fig. 3b), indicating that the variance is nearly three times greater during the summer months. These trends in pCO_2 mean values and variance are controlled by seasonal CO_2 flux into the cave and ventilation, most likely controlled by external temperatures and infiltrating rainfall. The following sections will use high resolution monitoring data to describe the seasonal ventilation regimes occurring in

Yok Balum. It should be noted that the summer and winter seasons are not synonymous with the wet and dry seasons. Summer is considered to be months April – October and winter November – March. During the summer months external temperatures are greater than within cave temperature and vice versa for winter.

5.1 Summer regime

Air density differences between the cave and the free atmosphere, controlled predominantly by external temperature, drives the summer season diurnal ventilation regime. Outside air temperatures (T_{atmos}) are higher on average than that inside the cave (T_{cave}) producing an almost constant negative air density difference (Fig. 3b). In a typical one-entrance cave system this could cause severe season-long stagnation, and subsequently very high pCO_2, as the cooler denser cave air becomes trapped at the lowest point of elevation in the cave (Cowan et al., 2013; Spötl et al., 2005). At Yok Balum complete stagnation does not occur because the dual-entrance system provides a means of outflow for density driven flow from the more elevated southern (second) entrance to the lower western (main) entrance.

Outside air temperature begins to rise around 06:00 and reaches a maximum in the early afternoon. At this point cave-atmosphere air density difference is greatest and air outflow is at a maximum (Fig. 4a). As the air density difference increases during this period, outflow occurs at both entrances; CO_2 concentrations will simultaneously increase as high pCO_2 air is drawn out of the overlying epikarst and soil zones (Fig. 5a). During the day biological activity in the soil will also be at a diurnal maximum, producing higher soil pCO_2. By late afternoon the cave-atmosphere air density difference begins to decrease and the volume of outflowing air decreases, reducing CO_2 drawdown from the epikarst. Outflow at the lower, main entrance weakens or ceases completely. As the cave-atmosphere air density difference reaches a minimum, around 01:00, cave air pCO_2 reaches minimal values. This is most likely due to minimised CO_2 drawdown and inflow of low pCO_2 atmospheric air from the second entrance (if T_{cave} reaches or surpasses T_{atmos}) flushing through the cave from the second entrance to the lower main entrance (Fig. 5b). If the outside air density remains considerably higher than that of the cave then pCO_2 may remain elevated, but will decrease somewhat due to decreased CO_2 drawdown from the epikarst, lower soil activity and some air movement driven by the venturi effect (Fig. 5b). Areas closest to the entrances can be expected to undergo the most ventilation, particularly at the second entrance, which is larger. Increased water through flow during the wet season is undoubtedly an additional driver of higher average summer pCO_2 as it increases dissolved CO_2 transport to the cave; increasing degassing and consequently producing higher cave pCO_2.

5.2 Winter regime

During the winter season outside air temperatures are generally cooler than those inside the cave, producing a positive air density difference and a ventilation regime dominated by inflow. Ventilation is therefore more continuous than during the summer.

Maximum air density difference occurs at night (around 03:00) when T_{atmos} is at a minimum (Fig. 4b). Cooler outside air flushes into the cave, predominantly through the more elevated second entrance but also at the main entrance. Cave air pCO_2 will therefore approximate that of the external atmosphere. Outside air temperatures begin to rise at ~06:00 and reach a maximum at ~14:00, as in the summer season. However, as the outside temperature increases it approaches that of the cave air, reducing the air density difference to near zero (or to negative values if T_{cave} surpasses T_{atmos}). This reduces air inflow to the cave and if a negative air density difference occurs then outflow may occur during this time (Fig. 5c). This variation of air density difference over a threshold value results in a daily ventilation regime whereby the cave inhales during the day and exhales at night. The inhalation during the day draws low pCO_2 air into the cave, flushing the cave and keeping pCO_2 values similar to atmospheric levels (Fig. 5d). Any weak exhalation at night continues effective air turnover and maintains low pCO_2 concentrations. Again, it is the areas close to the entrances that will undergo the most rigorous air turnover.

A combination of inflow dominated ventilation and less CO_2 from drip water degassing keeps winter cave air pCO_2 at near atmospheric levels. A less distinct diurnal regime is observed in CO_2 and air density difference variability. During the summer, increased water through flow, strong air outflow and large CO_2 drawdown, increase average pCO_2 and daily variability.

