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Inter-Relationships Between Cave and Outside Air Temperatures

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With 3 Figures

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Summary

Investigations into the thermal regime of a cave in the Peak District of Derbyshire show a strong seasonal variation. In summer the main chamber of the cave has an almost uniform temperature with a slight increase with height above the cave floor. Its value of 7 °C is close to the mean annual temperature recorded at a standard climatological station nearby. Whenever the outside temperature falls below about 7 °C, density currents slowly flow into the cave bringing cooler temperatures into the lowest part of the cave. Winds blowing directly into the cave also affect the temperature regime through forcing external air into the system. The nature of the association between outside and interior temperatures is investigated by correlation analysis.

1. Introduction

Cave temperature patterns have been described for different parts of the world and for varying cave sizes by a number of authors (e.g. Geiger, 1959; Smithson, 1982; Villar et al., 1984; Gewelt and Ek, 1986; De Freitas and Littlejohn, 1987; and Thibaudeau, 1988). Less frequently attempts have been made to account for the nature of cave temperature changes in terms of the processes involved (e.g. Wigley and Brown, 1976; De Freitas et al., 1982; Atkinson et al., 1983; and Lauriol et al., 1988). However, few are concerned explicitly with the relationships between temperature changes in a cave and those outside. This is surprising considering that much more is known about the external environment through preserved palaeoenvironmental indicators. The study of cave temperatures and associated airflows is important in the understanding of cave flora and fauna, spore and pollen preservation (Coles et al., 1989), carbon dioxide levels, which can affect some karst processes underground, radon levels and health underground (Atkinson et al., 1983) and for the use of caves for habitation (Gentles and Smithson, 1986) or industry (Branigan and Bayley, 1990), though for a full understanding of the cave environment, the relationship with the external climate must be understood.

From this work it is well known that cave temperatures change progressively from the cave entrance to the interior where eventually temperatures remain stable at a level corresponding closely to the mean annual temperature outside the cave. In a well-ventilated cave system with latent heat effects being ignored, summer temperatures decrease and winter temperatures increase exponentially from the entrance area but the precise shape of the curve will depend upon the degree of ventilation, the passage diameter and the nature of the external climate (Wigley and Brown, 1976). If the cave is a closed system with only a single entrance, ventilation is less effective than in an open system. In addition many natural cave passages have a highly variable radius, a high aerodynamic roughness factor, a sloping floor and a high sinuosity so that in many cases the ideal flows predicted by Wigley & Brown (1971, 1976) do not occur and the temperature pattern differs from their model. Each cave system has an element of uniqueness whilst following the general principles of cave temperature models.

Much of the published work concerning cave temperatures is based either on short periods of detailed observations (Thibaudeau, 1988) or on longer time periods at fewer sites (De Freitas and Littlejohn, 1987). Most work uses only cave floor observations despite the known thermal stratification which can occur in caves (Gewelt and Ek, 1986). Because of this, it is not always possible to follow the detailed variations of temperature in different parts of a cave nor relate these to their causative factors.

The cave atmosphere in an open system is a dynamic feature with the resulting climate being a function of air exchange with the outside atmosphere. This airflow can take place through three causes, gravity, density-induced convection and forced advection. The magnitude of the flow can then be modified by a variety of features connected with cave morphology particularly the size and shape of the tunnels and chambers. Normally the stronger the airflow generated, then the greater will be the influence of outside temperatures on those within the cave. The question to be investigated is the extent to which this influence is uniform or variable in the cave.

