

Fred L. Wefer and Philip C. Lucas

Abstract

Precise measurements of temperature and relative humidity were made along a traverse from the Butler Cave entrance to Sand Canyon and along the Butler trunk channel. Summer temperatures decrease with distance into the cave but stabilize at the cave ambient only 800–1000 feet inside. Winter temperatures rise more rapidly and reach cave ambient within 100 feet. Temperature rises by a small amount along the Trunk Channel with the highest temperature at the downstream end. The temperature rise with depth along the Trunk Channel is consistent with the geothermal gradient in the area. In a separate investigation, a fan was used to introduce an oscillating air current to one cave entrance which a sensitive anemometer and data-logger used to record air flow from a difference cave entrance. The recorded square-wave pattern confirmed connections between caves over considerable distances.

[Editor's Note: Until his untimely death, Fred Wefer maintained a series of observation stations in Butler Cave. He visited these stations periodically and made very careful meteorological measurements. The chapter that follows is constructed from the very detailed results that Fred published in *The Proceedings of the Appalachian Karst Symposium* (Radford, VA, 1991) and in the *BCCS Newsletter*.]

This chapter is more blatantly ghost-written than the others in this book. Fred wrote extensively and in detail about his meteorological measurements, totaling at least 128 pages. Rather than reproducing this mass

of material, the editor has attempted to extract the key results and present them in a single coherent narrative.

In a curious twist, Fred chose temperature, water vapor pressure, and relative humidity as the meteorological properties to measure. These, as expected, turn out to be very nearly constant. What was not measured, and what is definitely not constant, is the wind. It was the wind that attracted interest to Breathing Cave many years ago. It is the wind, often an elusive breeze whispering from a pile of breakdown, that keeps explorers going. And, in a new study, the wind can be used as a much more direct exploration tool. That study is presented at the end of this chapter.

With an addendum by Philip C. Lucas, Frank Marks, Jr. and Nevin W. Davis. Fred L. Wefer is deceased.

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22.1 Introduction

22.1.1 What Do We Mean by “Cave Weather?”

Cave weather really means much the same thing as “surface weather”. Any point in the atmosphere, at any given moment, has a temperature, a barometric pressure, a rate of air movement (wind) and a certain chemical composition. These variables are continuously changing. It is this assemblage of parameters observed over time that constitute the “weather.” There are also extreme excursions of the atmospheric variables, resulting in rainstorms, thunderstorms, tornados, ice storms, and blizzards. Chemically, the atmosphere is three quarters nitrogen which is not usually of much interest, and one quarter oxygen and a long list of minor components. The chemical variables of interest are the concentrations of water vapor, oxygen, and carbon dioxide. Of these, the air in Burnsville Cove caves is usually fresh, meaning that oxygen partial pressures are close to atmospheric normal. The CO₂ partial pressure is of importance in discussing the dissolution of limestone and the precipitation of speleothems but is otherwise not considered a “weather” variable. That leaves water vapor as the chemical variable to be measured. The concentration of water vapor can be expressed either as a partial pressure or as relative humidity.

The temperatures of cave atmospheres are often said to be constant, reflecting the mean annual temperature of the region. As will be demonstrated, this statement is not exactly true, although the temperature variations are not large. Relative humidity in caves tends to be high, often near saturation with respect to liquid water (100 % relative humidity). The barometric pressure in caves varies because the coupling between the cave atmosphere and the surface atmosphere results in cave winds. Cave weather is much less extreme than surface weather; there are no thunderstorms, blizzards, or tornadoes. However, in some locations and under some circumstances, cave temperatures fall below the freezing point of water and either seasonal or permanent ice may be formed. There has been much interest in caves containing ice—known as glaciers or freezing caverns—such as Fossil Mountain Ice Cave in the Rockies and the Eisenriesenwelt and Rieseneishöhle in Austria. Permanent ice such as that in the Scărișoara Glacier Cave in

Romania is now being investigated as a climate record. In temperate climate caves such as those of Burnsville Cove, ice is seasonal and limited to entrance areas.

There have been relatively few cave meteorological projects in the United States although a systematic literature search turned up 219 papers dealing with some aspect of the subject (Wefer 1991a). Data have been published for Lehman Caves, Nevada (Bamberg 1973) and Wind Cave, South Dakota (Nepstad and Pizarowicz 1989). Closest to Burnsville Cove are Cropley’s (1965) investigations of Organ Cave and Ludington’s Cave in Greenbrier County, West Virginia. The meteorology of caves was considered an important subject by early 20th Century European speleologists and early text books such as Kyrle in 1923 and Trombe in 1952 devote entire chapters to the subject. The background principles are discussed in some detail by Wigley and Brown (1976).

22.1.2 The Butler Cave Meteorology Project

The project was initiated in April, 1984 and by the time of the last publication in March, 1993 had accumulated 680 measurements. The study was concerned with temperature and relative humidity variations both at different points within the cave and also with variations with time. One sequence of measurements was made from the Nicholson entrance to Sand Canyon and another along the Trunk Channel from Penn State Lake to the 6th of July Room, a traverse of about 8000 feet. Additional measurements at Sand Canyon provided more time-series data.

Most of the results were published as a series of progress reports some of which also contain the raw data (Wefer 1984, 1985, 1988, 1989a, 1990, 1992). There was a report on the measurement technique (Wefer 1989b) and one formal paper concerning the measurements along the Trunk Channel (Wefer 1991b).

22.2 Measurement Techniques

Water as a vapor phase in air has a limited partial pressure above which liquid water condenses. This limiting pressure is known as the saturation pressure and is a function of temperature. The water vapor

partial pressure over liquid water increases with temperature until it reaches the atmospheric pressure, at which temperature water boils. If the water vapor partial pressure in the atmosphere increases to the saturation pressure, liquid water condenses as rain (large droplets) or fog (small droplets). Alternatively, if the temperature and thus the saturation pressure decrease to where the saturation pressure equals the existing water vapor partial pressure, condensation will also occur. The temperature at which moisture begins to condense out of the atmosphere is known as the dew point. If liquid water is in contact with an atmosphere with a water vapor pressure less than the saturation value, the liquid water will evaporate at a rate that depends both on the temperature and on the difference between the water vapor partial pressure in the atmosphere and the saturation pressure. The evaporation of water requires heat so that evaporating water has a cooling effect. This combination of phenomena provides the basis for the practical measurement of water vapor in the atmosphere.

