ZARA ENVIRONMENTAL LLC
1707 West FM 1626
Manchaca, Texas 78652
512-291-4555
www.zaraenvironmental.com

ANNUAL SUMMARY OF CARBON DIOXIDE MONITORING IN THREE BALCONES CANYONLANDS CONSERVATION PLAN CAVES IN TRAVIS COUNTY, TEXAS



Retrieval of a logging carbon dioxide meter in Grassy Cove Cave

Prepared for
Austin Water
Wildlands Conservation Division
3621 Ranch Road 620
Bee Cave, TX 78738

31 December 2018

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Brian Cowan

31 December 2018
Brian D. Cowan, Texas Professional Geoscientist No. 11180
Zara Environmental LLC Geoscience Firm Registration No. 50365

Abstract

Cave-air carbon dioxide concentration was measured in three Balcones Canyonlands Preserve caves, Whirlpool Cave, Ireland's Cave, and Grassy Cove Cave, using Vaisala logging carbon dioxide meters. Measurements began in October 2017 and this comprehensive report covers work occurring between October 2017 and October 2018. Cave carbon dioxide fluctuated both seasonally and diurnally in all three caves and within similar timeframes. Maximum and minimum carbon dioxide concentrations and the timing of carbon dioxide fluctuations differed between all three caves. Seasonal carbon dioxide concentrations were elevated May through October and were lowest December through March. Significant diurnal carbon dioxide fluctuations were measured in all three caves, and in one cave reached greater than 20,000 ppm in a 12-hour period. Surface weather conditions, especially storms and pressure fronts, significantly altered diurnal carbon dioxide fluctuations for periods lasting from hours to days. The results of this monitoring study are useful in decision making regarding cave visitation, biological monitoring, and management of the caves for listed species and species of concern.

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Introduction

Project Need

Many caves in central Texas are known to have high concentrations of carbon dioxide (CO_2) which can cause discomfort to humans and may impact the cave ecosystem in both positive and negative ways. Several Balcones Canyonlands Preserve (BCP) caves are open to the public for educational tours; therefore, it is important to better understand how cave-air CO_2 concentrations fluctuate in these caves so that public tours can be scheduled to maximize visitor comfort and safety. Most BCP caves also contain federally listed endangered species and species of concern that are protected under the Balcones Canyonlands Conservateion Plan (BCCP) which requires ongoing research and management of BCCP caves for the protection of the covered species. To better understand how caves ventilate and how cave-air CO_2 fluctuates, continuous monitoring of cave-air CO_2 concentration and cave airflow speed and direction was initiated in three BCCP permit caves in October 2017: Whirlpool Cave, Ireland's Cave, and Grassy Cove Cave. This report sumarizes the findings of the first year of data collection and offers suggestions for future research that could help improve management of all BCP caves, both for the protection of BCCP listed species and for the comfort and safety of educational tour groups.

Cave Ventilation

Caves within the central Texas region are known to ventilate (Cowan et al. 2013), both seasonally and daily, often with significant volumes of cave air expelled and significant volumes of surface air flowing in. The daily ventilation is caused by diurnal fluctuations of barometric pressure, also known as the "barometric tide". Caves in central Texas often ventilate a greater amount of air when storms or pressure fronts move overhead causing a significant change in barometric pressure (Cowan 2010). The concentration of CO_2 in cave air is effected heavily by cave ventilation. Cave ventilation and CO_2 fluctuation vary from cave to cave in central Texas likely due to factors such as cave volume, site geology, anthropogenic modifications, and the timing and rate of CO_2 input (Breeker et al 2012, Cowan 2010).

Cave ventilation is an important control on cave-air CO_2 concentrations, both seasonally and on shorter timescales, and is dependent on multiple factors including fluctuation of the outside air temperature and barometric pressure, cave geometry, and prevailing winds (Villar 1985; Fernandez et al, 1986; Hoyos et al. 1998; Buecher 1999; Bourges et al. 2001; Spotl et al. 2005; Baldini et al. 2006; Denis et al. 2005; Bourges et al. 2006; Baldini et al. 2008; Kowalczk and Froelich 2010). At mid latitudes like central Texas, density differences between cave air and atmospheric air caused by seasonal temperature variability exert a first order control on the seasonal ventilation of caves (James and Banner 2008). In many caves, seasonal air temperature varies by only a few degrees (Moore & Sullivan 1997); thus, cave ventilation is primarily controlled by surface air temperature and barometric pressure variability (Fairchild et al. 2006). During warmer months, cave air temperatures remain below atmospheric temperature, causing the cooler, denser cave air to stagnate and allowing CO_2 to build up. The cave can be thought of as a semi-closed system during this time as ventilation is less efficient. As long as CO_2 sources are

present (i.e. degassing of drip water or advection through fractures), the concentration of CO_2 in the cave air will continue to rise until CO_2 inputs reach equilibrium with CO_2 ventilation. When cave air temperatures are warmer than outside temperatures, the cave air becomes unstable with respect to the outside air and ventilation becomes more efficient as the denser outside air flows into the cave, mixing with and displacing the CO_2-rich cave air and causing CO_2 levels within the cave to decrease. This process only applies to caves whose primary volume is lower in elevation than its entrance.

The intensity of cave ventilation is governed by cave geometry (i.e. vertical vs. horizontal, large passages vs. numerous constrictions), density differences between the cave air and outside air, distance from the cave entrance, connectivity with the surface via pores and fracture networks (primarily governed by the stratigraphic occurrence of the cave), and cave volume (Batiot-Guilhe et al. 2007). In general, stronger ventilation occurs at sites near the cave entrance and at sites that are not separated from the entrance by constrictions (Bourges et al. 2006). Where ventilation is limited by constrictions or distance from the entrance, CO_2 levels may remain relatively constant or continue to increase as a function of the rate of CO_2 input.

Diurnal ventilation is caused by barometric tides that have a periodicity of 12 and 24 hours, with the 24-hour fluctuations being the strongest (Melcior 1993, Wallace and Hobbs 2006). As barometric pressure increases, the pressure differential between the atmosphere and cave air forces outside air, with a lower CO_2 concentration (~390 ppm), into the cave and dilutes the high-CO_2 cave air causing a decrease in the CO_2 concentration. When barometric pressure decreases, the pressure differential is reversed and air flows out of the cave, drawing higher CO_2 air from deeper within the cave toward the entrance, and causes the CO_2 concentration of the cave to increase. Evidence of such cave breathing and diurnal CO_2 fluctuations has been observed in Florida (Kowalczk and Froelich 2010), Spain (Duenas et al. 2005, Fernandez-Cortes et al. 2009), and France (Bourges et al. 2006, Perrier and Richon 2010).

Carbon Dioxide Sources

Known sources of cave-air CO_2 include decomposition of soil organic matter, root respiration, in-cave decomposition of organic matter, diffusion from deep sources, animal respiration, and degassing from CO_2-rich groundwater (Troester and White 1984, Ek and Gewalt 1985, Hanson et al. 2000, Baldini et al. 2006, Bourges; et al. 2001, Batiot-Guilhe et al. 2007, Crossey et al. 2006). The majority of CO_2 in the caves within the study area advects or diffuses into the caves from soils as a gas rather than being transported in aqueous solution via cave drips (Breeker et al. 2012). According to carbon isotopic values measured by Breeker et al. 2012, the majority of the CO_2 advecting and diffusing into the study area caves is derived from the respiration of deeply rooted vegetation. The rate of vegetative respiration is affected by changes in soil temperature and soil moisture, and the highest CO_2 production often occurs in warm months and when soils are moist (Amundson and Smith 1988, Daly et al. 2008, Lloyd and Taylor 1994, Raich and Schlesinger 1992). Advection and/or diffusion of vadose zone air through fractures, cracks, and dissolution cavities has also been recognized by others as a significant means of transporting CO_2 to the cave atmosphere (Baldini et al. 2006, Batiot-Guilhe et al. 2007, Perrier and Richon 2010).

