Karst micrometeorology of two caves on the Loser Plateau, Northern Calcareous Alps, Austria – Initial results

ZUSAMMENFASSUNG

Im Sommer 2007 begann die Cambridge Austrian Cave Science Expedition (CASCE) ein Programm zur Erfassung der Wärmeströme in der tageszeitlich heterothermischen Zone zweier Höhlen auf dem Loser Plateau (Totes Gebirge, Österreich), der Rundreisehöhle (1623/253) und der Steinbrückenhöhle (1623/204). Dabei wurden die relativen Beiträge von diffusivem, advektivem (Luftströmung) und latentem (Kondensation und Verdunstung) Wärmefluss untersucht. Während drei Beobachtungswochen wurden in der Rundreise- und Steinbrückenhöhle 105.500 bzw. 64.000 Temperaturdatenpunkte, sowie meteorologische Daten an der Oberfläche erfasst. Die große Eindringtiefe des Tag-Nacht-Temperaturwechsels in den beiden Höhlen weist auf einen Wärmefluss hin, der die diffusive Wärmeleitung um mehrere Größenordnungen übersteigt. Dies legt nahe, dass stattdessen advektive und/oder latente Prozesse die Hauptrolle spielen. In den Eingangsbereichen der Steinbrückenhöhle wurden bis zu 228,6 Liter Kondensationswasser gemessen (0,34 l m^{-2} Höhlenwand), was auf einen möglichen maximalen Wärmefluss von 555,6 kJ pro Tag^{-1} an den betroffenen Wänden hindeutet.

ABSTRACT

An ongoing micrometeorological program was initiated in the summer of 2007 by the Cambridge Austrian Cave Science Expedition (CASCE) with the intention of characterizing the heat flux into the diurnal heterothermic zone of two caves on the Loser plateau in the Totes Gebirge mountains, Rundreisehöhle and Steinbrückenhöhle. The relative importance of the diffusive, advective (airflow), and latent (condensation and evaporation) components of that flux were examined. Three weeks of intensive monitoring resulted in 105,500 temperature data points in Rundreisehöhle and 64,000 in Steinbrückenhöhle, as well as surface meteorological data. The long penetration distance observed for the diurnal temperature cycle into the caves implies an entrance heat flux several orders of magnitude greater than could be explained by diffusive processes alone, suggesting dominance of advective and / or latent processes. Up to 228.6 litres of condensation was present in the Steinbrückenhöhle entrance areas at peak periods (0.34 l m^{-2} of cave wall), representing a potential maximum heat flux to the affected walls of 555.6 kJ day^{-1}.

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INTRODUCTION

An understanding of subsurface atmospheric conditions is vital for nearly every cave-related investigation. Cave climate is largely forced by surface conditions, in a complicated and nonlinear manner (Fig. 1). The speleogenesis of a cave, the development of calcite formations (Dreybrodt et al., 2005), the cave's ability to act as an archive of climate history (e.g. (Spötl et al., 2005; Baker et al., 2007; Fairchild & McMillan, 2007) or a habitat for unique species of life (Chapman, 1993) are all dependant on the cave's climate. Even archaeological and anthropological studies often require knowledge of how the cave atmosphere responds to surface climates for understanding the preservation of rock art and artifacts (Hall et al., 2007).

Previous research into external atmospheric influences on cave conditions has highlighted processes which are affected heavily by climatic variations with latitude and altitude. In the particular setting of the Loser plateau karst climate investigation (47°N, 1730 m above sea level, July through August), Dublyansky &

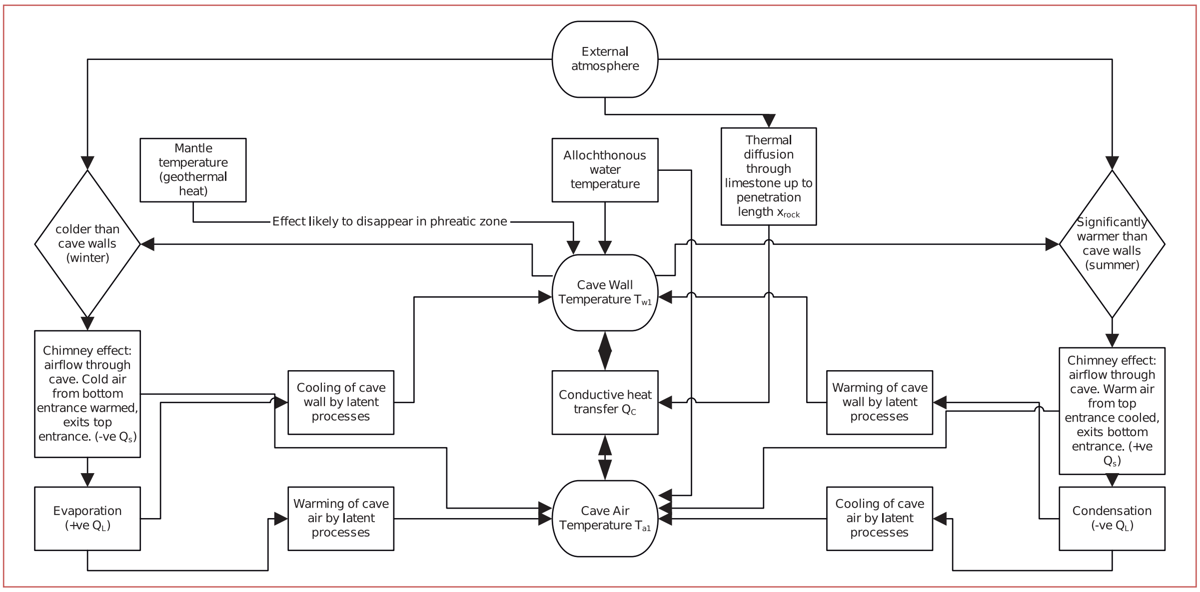

Fig. 1: Schematic overview of major processes acting in cave climates.