Atmospheric water vapor can be measured as either a partial pressure or as relative humidity. Relative humidity is defined as the ratio the water vapor partial pressure in the atmosphere to the saturation pressure expressed as percent. Partial pressure is the physically more meaningful parameter but relative humidity is the number that tells you if you're going to feel hot and sticky on a warm summer day. Water vapor partial pressures are given in inches of mercury (Hg) in the plots.

[Editor's Note: For reasons that seem mysterious for a person with a PhD in astronomy, Fred chose the totally obsolete unit of inches of mercury. The metric version of the same unit is millimeters of mercury, called the Torr (short for Torricelli who invented the mercury barometer in the early 1600s). The correct SI unit is the Pascal (Pa). One inch of mercury = 25.4 Torr = 3386 Pa.]

Relative humidity was measured with a psychrometer. The device consists of two thermometers side-by-side. One, the dry bulb thermometer, is simply exposed to the air. The other, the wet bulb thermometer, has a cloth sleeve over the thermometer bulb that is kept wet with water. Water will evaporate from the wet bulb causing a lowering of the wet bulb temperature. Psychrometric tables allow the calculation of relative humidity from the dry bulb temperature and the

temperature difference. If the relative humidity is 100 %, there will be no evaporation and both thermometers will read the same temperature. The device used in these measurements had a small battery-driven fan that blew a steady stream of air over the wet bulb. The dry bulb thermometer, of course, gives the cave air temperature directly. Both thermometers were calibrated in the Fahrenheit (°F) scale and all temperatures are plotted on this scale.

Because relative humidity is high in caves and because temperature variations are expected to be small, great care was taken to obtain accurate measurements. The procedure was to unpack the psychrometer, place it at the pre-designated observation station, turn on the fan, and then stand away and wait for the instrument to come to equilibrium. The observer was to approach the instrument quickly, using a flashlight (not a carbide lamp), read the thermometers to the nearest 0.1 °F, and then retreat. Return and do the readings again until successive readings give the same values.

22.3 Cave Weather in the Butler Cave Entrance Series

Temperature and humidity profiles were measured between the entrance and Sand Canyon at a series of specific observation stations (Table 22.1).

Representative data sets for summer and for winter are compared in Fig. 22.1a, b. On the day of the summer data, the cave was drawing in warm outside air. The air temperature (the dry bulb temperature) fell over the distance along the cave passages, but a distance of 1000 feet was required before the temperature fell to cave ambient. In contrast the relative humidity rose rapidly because the temperature fell below the dew point only 100 feet inside the entrance. Relative humidity remained nearly constant along the remainder of the traverse. Although the temperature continued to fall, the excess moisture condensed out locking in the relative humidity.

During the winter measurements air was blowing out of the cave and the outside temperature was only about 10 degrees cooler than the cave. As a result, the air temperature rose to cave ambient at the bottom of the entrance pit. Relative humidity also rose rapidly

Table 22.1 Observation stations for the Butler Cave entrance series

Station	Location	Elevation	Distance
1	Outside of entrance	2535	0
2	Bottom of entrance pit	2501	40
3	Top of 6 foot drop below Glop Slot	2481	80
4	Top of God-Is-My-Copilot climb	2475	130
5	Top of Breakdown Mountain	2438	175
6	Top of clay bank beyond window	2380	335
7	Top of bank beyond Rabbit Hole	2357	400
8	Intersection near Bean Room Overlook	2313	690
9	T-intersection at crawl to Rimstone Pools	2291	1000
10	Rimstone Pools	2275	1200
11	Middle of 90-Ugh Crawl	2245	1545
12	Sand Canyon	2240	1815

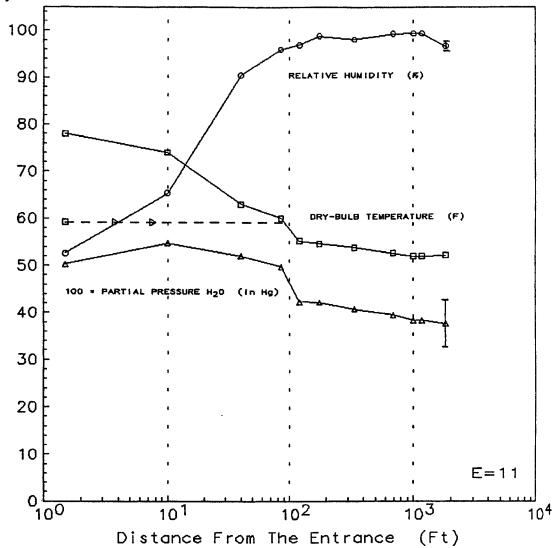
Elevations are in feet above mean sea level; distances are in feet beyond the entrance

and reached near saturation values at the bottom of the entrance pit. Dew point for the outside air was low and was never a factor in the behavior of the cave atmosphere. The key parameter in the contrasting behavior between summer and winter conditions seems to be the direction of air flow into or out of the cave.

The complete set of meteorological traverses between the entrance and Sand Canyon are shown in a single plot (Fig. 22.2). The first point represents the outside air temperature. The curves for all traverses converge with distance within the cave but only at the Bean Room overlook, almost 700 feet into the cave, do all of the curves converge to essentially a common value. When the outside air temperature is near or below cave temperature, the curves converge immediately inside the cave.

An alternative display of the same information is by means of the Cropley plot (Cropley 1965) (Fig. 22.3). In this display, the air temperature appears as a curved surface with time and distance from the entrance as the x- and y-coordinates. The seasonal effect on damping of air temperature with distance into the cave shows up clearly as the double-humped surface for two years of data.