5.3 Temperature observations

Hourly temperature data is used as an indicator of air movement in order to determine seasonal modes of ventilation and to understand exactly how air moves through the cave. We use Tinytag (TT) temperature loggers at different sites to assess thermal variability. TT3, a temperature logger located ~50m from the second entrance and shows more variance than TTI, located ~50m from the main entrance and TT2, located in the midsection of the cave ~100m from the main entrance and ~140m from the second entrance (Fig. 6e). TT2 displays the least variance and most moderated temperature (Fig. 6b). Entropy (see section 5) can be illustrated graphically through time as a cumulative curve, the slope of which indicates variability within the dataset. Entropy curves are calculated for each temperature dataset from the three loggers (Fig. 6a), thus facilitating comparison of their variance with time. TT3 displays the greatest variability over the whole time series, suggesting that this region of the cave is most strongly coupled with external air temperatures via air exchange. During the summer months TT3 increases by 0.4^{o}C, as air in this region responds to warmer external temperatures. TT2 is stable through the same period and TT1 displays an increase similar to that of TT3, but of only 0.3^{o}C. This thermal variability decreasing with distance from a cave entrance is in accordance with a traditional cave temperature models (Wigley, 1967) and previous thermal profile studies of caves (Sanchez-Canete et al., 2013; De Freitas et al., 1982).

During the winter, TT3 displays greater variance than the other two loggers, again indicating that this section of the cave is more closely coupled to the outside air during winter than summer (Fig. 6). This is consistent with the ventilation mechanism described in the previous section where inflow of cooler atmospheric air dominates the winter ventilation regime, simultaneously lowering long term cave air temperature in this area of the cave and mimicking the diurnal external temperature cycle in the cave. TT2 remains the least variable, due to its location in the midsection of the cave. TT1 decreases, indicating that cooler atmospheric air flows in, but that ventilation at the main entrance is less rigorous than at the second entrance. Furthermore, short-lived decreases in temperature recorded by TT1 (and to a lesser extent in TT2) are in anti-phase with TT3. This could be an indication of air entering at the main entrance and flushing through the cave, forcing warmer air from the less dynamic mid-section of the cave through to the second entrance, where it is recorded as a small increase in temperature at TT3. This thermal pulse process would also operate in reverse, with cooler air entering at the second entrance and forcing air through the cave to the main entrance.

Data collected through high-resolution temperature experiments, conducted over two 14-hour intervals in June and late October 2012, is used to characterise ventilation on short time scales. A transect of three temperature loggers placed in the cave recorded temperature every 10 seconds to capture very short-term thermal fluctuations overnight, from 18:00 to 08:00. Failure of one of the loggers during the June experiment limits the number of loggers to two, but does not affect data interpretation for this project. During the June experiment (Fig 7) the two temperature loggers, TT5 and TT7, record essentially static temperature, supporting the idea that air density driven outflow dominates during this season. During the logging interval, the cave – atmosphere air density difference does not drop below zero and so inflow does not occur. During the late October experiment thermal variance at all three sites is much greater (Fig. 8). TT5 and TT8 record more thermal variability than TT7 suggesting that air inflow close to the main entrance is less persistent. TT5 and TT7 both record cooler temperatures than TT8, presumably due to their proximity to a cave entrance. TT8 and TT5 track each other, roughly in accordance with cave – atmosphere air density difference and are weakly in anti-phase with TT7. This is similar to what we see in the longer-term record (Fig. 6) where cooler external air enters the main entrance and forces air along the main passage, which is recorded as a pulse of warmer deep cave air at the second entrance. It would appear from this high resolution time series that this occurs in both directions. The limited temporal timeframe of these two experiments hinders making firm conclusions about the diurnal movement of air at Yok Balum Cave; although it is encouraging that the results acquired are in agreement with the longer, hourly-resolution time series.

6. November 7th earthquake

On November 7th 2012 at 16:35 (UTC) (10:35 local time) a 7.4 magnitude earthquake struck off the coast of Guatemala (Fig. 1a). The epicentre was estimated to be at a depth of 24.0km and occurred as a result of thrust faulting on or near the subduction zone of the Cocos plate and the overlying Caribbean and North American plates (United States Geological Survey). Tremors were felt in parts of Belize and villagers from Santa Cruz village, 5km from Yok Balum Cave, reported feeling the tremors. According to United States Geological Survey estimates this shock would result in a seismic hazard, measured in peak ground acceleration at the cave site of 1.6 – 2.4 m/sec^2. A field crew returned to the cave in January 2013 to find large fallen blocks at the cave main entrance and numerous displaced and freshly broken stalagmites and stalactites within the cave. Reasonable evidence therefore suggests that the cave was subject to seismic activity on or around November 7th 2012. There are only a handful of published studies reporting earthquake damage to caves (Gilli, 1999; Gilli and Delange, 2001; Renault, 1970) and so direct monitoring observations of the effect of seismic activity are pertinent to the science of speleology in general and have implications for reconstructing climate from cave deposits. It will be particularly useful to determine how environmental variables that affect speleothem growth and carbonate deposition, such as drip hydrology and cave ventilation, may be affected be seismic activity. For example, if seismic activity causes considerable water re-routing, we might expect subsequent changes in speleothem growth for days to months, which can confuse a climate record. Similarly, atypical speleothem growth and/or carbonate isotopes could be produced from significant seismically induced changes in cave pCO_2.