Other less significant sources of cave-air CO_2 in the study area may include degassing from vadose water, decaying organic material, degassing of phreatic water, and animal respiration.

The concentration of CO_2 in vadose water is primarily controlled by the concentration of CO_2 in the soil air. As water flows through the soil zone, it becomes enriched in CO_2 until the partial pressure of CO_2 (pCO_2) of the water is equal to the pCO_2 of the soil, or the water flows out of the soil zone. When CO_2-charged water comes into contact with a lower pCO_2 environment (i.e. a cave), CO_2 degassing occurs and the air within that environment becomes slightly more CO_2-rich.

CO_2 generated from decaying organic material within caves may be a significant source for caves that collect detritus or bat guano. The significance of this contribution of CO_2 is likely to vary, depending on the ability of a given cave to capture storm-washed debris or the presence of a significant bat population. Overland flows of water into a cave, sinkholes, or soil piping features are required for a significant amount of organic debris to enter the caves that were monitored. Only Ireland's Cave receives significant amounts of organic debris via overland storm flow.

Degassing of CO_2 from phreatic water is another potential source within caves, especially where cave passages intersect the water table. Degassing occurs when high-pCO_2 phreatic water comes in contact with lower-pCO_2 air and will continue until the water reaches equilibrium with the air or until it is removed from the low-pCO_2 environment (i.e. flowing into a sump). Contribution of CO_2 from degassing of phreatic water will likely vary seasonally and in response to recharge events. Degassing of phreatic water may be a more significant source of CO_2 in Ireland's Cave as it is formed along a fault that forms the border between Trinity Aquifer rock units and Edwards Aquifer rock units.

Setting

The study area is located near Austin, Texas (Figure 1) and is composed of karstified Lower Cretaceous marine carbonates overlain by a thin calcareous clay soil that supports oak and juniper savannah. Soils across the study area are thin and commonly contain limestone fragments sourced from the underlying bedrock (Cooke et al. 2007). Grassy Cove Cave and Whirlpool Cave are located within Edwards Group rocks, and Ireland's Cave is located at the contact between Edwards Group rocks and the Upper Glen Rose Formation. The Edwards Group consists of highly karstified limestone, dolostone, and chert units within which caves are commonly formed. Certain members of the Edwards Formation are known for extensive cave formation (Hauwert 2009) including the Kirschberg Member, within which much of Whirlpool Cave and Grassy Cove Cave are formed. The Dolomitic Member, within which Ireland's Cave is formed, is known for cave development along bedding planes and fractures. The Glen Rose Formation is a shallow marine unit formed in the Cretaceous period, which is now exposed over a large area from south central to north central Texas. The Upper Trinity Aquifer is formed in the upper member of the Glen Rose Formation and yields small quantities of highly mineralized water. Some caves are known to form in the upper Glen Rose, especially at the contact between the overlying Edwards Group and upper Glen Rose (Clark 2003), notably Natural Bridge Caverns is formed at the contact.

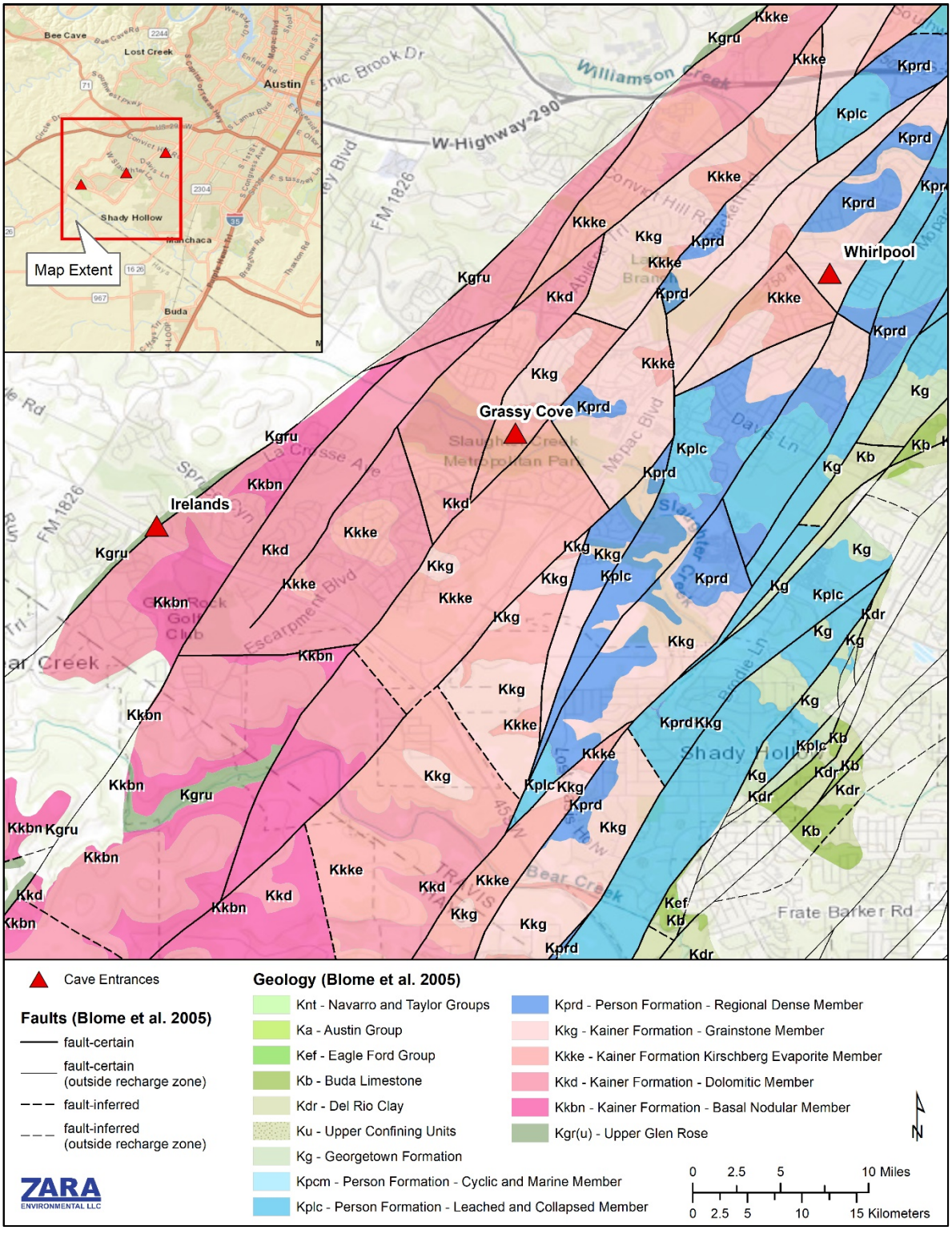

Figure 1. Project area overview showing location of caves and surface geology.

