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Prediction of condensation in caves

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Abstract

Condensation is an important process in karst environments, especially in caves where carbon dioxide enriched air can lead to high rates of condensation corrosion. The problem is there has been very little research reported in the literature dealing with condensation as a microclimate process. This study addresses the problem and reports on a method for measuring and predicting condensation rates in a limestone cave. Electronic sensors for measuring condensation and evaporation of the condensate as part of a single continuous process of water vapour flux are tested and used to collect 12 months of data. The study site is the Glowworm tourist cave in New Zealand. Condensation is a function of the vapour gradient between rock surfaces in the cave and cave air. The size of the gradient is largely determined by air exchange with the outside. The results show that the numerical model to predict condensation works well. Given that rock-surface temperature in the cave does not vary much, condensation is essentially a function of cave air temperature and the processes that affect it, mainly, air exchange with outside. The results show that condensation can be controlled by controlling ventilation of the cave.

Keywords: Condensation, Cave microclimate, Evaporation, Tourist cave management.

Introduction

Condensation is an important process in karst environments, especially in caves. For example, Hill and Forti (1986) cite seven different types of speleothems formed from condensation coupled with the evaporation of condensate. The condensation process plays a variety of roles, but two of these are particularly important. The first occurs where water condensing onto cave walls that are made of a soluble rock mineral (calcite, dolomite, gypsum, halite, carnallite etc.) is undersaturated with respect to the mineral, the potential exists for dissolution to occur. The process is called “condensation corrosion” (Ford and Williams, 1989, p. 309). It may create surface impressions on attractive speleogen features. Water from condensation can cause this because its chemistry makes it aggressive. Carbon dioxide, water and calcium carbonate (limestone or calcite) react to give soluble calcium and hydrogencarbonate ions in water. Condensation water becomes considerably more corrosive if it contains substantial amounts of dissolved carbon dioxide. In tourist or show caves, for example, visitors breathe out warm air saturated with water vapour together with over 4% by volume of carbon dioxide at a temperature usually much higher than the cave air. This air containing high concentrations of carbon dioxide will condense as it comes into contact with the colder surfaces of the cave. The second process occurs during times when condensation water evaporates and carbon dioxide is removed from saturated solutions of calcium and hydrogencarbonate ions causes precipitation of calcite. This process produces soft unattractive microcrystalline, flaky deposits of calcite. This cycle of condensation and evaporation of condensate is believed to enhance condensation corrosion (Tarhule-Lips and Ford, 1998).

Cave resources are essentially non-renewable and human impacts are cumulative and often irreversible (Gillieson, 1996). Increasing cave tourism worldwide presents problems because of this irreversible degradation. Previous work on caves, especially tourist caves, has shown that an understanding of cave microclimate processes is crucial to understanding, managing and protecting the cave ecosystem (de Freitas, 1998; de Freitas and Banbury, 1999), but gaps in understanding certain key processes remain, in particular, those governing condensation. The problem is that there has been very little research reported in the literature dealing with condensation as a microclimate process in caves. Papers by Dublyansky and Dublyansky (1998, 2000) that review the topic confirm this. Explanatory models of causal process are speculative and remain untested. Recently, however, de Freitas and Schmekal (2003) devised a reliable method for measuring condensation and evaporation as part of a single continuous process of water vapour flux. The aim here is to report further on this research, specifically on the method for predicting condensation rates on cave rock surfaces.

Background

The study site is the Glowworm Cave, New Zealand, widely regarded as an attraction of considerable aesthetic and ecological significance. It has one of the highest visitor usage rates of any conservation land in New Zealand. Four times the number of people visit the Glowworm Cave than the next most popular cave in either New Zealand or Australia. For this reason it is considered to be a valuable national resource and one that requires careful management if its attractiveness is to be protected and the resource sustained.

The Glowworm Cave is located in the North Island of New Zealand at latitude 38^{o}15'S, longitude 175^{o}06'E. The region has a subtemperate climate with an average annual rainfall of 1530 mm. Average daily maximum and minimum air temperatures in the warmest month, January, are 24.1 and 12.6 ^{o}C, respectively. Average maximum and minimum temperatures in the coolest month, July, are 13.1 and 3.3 ^{o}C, respectively. The water vapour content of the air is relatively high throughout the year in the region, with a mean vapour pressure of 13 hPa. The cave is situated in a ridge of Oligocene limestone. The area above the cave is a scenic reserve of native vegetation administrated by the New Zealand government agency called the Department of Conservation.

The Glowworm Cave is made up of 1,300 m of interconnected passageways with an estimated volume of approximately 4000 m^3. It consists of three levels - an upper, middle and lower level (Fig. 1). The cave has two entrances, an upper entrance and a lower entrance, 14 m vertically apart. The upper entrance is equipped with a solid door that, when closed, seals the opening preventing airflow. The upper level of the cave consists of the Blanket Chamber and the Blanket Chamber passage. The Blanket Chamber is 40 m long and ranges in diameter from 1 to 4.5 m^2. The Main Passage is a 39 m long section with an elliptical cross-section varying between 3 m^2 and 7 m^2. This passage leads past the Tomo, which connects the lower level (Grotto) and the upper level to the Catacombs, a much larger Chamber (Fig. 1).

