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ANNUAL SUMMARY OF CARBON DIOXIDE MONITORING IN THREE 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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26 January 2021
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Abstract

Cave-air carbon dioxide (CO_2) concentration was measured in three Balcones Canyonlands Preserve caves (Whirlpool Cave, Grassy Cove Cave, and Irelands Cave) using Vaisala logging CO_2 meters. Anemometers and wind vanes were also deployed in the caves to measure wind speed velocity and wind direction. This report covers data collected between October 2019 and November 2020. Cave CO_2 concentrations fluctuated both seasonally and diurnally in all three caves and within similar timeframes. Maximum and minimum CO_2 concentrations and the magnitude of CO_2 fluctuations differed in all three caves. Seasonal CO_2 concentrations were elevated May through October (the warm season) and were lowest December through February (the cool season). Diurnal CO_2 fluctuations during the warm season were generally smaller in magnitude in Irelands Cave than Whirlpool Cave, while Grassy Cove Cave had large diurnal fluctuations throughout the study period regardless of season. Surface weather conditions, especially atmospheric pressure fronts, significantly altered diurnal CO_2 fluctuations for periods lasting from hours to days. Measured CO_2 in Irelands Cave and Grassy Cove Cave fluctuated more than 20,000 ppm in response to some individual pressure fronts. Airflow data, measured by a newly deployed sonic anemometer in Whirlpool Cave, indicated a diurnal peak in airflow velocity followed by a drop in velocity. This drop in airflow velocity coincided with an abrupt change in airflow direction from approximately 45° to approximately 355°, and a significant increase in cave air CO_2. There were no measurable airflow events in Irelands Cave and Grassy Cove Cave, which do not yet have sonic anemometers deployed at their monitoring stations. The results of this cave-air CO_2 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 be dangerous to humans in high concentrations, 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 third year of data collection (October 2019-November 2020) from Whirlpool Cave, Grassy Cove 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 (e.g., degassing of drip water or gas 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 outputs due to 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 (e.g. 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 causing overall CO_2 concentration to increase. Evidence of such cave breathing and diurnal CO_2 fluctuations have been 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 caves, 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 this contact.

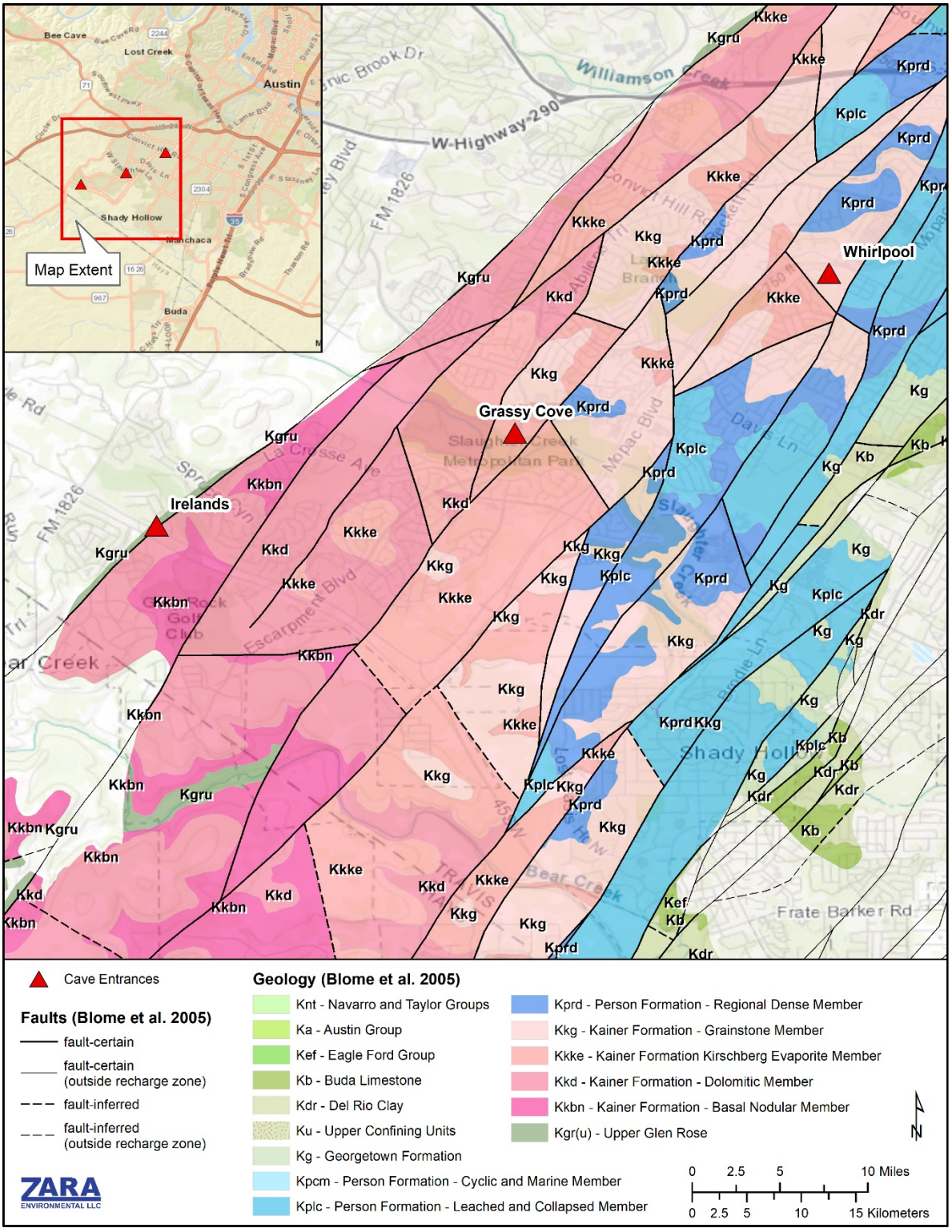


Figure 1. Project area overview showing the location of caves and surface geology.

Study Caves

Whirlpool Cave is approximately 22,000 cubic feet (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 33 ft 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, Grassy Cove Cave, and Irelands Cave (Figure 2, Figure 3, and Figure 4, respectively) with Vaisala GM70 hand-held CO_2 meters logging at 3-hour intervals. This logging interval was selected to collect the maximum amount of data given limitations of battery life of hand-held meters and approximately 1-month frequency of visits to Whirlpool Cave Irelands Cave. Cave-air CO_2 measurements in Grassy Cove Cave were collected using a Vaisala GMP252 CO_2 meter connected a surface station via a communication cable run through a borehole. Signal output from the CO_2 meter was converted to analog output using a Vasiala Indigo 201 Analog Output transmitter and logged at 5-minute increments using a DL4000 Universal Data Logger. A solar array and two-12V deep cycle marine batteries provided continuous power to the Grassy Cove surface station, allowing a much smaller logging interval than the hand-held meters deployed at Whirlpool Cave and Irelands Cave. Vaisala CO_2 meters measure CO_2 concentration using 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. Within Whirlpool Cave and Irelands Cave CO_2 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. Irelands Cave was ventilated with a blower for 20 minutes to lower CO_2 levels prior to entry for the safety of staff performing data collection.

