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



Carbon dioxide data retrieval at Whirlpool Cave.

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

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In accordance with the Texas Board of Professional Geologists rules at 22 Texas Administrative Code, Part 39, Chapter 851, Subchapter C, §851.156, this report is signed and sealed on the title page to assure the user that the work has been performed by or directly supervised by the following professional geologist who takes full responsibility for this work.

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30 December 2019
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Abstract

Cave-air carbon dioxide concentration was measured in two Balcones Canyonlands Preserve caves, Whirlpool Cave and Irelands Cave, using Vaisala logging carbon dioxide meters. Anemometers and wind vanes were also deployed in both caves to measure wind speed velocity and wind direction. Measurements began in October 2018, and this comprehensive report covers work occurring between October 2018 and October 2019. Cave carbon dioxide concentrations fluctuated both seasonally and diurnally in both caves and within similar timeframes. Maximum and minimum carbon dioxide concentrations and the timing of carbon dioxide fluctuations differed between both caves. Seasonal carbon dioxide concentrations were elevated May through October (the warm season) and were lowest December through March (the cool season). Significant diurnal carbon dioxide fluctuations were measured in both caves, with an increase of over 10,000 ppm being measured in Whirlpool Cave in a 12-hour period. Diurnal carbon dioxide fluctuations during the warm season were generally smaller in magnitude in Irelands Cave than Whirlpool Cave. Surface weather conditions, especially pressure fronts, significantly altered diurnal carbon dioxide fluctuations for periods lasting from hours to days. Measured carbon dioxide in Irelands Cave fluctuated more than 20,000 ppm in response to some individual pressure fronts. Airflow data indicated frequent measurable diurnal airflow events in Whirlpool Cave. Airflow events and measured airflow direction reversals in Whirlpool Cave were also frequent during pressure front events. There were no measurable airflow events in Irelands Cave. The results of this cave-air carbon dioxide 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 understand better 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 Conservation 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, cave-air CO_2 concentration and cave wind speed and direction was monitored continuously in three BCCP permit caves beginning in October 2017. This report summarizes the findings of the second year of data collection (October 2018-October 2019) from Whirlpool Cave and Irelands Cave; and offers suggestions for future research that could help improve management of all BCP caves, both for the protection of BCCP listed species and 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 through the region, causing a significant change in barometric pressure (Cowan 2010). The concentration of CO_2 in cave air is affected 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 et al. 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 fluctuations (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 influenced 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 reverses, 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 are observed in Texas (Cowan 2010), 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). Others have also recognized advection and/or diffusion of vadose zone air through fractures, cracks, and dissolution cavities 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 heavily influenced 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 monitored caves. Only Irelands 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 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 Irelands Cave as the cave was 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 within Edwards Group rocks, and Irelands 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 Irelands 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 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.

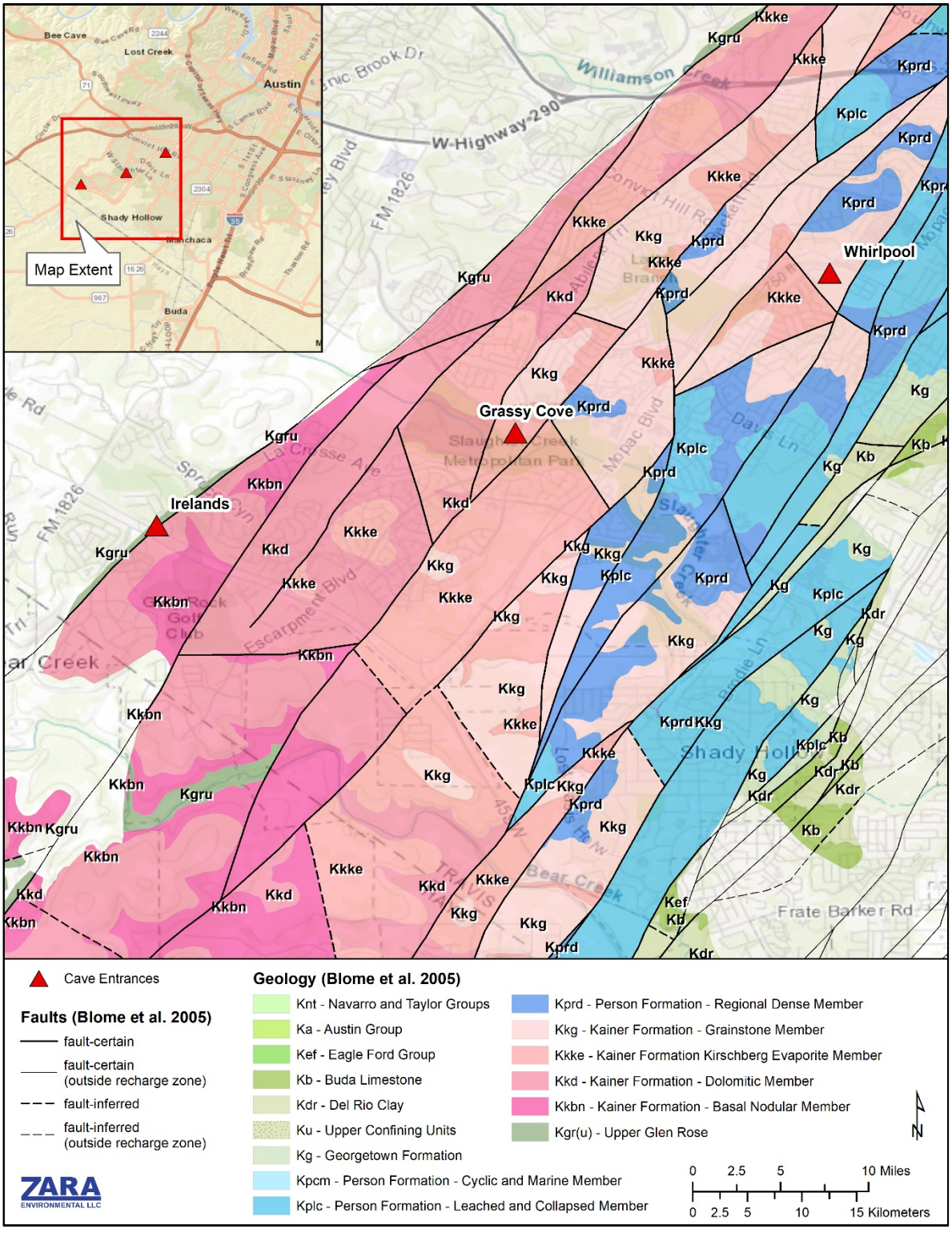

Figure 1. Project area overview showing the location of caves and surface geology.