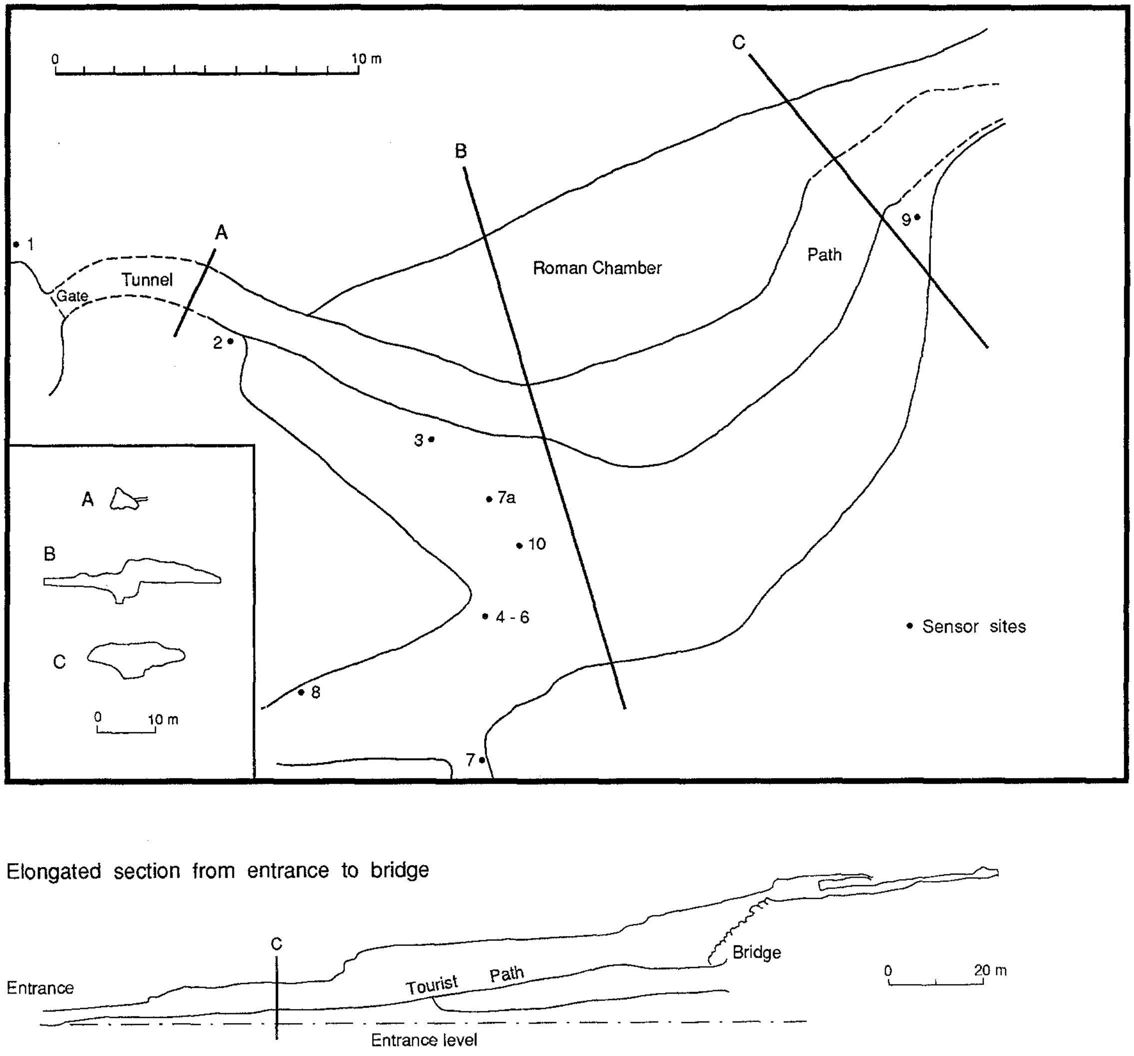

Fig. 1. Plan of the Roman Chamber, Poole's Cavern, longitudinal profile of cave and sensor positions. The dashed area of the tunnel is not to scale

2. Site and Location

The site of this study is Poole's Cavern, a small show cave, in Buxton, Derbyshire, U.K. It is located at an altitude of about 300 m above MSL with a north-facing entrance. The slope behind the entrance is well-wooded, whilst the entrance area itself is relatively sheltered so that interaction with outside air may be reduced slightly. The cave entrance has a sliding metal grill which allows air movement into a sinuous tunnel with an average diameter of about 1.8 m and a slight upward gradient extending for about 30 m before it broadens out into the Roman Chamber (Fig. 1). Roman remains indicating possible habitation and metal working have been found on a terrace in this chamber (Branigan and Bayley, 1990). As it was this area which was of most interest from an archaeological point of view, most of the thermal sensors were placed in this area at the sites shown in Fig. 1.