Study Caves

Whirlpool Cave is approximately 22,000 ft^3 in volume and is formed in the Grainstone and Kirschberg members of the Edwards Limestone. After entering Whirlpool Cave, the passage quickly descends approximately 10 m though the less-permeable Grainstone member. The cave passage then enters the Kirschberg member and become relatively wide and horizontal. Most of the cave volume is formed within the Kirschberg Member.

Grassy Cove Cave is approximately 13,200 ft^3 in volume and is formed mostly within the Kirschberg member near the contact with the underlying Dolomitic Member. Some passages extend into the Dolomitic member via pits located in the floor of the cave passage formed along vertical fractures. The passages formed in the Dolomitic Member are somewhat laterally extensive but tend to pinch out and become impassable.

Ireland's Cave is approximately 41,100 ft^3 in volume and is formed along a fault contact of the Upper Glen Rose Formation and the Dolomitic Member of the Edwards Group. Much of the cave is formed in the Dolomitic Member of the Edwards Group.

Methods

Cave-air CO_2 concentrations were measured at one station each within Grassy Cove Cave, Whirlpool Cave, and Ireland's Cave (Figure 2 through Figure 4) with Vaisala GM70 hand-held carbon dioxide meters. The CO_2 concentration is measured via infrared absorption technology as air diffuses into the probe chamber. Accuracy is within +/- 20 ppm CO_2 or 2% of the reading, whichever is larger, and long-term stability is <5%/2 years according to the manufacturer's specifications. Carbon dioxide meters were replaced with a fully charged unit every 3-5 weeks. At the same time, data was retrieved and accuracy and maintenance checks were performed.

Readings below 405 ppm are likely erroneous as this value represents the average atmospheric CO_2 concentration for the duration of the study as measured by the National Oceanic and Atmospheric Administration (NOAA) at a network of globally distributed monitoring sites (www.ncdc.gov). However, it is possible that photosynthetic and anthropogenic factors may slightly alter the local atmospheric CO_2 concentration. A study of the temporal and spatial variability of CO_2 concentrations in Essen, Germany (comparable in size to Austin, Texas) reveals that local atmospheric variability is small (+/- 50 ppm) and typically within the error of the meters (Henninger 2008). Therefore, readings as low as 355 ppm were included in the analyses.

Occasionally, CO_2 concentration values >100 ppm below atmospheric (405 ppm) or well above the typical range for the cave environment (>32,000 ppm) were recorded. These values typically occurred as single point outliers such that the rate of CO_2 increase or decrease could not be explained by natural processes; these values are considered erroneous and are not considered herein. Erroneous readings were likely due to a variety of reasons including electronics failure, human or animal tampering, and (most often) condensation on the probe tip due to the high humidity cave environment. Such condensation interferes with infrared absorption readings that

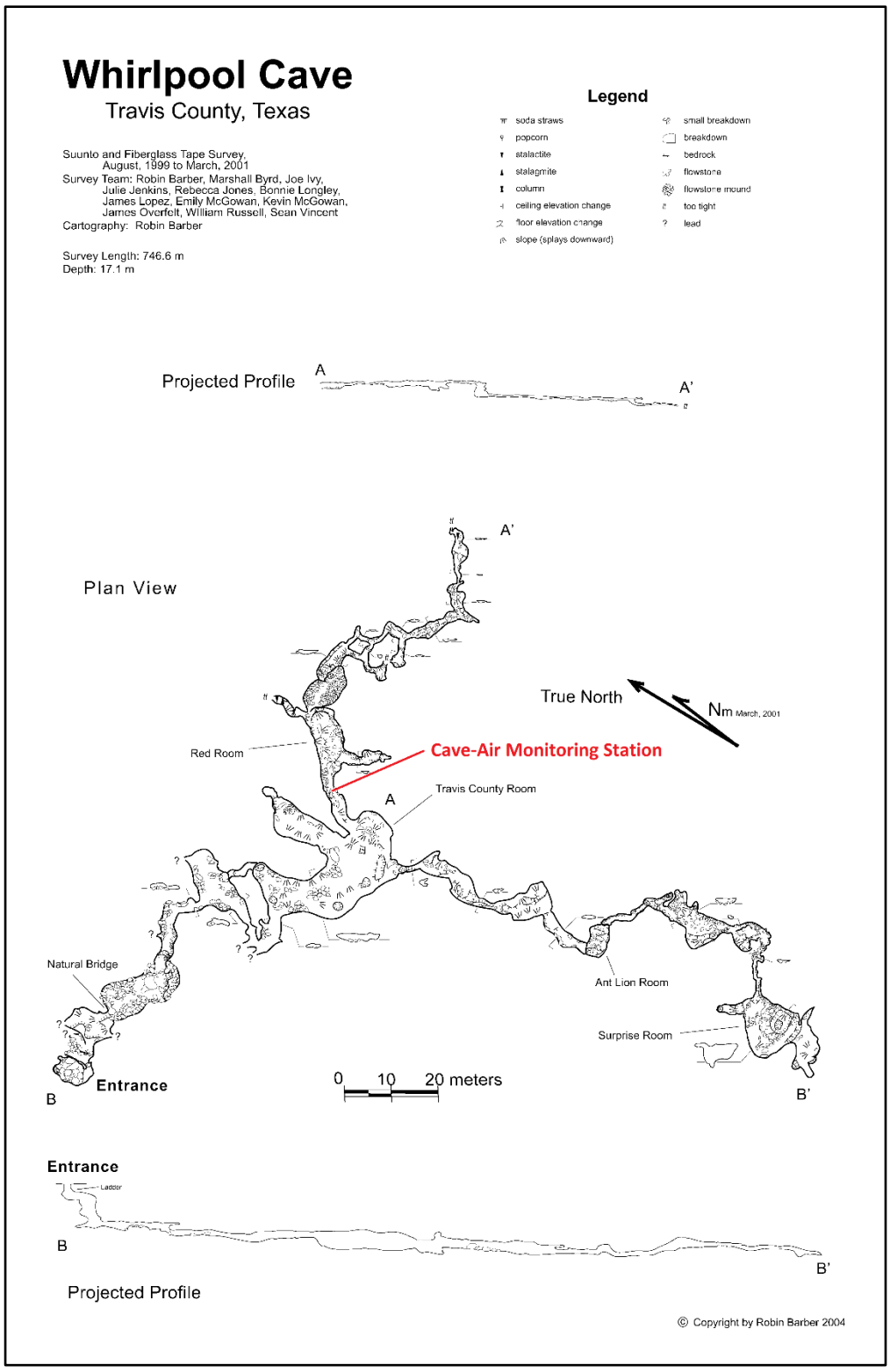

Figure 2. Location of the cave-air monitoring station in Whirlpool Cave.