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.

Irelands 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 within Whirlpool Cave and Irelands Cave (Figure 2 and Figure 3, respectively) with Vaisala GM70 hand-held carbon dioxide meters. Measurements were not made in Grassy Cove Cave during this study period due to the ongoing installation of permanent CO_2 monitoring equipment; therefore, Grassy Cove Cave will not be discussed further in the data reporting and analysis sections of this report. However, data collection in the coming year has been planned for Grassy Cove Cave and the cave will be an important study site for future investigations. 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, 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.

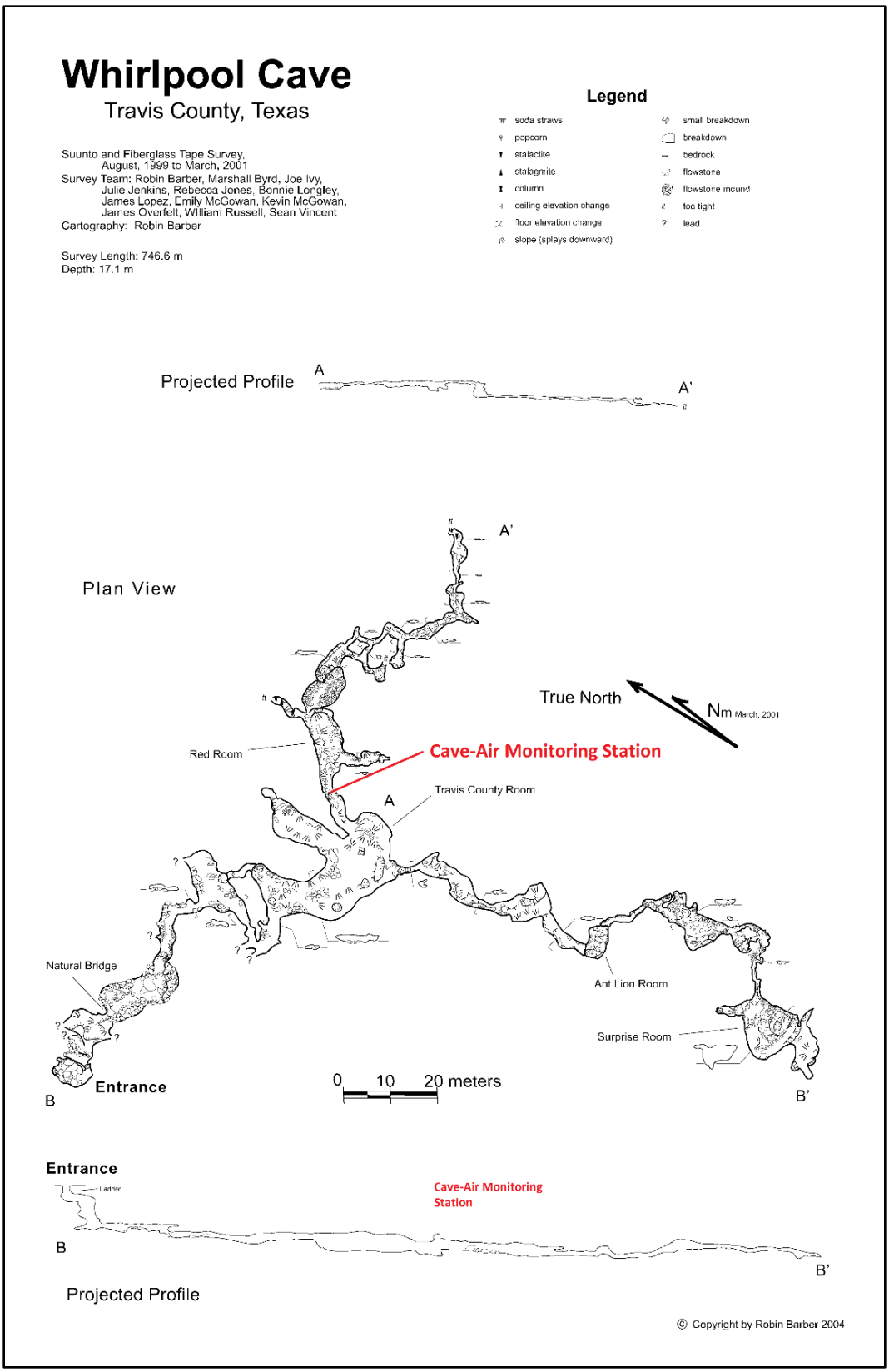

Figure 2. Location of the cave-air monitoring station in Whirlpool Cave.