Schematischer Überblick über die wesentlichen Höhlenklima-Prozesse.

Dublyansky (1998) predict high rates of condensation – up to 12 g of condensate for each m³ of air transported through the cave. Recognizing this, the primary purpose of the investigation is to characterize the daily summer heat flux into caves in terms of the relative magnitude of its components, including diffusive, convective, and latent processes.

The flux characterized here, Q_{Tot}, is the daytime summer flux into the diurnal heterothermic zones of the caves. The diurnal heterothermic zone is defined as the area of cave in which a 24-hour temperature periodicity is detectable and is analogous to the (seasonal) heterothermic zone discussed by Luetscher & Jeannin (2004). Q_{Tot} is normal to the boundary surface of the diurnal heterothermic zone air mass. This includes the boundary surface between cave walls and the cave air mass as well as the midair boundary surface at cave entrances which separates the external air mass from the internal air mass. Q_{Tot} is expected to be the sum of several component fluxes:

- Flux across boundary layer between external air and internal air (”dripline“ plane of cave entrance)
  - Advection of air through entrance; replacement of cave air mass by chimney effect: Q_S.
  - Diffusive and radiative flux from external air mass to internal air mass. Both assumed to be negligible.
- Flux across boundary layer between cave walls and internal air mass
  - Flux from cave air to cave wall driven by condensation: Q_L.
  - Diffusive and radiative flux from cave wall to cave air. Referred to here as Q_C.
- Flux from meteoric water to internal air mass
  - Assumed to be negligible in Rundreisehöhle and Steinbrückenhöhle because they are fossil cave systems with no significant streams in the upper 500 m (Luetscher et al., 2008).

The relative importance of these components is assessed here using data from simultaneous datalogged measurements of cave and surface atmospheric variables, as well as visual observation of condensation by a team of cavers. Q_C is determined to be a small component of the overall flux by demonstrating that the daily cycle penetration length through rock predicted by literature values for thermal diffusivity of limestone x_{rock} is miniscule compared to the penetration length observed in our cave air masses. Therefore, although we did not directly measure Q_C, we were able to shows that Q_C is irrelevant because the magnitude of heat transfer through limestone is negligible for the daily cycle. Evidence that Q_C alone is a very small component of heat transfer through the caves leads to a discussion of airflow through the cave and the ”chimney effect“ (Michie, 1997), representing Q_S. Likely latent heat flux (Q_L) is addressed through visual observation of condensation. Existing theories are critically evaluated in the light of our data, to develop a conceptual model of heat transfer with empirical limits based on our observations.

Although there are 172 caves accessible from the expedition Top Camp (listed at *http://cucc.survex.com/expo/smkridge/*), two caves were identified in which diurnal heterothermic zone microclimatic processes could be isolated; Rundreisehöhle and Steinbrücken-

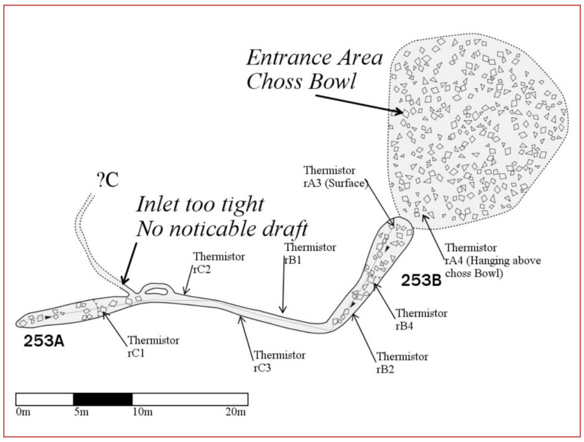

Fig. 2: Survey of Rundreisehöhle (1623/253), annotated with sensor placements for data collection. 253a and b are entrances, and ?C denotes an extremely tight passage which has not been explored. Arrows designate slope; they point downhill. Weather station was placed on the surface above 253b. North is up, see Fig. 3 for legend.

Plan der Rundreisehöhle (1623/253) mit Lage der Temperatursensoren. Die Nummern 253a und b bezeichen Höhleneingänge und ?C ist eine extreme Engstelle, die noch nicht erkundet wurde. Kleine Pfeile im Höhlenplan geben die Richtung des Gefälles an. Die Wetterstation befindet sich an der Oberfläche oberhalb von 253b. Norden ist oben. Legende siehe Fig. 3.