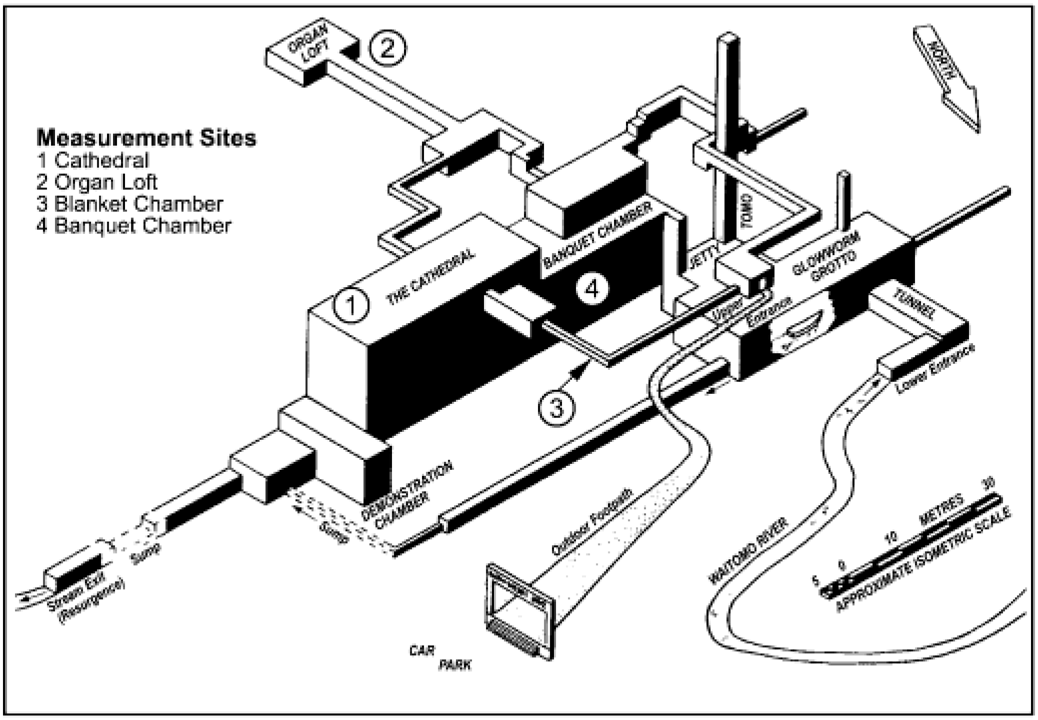

Fig.1. Schematic isometric plan of the Glowworm Cave showing measurement sites and named cave features (from Barthow, 1988).

Another part of the upper level of the cave is the Organ Loft and the Organ Loft Side Passage. The Organ Loft is a cul-de-sac passage. The Banquet Chamber and Cathedral form the intermediate level. The Cathedral is 40 m long, 11 m at its widest and up to 13 m high. It is the largest chamber in the cave and links all chambers. The third level is the Grotto, which is part of the stream passage of the Waitomo River. The Grotto is a large chamber approximately 30 m long and 10 m wide. The Grotto has the main displays of the glowworm (*Arachnocampa luminsosa*) in the cave. From here the stream flows down through a passage and sump and then past the Demonstration Chamber. After this the stream flows for approximately another 180 m before leaving the cave (Fig.1).

Airflow in the cave due to both convectional or gravitational forces (de Freitas *et al*., 1982) and this airflow is a key component of a cave's climate (de Freitas and Littlejohn, 1987). The speed and direction of flow is determined by the difference of mean density of the outside and inside air (de Freitas et al, 1982). Since air density is mainly a function of air temperature, the latter can be used as the main indicator of airflow (de Freitas *et al*., 1982). When the outside air is cooler and thus denser than the cave air, the warmer cave air rises and flows towards and then through the Upper Entrance and replaced by cold air at the Lower Entrance. This process, driven by convection, is called "winter" flow. In contrast, "summer" flow occurs when cave air is cooler and denser than the air outside the cave. The flow of air is driven by gravity through the cave and out the Lower Entrance (de Freitas *et al.*, 1982). In transitional times where the temperature gradient inside and outside the cave is small, there is little or no airflow.

Method

Modelling condensation

Condensation *per se* is a dynamic process of moisture flux that involves both condensation and evaporation of the condensate, depending on the direction of the vapour gradient between the air and moist surface. When the amount of condensation over a given period exceeds the evaporation of condensate over that same period, condensation is observed to have occurred. Condensation water will accumulate if this condition re-occurs, otherwise it will dissipate. In the case of caves, the flow is to or from the surface of cave walls and features in the cave. The assumption is that at the surface there is a boundary layer of air that is saturated and has the same temperature as the surface. This boundary layer interacts with the surrounding air causing condensation or evaporation of condensate in a dynamic relationship that is driven in large part by the vapour gradient. The moisture flux across this gradient - strictly speaking the resistance to the diffusion of vapour across the boundary layer - is controlled by the rate of air movement and the roughness of the surface (Monteith, 1957), collectively referred to here as the combined convection moisture transfer coefficient. Condensation occurs when the dewpoint temperature of the cave air is higher than the temperature of the rock surface. However, to quantify the movement of a mass of water vapour, specific humidity rather than dewpoint temperature must be used. The rate of condensation (C) is given as:

