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ENVIRONMENTAL LLC
Integrity | Science | Expertise
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



Atmospheric carbon dioxide data retrieval station in Whirlpool Cave.

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

31 August 2021

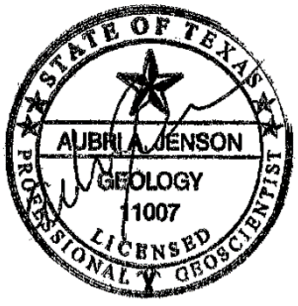
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31 August 2021
Aubri A. Jenson, Texas Professional Geoscientist No. 11007
Zara Environmental LLC Geoscience Firm Registration No. 50365

Abstract

Cave air carbon dioxide (CO_2) concentration was measured in three Balcones Canyonlands Preserve caves (Irelands Cave, Grassy Cove Cave, and Whirlpool Cave) using Vaisala logging CO_2 meters. Sonic anemometers were also deployed in the caves to measure the speed and direction of cave airflow. This report covers data collected between December 2020 and August 2021. 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 August (the warm season) and were lower December through March (the cool season), reaching the lowest levels during the cold front that occurred in mid-February 2021. Diurnal CO_2 fluctuations during the warm season were generally smaller in magnitude in Irelands Cave than in Whirlpool Cave, while Grassy Cove Cave exhibited 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 provided new information to identify cave ventilation patterns in relation to barometric changes and CO_2 fluctuations. Notably, airflow azimuths in Whirlpool Cave and Irelands Cave indicate airflow into the caves during cooler periods and out of the cave during warmer periods. In contrast, Grassy Cove Cave consistently exhibits airflow toward the cave entrance. 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 were monitored continuously in three BCCP permit caves beginning in October 2017. This report summarizes the findings of the fifth year of data collection (December 2020-August 2021) from Irelands Cave, Grassy Cove Cave, and Whirlpool 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 both seasonally and daily, often with significant volumes of cave air expelled and significant volumes of surface air flowing in (Cowan et al. 2013). 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). The regional geology 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.

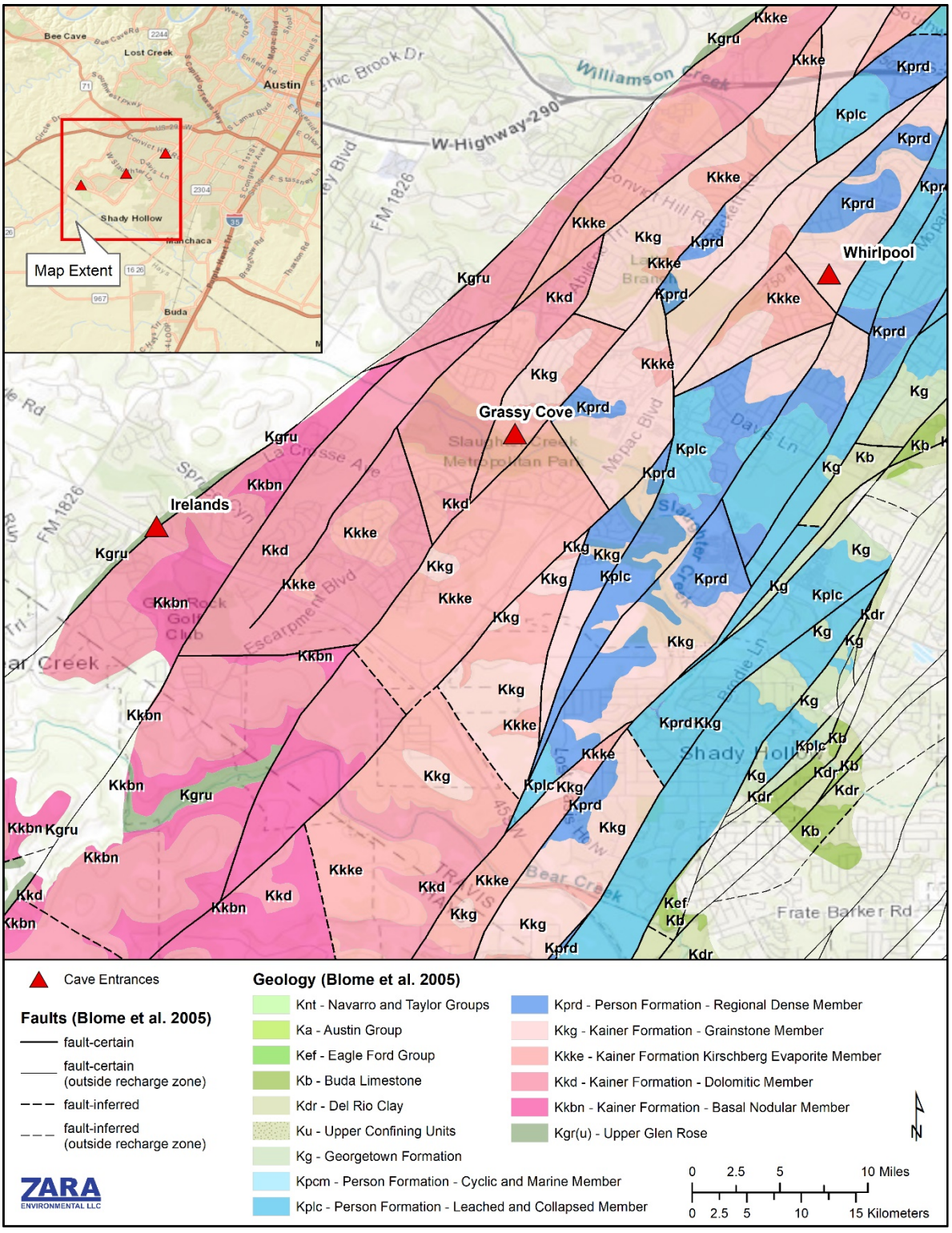


Figure 1. Project area overview showing the location of caves and surface geology.

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 becomes 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. The cave passage is low and horizontal with a flat ceiling and few side passages.

Methods

Cave air CO_2 concentrations were measured at one station within Irelands Cave, Grassy Cove Cave, and Whirlpool 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 for data retrieval. 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, along with data retrieval and accuracy and maintenance checks. Irelands Cave was ventilated with a blower to lower CO_2 concentrations to acceptable levels (<30,000 ppm) prior to entry for the safety of staff performing data collection, a process that typically took 20-30 min.