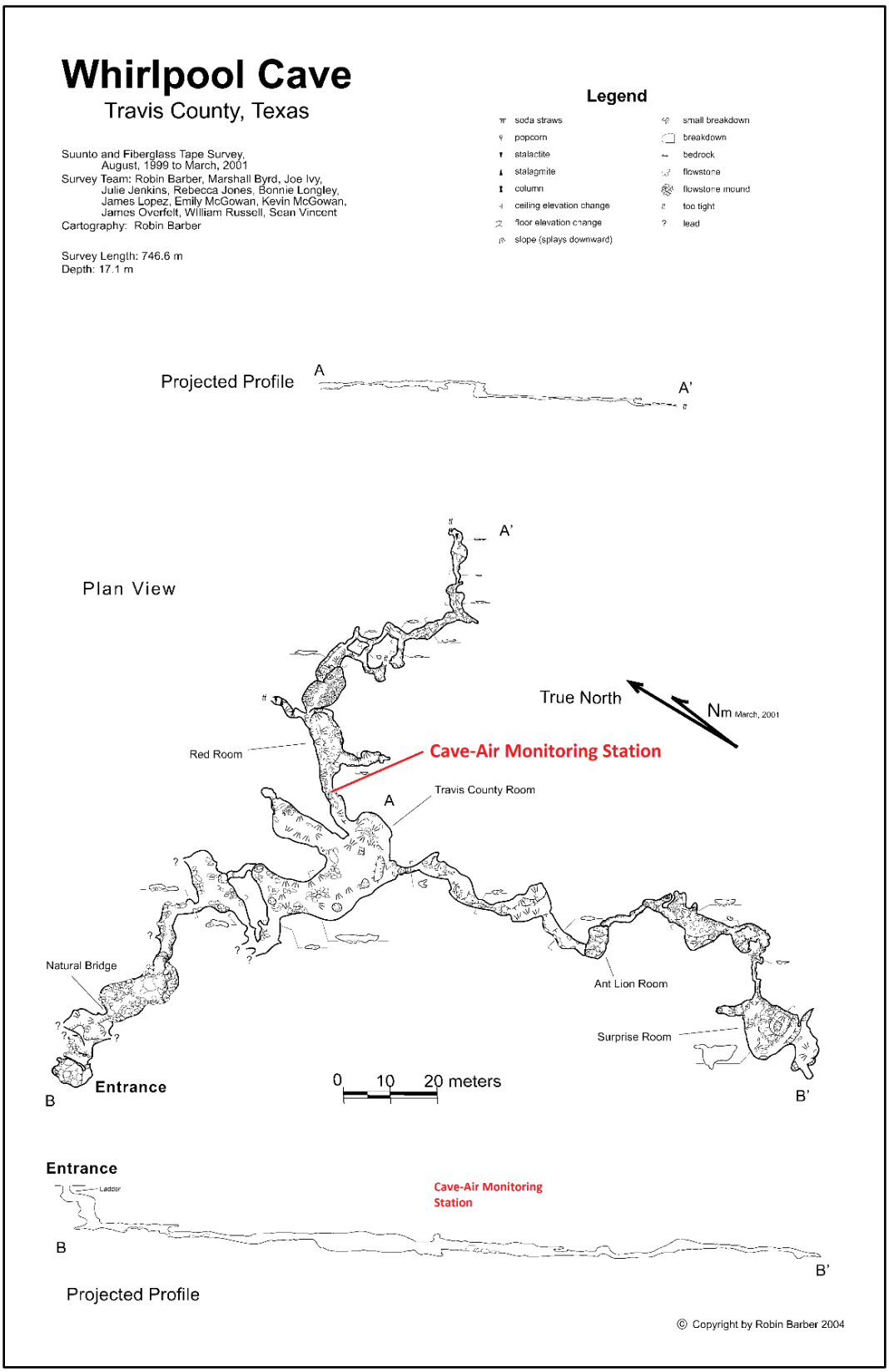


Figure 2. Location of the cave-air monitoring station in Whirlpool Cave

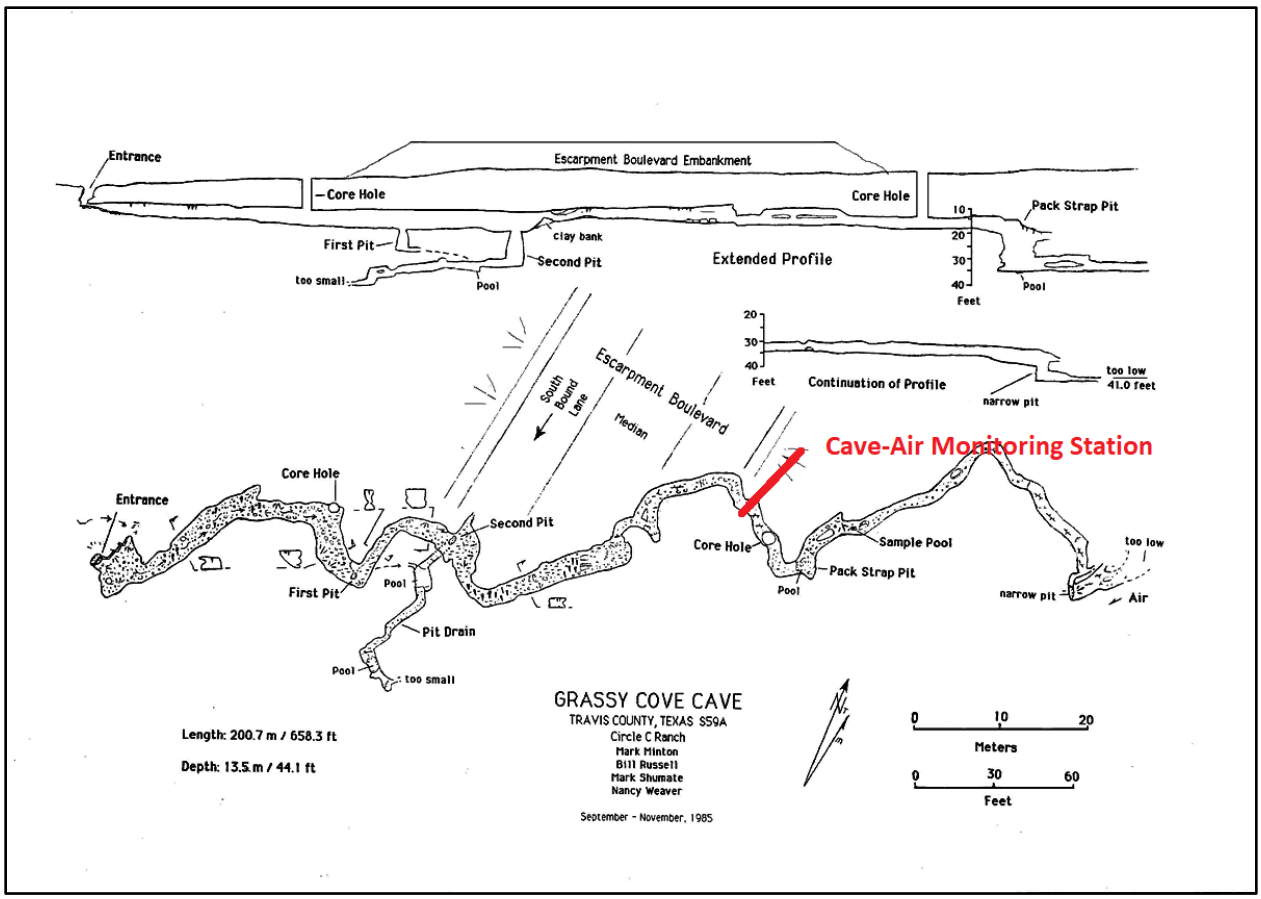


Figure 3. Location of the cave-air monitoring station in Grassy Cove Cave.

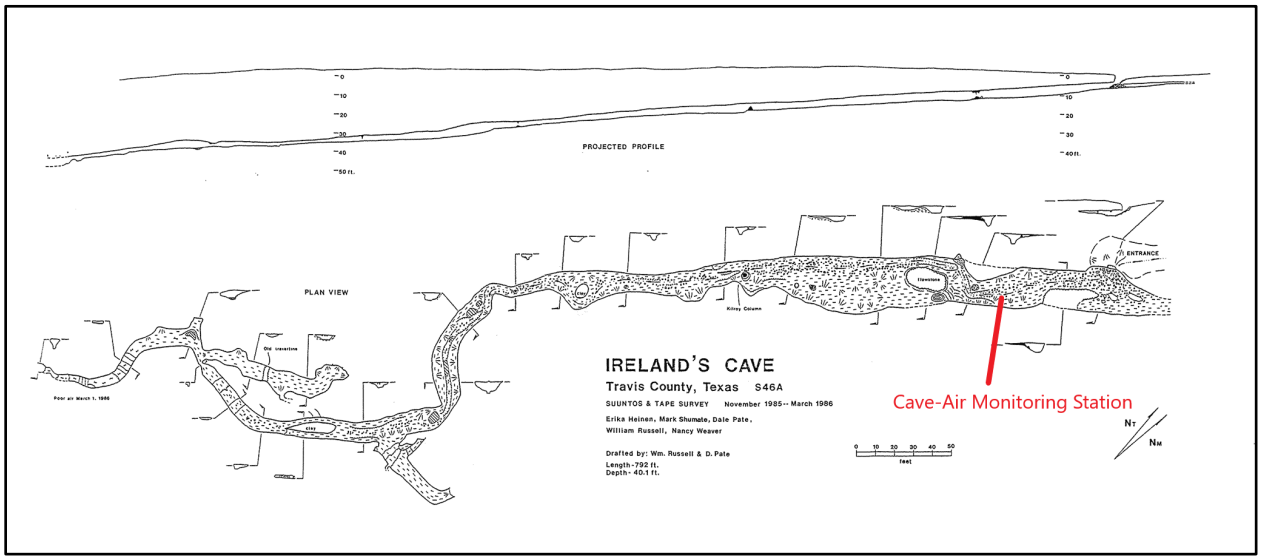


Figure 4. Location of the cave-air monitoring station in Ireland's Cave.

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.

Occasionally, CO_2 concentration values >100 ppm below atmospheric (approximately 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 CO_2 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.

Cave wind speed velocity and wind direction were measured in at all three 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 Incorporated. To-date the only measurable wind speed events have occurred in Whirlpool Cave during the two-year data collection period, and no measurable airflow has been reported from Irelands Cave and Grassy Cove Cave.

The CR 300 logger at Whirlpool Cave failed in April 2020, causing a data gap from April-late July 2020. In October 2020 the logger was replaced, and a new ATMOS-22 Sonic Anemometer was deployed in place of the mechanical wind vane. The sonic anemometer is likely better suited for cave deployment because it provides more accurate air-flow measurements at low velocity ranges typical of cave environments, and does not have any moving mechanical parts which may be affected by the high-humidity cave environment. Data was collected from the sonic anemometer in Whirlpool Cave from October-November 2020 and is included in this report. The CR 300 logger in Irelands Cave failed in August 2020 and will be replaced in early 2021. Also, the wind vanes currently deployed in Grassy Cove Cave and Irelands Cave will be replaced with sonic anemometers in 2021 to provide better quality airflow data.