(a) ENTRANCE PROJECT, 18 JUN 1988 (13:45-16:00) (FW)



(b) ENTRANCE PROJECT, 27 FEB 1988 (02:30-00:10) (FW)

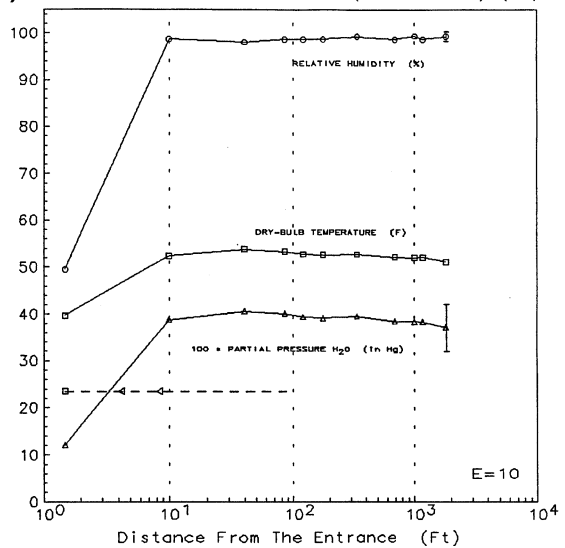


Fig. 22.1 Plots of relative humidity, air temperature, and water vapor partial pressure as a function of distance into Butler Cave from the entrance. Note that distance is plotted on a log scale. **a** Summer conditions—June 18, 1988. **b** Winter conditions—

February 27, 1988. The *horizontal dashed line* indicates the dew point for outside air. The *arrows* on the dew point line show the direction of air movement at the cave entrance

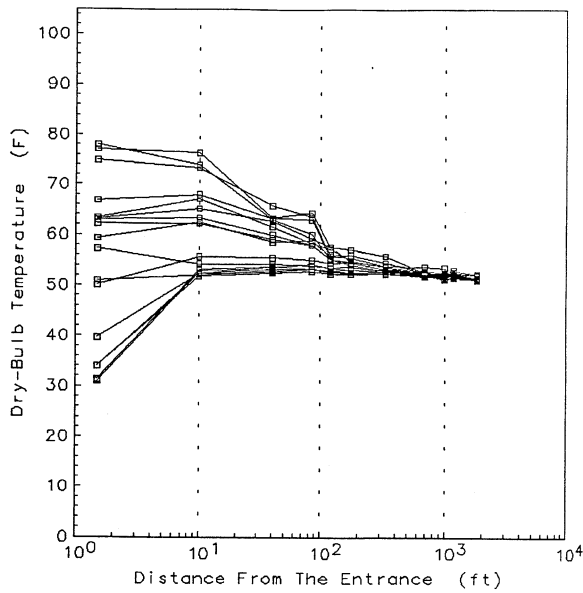


Fig. 22.2 Temperature plot for 12 traverses between the Butler Cave entrance and Sand Canyon

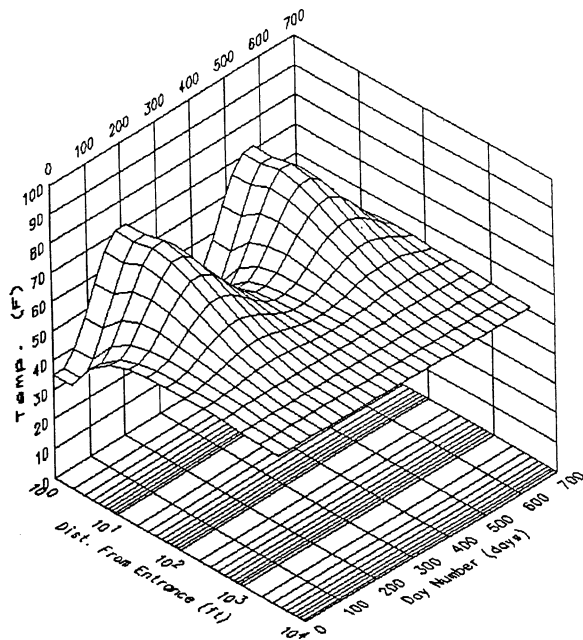


Fig. 22.3 Cropley plot for the entrance to Sand Canyon traverses. Two years of data were used in construction of the plot with day zero being January 1 of the first year of data. Distance from the entrance is again plotted on a log scale. Temperature is plotted on the vertical axis in °F

22.4 Cave Weather Along the Sinking Creek Trunk Passage

The 16 stations used for measurements along an 8000 foot traverse in the Trunk Passage are shown in Fig. 22.4. All stations are more than 1000 feet from any known air entry points. The depth below the surface varies from 150 to 300 feet. From Penn State Lake at the upstream end to the Moon Room area, the trunk passage is dry except during extreme storm events. Except for a segment at the Dry Sumps, the remainder of the Trunk Passage carries a stream, Sinking Creek in the upstream part and Sneaky Creek in the lower part. Stream flow rates and water temperatures were not measured although these data would be important for more quantitative modeling of the meteorological data.

Figure 22.5 shows one set of traverse data taken on January 26, 1991. Relative humidity is close to 100 % except for a few observations taken, curiously, along Sneaky Creek. The temperature rises slightly in the downstream direction. There is some variability but the overall trend is distinct. Note that the wind direction from both downstream and upstream of Sand

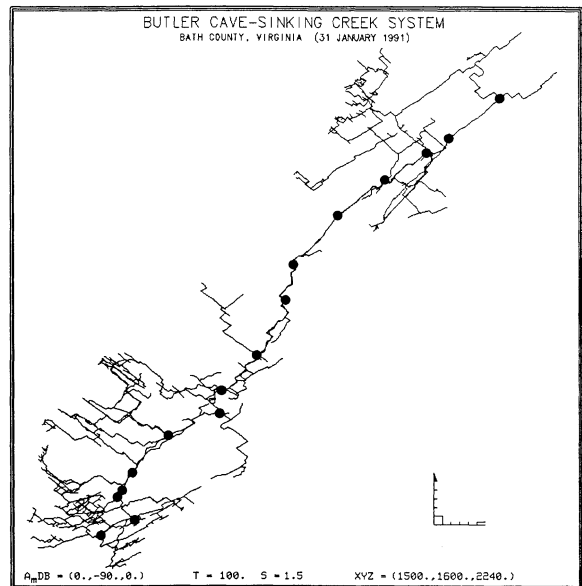


Fig. 22.4 Line map of the Butler Cave-Sinking Creek System showing location of measurement stations for the Trunk Passage

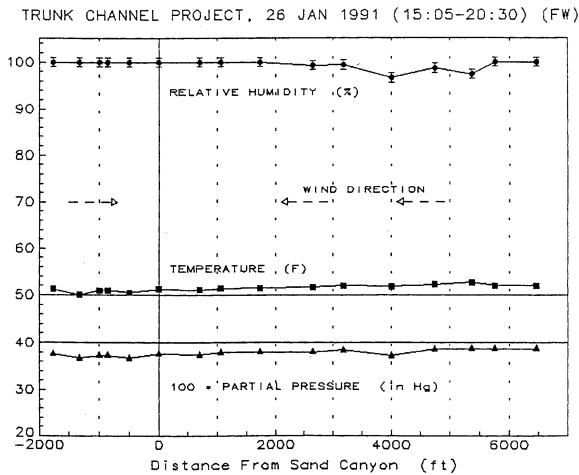


Fig. 22.5 Temperature, relative humidity, and water vapor pressure measurements taken along the Trunk Passage. Note arrows showing air flow direction

Canyon is toward Sand Canyon. This seems good evidence that the Nicholson Entrance was indeed the vent for the entire cave system with the air flow out of the entrance in these January measurements.