$$C = (q_r - q_a)\, k_v \qquad (1)$$

where C is rate of condensation (g m^{-2} s^{-1}), q_a is specific humidity of the air (g kg^{-1}), q_r is saturation specific humidity at surface temperature (g kg^{-1}), k_v is the combined convective water vapour transfer coefficient. Specific humidity terms q_a and q_r are a function of vapour pressure and can be calculated from Neiburger *et al*. (1982):

$$q_r = 0.622\, e_{sr} \qquad (2)$$

$$q_a = 0.622\, e \qquad (3)$$

where e_{sr} is saturation vapour (hPa) pressure at rock-surface temperature and e is vapour pressure of air (hPa). Vapour pressure and saturation vapour pressure terms can be found using any of number of formulae as, for example, from Grace (1983):

$$e = e_s - 0.666(T_{db} - T_{wb})\, P \qquad (4)$$

where e_s is saturation vapour pressure of the air (hPa), T_{db} is dry bulb temperature (^oC), T_{wb} is wet bulb temperature (^oC) and P is atmospheric pressure (hPa). Saturation vapour pressure is:

$$e_s = \exp[a+(b\,T - c)/(\,T - d)] \qquad (5)$$

where a is 1.80956664, b is 17.2693882, c is 4717.306081, d is 35.86 and T is air or surface temperature (K). However, where vapour gradients are very small, as is frequently the case in cave environments, more precise formulae are required for the calculation of vapour pressure and saturation vapour pressure, such as provided by Jensen (1983).

The combined convective water vapour transfer coefficient, k_v, is a function of air movement and surface roughness (Pedro and Gillespie, 1982; McAdams, 1954). Compared to the boundary layer outdoors, surface roughness is relatively constant in most caves. In an open environment where wind speed varies greatly and can reach much higher levels than in caves, wind is an important variable. In caves, however, airflow is limited and rate of flow in the case of the Glowworm Cave is extremely low. As a consequence, variability is small. With this in mind, de Freitas and Schmekal (2003) show empirically that k_v = 3.7 kg m^{-2} s^{-1} in equation (1) fits well with observations of C regardless of the location within the cave.

Measuring condensation

De Freitas and Schmekal (2003) devised a novel method for measuring the vapour flux to and from a surface using what they called "condensation sensors". They are simple to construct and their size can be customised so it is possible to install them on uneven surfaces such as a cave wall. The condensation sensors consist of an electrical grid of two sets of parallel wires mounted on a circuit board. When condensation occurs or evaporation of the condensate takes place on the sensor's surface, the resistance between the wires changes. To provide greater sensitivity, the wiring consisted of multiple fingers of interleaved conductive tracks made of copper (Fig. 2). Sensitivity can be altered by varying the number of conductors.

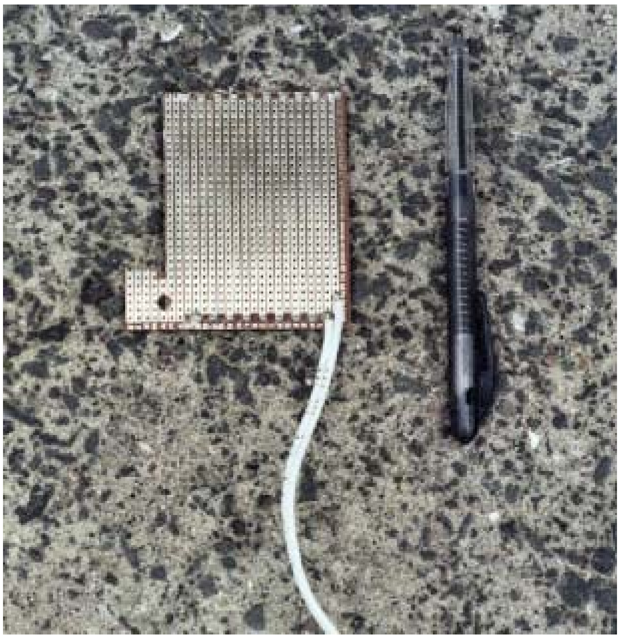

Fig. 2. Condensation sensor.

To obtain rates of condensation, conduction readings have to be converted to equivalent vapour fluxes. To do this the sensor are weighed when dry and the conductivity reading set at zero. Using an atomiser, very fine drops of water were sprayed onto the sensor in stages and weighed at each step (de Freitas and Schmekal, 2003). The sensors showed no influence of ambient temperature over the range tested (10.0°C – 20.0°C).