Weather data from October 2019-April 2021 was obtained from a National Oceanic and Atmospheric Administration (NOAA) weather station located at Camp Mabry in Austin, Texas (COOPID: 410428), located approximately 14 km north of Whirlpool Cave (NOAA 2021). In April 2020 a HOBO U20 pressure transducer was deployed at the Grassy Cove Cave surface station in

order to provide atmospheric pressure and temperature measurements closer to the study area. Both datasets are presented in this report. Excel was used to collate and organize CO_2, airflow, and weather data. Grapher 17 by Goldenware was used to generate time series graphs over different time periods. Representative warm and cold season periods were selected for each cave for analysis.

Results

Diurnal, seasonal, and pressure-front-related CO_2 concentration fluctuations were observed in all three caves during the 2020 data collection period (Figure 5).

Diurnal fluctuations in cave air CO_2 concentrations differed significantly between all three caves, and the duration and magnitude of fluctuations varied depending on time of year. Figure 6 presents data from a representative timeframe in early August 2020 when all three caves were showing diurnal fluctuations corresponding to diurnal fluctuations in atmospheric pressure and temperature. Irelands Cave showed the least amount of diurnal fluctuation (<2000 ppm-per-day). Grassy Cove Cave and Whirlpool Cave both displayed significantly larger diurnal fluctuations in CO_2 concentration (>20,000 and <10,000 ppm CO_2 respectively); and displayed a bimodal diurnal pattern where two drops in CO_2 occurred at roughly the same early morning and late evening timeframes. These diurnal drops in CO_2 coincided with atmospheric pressure increases likely associated with diurnal barometric tide fluctuations.

