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Carbon dioxide monitoring : preliminary results report 2019

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U.S. Department of the Interior

Carlsbad Caverns National Park

Carbon Dioxide Monitoring – Preliminary Results Report 2019

How Visitation is Affecting Air Quality in Carlsbad Cavern

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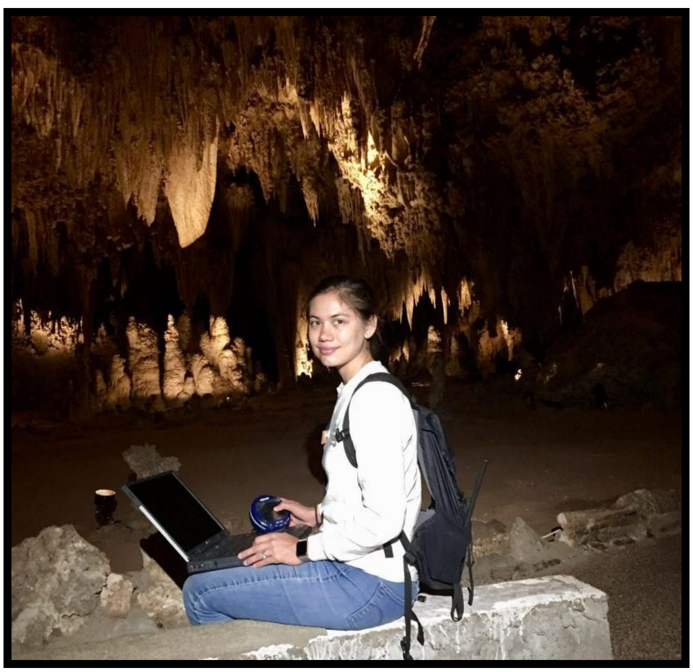

ON THE COVER
NPS Photos/Sonia Meyer – CO_2 sensor in King's Palace

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Abstract

Carlsbad Caverns National Park is monitoring carbon dioxide (CO_2) in Carlsbad Cavern to assess the park's current conditions as a component of a Visitor Use Management (VUM) study. Elevated CO_2 concentrations can impact visitor safety, cave conservation, and visitor experience. This preliminary work establishes standard operating procedures for a future yearlong study. CO_2 levels were monitored from June to July 2019 at a 5 minute sampling interval in three locations: lower elevator waiting area, Big Room Junction, and King's Palace. Two major limitations of this study are the sparsity and quality of data due to the short two-month monitoring period, various data losses, and the unreliability of the data due to mathematical corrections for automatic baseline calibrations. CO_2 levels increased consistently in June and July of 2019. While the CO_2 levels decreased in the evening, they did not return to starting levels. Visitor CO_2 fluxes were cumulative over time during these two months. There was a positive correlation between daily visitation numbers and CO_2 levels at the elevator and Big Room Junction. There was not enough data from the King's Palace sensor for data analysis. Given the limitations of this study, these results are preliminary and should not be extrapolated past June and July of 2019. Carbon dioxide monitoring should be continued for at least a year; with more data, stronger conclusions and seasonal patterns can be determined.

1. Introduction

The National Park Service (NPS) is monitoring carbon dioxide (CO_2) in Carlsbad Cavern to assess the park's current conditions as part of a Visitor Use Management (VUM) study. Following the VUM Framework, this study will define and analyze visitor impacts on both visitor experience and park resources (Figure 1). This ongoing process seeks to conserve our natural resources in a way that will leave them unimpaired for future generations. The first steps of the framework are to assess current conditions, define the desired conditions, select indicators, and establish threshold limits. Park managers following the framework will then develop and implement a monitoring strategy to compare the existing conditions to the desired conditions. If the data show that the park does not meet the desired conditions, then park management should consider taking action and adjust the process to allow conditions to return to desired levels. This process is iterative and should always rely on data-driven analysis.

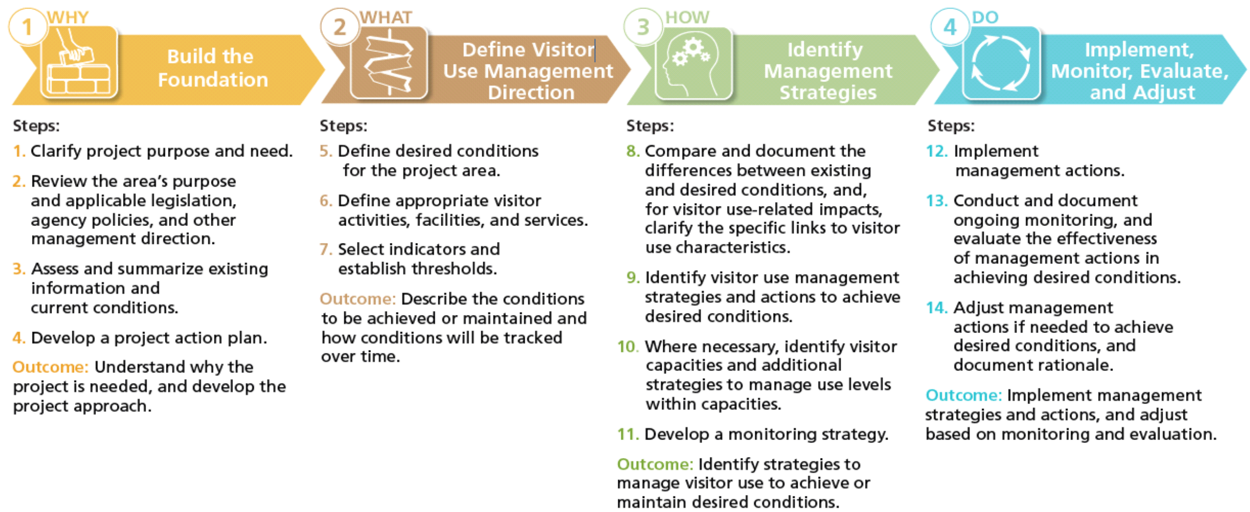

Figure 1. Elements and steps of the Visitor Use Management Framework (VUM 2016)

The impact of poor air quality on visitor safety is a concern, especially on high visitation days when visitors congregate in long elevator lines and elevate CO_2 levels. Anecdotal data indicates that visitors can wait in line for up to two hours on these busy days. Given the two elevators, elevator capacity of 16 persons, and 4-minute round-trip elevator cycle (including loading, the ride, unloading, and return), a two-hour line equates to over 960 people congregated in one place exhaling CO_2. CO_2 levels are also important to monitor to help establish the current conditions in Carlsbad Cavern. Additionally, several studies have shown that CO_2 levels can impact speleothem growth. If the monitoring reveals a strong correlation between CO_2 levels and visitation, these data can be used to establish management strategies to manage visitor use in the cave based on desired CO_2 levels.

2. Background

2.1 Impacts of Elevated CO_2 Levels

CO_2 is a naturally occurring gas in Earth's atmosphere, typically found in outdoor concentrations around 400 parts per million (ppm). At high concentrations the gas can act as an asphyxiant.[1] Depending on the level of CO_2, which displaces oxygen needed for breathing, symptoms can range from mild respiratory symptoms to death by asphyxiation.[2] Concentrations under 1,000 ppm for indoor spaces are recommended by US EPA, ASHRAE Standard 62-1989

[1] U.S. Department of Agriculture, Food and Safety Inspection Service (FSIS), Environmental, Safety and Health Group (ESHG). "Carbon Dioxide: Health Hazard Information Sheet." FSIS. https://www.fsis.usda.gov/wps/wcm/connect/bf97edac-77be-4442-aea4-9d2615f376e0/Carbon-Dioxide.pdf?MOD=AJPERES (accessed June 19, 2019).
[2] Ibid.

(Appendix A).[3] Complaints of drowsiness and stuffy air are typically reported between 1,000 and 2,000 ppm (Figure 2).[4] Concentrations greater than 2,000 ppm can result in headaches, sleepiness, stuffy air, poor concentration, loss of attention, increased heart rate, and slight nausea (Figure 2).[5] 10,000-20,000 ppm can result in electrolyte imbalances and other metabolic changes, which can be life-threatening if untreated.[6] Occupational Safety and Health Administration (OSHA) regulations specify a maximum 5,000 ppm workplace exposure limit of 8 hours a day during a 40-hour work week (Figure 2).[7] The American Conference of Governmental Industrial Hygienists (ACGIH) and Center for Disease Control (CDC) recommend similar exposure limits (Appendix A).[8]

CO_2 Concentration	Effect on Humans
300-400 ppm	Outdoor
350-1,000 ppm	Concentrations typical of occupied indoor spaces with good air exchange
1,000-2,000 ppm	Complaints of drowsiness and poor air
>2,000 ppm	Ventilation is necessary! Lung ventilation increases by 50 percent, headache after several hours exposure
2,000-5,000 ppm	Headaches, sleepiness and stagnant, stale, stuffy air; Poor concentration, loss of attention, increased heart rate and slight nausea may also be present; Lung ventilation increases by 100 percent, panting after exertion
5,000 ppm	Workplace exposure limit (as 8-hour TWA) in most jurisdictions; TLV-TWA (40-hour work week)

Figure 2. Table of CO_2 concentration safety limits from multiple sources (see Appendix A for full list)

The relationship between carbon dioxide and speleothem growth is an important and delicate one. Carbon dioxide is a driving factor in karstification.[9] The higher the concentration of CO_2 in cave water, the more calcite ($CaCO_3$) that water can hold, leading to calcite supersaturation. When this calcium laden water reaches an air-filled void, carbon dioxide will degas, then the

[3] Friedman, Dan. “Exposure Limits for Carbon Dioxide Gas CO2 Limits.” InspectAPedia. https://inspectapedia.com/hazmat/Carbon%20_Dioxide_Exposure_Limits.php (accessed June 19, 2019).; Wöhler USA Inc. (2011). *Wöhler CDL 210 CO_2 Logger: Operating Manual.* Danvers, MA.

[4] Bonino, Steve. “Carbon Dioxide Detection and Indoor Air Quality Control: Carbon dioxide gas detectors can utilize an automated background calibration program to set the clean air level on a regular basis.” Occupational Health & Safety (OHS). https://ohsonline.com/articles/2016/04/01/carbon-dioxide-detection-and-indoor-air-quality-control.aspx (accessed June 19, 2019).; Friedman, *Exposure Limits*.; Wöhler, *Wöhler CDL*.

[5] Bonino, *Carbon Dioxide*.; Kane International Limited. “What are safe levels of CO and CO2 in rooms?” kane.co.uk. https://www.kane.co.uk/knowledge-centre/what-are-safe-levels-of-co-and-co2-in-rooms (accessed June 19, 2019).

[6] Friedman, *Exposure Limits*.; National Institute for Occupational Safety and Health (NIOSH). “Carbon Dioxide: Immediately Dangerous to Life or Health Concentrations (IDLH).” Centers for Disease Control and Prevention. https://www.cdc.gov/niosh/idlh/124389.html (accessed June 19, 2019).

[7] NIOSH, *Carbon Dioxide*.

[8] Friedman, *Exposure Limits*.; NIOSH, *Carbon Dioxide*.

[9] Leutscher, Marc and Felix Ziegler. “CORA – a dedicated device for carbon dioxide monitoring in cave environments”. *International Journal of Speleology*. no. 2 (2012): 273-281.; Liñán, Cristina, Iñaki Vadillo, and Francisco Carrasco. “Carbon dioxide concentration in air within the Nerja cave (Malaga, Andalusia, Spain).” *International Journal of Speleology*. no. 2 (2008): 99-106.; Quan, Trinh Hong, et al. “First assessment on the air CO_2 dynamic in the show caves of tropical karst, Vietnam”. *International Journal of Speleology*. no. 1 (2018): 93-112.

solution can no longer hold as much calcite, and the calcite is deposited creating speleothems.[10] However, when CO_2 air levels are high, it disrupts the natural balance by preventing CO_2 degassing from the water to the air, thereby preventing calcite deposits and slowing speleothem growth.[11] In addition, high concentrations of carbon dioxide in cave air can deteriorate cave walls by corroding speleothems and cultural resources such as images painted on or pecked in to the rock.[12] Several researchers have calculated limestone corrosion thresholds ranging from 2,400-2,900 parts per million (ppm), which could damage or destroy rock art and speleothems.[13] In addition to the human health effects, the alteration of Carlsbad Cavern's fragile microclimate via elevated carbon dioxide levels could severely impact the cave.

2.2 Sources and Mechanisms Affecting CO_2 Levels in Caves

Visitor exhalation has repeatedly been found to be the primary anthropogenic source of CO_2 in show caves.[14] Kim et al. (2012) conducted a CO_2 study in Baekryong Cave, South Korea, which was reopened to the public in 2010. Before the cave reopened, they recorded hourly CO_2 readings from February to July 2010, and again after being reopened, from February to July 2011. By comparing the before and after readings, Kim et al. (2012) found that visitors had the strongest influence on carbon dioxide levels. Lang et al. (2015) conducted a study in Balcarka Cave, Czech Republic where they organized 48-hour monitoring sessions once a month from September to November 2013. They found that anthropogenic fluxes could as much as triple the natural CO_2 levels in the cave during extended visitor stays.[15] Quan et al. (2018) found a correlation between high visitation days and CO_2 levels, likely from human respiration, but Quan and other researchers concluded that this topic needs further investigation.[16] Dragovich and Grose (1990) conducted a study at Jenolan Caves in Australia and found a clear positive correlation between peak daily carbon dioxide concentrations and visitation numbers; R=0.86 and R=0.94 for two caves monitored. They also found that poor ventilation can exacerbate and increase the CO_2 levels (Dragovich 1990). Other anthropogenic sources of CO_2 can include

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[10] Hildreth-Werker, Val and Jim C. Werker. *Cave Conservation and Restoration*. 2006 Edition. Huntsville, AL: National Speleological Society, Inc., 2006.; Kim, Tae Hyeong et al. "A study on the changes of air quality the Baekrying Cave in Pyeonchang (Natural Monument Number 260)". *Journal of Korean Nature*. no. 3 (2012): 237-241.; Quan, *First assessment*, 93-112.

[11] Hildreth-Werker, *Cave Conservation*.; James, J.M., 2004, Tourist caves: air quality, in Gunn, J., ed., Encyclopedia of cave and karst science: New York, Fitzroy Dearborn, p. 730–731.; Guirado, E., et al. "Modeling carbon dioxide for show cave conservation." *Journal for Nature Conservation*. no. 49 (2019):76-84.; Leutscher, *CORA*, 273-281.; Novas, Nuria et al. "A real-time underground monitoring system for sustainable tourism of caves." *Journal of Cleaner Production*. no. 142 (2017): 2707-2721.; Quan, *First assessment*, 93-112.