The sites were chosen to demonstrate the changes in temperature with distance into the cave and to assess the environment of the higher terrace where the Roman remains had been found. At the same time, the use of the cave by visitors restricted where sensors could be placed. Site 1 was located outside the cave, near ground level and shielded from direct sunlight. It was above the main cold air outflow of the cave so it should indicate the ambient ground-level temperature at the cave entrance. Site 2 was at the lowest point of the access path though the actual height difference from the entrance was small. Site 3 was in the tunnel but on a slope between the cave wall and the path. Site 4 was at floor level on the terrace with sites 5 and 6 one and two metres respectively vertically above site 4 to determine the vertical temperature variation in the Roman Chamber. This aspect will be examined in another paper. Sites 7 and 8 were positioned close to the cave wall furthest away from outside influences. Results were so similar that site 7 was later moved to a new site (7 a) on the slope between the terrace and the path. Site 9 was furthest from the entrance but being close to the path, it could be affected by air currents flowing along the path from the entrance. Site 10 was also positioned on the slope to provide greater detail about the vertical variation of temperature.

3. Sampling and Data Collection

Temperatures at each site within the cave were recorded by thermistors onto a data logger every 10 minutes, then averaged over a 30 minute period so that for each site 48 observations were recorded each day. Prior to commencement of the experiment, all thermistors were checked in a constant temperature bath to ensure comparability. At the end of each observation period, the data were down-loaded onto a computer for subsequent analysis.

Unfortunately it was not possible to obtain continuous airflow observations in the cave although occasional samples were taken in the tunnel during visits to the cave using Shepherd sensitive anemometers to provide estimates of the magnitude of the airflow at different heights within the tunnel. A portable hot-wire anemometer was also used to determine rates of airflow between the entrance and the Roman Chamber. It was only in this zone that measureable readings occurred. As interior cave temperatures tend to be fairly stable, it was decided to sample during the course of a year rather than obtain a continuous record. Sampling periods are shown in Table 1.

Climatological observations were available in central Buxton about 1.2 km north-east of the cave and at a similar altitude. The site is located in a park with the nearest buildings some distance away, so its observations record a semi-rural location rather than a typical urban site. Data used in this study included daily maximum, daily minimum, grass minimum, and 9 a.m. GMT temperatures and wind speed and direction at 9 a.m. GMT. As all standard climatological observations are made at such sites, the data obtained from here are likely to be more representiative of the region rather than those obtained from the entrance micro-climate at site 1.

4. Cave Temperature Patterns

Although the Roman Chamber is located close to the entrance, temperature variations in it were generally small. Table 2 summarizes the results for

Table 1. *Sampling Periods*

9–30 August 1989
5–29 September 1989
24 October–21 November 1989
19 December 1989–16 January 1990
25 January–25 February 1990
23 March–23 April 1990
25 May–24 June 1990

Table 2. *Mean Temperatures, Standard Deviations and Maximum, Minimum and Range of Temperature at Each Site (°C)*

