Climate Modeling for Two Lava Tube Caves at El Malpais National Monument, New Mexico USA

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Abstract

Reliable data on cave microclimate benefits those who manage caves for human visitation, protection, and the conservation and restoration of bat roosts. Information, both published and unpublished, on cave climates is limited. Mathematical models of cave climate are even more limited, and for lava tube caves, these appear to be totally lacking. Because lava tube caves are simpler than many limestone caves (thus making the task of modeling tractable) we tested the use of lava tube caves as laboratories for climate modeling.

We present the results of investigating temperature and humidity in two lava tube caves at El Malpais National Monument, New Mexico, USA. One cave was a single-entrance cave with an ice sheet, the other a tube with detectable airflow to/from cracks on the surface. One and one-half years of data were collected in these two tubes using data loggers. Using these data, we investigated temperature and humidity changes with seasons and distance from the entrance, and propose mathematical models to predict future temperatures based on heat flow from the surface as well as advection.

Our models show a good fit to the equation

$$T(t) = a_1 + a_2 \cos[(t2\pi)/365.24] + a_3 \sin[(t2\pi)/365.24] + a_4 \cos(t2\pi) + a_5 \sin(t2\pi)$$

This implies that, at least in these lava tube caves, accurate prediction of temperature is possible.

Introduction

Cave managers need temperature and humidity data to assess the impact of visitors, conservation and restoration of bat roosts, etc. For example, in an ice cave, the question might arise, "Is human visitation melting the ice?" We show that for some caves, a manager could start by collecting data during a time without visitation. Once the baseline data exists, the predictions can allow the manager to know if the visitation is affecting the cave climate.

This paper presents the results of a cave climate study from October 1993 through August 1995 of two lava tubes at El Malpais National Monument, New Mexico, USA. The original goal was to study the impact of prescribed fire on lava tube caves; however, for political reasons the prescribed fire never occurred. If we had planned to do a cave climate study, we would have placed data loggers differently.

Description of the caves

Both of the lava tubes are located in an open Ponderosa pine forest on El Malpais National Monument, in westcentral New Mexico, USA (Figure 1).

Lava Wall cave (also known as Peel Bark cave) is the smaller of the two lava tubes. It has a large wide entrance (Figure 2) approximately 6.5m x 1.5m, and it gets progressively narrower and lower. Within 6m, it turns into a muddy crawl which continues for at least 24m. The crawl shows evidence of repeated flooding and organic input, and a commonly-felt breeze implies that it connects to cracks in a nearby (30m distant) sink. Figure 3 shows an approximate crosssection of the cave. Note that this cave is



Figure 1. Approximate location of El Malpais National Monument, where the two lava tubes are located.





- Temperature recorder
- Humidity recorder





Temperature recorder

Humidity recorder

Figure 2. Entrance of Lava Wall cave.

Figure 3. Cross section of Lava Wall cave.

relatively level once you are inside.

Frozen Mat cave is larger, with two rooms and a passage. The small (less than 1 meter square) entrance leads into a breakdown room (about 4m x 9m). Over a breakdown pile is a second room (about 5m x 20m) containing a 5m x 6m ice sheet (Figure 4), covered with up to 2.5cm of water in the summer. The ice is about 3m-4.5m below the entrance and about 20m from the entrance. The ice sheet varies in extent and depth throughout the year and year-to-year. The room extends no more than about 7.5m beyond the ice. Figure 5 shows an approximate cross-section of the cave.

On the left side of the entrance room in Frozen Mat is a low passage that proceeds for at least 13m and appears to pinch out. No airflow was detected through this passage.

Literature Review

Heat drives much of the airflow, and airflow can move heat around. As a result, we review previous work by looking at what is known about heat flow and caves, and then looking at previous studies of airflow.

Heat

Heat is important for two reasons. First, to predict the temperatures inside caves, we need to know from where the heat comes. Second, heat is sometimes responsible for airflow.