The complete Trunk Passage data set is shown plotted as temperature vs elevation in Fig. 22.6. For a total of 308 observations, there is considerable variation at each observation station but the trend line is significant. Because these data are plotted as a function of elevation, the 2300 foot elevation points are at Penn State Lake and the 2000 foot points are at the 6th of July Room. The warmest part of the traverse is at the downstream end. The Trunk Passage follows the surface valley of Sinking Creek, both losing elevation in the downstream direction so that the depth below the surface does not change much.

The regression line fitted through the temperature data gives a thermal gradient of 5.1 °F/1000 feet. Converting the units, the gradient becomes 9.2 °C/km, a number which is in the right range, although a little low, to be the geothermal gradient in the tectonically stable Burnsville Cove.

22.5 Long Term Observations at Sand Canyon

Sand Canyon is an easily accessed measurement station that lies on both the entrance series traverses and the Trunk Passage traverses. As the entrance

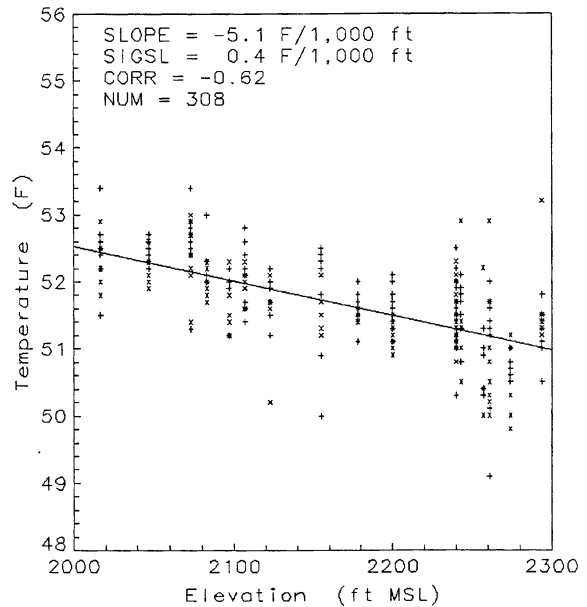


Fig. 22.6 Temperature data along the trunk passages as a function of elevation. Note that downstream is to the left. Data collected during the warmer months are plotted as +. Data collected during the cooler months are plotted as x

series data show, it is well beyond the zone of influence of in-flowing surface air. As such, Sand Canyon provides a useful data set for examining the seasonal variability of cave meteorological parameters (Fig. 22.7).

Sand Canyon is regarded as a dry area in the cave. It was the chosen camp site for the early explorers before shorter and more time efficient routes were discovered. “Dry” is a relative term. For many of the observations, the relative humidity at Sand Canyon was near 100 %. “Dry” in a cave means relative humidity in the range of 96–98 %.

[Editor’s Note: Turner Avenue in the Flint Ridge section of Mammoth Cave is extremely dry and dusty with speleothems made of water-soluble sodium salts. The lowest value obtained in a relative humidity traverse was 85 %.]

Although the variability is low, it is not appropriate to say that the cave temperature is constant. Ninety temperature measurements at Sand Canyon are shown on an expanded scale in Fig. 22.8. The precision of the temperature measurements, limited by the scale interval of the dry bulb thermometer, is about 0.1 °F so the

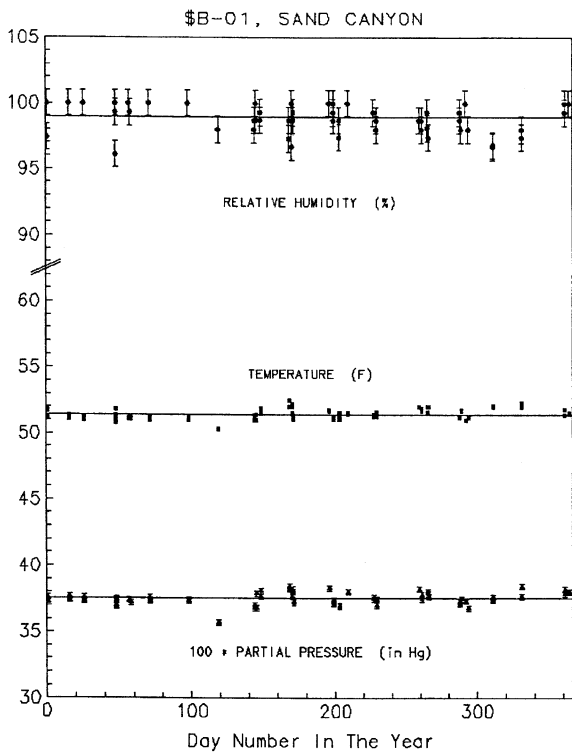


Fig. 22.7 Relative humidity, temperature, and water vapor partial pressure data taken at Sand Canyon as a function of day of the year. Day 1 is January 1. Dates arranged in this fashion are generally known as Julian days

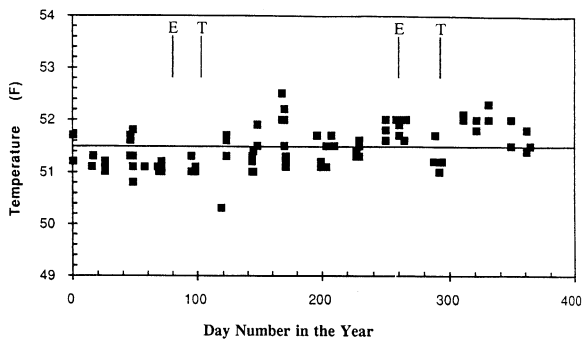


Fig. 22.8 Ninety dry bulb temperatures at Sand Canyon plotted on an expanded scale

variations shown in Fig. 22.9 represent real temperature variations, not measurement uncertainty.