Site	1	2	3	4	5	6	7	7a	8	9	10	Buxton
August												
Mean	12.6	7.1	7.1	7.0	7.0	7.2	6.9	–	6.9	7.1	–	14.5
S. D.	2.1	0.1	0.1	<0.1	0.1	0.1	0.1	–	<0.1	0.1	–	–
Max.	18.7	7.5	7.5	7.1	7.4	7.7	6.9	–	7.0	7.4	–	22.4
Min.	5.4	6.5	6.8	7.0	6.9	7.1	6.7	–	6.8	7.0	–	4.6
Range	13.3	1.0	0.7	0.1	0.5	0.6	0.2	–	0.2	0.4	–	17.8
September												
Mean	11.5	7.3	7.1	6.8	7.0	7.2	7.2	–	6.9	7.2	–	13.3
S. D.	1.7	0.3	0.1	0.1	0.1	0.1	<0.1	–	<0.1	<0.1	–	–
Max.	15.6	9.3	7.8	7.2	7.6	7.8	7.3	–	6.9	7.5	–	21.9
Min.	6.8	7.0	7.0	6.8	7.0	7.1	7.0	–	6.8	7.1	–	5.7
Range	8.8	2.3	0.8	0.4	0.6	0.7	0.3	–	0.1	0.4	–	16.2
November												
Mean	6.7	6.5	6.6	7.1	7.0	7.2	7.2	–	7.0	6.9	7.2	7.2
S. D.	2.1	0.9	0.6	0.1	0.1	0.1	<0.1	–	<0.1	0.3	0.2	–
Max.	11.8	8.0	7.3	7.2	7.3	7.5	7.3	–	7.1	7.3	7.3	13.9
Min.	0.6	2.2	3.9	6.8	6.9	7.0	7.0	–	6.9	5.9	6.8	−2.0
Range	11.2	5.8	3.4	0.4	0.4	0.5	0.3	–	0.2	1.4	0.5	15.9
December/January												
Mean	3.8	4.4	4.6	6.2	6.3	6.6	–	5.4	6.5	5.4	5.8	4.7
S. D.	2.6	1.0	1.0	0.2	0.2	<0.1	–	0.5	0.1	0.5	0.3	–
Max.	9.5	6.2	6.0	6.5	6.7	6.7	–	6.1	6.8	6.2	6.5	11.2
Min.	−1.5	2.0	2.2	5.8	6.1	6.5	–	4.1	5.7	4.1	5.0	−1.2
Range	11.0	4.2	3.8	0.7	0.6	0.2	–	2.0	1.1	2.1	1.5	12.4
February												
Mean	3.8	4.6	4.8	6.3	6.4	6.6	–	5.5	6.7	5.6	6.0	5.3
S. D.	3.0	1.0	0.9	0.1	0.1	0.1	–	0.4	0.1	0.4	0.2	–
Max.	10.8	6.2	6.2	6.5	6.5	6.8	–	6.4	7.0	6.4	6.4	14.3
Min.	−3.1	1.8	2.0	6.0	6.2	6.5	–	4.4	6.5	4.2	5.4	−1.8
Range	13.9	4.4	4.2	0.5	0.3	0.3	–	2.0	0.5	2.2	1.0	16.1
April												
Mean	4.1	4.3	4.8	6.2	6.3	6.6	–	5.6	6.7	5.6	5.9	5.5
S. D.	3.0	1.0	1.0	0.2	0.1	0.1	–	0.5	0.1	0.5	0.3	–
Max.	11.5	5.9	6.3	6.5	6.5	6.8	–	6.5	7.0	6.5	6.4	16.1
Min.	−2.6	1.2	1.5	5.8	6.0	6.3	–	4.0	6.3	3.9	5.1	−3.5
Range	14.1	4.7	4.8	0.7	0.5	0.5	–	2.5	0.7	2.6	1.3	19.6
June												
Mean	10.3	6.6	6.5	6.7	6.7	6.9	–	6.8	7.0	6.7	6.8	11.7
S. D.	2.1	0.2	0.2	<0.1	0.1	0.1	–	0.1	<0.1	0.1	0.1	–
Max.	15.9	6.8	6.9	6.9	7.1	7.1	–	7.0	7.2	6.9	7.0	22.0
Min.	3.1	5.2	5.4	6.6	6.6	6.8	–	6.1	7.0	6.2	6.6	1.7
Range	12.8	1.6	1.5	0.3	0.5	0.3	–	0.9	0.2	0.7	0.4	20.3

each of the observation periods. As expected the most stable situation occurred during the summer and early autumn when outside temperatures were well above those of the cave. At virtually all sites within the cave, variability about the mean as indicated by the standard deviation was only 0.1°

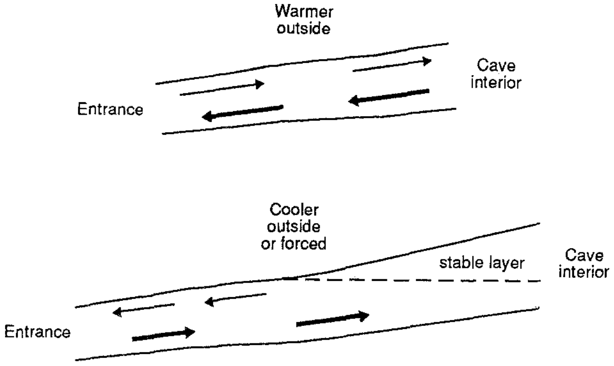

Fig. 2. Schematic diagram of airflows when outside temperatures are warmer and cooler than those within the cave

despite the presence of cave lighting and parties of visitors. Even extreme values during each of these observation periods indicated a stable environment with little mixing from outside.