[12] Guirado, *Modeling carbon*.; Quan, *First assessment*.; Toomey, Rickard S. "Geological monitoring of caves and associated landscapes". *Geological Monitoring: Boulder, Colorado, Geological Society of America*. (2009): 27-46.

[13] Dragovich, D and J Grose. "Impact of tourists on carbon dioxide levels at Jenolan Caves, Australia: an examination of microclimatic constraints on tourist cave management." *Geoforum*. no. 1 (1990): 111-120.; James, *Encyclopedia*, 730-731.; Guirado, *Modeling carbon*.

[14] Dragovich, *Impact of*, 111-120.; Killing-Heinze, M., et al. "The importance of air temperature as a key parameter to identify climatic processes inside Carlsbad Cavern, New Mexico, USA." *Journal of Cave and Karst Studies*. v. 79, no. 3 (2017):153-167.; Guirado, *Modeling carbon*, 76-84.; Kim, *A study*, 237-241.; Lang, Mark, Jiri Faimon, and Camille Elk. "The relationship between carbon dioxide concentration and visitor number in the homothermic zone of the Balcarka Cave (Moravian Karst) during a period of limited ventilation". *International Journal of Speleology*. no. 2 (2015): 167-176.; Liñán, *Carbon* dioxide, 99-106.; Novas, *A real-time*, 2707-2721.

[15] Lang, *The relationship*, 167-176.

[16] Kim, *A study*, 237-241.; Leutscher, *CORA*, 273-281.

vehicle exhaust and increased micro-organism respiration attributed to food brought into the cave.[17]

The CO_2 found in caves does not solely originate from its visitors, as there are several natural sources of CO_2, including diffusion from soils and epikarst, dripwater degassing, microbial decay of organic matter, and transport of endogenous CO_2 in geologically active regions.[18] CO_2 is found to increase following a period of intense rainfall from water degassing[19], yet conversely, caves with actively flowing water can reduce carbon dioxide via dissolution into water.[20] Other natural methods of reducing CO_2 levels include air diffusion and advection.[21]

Barometric and convective airflow plays an important role in natural CO_2 fluctuations.[22] Convectively driven caves can be classified into three types: static with one entrance, dynamic with multiple entrances at different altitudes, and statodynamic, which transitions between the static and dynamic. Each of these three types has a different ventilation regime depending on the season and specific characteristics of the cave.[23] Liñán et al. (2008) conducted CO_2 concentration research in Nerja Cave, Spain in 2005 when surface CO_2 concentrations were 320 ppm—they found that seasonally driven ventilation affected CO_2 levels with a low in the winter of 525 ppm and a summer high of 750 ppm corresponding to a period of low ventilation. Dragusin et al. (2018) found that CO_2 levels in Ascunsă Cave in Romania are elevated in the winter (up to 3,500 ppm) and lowest in the summer due to seasonal microbial decay. Quan et al. (2018) found that for show caves in Vietnam's karst region, CO_2 levels are highest in the summer and lowest in the winter in accordance with their ventilation models for single entrance static caves that have highest air circulation in the winter. Such caves reach up to 8000 ppm due to natural sources of CO_2 and stagnation of summer air. These examples of the research on CO_2 levels in caves around the world show both natural and anthropogenic sources of CO_2, but the main conclusion is that airflow, whether it is barometric or convective, affects CO_2 levels.

2.3 Microclimate Research in Carlsbad Cavern and Other Caves

Cave water also helps to mediate CO_2 levels in wet caves, by stimulating airflow and providing opportunities for gas dissolution into water.[24] Since Carlsbad Cavern is a dry cave, in that it does not have any flowing water, air advection is the most likely mechanism to return CO_2 levels to starting levels after tours finish and visitors exit the cave. Starting levels are considered to be the CO_2 concentration at the time Carlsbad Cavern begins operation at 8:30 AM.

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[17] Dragovich, *Impact of*, 111-120.; Guirado, *Modeling carbon*, 76-84.; James, *Encyclopedia,* 730–731.
[18] Dragusin, Virgil et al. "Transfer of environmental signal from the surface to the underground at Ascunsa Cave, Romania". *Hydrology Earth System Sciences*. no. 21 (2017): 5357-5373.; James, *Encyclopedia,* 730–731.; Lang, *The relationship*, 167-176.; Liñán, *Carbon dioxide*, 99-106.
[19] Quan, *First assessment*, 93-112.
[20] James, *Encyclopedia,* 730–731.
[21] Ibid, 730-731.
[22] James, *Encyclopedia*, 730-731.; Lang, *The relationship*, 167-176.; Liñán, *Carbon dioxide*, 99-106.
[23] Dragusin, *Transfer of*, 5357-5373.; Lang, *The relationship*, 167-176.; Quan, *First assessment*, 93-112.;
[24] Quan, *First assessment*, 93-112.

Historically, climate research at Carlsbad Caverns National Park has been conducted with a focus on airflow with concern to its relation to the drying of cave formations. This drying was due to the chimney effect created by the artificial entrance—the elevator shaft.[25] While Carlsbad Cavern does have a second natural entrance, because it is similar in elevation to the Natural Entrance, it does not significantly affect the airflow. As a result of this research, revolving doors with airproof seals were installed at the base of the elevator shaft in August 1972 to act as an airlock and reduce (but not eliminate) the airflow. While this research primarily concentrated on air circulation patterns throughout the cave, it also included a period of carbon dioxide monitoring in the Underground Lunch Room and at Devil's Den.

An early report by Christensen (1943) observed patterns in air circulation in Carlsbad Cavern. Those patterns were also confirmed by Kittams (1970) and McLean (1971)—that Carlsbad Cavern was a static cave where cold dense winter air easily enters the cave, displacing the internal air and resulting in high ventilation regimes in the winter. The researchers all noted that the increased ventilation during the winter results in evaporation while the summer resulted in condensation on railings, trails, and formations. Christensen (1943) observed that strong winds outside the Natural Entrance could cause updrafts in the elevator shaft, and McLean (1971) noted that sealing the elevator shaft would likely reduce the air exchange caused by the chimney effect. Reduced airflow would increase CO_2 levels. Figure 4 shows an increase in CO_2 levels in 1973 after the installation of the revolving doors, although visitation and local weather patterns may have been a factor. Christenson (1943) observed that airflow moved from the Natural Entrance, down the Main Corridor, and eventually to Lower Cave. This observation was confirmed by McLean (1971).

Beckman's 1975 study sampled carbon dioxide concentrations in Carlsbad Cavern in the pump room at 0.06 on November 4, 1975, but did not provide units for the measurement. McLean (1971) noted that the atmospheric carbon dioxide concentration at that time was 330 ppm and the CO_2 concentration in the lunch room varied from 345 ppm in March 1969 to 490 ppm in August 1969 as shown in the graph below. The periods of time with lower CO_2 concentrations were due to increased air circulation during the winter months (Figure 3). The Devil's Den sensor did not vary significantly from the Lunch Room findings. McLean (1976) conducted another microclimate study in Carlsbad Caverns from 1969 to 1972 and collected more data on carbon dioxide levels in the Lunch Room (Figure 4). Both Figures 3 and 4 show seasonal variation in carbon dioxide concertation, with a winter minimum and summer maximum, in accordance to the cold trap ventilation regime.

[25] Killing-Heinze, *The importance,* 153-167.

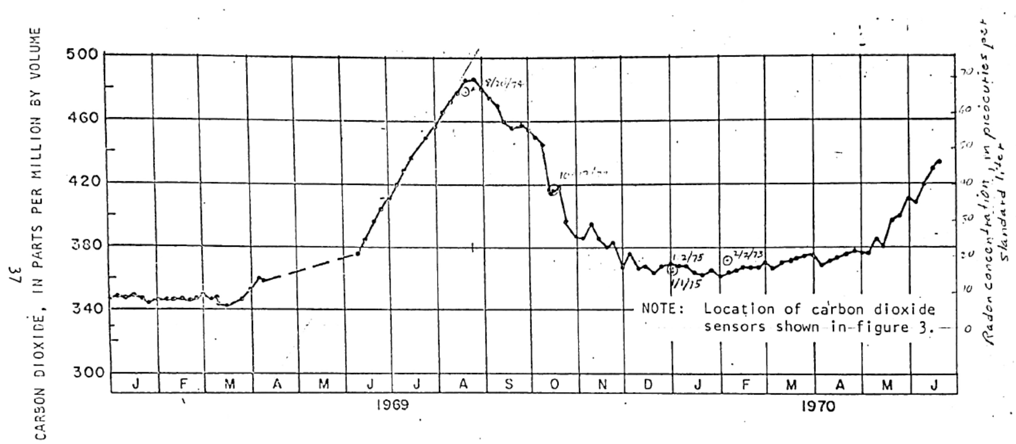

Figure 13.--Carbon dioxide content of the air in the Lunch Room.

Figure 3. Graph of CO_2 levels in the Lunch Room, 1960-1970 (McLean 1971)

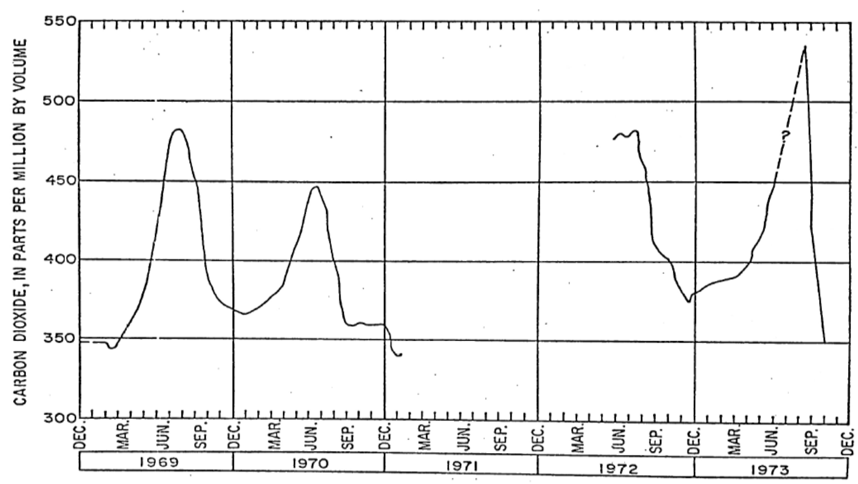

Figure 4.--Carbon dioxide content of the air in the Lunch Room (near base of elevator shaft).

Figure 4. Graph of CO_2 levels in the Lunch Room, 1969-1973 (McLean 1976)

Previous research had concluded that airflow in Carlsbad Cavern depended on air temperature outside the cave resulting in convective effects; however, the most recent research on airflow and microclimatology in Carlsbad Cavern conducted by Dr. Andreas Pflitsch and his graduate students determined that the influences are more complicated than previously thought.[26] Killing-Heinze (2017) determined that Carlsbad Cavern has complex air circulation patterns due to the combination of huge chambers with smaller connecting tunnels. Barometric airflow is a secondary component that affects the climate in Carlsbad Cavern.

[26] Killing-Heinze, *The importance*, 153-167.; National Park Service Research Permit and Reporting System. Carlsbad Caverns National Park. *Cave Climatology*. Permit submitted by Andreas Pflitsch. Permit#: CAVE-2015-SCI-0012. 2018.

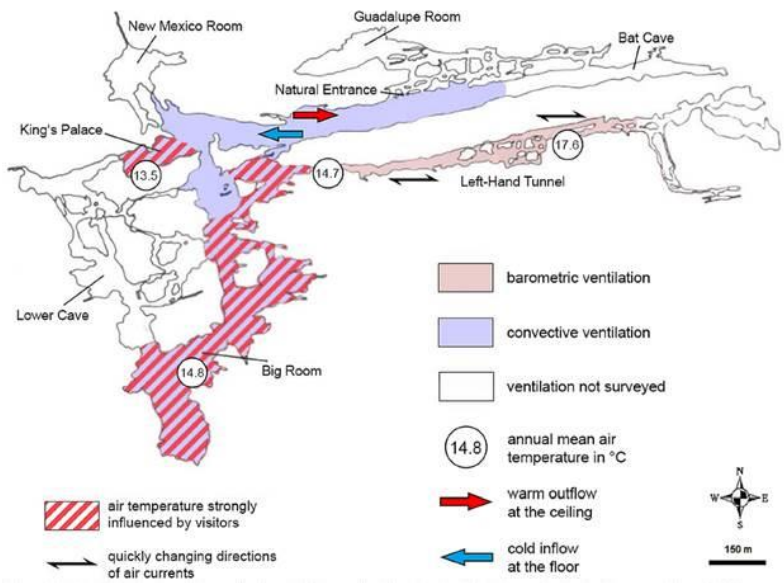

Figure 5. Spatial distribution of the predominant effects on the climate in Carlsbad Cavern (Killing-Heinze 2017)

Figure 5 shows that the Main Corridor, King's Palace, and the Big Room have convective ventilation that act as cold traps in the winter, but go through a stable summer phase where airflow is not affected by surface temperatures (Figure 6). The Left Hand Tunnel has a barometric ventilation system due to the large volume beyond its comparatively small entrance (Figure 5).