The 52 data points for temperature and relative humidity collected by 1989 are shown in histogram form in Figs. 22.9 and 22.10. The mean temperature at

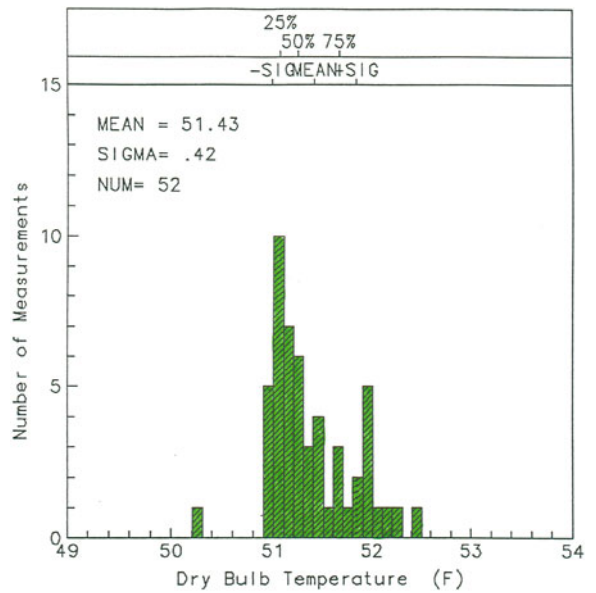


Fig. 22.9 Temperature at Sand Canyon

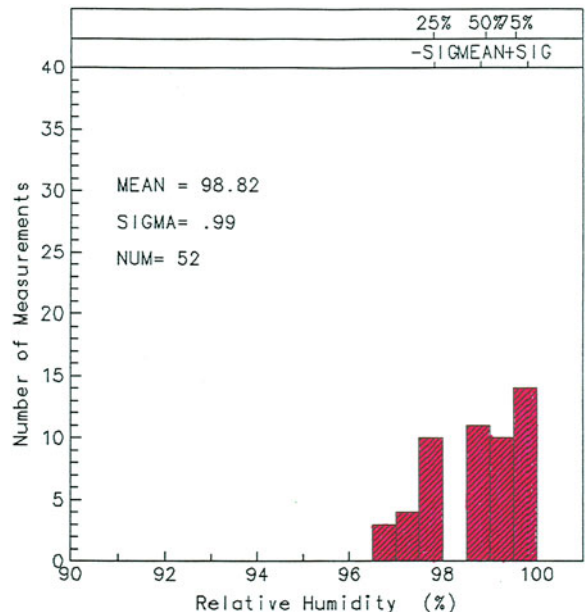


Fig. 22.10 Relative humidity at Sand Canyon

Sand Canyon is 51.4 °F and the relative humidity is 98.8. The distributions do not have a smooth Gaussian form suggesting that individual values depend on some combination of factors which vary independently.

22.6 Conclusions and Implications Written by the Editor

Fred's medical condition interrupted his measurement plan so that he never had a chance to draw conclusions from his very extensive data base. What was established is that even in a relatively dry, stable cave such as Butler, there are temperature and water vapor variations that extend deep into the cave. Surface influence on temperature extends at least 800 feet from the entrance. Along the Trunk Passage deep in the cave, temperatures can vary by more than one degree Fahrenheit. Relative humidity fluctuates with temperature as well as with water vapor partial pressure. Air current velocity and air flow direction are the dominant controlling variables but the amount and temperature of water flowing through the cave likely plays some role particularly in the deep cave measurements.

So why should we care? Although there are measurable variations in cave environmental parameters, these variations are small and do not deviate much from the mean values. Why we should care is that caves are becoming extremely important paleoclimate archives. Speleothems that contain trace amounts of uranium can be assigned absolute ages by measuring the isotopes ^{234}U , ^{238}U and the daughter isotope ^{230}Th . A great amount of effort is being expended on the measurement of oxygen isotope ratios in speleothems and using these data along with the ages to calculate the cave temperature at the time when the speleothem was deposited (see Fairchild and Baker 2012 for a recent summary of this type of research). The basic assumption is that the cave temperature represents annual mean of the surface temperatures. By establishing the cave temperature from speleothem isotope measurements, the mean surface temperature, a key climatic variable, can be established. Studies such as Fred's are useful in establishing the uncertainty in the basic assumption that cave temperature equals mean surface temperature.

22.7 Addendum: A Method for Detecting Cave Connections by Induced Air Flow by Philip C. Lucas, Frank Marks Jr., Nevin W. Davis

[**Editors Note:** The following short paper was extracted from the Proceedings of the 15th International Congress of Speleology, Kerrville, TX, 2009.]

22.8 Introduction to the Addendum

"Follow the Air" has certainly been the creed of cavers, rewarding them in many instances. The feel of a cave breeze blowing from some unknown source is intriguing and exciting. Can the source be from some vast cave system not yet discovered? Is it possible that a "far distant blowhole" is somehow connected to a known cave? The possibility of finding such a connection becomes an exciting prospect especially if it might lead to the discovery of virgin cave passages. But air flow can be elusive and trying to follow a tantalizing, barely discernable draft, can be exasperating. Many times the question is raised "Are we on the right track or is this just a local circulation?" "Should we dig here?" or "Is that dome worth a bolt climb?" To have the knowledge of the source or ultimate destination of air flow can be very useful. To determine that a cave is connected, at least by air currents, to another cave 6 km down the valley is an exciting prospect.

In the past various methods have been used to attempt to trace air currents. These range from injecting some type of smoke into the air stream such as white phosphorus, burning wood, leaves or even tires. Ethanol, an air scent tracer producing an "essence of skunk" odor has been used with limited success. But none of these methods has proven to be effective in detecting a cave's air flow over long distances.

The method described in this paper is simple. It is based on the premise that under certain conditions if two entrances are connected, then mechanically blowing air into (and out of) one entrance will rapidly change the air flow velocity at the other entrance.