In August the greatest temperature range for any site over the 21 day period was only 1° whilst in September it rose to 2.3°, both being at site 2. Otherwise differences were very small. Diurnal changes were naturally smaller with ranges always being less than 1° except at site 2 during northerly winds in early September.

By November the difference between cave temperatures and those outside had decreased. Some indication of outside interaction appeared at sites 2, 3, and, perhaps surprisingly, 9, where the standard deviations had increased and the minimum temperature recorded dropped well below the mean levels within the cave. For the December/January and February sampling periods, a similar pattern emerged though the transfer of two sensors onto the slope above the path provided evidence for some activity above the path. Only sites 6 and 8, both effectively at the highest points above the path and furthest from the source of cold air, indicated extreme stability. It would appear therefore that when outside temperatures fall below those within the cave, the usual density-induced outflow of cold air from the cave is reversed and colder air flows in along the path, the lowest part of the Chamber, and into the higher parts of the cave (Fig. 2). Despite the slight upward gradient of the path, the influx of cold air is relatively rapid, the time of the lowest temperature recorded outside the cave corresponds closely with those inside but the absolute fall of temperature compared with the cave mean decreases rapidly. For example, on April 9 1990, the minimum temperature outside was in the 30 minute period finishing at 5.33. Sites 2, 3, 5, 6, and 7a had an identical time for the minimum temperature whilst at sites 4, 9, and 10 it occurred at 6.33. At site 8 in the more distant part of the cave the minimum occurred at 14.03. Hence it is the higher or more distant parts of the cave which are last to experience a sudden decline of temperature associated with an incursion of cold air. Unfortunately it was not possible to monitor conditions in the further reaches of the cave, beyond site 9, to investigate the extent of this cold air inflow. As the winter was relatively mild, prolonged periods with outside temperatures below those prevailing in the cave were infrequent. As a result, inflows of significantly colder air were not maintained for long and the cold air slowly acquired the ambient wintertime temperature of the cave air and rock surfaces at about 6.0°.

As well as demonstrating cold air inflows, the maximum temperatures recorded also indicate inflows of warmer air from outside. With cooler, denser air flowing out of the cave near floor level, it would be expected that warm air, being of lower density, would enter through the upper part of the entrance tunnel, reach the Roman Chamber and affect higher sites (Fig. 2). Although the differences are not large, the maximum temperatures in summer and autumn are normally found at sites 2, 3, and 6; the first two being in the entrance passage and the third at 2 m above the terrace. This is unexpected as warm air entering through convection should not have affected sites 2 and 3 close to the floor where cold air drainage would be strongest. Short-term observations with the hot-wire anemometer at the tunnel roof where it emerged into the Roman Chamber showed flows of warmer air with speeds of about $0.1\,\mathrm{ms}^{-1}$ entering the Chamber. Presumably turbulent mixing within the tunnel was sufficient to raise the temperatures at sites 2 and 3.

By June, the thermal pattern had returned to that of the previous summer though the mean temperatures were slightly lower. This was a reflection of the shorter period of higher temperatures by sampling earlier in the summer and of the generally cool June 1990 which decreased the build-up of warm air. The range of mean temperatures within the cave was down to 0.5° compared with 0.3° in August.