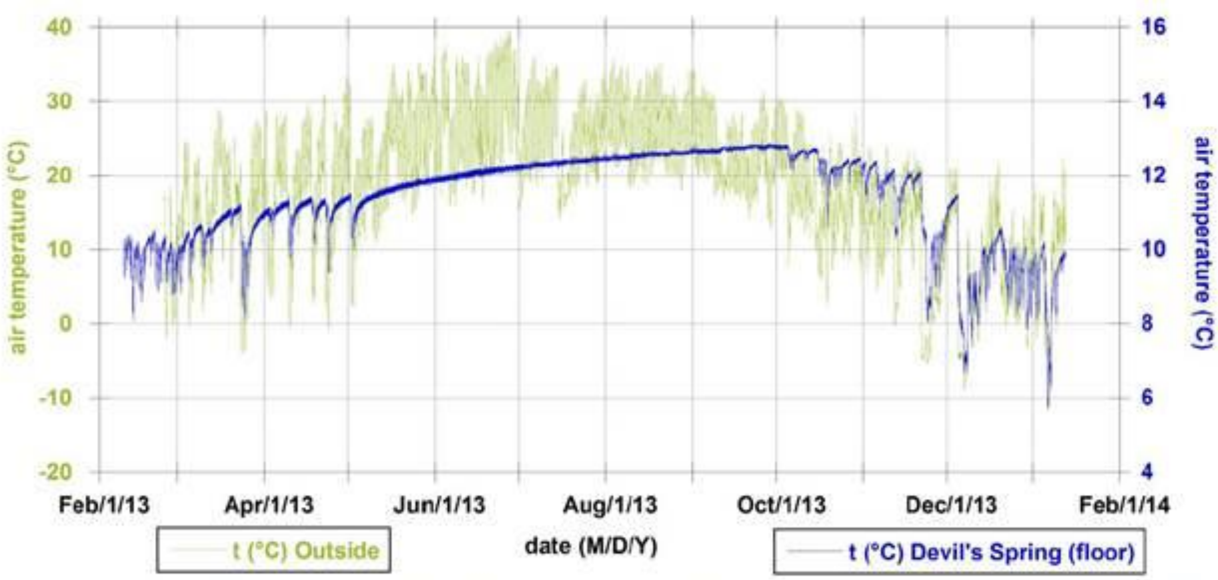

Figure 6. Records of the near-ground air temperature on the surface and near Devil's Spring inside Carlsbad Cavern from February 2013 to January 2014, recorded every 5 minutes (Killing-Heinze 2017)

Figure 6 shows the air temperature on the surface and inside the cave at Devil's Spring in the Main Corridor. In the winter months, the cave temperature is strongly influenced by the surface

temperature, while in the summer months, the cave temperature steadily increases irrespective of the surface temperature.[27] During their research, the dramatic influence of visitation on cave temperatures was evidenced by the lack of temperature fluctuations in King's Palace while the cave was closed for a 16-day government shutdown. Instead of fluctuating at the times of the five daily tours, the temperature decreased slightly, demonstrating that anthropogenic influence constantly elevates temperature year-round (Figure 5).[28] This effect was also seen in the Big Room (Figure 5).[29]

Recent research in El Soplao Cave, Spain on real-time underground monitoring systems and modeling carbon dioxide for show cave conservation may be highly relevant to Carlsbad Cavern. Novas (2017) wrote about a wireless in-cave monitoring network that uploads real-time data; they focused on CO_2, humidity, and temperature as indicators of good cave health. During this study, monthly averages in El Soplao Cave reached 1000 ppm. Novas (2017) found a high correlation between CO_2 and the number of visitors, but noted that more data was needed to determine long-term cumulative effects. Guirado (2019) used five years of data from El Soplao Cave to create a linear model to predict CO_2 throughout the day with variables including pattern of visit and starting value. This predictive model can be used to determine the maximum number of visitors that can be supported without exceeding a given CO_2 threshold, and can be applied to other show caves with modification of the parameters (Guirado 2019).

Given that anthropogenic influences such as human exhalation can in some cases triple CO_2 levels, this study focuses on the relationship between CO_2 levels and park visitation. Once enough data is collected, using Guirado's (2019) model, this study may reveal a carrying capacity for the cave in regards to CO_2 levels from multiple viewpoints—visitor safety, cave conservation, and visitor experience. Ultimately, the study will be used to establish current CO_2 conditions in Carlsbad Caverns as part of the ongoing VUM study.

3. Methods

3.1 Monitoring Equipment

Throughout this study, CO_2 concentrations were measured using four auto-logging CO_2 monitoring devices: one GE Telaire 7001 CO_2/Temperature Monitor (serial no. 1072632) with a working range of 0 to 10,000 ppm, a resolution of 1 ppm, an accuracy of 50 ppm or 5% of the reading up to 5,000 ppm, and a sampling at a rate of 5 minutes; and three Wöhler CDL 210 CO_2 Data Loggers (Wöhler A—serial no.100013844, Wöhler B—serial no. 100012709, Wöhler C—serial no. 100012840) with a working range of 0 to 2,000 ppm, a resolution of 1 ppm, an accuracy

[27] Killing-Heinze, *The importance,* 153-167.
[28] Ibid, 153-167.
[29] Ibid, 153-167.

of 50 ppm or 5% of the reading, and a sampling at a rate of 5 minutes (Appendix B).[30] Both sensors use a stable non-dispersive infrared (NDIR) laser measuring technique. NDIR is the recommended technique for measuring in-cave CO_2 (James 2004).

The Wöhler CDL 210 Data Loggers require an AC Adapter 5V plug to draw power, which limits the locations it can be placed, but saves person-hours needed to replace batteries every few days. This can be especially useful because data loss can happen if batteries are not replaced before the battery depletes (Appendix B). For instrument set up, the Wöhlers were calibrated according to the operating manual instructions. The alarm was turned off, the units were set to record temperature in Fahrenheit, date/time were set to local time (Mountain Daylight Time), and the sampling rate was set to 5 minutes (Appendix B). Since the data will often need to be correlated with the cavern's operating hours, which follows daylight savings time, the SOP recommends that the sensor time be changed in accordance with daylight savings time (Appendix B). There will be no data loss during this time change since it will take more than an hour to remove the devices for weekly recalibration. The CDL 210 can store 15,999 data points, but can only store one data set, meaning that each new logging session will overwrite the old one (Appendix B). At the selected sampling rate of 5 minutes, the device's memory will be full after 18 days of data logging. The devices need to be recalibrated and data downloaded every 5 days (Appendix B).

3.2 Monitoring Locations

The sensors were deployed in June 2019 at locations shown in Figure 7. Wöhler B (serial no. 100012709) was placed where the Telaire was previously located, near the elevator using a 25-foot extension cord to reach the pump room outlet (Appendix C, D; Figure 7). This location was chosen to collect CO_2 concentrations because it is an area that sees large congregations of people waiting in long elevator lines on peak days. Wöhler A (serial no. 100013844) was placed in the Big Room Junction using a 50-foot extension cord to reach the nearby outlet (Appendix C, E; Figure 7). This location was chosen because it is a central point in the cave that receives traffic both from the elevator and the Main Corridor, and anecdotally has good airflow going over Appetite Hill and up the Main Corridor. Wöhler C (serial no. 100012840) was placed in King's Palace near the ranger outpost in front of the audience seating using a 50-foot extension cord to reach the nearby outlet (Appendix C, F; Figure 7). This location was chosen because the park runs five tours a day to King's Palace every 1.5 hours starting at 9:00 AM in the summer and a once daily tour at 10:00 AM in the winter.

Badino (2009) disproved the myth that CO_2 is heavier than air and falls to the floor; instead, a series of environmental factors can result in CO_2 traps. In a typical complex cave environment such as Carlsbad Cavern, CO_2 would not pool near the ground. For this reason, and to keep sensors out of sight and reach of visitors, sensors in the Big Room Junction, King's Palace, and Bottomless Pit were placed on the ground behind the constructed trail wall. The elevator sensor

[30] GE Sensing. (2006). *Telaire ®7001 CO_2 and Temperature Monitor Use Instructions*. Billerica, MA.

was placed on top of a constructed wall about 2.5 feet off the ground hidden by a sign and behind a roped off area.

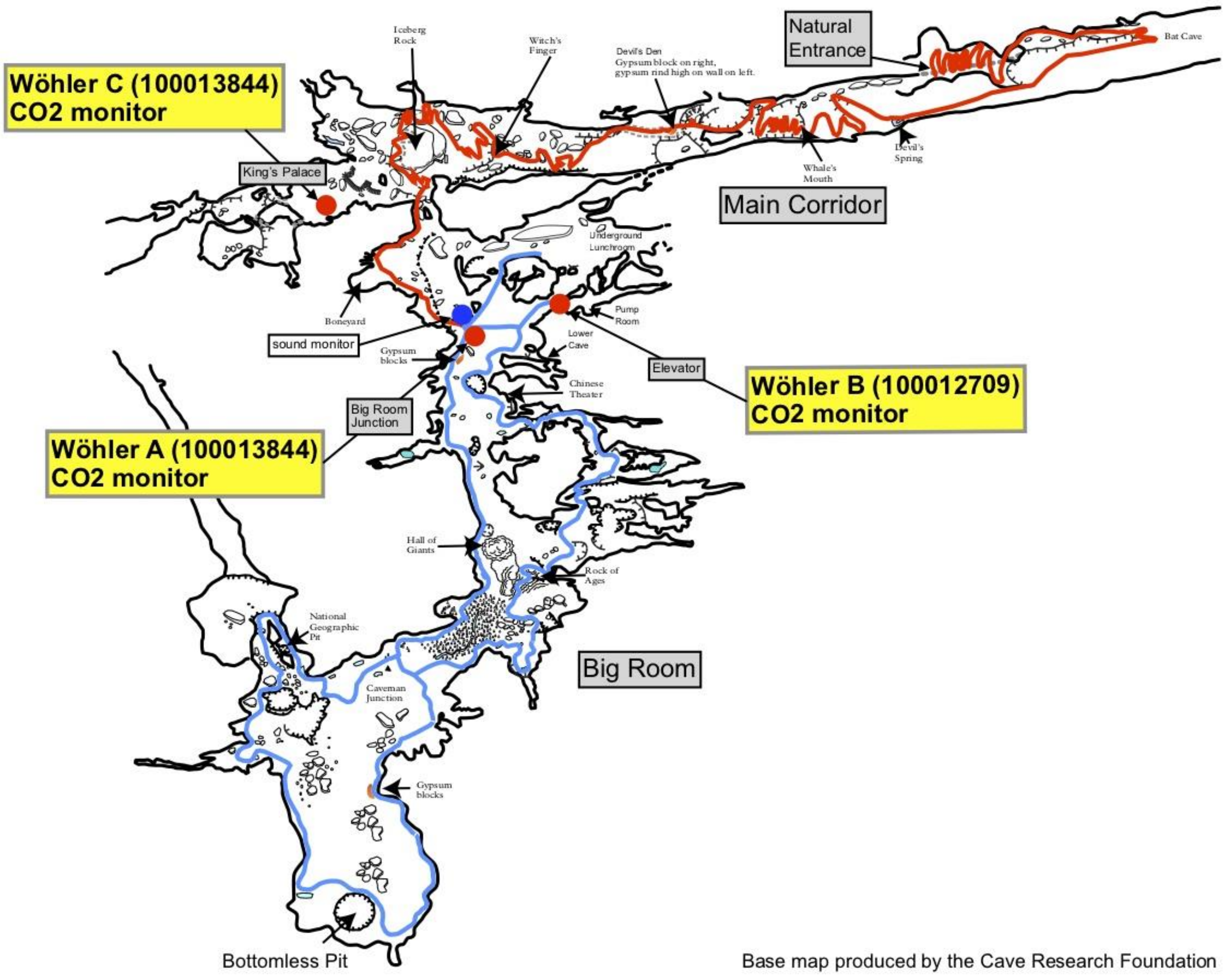

Figure 7. Map of CO_2 sensor locations in Carlsbad Cavern

3.3 Monitoring Efforts

Data collection began in June 2018 and continued through May 2019 at the lower elevator waiting area. Unfortunately, much of the data is inaccessible or determined to be unusable due to insufficient device calibration. The Telaire was used to log CO_2 measurements at the lower elevator waiting area from December 2018 through May 2019. On May 29, 2019, three new instruments (Wöhler A, Wöhler B, and Wöhler C) were deployed at the Ugly Desk in the Underground Lunchroom, and the Telaire was moved to the same location to test for comparable readings. The Wöhler instruments were turned on and logging began on May 29, 2019, 11:35 AM, but readings did not stabilize until 12:30 PM, so only data from 1:00 PM to 5:00 PM were used for analysis. Data from the Telaire was pulled from the same time period to compare against data from Wöhler A and Wöhler C. No data was pulled off of instrument Wöhler B due to user error. The data showed that the Wöhler instruments were calibrated in

reference to each other, but the Wöhler instruments and the Telaire were recording significantly different readings. Despite the differences in readings, all of the sensors seemed to be accurately reflecting changes in the environment. Anecdotal data indicated that the Telaire had not been calibrated in many years so the CO_2 measurements were likely inaccurate. Given the results of the in-cave test, all four devices were tested on the surface where the CO_2 concentration in the air is known to be near 400 ppm. The 24-hour test began on June 5, 2019, 9:17 AM. The results showed that the Wöhler instruments were reading similar values at the expected atmospheric CO_2 concentration, while the Telaire's readings were inaccurate. The Wöhler instruments were determined to be calibrated correctly and can be used to collect data in the cave, while the Telaire needs further testing or recalibration before it can be used again.

Data analyzed in this paper was collected from June to July 2019 from the CO_2 monitors in the following locations: elevator, Big Room Junction, and King's Palace. CO_2 levels are compared to sound monitor decibel levels, daily visitation data, King's Palace tickets sold, and surface temperature readings. The sound monitor is in close proximity to the CO_2 sensor at the Big Room Junction and records decibel levels every 30 seconds. The visitation and tour data provided by the fees staff are based on the number of tickets sold. The sound data and tour tickets sold may provide a more detailed real-time picture of visitor traffic when compared to CO_2 data in the Big Room and King's Palace respectively. The surface temperature data, logged hourly, are provided by the Bureau of Land Management and National Park Service from BATDRAW weather station. Additionally, this study aims to determine if the cave air returns to its starting level, how long it takes for CO_2 concentrations to return to starting levels in the absence of visitors, if the levels are consistently rising, if CO_2 levels are reaching unsafe concentrations, and if CO_2 levels are adversely impacting the natural cave environment. Peak days and times of elevated CO_2 concentrations in the cave are identified to reveal trends. Ultimately, this data will be used to establish current conditions and thresholds for CO_2 levels inside the cave as a part of the Visitor Use Management study.

4. Results

The data used for analysis has been gathered from carbon dioxide monitoring from June to July 2019. In order to establish current conditions for the cave, carbon dioxide monitoring will need to continue for at least a year—August 2019 to August 2020. When the cavern is open, visitors create fluxes in carbon dioxide that have a cumulative effect over time. In the evening, when the cavern is closed, carbon dioxide decreases with time. Both processes are additionally influenced by airflow, which can be correlated with the surface temperatures during the winter. During the summer (Memorial Day to Labor Day), the cavern operates from 8:30 AM to 6:45 PM, and during the winter, the cavern operates from 8:30 AM to 4:45 PM with exception during some federal holidays. During the summer, King's Palace tours run 5 times a day: 9:00 AM, 10:30 AM, 12:00 PM, 1:30 PM, and 3:00 PM. During the winter, King's Palace tours run once daily at 10:00 AM.