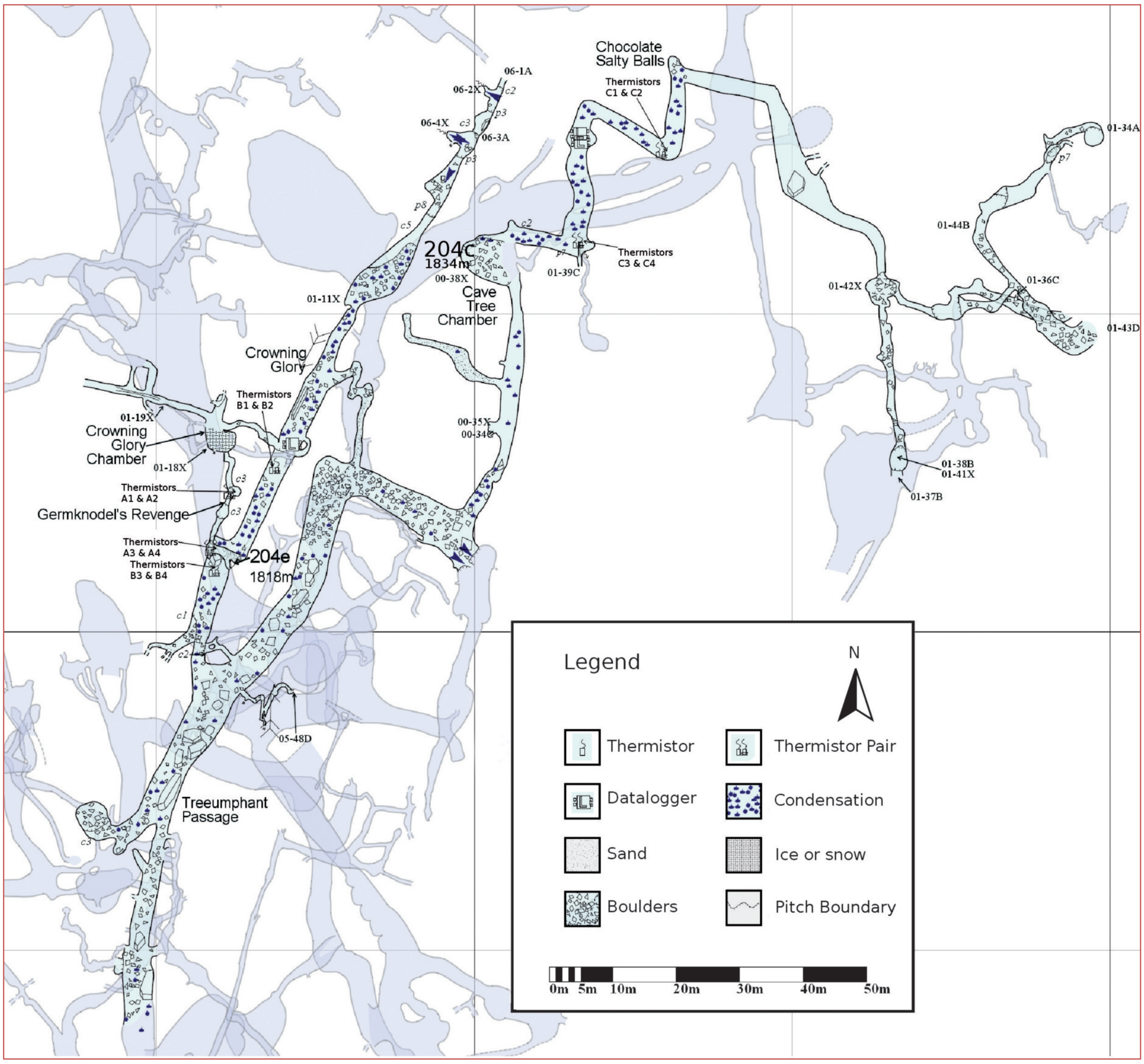

Fig. 3: Survey of Steinbrückenhöhle (1623/204), annotated with sensor placements for data collection, and extent of observed condensation. The relevant entrances are marked 204e and 204c. Note that 204e does not connect directly to the wide passage below, but connects via Crowning Glory Chamber. 204c is an aven which connects Cave Tree Chamber to the surface.

Plan der Steinbrückenhöhle (1623/204) mit Lage der Temperatursensoren und räumlicher Verbreitung von Kondensation. Die Nummern 204e und 204c bezeichen Höhleneingänge. Man beachte, dass 204e keine Verbindung zum großen Gang unterhalb, sondern zur Crowning Glory Chamber besitzt. 204c ist ein Schacht, der eine Verbindung von der Cave Tree Chamber zur Oberfläche herstellt.

höhle. Rundreisehöhle was selected for its simple geometry. It stands alone in the area as the only cave of over 10m length with exactly two entrances. It is a simple ”tunnel“ of 25 m length, with one entrance at each end, running almost exactly east to west (Fig. 2). It can be treated as a single airflow pathway with relatively little leakage to or from side passages. Steinbrückenhöhle, on the other hand, is a complex cave system in which exploration is ongoing. In Steinbrückenhöhle, research and exploration trips could be combined. Two transects near entrances (Fig. 3), each approximating a single airflow pathway with no major turnoffs, were monitored for temperature using HOBO TMC50-HD thermistors connected to U12-H008 dataloggers, with temperature recorded once every two minutes. In Rundreisehöhle, thermistors (labeled A3, A4, B1, B2, B4, C1, C2, C3), were placed roughly every three meters along the cave. A Campbell Scientific weather station with a CR10 datalogger was installed on the surface near Rundreisehöhle, recording windspeed and direction, relative humidity, and temperature. All thermistor locations were surveyed to (BCRA grade 5). Attempts to record cave airflow and high-resolution humidity were unfortunately unsuccessful due to malfunction and breakage of equipment. Table 1 summarizes what data was acquired, when and where.