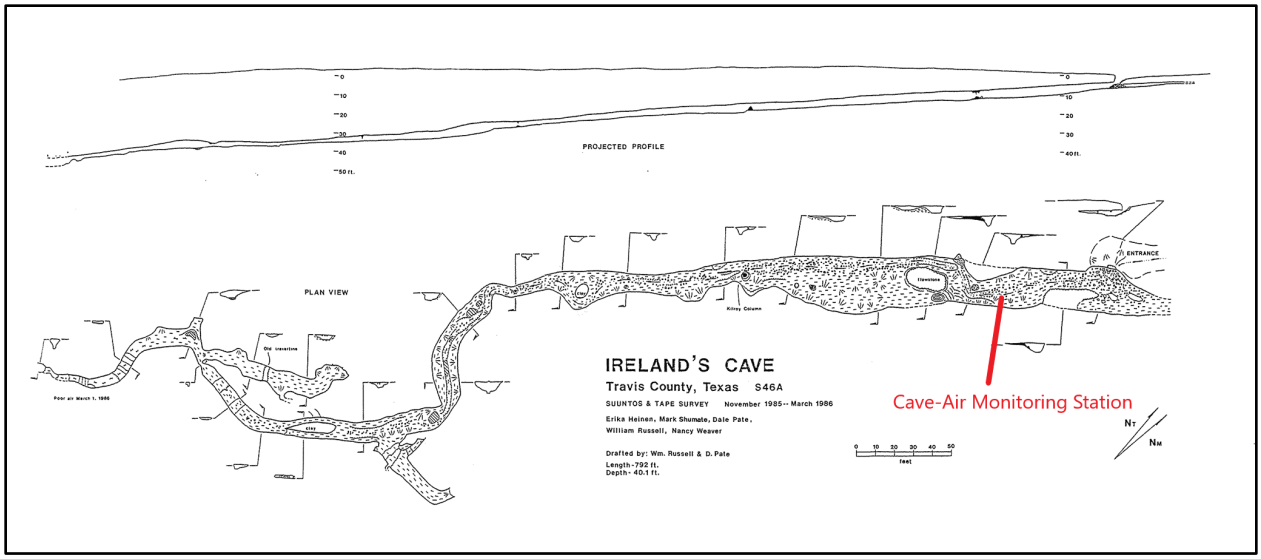


Figure 2. Location of the cave air monitoring station in Irelands Cave

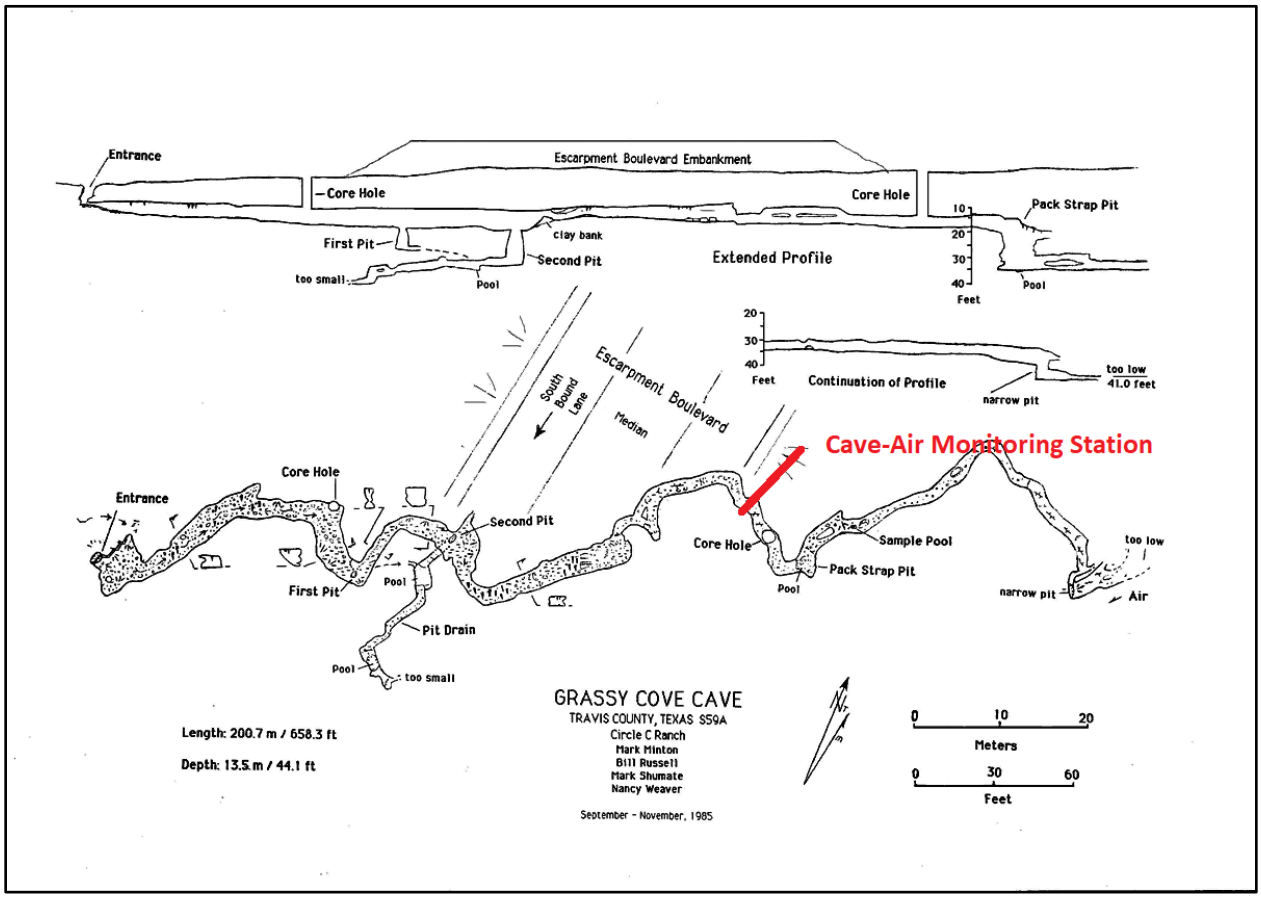


Figure 3. Location of the cave air monitoring station in Grassy Cove Cave.