Irelands Cave showed less pronounced CO_2 fluctuations in the warm season (Early June 2020-Late September 2020; Figure 7) than the cool season (Early October 2019-Late February 2020; Figure 8) when diurnal CO_2 fluctuated as much as 8,000 ppm.

Table 1, Table 2, and Table 3 summarize cave-air CO_2 concentration and weather conditions during periods representative of the cool season and warm season in Irelands Cave, Whirlpool Cave, and Grassy Cove Cave, respectively. Maximum, minimum, average, and standard deviation of CO_2 concentration varied by cave and by season. During the cool season, all three caves had lower average CO_2 levels than during the warm season, and had minimum CO_2 levels approaching atmospheric concentrations (<1,000 ppm). Grassy Cove Cave and Irelands Cave still had CO_2 levels above 20,000 ppm during the cold season, while the maximum in Whirlpool was 9,210. During the warm season, all three caves had a maximum CO_2 level above 25,000 ppm. Grassy Cove Cave had the highest registered CO_2 reading at 32,991 ppm. Irelands Cave had a consistently high CO_2 level during the warm season which rarely dropped below 16,000 ppm, and generally remained close to the mean of 20, 948 ppm (Figure 7). Whirlpool Cave was the only of the three caves to regularly reach near-atmospheric CO_2 concentrations (slightly above 1,000 ppm) during the warm season, suggesting that it fully ventilates more frequently than Irelands Cave and Grassy Cove Cave during this time period.

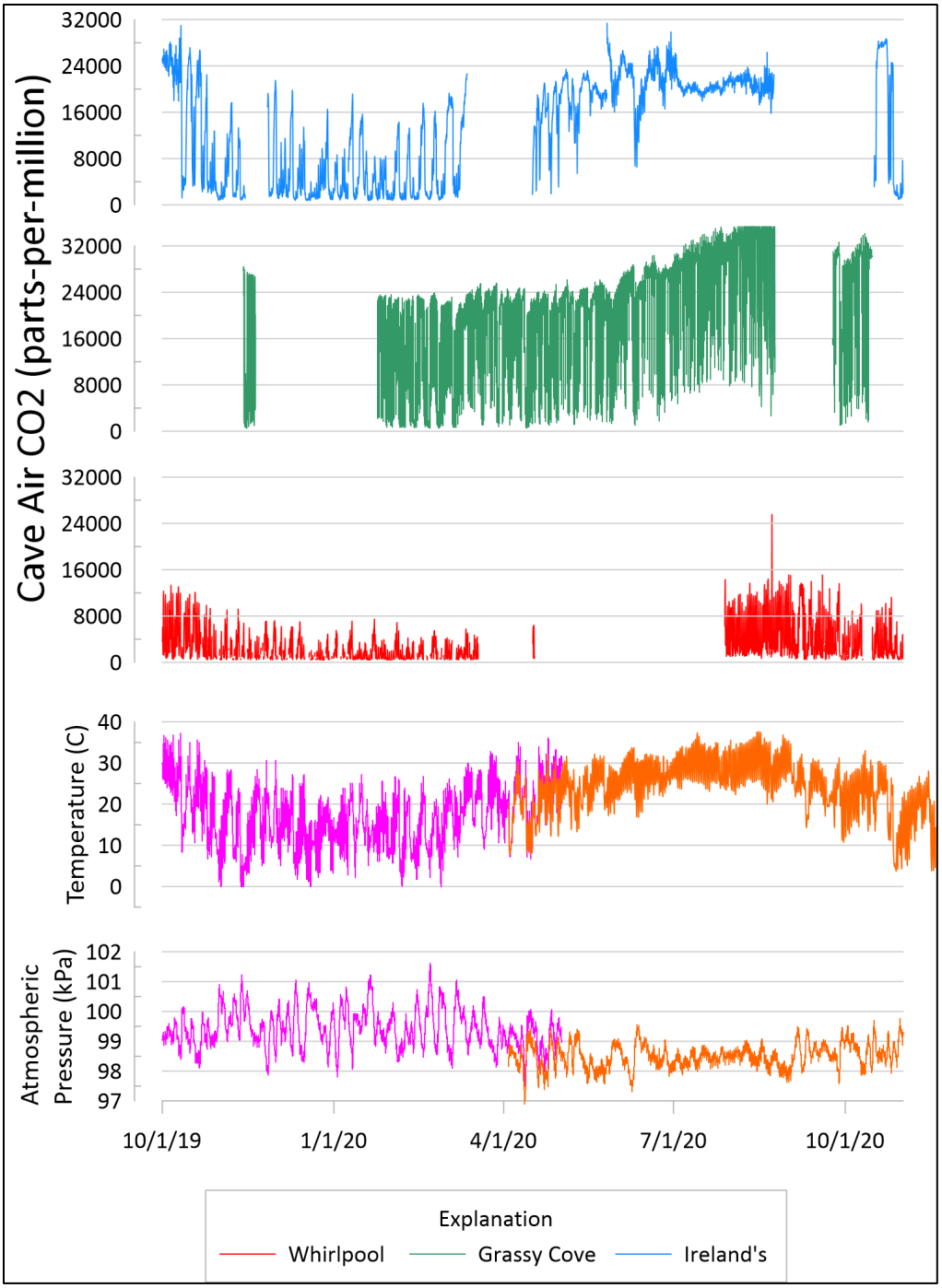


Figure 5. 1-year time series data of CO_2 concentration in Whirlpool Cave, Grassy Cove Cave, and Irelands Cave compared to temperature and barometric pressure. Magenta lines represent NOAA surface data from the Camp Mabry Station (NOAA 2021); orange lines represent data from a transducer deployed outside of Grassy Cove Cave in April 2020. Some time intervals are missing from all three caves due to monitoring equipment failures.