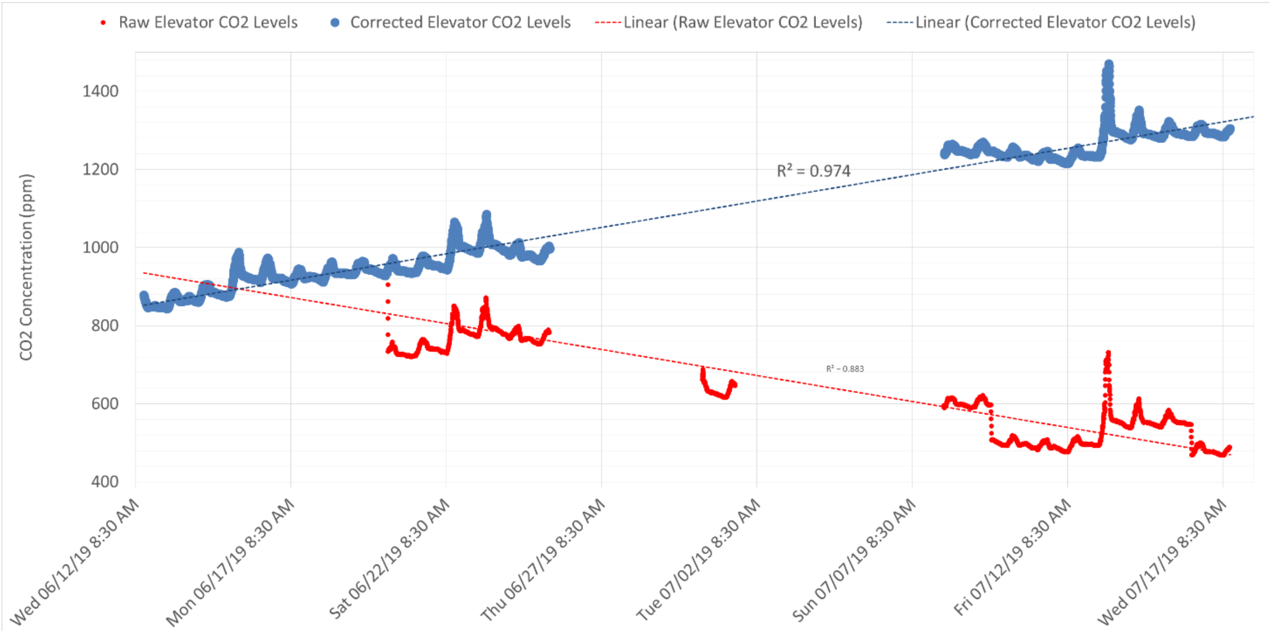

Figure 8. Graph of raw and corrected CO_2 levels at the elevator, June-July 2019

Upon analysis of the raw data, a pattern appeared of steep and sudden drops about every 7.5 days (Figure 8). Automatic baseline calibration (ABC) was determined to be the cause of these drops. Every 7.5 days, the device recalibrates based on the assumption that the lowest reading during the previous 7.5 days corresponds to 400 ppm (the normal background concentration in outdoor ambient air) (Appendix G). As the device remained underground for the entire sampling period, the lowest readings were in fact well above 400 ppm, and thus the ABC introduced an offset error in the data. When this error was discovered, sensors were reading 500 ppm, and after recalibration, they read 1300 ppm. The raw data from the sensors show a marked decrease in carbon dioxide over time (Figure 8); however, this runs contrary to expectations as Carlsbad Cavern has decreased ventilation and increased visitation in the summer. Given this knowledge, it is extremely unlikely that the cavern's internal carbon dioxide levels are that close to those of outdoor ambient air.

Once the data was corrected, it showed a clear increase in CO_2 levels over time (Figure 8). Several steps were used to mathematically correct the data. For the elevator, the difference between the final reading and the recalibrated reading was using to correct the data. The 7.5 day ABC is not exact, so to identify when the ABC interval took place, the absolute value of the difference between each successive reading was examined. For the elevator data, statistics on the differences between readings are $\mu=2.5$, $\sigma=5.5$, min=0, max=215. Given the low variability in the difference between readings, it is easy to distinguish sudden decreases in the data. Approximately 7.5 days after the first recording began, CO_2 levels suddenly dropped 215 ppm. The subsequent data set was corrected by adding 215 ppm. During this two-month timeframe, several significant data losses occurred for a variety of reasons: power loss from unplugging device without ceasing logging, manual error by overwriting data, power loss from

thunderstorm power surges, and removing devices for recalibration (Appendix H). Due to such data losses in King's Palace and Big Room Junction, it was not always possible to identify when or by how much the ABC occurred, so linear regression of recalibrated CO_2 monitors were used to calculate previous data points (Appendix H). A detailed data log is provided in Appendix H.

To account for outliers and to display the general trend of the data, all data has been smoothed using a simple moving average using the average of the data point and surrounding four data points. Days that do not have a full set of data during cavern operating hours (8:30 AM-6:45 PM) have been excluded so as to not skew results. For the purpose of this study, the starting level for a given day is defined as the CO_2 concentration at the time the cavern opened (8:30 AM). CO_2 levels predictably peak during the day, then drop sharply and relax in the evening, with weekly peaks on the weekend (Figure 8). Figure 8 shows a marked increase in CO_2 levels over time with the evening CO_2 concentration not returning to the starting level, but rather consistently rising over time.

In order to more clearly analyze the day-by-day influence of visitation numbers on CO_2 levels, normalized CO_2 values were calculated. The starting level was subtracted from the CO_2 concentration at a given time throughout that day, thus removing the effect of the cumulative increase in CO_2. The following graph shows the normalized CO_2 values at the elevator—the starting levels are equalized so the days can be compared against each other.

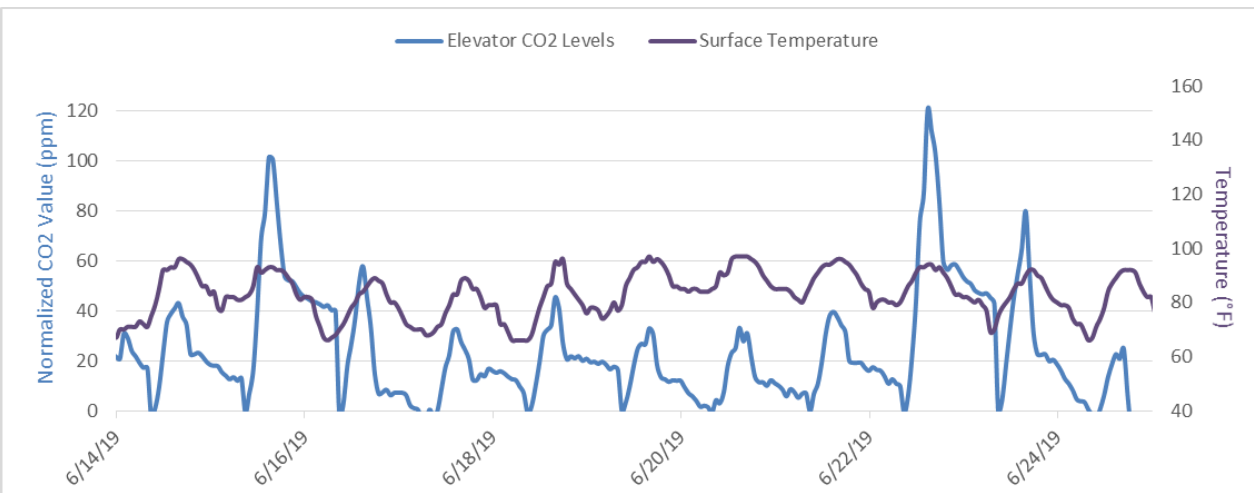

Figure 9. Graph of surface temperature versus CO_2 level at the elevator, June 2019

Figure 9 shows a comparison of the surface temperature at the BATDRAW weather station with normalized CO_2 concentrations at corresponding times. Since Carlsbad Cavern's internal temperature is relatively constant, only the surface temperatures were used in this comparison. While there appears to be a matching in oscillations between the two variables, there does not seem to be a correlation, since the CO_2 peaks are not reflected in the temperature fluctuations (Figure 9). Given the lack of data in the Big Room Junction and King's Palace, the surface temperature difference was only compared to data from the elevator sensor. These findings

correspond with Killing-Heinze's (2017) stable summer and cold trap winter model of Carlsbad Cavern's Big Room.

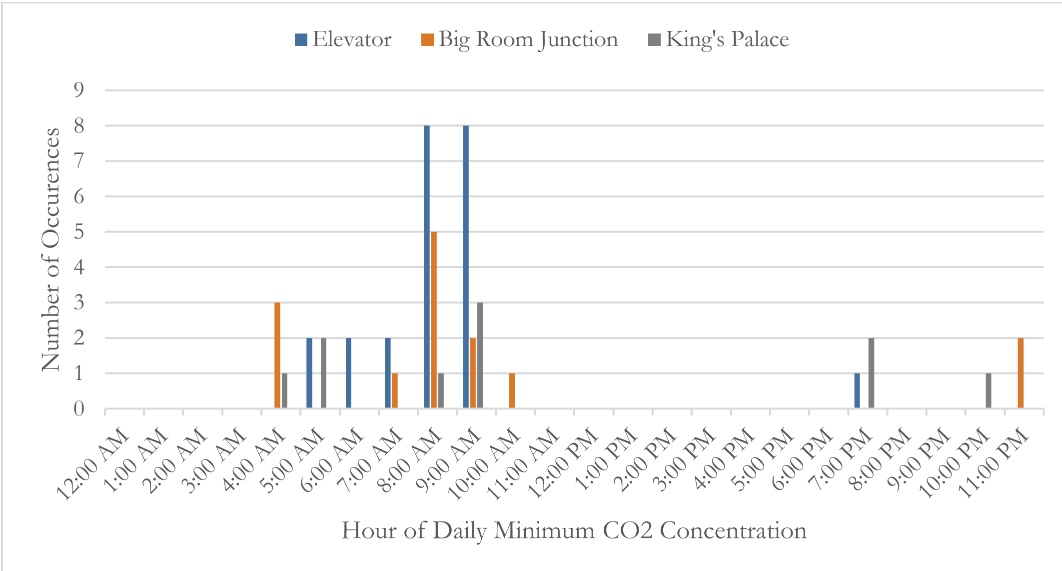

Figure 10. Histogram of times with lowest CO_2 concentrations, June-July 2019

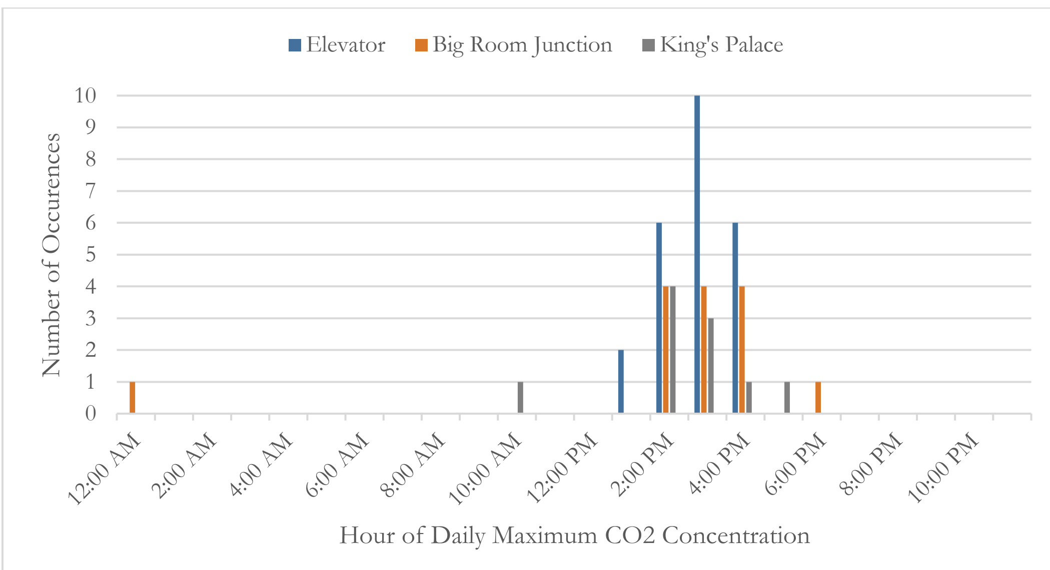

Figure 11. Histogram of times with highest CO_2 concentrations, June-July 2019

To determine the times with highest and lowest CO_2 concentrations, the hour associated with the daily maximum and minimum CO_2 concentration were analyzed with a histogram (Figures 10, 11). The lowest CO_2 concentrations were logged between 8:00 AM to 9:00 AM (Figure 10). The highest CO_2 concentrations were logged between 2:00 PM to 4:00 PM (Figure 11). This corresponds with the peaks seen in Figure 8.

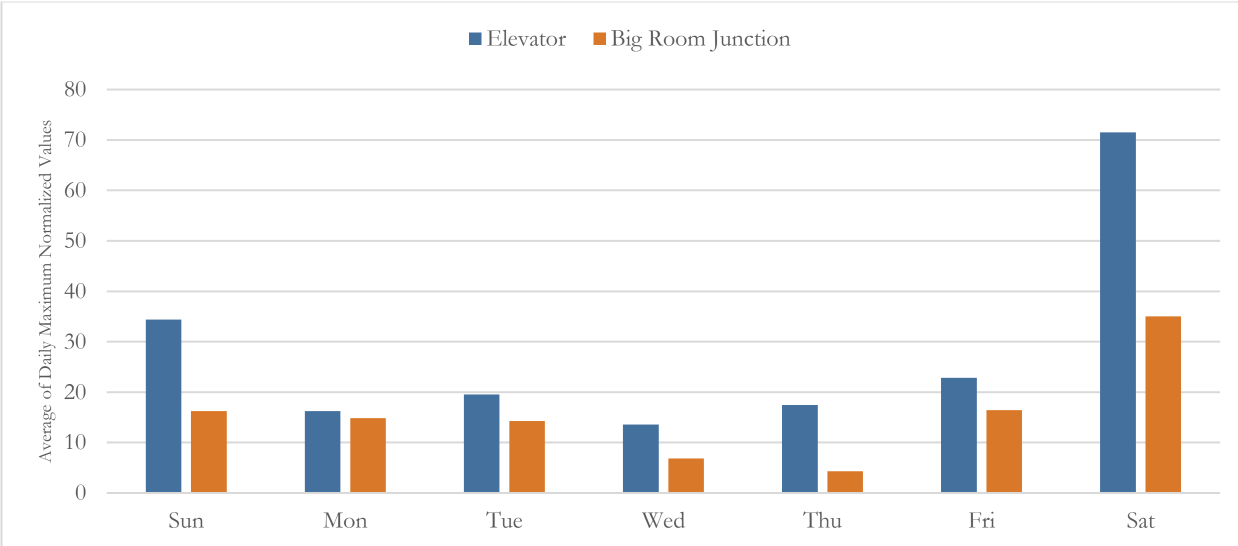

Figure 12. Graph of CO_2 peak days of the week, June-July 2019

The daily maximum CO_2 concentrations were normalized to be compared across days. These values from the same location on the same day of the week were averaged together to show peak days of the week. Due to insufficient data, King's Palace peak days were not included in this graph (Figure 12). For both the elevator and the Big Room Junction, CO_2 levels peaked on the weekend, with Saturday having the highest average of daily maximum normalized values (Figure 12).