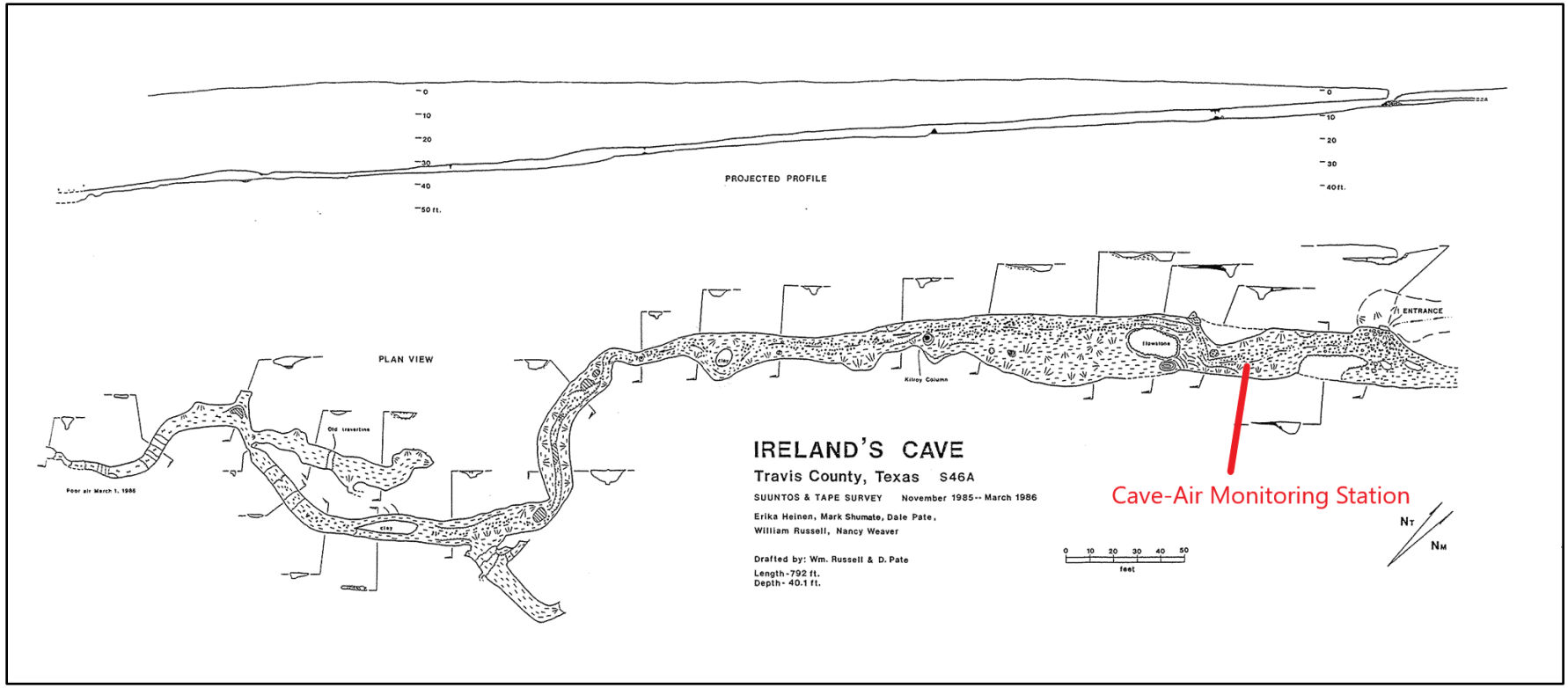

Figure 3. Location of the cave-air monitoring station in Irelands Cave.

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 natural processes could not explain the rate of CO2 increase or decrease; 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 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. Additionally, a large flooding event that occurred in June 2019 caused equipment failure at Whirlpool Cave and, subsequently, a loss in data (June 10th, 2019 to August 15th, 2019).

Cave wind speed velocity and wind direction were measured in both caves by deploying a 034B-L Anemometer and Vane set, manufactured by Cambell Scientific. These measurement devices were deployed at the same location in the Caves as the CO_2 sensors. Wind speed and direction data were logged using an CR 300 data logger, manufactured by Cambell Scientific.

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 were observed in both caves during the 2019 data collection period (Figure 4).

The timing of diurnal ventilations within both caves was similar, with a bi-modal pattern of two peaks in CO_2 concentration occurring daily: a small peak in the morning, and a larger peak in the afternoon (Figure 5). Similar to data collected in the 2018 collection period (Zara 2018), the magnitude of the diurnal change in CO_2 concentration was significantly higher in Whirlpool Cave than Irelands Cave (Figure 6). Maximum CO_2 concentrations were typically reached between 16:00 and 20:00 central standard time (CST) and minimum CO_2 concentrations were typically reached between 00:00 and 06:00 CST each day. The magnitude of diurnal CO_2 fluctuations was significantly larger in both caves during the warm season (Early June-Late September; Figure 6) than the cool season (Late November-Mid February; Figure 7).

Table 1 and Table 2 summarize cave-air CO_2 concentration and weather conditions during periods representative of the cool season and warm season in Irelands Cave and Whirlpool Cave, respectively. 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 nearly reached surface atmospheric concentrations

(approximately 410 ppm). However, during the same timeframes, Irelands Cave did not reach atmospheric concentrations, suggesting that it was not ventilating as regularly (Table 1, Table 2, Figure 6, Figure 7). During the warmer season, Irelands Cave did not reach near atmospheric CO_2 concentrations, and Whirlpool Cave reached near atmospheric concentrations less frequently than in the cooler season (Figure 4).