Data collection

Data were assembled using a fully automated system of sensors and recorders and supplemented by direct measurement using hand-held instruments. Automated measurements were made of wet (T_{wb}) and dry bulb (T_{db}) air temperature, rock temperature (T_r), and airflow rate and direction. Wet and dry bulb temperatures (Campbell 107B thermistors) were measured at the Tomo, Banquet Chamber and at the Jetty. Another dry bulb thermister and humidity sensor (Vaisala Hummitter 50Y) was installed outside the cave. Readings were recorded every thirty minutes by a data logger (Campbell CR10). Rate of airflow and direction into and out of the cave are measured using a sensitive Pulse Output Anemometer (A101M) and an airflow direction sensor (Potentiometer Windvane W200P). The airflow instruments were located in the entrance area, just inside the cave door. An electronic sensor records periods when the entrance-door is open and airflow readings are taken every three seconds. The data logger then records the maximum wind speed for each one-minute interval, and these are then averaged for the length of the time the entrance-door is open. Rock temperature was measured using a thermister (Campbell 107B). Internal rock temperatures give an indication of trends in the longer-term thermal state of the cave, as well as the direction of heat flow to and from the rock-surface (de Freitas, 1998). Rock temperatures are measured at the Tomo recorded every six hours.

To sample more extensively through the cave, direct measurements were made using hand held instruments. Wet bulb temperature and dry bulb temperature were measured using a full-sized Assmann Psychrometer (Casella, Type 8900/1). The instrument can be read with accuracy to a resolution of 0.1 ^{o}C. From these data, saturation vapour pressure, humidity and dew-point temperature were determined using the procedure described earlier. For detailed measurements of airflow in various parts of the cave, a Dwyer hot-wire anemometer (Series 470), accurate to 0.05 m s^{-1}, was used. Rock-surface temperatures were measured using a portable electronic instrument (Ultrakust, Type 4444-1B) and probe especially designed for measuring surface temperature of flat, solid objects. The flat temperature-sensing element of the probe is covered with an insulating epoxy and fibreglass resin attached to Teflon insulated leads to protect it from the thermal influences of air when it is pressed against the surface to be measured. The sensor is a small thermister pearl of high thermal-conductivity material (silver and gold) so that short response times and small heat capacity are achieved. Accuracy of the instrument is better than 0.1 ^{o}C with a full-scale response time of four seconds. Two readings were taken with the Ultrakust instrument at the condensation measurement sites described below. One reading was of the surrounding cave wall and the second reading of the "dummy" metal plate used to check that sensor surface temperatures were the same as rock-surface temperatures.

To ensure that the assembled data was characteristic of the cave as a whole, four measurement sites were selected that represented different parts of the cave, namely the Organ Loft (deep cave), Cathedral (cavernous interior), the Banquet Chamber (transitional zone) and Blanket Chamber (near entrance zone). The locations of these sites are shown in Fig. 1. The Organ Loft is a cul-de-sac passage. Here there is little air exchange with the outside and conditions are stable. The Cathedral site is also within the deep cave zone, but in this case along the main airflow route. This area is also the biggest chamber in the cave. The Banquet Chamber is within the transitional zone and like the Cathedral site is in the main airflow route. The fourth site was in the Blanket Chamber, which represents an area where the cave air can readily interact with the outside air. Four condensation sensors were installed at each measurement site on a vertical portion of the cave wall 900 mm above the floor and attached to four dedicated Campbell Scientific CR 10 data loggers. Readings were taken every five seconds and recorded as 10-minute averages. Measurements were taken over a 13-month period from December 1999 to December 2000.

Results

To assess the performance of the model, the difference between observed rates of condensation (C_o) and calculated values (C_c) were tested using Pearson's product moment correlation (r^2). The sample size is 750. The mean difference between C_c and C_o is 0.062 g m^{-2} h^{-1}and the standard deviation 0.165 g m^{-2} h^{-1}. The correlation coefficient is 0.97 (Fig. 3). Overall the results show that the model performs well.