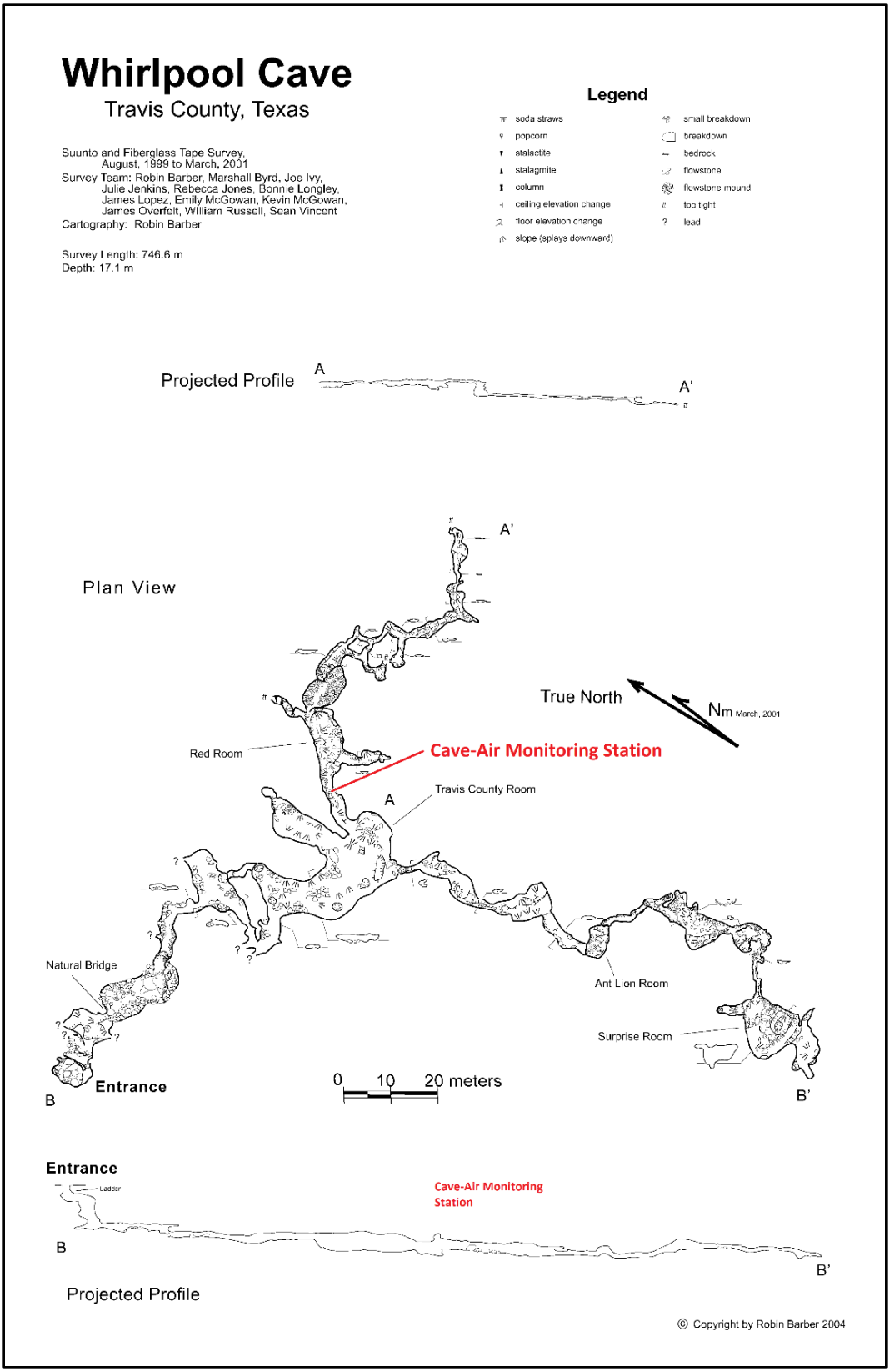


Figure 4. Location of the cave air monitoring station in Whirlpool Cave.

Readings below 400 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.

Cave airflow speed and direction were measured in all three caves by deploying an ATMOS-22 Sonic Anemometer manufactured by Campbell Scientific (accuracy +/- 0.3 m/s and 5^o azimuth). The sonic anemometers replaced vane-and-cup style anemometers that had failed to detect air movement in Grassy Cove Cave and Irelands Cave, and only intermittently in Whirlpool Cave during the previous reporting period. Sonic anemometers are better suited for cave deployment because they provide more accurate air-flow measurements at low velocity ranges typical of cave environments, and do not have any moving mechanical parts which may be affected by the high-humidity cave environment. These measurement devices were deployed at the same location in the caves as the CO_2 sensors. The first anemometer was placed in Whirlpool Cave on 14 September 2020, and after positive results were confirmed, the other two were placed in Grassy Cove Cave and Irelands Cave on 8 March 2021. Wind speed and direction data were logged using an CR 300 data logger, manufactured by Campbell Scientific Incorporated.

Temperature and pressure data were recorded using Onset Hobo Barometric loggers (accuracy +/- 0.44^{o}C and +/-0.43 kPa). Surface temperature and pressure were recorded at the CO_2 monitoring station above Grassy Cove Cave on Escarpment Boulevard. Hobo loggers were placed at the monitoring sites in Irelands Cave and Grassy Cove Cave on 25 January 2021 and in Whirlpool Cave on 8 March.

Data was collected during this reporting period (December 2020- August 2021) on the following dates: 25 January, 8 March, 10 May, 29 June, and 20 August. Instrument-specific software made by Vaisala, Campbell Scientific, and Hobo was used to download CO_2, airflow, and temperature/barometric data respectively. All data organization and analyses were done in Excel. Rose diagrams of airflow direction were plotted using GeoRose, a freeware Windows application produced by Yong Technology, Inc.

Results

Seasonal, diurnal, and pressure-front-related CO_2 concentration fluctuations were observed in all three caves during the 2021 data collection period (Figure 5). Irelands cave exhibited lower CO_2 values on the order of 1,000 – 10,000 ppm during winter and early spring, but CO_2 concentrations rose with warmer conditions and remained consistently above 10,000 by mid-May. The time period from 29 June to 20 August is missing due to equipment failure; however, concentrations likely continued to rise and were measured at 45,000 ppm using a hand-held ToxiRAE CO_2 meter during the last visit on 20 August. Grassy Cove Cave consistently reached CO_2 levels near 25,000 ppm throughout the entire sampling period and rose to between 30,000 and 35,000 pm by early June. Whirlpool exhibited the lowest CO_2 levels, which generally remained below 10,000 ppm and often were equivalent to levels expected at the surface (~400 ppm). Concentrations in Whirlpool cave were only slightly elevated during summer months, rarely reaching 12,000 ppm.

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 June 2021 when all three caves were showing diurnal fluctuations corresponding to diurnal fluctuations in atmospheric pressure and temperature. Figure 7 shows a two-week warm period in early June, representative of warm conditions associated with high-pressure fronts. Diurnal fluctuations were greatest in Grassy Cove Cave, frequently rising or dropping 20,000 ppm in a few hours. Figure 8 displays data from an exceptionally cold two-week period that occurred in mid-February 2021 when surface temperatures reached historic record lows of -15^{o}C. CO_2 levels in Irelands Cave fell from 8,000 ppm on 8 February to 2,000 on 10 February and remained near 1,000 ppm until 21 February. CO_2 values in Whirlpool Cave generally stayed near surface level concentrations, rising occasionally in response to brief rises in temperature. Data is missing from Grassy Cove Cave for this period because instrumentation at the surface station failed in such low temperatures. Table 1, Table 2, and Table 3 summarize cave air CO_2 concentration and cave climate conditions during periods representative of the cool season (25 January- 25 March 2021) and warm season (25 May- 25 July 2021) in Irelands Cave, Grassy Cove Cave, and Whirlpool Cave, respectively. Summary statistics are skewed by portions of data missing due to various equipment failures, as well as the delayed installation of anemometers on 8 March 2021. As expected, all three caves exhibit higher CO_2 values during the warm period. Variability in CO_2, indicated by standard deviation, was slightly higher at Irelands Cave and Grassy Cove Cave during cooler months and slightly higher at Whirlpool Cave during warmer months. Mean air speed was notably higher in Whirlpool cave during both cold and warm periods. The maximum recorded value of 7.56 m/s in Whirlpool is too high to be reasonable and is likely an erroneous result. Mean cave air temperatures differ slightly. Irelands Cave was the coolest at 17.7^{o}C and also showed the greatest temperature difference of 2 degrees between cold and warm periods. Grassy Cove Cave was the warmest cave at 23.1^{o}C but in fact cooled by 1 degree during the warmer period. Whirlpool Cave maintains the most consistent temperature, almost always between 19-20^{o}C. Barometric pressure remained relatively stable between warm and cold periods and was similar in all caves.