6.1 Cave atmosphere response

No clear change occurred in cave air pCO_2 or ^{222}Rn during or for the week following the earthquake (Fig. 9). Two ^{222}Rn peaks occur around the earthquake (Fig. 9a) and although fracture distillation induced by seismic activity may cause such peaks in cave atmosphere ^{222}Rn, these peaks are not significant, in terms of magnitude or duration, when the entire ^{222}Rn dataset is considered (Fig. 3c). A sharp increase in both ^{222}Rn and CO_2 occurs on the 20th of December (Fig. 3 b and c) but given the short half-life of radon (3.8 days) it is extremely unlikely that this is a delayed signal of the November 7th event. This increase could be explained instead by a coincident decrease in air density difference, associated with a moderate rainfall event, temporarily reducing air inflow to the cave and resulting in a short-lived increase in CO_2 and ^{222}Rn.

A significant change in cave atmosphere may not be observed due to the seasonal timing of the earthquake. As previously observed, cave ventilation during the winter is dominated by inflow which acts to keep pCO_2 levels low. Seismic activity of a similar magnitude occurring during the summer season when outflow is dominant, may lead to a discernible increase in cave air ^{222}Rn and CO_2. Potentially a clearer influence could be observed in less well-ventilated cave. Prior to the collapse and opening of the second entrance at Yok Balum, ventilation would have been less effective and cave air pCO_2 and ^{222}Rn higher. Considerable seismic activity at this time may have created uncharacteristically high pCO_2 and ^{222}Rn values as a result of limited ventilation and should be a consideration when studying speleothems from Yok Balum deposited prior to the collapse of the second entrance, when ventilation would have been restricted. Similarly, in caves where ventilation is less efficient it may be pertinent to assess the impact of seismic activity on cave atmospheric composition; particularly when speleothem from the cave are being considered for palaeoclimate reconstruction.

6.2 Hydrological response

Three drip loggers were deployed during the November 2012 earthquake: ‘YOK-SK’, ‘YOK-SD’ and ‘YOK-LD’. Of these drips, two (YOK-LD and YOK-SD) were ‘static’ in nature (Smart and Friederich, 1987; Baker et al., 1997), because they displayed low drip rates and low variability (Fig. 10a), indicative of a diffuse flow dominated hydrology. YOK-SK is classified as a ‘seasonal’ drip (Baker et al., 1997) because it responds to local rainfall events and seasonal climate variability (Fig. 10a), suggesting that a fracture flow pathway is activated once a threshold rainfall rate or epikarst saturation is achieved. YOK-SK responds to local rainfall with a lag time of < 6 days, but displays greater variability during the wet season when the epikarst and soil are closer to saturation.

None of these three loggers recorded any clear drip response to the seismic activity on November 7th (Fig. 10b). YOK-LD and YOK-SD, the two static drips, show no response, suggesting that diffuse flow regimes are not affect by seismic activity of substantial magnitude. Similarly, YOK-SK, which at the time of the earthquake was displaying a peak in drip rate in response to rainfall events in the preceding days, shows no response outside what would be expected from the longer time series. These data suggest that preferential flow routes are not necessarily altered by seismic activity of this nature. This observation is of significant value for speleothem based paleoclimate studies as it suggests that seismic activity does not affect hydrological flow pathways and hence alter carbonate geochemistry.

7. Conclusions

Yok Balum is an extremely well ventilated cave system that displays distinct seasonal ventilation regimes, consistent with changes in air density differences between the cave and outside atmosphere. The winter regime is dominated by air inflow, low pCO_2 and lower epikarstic drawdown and CO_2 flux into the cave. Conversely, air outflow, high epikarstic CO2 drawdown, increased drip water degassing and a strong diurnal signal dominates the summer regime. Based on air temperature changes the degree of air exchange increases from the centre of the cave to the entrances and the second entrance experiences greater air exchange than the main entrance, presumably due to its size. By looking at thermal fluctuations of cave air on a ten-second timescale, direction of air movement is identified during summer and winter nights respectively and both entrances are found to display active dual-directional connections to the free atmosphere. The three datasets presented here: long term three-hourly CO_2, hourly temperature and the two high resolution studies all help to build a comprehensive understanding of ventilation at Yok Balum Cave. This will be pertinent as on-going paleoclimate research at this cave. Continued monitoring will help to discern inter-annual fluctuations and identify long term links between cave pCO_2 and local climate.