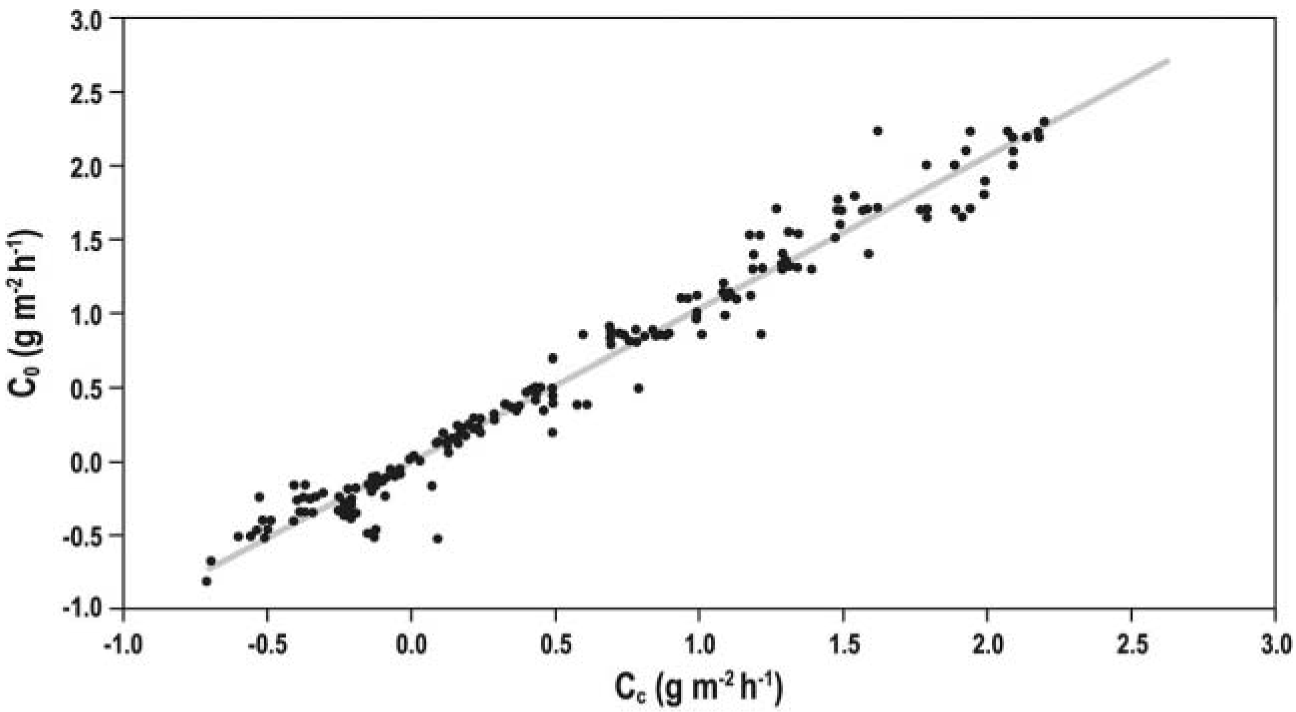

Fig. 3. A comparison of calculated and observed condensation rates, C_c and C_o respectively (g m^{-2} h^{-1}). The standard deviation is 0.165 g m^{-2} h^{-1}, the correlation coefficient r^2 is 0.97 and the sample size is 750. Note that over plotting of data points occurs frequently because condensation rates change only very gradually over time.

Next, the data were examined to assess the influence of outside conditions on condensation rates. Since rock-surface temperature is relatively stable, cave air temperature is the main factor that influences condensation rates. Cave air temperature is jointly determined by outside air temperature and cave ventilation rate, which is itself a function of outside air temperature. While temperature fluctuations outside the cave are much larger (0.2°C to 28.1°C) than inside the cave (12.4 °C to 18.9 °C), they both tend to follow the same pattern. Figures 4 and 6 are typical examples of this. It follows that, as outside air temperature influences the cave climate, the different outdoor thermal conditions play a vital role in condensation rates. In general, when it is warm outdoors q_a exceeds q_r during the daytime and condensation occurs. When temperatures are low outside, q_a is in general lower than q_r and no condensation occurs. The closing and opening of the entrance-door can be used to control airflow through the cave and consequently cave air temperatures.

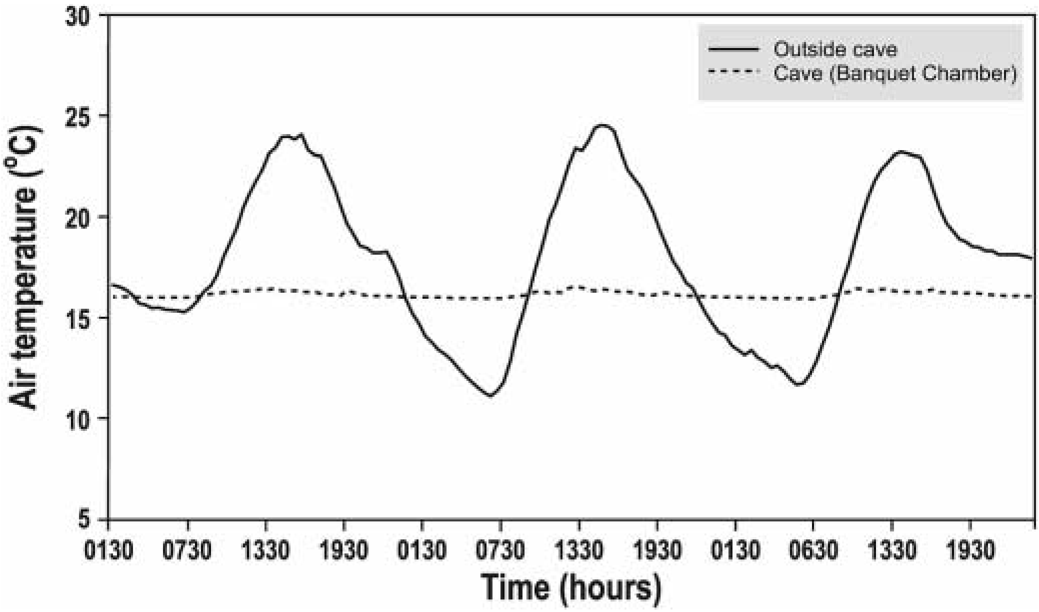

Fig. 4. Air temperature in the cave at the Banquet Chamber site and outside the cave during the closed-door experiment, 23-26 February 2000.