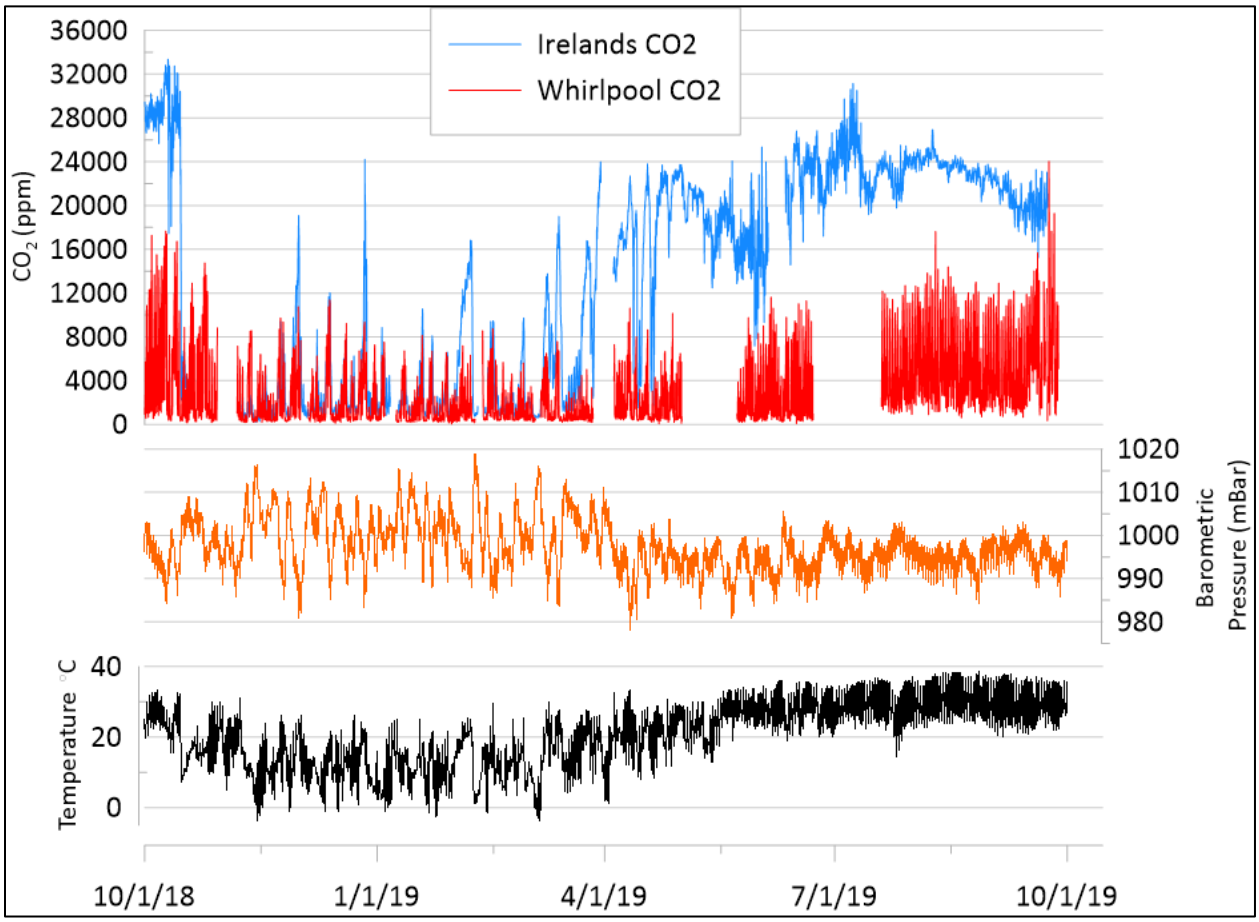

Figure 4. 1-year time series data of CO_2 concentration in Irelands Cave and Whirlpool Cave compared to temperature and barometric pressure as reported by the NOAA weather station at Austin Bergstrom International Airport. Some time intervals are missing from Whirlpool Cave due to flooding events which temporarily took monitoring equipment out of service.

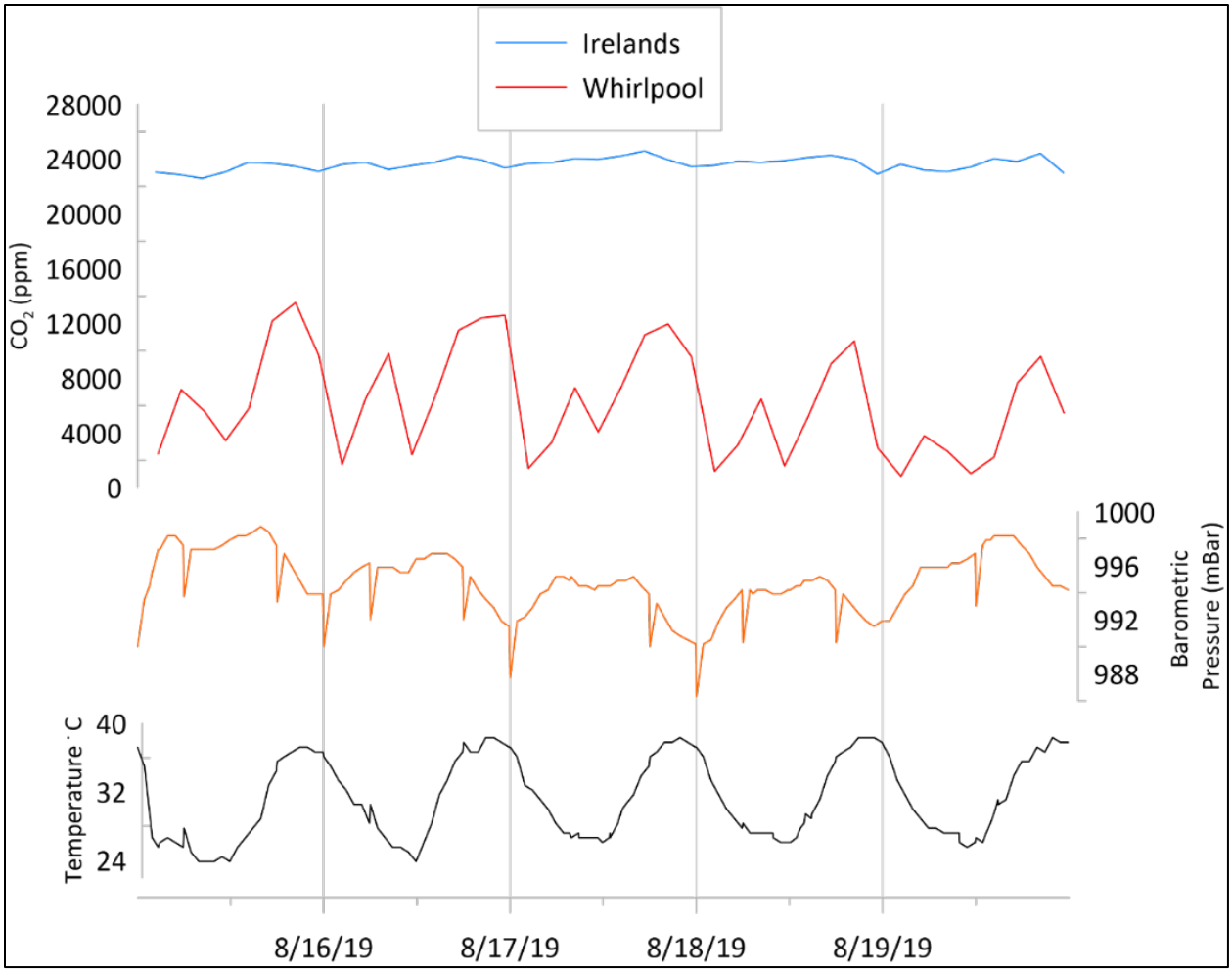

Figure 5. Surface air pressure, temperature, and cave air CO_2 measured in Whirlpool Cave and Irelands Cave in mid-August. The data show a clear diurnal signal in CO_2 increases.