22.9 Instrumentation and Equipment Used

1. One 10.16 cm wind run meter modified to act as an optically detected bidirectional anemometer with associated electronics. Startup wind speed 0.27 m/s and a maximum wind speed in or out of 4 m/s.
2. Four 10.16 cm optically detected bidirectional anemometers with associated electronics. Startup wind speed 0.36 m/s and a maximum wind speed in or out of 4 m/s. This instrument was designed and constructed by the authors.
3. One 480 watt 5 blade fan (76 cm diameter) modified to reverse direction every 65, 100 or 200 s, which includes a 9 s. off period while reversing.
4. Five HOBO U12 4-Channel Data Loggers.
5. One ultrasonic bidirectional anemometer with associated electronics. The anemometer is able to measure wind speed as low as 0.045 m/s with no practical limit on the high end. The output is recorded on two channels of a data logger. The math necessary to calculate a wind velocity is performed in an Excel Spreadsheet. This instrument was designed and constructed by an author.

22.10 Summary of Results

22.10.1 Butler Cave—Nicholson and Sofa Entrances

Butler Cave has 27 km of passages many of which are of large volume. It has two known entrances. The Nicholson entrance is located 144 m to the north and 41 m higher from the SOFA entrance. The two entrances are separated by about 478 m of passages generally large in volume (6 m by 15 m) but with many turns and several restrictions (crawlways). The upper Nicholson entrance has an air current consistent with the direction of a convection flow. However the SOFA entrance generally has a neutral or an oscillating air

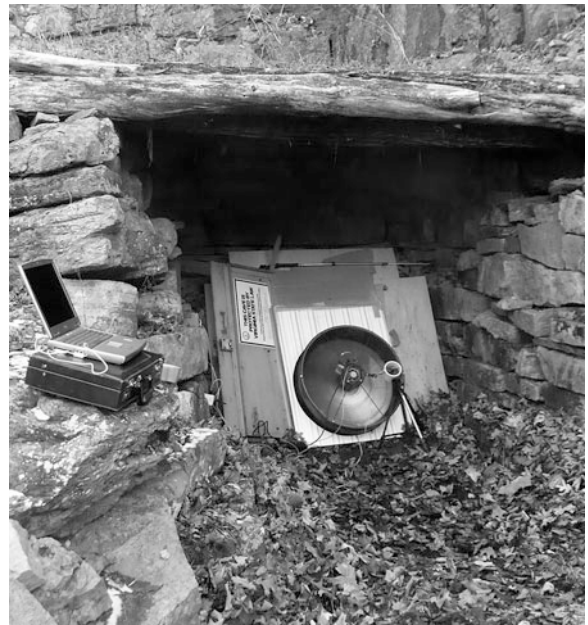


Fig. 22.11 The rectangular doorway Butler Cave's SOFA entrance has been sealed around a fan. The fan blows alternately in and out of the cave in even intervals. A signal is sent from the fan to a recording data logger when the fan changes direction (photo by P. C. Lucas)

current indicating it is an intermediate (in elevation) entrance and that a lower, presently unknown, entrance, exists elsewhere. Figure 22.11 shows a 480 W reversing fan (76 cm diameter) placed in the SOFA entrance (a rectangular opening reduced to the fan's dimensions). Power was supplied by a generator. A signal is sent from the fan to a recording data logger when the fan changes direction. For redundancy an anemometer is also placed at the fan to record the air flow and direction. Part of the Nicholson entrance is a small opening that allows bats access. The anemometers were placed in this opening during the testing (Fig. 22.12). All anemometers were connected to data loggers and the air velocities recorded at one second intervals.

Figure 22.13 shows the air velocity at the Nicholson Entrance. It includes a 500 s period before the fan operation (base-line) and the next 500 s period during the fan's operation of alternately blowing in and out of the SOFA Entrance. The measurements are summarized as follows:

- The "base-line" air flow is blowing out from the cave (the direction of a convection air current) but with small variations. These variations are assumed to be caused by small changes in barometric



Fig. 22.12 An ultrasonic anemometer (left) and a mechanical anemometer (right) recording data are located in the bat access hole to measure the rate of air flow (photo by P. C. Lucas)

pressure (atmospheric waves). They are referred to as “noise” in this paper. Much of the noise is caused by surface winds and it increases with increasing surface wind speeds.

- With each fan reversal there is a corresponding change in the air velocity at the Nicholson entrance.
- The change in air flow takes place 3 s after the fan is reversed.

Note that during the period of 600–650 s, the anemometer was being re-aligned. Being out of the main air stream the blades anemometer slowed their rotation and the effect is seen as lower velocities during that 50 s.

22.10.2 Big Bucks Entrance, Buckwheat Cave, Backyard Cave, and Basswood Cave

Barberry Cave, about 5.5 km in length, has a large passage extending roughly along a small valley trending northeast. Big Bucks Pit, its northern-most entrance, is unusual in that it is located in a small building used as an apple shed. The entrance is a 43 m pit that extends down from the floor of the apple shed. The building is sealed to the top of the pit. The fan was placed in the apple shed’s door which provided the same sealed fan attachment as at the Butler site (Fig. 22.14). There are three other cave entrances that lie to the northeast of the Big Bucks Pit entrance, Basswood, Backyard, and Buckwheat.

The Basswood Cave entrance, a 76 cm metal culvert, is located just 524 m northeast of Big Bucks Pit. There is only moderate air flow at the entrance. The cave is formed in upper limestone units above

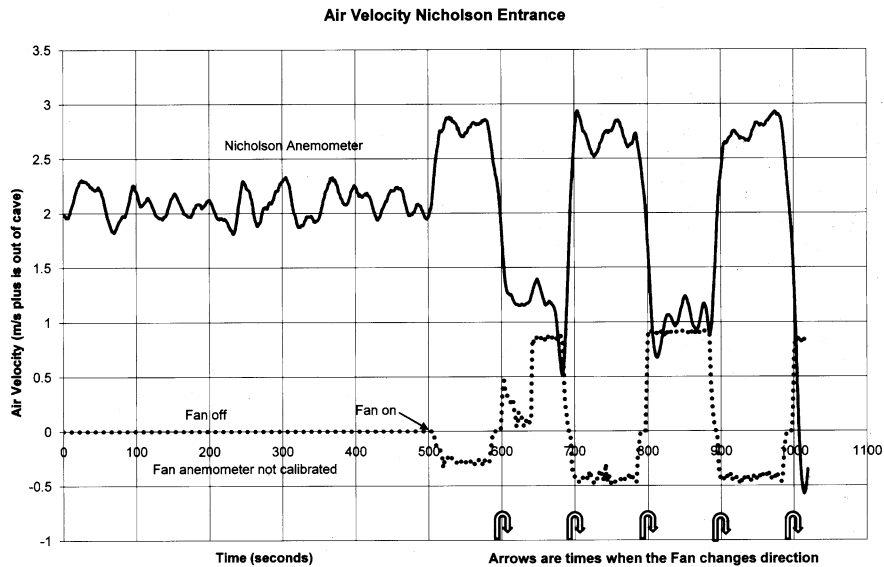


Fig. 22.13 Butler Cave entrances air flow test. With the fan placed in the SOFA Entrance and an anemometer placed at the Nicholson Entrance, this chart shows the result of changing air velocities before and during the fan’s operation. When the fan