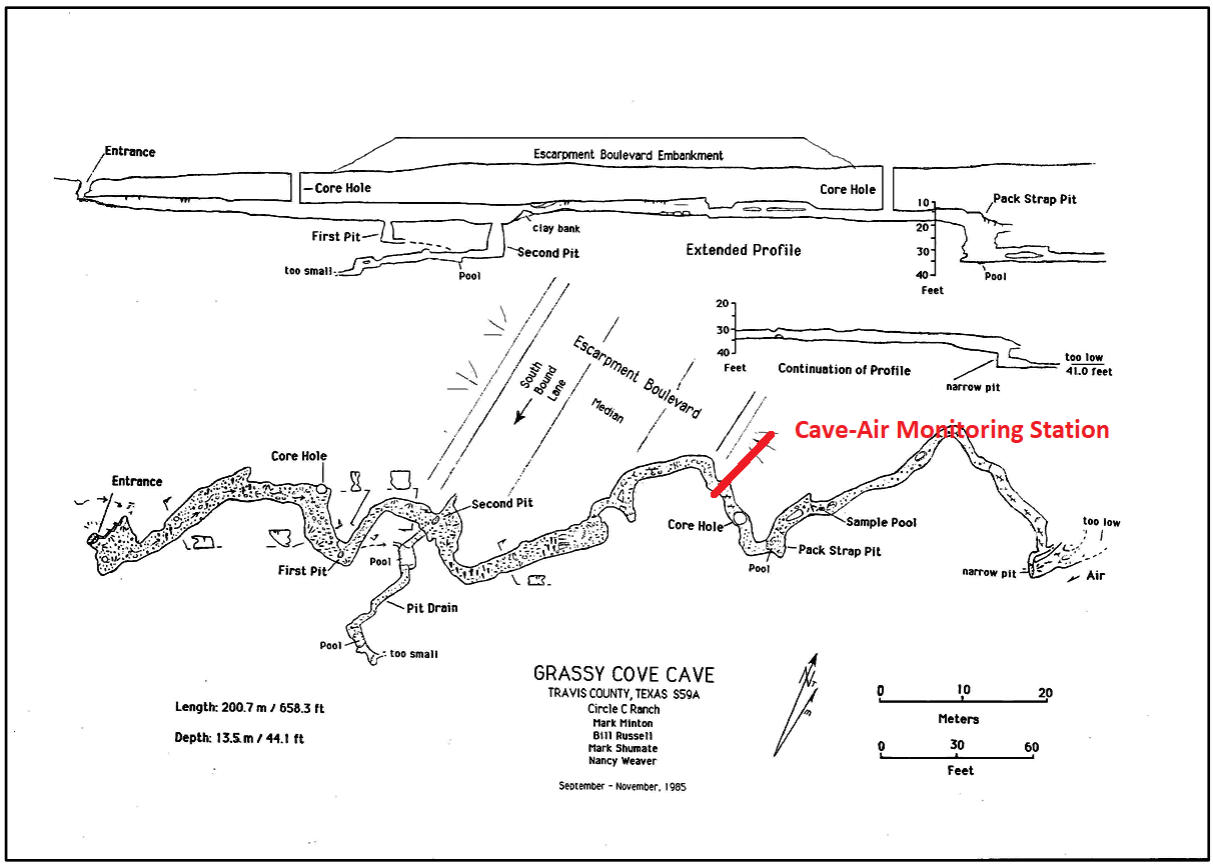

Figure 3. Location of the cave-air monitoring station in Grassy Cove Cave.

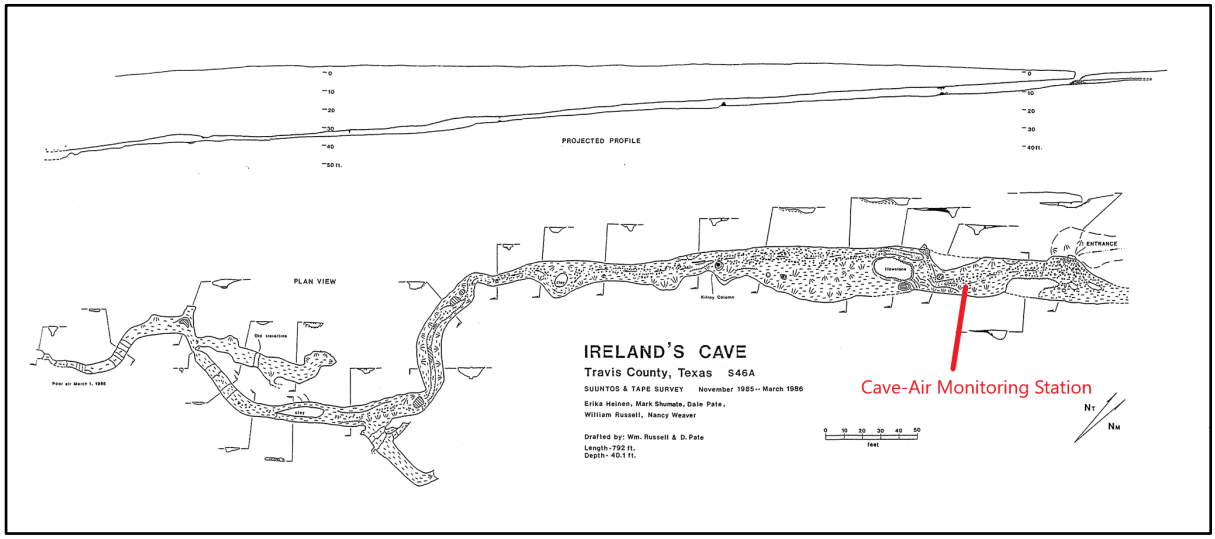

Figure 4. Location of the cave-air monitoring station in Ireland's Cave.

the meters use to calculate CO_2 concentrations. A small number of erroneous data points are typical of Vaisala meters deployed in caves; however, if a significant number (>10) of erroneous values were recorded during the deployment of a meter, all data from that deployment are considered unreliable and are not reported here.

All weather data was obtained from a National Climate Data Center (NCDC) weather station located at Camp Mabry in Austin, Texas (COOPID: 410428) located approximately 14 km north of Whirlpool Cave. The weather data may all be accessed at http://www.ncdc.noaa.gov.

All CO_2 and weather data were imported into a Microsoft Excel file for graphical and statistical analysis. Representative warm and cold season periods were selected for each cave for analysis.

Results

Diurnal, seasonal, and weather-related CO_2 concentration fluctuations due to cave ventilation were observed in all three caves in this study. The timing of diurnal ventilations within all three caves was similar, but the diurnal ventilations in Ireland's Cave were typically not as strong as in the other two caves. However, when significant ventilations occurred in Ireland's Cave, they typically occurred with similar timing as the other two caves (Figure 5 - Figure 7). Maximum CO_2 concentrations were typically reached between 14:00 and 18:00 central standard time (CST) each day and minimum CO_2 concentrations were typically reached between 00:00 and 06:00 CST each day. The magnitude of CO_2 fluctuations varied greatly between all three caves, and there was a significant difference between the magnitude of CO_2 fluctuations during the warm and cool seasons. The warm season is defined as May through October and the cool season is defined as December through March. These definitions are generalized as the individual cave CO_2 concentration fluctuations enter warm and cool season patterns at different times.

Table 1 through Table 3 summarize cave-air CO_2 concentration and weather conditions during periods representative of the cool season and warm season. Because all three caves transition into cool and warm season patterns at different times, representative cool and warm season periods were chosen based on a visual examination of graphs of CO_2 concentration at each cave and are not the same timeframe for each cave. The average maximum and minimum diurnal CO_2 concentrations varied by cave and by season. During the cooler season, Whirlpool Cave ventilated strongly on a nearly daily basis, and minimum CO_2 concentrations reached near surface atmospheric concentrations of 405 ppm (Blunden et al. 2018); however, during the same timeframes Grassy Cove Cave and Ireland's Cave did not fully ventilate daily and often went several days without reaching atmospheric concentrations (Table 1 - Table 3; Figure 5 and Figure 6). During the warmer season, Ireland's Cave and Grassy Cove Cave did not reach near atmospheric CO_2 concentrations and Whirlpool Cave reached near atmospheric concentrations less frequently than in the cooler season (Table 1 - Table 3; Figure 6 and Figure 7).