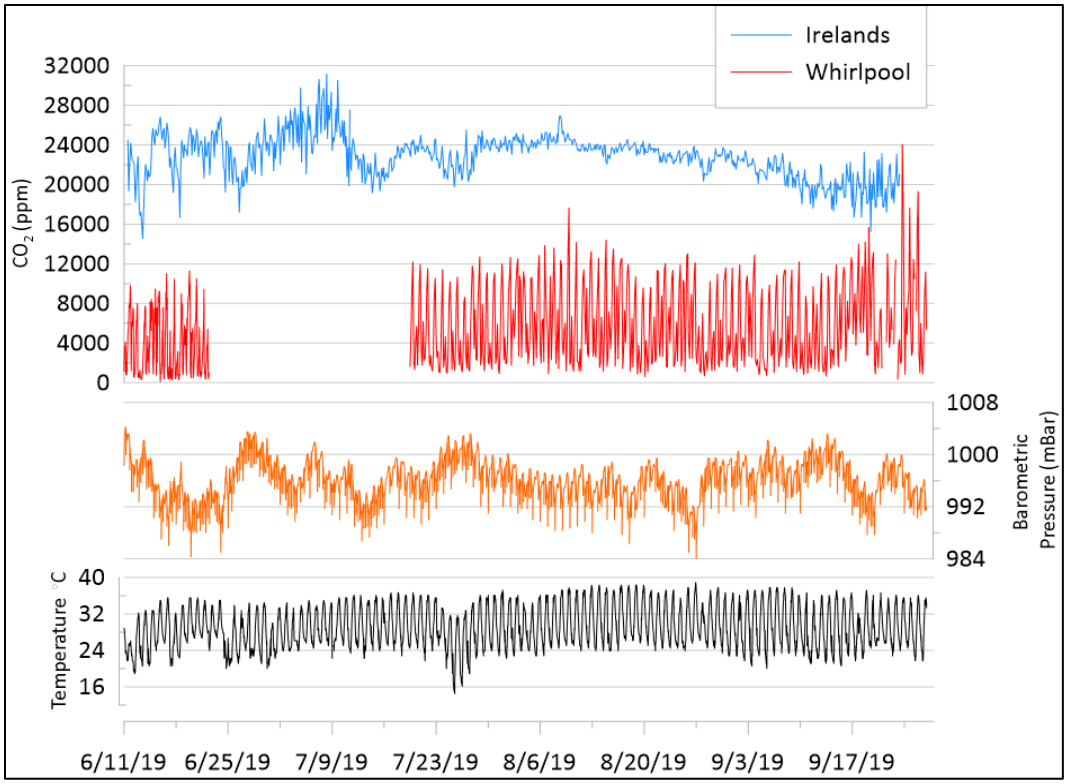

Figure 6. Representative cave-air CO2 concentrations at Irelands Cave and Whirlpool Cave during the warm season.

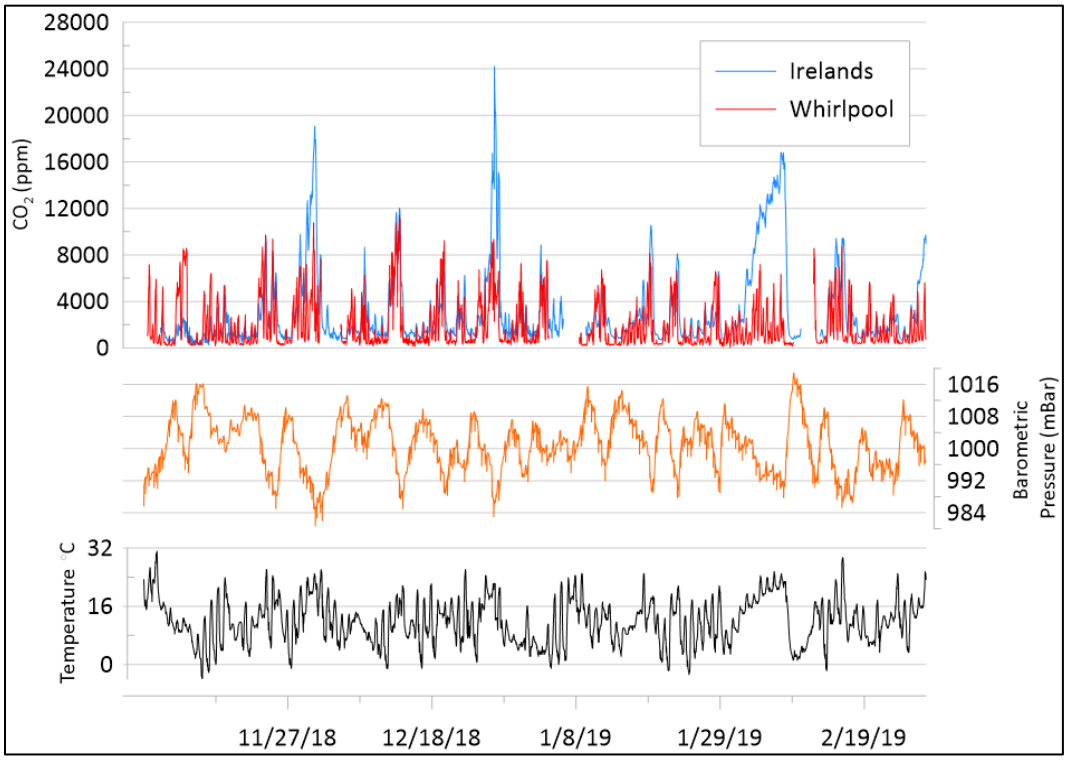

Figure 7. Representative cave-air CO_2 concentrations at Irelands Cave and Whirlpool Cave during the cool season.

Table 1. Summary of CO_2 concentration measurements at Irelands Cave and temperature and pressure measured at Camp Mabry in Austin, Texas. A period representative of cold[1] and warm[2] season cave CO_2 fluctuations was chosen for statistical analysis.

Irelands Cave		CO_2 (ppm)		Temperature (C)		Pressure (Slp)	
		Cold	Warm	Cold	Warm	Cold	Warm
	min	380	14560	-1.7	17.8	1002	1005
	max	24220	31150	32.2	40	1035	1021
	mean	1820	22805	15.0	29.1	1016	1014
	SD	3448	2227	3.8	4.3	6.6	2.9

[1]Cold: 11/08/2018–02/28/2019;
[2]Warm: 06/11/2019–09/23/2019

Table 2. 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[1] and warm[2] season cave CO_2 fluctuations was chosen for statistical analysis.