Cave pCO_2 and ^{222}Rn did not show any discernable response to the November 7th earthquake. Likewise, none of the three drips displayed any discernible hydrological response to the earthquake, suggesting that seismic activity, even of considerable magnitude, has minimal hydrological repercussions at Yok Balum and is insufficient to result in perturbations in speleothem petrographical or geochemical records. It is noteworthy that the three loggers represent two end members of ‘standard’ drip types, from highly diffuse, slow and static drip rates (YOK-LD and YOK-SD), to highly variable and relatively fast drip rates (YOK-SK). This suggests that intermediate drip types would probably be similarly unaffected by seismic activity of a similar magnitude. The primary effect seismic activity may have on a speleothem record is by altering the growth axis position or orientation, rather than a direct disruption of the overlying hydrology. This could appear as a hiatus or sudden shift in isotope values if the growth axis movement was not accounted for during milling.

This study provides real time data on the effect of seismic activity on cave hydrology and atmosphere. In seismically active regions, determining this site-specific response is a desirable outcome of cave monitoring studies designed to aid speleothem paleoclimate proxy interpretation. These data provide encouraging evidence that seismic activity of this level does not have implications for speleothem paleoclimate proxy interpretations from caves with similar ventilation dynamics as Yok Balum.

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Table captions

Table 1. Summary of equipment used in this study, including equipment accuracy, sampling interval and additional comments.

Figure Captions

Figure 1.a) Tectonic setting of Belize region, including tectonics boundaries (adapted from the United States Geological Survey). Estimated epicentre (yellow dot) and epicentral region (blue rectangle) of 7th November 2012 earthquake. Red box identifies Belize, Yok Balum Cave (red dot) and the area covered in **b)** a geological schematic of Belize (adapted from Miller 1996) and the location of Yok Balum Cave (red dot). **c)** Map of Yok Balum Cave with equipment locations and drip sites monitored in this study.

Figure 2. 26.5-month time series of hourly Cave temperature (T_{cave}), soil temperature (T_{soil}) and outside air temperature (T_{atmos}).

Figure 3. Seasonal regimes and dominant characteristics of **a)** hourly inside versus outside cave air density difference **b)** Three hourly cave pCO_2 and summer (April through October) and winter (December through March) pCO_2 Entropy values (E) **c)** Three hourly ^{222}Rn and **d)**

daily rainfall at Santa Cruz. November 7th earthquake indicated by the red dashed line and surrounding two-week period by the grey shaded section.

Figure 4. Hourly cave air density difference and cave pCO_2 over **a)** 7th – 16th December 2011 (winter) and **b)** 20th – 29th May 2011 (summer).

Figure 5. Yok Balum long profile with schematic of theorised primary air flows and CO_2 flux during the summer at 12:00 (panel **a**) and 00:00 (panel **b**) and schematic of theorised primary air flows and CO_2 flux during the winter at 12:00 (panel **c**) and 00:00 (panel **d**).

Figure 6. 14-month time series of **a)** variability of three time series loggers expressed as entropy (cumulative sum of the absolute first differences) against time L(t) **b)** hourly temperature from three temperature loggers in the cave **c)** hourly inside and outside cave temperature **d)** three hourly cave air pCO_2. **e)** Location of temperature loggers within the cave.

Figure 7. High-resolution summer experiment. 14-hour time series of **a)** hourly cave temperature, external air temperature and internal - external air density difference and **b)** 10 second temperature measurements of TT5 and TT7. **c)** Location of TT5 and TT7 in the cave.

Figure 8. High-resolution winter experiment. 14-hour time series of **a)** hourly cave temperature, external air temperature and internal - external air density difference and **b)** 10

second temperature measurements of TT8, TT5 and TT7 **c)** location of TT8, TT5 and TT7 in the cave.

Figure 9. Response of **a)** cave air Rn^{222} **b)** CO_2 **c)** inside vs outside cave air density difference and **d)** daily rainfall at Santa Cruz during a 15 day time period surrounding the November 7th earthquake (red dashed line).

Figure 10. a) 22-month time series if drip regimes of YOK-LD, YOK-SK and YOK-SD against Santa Cruz daily rainfall. November 7th earthquake indicated by red dashed line. Black arrows indicate visits to the cave. **b)** YOK-LD and YOK-SK drip rates and Santa Cruz daily rainfall from 1st through 15th November with earthquake indicated by red dashed line.