Heat in caves comes from three sources:

- the radioactive decay of elements in the Earth's core (geothermal heating).
- surface heat generated by the sun and transported by conduction through the soil and rock.
- surface heat generated by the sun and carried into the cave by air movement (advection).
- heat moved by a stream running through a cave (which does not apply to the caves we studied).

Figure 4. The ice sheet in Frozen Mat cave.

Figure 5. Cross section of Frozen Mat cave.

Geothermal heating. Atkinson, Smart, and Wigley [2] used geothermal heating to explain the difference between the mean annual temperature and the actual measured temperature deep in Castleguard cave in Alberta Canada. Most likely, geothermal heat is omitted from studies because most caves (especially the lava tubes we were studying) are close to the surface, and the other factors dominate their temperature.

Solar heat transported by conduction. Daily variations in temperature in the soil and rock die out about 1m deep [16]. Annual variations in temperature may be observed as deep as 20-24m [16] depending on the rock and soil types. At depths below below where the surface influence is felt, the temperature of a cave should be stable at the mean annual surface temperature [4, 8, 14, 16].

Heat transferred by advection. Advection is the transfer of heat by air movement. In this case, rather than the heat which is being moved causing the movement (as in convection), some other factor is causing the air movement.

Airflow

To know about airflow, we must look at the factors that can cause air to move in caves:

- density differences in air caused by temperature variations,
- the number of entrances a cave has and their relative elevation, and
- differences in air pressure from various factors considered below.

The single most important factor affecting airflow is the number of entrances a cave has and the relative height of these entrances. A cave with multiple entrances where those entrances are not at the same level will nearly always have a breeze blowing through it. When the temperature inside is lower than the temperature outside (as it is in summer), the cool (and therefore denser) air will exit the lower entrance, and the outside, warmer air will enter at the upper entrance. Conditions reverse when the temperature inside is higher than the temperature outside (as it is in winter). During times when the inside and outside temperatures are nearly the same, no breeze may blow or other factors may dominate the airflow. The velocity of the air movement in this chimney effect is directly related to the temperature (and to some extent the humidity) differences between the air inside and outside of the cave. Airflow velocities will also be affected by the volume of the cave as well as the sizes of the entrances.

Wigley and Brown [19] and Atkinson, Smart, and Wigley [2], note that a cave may have extra "entrances" in terms of fractures leading to the surface which may be too small for humans to travel but are large enough to allow air to flow. These airflow routes will cause the chimney effect to occur even in what appear to be single entrance caves. This effect probably occurs in Lava Wall cave.

For caves with a single entrance, airflow is controlled by a complex collection of factors including:

- convection,
- the current barometric pressure and how it is changing, and
- wind blowing across or into an entrance.

Additionally, surface roughness, and the sinuosity of passage affect the airflow by making it more turbulent and hence slowing it down.

Since warm air is less dense that cool air, it will tend to rise or flow along the upper part of the cave. Similarly, cool air will flow along the bottoms of the passages. The slope of the cave and orientation of the entrance will determine if or how convection will cause air exchange with the interior portions of the cave [19]. This convection was the primary air movement discovered at Altimira Cave in Spain by Villar et al. [17]. It also is a part of the airflow at Glowworm Cave in New Zealand [6]. Another example where convection is a major cause of the airflow was investigated by Smithson [15]. He looked at vertical variations of temperature in Poole's Cavern U.K. and saw the effects of convective airflow.

Convection explains why singleentrance caves which slope downward are cold traps. In the winter cold air flows into the cave. In the summer it becomes stagnant, and hence remains cool and in some cases collects ice [3, 8]. In upward-trending caves, the reverse would happen and cooler air would fall out the entrance when it was cooler in the cave than outside [19].