Tab. 1: Data collection scheme / Datenerhebung

Instruments	From	To	Useful for study of
Rundreisehöhle			
Dry bulb thermistors (10)	15-Jul	30-Jul	Penetration length
	17-Jul	30-Jul	Penetration length, Wind forcing
Easysense 100 datalogger (barometric pressure, temperature, RH)	15-Jul	30-Aug	N/A (data lost due to underpreforming battery)
Steinbrückenhöhle: E entrance and Crowning Glory			
Wet / dry thermistor pairs (3)	4-Aug	14-Aug	Penetration length
Surface weather station			N/A (data lost due to faulty battery contact)
Observant cavers and digital cameras	6-Jul	18-Aug	Condensation droplets
Steinbrückenhöhle: CSB area			
Wet / dry thermistor pairs (4)	4-Aug	14-Aug	Humidity / Condensation
Observant cavers and digital cameras	6-Jul	18-Aug	Condensation droplets

An overview of the data collection scheme. Does not include the micropsychrometer or sonic anemometer, which both failed to produce useful data during the study period due to malfunction and breakage.

Überblick über das Messprogramm (ohne den Mikropsychrometer und das Ultraschall-Anemometer, welche beide nicht funktionierten).

DIFFUSIVE HEAT TRANSFER (Q_C)

If the cave is modeled as rock, we would expect a sinusoidal temperature cycle over time at any point at which decreases in amplitude with distance into the rock (Oke, 1996). Longer period cyclicities (such as seasonal or even glacial cycles) would be expected to cause the same amplitude signal further into the cave. For each period length, there is a distance at which the amplitude is effectively zero. This is referred to as the “penetration length,” x_{rock}, commonly defined as

$$x_{rock} = \sqrt{\frac{\alpha}{\pi}\tau}$$

where a is conductive thermal diffusivity (in $m^2\ s^{-1}$) of the limestone, and ô (in s) is the period of the forcing cycle and x_{rock} is in units of m (Holman, 1996 in Badino 2004). This is similar to Oke’s (1987) calculations for the ”depth of zero annual range.“

Taking only diffusive heat transfer through cave walls into account, we can use values for a obtained for limestone through laboratory analysis, around 1.0×10^{-6} $m^2\ s^{-1}$. Using this value, the daily cycle should disappear only 0.17m into the rock, and annual (8760 hours) influences should disappear 3.16 m into the rock. Moore and Sullivan (1997, in Pflitsch & Piasecki, 2003) empirically measured slightly longer penetration lengths through real rock, saying that a 30°C daily amplitude is reduced to < 1°C at 57 cm into limestone. To detect and quantify periodic trends, the timeseries data for each thermistor probe was subjected to a Fourier-transform based spectral analysis using the XLStat statistics package for Excel, along with the contemporaneous external temperature timeseries from the weather station which was at the surface.

For Rundreisehöhle, the signals are shown in the time domain in Fig. 4. A visual appraisal of the plot suggests

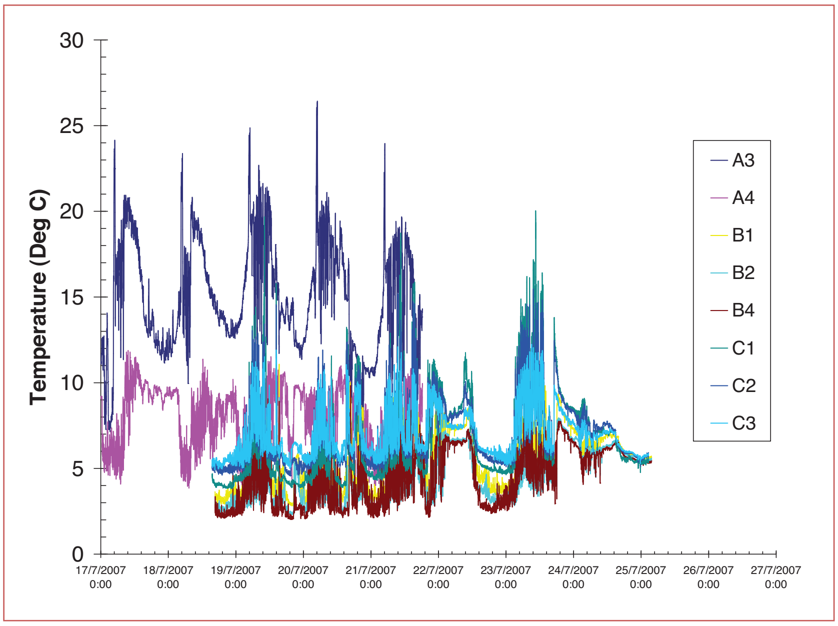

Fig. 4: Temperature in Rundreisehöhle from eight thermistors. See Fig. 5 for spectral analysis.

Temperatur in der Rundreisehöhle anhand von acht Temperatur - sensoren. Siehe Fig. 5 für eine Spektralanalyse der Daten.