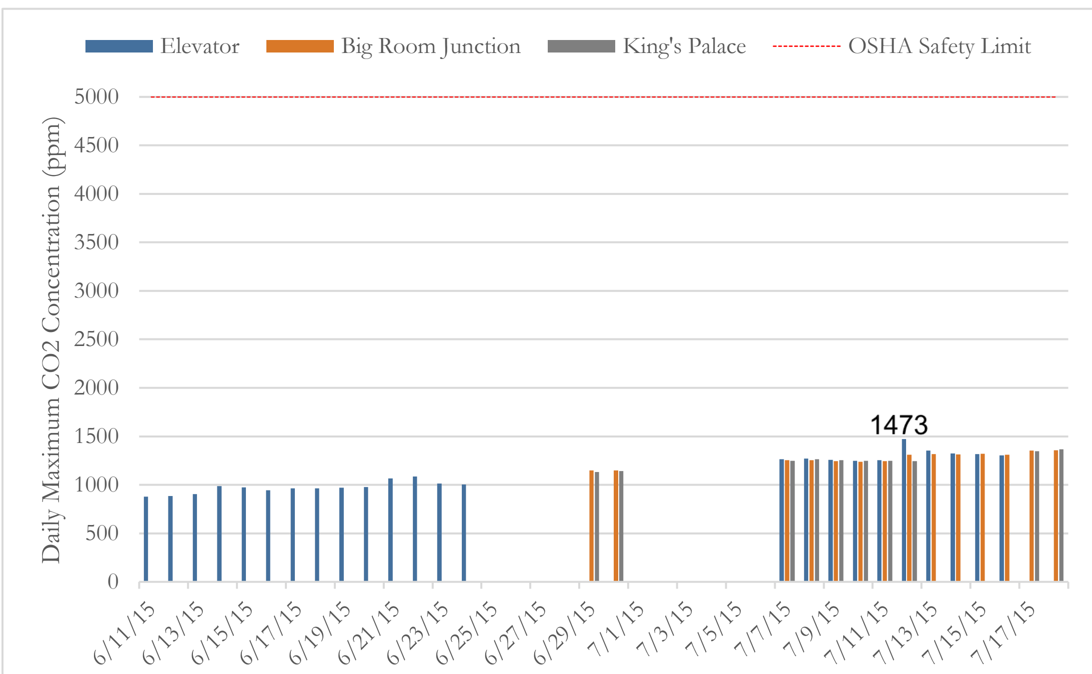

Figure 13. Graph of daily maximum concentrations and OSHA safety limit line, June-July 2019

Figure 13 shows the daily maximum values for all data collected in all three locations with the OSHA safety limit of 5,000 ppm marked as a reference. Figure 13 also clearly shows the data losses outlined in Appendix H.

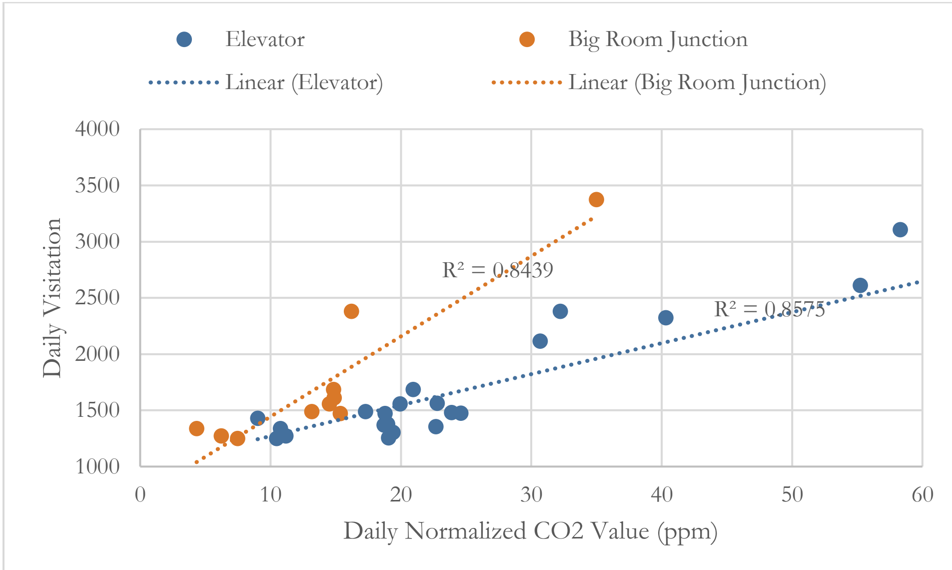

Figure 14. Scatterplot of daily visitation and CO_2 values at the elevator and Big Room Junction, June-July 2019

The daily normalized CO_2 values were compared against corresponding visitation numbers for June to July 2019 at the elevator and in the Big Room Junction. The correlation coefficient between daily visitation and CO_2 values at the elevator was: R=+0.93, and the coefficient of determination was: R^2=0.86 (Figure 14). The correlation coefficient between daily visitation and CO_2 values in the Big Room Junction was: R=+0.92, and the coefficient of determination was: R^2=0.84 (Figure 14). Due to data losses, there was not enough data from the King's Palace sensor to run this analysis. R>±0.7 are considered strong correlation coefficients indicating the strength and direction of a linear relationship between two variables. The coefficient of determination (R^2) represents the percent of data that can be explained by a regression equation, and therefore the strength of its predictive quality. 86% of the elevator data can be explained by linear regression while 14% of the variation is unexplained. 84% of the Big Room Junction data can be explained by linear regression while 16% of the variation is unexplained.

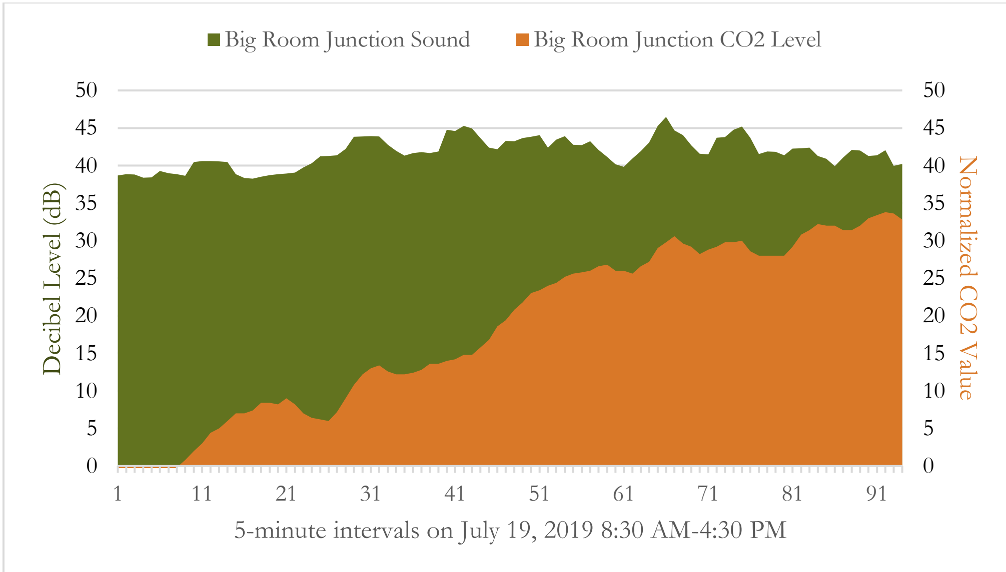

Figure 15. Scatterplot of decibel and CO_2 levels in Big Room Junction, July 19, 2019

Due to the same thunderstorm that affected the King's Palace CO_2 monitor, the Big Room Junction sound monitor also lost data. There is less than a day of data with which to compare the Big Room Junction decibel levels to CO_2 levels. Figure 15 compares the daily normalized CO_2 concentration at a given 5-minute time interval and with decibel levels smoothed by simple moving average at the corresponding time on July 19, 2019 in the Big Room Junction. There appears to be a matching pattern between sound and CO_2, but CO_2 is cumulative throughout the day whereas sound is not, which explains the rising CO_2 levels. Given that this is less than a full day of data, no conclusions can be drawn from such a small sample.

5. Discussion

5.1 Limitations

Data collection began in June 2019 and continued through July 2019. Two major limitations of this study are the sparsity and quality of data due to the short two-month monitoring period, various data losses, and the unreliability of the data due to the mathematical corrections for automatic baseline calibrations (Appendix H). It is impossible to draw strong conclusions from a small sample size and unreliable data. Starting in August 2019, carbon dioxide monitoring will continue for a year. The Wöhler sensors must be manually calibrated on the surface once a week to counteract the automatic baseline calibration (ABC), and the SOP must be carefully followed to avoid future data losses. ABC requires exposure to fresh air once a week; this feature is hardwired into the device and cannot be turned off. If placed inside the cave, the devices will not be exposed to fresh air and results in inaccurate calibrations; these devices are not designed for in-cave carbon dioxide monitoring. Given the cost of person hours to recalibrate devices weekly (3 hours), it may be worth considering an alternative sensor; however, there may be

more trials and tribulations with a new device that could further delay monitoring efforts. Recalibrating the Telaire is a possibility; however, it would take time to purchase more sensors and the Telaire staffing cost is almost equivalent requiring a battery change every four days (1 hour).[31]

5.2 Significance of Results

Given the limitations of this study, all results should be considered preliminary and not conclusive. Further monitoring needs to be done for at least a year to reveal seasonal trends. Despite the limitations, this study shows that throughout June and July 2019, CO_2 levels were cumulatively increasing and not returning to starting levels in the evening (Figure 8). The data revealed a very strong positive correlation between visitation numbers and CO_2 levels at the elevator (R=+0.93) and Big Room Junction (R=+0.92) (Figure 14). This is expected given the high visitation and low air circulation in summer months in accordance with the Carlsbad Cavern's ventilation regime of summer stagnation. This may change over time as visitation declines and air circulation increases in the winter months in accordance with the wintertime cold trap ventilation regime. It is important to not extrapolate these preliminary results across the year, as further carbon dioxide monitoring is needed to capture the effects of this seasonal variation.

During the period of the study, the highest CO_2 concentration was recorded at 1,473 ppm. While this is well below the OSHA safety limit of 5,000 ppm for a 40-hour work week, concentrations over 2,000 ppm can have some adverse health effect on humans and may impact visitor experience. Limestone corrosion thresholds range from 2,400-2,900 ppm.[32] The CO_2 levels are continually increasing throughout the summer. This signifies the importance of carbon dioxide monitoring throughout the year.

5.3 Future Data Analysis

It will be interesting to compare data from the three sensors to see if there is a significant difference in CO_2 levels in different parts of the cave at the same time. If there is no significant difference between the three locations, the comparison of CO_2 levels to temperature can be done in just one location. In this study, the patterns of temperature and CO_2 at the elevator were compared, but they were not statistically correlated. The similarity of patterns warrant further study. The comparison against temperature is an important one since temperature is a driving force in cave ventilation, and air advection is the primary mechanism for naturally removing CO_2.

Airflow is an important mechanism influencing CO_2 levels in caves, and airflow in Carlsbad Cavern is driven by differences in air temperature and pressure. In the winter, cold dense air easily enters the cave increasing airflow and ventilation. The lower the surface temperature, the greater the airflow. In the summer, temperatures are high, the difference between surface and

[31] GE Sensing, *Telaire*.
[32] Dragovich, *Impact of*, 111-120.; James, *Encyclopedia,*730-731.

cave temperature is high, and the airflow is low. In the summer, outside temperatures are higher than the cave temperature, and the airflow is low. External pressure also plays a role in cave ventilation. When the external pressure is low, the cave "exhales"; when external pressure is high, outside airflows into the cave. The influence of temperature and pressure on cave ventilation must be taken into consideration when attempting to calculate the effect of visitor numbers on underground CO_2 levels.

With the brevity of the preliminary monitoring period, it was not possible to reveal seasonal trends. Once additional data is collected, CO_2 levels can be compared across months and seasons. Data from the 1970s reveals seasonal variation in CO_2 levels with summer maxima and winter minima (McLean 1976). The results of this study showed that during the June to July 2019 timeframe, evening CO_2 levels did not return to starting levels. Will this change as visitation declines and ventilation increases in the winter? How will seasonal weather patterns affect the rate of CO_2 recovery in the absence of visitors? It would also be interesting to monitor CO_2 levels on the days when the cave is closed (i.e., Thanksgiving, Christmas, and New Year's Day) to see if an actual baseline CO_2 level can be established for the cave. One day without visitors may not be enough time for the cave to return to its baseline levels, but wintertime should also have the highest ventilation. Peak days and hours can be identified across the year, and if CO_2 levels consistently rise during certain times of year, or if the concentrations do not return to starting levels overnight, this data will help management make decisions to mitigate visitor impacts at that level of visitation.

Due to untimely data losses, this study was not able to reliably compare CO_2 data from the Big Room Junction to sound data from the same area or make many comparisons with the CO_2 data from King's Palace and tour tickets sold, which will provide more accurate data as to when visitors move through that space. When more data is collected in these areas, distribution lag analysis can be used to determine how long it takes for visitors to affect CO_2 levels.

Preliminary results indicate a strong correlation between visitation and CO_2 levels; however, more data needs to be collected for a year. In order to establish the correlation between visitation and CO_2 levels, it is important to understand the effect of seasons, temperature, pressure, and ventilation on CO_2 levels. Guirado's (2019) carrying capacity model for CO_2 in show caves should be closely examined to see if it can be appropriately applied to Carlsbad Cavern.

5.4 Future Considerations

If these data collection methods are to help establish current conditions for future comparison of desired conditions, climate change needs to be taken into account. Since the 1971 Carlsbad Cavern climatology study, atmospheric carbon dioxide levels have risen from 330 ppm to 400 ppm (McLean 1971). Any change in atmospheric carbon dioxide levels over time should be taken into account when comparing against this study. An external CO_2 sensor to measure atmospheric carbon dioxide should be referenced; there may be a third party source for these data.