Other than convection, airflow also

results whenever the barometric pressure outside is different from the pressure inside. When this difference occurs, the cave will inhale or exhale to equalize the pressure. Lewis [12] and Wigley and Brown [19] noted many factors which affect the atmospheric pressure outside and hence the breathing of a cave:

- weather patterns as high and low pressure systems move across, the cave lags the outside by a small amount as air flows to equalize the pressure.
- atmospheric tides are caused by the atmosphere absorbing heat directly from the sun and from the heat reflected from the earth's surface. A typical tidal curve has two maxima and two minima in 24 hours.
- gravity waves are the atmospheric equivalent of the waves we commonly associate with the ocean. They have periods from about three minutes to three hours.
- infrasound from sources such as the aurora, nuclear blasts, distant storms, waterfalls, the jet stream, volcanic explosions, earthquakes, waves on the ocean, large meteorites, supersonic aircraft.
- cave resonance from wind blowing across an entrance, much like a bottle resonates when blown across its opening.

Wigley and Brown [19] noted that a cave with widely separated entrances which has a strong storm (such as a summer thunderstorm) over one entrance may have a notable difference of pressure between the entrances which causes airflow.

Wind blowing into an entrance can cause airflow as noted by Smithson [15]. In multi-entrance caves, the wind may blow in one entrance and out another. Wind blowing across an entrance will lower the pressure at that entrance which will affect the airflow.

Any of the above mechanisms for airflow can act simultaneously to result in airflow which may be barely detectable (as in the flickering of a candle) all the way up to wind which moves gravel [19].

Temperatures in the cave

When the temperatures are different from the mean annual temperature, it is due to one of the causes mentioned above. First, we note that rock stores heat, and it will release that heat to cooler air or will absorb heat from warmer air [18].

Second, adding humidity to air cools it [7, 18] because of the heat needed to change liquid water to water vapor (about 540 calories/gram, depending on temperature). Therefore unsaturated air (from the surface) moving across a source of water (such as water percolating in from the surface) will cool as the water evaporates into it.

Taking these two factors into consideration, Wigley and Brown [18] develop the following formula to describe the temperature in the cave:

$$T = T_a + (T_0 - T_a)e^{-X}$$
$$+ \frac{L_v}{c_p}w(q_0 - q_a)Xe^{-X}$$

where T_a is the deep cave rock temperature, T_0 is the temperature of the air entering the cave, X is the ratio of the distance from the entrance (x) and the relaxation length (x_0) , L_y is the latent heat of vaporization, c_p is the specific heat of air, w is cave wetness which indicates the fraction of the cave wall which is wet, q_0 is specific humidity of the air entering the cave, q_q is the specific humidity of the outside air when it is cooled to T_q .

The relaxation length, $x_0 = 36.44$ $a^{1.2}V^{0.2}$, where *a* is the radius of the cave in cm and *V* is the velocity of the air moving into the cave in cm/sec. It is the distance it takes the temperature T_a to decay to $T_a e^{-1}$. In some caves it may be easier to calculate this distance rather than measure the airflow [5]. Wigley and Brown [19] found relaxation lengths in the range of 10 to 500m.

Given the equation of Wigley and Brown along with data obtained from monitoring the cave, we can predict the temperatures in the cave based on temperature and humidity outside the cave, current airflow, and amount of moisture on the wall of the caves. Preceding a prescribed fire, the cave should be monitored, a plan suggested by Smithson and Wigley and Brown [13, 19]. These predictions then should be compared with actual conditions observed to determine how the cave varies from predicted. During the prescribed fire, the cave can be monitored and any effects of the fire can be noted as divergence from the

predicted values.

Humidity

Humidity is of interest because when water evaporates, it absorbs heat. Conversely, when it condenses, heat is released. So humidity is tied together with heat. Additionally, Howarth [1, 10, 11] states that the key environmental factor that determines the distribution of troglobites is the degree to which the atmosphere is saturated.

As you travel deeper into a lava tube (provided there are not additional entrances), evaporation decreases. Howarth [9] found that the rate of potential evaporation in the deep cave zone was only 8% of that of the twilight zone and hypothesized that the rate within the mesocaverns was much lower still. Cave organisms further take advantage of areas with low evaporation by moving into the small voids, which are often sites of accumulation of organic matter [1].