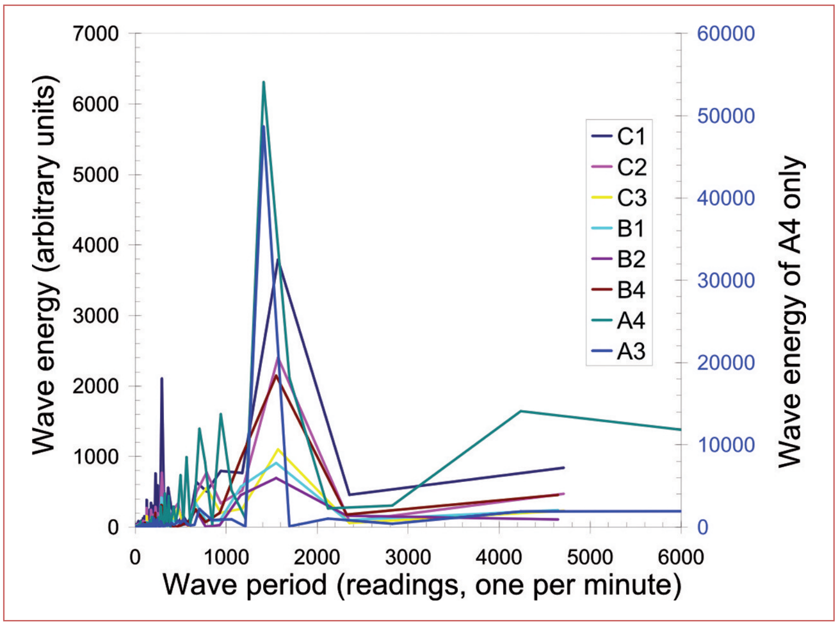

Fig. 5: Fourier transform of Rundreisehöhle temperature timeseries. Time domain shown in Fig. 4.

Fourier Transformation der Temperatur-Zeitreihe aus der Rundreisehöhle. Der analysierte Zeitabschnitt ist in Fig. 4 ersichtlich.

that there are regular, but very noisy peaks, on the diurnal scale. However, there is a clear anomaly from the beginning of the 22 July until the beginning of the 23 July. This anomaly was not restricted to the cave data. Our surface weather station data suggests that a daytime storm greatly reduced the temperature peak for that day; periods of 100% humidity during that day suggest rainfall, and high winds were recorded. In light of this storm action, which greatly dampened the diurnal effect for which we are testing, it was decided to remove these 24 hours from the spectral analysis. Fortunately, they were at the end of the recording period, so they can be removed without risk of interrupting the periodicity through splicing effects.

All six in-cave thermistors in the Rundreisehöhle demonstrated convincingly diurnal peaks in their spectral analyses, indicating that the penetration length was at least 12.5 m. The surface weather station demonstrated peak wave energy at 23.75 hours. Referring to Fig. 5, we see that the Rundreisehöhle peaks occur at slightly longer periods of 1549 and 1570 minutes, or 25.8 and 26.1 hours. Noise is probably

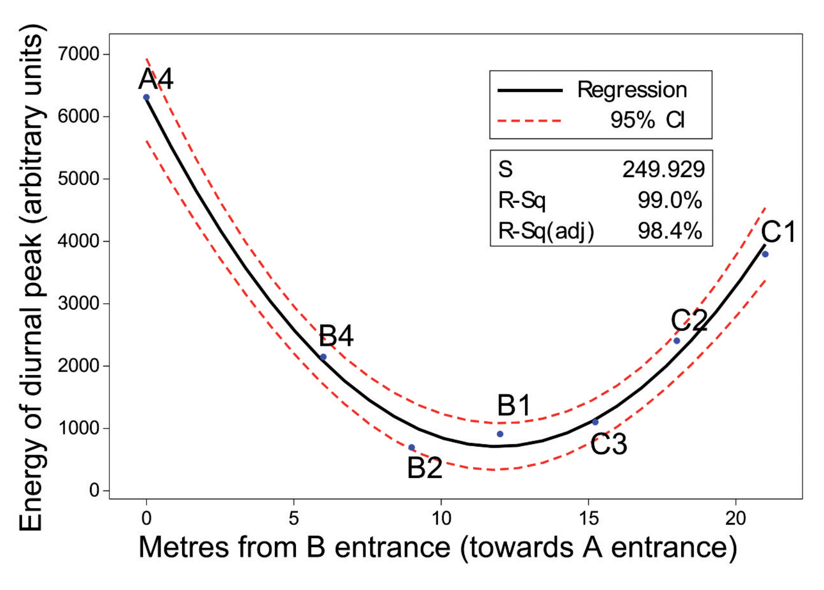

Fig. 6: Amplitude of energy peak for diurnal wavelength from Fourier transform (Fig. 5) for each sensor, with distance into the cave. A parabolic regression fits well: $a = 6273 - 934.8d + 39.26d^2$ where a is the diurnal amplitude (°C) d is the distance into the cave (m). Entrances are at 0 and 25m.