Whirlpool Cave		CO_2 (ppm)		Temperature (C)		Pressure (Slp)	
		Cold	Warm	Cold	Warm	Cold	Warm
	min	360	610	-1.7	17.8	1002	1005
	max	11380	24040	29.4	40	1035	1021
	mean	2310	5858	15.1	30.0	1015	1014
	SD	2327	4019	4.2	4.3	6.7	2.7

[1]Cold: 11/06/2018–01/04/2019;
[2]Warm: 07/19/2019–09/27/2019

Wind speed data in Whirlpool Cave showed regular daily intervals of measurable airflow into the cave (Figure 8). The end of these airflow events were followed by diurnal increases of CO_2 concentration in the cave. During these diurnal fluctuations, there was no measurable airflow out of the cave. However, airflow reversals occurred during periods of large barometric pressure and temperature changes –i.e., cold/warm fronts— (Figure 9). There were no measurable airflow events in Irelands Cave.

CO_2 concentrations in both Irelands Cave and Whirlpool Cave responded to weather events where barometric pressure significantly increased or decreased (i.e., a cold front or warm front). Cave CO_2 concentration generally increased in response to decreasing barometric pressure and decreased in response to increasing barometric pressure, with Irelands Cave showing significantly larger spikes in CO_2 concentration than Whirlpool (Figure 9). Also coincident with these fronts were more frequent measured airflow events and airflow direction reversals in Whirlpool Cave.

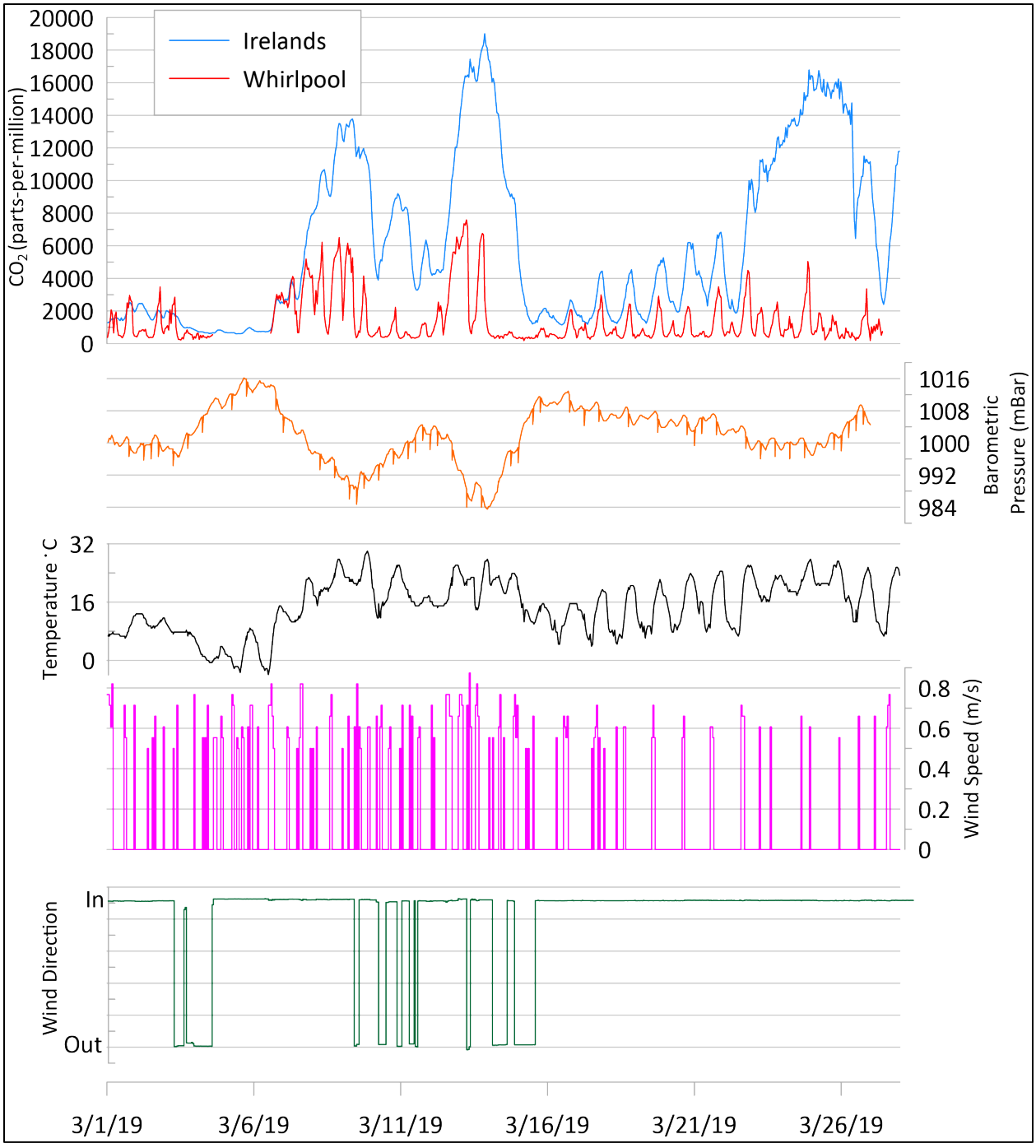

Figure 8. Surface air pressure, temperature, airflow velocity, airflow direction, and cave-air CO_2 concentrations at Whirlpool Cave and Irelands Cave in March 2019. Measurable cave airflow events and airflow reversals were more frequent during pressure front events (early March) than when surface air pressure was more stable (late March). Wind direction measurenebt