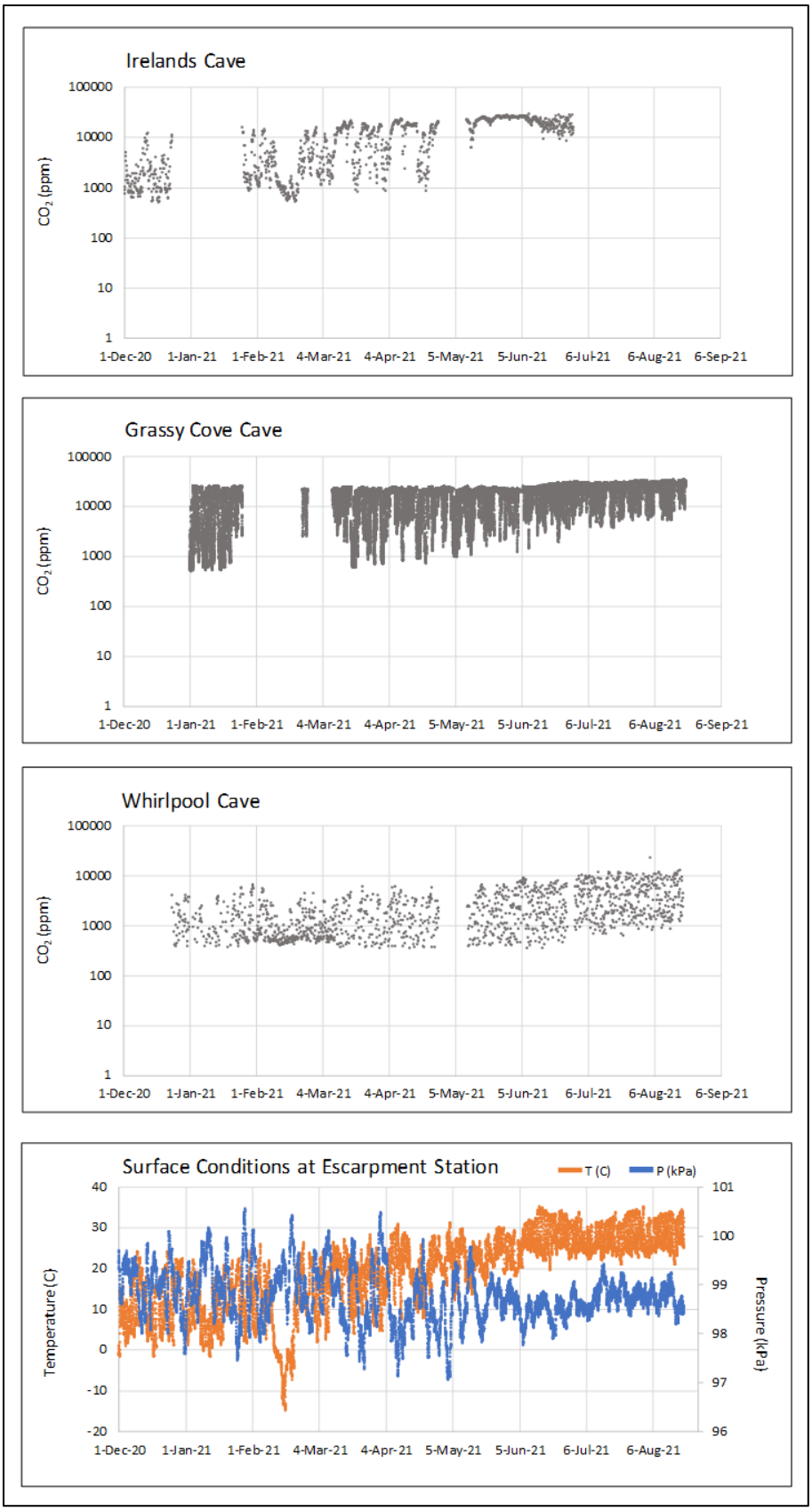


Figure 5. Time series data of CO_2 concentration in Irelands Cave, Grassy Cove Cave, and Whirlpool Cave compared to surface temperature and barometric pressure. Intervals are missing from all three caves due to monitoring equipment failures.



Figure 6. A comparison of CO_2 fluctuations detected in Irelands Cave, Grassy Cove Cave, and Whirlpool Cave from 8-11 June 2021. Fluctuations are shown with a 6-hr moving average at Irelands and Whirlpool, and a 10-minute moving average at Grassy Cove Cave. A clear diurnal signal is apparent correlating to surface temperature and pressured measured above Grassy Cove Cave.

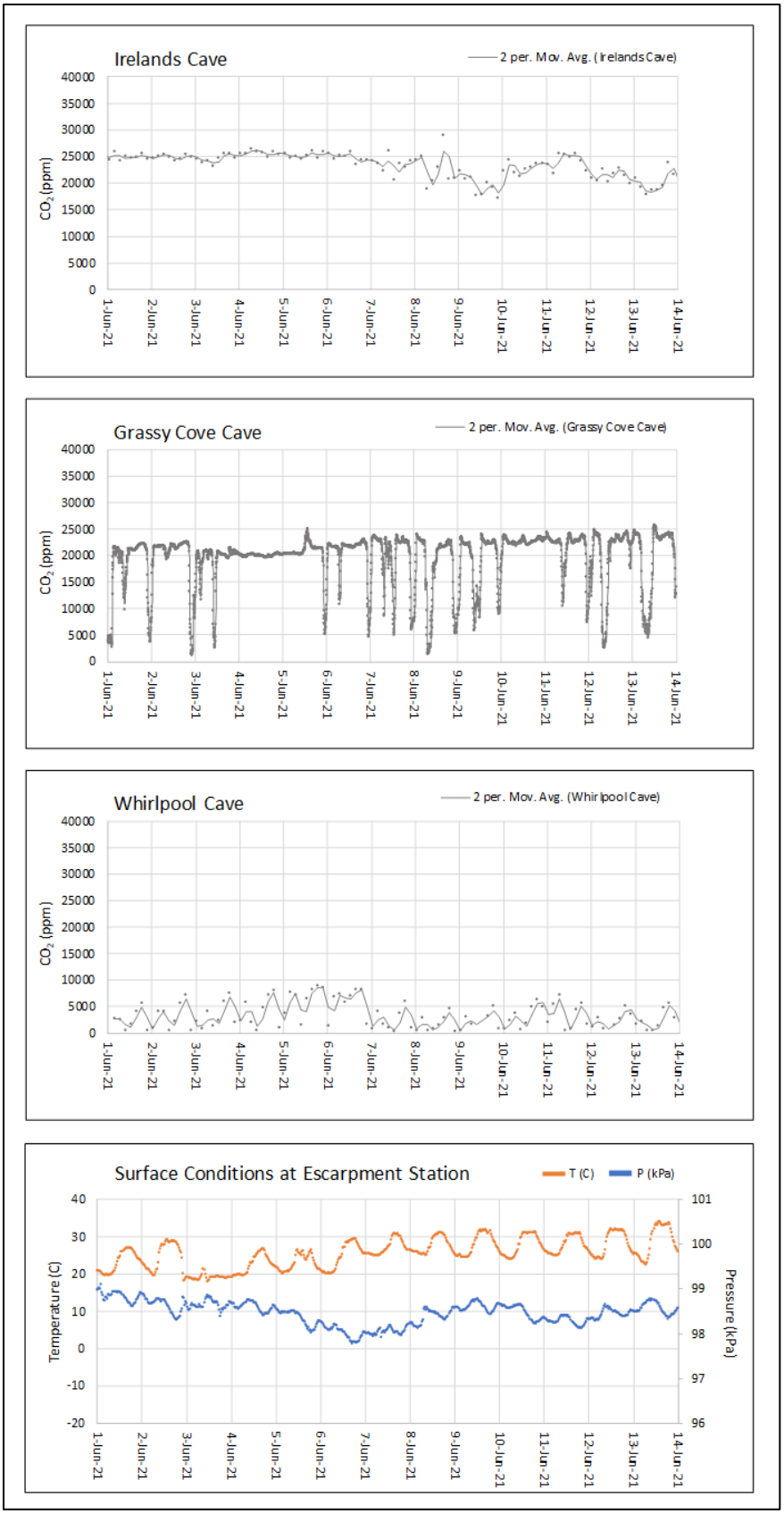


Figure 7. Representative cave air CO_2 concentrations at Irelands Cave, Grassy Cove Cave, and Whirlpool Cave during the warm season in comparison with surface temperature and pressure.