Amplitude des Energie Peaks der tageszeitlichen Wellenlänge basierend auf der Fourier Transformation (Fig. 5) für jeden Sensor, mit zunehmendem Abstand vom Höhleneingang. Eine parabolische Beziehung beschreibt diesen Zusammenhang: $a = 6273 - 934.8d + 39.26d^2$ wobei a die tageszeitliche Amplitude (°C) und d der Abstand vom Höhleneingang sind (m). Die Eingänge befinden sich bei 0 und 25 m.

responsible for the deviation of these peaks from 24 hours.

The peaks do attenuate towards the centre of the cave, as shown in Fig. 6, effectively an east-west transect of Rundreisehöhle where the energy of the diurnal peaks from the spectral analyses has been plotted against distance along the cave. We can investigate the nature of the relationship between diurnal amplitude and distance into the cave by fitting regressions to our data. A parabolic regression fits best, and explains 98.4% of the data (adjusted R2), well within the 95% confidence intervals displayed on the graph. This weakening of the diurnal cycle's wave energy with distance into the cave is a pattern that is not exclusive to a Q_C-driven system; it could be observed in a Q_S or Q_L dominated system as well. The 12.5 m penetration length is nearly two orders of magnitude further than the 0.17 m predicted by conduction through limestone, and therefore, Q_C is only responsible for a small portion of the total heat transfer into Rundreisehöhle.

The Rundreisehöhle measurements provided us with a lower bound for penetration length of 12.5 m, but no upper bound on that value because the cave was too short for the wave energy of the diurnal cycle to approach zero at any point. Because Steinbrückenhöhle is a larger cave, however, we were able to place thermistors as far as 180 m from any entrance. Table 2 shows the results of the spectral analysis, which raises our lower bound for penetration length to 15m, and provides an upper bound of 35 m.

Thus, in both Rundreisehöhle and Steinbrückenhöhle we have shown that daily temperature cycles extend far enough beyond x_{rock} that thermal conduction through limestone can be considered a negligible component of the cave air temperature. This agrees with some published data; for example Forbes (1998) observed clear diurnal temperature cycles 75 m from any entrance in Torgac Cave, NM. Thermal conduction through limestone may yet be an important control on cave wall rock temperatures (which we did not measure), but not cave air temperatures, since heat transfer from the cave walls to cave air is likely to be inefficient. The important finding is that Q_C is dwarfed by other components of Q_{Tot}.

Table 2: Spectral analysis of thermistors in Steinbrückenhöhle / Spektralanalyse der Temperaturdaten aus der Steinbrückenhöhle

	sA3 & sA4	sA1 & sA2	sB1 & sB2	sB3 & sB4	sC1 & sC2	sC3 & sC4
Distance from 204e entrance	4	15	35	75	150	180
Spectral analysis peak period	23.8 hours	24.0 hours	None	None	None	None
Peak amplitude	795.8	719.8	None	None	None	None

AIRFLOW (Q_S)

Because Rundreisehöhle is nearly straight, we can test the influence of external, cave-parallel wind using weather station and cave thermistor data. If external wind controls air movement in the cave (rather than the "chimney effect"), we would expect to see a temperature increase when a strong wind blows in a direction parallel to the cave, as this would increase Q_S, the advective flux of heat from the entrance of warm outside air into the cave.

To extract the component of wind WEW that flows either towards 90 compass degrees or 270 compass degrees, we used the formula

$$W_{EW} = SsinD$$

where S is the wind speed and D is the wind direction. For comparison,

$$W_{NS} = ScosD$$

was used for the N-S component of the wind.

A Pearson correlation matrix of the eight Rundreisehöhle thermistors with wind speed, N-S wind component, and E-W wind component showed that the temperatures are not controlled by surface airflow, suggesting either a lack of significant cave air movement or a dominance of the chimney effect. Correlations with p=0.05 for the wind variables occur for thermistor A4, B2, B4, C2 and C3, and A3 has one at p=0.08. A4 and A3 are the surface and entrance thermistors. It is interesting to note that A3, located in the sheltered entrance depression but outside the cave entrance, shows a fairly strong relationship with N-S wind but not E-W wind. A4, on the surface but below the dwarf pine canopy correlates with wind blowing in both directions. The remaining wind-correlated thermistors, B2, B4, C2, and C3, are correlated with wind but not cave-parallel wind. External wind is almost certainly not a factor in Steinbrückenhöhle, where two transects of sensors were placed. Although this cave would certainly be classified as a Type V (multiple entrances at different levels, chimney effect likely) cave according to the scheme of (Michie 1997), for our purposes we can think of the specific sections we are monitoring as simpler caves. The E entrance transect can be approximated as a type III cave (single entrance, descending passage), and the CSB area can be viewed as a type IV (single entrance, ascending passage). In this case we are merely considering the effect of entrances 204e and 204c on the nearby cave climate.

A miniature rotating vane anemometer (Silva Windwatch) failed to register airflow in Steinbrückenhöhle, because the air velocities are too small to overcome the inertia and friction which gives the windwatch its lower measuring limit of 10 cm s^{-1}. The present study attempted to construct ultrasonic anemometers following Campbell & Unsworth (1979). Although we were able to construct intermittently functioning anemometers which appeared sensitive to airflow on the order of a few cm s^{-1}, the devices were not sufficiently reliable for use underground by the time of the expedition. In future expeditions, ultrasonic anemometers should be used to quantify the chimney effect, and thus Q_S. Extreme precision is not required according to Wigley & Brown's (1971) model of pipflow, which calculates that that airflow velocity is a minor predictor of temperature relative to passage geometry in advective pipeflow heating. However, we do need to confirm that airflow exists and determine its general magnitude.