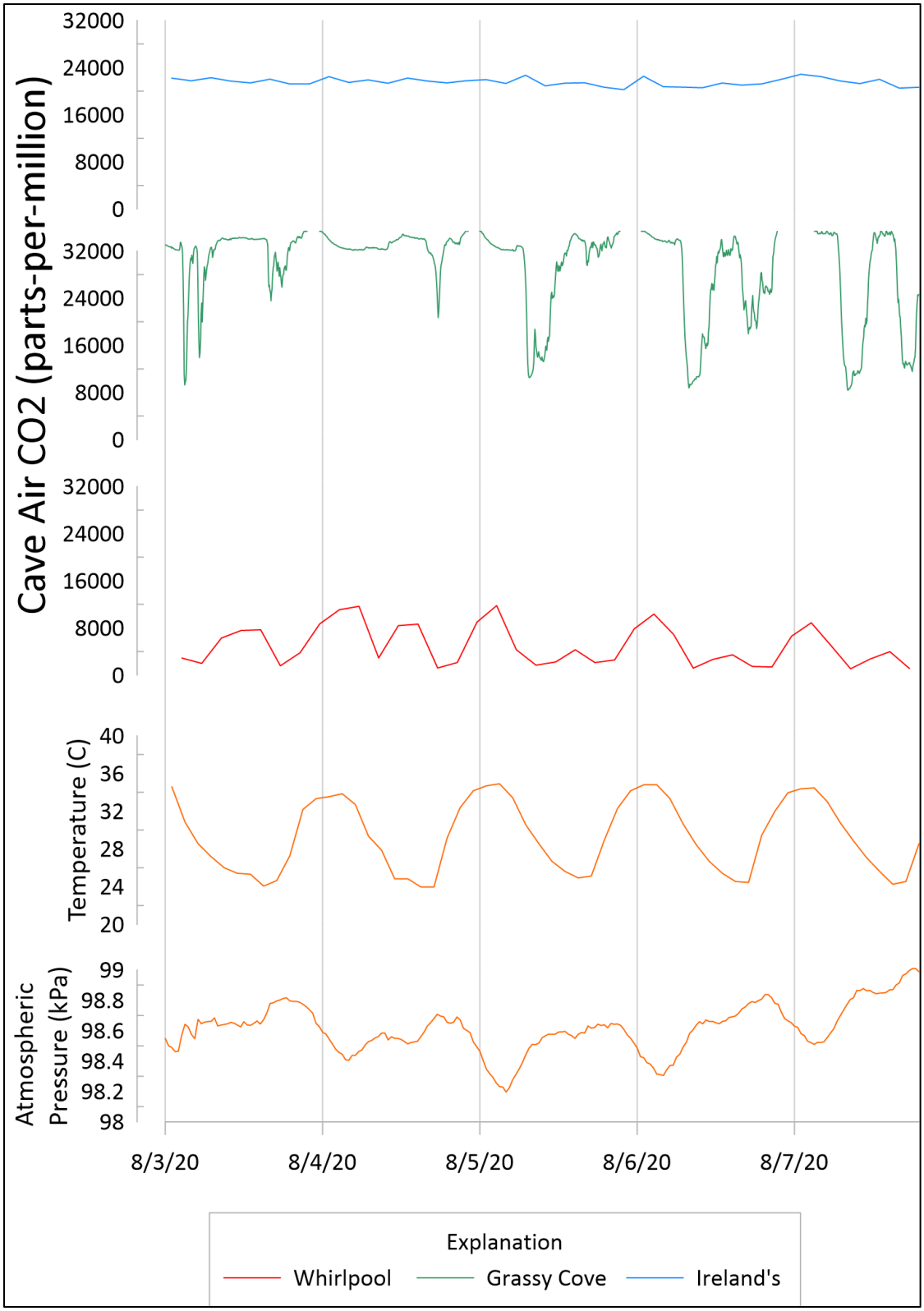


Figure 6. Surface air pressure, temperature, and cave air CO_2 measured in Whirlpool Cave and Irelands Cave, Grassy Cove Cave, and Whirlpool Cave in August 2020. Data show a clear diurnal signal in CO_2 increases for Grassy Cove and Whirlpool caves with significantly less CO_2 variability in Irelands Cave.