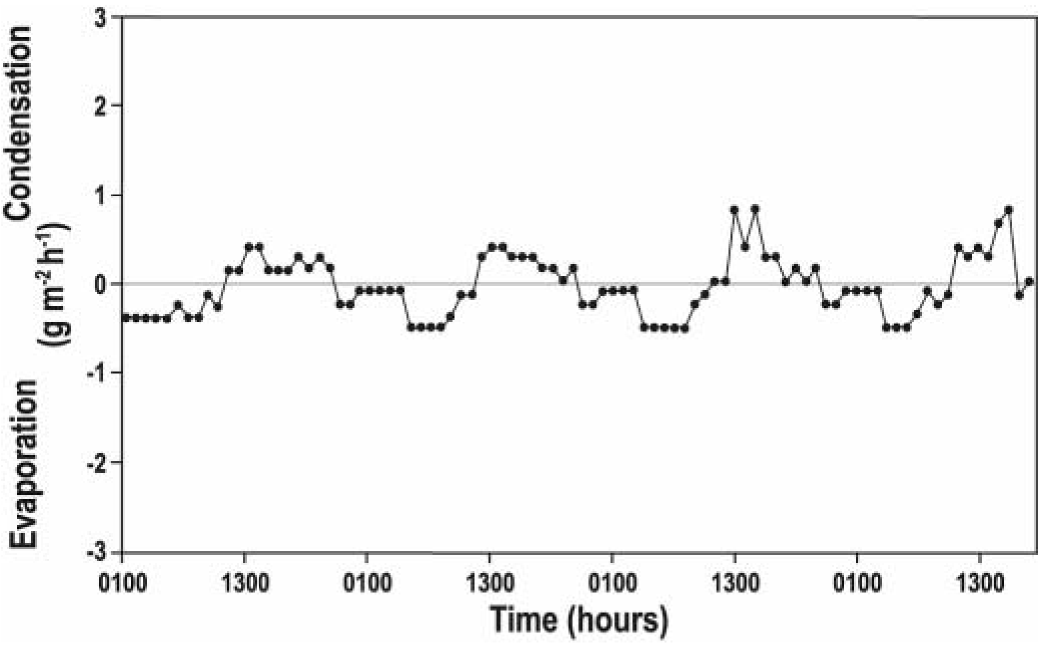

Fig. 5. Results of closed-door experiment for the Banquet Chamber site showing condensation and evaporation rates. The entrance door was closed from 18:00 h on 22 February 2000 to 09:00 h on 26 February 2000.

With above in mind, two experiments were conducted to determine what influence the exchange of cave air with outside air has on condensation rates. In the first experiment, the solid cave entrance-door remained closed for 85 hours, thereby minimising cave ventilation. The door was opened for two-to-three minutes about twice an hour during the business day (0900 to 1730 h) to give entry to tour groups. In the second experiment, the solid door at the upper entrance was left open continuously for 87 consecutive hours, thus facilitating continuous air exchange with the outside. Conditions in the cave are represented by measurements taken at the Banquet Chamber site (Fig. 1). Thermal conditions inside and outside the cave during these experiments are shown in Figures 4 and 6. The effects on condensation are shown in Figures 5 and 7. On both occasions airflow in both directions through the cave was recorded. When outside temperatures were lower than the cave air temperatures, upward flow occurred and the cave cooled. When the outside temperature was higher than cave air temperatures, downward flow took place and a warming of cave air occurred. In Figures 5 and 7, a rising trend indicates that condensation ($C_{(+ve)}$) is occurring while a downward trend indicates that evaporation of condensate ($C_{(-ve)}$) is taking place.

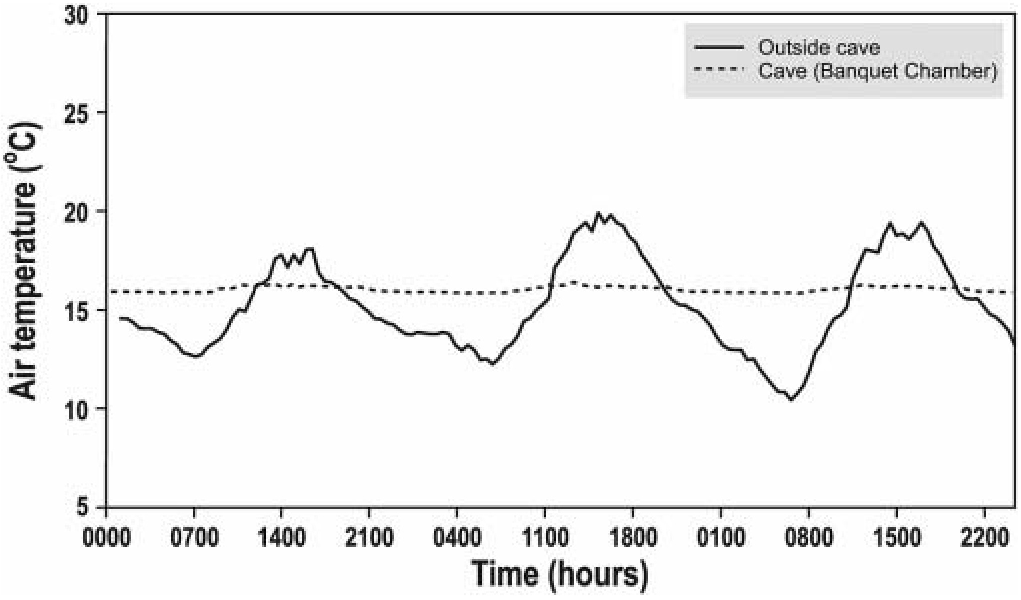

Fig. 6. Air temperature in the cave at the Banquet Chamber site and outside the cave during the open-door experiment, 2-5 March 2000.