Overall the mean temperature patterns do not

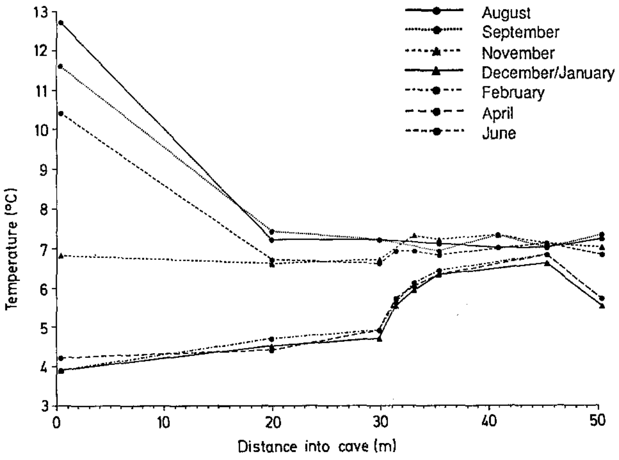

Fig. 3. Mean temperatures for each sampling period in relation to distance into the cave

fully support the theory of Wigley and Brown (1976) that temperatures decline exponentially in summer and increase exponentially in winter with respect to distance from the entrance. The pattern in Poole's Cavern shows an irregular increase in mean temperatures in winter whilst summer temperatures show little change because of the lack of summer inflow and the consistency of the air outflow (Fig. 3). Some of the anomalies shown in Fig. 3, such as the sudden rise at 30 m and decline from 42 m to 50 m, are better understood if height above the cave floor is considered as well as distance from the entrance. The maximum and minimum temperature patterns are similar.

5. Inter-Relationships

In order to quantify the degree of association between outside conditions and those in the cave, Kendall product moment correlation coefficients were calculated. As continuous records were not available at Buxton, the maximum, the minimum and the 9 a.m. GMT temperatures were correlated with the equivalent temperature at each cave site for each time period. In addition, coefficients were calculated between the 30-minute temperature averages at each cave site and those immediately outside the cave at site 1. As there was a close and statistically significant correlation between the temperature variations at this site and those at Buxton (about +0.85 and +0.94 for maximum and minimum temperatures respectively), then these figures should provide a more detailed picture of the relationships between the ambient temperature and those inside the cave.

When temperatures at Buxton are correlated with those in the cave a clear pattern emerges as illustrated in Table 3. In general values are low and statistically non-significant for the first two sample periods. This is the result of the stability of temperatures in the cave at this time. For this reason, no coefficients were calculated for site 8 where stability was most marked. Overall, temperature variations outside the cave in August and September were not directly related to what was happening within the cave. Occasionally some interaction took place, suddenly affecting interior temperatures. This aspect will be discussed in more detail later. From late-autumn, as outside temperatures fell, the coefficients became positive and highly significant at the 5% or even 1% levels for maximum, minimum and 9 a.m. temperatures at most sites. As expected, the highest coefficients occur for the sites nearest the cave entrance (sites 2 and 3), though values at sites 7 a, 9, and 10 are only slightly lower despite being further into the cave. The lowest, though still significant coefficients, are found at site 4 and 6, on the terrace and 2 m above the terrace floor respectively. It would appear that the degree of interaction as indicated by the correlation coefficients declines vertically above the cave floor rather than with distance into the cave over this small horizontal range. Minimum temperatures in Buxton during winter are normally well below those of the cave interior. Cold air will enter the cave on many nights, and even during some days, to produce a strong positive correlation between outside and cave minimum temperatures (Fig. 2). With the maximum temperatures, the difference between outside maximum and cave maximum is not so great, so the correlation is still positive but not so strong.

It had been expected that the August and June relationships would be similar. Whilst this was true for maximum temperatures where coefficients are all non-significant and close to zero, it was not true for minimum temperatures. In June, the coefficients were strongly positive at all sites within the cave. The reason for this effect was the lower mean minimum temperature at Buxton in June 1990 (7.9°) compared with August 1989 (10.5°). As a result, there were more incursions of cool air affecting the cave in the former period to produce

Table 3. *Correlation Coefficients Between Buxton Climatological Station and Selected Sites Within Poole's Cavern.* Coefficients underlined are statistically significant at the 1% level