New airlocks preventing flow of cave air into the Visitor Center to mitigate radon risks may be installed in the underground elevator lobbies. Similar to the revolving doors that were installed in 1972, such airlocks would reduce airflow caused by the chimney effect of the artificial elevator shaft entrance. A reduction in airflow could increase CO_2 levels in that part of the cave.

6. Conclusion

CO_2 levels rose consistently in June and July of 2019. While the CO_2 levels decreased in the evening, they did not return to starting levels. Visitor CO_2 fluxes were cumulative over time during these two months (Figure 8). There was a positive correlation between daily visitation numbers and CO_2 levels accounting for the consistent rise of CO_2 levels over time at the elevator (R=+0.93) and Big Room Junction (R=+0.92) (Figure 14). There were significant limitations in this study due to sparsity and quality of data; these results are preliminary and should not be extrapolated past June and July of 2019. Carbon dioxide monitoring should be continued for at least a year—August 2019 to August 2020. With more data, stronger conclusions and seasonal patterns can be determined.

The lowest CO_2 concentrations are logged between 8:00 AM to 9:00 AM (Figure 10). The highest CO_2 concentrations are logged 2:00 PM to 4:00 PM (Figure 11). In both the elevator and the Big Room Junction, CO_2 levels peak on the weekend, with Saturday producing the highest values (Figure 12). Daily maximum CO_2 concentrations are compared against the OSHA safety limit of 5,000 ppm with a peak of 1,473 ppm during that time period (Figure 13). While the surface temperature does not appear to have an effect on CO_2 levels in the summer, it is expected to have a significant effect in the winter (Figure 9).

This preliminary work establishes standard operating procedures for a future yearlong study. The results from the yearlong carbon dioxide study will be used to establish a current CO_2 conditions in Carlsbad Caverns as part of VUM study to monitor microclimate changes over time. In addition to establishing a current conditions, CO_2 is important to monitor with regards to visitor safety, cave conservation, and visitor experience.

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Appendix A. CO_2 Concentration Safety Limits from Multiple Sources

CO_2 Concentration	Effect on Humans	Source
250-350 ppm	Normal background concentration in outdoor ambient air	[1,4,6]
300-400 ppm	Outdoor	[7]
350-1,000 ppm	Concentrations typical of occupied indoor spaces with good air exchange	[1,4]
500 ppm	Lung ventilation increases by 5 percent	[6]
600-900 ppm	Metropolitan areas	[7]
<700 ppm	Good	[8]
<1,000 ppm	Continuous exposure; Indoor air ventilation standard	US EPA[2]; ASHRAE standard 62-1989[2,8]
1,000-2,000 ppm	Complaints of drowsiness and poor air	[1,4,8]
>2,000 ppm	Ventilation is necessary! Lung ventilation increases by 50 percent, headache after several hours exposure	[6,8]
2,000-5,000 ppm	Headaches, sleepiness and stagnant, stale, stuffy air. Poor concentration, loss of attention, increased heart rate and slight nausea may also be present; Lung ventilation increases by 100 percent, panting after exertion	[1,4,6]
5,000 ppm	Workplace exposure limit (as 8-hour TWA) in most jurisdictions; TLV-TWA (40-hour work week)	[4]; ACGIH[2,5]; NIOSH[5]; OSHA[1,3,5,7]
10,000 ppm	Typically no effects, possible drowsiness	[7]
10,000-20,000 ppm	Electrolyte imbalances and other metabolic changes	ACGIH[5]
15,000 ppm	Mild respiratory stimulation for some people	[7]
15,000-30,000 ppm	Few, if any, adverse effects	ACGIH[5]
30,000 ppm	Moderate respiratory stimulation, increased heart rate and blood pressure, ACGIH TLV-Short Term	[6,7]
<30,000 ppm	Ceiling for any 10-minute exposure; TLV-STEL (short term exposure limits); 15-min STEL	NIOSH[2,5]; ACGIH[2,5]; OSHA[5]
40,000 ppm	Immediately Dangerous to Life or Health (IDLH)	[7]
>40,000 ppm	Exposure may lead to serious oxygen deprivation resulting in permanent brain damage, coma, even death; Immediately dangerous to life or health (IDLH)	[4]; NIOSH[1,5,6]
50,000 ppm	Strong respiratory stimulation, dizziness, confusion, headache, shortness of breath	[7]
80,000 ppm	Dimmed sight, sweating, tremor, unconsciousness, and possible death	[7]

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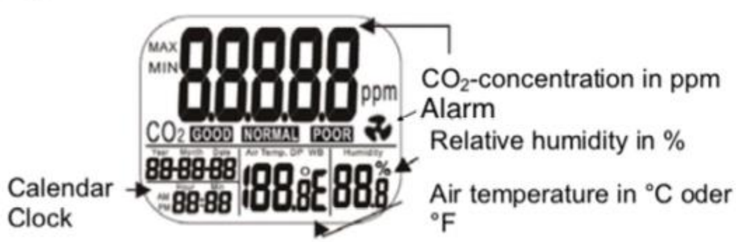
Appendix B. Wōhler CDL 210 Carbon Dioxide Monitor SOP

CO_2 Monitor SOP: Wöhler CDL 210

Display



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CO_2 Monitor SOP: Wöhler CDL 210

Contents

CO_2 Monitor SOP: Wöhler CDL 210

Specifications

Specifications	Description	Data
CO_2 Measurement	Range	0-2,000 ppm (2001, 9.999 ppm out of scale range)
	Resolution	1 ppm
	Accuracy	±50 ppm ±5% of reading (0-2000 ppm)
	Pressure dependence	±1.6% of reading per kPa deviation from normal pressure, 100 kPa
	Sensor	Stable NDIR sensor
Temperature	Range	-10°C to +60°C
	Resolution	0.1°C (0.1°F)
	Accuracy	±0.6°C (±0.9°F)
Relative Humidity	Range	5-95%
	Resolution	0.1%
	Accuracy	±3% (10-90%, 25°C) 5% (other values, 25°C)
Data Logging	Number of measurement series	5.333 per reading (°C, %RH, CO_2)
	Data logging	15,999
	Sampling rate	From 1 second to 4:59:59 hours
General technical data	Display	Simultaneous indication of CO_2 level, temperature and relative humidity
	Indoor air quality indication	Good Normal Poor
	Power supply	AC Adapter 5V, 0.5A output
	Connection to PC	USB-interface
	Dimensions (LxBxD)	120mmx100mmx110mm
	Visible and audible CO_2 warning alarm	

CO_2 Monitor SOP: Wöhler CDL 210

Mode	Parameter
P1.1	CO_2 limit for good interior air quality
P1.2	CO_2 limit for normal interior air quality
P1.3	CO_2 beep alarm
P2.0	temperature scale
P3.1	year
P3.2	month
P3.3	day
P3.4	12 hour or 24 hour display
P3.5	hour
P3.6	minute
P4.0	reset
P5.1	lograte: hours
P5.2	lograte: minutes
P5.3	lograte: seconds

CO_2 concentration in the air	Recommendations
<700 ppm	GOOD No further ventilation is needed.
<1000 ppm	NORMAL No further ventilation is needed.
<1000 ppm	POOR Ventilation is required; improve ventilation behavior
>2000 ppm	Ventilation is absolutely necessary! Further ventilation measures are needed (more ventilation, reduction of the number of persons in the room)

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CO_2 Monitor SOP: Wöhler CDL 210

Device/Software Initial Set Up

<u>Supplies needed:</u>

- Wöhler CDL 210 CO_2 Logger
- Wöhler CDL 210 power supply
- Extension cables
- Outdoor calibration station on surface
- Windows computer/laptop with CD/USB ports (2000/Vista/XP/7/98 supported)
- Wöhler USB driver
- Wöhler CD

Install USB Driver

- From CD, open driver software CP210x_VCP_Win2K_XP_S2K3.exe (Windows 2000/XP/Vista/7) or CP210x_VCP_Win98SE.exe (Windows 98)
- Follow prompts to complete installation
- Restart computer
- To confirm installation:
    - Plug in USB driver
    - Open 'Device Manager' in 'Control Panel'
    - Find 'Ports (COM & LPT)' and look for 'Silicon Labs CP210x USB to UART Bridge (COM3)' (see below)

Install/Set Up Wöhler CDL 210 Software

- Install Wöhler CDL 210 software from CD or internet
- Change language to English: Settings/Einstellungen > Language/Sprache > English
- Change temperature unit: Settings > Temperature > Fahrenheit
- Set Company Address: Settings > Company Address
    - Carlsbad Caverns National Park
    - 727 Carlsbad Caverns Highway
    - Carlsbad, NM 88220
    - 575-236-1443
    - erin_lynch@nps.gov
    - www.nps.gov/cave

(Section 8) CO_2 Calibration

- On a sunny day, plug in device and set up at calibration station—end of picnic table outside resource office back door
    - Rain brings changes in pressure, humidity, and CO_2 which can alter calibration
    - Be careful not to introduce device to sources of CO_2 (i.e. your breath, crowds of people, ventilation outlets, fireplaces, etc.)
- Press and hold SET, LOG/▲, and MIN/MAX▼ simultaneously for three seconds to enter

calibration mode
    - "400 ppm" and "CO_2" will blink to indicate calibration mode
- Calibration takes 30 minutes
    - Leave calibration station to allow device to calibrate
    - To abort, press ESC for three seconds

(Section 7.5) Turn off alarm beep:

- Press and hold SET in normal mode for three seconds to enter P1.0 mode.
- Press SET in P1.0 mode to cycle through to enter P1.4 mode for alarm settings
- Alarm ON/OFF setting will blink. Press LOG/▲ or MIN/MAX▼ to cycle up and down. Select OFF.
- Press SET to save the settings.
- At any time, press ESC to return to P1.0 mode without saving.

(Section 7.6) Change temperature unit to Fahrenheit:

- Press and hold SET in normal mode for three seconds to enter P1.0 mode.
- Press LOG/▲ in P1.0 mode to cycle through to enter P2.0 mode for temperature settings
- Press SET to enter P2.1 mode. Temperature unit will blink. Press LOG/▲ or MIN/MAX▼ to cycle up and down. Select °F.
- Press SET to save the settings.
- At any time, press ESC to return to P2.0 mode without saving.

(Section 7.7) Clock and calendar:

- Press and hold SET in normal mode for three seconds to enter P1.0 mode.
- Press LOG/▲ in P1.0 mode to cycle through to enter P3.0 mode for setting clock and calendar
- Press SET to enter P3.1 mode. Current year will blink. Press LOG/▲ or MIN/MAX▼ to cycle up and down.
- Press SET to save the settings and enter P3.2 mode. Current month will blink. Press LOG/▲ or MIN/MAX▼ to cycle up and down.
- Press SET to save the settings and enter P3.3 mode. Current date will blink. Press LOG/▲ or MIN/MAX▼ to cycle up and down.
- Press SET to save the settings and enter P3.4 mode. Current time setting (12/24 hr) will blink. Press LOG/▲ or MIN/MAX▼ to cycle up and down.
- Press SET to save the settings and enter P3.5 mode. Current hour will blink. Press LOG/▲ or MIN/MAX▼ to cycle up and down.
- Press SET to save the settings and enter P3.6 mode. Current minute will blink. Press LOG/▲ or MIN/MAX▼ to cycle up and down.
- Press SET to save the settings.
- At any time, press ESC to return to P3.0 mode without saving.

(Section 7.9) Sampling rate

- Press and hold SET in normal mode for three seconds to enter P1.0 mode.

CO_2 Monitor SOP: Wöhler CDL 210

- Press LOG/▲ in P1.0 mode to cycle through to enter P5.0 mode for setting the sample rate of data logging.
- Press SET to enter P5.1 mode. Hour digits will blink. Press LOG/▲ or MIN/MAX▼ to cycle up and down. Select 0 hours.
- Press SET to save the settings and enter P5.2 mode. Minute digits will blink. Press LOG/▲ or MIN/MAX▼ to cycle up and down. Select 5 minutes.
- Press SET to save the settings and enter P5.3 mode. Second digits will blink. Press LOG/▲ or MIN/MAX▼ to cycle up and down. Select 0 second.
- Press SET to save the settings.
- At any time, press ESC to return to P5.0 mode without saving.

(Section 5.4) Data logging

- After set up is complete, press LOG/▲ for 2 seconds in normal mode to start logging.
- A green LED light blinks and the main display alternates current CO_2 reading and "rEC" to indicate logging status.
- To terminate data logging, press ESC for 2 seconds.
- The green LED light stops blinking and the main display alternates current CO_2 reading and "End".
- Press and hold ESC for 2 seconds to return to normal mode.

24-Hour Test Run

- Set up device outside under the roof to protect from rain and elements.
- Start data logging (see above).
- Data log for 24 hours. This allows the internal battery to charge for 24 hours as well.
- Terminate data logging (see above).
- Retrieve and analyze data (see instructions in sections: Retrieve Data, Data Processing).

Highlighted in green are device settings that need to be manually updated before deployment.

Deployment

Supplies needed:

- Wöhler CDL 210 CO_2 Logger
- Wöhler CDL 210 power supply
- Extension cables (if necessary)
- Opaque tape to cover blinking light if placed in visitor view
- Light source (preferably helmet-mounted)
- Uniform/Volunteer Vest
- Closed toe shoes

Procedure:

1. After set up is complete and the monitoring location has been selected with power supply in mind, bring supplies to the selected location.