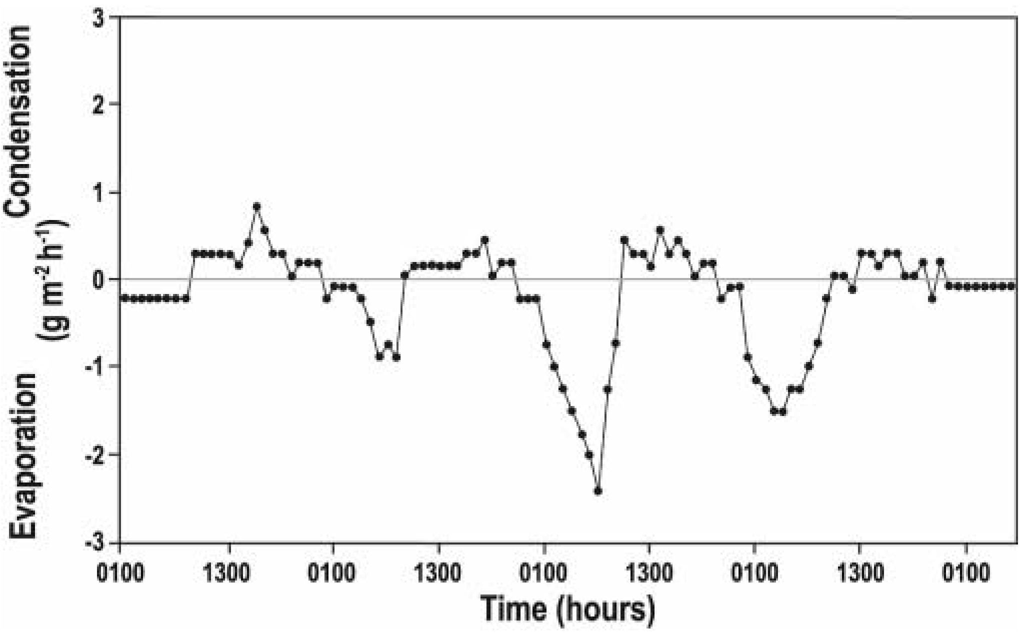

Fig. 7. Results of the open-door experiment for the Banquet Chamber site showing condensation and evaporation rates. The entrance door was kept open from 09:00 h on 2 March 2000 to 18:00 h on 5 March 2000.

In the door-closed experiment (Figures 4 and 5) airflow through the cave was kept to a minimum, despite a strong cave-to-outside thermal gradient (Fig. 4). The results show a small vapour flux hovering just above and just below zero (Fig. 5). A near equilibrium moisture balance was sustained over the period: $C_{(+ve)} = 10.3$ g m^{-2}, $C_{(-ve)} = 9.9$ g m^{-2}. In the door-open experiment (Figs. 6 and 7) evaporation rates in the cave are up to five times larger than on nights when the entrance-door was shut (Figs. 4 and 5). The largest evaporation rate was recorded on the third day of the door-open experiment at 0700 h, when the temperature dropped to 14.8 C in the Banquet Camber and evaporation rose to 2.41 g m^{-2} h^{-1} (Fig. 7).

Generalised statements can be made about controls on cave microclimate. In conditions where outside air are warmer than the cave air, the relatively cool cave air drains from the cave via the lower entrance and is replaced through the upper entrance by warm outside air (de Freitas *et al*., 1982). As the air moves deeper into the cave it is cooled more, reducing its moisture holding capacity further which causes more condensation. Condensation occurs when the dewpoint temperature of the air is equal to or greater than the dewpoint temperature of the surface boundary layer of the cave rock. During conditions in which outside air is cooler than cave air, the process is reversed. Cool and relatively dry air enters the cave through the Lower Entrance. There is an immediate transfer of sensible heat and vapour into the colder air because of the large heat and vapour gradient. Evaporation then occurs. The further the air moves into the cave, air temperature increases and the heat and vapour gradient decreases until equilibrium is reached with the cave environment (de Freitas *et al*., 1982). If the air is saturated, an increase in temperature increases its moisture holding capacity and further evaporation occurs. This is the reason why significant amounts of evaporation can occur even when relative humidity reaches 100 per cent (de Freitas and Littlejohn, 1987).

Conclusions

Condensation is an important atmospheric environmental process but it has been neglected in climate research, especially in cave microclimatology where condensation is recognised as a vital component of the cave environment. It is important because the condensation/evaporation process leads to weathering of cave surfaces. Water vapour loaded with carbon dioxide condenses on the limestone or calcite leading to corrosion, while evaporation leaves residual flaky, unsightly deposits of calcite. High carbon dioxide levels in the cave brought about by the presence of large numbers of visitors may exacerbate this. Also, air exchange with the outside and, therefore, the potential for condensation and evaporation, is affected by air movement to and from the cave through entrances. However none of this can be reliably assessed, and then if necessary controlled, until amounts and rates of condensation-evaporation can be predicted and the processes that determine them understood.