begins running for each 100 s interval there is a distinct signal (change in air velocity) measured by the anemometer. At the end of each interval, the fan stops for 9 s and begins rotating in the opposite direction (chart prepared by N. W. Davis)



Fig. 22.14 Inside this shed used for apple storage is Big Bucks Pit, a 43 m drop into Barberry Cave. The pit is sealed to the floor of the building. The door to the building has been reduced to the size of the fan. Accordingly, as the fan blows in and out of the building the air is exchanged in the cave (photo by P. C. Lucas)

Barberry Cave so a connection to Barberry Cave seemed unlikely. Backyard cave is a 61 cm metal culvert located 772 m northeast of Big Bucks Pit. Although it has strong air currents and is in upper limestone units it was not suspected to be connected. The Buckwheat entrance is a 61 cm metal culvert and is located 773 m to the northeast of Big Bucks Pit. Prior to this investigation it was suspected that Buckwheat Cave might have some connection to Barberry Cave through an area of breakdown although no human sized opening has been found.

The test consisted of anemometers being placed in each of these three cave entrances to record changing air velocities when the fan at Big Bucks Pit was in operation. At Backyard and Buckwheat the anemometers were placed inside the metal culvert entrances that had strong air currents. However at Basswood where air flow was weaker, cardboard was placed on top of the entrance pipe. A small hole in the cardboard accommodating the anemometer concentrated the air flow. Figure 22.15 shows this arrangement.

Figure 22.16 shows the result of an air flow test between Big Bucks and Basswood where the signal is present but is weaker than the signals found in the Butler entrances test. Shown are nine cycles of the reversing fan operation and the resulting air velocity as



Fig. 22.15 Cardboard has been placed over the entrance (a vertical culvert pipe) to Basswood Cave. The anemometer placed over a hole in the cardboard records the rate of air flow (photo by P. C. Lucas)

measured at the cardboard restriction in the Basswood Cave entrance. Identifying the weaker signal against the background “noise” is still possible with this chart but it demonstrates that weak signals can become buried in the noise. There is a simple mathematical method of suppressing the random noise in a signal when the period of the repetitive signal, the fan, is known. If we add the periods together, first second to first second, to next second, over all nine periods (in this case), the signal will be enhanced and the noise, being random, will be suppressed. We can make an average out of this by dividing by the number of periods. Figure 22.17 shows the effect of this method. It shows the nine cycles of the air flow velocity combined to show the maximum effect from any changes from the fan operation. A dark line representing the overall average air velocity for the entire test separates the periods for the fan blowing in each direction. This simple method clearly shows that the velocity is significantly altered from the overall average by the fan’s influence and demonstrates the two entrances being connected.

Results of all the air flow tests at these three entrances show that all are connected to Barberry Cave (Big Bucks Pit). Buckwheat’s anemometer/logger recorded the strongest signal from the fan’s operation at Big Bucks Pit. The delay time was 13 s. Backyard Cave had a weak but definite response and had a 13 s delay time. Basswood Cave had a definite response but one that was delayed by 12 s. This curious delay

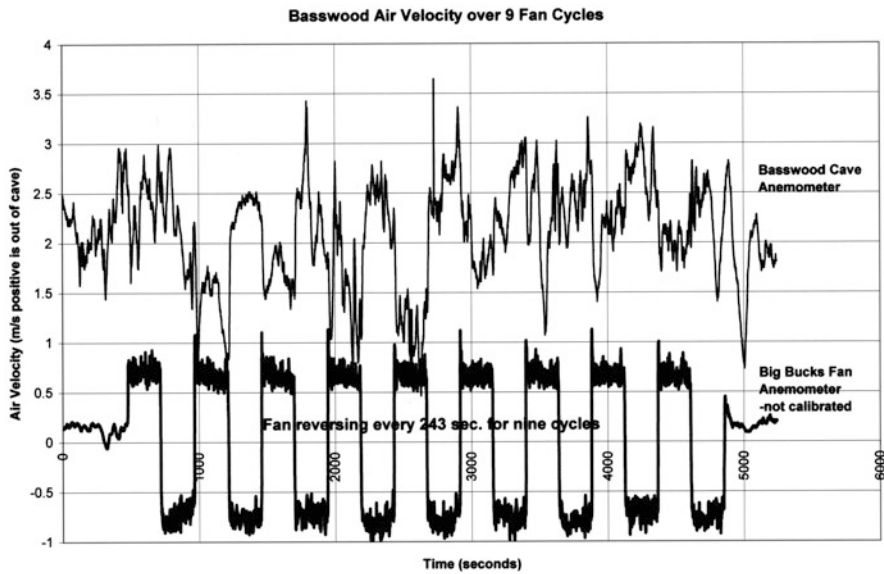
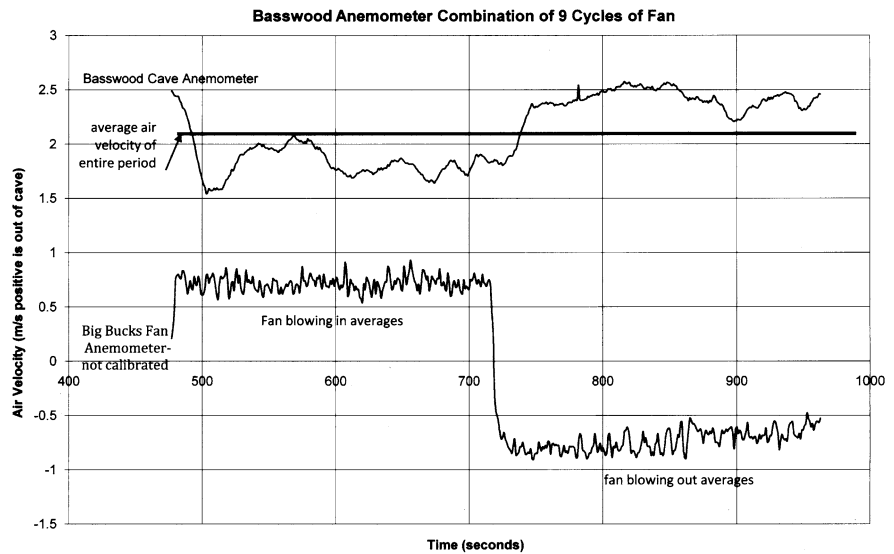