Maximum temperatures

Sites	2	3	4	6	7a	9	10
August	−0.38	−0.10	−0.43	−0.14	–	−0.32	–
Sept.	−0.42	−0.32	−0.01	−0.39	–	−0.38	–
Oct.–Nov.	0.72	0.74	0.60	0.55	–	0.72	–
Dec.–Jan.	0.92	0.92	0.76	0.54	0.88	0.89	0.83
Feb.	0.81	0.81	0.43	0.08	0.73	0.74	0.57
April	0.72	0.68	0.43	0.29	0.58	0.57	0.49
June	−0.15	0.30	0.10	0.40	0.43	0.26	0.09

Minimum temperatures

Sites	2	3	4	6	7a	9	10
August	0.00	0.04	−0.14	−0.05	–	−0.21	–
Sept.	0.08	0.29	0.24	0.06	–	0.10	–
Oct.–Nov.	0.93	0.86	0.47	0.43	–	0.76	–
Dec.–Jan.	0.84	0.91	0.50	0.35	0.69	0.75	0.61
Feb.	0.86	0.89	0.50	0.22	0.83	0.84	0.70
April	0.84	0.90	0.39	0.22	0.71	0.74	0.50
June	0.74	0.75	0.67	0.72	0.80	0.74	0.71

9 a. m. GMT temperatures

Sites	2	3	4	6	7a	9	10
August	−0.51	−0.47	−0.51	−0.54	–	−0.63	–
Sept.	−0.34	−0.01	0.14	−0.31	–	−0.29	–
Oct.–Nov.	0.91	0.87	0.63	0.57	–	0.82	–
Dec.–Jan.	0.89	0.93	0.66	0.51	0.83	0.86	0.78
Feb.	0.85	0.88	0.42	0.07	0.76	0.78	0.59
April	0.72	0.79	0.32	0.10	0.67	0.66	0.44
June	−0.05	0.03	−0.01	−0.01	0.21	−0.01	−0.03

Table 4. *Correlation Coefficients Between Site 1 and All Other Sites.* All coefficients >0.08 are statistically significant at the 1% level

Sites	2	3	4	5	6	7	7a	8	9	10
August	0.36	0.42	0.05	0.39	0.42	−0.24	–	0.14	0.34	–
September	−0.09	0.21	0.01	0.07	0.07	0.08	–	−0.14	0.17	–
Oct.–Nov.	0.85	0.81	0.54	0.17	0.49	0.46	–	0.55	0.73	–
Dec.–Jan.	0.80	0.86	0.54	0.42	0.36	–	0.71	0.48	0.76	0.61
February	0.89	0.91	0.50	0.55	0.23	–	0.82	0.42	0.84	0.67
April	0.83	0.86	0.45	0.45	0.29	–	0.74	0.32	0.76	0.55
June	0.43	0.60	0.40	0.45	0.61	–	0.67	0.67	0.60	0.40

a higher degree of statistical association between the sites than was observed in August. Later in the summer the coefficients should approach zero again.

The coefficients between site 1 and the sites inside the cave for each sample time period are shown in Table 4. The large sample size means that most of the coefficients are statistically significant at the 1% level even though this may not be meaningful or useful for predictive purposes. In August and particularly in September, there is only a low positive correlation between temperatures outside the cave entrance and those inside supporting the previous conclusion that overall there is little external interaction at this time of year. By November the situation changes with an increase in coefficients, some of which are high. Coefficients above 0.70 with a sample size of over 1 300 are obtained for sites 2, 3, and 9. At all sites, the magnitude of the coefficients has increased with the lowest values at the highest (5 and 6) or most distant sites from the entrance. The effects of cold air incursions along the lowest areas of the cave are apparent. For January and February a similar pattern is maintained though the change of site 7 to 7a and the addition of site 10 has resulted in high correlations at both sites on the slope between the terrace and the path. The diurnal temperature variation recorded outside will produce strong positive coefficients with those sites which also experience some variation; these are the lower sites where cool air flows in at night to affect them.