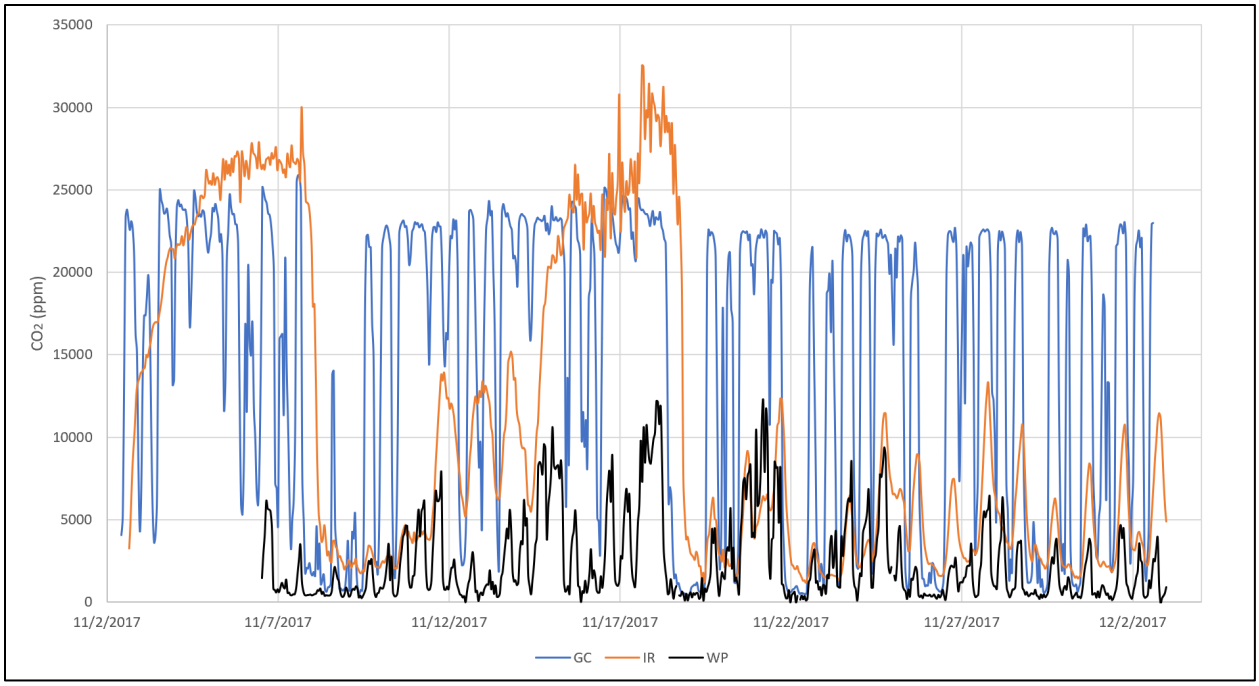

Figure 5. Representative cave-air CO_2 concentrations at all three study caves during the cooler season. (GC = Grassy Cove Cave; IR = Ireland's Cave; WP = Whirlpool Cave)

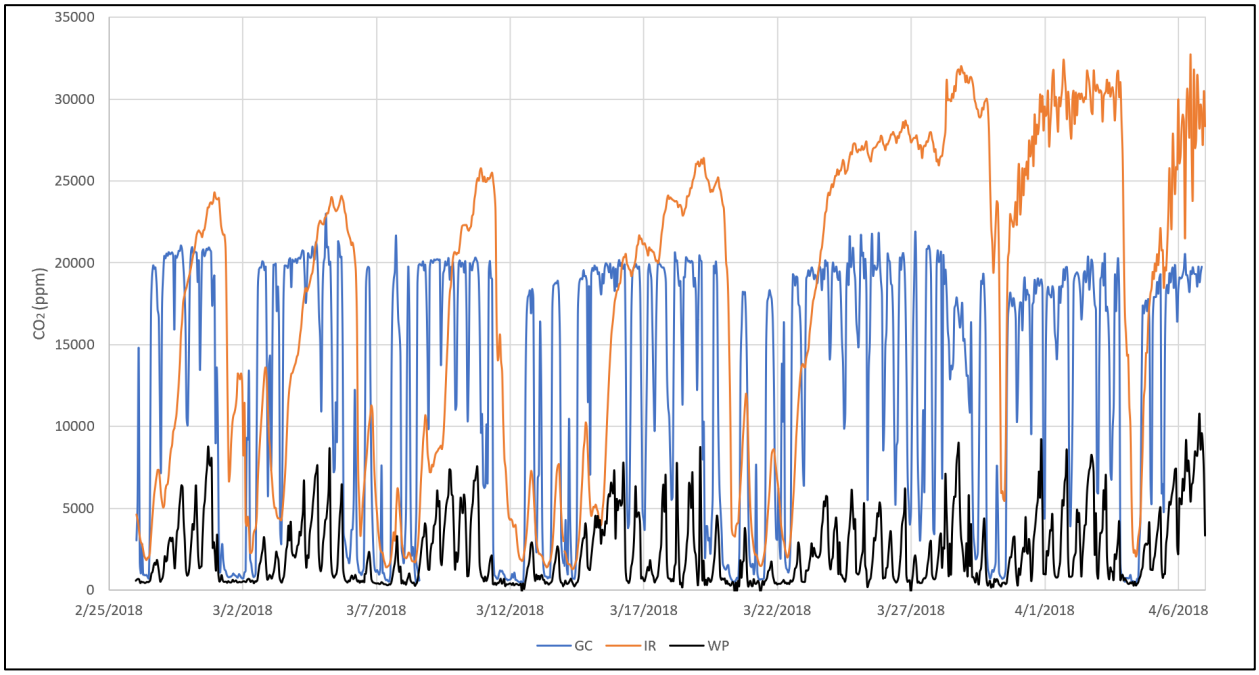

Figure 6. Representative cave-air CO_2 concentrations at all three study caves during a transition from the cooler season to the warmer season. Note that Grassy Cove Cave does not appear to transition as strongly to a warmer season pattern. (GC = Grassy Cove Cave; IR = Ireland's Cave; WP = Whirlpool Cave)