The degree of saturation of air in lava tubes is dependent on several surface factors and is a dynamic phenomenon. Climate on the surface influences the movement of air in lava tubes. When the temperature is lower outside than inside, as often happens at night in the winter, the vapor pressure of water is higher inside the cave than outside causing moist air to diffuse out of the cave. If the daytime water vapor pressure is still less than that in the cave, the water vapor will continue to diffuse out of the cave in the daytime, resulting in a winter drying of the cave known as the "wintering effect" [1]. When conditions reverse, the cave will gain moisture from the surface air.

The "wintering effect" does not seem to apply to the blind tubes at El Malpais. Frequent snowpacks that remain for days or weeks provide moisture for the lava tubes both in the form of atmospheric moisture and as melting water percolating through cracks. Ice in the lava tubes accumulates over winter, reaching a peak in early spring.

The deeper in to the cave you go, the longer the lag between changes in the surface conditions and the corresponding changes in the cave environment. Similarly, the amount of change becomes less with increasing distance from the entrance [1].

Materials and methods

Onset Hobo (Onset Computer, 470 MacArthur Blvd., Bourne, MA 02532, +1-508-759-9500, http://www .onsetcomp.com/) temperature and humidity data loggers capable of storing 1800 observations were used to collect the data. The recording interval varied from 5.6 minutes to 96 minutes, and was based on our expected return date to download data. During the winter, access to the caves was often impossible. The data loggers themselves were stored in plastic containers to shield them from the elements, with the temperature sensor outside of the container.

Unfortunately, animals destroyed some of the remote sensors. To protect the sensor, we moved the sensor for two data loggers inside the plastic container. This changed the reaction time from two to 40 minutes.

Results

Plotting raw data from the data loggers results in a graph such as the one from Frozen Mat cave (Figure 6). The data from the other data loggers were similar, and all exhibit a diurnal cycle.

A Fast Fourier Transform requires data with equal intervals, a requirement we could not meet due to the varied data collection intervals. We tried a traditional Fourier Analysis, but the resulting spectrums were not helpful in predicting temperatures.

We used a least-squares algorithm to fit sine and cosine to the daily and annual data, specifically:

$$T(t) = a_1 + a_2 \cos(\frac{t2\pi}{365.24}) + a_3 \sin(\frac{t2\pi}{365.24}) + a_4 \cos(t2\pi) + a_4 \sin(t2\pi)$$

By using both the sine and cosine, we are able to represent the annual/diurnal cycles, as well phase information.

The resulting equations for Lava Wall are in Table 1, and for Frozen Mat are in Table 2.

Discussion

Not surprisingly, diurnal cycles are strongly evident in all temperature data. Both caves are small, and have an interaction coupled to the surface temperature. The oscillations diminish as you go deeper in the cave. In Frozen



Figure 6. A week of data from the ceiling data logger in Frozen mat cave.