CONDENSATION (Q_L)

Extensive measurements of condensation have been carried out in the caves of the Crimea and the Caucasus, reviewed by Dublyansky & Dublyansky (1998). In that paper, condensation was related to discharge of streams fed by karst aquifers, and several proposed formula for predicting underground condensation were put forth. Corrosion in association with condensation is an agent of speleogenesis and has been discussed by Dreybrodt et al. (2005). Here, we are particularly interested in the latent heat transfer (Q_L) associated with cave condensation. Michie (1997) stresses that condensation always results in a net transfer of heat from the cave air to the cave walls. The thermal effect of condensation and evaporation tends to counteract warming of the cave in the height of summer and cooling of the cave during the winter, but reinforces such equilibration during the "transition periods" of spring and fall Wigley & Brown (1971). During our period of observation, we would therefore expect to be a flux in the opposite direction of Q_{Tot}, Q_C and Q_S. To observe condensation, expedition members were instructed to look for morphologies that suggest condensation corrosion (Dreybrodt et al., 2005). According to (Jameson, 2005), these include "drop dents," "rill trails,“ and ”splash patches.“ However, despite 30 pairs of observant caver eyes inspecting the rock for these features, none were reported.

Direct, visual surveys of condensation itself proved more effective. Making use of the frequent trips to various parts of Steinbrückenhöhle, expedition members were asked to keep an eye out for any walls covered partially or completely in water droplets, and afterwards surveyed the cavers informally. Responses highlighted three main areas in which striking examples of the phenomenon were commonly observed. These three areas are shown in Fig. 3. All three were near entrances, and conveniently, these happened to be in close proximity to our temperature transects: 204e entrance, CSB passage, and Crowning Glory. One caver described the fields of droplets as ”really pretty,“ while another remarked that droplets were ”quite extensive“ and occurred ”generally on ‘underside’ surfaces.“ There was a general feeling that condensation on this scale is not typical of the UK caves in which expedition members did most of their caving, perhaps a confirmation of Dublyansky & Dublyansky’s (1998) prediction that this altitude and latitude provides better conditions for condensation than those of Britain. (Fig. 7)

To an observer, the condensation droplets appear similar to the ”reflective dots“ described by (Rowling 2001). Rowling holds that such droplets are not caused solely by thermodynamic phase change, but those bacteria colonies of the genus Actinomyce encourage nucleation of condensation droplets and attract water using hydrophilic fibers. This is in accordance with the increasing realization that bacteria are important agents in caves and that many geophysical processes which occur underground depend on microbiology, as evidenced in Barton (2006) and in a special speleological issue of Geomicrobiology Journal (volume 18, 2001). However, the condensation droplets that we observed do not show the features which Rowling considers indicative of the biological origin of these droplets. Rowling expects the droplets may exhibit a gold, yellow, or brown color, which (Moore & Sullivan, 1997) attribute to presence of the pigment beta carotene in association with the actinomycetes. Additionally, bacterial droplets should be small: 0.1 to 2 mm. Because our droplets are clear and range from 4mm to 8mm, it is unlikely that this bacterial mode of formation is involved. (Fig. 8)

Two trips into Steinbrückenhöhle were conducted to photograph condensation. By measuring the pixel size of droplets and scaling with the use of a measuring tape included in the photos, we found that the vast majority of droplets were between 4.6 and 7.7 mm in diameter, and were spaced at approximately one drop every 2 cm². If each droplet is modeled as a half-sphere, then the volume of water in each square meter [illegible]

$$0.375\pi(0.5D)^3F$$

The average wall and ceiling perimeter of the affected passages based on drawn survey cross-sections is around 4 m, and length of affected passages amounts to 170 m (Fig. 3). Therefore, we have observed between 49.0 and 228.6 litres of condensate at these two entrances.

While it is possible to make these limited guesses as to the abundance of condensed water, the actual net rate of condensation rather than the amount visible at any one time is required in order to understand the thermal effects of the condensation. The condensation

Fig. 7: CSB-passage, with condensation droplets.
Der CSB-Gang mit Kondenswassertröpfchen.

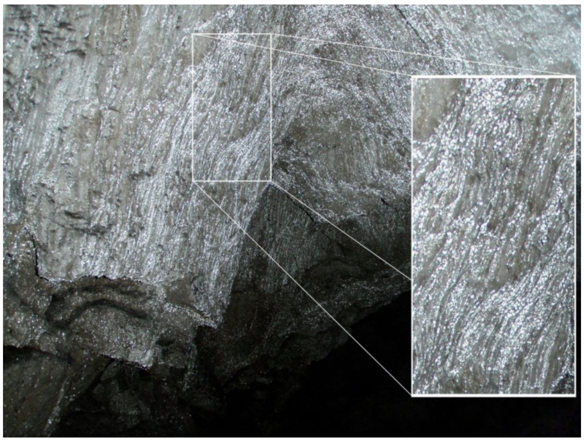

Fig. 8: Condensation in Treeumphant passage near Crowning Glory. Streaks detailed in inset are interpreted in the text as rivulets down which condensate slowly flows.
Kondensation im Treeumphant Gang nahe Crowning Glory. Die Fäden im Detailbild werden als kleine Rinnsale interpretiert, entlang denen das Kondenswasser langsam nach unten fließt.