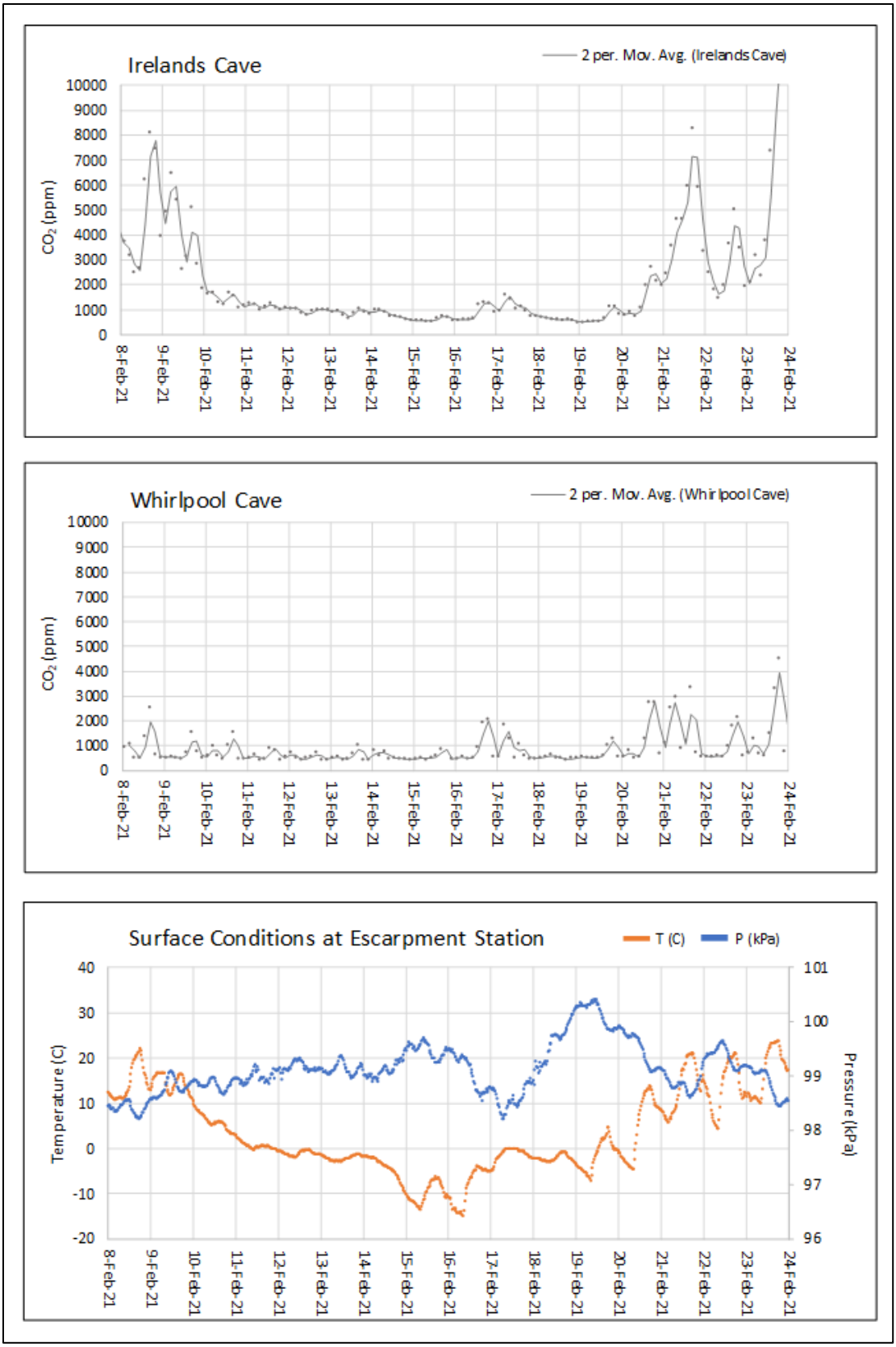


Figure 8. Representative cave air CO_2 concentrations at Irelands Cave and Whirlpool Cave during an unusually cold period that occurred in February 2021. Data from Grassy Cove is missing due to equipment failure at low temperatures.

Table 1. Summary of descriptive statistics for cave climate measurement at Irelands Cave. A period representative of cold season (25 January- 25 March) and warm season (25 May – 25 July) cave CO_2 fluctuations was chosen for comparison. Gaps in data are attributed to equipment failure, with the exception of air speed data, which was due to delayed installation of the anemometer.

	Irelands Cave							
	CO_2 (ppm)		*Air Speed (m/s)*		*Temperature (C)*		*Pressure (kPa)*	
	Cold	Warm	Cold	Warm	Cold	Warm	Cold	Warm
min	510	8210	0.16	0.14	16.2	19.0	97.0	97.5
max	20690	29070	0.69	2.4	19.5	23.4	100.3	99.1
mean	6004	21063	0.32	1.25	17.7	19.8	98.7	98.4
mode	1080	24640	0.27	0.83	17.8	19.6	98.9	98.5
std dev	5643	4602	0.10	0.72	0.5	0.5	0.6	0.3

Cold: 25 Jan - 25 Mar; missing 25 Jan- 7 March Air speed

Warm: 25 May - 25 July; missing 29 June- 25 July CO_2

	Grassy Cove Cave							
	CO_2 (ppm)		*Air Speed (m/s)*		*Temperature (C)*		*Pressure (kPa)*	
	Cold	Warm	Cold	Warm	Cold	Warm	Cold	Warm
min	591	1219	0.26	0.04	22.7	22.2	97.5	98.1
max	25394	30980	1.43	1.49	23.4	24.1	100.7	99.6
mean	14741	21715	1.09	0.39	23.1	22.3	99.1	98.9
mode	21807	28174	1.02	0.22	23.0	22.3	99.3	98.9
std dev	8425	7249	0.16	2.04	0.2	0.1	0.6	0.3

Cold: 25 Jan - 25 Mar; missing 24 Feb-8 March CO_2 and 25 Jan -7 March Air speed

Warm: 25 May - 25 July; missing May 25-June 28 Air speed

Table 3. Summary of descriptive statistics for cave climate measurement at Whirlpool Cave. A period representative of cold season (25 January- 25 March) and warm season (25 May – 25 July) cave CO_2 fluctuations was chosen for comparison. Gaps in data are attributed to equipment failure.

	Whirlpool Cave							
	CO_2 (ppm)		*Air Speed (m/s)*		*Temperature (C)*		*Pressure (kPa)*	
	Cold	Warm	Cold	Warm	Cold	Warm	Cold	Warm
min	370	360	0.36	0.03	19.3	19.8	97.8	98.4
max	6700	11750	2.46	7.56	20.7	22.6	100.5	99.9
mean	1269	3619	1.22	1.84	19.7	20.0	99.2	99.2
mode	520	860	1.12	1.84	19.6	20.0	99.6	99.1
std dev	1150	2807	0.24	1.22	0.2	0.1	0.7	0.3

Cold: 25 Jan - 25 Mar; missing 25 Jan-7 March Temperature & Pressure

Warm: 25 May - 25 July; missing 18-25 March & 2-25 July Air Speed

Figure 9, Figure 10, and Figure 11 for periods where all data generally overlap. Diurnal fluctuations in airflow speed were detectable in Whirlpool Cave, and an example from a one-week period in May is shown in Figure 12. Changes in airflow direction were discernable between cold and warm periods in Irelands Cave and Whirlpool Cave, altering from southwest to north and from northeast to southwest, respectively. In contrast, airflow direction in Grassy Cove Cave was consistently from the southeast (Figure 13).