Table	1. Equations	fitting the	data for t	he data	loggers	in Lava	Wall o	cave.
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ceiling	$T(t) = 0.0(\pm 0.0) + -10.843922(\pm 0.016795)\cos(\frac{t2\pi}{365.24})$	+
	$-14.900744(\pm 0.015138)\sin(\frac{t2\pi}{36524}) + -0.147362(\pm 0.015631)\cos(t2\pi)$	+
	$-0.261526(\pm 0.015624)\sin(t2\pi)$	
floor	$T(t) = 0.0(\pm 0.0) + -7.237748(\pm 0.016262)\cos(\frac{t2\pi}{365.24})$	+
	$-15.836785(\pm 0.013960)\sin(\frac{t2\pi}{365.24}) + -0.129653(\pm 0.014451)\cos(t2\pi)$	+
	$-0.361877(\pm 0.014440)\sin(t2\pi)$	
crawl	$T(t) = 0.0(\pm 0.0) + -1.427401(\pm 0.033754)\cos(\frac{t2\pi}{365.24})$	+
	$-10.884780(\pm 0.025210)\sin(\frac{t2\pi}{36524}) + -0.261690(\pm 0.020269)\cos(t2\pi)$	+
	$-0.531103(\pm 0.020291)\sin(t2\pi)$	
sink	$T(t) = 0.0(\pm 0.0) + -19.417273(\pm 0.016925)\cos(\frac{t2\pi}{365.24})$	+
	$-13.317093(\pm 0.016707)\sin(\frac{t2\pi}{365.24}) + 0.625014(\pm 0.016633)\cos(t2\pi)$	+
	$0.546246(\pm 0.016627)\sin(t2\pi)$	
dome	$T(t) = 0.0(\pm 0.0) + 31.512697(\pm 0.054709)\cos(\frac{t2\pi}{365.24})$	+
	$-25.051178(\pm 0.054308)\sin(\frac{t2\pi}{265.24}) + -0.198811(\pm 0.052696)\cos(t2\pi)$	+
	$-0.744981(\pm 0.052707)\sin(t2\pi)$	
relative humidity	$T(t) = 0.0(\pm 0.0) + -16.574255(\pm 0.016254)\cos(\frac{t2\pi}{265.24})$	+
	$-36.632496(\pm 0.013953)\sin(\frac{t2\pi}{265.24}) + -1.820918(\pm 0.014438)\cos(t2\pi)$	+
	$-0.763961(\pm 0.014441)\sin(t2\pi)$	

Table 2. Equations fitting the data for the data loggers in Frozen Mat cave.

ceiling	$T(t) = 0.0(\pm 0.0) + -8.430573(\pm 0.012779)\cos(\frac{t2\pi}{365.24}) +$
	$-20.716593(\pm 0.011610)\sin(\frac{t2\pi}{36524}) + -0.368887(\pm 0.012041)\cos(t2\pi) +$
	$0.136714(\pm 0.012025)\sin(t2\pi)^{-1}$
sink	$T(t) = 0.0(\pm 0.0) + -23.819973(\pm 0.015790)\cos(\frac{t2\pi}{365.24}) +$
	$-22.008461(\pm 0.013915)\sin(\frac{t2\pi}{36524}) + -3.382733(\pm 0.014441)\cos(t2\pi) +$
	$-0.264057(\pm 0.014429)\sin(t2\pi)$
floor	$T(t) = 0.0(\pm 0.0) + -8.482291(\pm 0.015796)\cos(\frac{t2\pi}{36524}) +$
	$-17.615507(\pm 0.013921)\sin(\frac{t2\pi}{36524}) + 0.014079(\pm 0.014441)\cos(t2\pi) +$
	$-0.054044(\pm 0.014440)\sin(t2\pi)$
relative humidity	$T(t) = 0.0(\pm 0.0) + -5.646605(\pm 0.015349)\cos(\frac{t2\pi}{365.24}) +$
	$-38.756611(\pm 0.013631)\sin(\frac{t2\pi}{36524}) + 0.471688(\pm 0.014182)\cos(t2\pi) +$
	$0.210453(\pm 0.014171)\sin(t2\pi)$

Mat cave, the ice sheet melting produces nearly constant temperatures until the ice retreats far enough from the data logger. The humidity is lowest mid-afternoon, which corresponds to the high point in the diurnal temperature cycle.

The error values show that the daily plus annual sine and cosine functions fit the data well. This good fit implies that the temperatures in these caves are predictable. Other, simple caves should be as predictable. More complex caves, e.g., those with multiple entrances, may be more difficult to model due to more factors affecting the temperature and/ or humidity. Because each cave has a different geometry, airflow, etc., the optimal placement for climate sensors will vary.

Since our data loggers were placed for observing effects of fire, we were unable to test the prediction by Wigley and Brown [18]. To confirm their prediction would have required airflow data and/or additional temperature data in order to determine the relaxation length.