Here the nature and performance of an explanatory model of processes leading to condensation is described using data based on measurements of condensation and evaporation as part of a single continuous process of water vapour flux. The results show that the model works well. Condensation is a function of the vapour gradient between rock surfaces in the cave and cave air. The size of the gradient is largely determined by air exchange with the outside. Given that rock-surface temperature in the cave does not vary much, condensation is essentially a function of cave air temperature and the processes that affect it, mainly, air exchange with outside. The results show that condensation can be controlled by controlling ventilation of the cave, in this case, by opening or closing the entrance-door. By facilitating ventilation during warm conditions outside, condensation occurs and condensation rates rise as air temperatures rises. During cooler conditions outside or at night, the cave ventilation leads to evaporation and cave drying. To increase condensation rates, ventilation needs to be encouraged (cave entrance-door opened) whenever outside temperatures are higher than cave air temperatures; downward "summer" flow will then occur, the cave air will warm up, and rates will increase. To reduce condensation rates or induce negative rates (evaporation and cave drying), the cave entrance-door needs to be kept open when outside air temperatures are lower than the cave air temperature. During the cold months, as cave air temperatures are lower than rock-surface temperatures, condensate evaporates because the vapour flux is away from the rock surfaces. Generally speaking, only very small to nil rates of condensation occur during the cold months. Condensation rates will only increase during mild winter days when outside temperatures exceed cave air temperatures. To increase condensation at these times, the solid upper entrance-door should be opened.

The results provide insight into the environmental effects of management induced changes, but there is need for more work on caves in other climate regimes. Future research should also aim to develop an understanding of the role of condensation in the water and energy balance of caves, especially large systems. Other work might focus on spatial variation of condensation through large caves and factors that affect the geochemical composition of condensate.

Acknowledgements

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References

Barthow D.C. 1988. The Waitomo Glowworm Cave. In Crossley P (ed). *The New Zealand Cave Atlas: North Island*. New Zealand Speleological Society, Occasional Publication No. 6: Waitomo, 287.

De Freitas C.R. 1998. Cave monitoring and management: The Glowworm Cave, New Zealand. In: *Cave and Karst Management in Australasia XII. Proceedings of the Twelfth Australasian Conference on Cave and Karst Management*, Waitomo, Australasian Cave and Karst Management Association, Carlton South, Victoria, 55-66.

De Freitas C.R. and Banbury K. 1999. Build up and diffusion of carbon dioxide in cave air in relation to visitor numbers at the Glowworm Cave, New Zealand. In: *Cave Management in Australasia XIII*. Proceedings of the Thirteenth Australasian Conference on Cave and Karst Management, Mount Gambier, South Australia. Australasian Cave and Karst Management Association, Carlton South, Victoria, 84-89.

De Freitas C.R. and Littlejohn R.N. 1987. Cave climate: assessment of heat and moisture exchange. *International Journal of Climatology,* **7**: 553-569.

De Freitas C.R. Littlejohn R.N., Clarkson, T.S. Kristament IS 1982. Cave climate: assessment of airflow and ventilation. *International Journal of Climatology* **2**: 383-397.

De Freitas, C.R. and Schmekal, A.A. 2003. Condensation as a microclimate process: Measurement, numerical simulation and prediction in the Glowworm Tourist Cave, New Zealand. *International Journal of Climatology* **23** (5), 557-575.

Dublyansky V.N. and Dublyansky Y.V. 1998. The problem of condensation in karst studies. *Journal of Cave and Karst Studies* **60** (1): 3-17.

Dublyansky V.N. and Dublyansky Y.V. 2000. The role of condensation in karst hydrogeology and speleogenesis. In: A.B Klimchouk D.C., Ford A.N. Palmer & W. Dreybrodt *Eds*: *Speleogenesis, Evolution of Karst Aquifers*: Huntsville, National Speleological Society: 100-112.

Ford T.D. and Williams P.W. 1989. *Karst Geomorphology and Hydrology*. Unwin Hyman: London.

Gillieson D. 1996. *Caves: Processes, Development, and Management*. Blackwell, Oxford, 324pp.

Grace J. 1983. *Plant-Atmosphere Relationships.* Chapman Hall, London, 92 p.

Jensen D. 1983. Computer simulation of an aerological diagram. *Meteorology Australia*. **3** (2): 13-16.

Monteith J.L. 1957. Dew. *Quarterly Journal of the Royal Meteorological Society* **83**: 322-341.

Neiburger M., Edinger J.G. and Bonner W.D. 1982. *Understanding Our Atmospheric Environment* (second edition). W.H. Freeman and Company, San Francisco.

Pedro M.J. and Gillespie T.J. 1982. Estimating dew duration. I. Utilizing micrometeorological data. *Agriculture Meteorology* **25**: 283-296.

Tarhule-Lips R.F.A. and Ford D.C. 1998. Condensation corrosion in caves on Cayman Brac and Isla de Mona. *Journal of Cave and Karst Studies* **60** (2): 84-95.