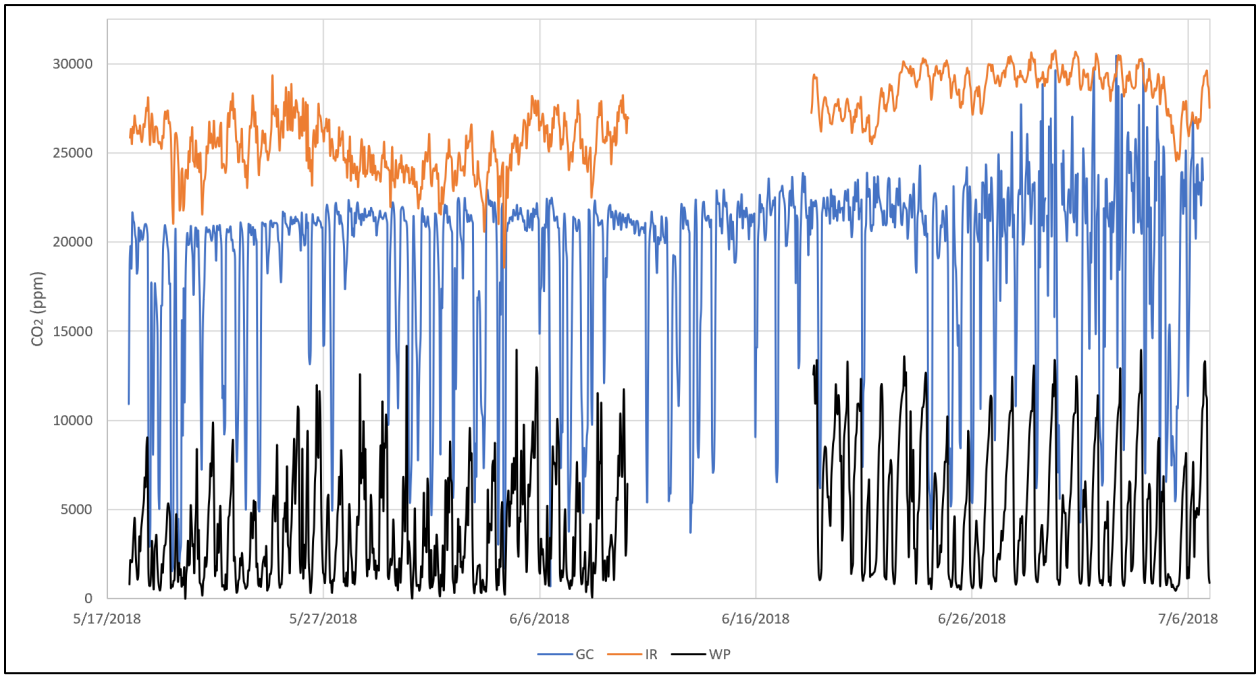

Figure 7. Representative cave-air CO2 concentrations at all three study caves during the warm season. (GC = Grassy Cove Cave; IR = Ireland's Cave; WP = Whirlpool Cave)

Table 1. Summary of CO_2 concentration measurements at Grassy Cove Cave and temperature and pressure measured at Camp Mabry in Austin, Texas. A period representative of cold and warm season cave CO_2 fluctuations was chosen for statistical analysis.

		CO_2 (ppm)		**Temperature (C)**		**Pressure (Slp)**	
		Cold	Warm	Cold	Warm	Cold	Warm
Grassy Cove Cave	**min**	444.3	4282	-7.8	21.9	1003	1008
	max	22670	30011	32.0	42.6	1043	1019
	mean	11954	20761	15.8	30.8	1018	1014
	SD	7866	5310	6.9	4.5	7.37	2.09

Cold: 01/17/2018–04/06/2018; Warm: 07/16/2018–08/12/2018

Table 2. Summary of CO_2 concentration measurements at Ireland's Cave and temperature and pressure measured at Camp Mabry in Austin, Texas. A period representative of cold and warm season cave CO_2 fluctuations was chosen for statistical analysis.

		CO_2 (ppm)		Temperature (C)		Pressure (Slp)	
		Cold	Warm	Cold	Warm	Cold	Warm
Irelands Cave	**min**	640	16490	-5.4	10.7	1008	1004
	max	32792	31209	31.1	39.5	1043	1022
	mean	7116	26623	13.9	27.8	1022	1013
	SD	8089	2063	7.5	4.7	6.35	3.65

Cold: 11/02/2017–01/08/2018; Warm: 05/01/2018–07/11/2018

Table 3. Summary of CO_2 concentration measurements at Whirlpool Cave and temperature and pressure measured at Camp Mabry in Austin, Texas. A period representative of cold and warm season cave CO_2 fluctuations was chosen for statistical analysis.

		CO_2 (ppm)		Temperature (C)		Pressure (Slp)	
		Cold	Warm	Cold	Warm	Cold	Warm
Whirlpool Cave	**min**	357	439	-7.9	21.7	1006	1006
	max	8511	14302	23.7	42.5	1044	1022
	mean	1453	5410	9.5	30.1	1025	1014
	SD	1589	3806	6.5	4.5	7.78	2.87

Cold: 12/22/2017–02/06/2018; Warm: 06/18/2018–08/10/2018

Discussion

Seasonal Ventilation

CO_2 concentrations vary seasonally in all three monitored caves, with elevated CO_2 concentration in the warmer months and lower CO_2 concentrations in the cooler months. These seasonal CO_2 fluctuations are attributed to seasonally variable cave ventilation that is controlled by atmospheric temperature fluctuations. Cave-air CO_2 concentrations are lowest in the cooler months due to stronger ventilation. In the cooler months when the outside air is denser than the cave air, lower CO_2 outside air sinks into the cave and mixes with the CO_2 rich cave air causing a decrease in the cave-air CO_2 concentration. In the warmer months, when the outside air is less dense, cave ventilation becomes much weaker and CO_2 concentration increases. Seasonal CO_2 fluctuations in the three study area caves do not appear to be caused by anthropogenic influences, including cave visitation. Whirlpool Cave and Grassy Cove Cave both receive significant visitation as they are utilized by the City of Austin for educational tours. If human visitation were causing seasonal CO_2 fluctuations, then we would expect to see seasonal

fluctuations at Whirlpool Cave and Grassy Cove Cave and no seasonal CO_2 fluctuation in Ireland's Cave. Ireland's Cave receives no visitation outside of this study monitoring, and very infrequent biological monitoring conducted by BCP staff. However, significant seasonal CO_2 fluctuations were measured in all three caves.

Diurnal Ventilation

Diurnal air flow into and out of caves is dominated by barometric tides and generally flows out of the caves from early morning (06:00-09:00 CST) to late afternoon (15:00-18:00 CST) and then reverses direction, flowing into the caves from late afternoon to early morning. Barometric tides are a well-known global phenomenon (Melchor 1993, Wallace and Hobbs 2006) that has been shown to affect cave meteorology (Sondag et al. 2003, Bourges et al. 2006). As barometric pressure increases, the pressure differential between the surface and cave forces outside air with a lower CO_2 concentration (~405 ppm) into the cave, displacing and diluting the higher CO_2 cave air, causing a decrease in cave-air CO_2 concentrations. When barometric pressure decreases, the pressure differential is reversed and air flows out of the cave, drawing higher CO_2 air from deeper within the subsurface toward the entrance and causing cave-air CO_2 concentrations to increase. Hereafter this phenomenon is referred to as "barometric pumping" (Perrier and Richon, 2010).

CO_2 concentrations and airspeed previously measured by Cowan (2010) at the entrances of Whirlpool Cave and Maple Run Cave, a cave that is also located in the BCP, offer more compelling and detailed evidence for barometric pumping (Figure 8). Airspeed measurements and CO_2 concentrations were measured at the entrances of both caves during an airflow reversal from flow out of the cave to flow into the cave. During the time when air was flowing out of the cave due to decreasing surface barometric pressure, the CO_2 concentration steadily increased. This continual increase of CO_2 is due to the exhalation of air sourced from deeper within the subsurface as time elapsed. When air began flowing into each cave, the CO_2 concentration at the entrances dropped to near atmospheric concentrations within a few minutes of the reversal, confirming that lower CO_2 outside air was flowing into the cave and displacing cave air further into the subsurface.

The simultaneous deployment of three logging CO_2 meters within Whirlpool Cave further support the hypothesis that barometric pumping is the primary cause of diurnal CO_2 fluctuations (Cowan 2010). Three logging CO_2 meters were deployed in Whirlpool Cave at distances of 12 m, 60 m and 100 m from the cave entrance, and were allowed to collect data for 36 days. All stations throughout the length of Whirlpool Cave experienced significant diurnal CO_2 fluctuations, suggesting that cave ventilation is not limited to portions of a cave located near the entrance (Figure 9). The magnitude of CO_2 fluctuations increased with distance from the cave entrance.