Conclusion

Cave managers can use temperature and humidity predictions for guiding their decisions for cave management. For example, bats require temperature and humidity within certain tolerances in order to use the cave. Ice formations in lava tubes may melt from the heat produced by humans visiting the cave. We have shown that for simple caves, accurate prediction of temperature and humidity is possible.

References

- 1. G. A. Ahearn and F.G. Howarth. Physiology of cave arthropods in Hawaii. The Journal of Experimental Zoology, 222:227-238, 1982.
- 2. T. C. Atkinson, P. L. Smart, and T. M. L. Wigley. Climate and natural radon levels in Castleguard Cave, Columbia Icefields, Alberta, Canada. Artic and Alpine Research, 15(4):487-502, 1983.
- 3. Alfred Bögli. Karst hydrology and physical speleology. Springer-Verlag, 1980.
- 4. J. B. Cropley. Influence of surface conditions on temperatures in large cave systems. Bulletin of the National Speleological Society, 27(1):1-10, January 1965.
- 5. C. R. De Freitas and R. N. Littlejohn.

One week of Frozen Mat Ceiling

Cave climate: assessment of heat and moisture exchange. *Journal of Climatology*, 7:553-569, 1987.

- C. R. De Freitas, R. N. Littlejohn, T. S. Clarkson, and I. S. Kristament. Cave climate: assessment of airflow and ventilation. *Journal of Climatol*ogy, 2:383-397, 1982.
- Adolfo Eraso. Tentative nomogram for cave climate calculations. In Dr. Otakar Stecl, CSc., editor, Problems of the Speleological Research: Proceedings of the International SpeleologicaConference held in Brno June 29-July 4 1964. Academia, Publishing house of the Czechoslovak Academy of Sciences, 1965.
- William R. Halliday. Ice caves of the United States. *Bulletin of the National Speleological Society*, 16:3-28, December 1954.
- Francis G. Howarth. The evolution of non-relictual tropical troglobites. *International Journal of Speleology*, 16:1-16, 1987.

- 10. Francis G. Howarth. Evolutionary ecology of aeolian and subterranean habitats in Hawaii. *Trends in Ecology and Evolution*, 2(7):220-223, July 1987.
- 11. Francis G. Howarth. Hawaiian cave faunas: macroevolution on young islands. In E. C. Dudley, editor, *The unity of evolutionary biology: fourth international congress of systematic and evolutionary biology, College Park, Maryland, USA, June 30-July 7, 1990*, volume v1,v2, pages 285-295, Portland, Oregon, April 1991. Dioscorides Press.
- 12. Warren C. Lewis. Atmospheric pressure changes and cave airflow: a review. *The NSS Bulletin*, 53(1):1-12, June 1991.
- P. A. Smithson. Temperature variations in Creswell Crags Caves (near Worksop). *East Midland Geographer*, 8:51-64, 1982.
- 14. P. A. Smithson. Inter-relatonships between cave and outside air

temperature. *Theor. Appl. Climatol.*, 44:65-73, 1991.

- P. A. Smithson. Vertical temperature structure in a cave environment. *Geoarchaeology: An International Journal*, 8(3):229-240, 1993.
- 16. A. K. S. Thakur and M. Musa Momoh. Temperature variation in upper Earth crust due to periodic nature of solar insolation. *Energy Convers. Mgmt*, 23(3):131-134, 1983.
- 17. E. Villar, P. L. Fernández, L. S. Quindos, J. R. Solana, and J. Soto. Air temperatures and airinterchanges at Altimira Cave (Spain). *Transactions* of the Britsh Cave Research Association, 11(2):92-98, July 1984.
- T. M. L. Wigley and M. C. Brown. Geophysical applications of heat and mass transfer in turbulent pipe flow. *boundary-layer meteorology*, 1:300-320, 1971.
- 19. T. M. L. Wigley and M. C. Brown. *The physics of caves*, chapter 9, pages 329-358. Academic Press, 1976.