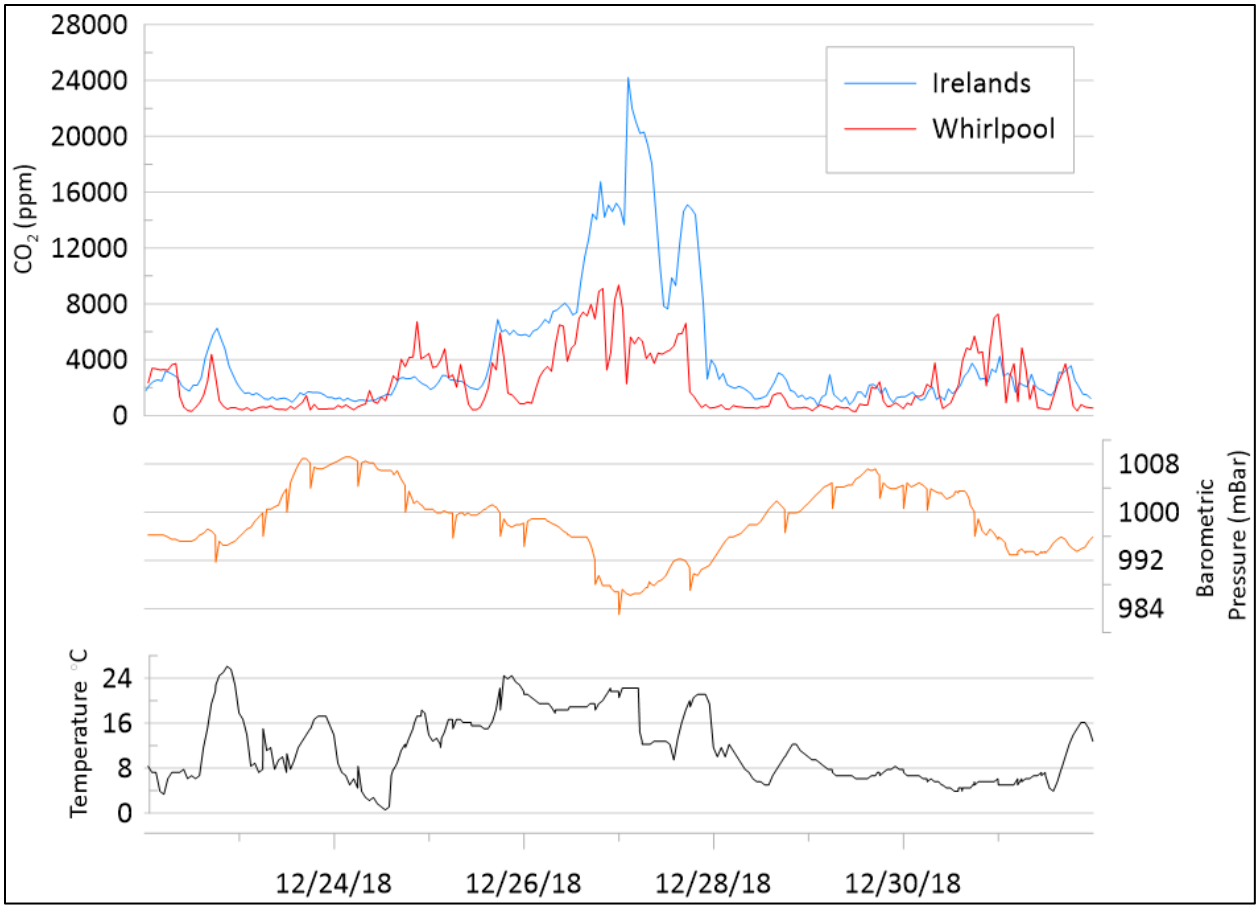

Figure 9. Surface air pressure, temperature, and cave-air CO_2 concentrations at Whirlpool Cave and Irelands Cave during a low-pressure front. Cave air CO_2 increased significantly when surface air pressure dropped and subsequently decreased when the pressure rose again.

Discussion

Seasonal Ventilation

CO_2 concentrations varied seasonally in both caves during the 2019 data collection period, with elevated CO_2 concentrations 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 ovarall cave-air CO_2 concentration. In the warmer months, when the outside air is less dense, cave ventilation becomes much weaker and average CO_2 concentration increases (Figure 4). Seasonal CO_2 fluctuations in the three study area caves do not appear to be caused by anthropogenic influences, including cave visitation. Whirlpool Cave receives significant visitation as the City of Austin utilizes it for educational tours. If human

visitation were causing seasonal CO_2 fluctuations, then we would expect to see seasonal fluctuations at Whirlpool Cave and no seasonal CO_2 fluctuations in Irelands Cave. Irelands 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 both caves.

Diurnal Ventilation and Cave Air CO_2 and Response to Warm/Cold Front Events

Barometric tides dominate diurnal airflow into and out of caves, and generally flow 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) which 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 (~410 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 airflow data collected during the 2019 data collection period provide evidence for barometric pumping in Irelands Cave and Whirlpool Cave. However, the onset of diurnal peaks in cave air CO_2 were typically out of phase with periods of low barometric pressure by several hours (Figure 10). In addition, the onset of measurable cave airflow events into the cave was often coincident with the onset of diurnal CO_2 peaks (early-to-late afternoon), rather than during periods of low cave air CO_2 when these airflow events would be expected (Figure 10). This suggests that there may be a several-hour time lag between changes in barometric pressure and subsequent CO_2 response. However, these discrepancies may also be a result of using NOAA barometric data from Camp Mabry in Austin, TX; which is over 10 miles from the cave entrances. For future CO_2 monitoring it is recommended that surface barometric pressure be measured in situ at the cave entrance. This would improve the surface pressure time series; and allow for a more reasonable evaluation of the timing of diurnal barometric fluctuations and CO_2 peaks.