6. Short-Period Interactions

The figures obtained above when using the full range of values can obscure important relationships resulting from short period interruptions to the normal temperature levels within the cave. In summer and early autumn, cave temperatures are normally fairly stable. On two occasions, major anomalies were experienced. At the end of August, 1989, outside temperatures associated with cool northerly winds fell well below mean values to record air minimum and grass minimum temperatures at Buxton of 4.6° and 1.3° respectively. These are well below mean cave temperatures and so the normal summer-time thermal regime was disturbed. Colder and denser external air, assisted by forced advection, was able to penetrate into the cave. As a result, minimum temperatures on August 28 at sites 2 and 3 near the entrance fell to their lowest values for the month, in both cases more than 4 standard deviations below their mean minimum temperatures. However, the short duration of low temperatures meant that the effect of this incursion did not extend beyond the tunnel area.

The northerly winds, gusting to 30 knots, also had an effect on maximum temperatures. Forced advection into the cave brought external air which was cooler than average for outside temperatures in August, but was warmer than temperatures within the cave. As a result, maximum temperatures in the cave on August 27 and 28 were above average at all sites except the most distant (site 8). Increases were between 2 and 3 standard deviations above the mean maximum temperature for each site. This relationship between low maxima outside the cave and high values inside the cave accounts for the negative, though non-significant, correlation coefficients discussed earlier and shown in Table 3. A more dramatic incident was experienced in early September. On September 7 the wind became northerly with mean hourly speeds above 5 ms^{-1}. At the cave entrance site (1), no distinctive featues were recorded. Temperatures were somewhat below average as would be expected during northerly winds. Inside the cave, marked differences occurred. Both maximum and minimum temperatures increased above their mean values by between 2 and 3 standard deviations at all sites except the innermost (8). The effect was maintained whilst the northerly winds were blowing, though its magnitude declined as the wind strength decreased until the normal pattern became re-established on September 13. At sites 2 and 3, maximum temperatures of 9.5° and 8.0° were recorded respectively. Minimum temperatures were also affected as turbulence would mix the cold air outflow with the warmer inflowing air to modify even path level sites. At site 2, the minimum on September 10 of 8.0° was 3.6 standard deviations above the mean and at site 3 it was 2.8 standard deviations above the mean despite the minimum temperature at Buxton being 0.8° below average for the period.

During winter, cold air incursions were more frequent and form part of the normal thermal regime leading to a decrease in air temperatures within the cave (Table 2). However, the winter was extremely mild so that low minimum temperatures at Buxton were absent. The lowest minimum temperature recorded during observation periods was on April 9 with an air minimum of −3.5° though frost did not penetrate to site 2 in the cave tunnel.

7. Conclusions

Whilst it is clear that mean temperature levels in the cave have similarities with the general model of Wigley and Brown (1976), the pattern differs in detail from the model for a variety of reasons. The nature of the cave system, height of an observation site above the cave floor, distance from the entrance, the temperature difference between outside and inside the cave and external wind speed and direction relative to the cave entrance will all influence the pattern at any specific time. In summer and early autumn when external temperatures are higher than those within the cave there is little interaction except during three particular circumstances: (1) when it is very warm outside, some warmer air can be drawn into the cave above the ouflow of cold air and reach higher parts of the cave system; (2) with strong northerly winds, inward blowing air can overcome the cold air outflow and extend into the cave system. When the temperature of the northerly winds is above the mean cave temperature, the cool exterior air will be warm relative to that inside to produce an inverse correlation in maximum temperatures. The extent of this penetration of warmer air will depend on the duration and strength of the northerly winds; and (3) when outside temperatures fall below mean cave temperature levels, then cold air will flow into the cave reversing the normal summer outflow circulation irrespective of wind direction. In summer this occurs infrequently, but in winter it is the main method of interaction between outside and interior environments for this particular cave. Caves with openings in other directions, especially west or south-west, are more likely to be affected by advectional interchange. Although these detailed results are site-specific, it is probable that the above three conditions required for interaction would be applicable to any single entrance cave system.

The thermal environment in the interior of a cave will show considerable variety depending upon the above mentioned site factors, as well as the nature of the external climate. Through examining the relationships under present conditions, it should be possible to make inferences about the cave environments of former times, assuming that the controls remain the same. Thus the understanding of such aspects of caves as their flora, pollen and spore preservation and archaeological usage can only be obtained through an assessment of these site factors and the extent to which they have differed through time.

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