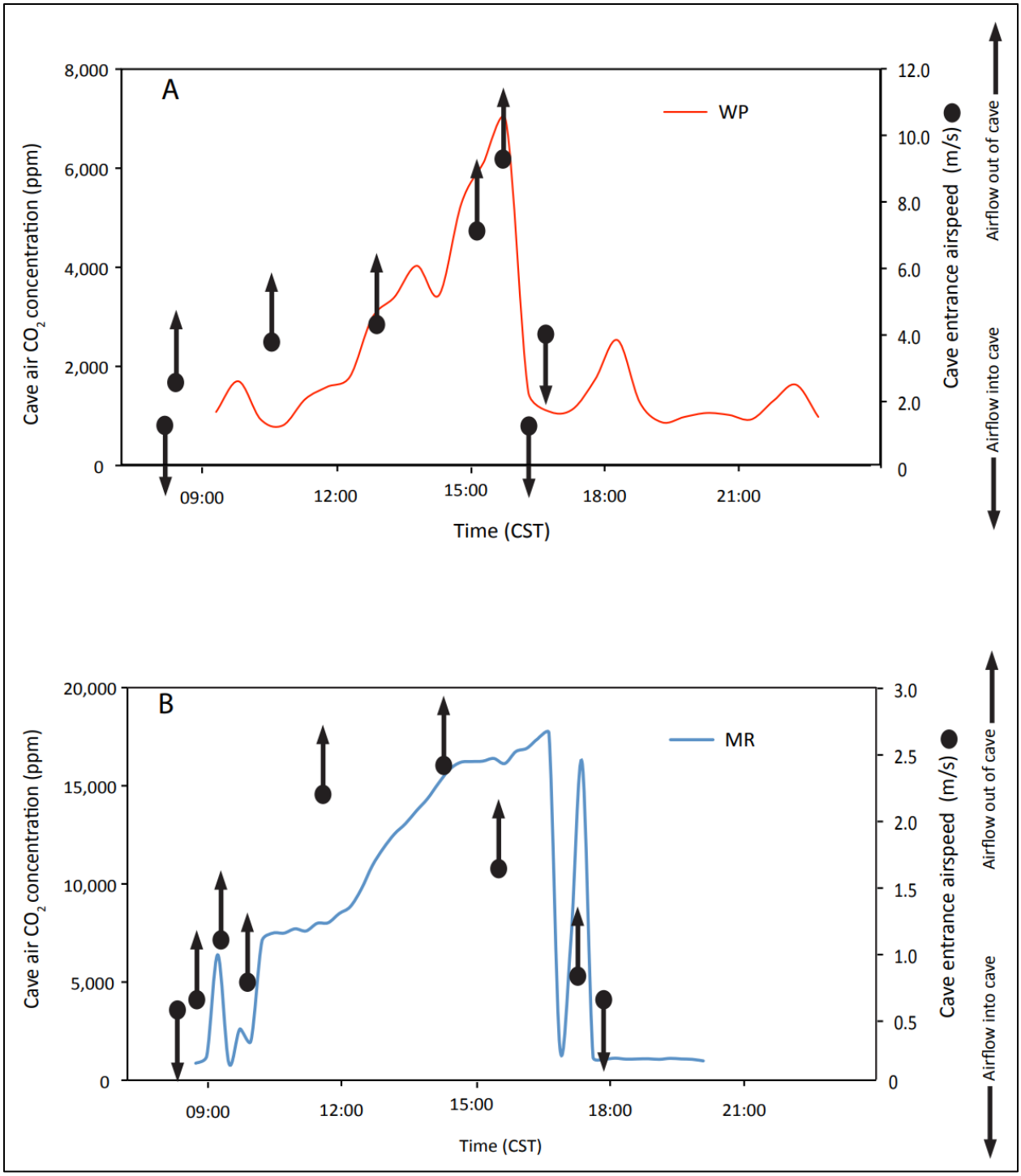

Figure 8. The concentration of CO_2 and airspeeds measured at the entrances of Whirlpool Cave (A) and Maple Run Cave (B) during airspeed measurements. Note that airspeeds at Whirlpool Cave are much higher than airspeeds at Maple Run as the entrance to Whirlpool Cave had a much smaller area at the time of the measurements. The entrance of Whirlpool Cave has since been modified in a way that increased the entrance area and likely decreased airspeeds. Figure from Cowan 2010.