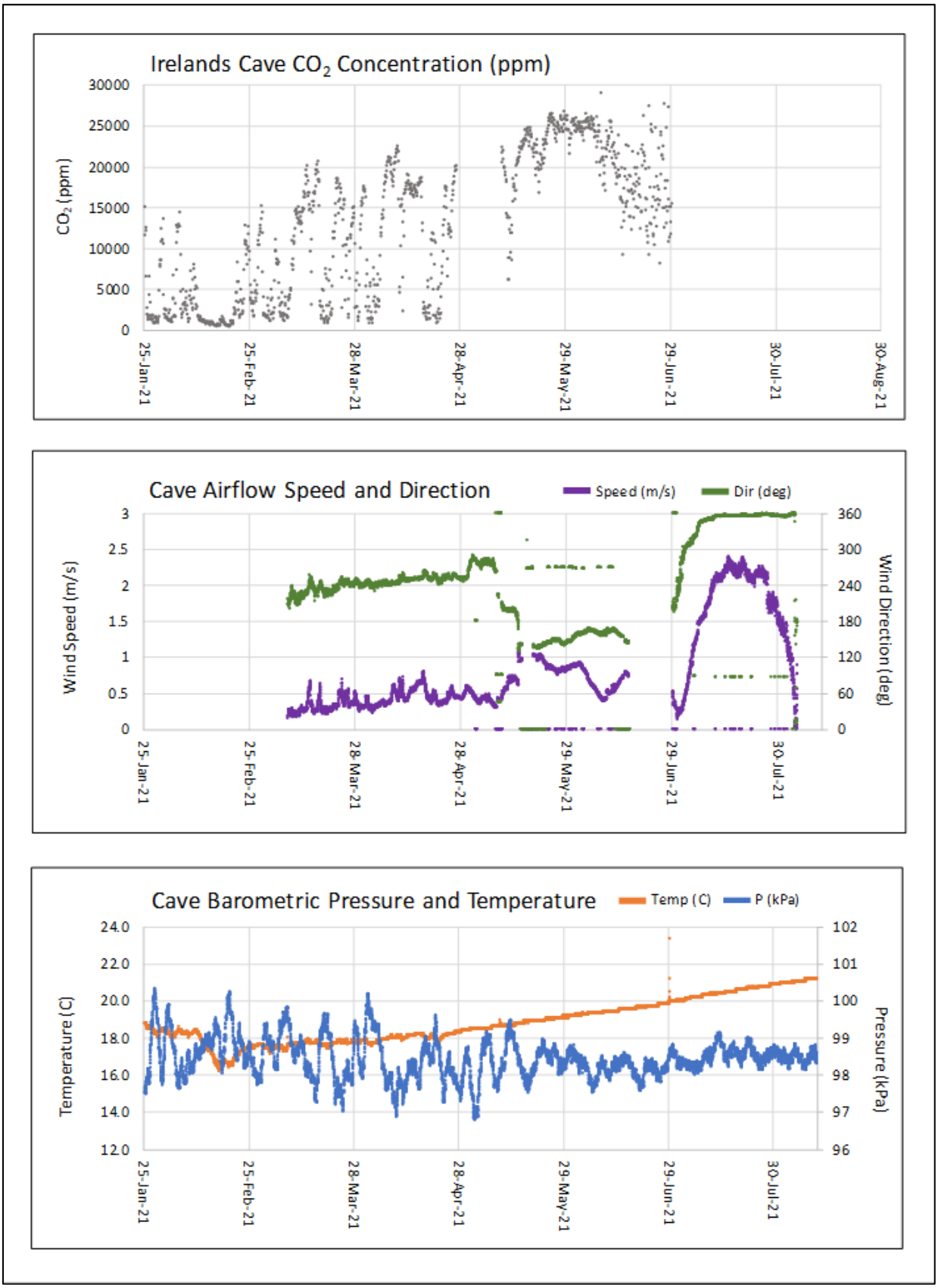


Figure 9. Cave climate data collected in Irelands Cave, showing seasonal trends in CO_2 possibly correlating with changes in airflow speed and direction. Temperature and pressure were measured at the instrumentation site in the cave.

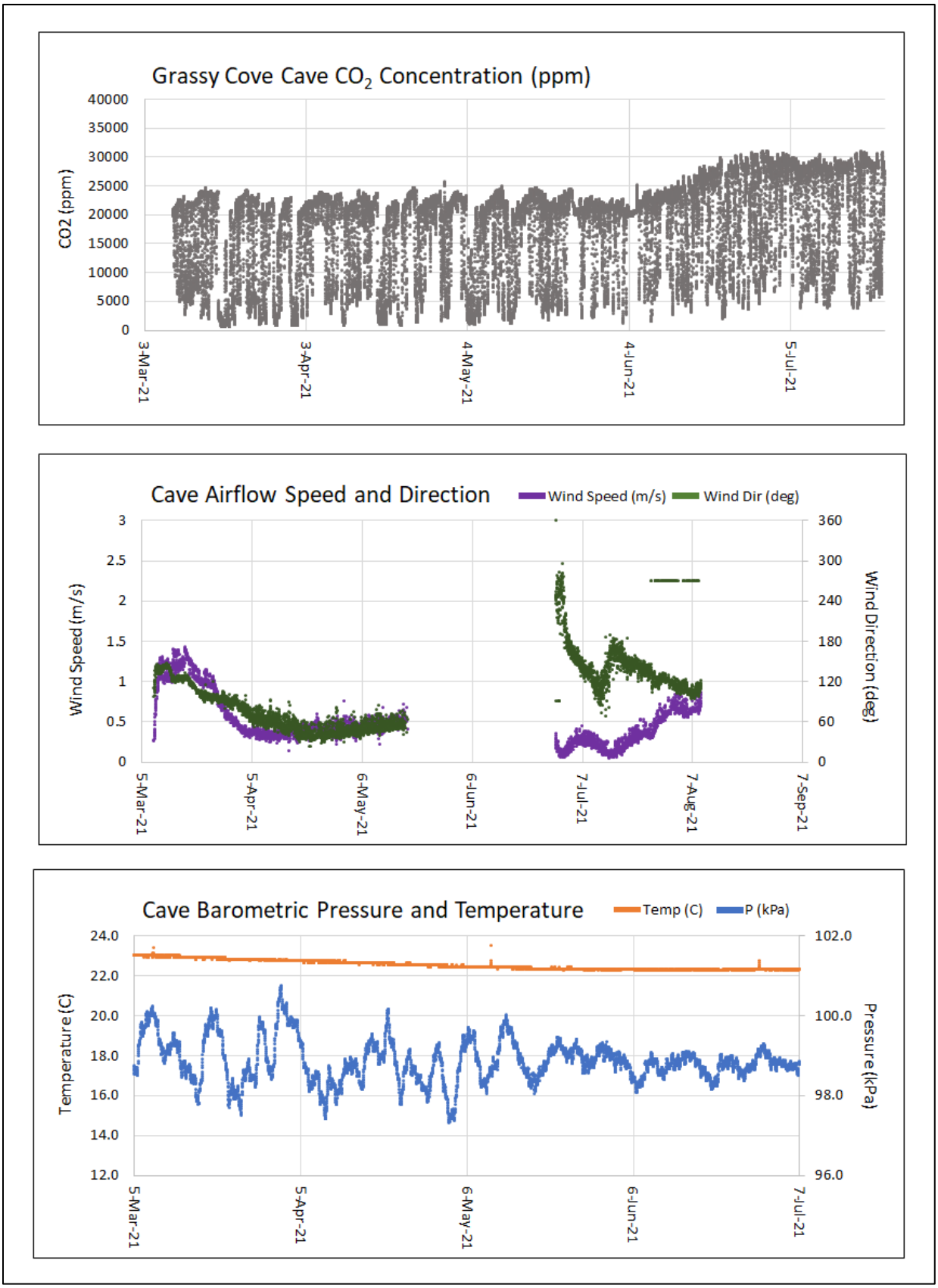


Figure 10. Cave climate data collected in Grassy Cove Cave, showing seasonal trends in CO_2 possibly correlating with changes in air speed and direction. Temperature and pressure were measured at the instrumentation site in the cave.