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CO_2 Monitor SOP: Wöhler CDL 210

2. Plug in device. If the voltage is too high or low, "bAT" will flash in the display. See troubleshooting to address.
3. Start data logging:
   - After set up is complete, press LOG/▲ for 2 seconds in normal mode to start logging.
   - A green LED light blinks and the main display alternates current CO_2 reading and "rEC" to indicate logging status

Retrieve Data – Every 5 Days

Supplies needed:

- Collect: Wöhler CDL 210 CO_2 Logger and chargers
- Office: Wöhler USB Driver, Windows computer with with Wöhler USB Driver and CDL 210 Software installed
- Light source (preferably helmet-mounted)
- Uniform/Volunteer Vest
- Closed toe shoes

Procedure:

1. At logger location, terminate data logging:
   - To terminate data logging, press ESC for 2 second.
   - The green LED light stops blinking and the main display alternates current CO_2 reading and "End"
   - Press and hold ESC for 2 seconds to return to normal mode
   - If the device loses power before terminating data logging, the data will not be saved.
   - Download data every time after terminating data logging and before restarting data logging or the first data set will be overwritten.
2. Bring device office
3. Plug in USB Driver from computer to powered device
4. THEN open Wöhler CDL 210 Software
5. Choose Wöhler USB Port: Settings > COMPort > COM[#] (Woehler USB-Port)
6. Click 'Read data' (this takes a few minutes)
   - A graph will be produced when it is finished
7. Print graph: File > Print > Save as PDF
   - File naming convention: CO2_[Location]_[Device]_YYYYMMDD.filetype
     - Example: CO2_Elevator_Telaire_20190604.pdf
   - File location: *S:\RM\Caves\Branch Only\Cave Management\VUM\2019 Cave Climate\CO2 Data*
8. Export data to .csv file: File > Export > act. Measurement (*.csv)
   - Select all files if multiple
   - File naming convention: CO2_[Location]_ [Device]_YYYYMMDD.filetype
     - Example: CO2_Surface_WohlerC_20190604.csv

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   - File location: *S:\RM\Caves\Branch Only\Cave Management\VUM\2019 Cave Climate\CO2 Data*
9. Export data to .db file: File > Export > Database (*.db)
   - Select all files if multiple
   - File naming convention: CO2_[Location]_ [Device]_YYYYMMDD.filetype
     - Example: CO2_Surface_WohlerC_20190604.db
   - File location: *S:\RM\Caves\Branch Only\Cave Management\VUM\2019 Cave Climate\CO2 Data*
10. Deleting data is unnecessary; it will be overwritten

Data Processing

1. Examine graph to check for automatic baseline calibration (ABC) offsets
   - Via printed PDF or through the software
2. Saves .csv file as .xlsx file retaining same file name, delete the .csv file
   - If values are not delineated, use Data > Text to Columns to separate values
   - If values do have an ABC offset, determine when and by how much the offset occurred by looking at the difference of consecutive values, then mathematically correct the data.
3. Remove bad data and update data gaps in the Data Log sheet in *S:\RM\Caves\Branch Only\Cave Management\VUM\2019 Cave Climate\CO2 Monitoring Study Logs 2019*

Note from Sonia: I had a lot of trouble with the 1904 time setting. This may be because I used a very old laptop. Unfortunately all my current data analysis files are in this time setting. To deal with excel files from different time settings, I converted the date into text '=TEXT(B10,"mm/dd/yyyy")', copy and paste just the values, change the time setting, then convert the text back to date using Text to Columns.

Data Analysis

1. When ready to analyze data, open data analysis file: CO2_[Location]_[Device]_alldata.xlsx
   - Ex: CO2_Elevator_WohlerB_alldata.xlsx
   - Drag all new data sheets to this workbook
2. Copy date, time, and CO2 columns to sheet called "all data"
   - Add a date/time to one column by using the SUM function
   - Format (CTRL+1) to show both date and time
   - If data is formatted as text, convert to time or date using Text to Column
   - Sometimes you will want just the date, just the time, or both date and time, better to have separate columns
3. Create a new column for smoothed data
   - Smooth data by taking the average of the surrounding 4 values to remove outliers
   - Use the smoothed data for analysis

CO_2 Monitor SOP: Wöhler CDL 210

4. Within all data, you will want to pull out the following variables:
   - Date
   - Daily Starting Time (=SUM(DATE+"8:30 AM")
   - CO2 @ Start (use VLOOKUP function)
   - Daily Closing Time (=SUM(DATE+"6:45 PM")
   - CO2 @ Close (use VLOOKUP function)
   - Min Time (copy when copying the MIN)
   - Min Hour
     - =CONCATENATE(HOUR(R2),":00")
   - MIN
     - Sort smoothed value from low to high
     - Manually filter every single day
     - Highlight the lowest value with a certain color
     - Do this for every single day
     - Filter based on that color
     - Copy and paste date, time, and MIN value
   - Max Time (copy when copying the MAX)
   - Max Hour
     - =CONCATENATE(HOUR(R2),":00")
   - MAX
     - Same as MIN, but sort from high to low
     - Use a different highlight color
   - Daily average
     - =AVERAGEIFS($D$2:$D$6420,$B$2:$B$6420,J2,$C$2:$C$6420,">=8:30",$C$2:$C$6420,"<=16:45")
     - You'll need to figure out the ranges
   - Daily Normalized Value
     - Daily Average – CO2 @ Start
   - Day of Week
     - =TEXT(J2,"ddd")
   - Visitation (use VLOOKUP)
5. Add sheets for CAVE Visitation, KP Tours, sound data, and surface temperature as appropriate
   - Visitation numbers are available on the shared drive and updated daily (just copy the daily stats and add the date)
   - Contact Carolina Rascon (carolina_rascon@nps.gov) to email the fee's file for King's Palace tour numbers (x1359) (Ticket Counter: x1376) (just copy the KP tour stats)
   - Sound meter data is found here: *Shared\RM\Caves\Branch Only\Cave Management\Visitor Use Management\Monitoring\2019 Cave Climate\Sound Meter Data*

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CO_2 Monitor SOP: Wöhler CDL 210

- Surface temperature data is available through the shared drive

6. Analysis Options
   - General trends: plot all data
   - Temperature: compare surface temperature and normalized values at corresponding times (use VLOOKUP to find values around associated times)
   - Peaks: make a pivot table, then histogram of the hours associated with daily minimum and maximum values
   - Peak days: make a pivot table/chart of the day of the week and the average maximum normalized values
   - Daily Maximum Values: make a bar graph of all daily maximum values; add the OSHA limit as another column and add to graph as a line (Google: how to add a benchmark line to a graph)
   - Visitation: make a scatterplot of daily visitation numbers and the daily normalized value
   - Sound: compare sound and normalized CO2 values (use VLOOKUP to find associated sound value at same time interval as CO2)
   - More ideas:
     - Compare for variation across locations
     - Compare winter and summer trends (do evening CO2 levels return to starting?)
     - Read Guirado 2019 and try to apply their mathematical model to create a carrying capacity for Carlsbad Cavern
     - Distribution lag analysis for BRJ sound/BRJ CO2 and KP tickets/KP CO2
     - What is the rate of CO2 relaxation in the evening?

Notes and Planning

Calibration:

- Wöhler CDL 210 should be manually calibrated every 5 days to counteract automatic baseline calibration (ABC).
- ABC is hardwired into the device. Every 7.5 days, the device recalibrates based on the assumption that the lowest reading during the previous 7.5 days corresponds to 400 ppm. Since the device will not be exposed to fresh air at that CO_2 concentration, the ABC introduces an offset error. In actually, the ABC has occurred in as little as 6 days, so it must be manually recalibrated every 5 days.
- As a last resort, if staffing does not allow for recalibration every 5 days, it is acceptable to mathematically correct the data for the ABC offset, but only once. It absolutely must be calibrated every 10 days. Every effort should be made to recalibrate the device every 5 days.
- Temperature readings take a while to return to normal after recalibrating on the surface.

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CO_2 Monitor SOP: Wöhler CDL 210

- Wöhler USA does not offer factory calibrations. If the manual calibrations are no longer sufficient, buy a new device. The manufacturer does not recommend sending back to Germany for calibration.

(Section 8) CO_2 Calibration

- On a sunny day, plug in device and set up at calibration station—end of picnic table outside resource office back door, but do not place directly in the sun
  - Rain brings changes in pressure, humidity, and CO_2 which can alter calibration
  - Be careful not to introduce device to sources of CO_2 (i.e. your breath, crowds of people, ventilation outlets, fireplaces, etc.)
- Press and hold SET, LOG/▲, and MIN/MAX▼ simultaneously for three seconds to enter calibration mode
  - "400 ppm" and "CO_2" will blink to indicate calibration mode
- Calibration takes 30 minutes
  - Leave calibration station to allow device to calibrate
  - To abort, press ESC for three seconds

Power:

- Wöhler CDL 210 has an internal rechargeable battery that takes 24 hours to charge and provides 10 hours of battery power if device loses power supply (i.e. unplugged or power outage).
- If the device loses power for more than 10 hours, the internal clock will need to be reset and data logging restarted.
- If the voltage is too high or low, "bAT" will flash in the display. See troubleshooting to address.
- If the device loses power before terminating data logging, the data will not be saved.

Device Readings:

- Humidity readings take 10 minutes to update.
- Temperature and CO_2 readings take 2 minutes to update.

Site Selection:

- Avoid locations where people may breathe directly onto the sensor
- Avoid placing sensors close to intake or exhaust ducts, windows, and doorways
- Once location is selected, use survey forms to survey to the logger location, take picture, and save a written description of location

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CO_2 Monitor SOP: Wöhler CDL 210

Choosing Log Rate:

Number of logging days given different sampling rates at device storage capacity			
log rate (min)	date/time in	date/time out	length of time (days)
1	06/04/19 8:00	06/08/19 00:53	3.7
2	06/04/19 8:00	06/11/19 17:46	7.4
3	06/04/19 8:00	06/15/19 10:39	11.1
5	06/04/19 8:00	06/22/19 20:25	18.5
Calculations provided by Wohler CDL 210 Software			

- Wöhler CDL 210 can store 16,000 data points
- Wöhler CDL 210 sample rate ranges from 1 second to 4:59:00 (5 hours)
- The Wohler can only hold one data set, so if you restart data logging without downloading the data first, it will overwrite the first set of data. Download the data every time recording stops and before restarting data logging.
- Log rate calculations are stored in the file "CO2 Monitoring Study Logs 2019" in *S:\RM\Caves\Branch Only\Cave Management\VUM\2019 Cave Climate\ CO2 Monitoring Study Logs 2019*

Bad Data:

- Do not breath on monitor when logging
- If you cannot account for the ABC offset due to data loss or any other reason, this data should be considered bad data.
- Data log: a data log "CO2 Monitoring Study Logs 2019" will be kept in *S:\RM\Caves\Branch Only\Cave Management\VUM\2019 Cave Climate\ CO2 Monitoring Study Logs 2019* to track bad data (see example below)

Device	Start Date/Time	End Date/Time	Reason
Telaire	5/26/19 15:00	5/27/19 16:30	moved device for testing
Telaire	5/29/19 11:35	5/29/19 18:00	moved device for testing

Daylight Savings Time:

- New Mexico and Carlsbad Caverns National Park operate on Daylight Savings Time
- In order to better correlate the data with park opening/closing and tour times, please make sure to adjust the time on the devices when daylight savings time occurs.
- Since daylight savings time occurs early in the morning, manually correct the applicable data at the next recalibration cycle. Data will not be lost because it will take more than an hour to download the data and recalibrate the device.

CO_2 Monitor SOP: Wöhler CDL 210

Carlsbad Caverns National Park Hours:

- Summer Season (Memorial Day to Labor Day)
  - Cavern Hours: 8:30 AM – 6:45 PM
  - King's Palace Tour Times (1.5 hours): 9:00 AM, 10:30 AM, 12:00 PM, 1:30 PM
- Winter Season
  - Cavern Hours: 8:30 AM – 4:45 PM
  - King's Palace Tour Times (1.5 hours): 10:00 AM
  - Elongated hours and increased tour times during winter holidays

Manuals, Software, and Additional Logs:

- The operator manual for the Wöhler CDL 210 is saved under *S:\RM\Caves\Branch Only\Cave Management\VUM\2019 Cave Climate\Data Logger Manuals* OR available online at: https://www.pce-instruments.com/us/slot/11/download/2150962/wohler_cdl210_manual.pdf
- The operator manual for the PC-Software Wöhler CDL 210 is saved under *S:\RM\Caves\Branch Only\Cave Management\VUM\2019 Cave Climate\Data Logger Manuals* OR available online at: https://www.pce-instruments.com/english/slot/2/download/62410/wohler_cdl_210_sw_guide.pdf
- The installation guide for the Wöhler USB Driver is saved under *S:\RM\Caves\Branch Only\Cave Management\VUM\2019 Cave Climate\Data Logger Manuals*
- The Wohler CDL 210 software is saved under *S:\RM\Caves\Branch Only\Cave Management\VUM\2019 Cave Climate\Data Logger Manuals*
- Logger location surveys are saved under *S:\RM\Caves\Branch Only\Cave Management\VUM\2019 Cave Climate\CO2 Logger Locations*
- The calibration log, log rate calculations, and data log are in the file "CO2 Monitoring Study Logs 2019" saved under *S:\RM\Caves\Branch Only\Cave Management\VUM\2019 Cave Climate\CO2 Monitoring Study Logs 2019*

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CO_2 Monitor SOP: Wöhler CDL 210

Troubleshooting

Error Message/Code	Possible Reason	Solution
Meter cannot be powered on	The power supply is not well plugged.	Check if the power supply is well plugged.
	System crash	Do a hardware reset: Press a paper clip (or similar) into the small opening in the bottom of the device.
Readings in the display do not change	The meter is in maximum or minimum mode.	Press and hold the RESET key for more than one second.
"Bat" and the green LED keep flashing.	The power supply output voltage is too high or too low.	Use the adaptor with 5V (±105), >0.5A.
Data cannot be transferred from the Wöhler CDL 210 to the PC	Data transfer disturbed	Do a hardware reset: Press a paper clip (or similar) into the small opening in the bottom of the device.
E01 (CO_2)	CO_2-sensor is damaged.	Send back for repair.
E02 (CO_2)	CO_2 value is under the lower limit.	Recalibrate the CO_2. If the error code still appears, send it back for repair.
E03 (CO_2)	The CO_2 reading exceeds the upper limit.	Put the meter in fresh air and wait for 5 minutes. If the error code still appears, recalibrate the meter.
E17 (CO_2)	The ABC mode of the CO_2 sensor fails and might cause wrong CO_2 readings.	Send back for repair.
E02 (Temperature)	The air temperature value is under the lower limit.	Put the meter in regular room temperature for 30 minutes, if the error message still appears, send the device for repair.
E03 (Temperature)	The air temperature value exceeds the upper limit.	Put the meter in regular room temperature for 30 minutes, if the error message still appears, send the device for repair.
E31 (Temperature)	The temperature sensor or measuring circuit is damaged.	Send back for repair.
E04 (Humidity)	The air temperature measurement has an error code.	Refer to the above mentioned temperature error code.
E11 (Humidity)	The RH calibration has failed.	Send back for calibration.
E34 (Humidity)	The RH sensor or the measuring circuit is damaged.	Send back for repair.