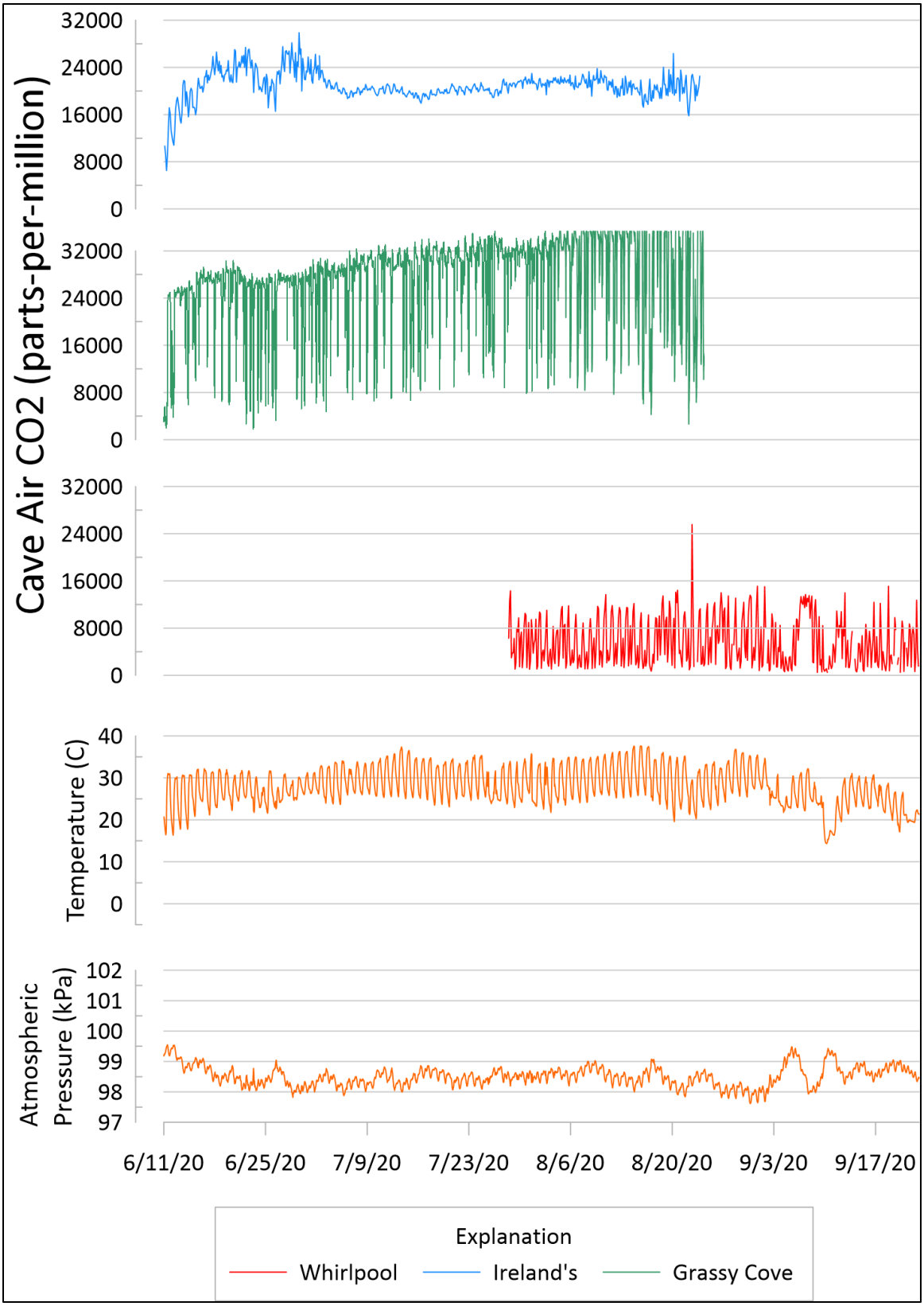


Figure 7. Representative cave-air CO2 concentrations at Irelands Cave, Whirlpool Cave, and Grassy Cove Cave during the warm season. Temperature and atmospheric pressure data from NOAA (2021).

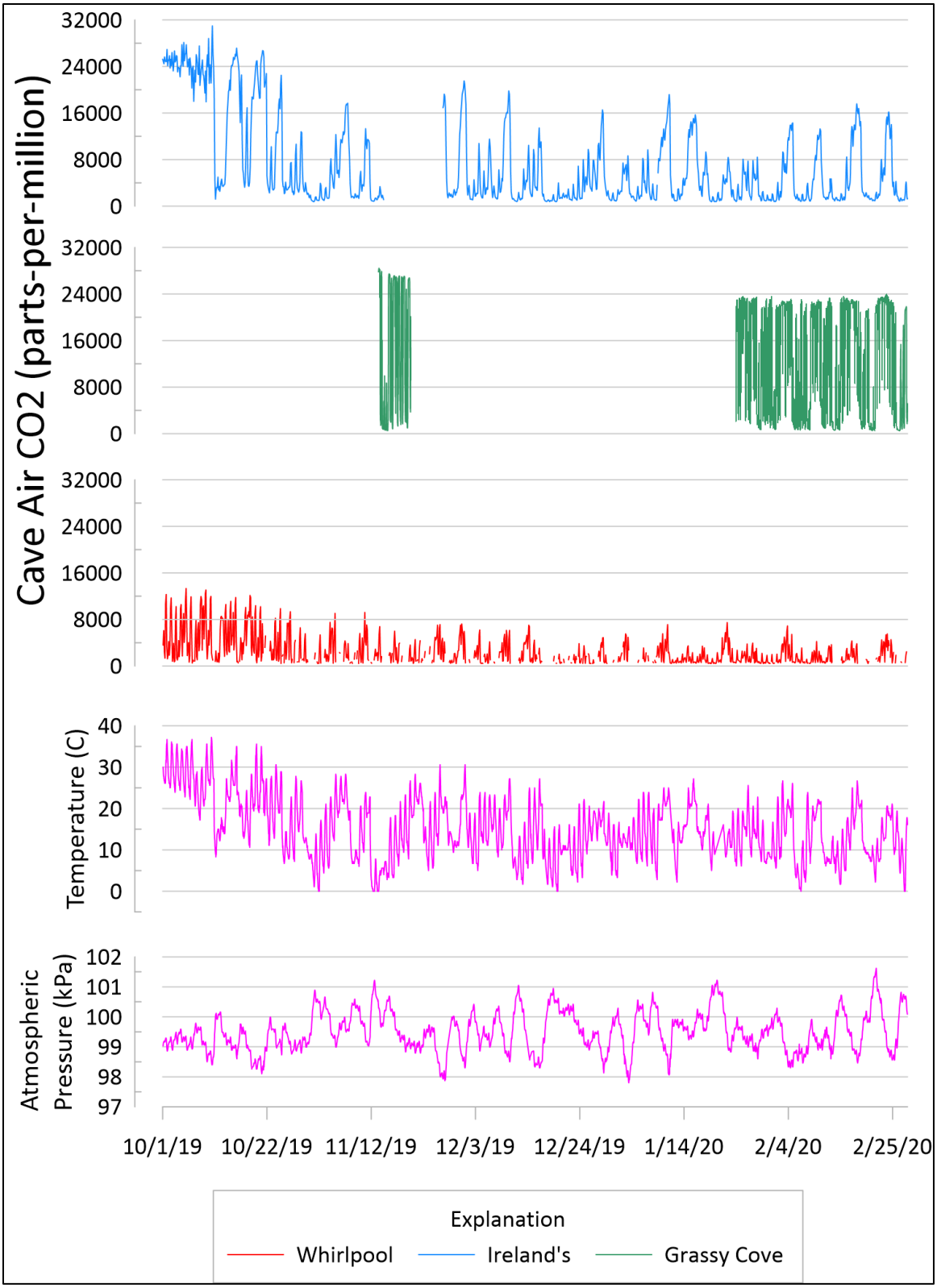


Figure 8. Representative cave-air CO_2 concentrations at Irelands Cave, Whirlpool Cave, and Grassy Cove Cave during the cool season. Temperature and atmospheric pressure data from pressure transducer deployed at Grassy Cove Cave surface station.

Table 1. Summary of CO_2 concentration measurements at Irelands Cave, and temperature and pressure measured at Camp Mabry in Austin, Texas (cold season) and by a pressure transducer deployed at Grassy Cove Cave (warm season). A period representative of cold[1] and warm[2] season cave CO_2 fluctuations was chosen for statistical analysis. CO_2 data was not available for the following date ranges: 11/14/19-11/26/19; 3/12/20-4/16/20; 8/23/20-10/16/20.

Irelands Cave		CO_2 (ppm)		Temperature (C)		Pressure (kPa)	
		Cold	Warm	Cold	Warm	Cold	Warm
	min	740	6530	0.0	14.3	97.80	97.6
	max	21530	29870	30.4	37.6	101.62	99.55
	mean	4643	20948	13.3	28.0	99.54	98.51
	SD	4706	2287	7.2	4.4	0.64	0.33

[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 (cold season) and by a pressure transducer deployed at Grassy Cove Cave (warm season). A period representative of cold[1] and warm[2] season cave CO_2 fluctuations was chosen for statistical analysis. CO2 data was not available for the following date ranges: 3/18/20-4/16/20; 4/17/20-7/28/20.