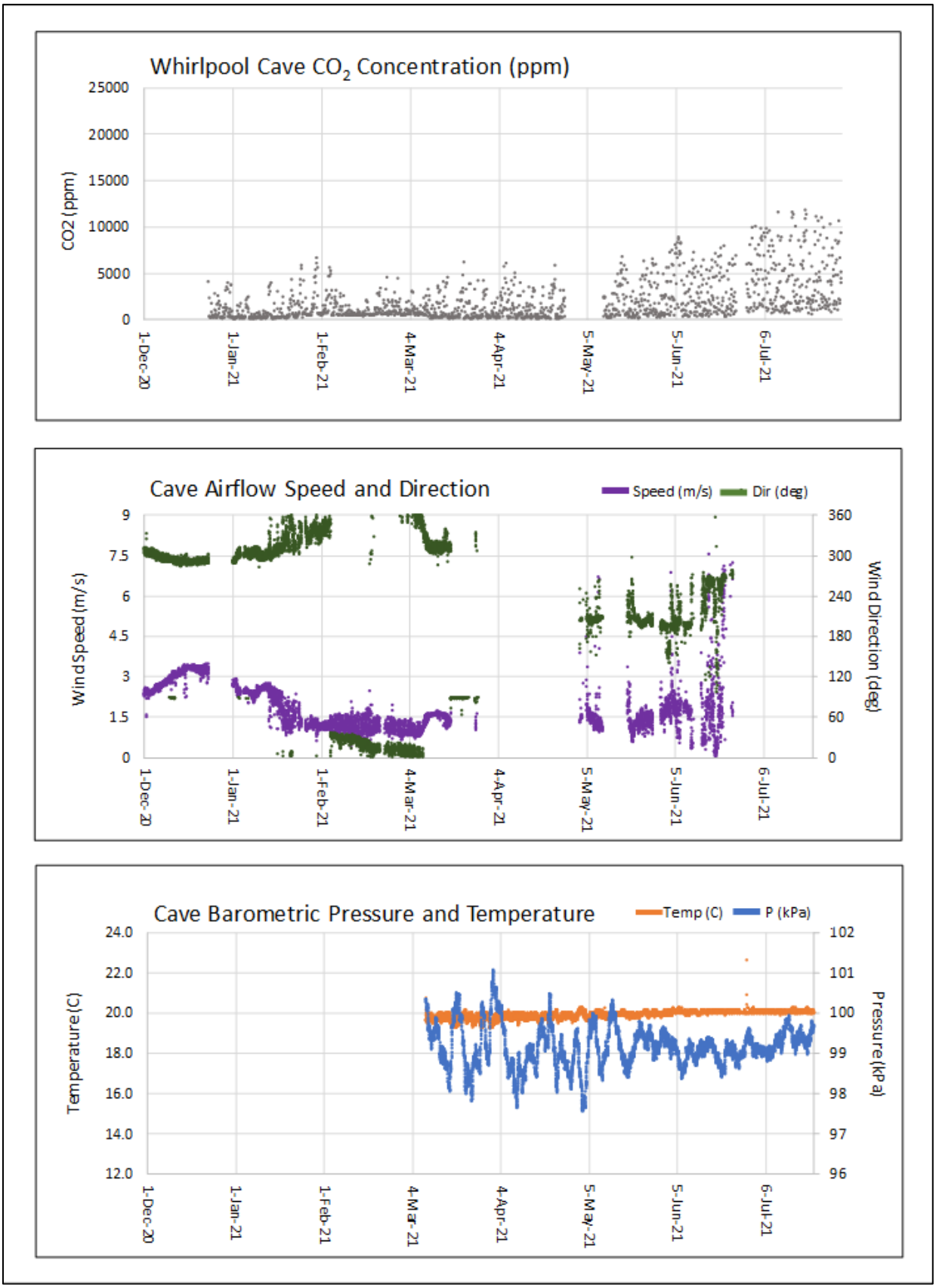


Figure 11. Cave climate data collected in Whirlpool Cave, showing seasonal trends in CO_2 possibly correlating with changes in air speed and direction. Temperature and pressure were measured at the instrumentation site in the cave.

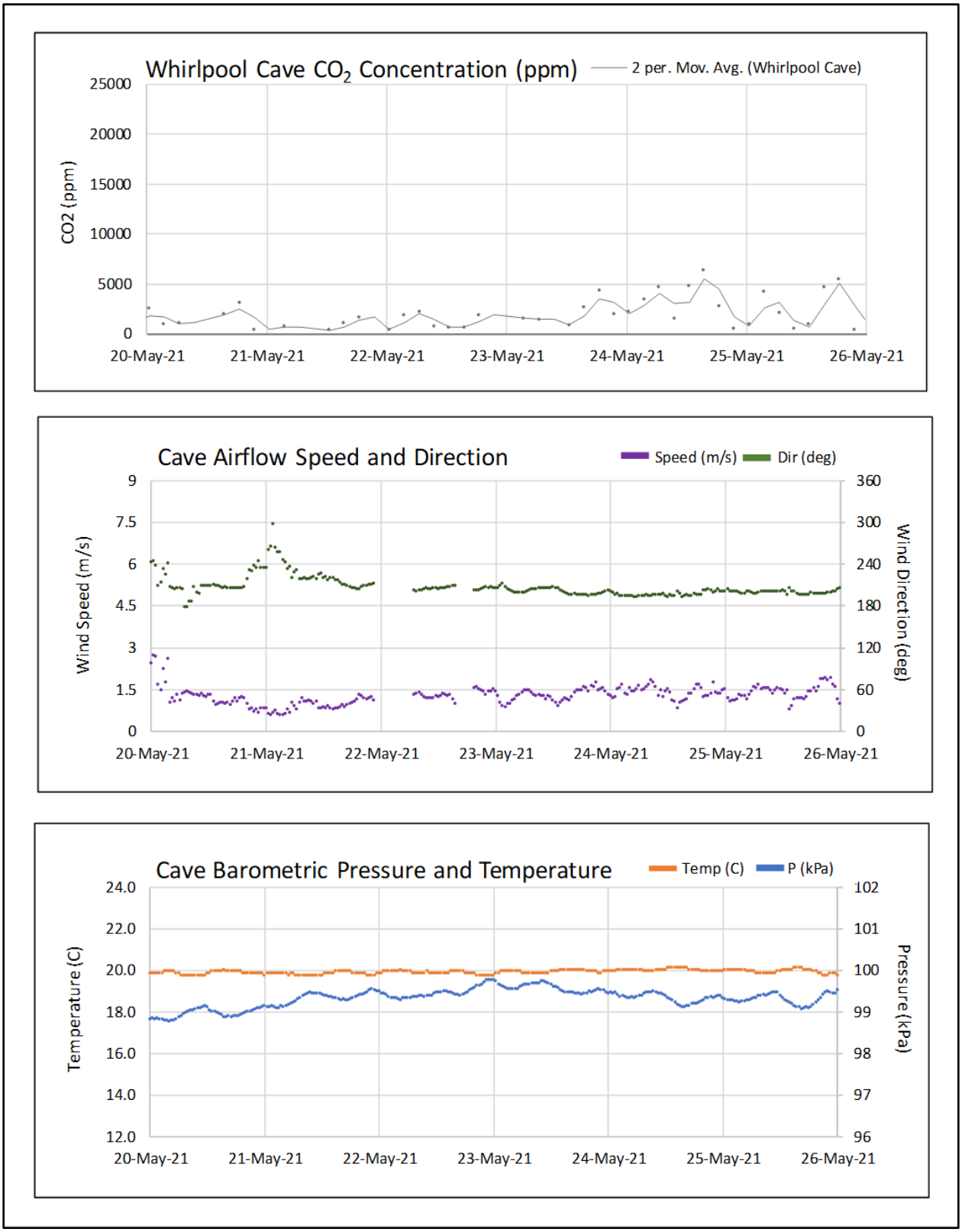


Figure 12. Cave climate data collected in Whirlpool Cave from 20-26 May 2021, showing diurnal signals observed in CO_2 as well as in airflow speed and direction. Peaks in CO_2 correlate to peaks in windspeed and reduced barometric pressure.