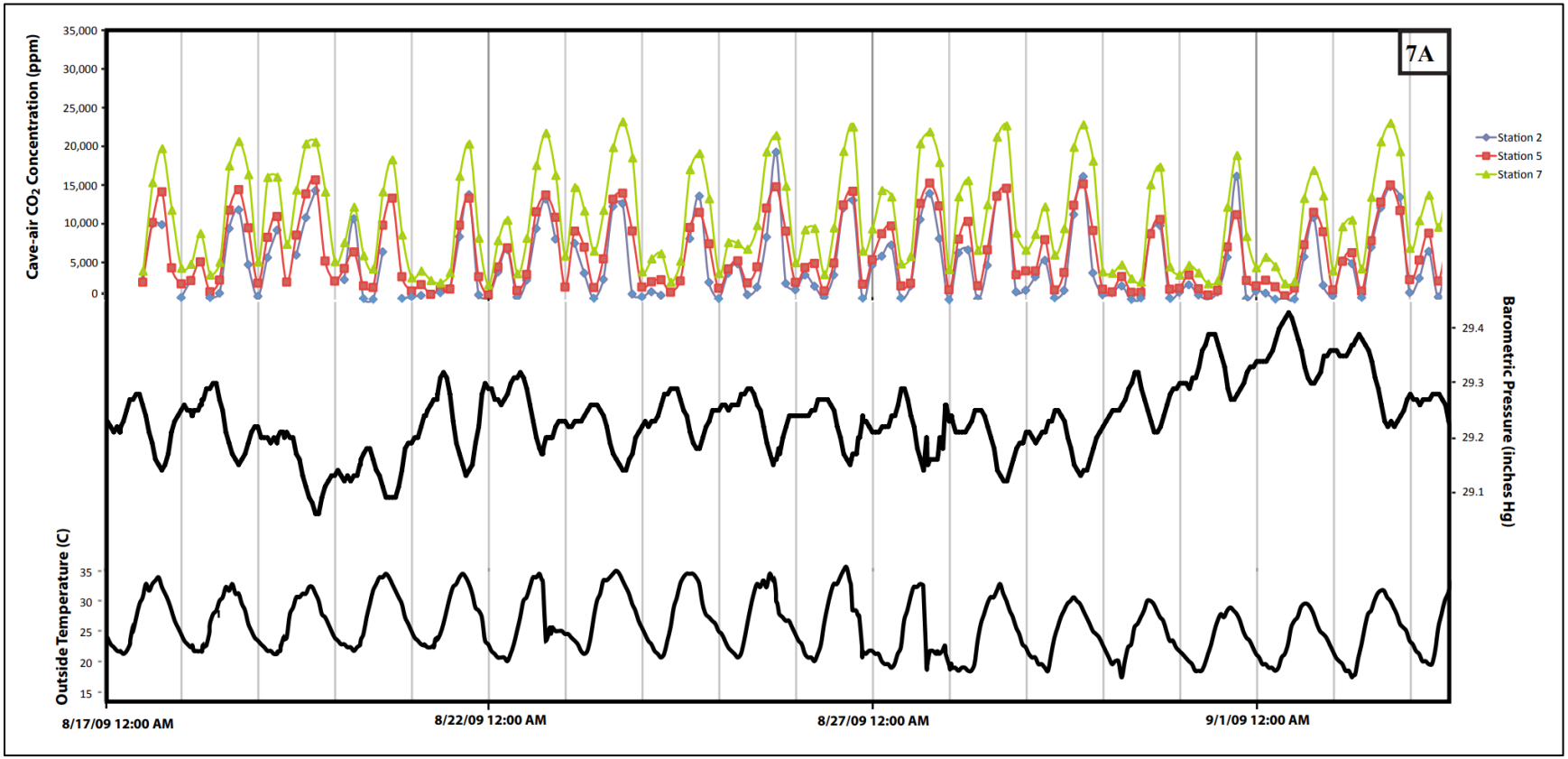

Figure 9. Surface air pressure and temperature and cave-air CO_2 concentrations at Whirlpool Cave monitoring stations 2, 5 and 7 located 12 m, 60 m, and 100 m from the cave entrance, respectively. Large diurnal CO_2 fluctuations are typical in Whirlpool Cave and are better correlated with barometric pressure than outside temperature. Note that CO_2 concentrations generally increase with increasing distance from the cave entrance. Figure from Cowan 2010.

During times when air flowed into Whirlpool Cave, stations nearest to the entrance reached minimum CO_2 concentrations prior to stations located furthest from the entrance, due to the time required for the lower CO_2 outside air to flow farther into the cave and reach the stations furthest from the entrance. During times of exhalation, peak CO_2 concentrations were reached by deeper stations prior to those nearer to the entrance as the higher CO2 air sourced from deeper within the subsurface flowed toward the entrance. The timing of these fluctuations was coincident with surface barometric pressure fluctuations. When surface pressure increased CO_2 within the cave decreased and when surface pressure decreased CO_2 in the cave increased.

In summary, the flow of air into and out of caves in the region is known to reverse twice every 24 hours (except when weather fronts or other disturbances move through the region) and these reversals coincide with daily maximum and minimum barometric pressure. In essence, caves in the region are "breathing" due to barometric pressure fluctuations, with "exhalations" from the caves occurring when barometric pressure is falling, and air is pulled from the subsurface to replace the exhaled air. "Inhalations" then occur when barometric pressure rises, forcing air into the subsurface. This daily breathing causes airflow within the caves to act much like a piston. During inhalations, higher CO_2 cave air is displaced away from the entrance as low CO_2 atmospheric air is forced deeper into the cave by rising barometric pressure. This influx of atmospheric air lowers the overall CO_2 concentrations within the cave and this effect is greatest near the cave entrance. To accommodate the large volume of air entering the cave (which has a fixed accommodation volume), pre-existing cave air is forced into the network of fractures and cavities that connect the cave to the surrounding epikarst. During exhalations, falling barometric pressure sucks air from the cave, causing air to flow from deeper within the cave and from fractures and cavities to replace the volume of air that was ventilated. Because air deeper within the cave and from fractures and cavities has a higher concentration of CO_2, the overall concentration of CO_2 within the cave increases during the exhalation. The daily repetition of cave breathing leads to the significant diurnal cave-air CO_2 fluctuations that are typical of most studied caves in the region.

Recommendations

The results of this study can help guide management decision regarding all three caves. Grassy Cove Cave and Whirlpool Cave are utilized for educational and public outreach purposes. These two caves receive hundreds of visitors every year to educate the public about local karst resources and the need to protect them and the Edwards Aquifer. People can experience negative effects if exposed to extremely high concentrations of CO_2 (U.S. DHEW 1976). Above CO_2 concentrations of 20,000 ppm, humans may begin to experience increased heart rate, increased respiration, and headache, and these symptoms become more pronounced above 30,000 ppm. Above 30,000 ppm symptoms may include exhaustion, increased heart rate, and headache. Loss of consciousness may occur above 50,000 ppm. These symptoms rapidly subside once a person is moved to fresh air. To ensure the comfort and safety of tour groups and research staff, it is important to understand how cave CO_2 concentrations fluctuate temporally and the typical concentrations that are likely to be encountered in each cave.

The lowest overall CO_2 concentrations were measured in Whirlpool Cave (Figure 5 - Figure 7, Table 3). CO_2 concentrations in Whirlpool Cave typically reached near atmospheric concentrations daily, even in the warmer months. Maximum CO_2 concentrations were typically 8,000 ppm or less in the cooler months, and 10,000 ppm to 13,000 ppm in the warmer months. These concentrations are well within a range where most people will not experience any noticeable symptoms of CO_2 exposure. Whirlpool Cave can be considered safe to visit at any time of the year, but it is important to always monitor CO_2 concentrations with a handheld meter when any group is visiting the cave.

Grassy Cove Cave experienced larger CO_2 fluctuations than Whirlpool Cave, and regularly met or exceeded the 20,000-ppm threshold where many persons can begin to feel the effects of CO_2 exposure. Grassy Cove Cave regularly ventilated to near atmospheric CO_2 concentrations in the coolest months, but it was not uncommon for the CO_2 concentrations in the cave to remain elevated above 15,000 ppm for multiple days at a time. In the warmer months, CO_2 concentrations often remained elevated above 10,000 to 15,000 ppm, with only brief excursions below 10,000 ppm. Seldom did Grassy Cove Cave reach atmospheric CO_2 concentrations in the warmer months. Maximum CO_2 concentrations were typically reached between 14:00 and 18:00 CST each day, and minimum CO_2 concentrations were typically reached between 00:00 and 06:00 CST each day. During the cooler months, CO_2 concentrations were typically below 20,000 ppm until 11:00 or 12:00 CST. The optimal timing for groups to visit Grassy Cove Cave would be in the early morning while ensuring that all persons are out of the cave by 10:00 CST. It is important to note that weather conditions such as fronts may alter the timing of CO_2 fluctuations, so it is imperative that any group entering Grassy Cove Cave carry and use a handheld CO_2 meter and exit the cave if CO_2 concentrations reach an unacceptable level.

The highest CO_2 concentrations were measured in Ireland's Cave where CO_2 concentrations regularly exceeded 30,000 ppm during the warmer months and 25,000 ppm in the cooler months. Excursions above 30,000 ppm during the cooler months were not uncommon. It is important to note that the monitoring station in Ireland's Cave is located near the entrance, and that CO_2 concentrations farther from the entrance are likely more elevated than those reported here. It is also important to note that CO_2 exposure symptoms become more severe above 30,000 ppm and include dizziness, confusion, increased heart rate and respiration, headache, and loss of consciousness above 50,000 ppm. Ireland's Cave is not suitable for tour groups at any time of day. Personnel should always check weather forecasts prior to entering this cave, and time their work in the cave to coincide with increasing surface barometric pressure which forces lower CO_2 air further into the cave. Also, entering this cave during the coldest days of the year will increase the likelihood of lower CO_2 concentrations. Personnel should be aware that weather conditions such as fronts can cause sudden drops in barometric pressure which may result in sudden increases in CO_2 within Ireland's Cave. Only experienced persons, knowledgeable about cave safety and high CO_2 environments, should enter this cave. Prior to entering Ireland's Cave, a blower and tubing should be used to artificially ventilate the cave. Personnel should always carry and use a reliable handheld CO_2 meter while in Ireland's Cave, and should be ready to evacuate the cave quickly if CO_2 concentrations reach an unacceptable level.

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