Whirlpool Cave		CO_2 (ppm)		Temperature (C)		Pressure (kPa)	
		Cold	Warm	Cold	Warm	Cold	Warm
	min	410	410	0.0	14.3	97.80	97.6
	max	9210	25560	30.4	37.6	101.62	99.55
	mean	2100	5664	13.3	28.0	99.54	98.51
	SD	1795	4043	7.2	4.4	0.64	0.33

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

Table 3. Summary of CO_2 concentration measurements at Grassy Cove Cave, and temperature and pressure measured at Camp Mabry in Austin, Texas (cold season) and by a pressure transducer deployed at Grassy Cove Cave (warm season). A period representative of cold[1] and warm[2] season cave CO_2 fluctuations was chosen for statistical analysis. CO2 data was not available for the following date ranges: 11/8/19-11/13/19; 11/19/19-1/24/20; 8/24/20-9/24/20.

Grassy Cove Cave		CO_2 (ppm)		Temperature (C)		Pressure (kPa)	
		Cold	Warm	Cold	Warm	Cold	Warm
	min	412	1757	0.0	14.3	97.80	97.6
	max	28430	32991	30.4	37.6	101.62	99.55
	mean	13058	25209	13.3	28.0	99.54	98.51
	SD	9520	7279	7.2	4.4	0.64	0.33

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

In Irelands Cave and Grassy Cove Cave the standard deviation from mean CO_2 levels was significantly larger during the cold season than during the warm season, suggesting that fluctuations in CO_2 levels are higher in the cold season for these caves. Whirlpool Cave CO_2 data showed the opposite of this trend, with higher standard deviation in the warm season. However, Whirlpool Cave CO_2 monitoring equipment was down for much of June and July 2020, which may reduce the quality of this statistical analysis.

CO_2 concentrations in all three caves 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 (Figure 9). The magnitude of CO_2 fluctuations coinciding with atmospheric pressure fronts was often larger than fluctuations associated with the diurnal barometric tide.

There was limited cave airflow data available during the 2020 study period due to a data logger failure in Whirlpool Cave, and the lack of measurable airflow events to-date in Grassy Cove Cave and Irelands Cave. However, in late 2020 a new data logger was installed in Whirlpool Cave and the wind vane was replaced with a sonic anemometer, which provides higher resolution airflow data at low airflow velocities than the wind vane. The first round of data was collected from this new measurement array in October-November 2020. An 8-day time period of this data is presented in Figure 10 which showed regular airflow and airflow fluctuations throughout the period of measurement. Wind gust velocity in the cave increased in response to increases in atmospheric pressure, and had two distinctive directions: ~45° and ~355° azimuthal.

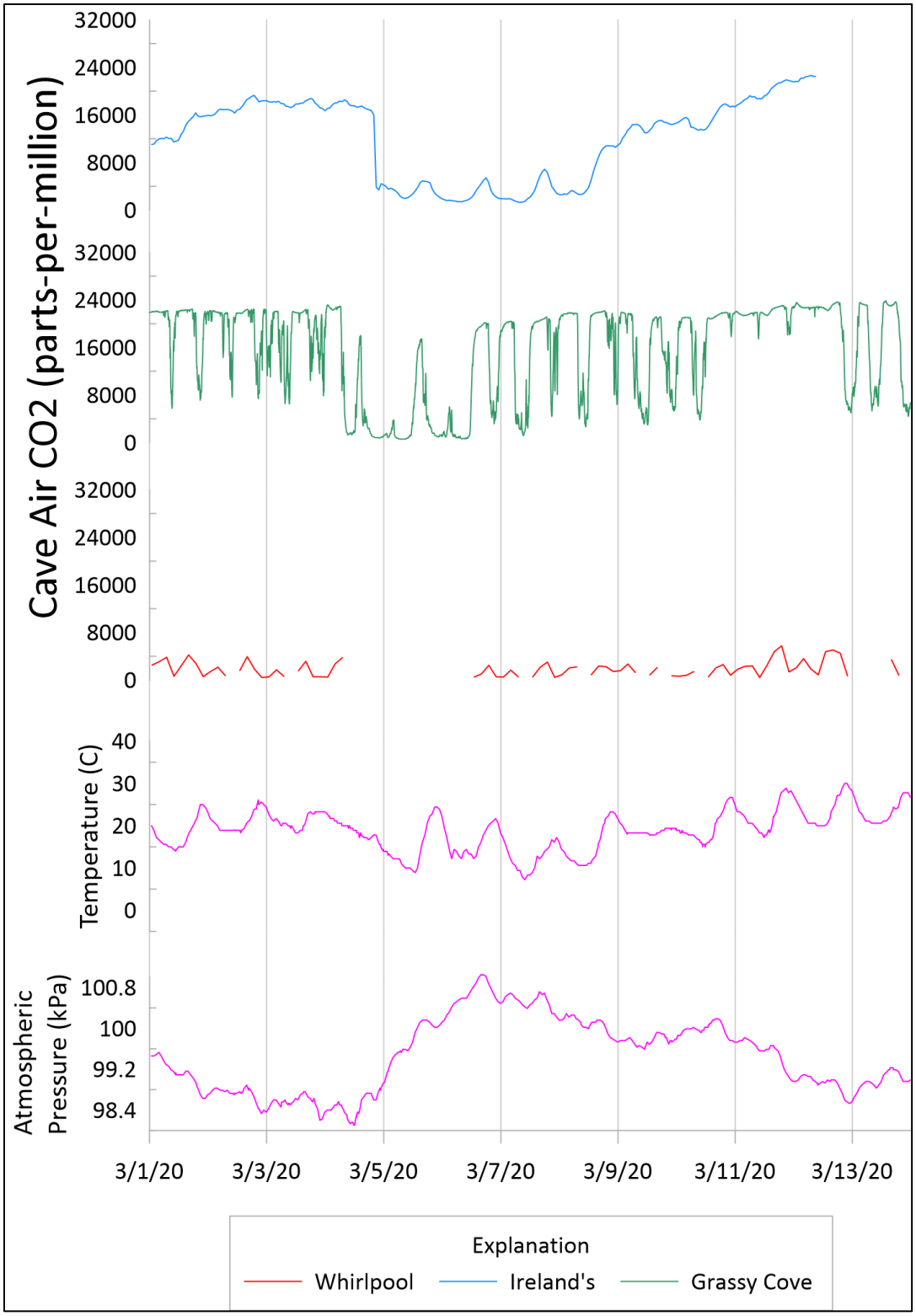


Figure 9. Atmospheric pressure, temperature, and cave-air CO_2 concentrations at Whirlpool Cave, Irelands Cave, and Grassy Cove Cave during a high-pressure front. Data gaps in Whirlpool Cave represent data points where measured CO_2 was below 410 ppm; thus, those points were removed in the data quality control process (see methods section). However, these gaps can be interpreted as "low CO_2" time periods.