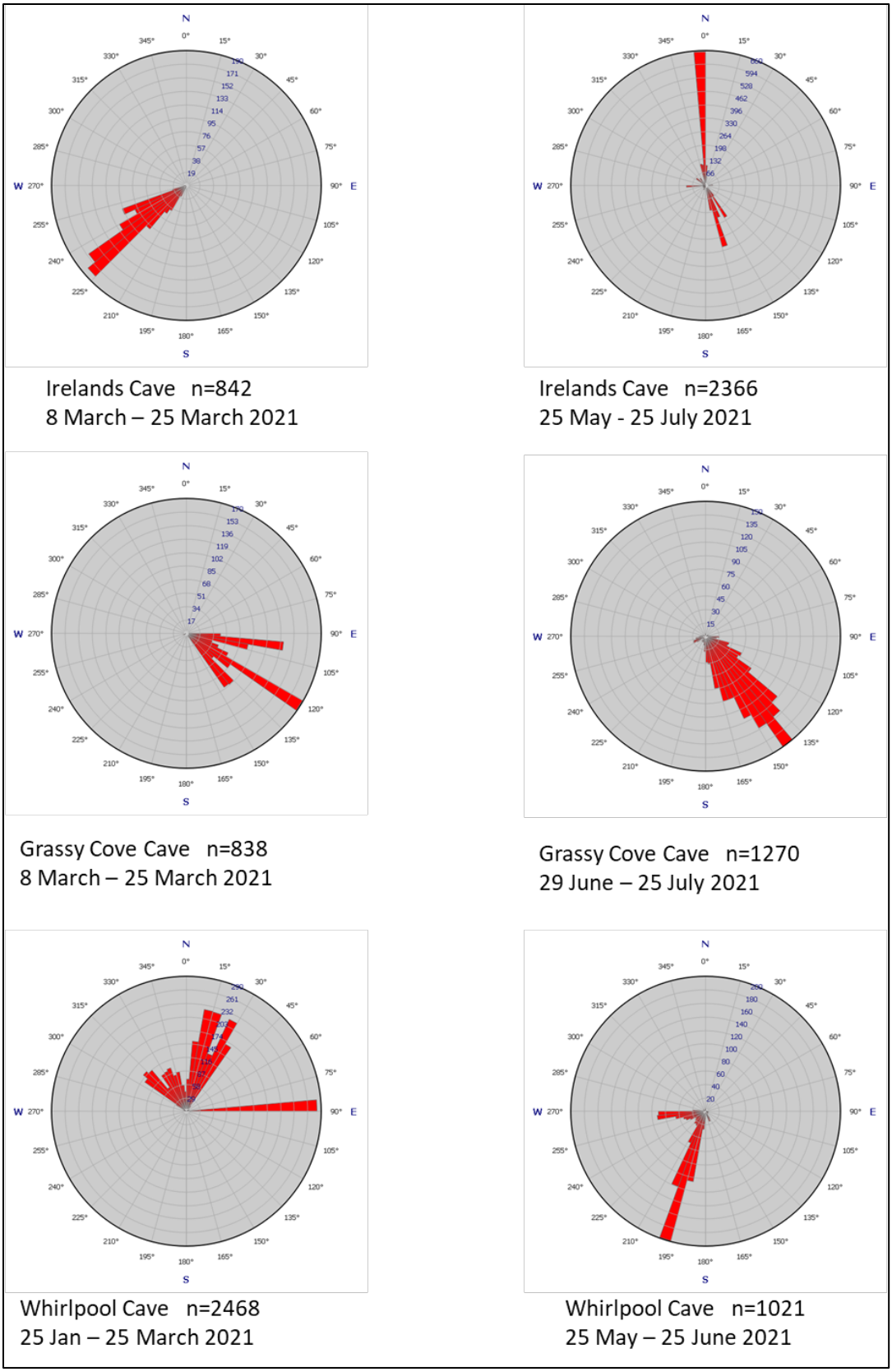


Figure 13. Rose plot diagrams showing the direction of airflow during cold and warm periods in Irelands Cave, Grassy Cove Cave, and Whirlpool caves. The sonic anemometer records the direction from which air flows (i.e., the red marks indicate the originating azimuth of cave airflow).

Discussion

Seasonal Ventilation

CO_2 concentrations varied seasonally in all three caves during the 2021 data collection period, with generally elevated CO_2 concentrations in the warmer months and lower CO_2 concentrations in the cooler months (Figure 5). 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 driven by the displacement of cave air. 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. 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. Irelands Cave receives no visitation outside of this study monitoring, and very infrequent biological monitoring conducted by BCP staff. 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. 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

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. The magnitude of CO_2 fluctuations coinciding with atmospheric pressure fronts was often larger than fluctuations associated with the diurnal barometric tide.

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.

Cold and warm fronts are weather events typically accompanied by a significant increase or decrease in pressure, respectively. The 2021 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 the cold front that occurred in February 2021 (Figure 8). In response to less extreme warm fronts, all three caves exhibited elevated CO_2 concentrations, although Irelands Cave and Whirlpool Cave reached significantly higher levels 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. Nonetheless, these results suggest that front-related pressure differences exert greater influence on CO_2 fluctuations than diurnal pressure differences. The magnitude of the CO_2 fluctuations was significantly larger than those observed during diurnal cave ventilation caused by the barometric tide.

Airflow data measured by the newly deployed sonic anemometers provides a previously unavailable dataset of cave air speed and direction. All anemometers were able to detect near continuous flow for the duration of the reporting period, ranging from 0.03 m/s to 2.46 m/s. The measurements reported are averaged values from logging at 10-second intervals over a 30-min period. The anemometers have a function to detect “gusts” reported as a maximum observation within each 30-min period; however, gust data was in almost all cases either identical to the normal reading or unreasonably high (>7 m/s), perhaps due to disturbance of the sensors by insects or a result of humid conditions in the cave. Because of the very low air speeds being measured, the gusts values were considered negligible for purposes of analysis. Average air speed in all caves was slightly higher during warmer months, consistent with air being drawn out of the cave due to a greater pressure differential.

Diurnal peaks in cave air speed observed in Whirlpool Cave coincided with increases in atmospheric pressure associated with diurnal barometric tide (Figure 12). These diurnal peaks were followed by reduced air speeds 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. The opposite case occurs in Grassy Cove, where the consistent trend of airflow from the southeast is observed blowing through the main cave passage toward the entrance. Further work can be done to more closely examine the timing of changes in airflow speed and direction and possible correlation with differences between surface and cave barometric pressures.

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