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Carlsbad Caverns National Park
Cave Sample Tracking Form

Collector	Sonia Meyer & Angelina Guerra	**Cave Name**	Carlsbad Caverns
Principal Investigator		Date Collected	07/08/2019
Permit Number			

Sample Type

- ☐ Rock
- ☐ Corrosion residue
- ☐ Water
- ☐ Mineral
- ☒ Other (specify):

carbon dioxide

Notes:

Wöhler CDL 210 (CO2):
Wöhler A: 100013844 (King's Palace)
Wöhler B: 100012709 (Elevator)
Wöhler C: 100012840 (Big Room Junction)

DistoX: SN3796

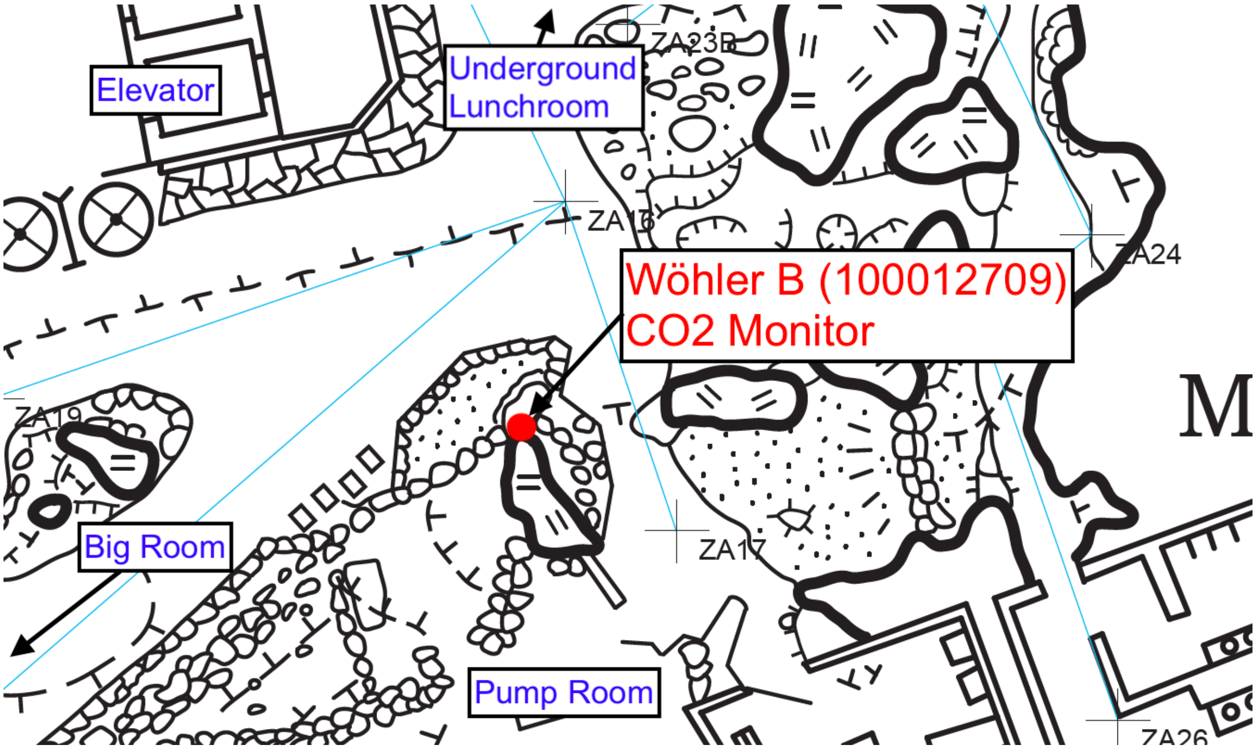
Equipment left in cave:

Type	Tracking #	Date Removed
CDL210	100013844	
CDL210	100012709	
CDL210	100012840	

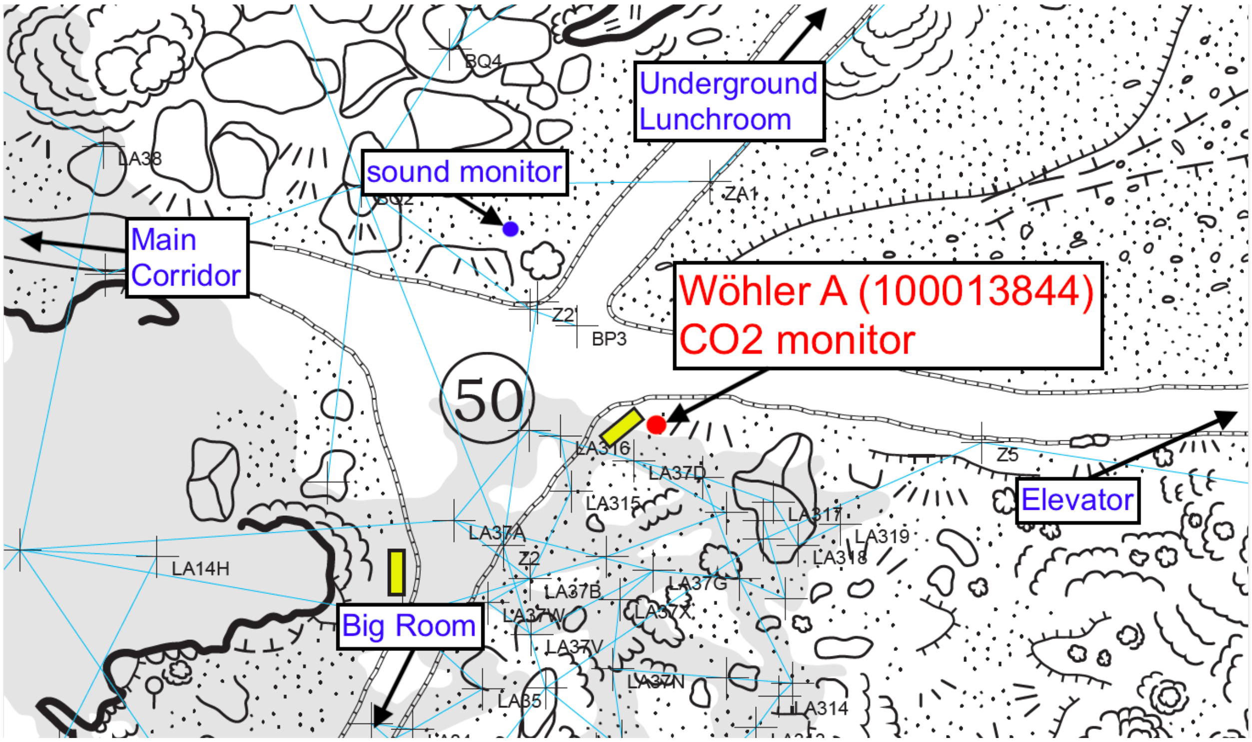
Survey to Sample or Science Station

From Station	To Station	Distance	Azimuth	Inclination	Sample Notes
RSC12	intermediary station	7.61	8.0	+11.3	edge of construction trail near RSC12
intermediary statior	intermediary station	17.56	22.5	+0.4	rock projection from constructed trail across seating area
intermediary statior	(A) 100013844	6.15	48.6	-12.8	sensor placed near ranger outpost
ZA17	(B) 100012709	14.36	286.5	+13.9	could not find exact location, approximated based,
					on map assumed station was on the floor, sensor
					placed behind old men's restroom sign near elevator
Z2	(C) 100012840	23.36	30.0	-0.1	behind wall near Big Room Junction map sign

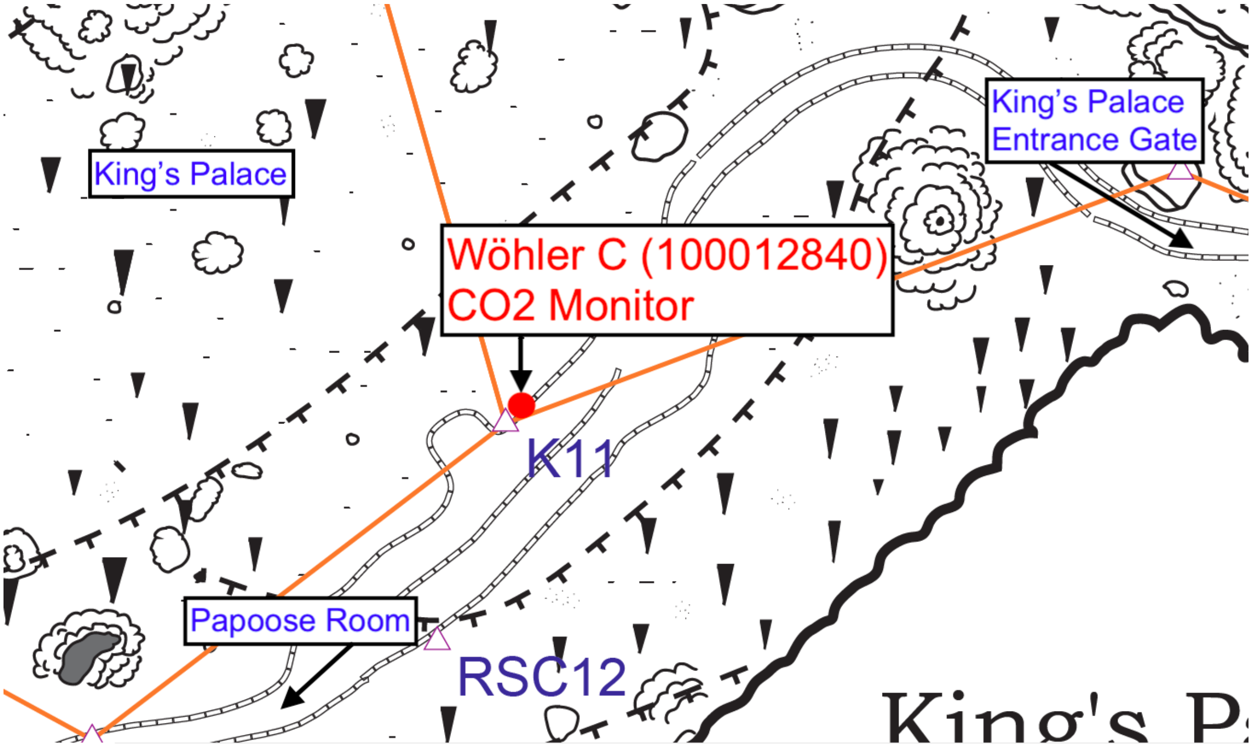
Appendix D. Map of CO_2 Monitor Wōhler B (100012709) at Elevator



Appendix E. Map of CO_2 Monitor Wōhler A (100013844) at Big Room Junction



Appendix F. Map of CO_2 Monitor Wōhler C (100012840) at King's Palace



Appendix G. Automatic Baseline Calibration from Wōhler CDL 210 Manual

CO2-Calibration

EN

7.1 Automatic Baseline Calibration

The automatic baseline calibration (ABC) eliminates the zero drift of the infrared sensor. The ABC function is always ON when turning on the meter.

ABC is to calibrate the meter at the minimum CO_2 reading detected during 7.5 days continuous monitoring (power on). It is supposed that in the ventilating area there is fresh air with CO_2 level around 400 ppm during a period of time.

> ! **WARNING!**
> For the described reasons, the automatic baseline calibration cannot be done in close area with higher CO_2 level such as places with windows shut.

Appendix H. Data Log

Location	Start Date/Time	End Date/Time	ABC* Adjustment	Reason
Elevator*	6/12/19 14:56	6/20/19 11:46	none	calibrated correctly
Elevator	6/20/19 11:51	6/25/19 16:41	+215 ppm*	6/20/2019 11:51 AM - 215 ppm drop
Elevator	6/25/19 16:46	6/30/19 14:22	no data	device lost power; did not log data
Elevator	6/30/19 14:27	7/1/19 16:12	no data	cannot account for ABC adjustment
Elevator	7/1/19 16:17	7/8/19 9:00	no data	data accidentally overwritten
Elevator	7/8/19 9:05	7/9/19 21:49	+817-77-90	7/9/19 9:49 PM - 90 ppm drop
Elevator	7/9/19 21:49	7/16/19 8:24	+817-77 ppm	7/16/19 8:24 PM - 77 ppm drop
Elevator	7/16/19 8:24	7/17/19 14:09	+817 ppm	817 ppm is difference in calibrated and uncalibrated values at similar times
Elevator	7/17/19 14:14	7/18/19 18:19	no data	data accidentally overwritten
Elevator	7/18/19 18:10	7/19/19 17:09	none	calibrated correctly
BRJ*	6/12/19 14:56	6/30/19 14:19	no data	device lost power; did not log data
BRJ	6/30/19 14:24	7/1/19 16:24	+419 ppm	liner regression of 7/8-7/19 data set: y=0.0361x+1147.1, CO2 value at 7/1/19 4:24 PM is 1147.1, difference between this calculated value (1147) and recorded value (728) is 419
BRJ	7/1/19 16:29	7/8/19 10:00	no data	data accidentally overwritten
BRJ	7/8/19 10:05	7/8/19 20:50	+819-109-157 ppm	7/8/19 8:50 PM - 157 ppm drop
BRJ	7/8/19 20:50	7/15/19 7:54	+819-109 ppm	7/15/19 7:54 AM - 109 ppm drop
BRJ	7/15/19 7:54	7/17/19 14:19	+822 ppm	liner regression of 7/18-7/19 data set: y=0.0465x+1328.7, CO2 value at 7/17/19 2:19 PM is 1313, difference between this calculated value (1313) and recorded value (491) is 822
	7/17/19 14:19	7/18/19 18:17	no data	data accidentally overwritten
BRJ	7/18/19 18:17	7/19/19 17:32	none	calibrated correctly
KP*	6/12/19 14:56	6/30/19 14:11	no data	device lost power; did not log data
	6/30/19 14:11	7/1/19 16:46	+415 ppm	liner regression of 7/8-7/19 data set: y=0.039x+1140.4, CO2 value at 7/1/19 4:46 PM is 1140, difference between this calculated value (1140) and recorded value (725) is 415
KP	7/1/19 16:46	7/8/19 9:41	no data	data accidentally overwritten
	7/8/19 9:41	7/9/19 15:12	+720-154 ppm	7/9/19 3:12 PM - 154 ppm drop
KP	7/9/19 15:12	7/13/19 10:12	+720 ppm	liner regression of 7/18-7/19 data set: y=0.0595x+1338.1, CO2 value at 7/13/19 10:12 AM is 1248, difference between this calculated value (1248) and recorded value (528) is 720
KP	7/13/19 10:12	7/18/19 16:38	no data	power surge from thunderstorm required hardware reset
KP	7/18/19 16:38	7/19/19 17:23	none	calibrated correctly

*ABC – Automatic Baseline Calibration; Elevator (Wohler B – Serial No. 100013844); BRJ – Big Room Junction (Wohler C – 100013844), KP – King's Palace (Wohler A – 100012840); ppm (parts per million)