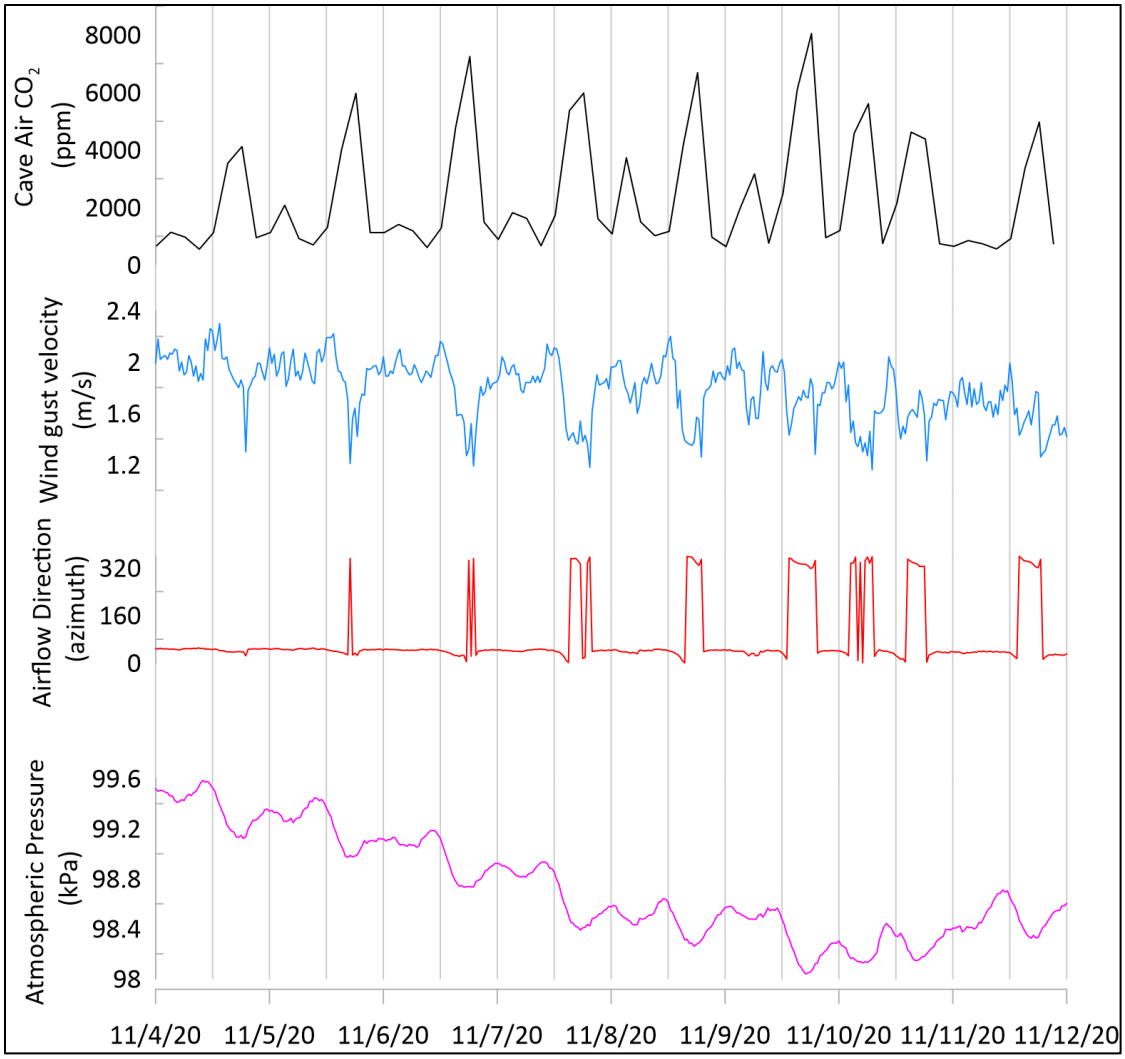


Figure 10. Cave air CO_2, airflow gust velocity, and airflow direction in Whirlpool Cave during diurnal ventilation events. Airflow data was measured by a sonic anemometer installed in late 2020.

Discussion

Seasonal Ventilation

CO_2 concentrations varied seasonally in all three caves during the 2020 data collection period, with generally 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 in part 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 overall 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 5). Higher CO_2 concentrations in the warmer months are also likely influenced by increased soil respiration resulting from warmer temperatures.

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 all three 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 (Melcior 1993; Wallace and Hobbs 2006) which have 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. Deploying pressure transducers at the cave monitoring locations would possibly allow direct measurement of differences between barometric pressure in caves and on the surface.

Low pressure and high pressure fronts are weather events typically accompanied by a significant increase or decrease in temperature, respectively. The 2020 cave-air CO_2 concentration measurements showed distinct responses to these weather events in all three caves. Significant decreases in CO_2 concentration were observed in the caves coinciding with a high pressure front in March 2020 (Figure 9). The magnitude of the CO_2 decrease was significantly larger than those 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 diurnal barometric tide-driven responses. In response to low pressure fronts, Irelands Cave and Whirlpool Cave reached significantly higher CO_2 concentrations than Whirlpool Cave. The cause of different CO_2 responses between Irelands Cave, Grassy Cove Cave, and Whirlpool Cave is a topic that warrants further investigation.

Airflow data measured by a newly deployed sonic anemometer in Whirlpool Cave in late 2020 provides a previously unavailable dataset of cave air velocity and direction, because it has a higher accuracy at low airflow velocities than the weather vane which was previously deployed. In October-November 2020, the anemometer measured nearly continuous airflow over the study period. Diurnal peaks in cave air velocity observed in Whirlpool Cave coincided with atmospheric pressure increases associated with diurnal barometric tide (Figure 10). These diurnal peaks were followed by air velocity drops which coincided with drops in atmospheric pressure, an abrupt

change in airflow direction from ~45° to ~355°, and rapid increases in cave-air CO_2 concentration. The ~355° bearing is aligned with a large cave passage which leads away from the entrance and to a deeper section of the cave (Figure 2, Projected Profile A-A'), which implies that CO_2 is being drawn into the cave from this deeper passage. Deployment of sonic anemometers in Irelands Cave and Grassy Cove Cave is planned for the 2021 data collection period, and should provide additional insights on how cave airflow controls CO_2 concentrations; and how cave airflow events are controlled by both diurnal and weather-related atmospheric pressure fluctuations.

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