Fig. 22.16 Big bucks to Basswood Cave air flow test. This shows nine cycles with the fan placed at Big Bucks Pit and anemometer at Basswood Cave. In this instance the signal was much weaker than at Butler Cave entrances (*chart prepared by N. W. Davis*)

Fig. 22.17 Big bucks to Basswood average. This shows the combined average air velocity for the nine cycles of fan operation compared to the overall average. This calculation produces a clearer signal by cancelling much of the background noise (*chart prepared by N. W. Davis*)



might mean that the connection is a long route despite the two entrances being only separated by 524 m.

22.10.3 Helictite Cave to Subway

Helictite is a compact maze cave with over 11 km of canyon passages averaging 6 m high by 2 m wide.

The cave has only one known entrance. At this site the fan was placed directly into the 76 cm steel culvert entrance to Helictite Cave. The anemometer was placed at an entrance to the Subway (a major section of the Water Sinks Cave). The two entrances are only 159 m apart but are on opposite sides of a large sinkhole. The air flow testing shows no detectable signal between entrances.

22.10.4 Helictite to a Blowhole

With the fan placed in the Helictite entrance, an anemometer was placed at a surface blowhole 880 m to the north. Previously some digging has taken place at the blowhole in an attempt to find a possible cave. As a result of the digging the air flow was coming up through an area of broken loose rock measuring about 4 m² on one side of the excavation. To concentrate the air flow, a tarp was placed over the loose rock with the anemometer placed in a small hole cut in the tarp (Fig. 22.18). The result of this test shows a connection exists between Helictite Cave and the blowhole. The effect at the blowhole was slight and delayed by 40 s.



Fig. 22.18 A tarp was fastened to one side of an excavation to cover an area where air was passing through a zone of rocks. Cardboard was taped to the tarp to provide a rigid surface and a hole was cut in the cardboard and tarp. An anemometer was placed in this hole where the air flow was then concentrated (photo by P. C. Lucas)

The blowhole is now the entrance to Wishing Well Cave.

An interesting observation was made during the Helictite tests. A strong outflow of air would follow after the fan had been blowing into the cave for a ten minute period. Even though the entrance displays a convection air flow, the fan's operation was enough to create increased pressure within the cave that it far exceeded the outflow for the convection air flow.

22.11 Conclusions

The results from these tests vary from strong changes in air flow to weak changes or no detectable changes. The time it took for the effect to occur changed from just a few seconds to nearly 30 s. As this method of testing was being developed and preliminary testing was performed, it was apparent that testing done on windy days was not satisfactory. Gusty winds over hills and ridges create many pulses that tend to be amplified at entrances and this "noise" overwhelmed the signal the fan introduces. Also the clearest signals were obtained when the outside temperatures and cave temperatures are close to each other thereby creating only weak convection currents. All of the caves tested with possibly one exception are thought to have convection as the primary energy driving the air flow. Helictite Cave's airflow might have a strong barometric component as determined by another test (not described in this paper). Accordingly additional testing using this method between barometric caves entrances will be interesting. Although, these tests reveals a connection between some cave entrances it does not provide information about the nature of the connection or its location. It does not say whether this connection is humanly traversable. The different time delays suggest that some connections are more distant, longer in length or more restricting than others but a more examination of this is needed. This testing requires some preparation of the placement of the equipment, fan, and anemometer/loggers along with a power source. But the outcome can provide a valuable insight about the relationship of caves in a karst area. This method of air tracing is certainly less polluting to the cave than past methods.

References

- Bamberg, S.A. 1973. Environments in Lehman Caves, Nevada. *National Speleological Society Bulletin* 35: 35–47.
- Cropley, J.B. 1965. Influence of surface conditions on temperatures in large cave systems. *National Speleological Society Bulletin* 27: 1–10.
- Fairchild, I.J., and A. Baker. 2012. *Speleothem science*. Chichester, UK: Wiley-Blackwell. 432 pp.
- Nepstad, J., and J. Pizarowicz. 1989. Wind Cave, South Dakota: temperature and humidity variations. *National Speleological Society Bulletin* 51: 125–128.
- Wefer, F.L. 1984. Cave meteorology. *BCCS Newsletter* 10: 33–49.
- Wefer, F.L. 1985. More on cave meteorology. *BCCS Newsletter* 11: 25–56.
- Wefer, F.L. 1988. Still more on cave meteorology. *BCCS Newsletter* 14: 76–84.
- Wefer, F.L. 1989a. Yet still more on cave meteorology. *BCCS Newsletter* 15: 18–38.
- Wefer, F.L. 1989b. On the measurement of relative humidity in cave meteorology projects. *Nittany Grotto News* 36(1): 6–14.
- Wefer, F.L. 1990. Even yet still more on cave meteorology. *BCCS Newsletter* 16: 20–41.
- Wefer, F.L. 1991a. An annotated bibliography of cave meteorology. *Cave Geology* 2: 83–119.
- Wefer, F.L. 1991b. Meteorology of the butler cave-sinking creek system. In *Appalachian Karst*, ed. E.H. Kastning, and K.M. Kastning, 65–74, Huntsville: National Speleological Society.
- Wefer, F.L. 1992. Meteorological conditions far inside a large cave system. *BCCS Newsletter* 18: 36–41.
- Wigley, T.M.L., and M.C. Brown. 1976. The physics of caves. Chap. 9. In *The science of speleology*, ed. T.D. Ford, and C.H.D. Cullingford, 329–358. London: Academic Press.