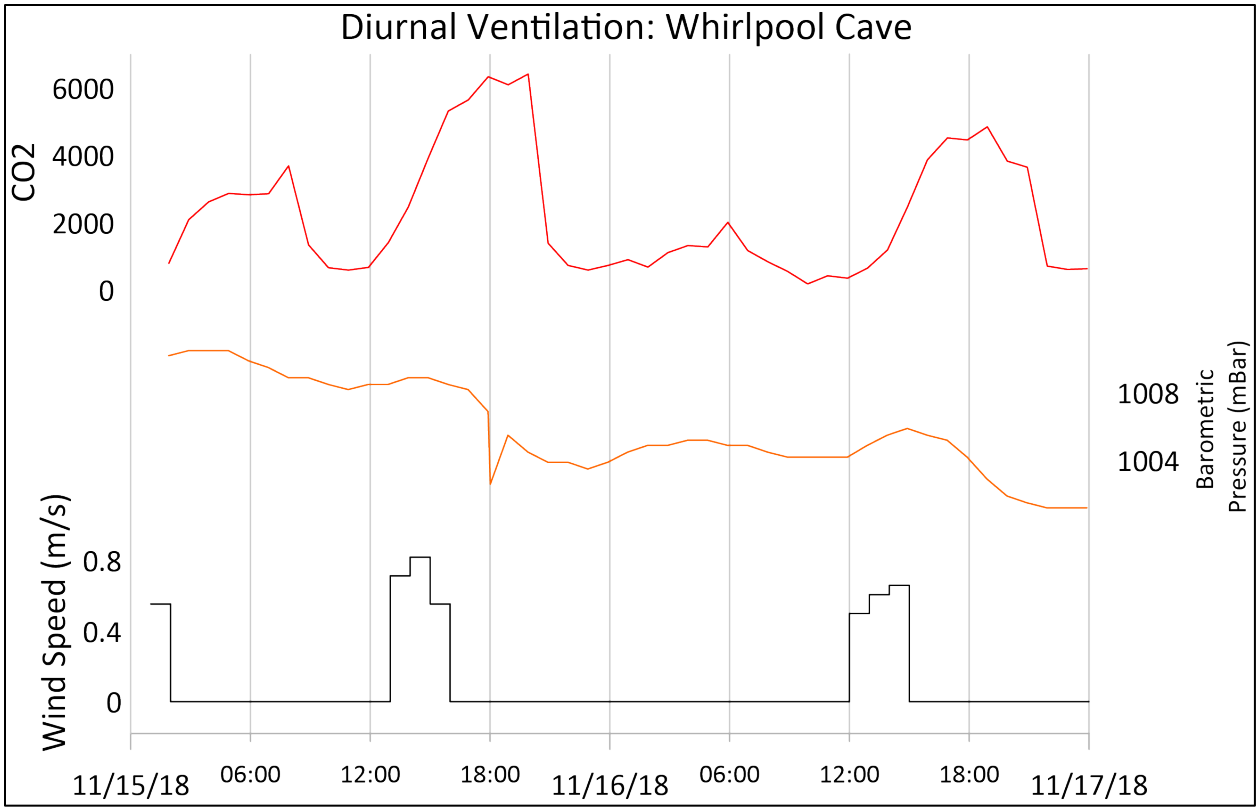

Figure 10. Measured cave air CO_2 and airspeed in Whirlpool Cave during diurnal ventilation events. Airflow direction was into the cave for these measured airflow events.

Low pressure and high pressure fronts are weather events typically accompanied by a significant increase or decrease in temperature, respectively. The 2019 cave air CO_2 showed distinct responses to these weather events in both Irelands Cave and Whirlpool Cave. Significant increases in CO_2 were observed in both caves coinciding with a low pressure front in late December 2018 (Figure 9). The magnitude of CO_2 increases in both caves was significantly larger than the increases observed during diurnal cave ventilation caused by the barometric tide. This suggests that pressure fronts can cause significantly larger cave air CO_2 responses than barometric tide-driven responses. Low pressure fronts cause significant increases in cave air CO_2 while high pressure fronts cause decreases in cave air CO_2. Irelands Cave reached significantly higher CO_2 concentrations in response to low pressure fronts than Whirlpool Cave. This may be due to higher soil gas CO_2 concentration adjacent to Irelands Cave than Whirlpool Cave, causing a larger spike in cave air CO_2. The difference in CO_2 responses between Irelands Cave and Whirlpool Cave is a topic that warrants further investigation.

Airflow data collected at Whirlpool Cave in 2019 showed regular measurable airflow events, with air flowing into the cave during barometric tide-driven low CO_2 periods. However, measurable airflow out of the cave was rare during barometric tide-driven high CO_2 periods. Airflow out of the cave was likely occurring during these diurnal ventilation events, but the magnitude was too small to be measured. It is unclear why airflow velocity out of the cave would be a lower magnitude than airflow into the cave; this observation warrants further investigation. Measurable airflow out of the cave was most frequent during cold front/warm front events.

During these events, it is common for larger swings in barometric pressure to occur than the regular diurnal changes caused by the barometric tide. Consequently, larger pressure gradients between the cave air and the atmosphere would be expected to drive more airflow and higher magnitude airflow velocities. Cave airflow data collected in early March 2019 showed more frequent measurable airflow events with higher average airflow velocities, which coincided with two cold front/warm front cycles (Figure 8). Measurable airflow direction reversals were also more frequent during these front events.

In summary, during 2019, the flow of air into and out of Whirlpool Cave and Irelands Cave appeared to reverse twice every 24 hours, except when high or low pressure fronts or other disturbances moved through the region. These reversals coincided with daily maximum and minimum barometric pressure and appeared to be driven by the diurnal barometric tide. In response to this diurnal airflow pattern, CO_2 decreased when lower CO_2 atmospheric air was pushed into the caves. When airflow reversed, high CO_2 air was pulled into the cave from the adjacent soil and epikarst, causing an increase in cave air CO_2. In the summer months, the magnitude of diurnal CO_2 fluctuations was significantly higher in Whirlpool Cave than Irelands Cave. This suggests that daily barometric tide-driven ventilation has a greater influence on Whirlpool Cave than Irelands Cave. In contrast, Irelands Cave appeared to be more responsive to large pressure fronts than Whirlpool Cave, with significantly larger CO_2 increases coinciding with low pressure fronts. The cause of these different CO_2 responses could be related to differences cave morphology, geology, or levels of microbial CO_2 production in the soils and epikarst overlying the caves. Additional investigations could help to clarify the varied CO2 reponse in these two caves.

Recommendations

The results of this study can help guide management decisions regarding caves within the BCP. 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 (2% CO_2), 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 (3% CO_2) symptoms may include exhaustion, increased heart rate, and headache. Loss of consciousness may occur above 50,000 ppm (5% CO_2). 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 7 - Figure 6, Table 2). 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 (0.8% CO_2) or less in the cooler months, and 10,000 ppm (1% CO_2) to 13,000 ppm (1.3% CO_2) 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 monitor cave visitors for symptoms of carbon dioxide poisoning and exit the cave immediately if any symptoms are observed.

The highest CO_2 concentrations were measured in Irelands 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 Irelands 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. Irelands Cave is not suitable for tour groups at any time. Personnel should always check weather forecasts before 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 Irelands Cave. Only experienced persons, knowledgeable about cave safety and high CO_2 environments, should enter this cave. Before entering Irelands Cave, a blower and tubing should be used to ventilate the cave artificially. Personnel should always carry and use a reliable handheld CO_2 meter while in Irelands Cave and should be ready to evacuate the cave quickly if CO_2 concentrations reach an unacceptable level.

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