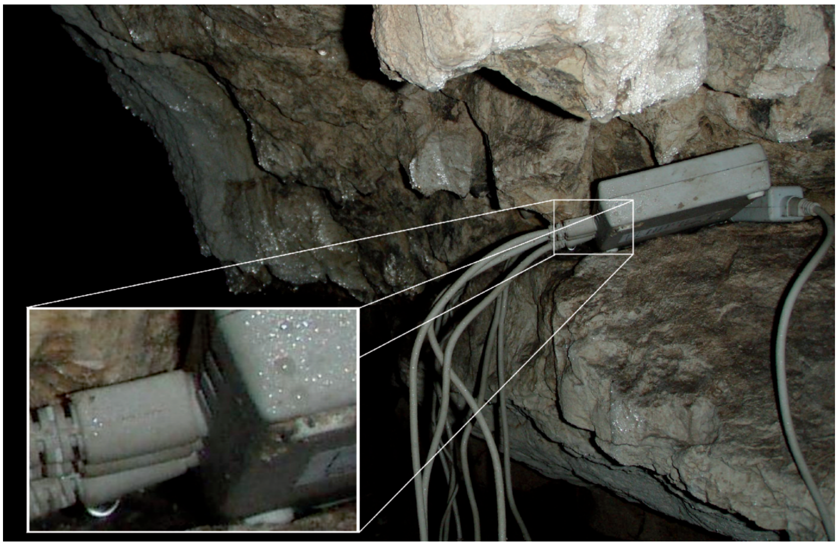

Fig. 9: Condensation droplets in CSB passage. Moisture on the logger (inset) demonstrates that the droplets formed during the study period.

Kondenswassertröpfchen im CSB Gang. Feuchtigkeit am Datensammler (Detailbild) belegt, dass diese Tröpfchen während der Untersuchungsperiode entstanden sind.

fields form on the timescale of days; it was observed that the Easysense datalogger in CSB passage was thoroughly coated in droplets after a few days in the cave (Fig. 9). Surveys of cavers suggest that there is a diurnal cyclicity to the formation of this condensation. The majority of reports of extensive condensation occurred in the evening; cavers noticed condensation while leaving rather than entering the cave, and one caver remarked that there was ”more in the evening / afternoon.“ Condensation in the 204e entrance passage, Germknödel's Revenge, was observed exclusively in the evening. According to the expedition logbook, few trips were underground during the period between 2 a.m. and 10 a.m., however, so we cannot be certain that droplets were not present then, although it seems likely due to the absence of condensation from 11 a.m. to around 2 p.m.

This is not entirely in accordance with the predictions put forth by Dublyansky & Dublyansky (1998) with the ”microclimatic method“ for condensation estimation. They imagine a maximum at 10am to 4 p.m. and a minimum at 10 p.m. to 2 a.m., corresponding with maxima of surface temperature and humidity. However, by observing condensation droplets, we are not observing the rate of condensation, but rather the cumulative volume since the process began. Maximum visible condensation is likely to occur at the end of the period, which is likely to be the afternoon through early evening.

If droplets were not present in the morning, this implies that not only are condensation processes more active during the evening, but crucially that the droplets were removed from the walls by another process during the night or morning. Evaporation is one possibility. De Freitas & Schmekal (2006) produced a ”conceptual model“ of the vapor flux between cave air and walls as a continuum, cycling sinusoidally between condensation and evaporation. Besides evaporation, it is also possible that the droplets are removed by mechanical means. Gravity is the most likely culprit. The majorities are attached to the underside of rock by adhesion and surface tension, and appear to be stationary, without flowing or dripping, to casual observation. However, the droplets could be moving slowly, coalescing and flowing down the side of the rock. Dreybrodt et al. (2005) described such ”flow from the rock surface down to the cave floor.“ Close observation of Fig. 4, a photograph taken of the roof of Crowning Glory Passage, suggests this is a case. One can clearly make out vertically aligned ”stripes“ in the condensation pattern, presumably representing long timescale rivulets.

Assuming that the droplets are removed nightly by a non-evaporative process, we can estimate the daily latent transfer of heat to the cave walls, using water's enthalpy of condensation, which is approximately –2.5 kJ g^{-1} in the range of temperatures (near 0°C) which concern us (Geiger, 2009).

$$228.6 \cdot 10^4 g\, day^{-1} \cdot -2.5\, kJ\, g^{-1} = -555.6\, kJ\, day^{-1}$$

If this much condensation is occurring each day, it may be a major control on the cave wall temperature. However, this is only a first order approximation at best, and it is very likely that a significant percentage of the condensation droplets remain in the cave overnight, reducing the daily heat transfer into the cave. To determine whether the droplets are removed by flowing, dripping or by evaporation, time-lapse photography could be employed.

CONCLUSIONS AND FOUNDATION FOR CONTINUING RESEARCH

The major conclusions reached here are:

- Rundreisehöhle lies entirely within the diurnal heterothermic zone, but the diurnal temperature signal attenuates towards the middle of the cave in a quadratic fashion.
- The diurnal heterothermic zone in Steinbrückenhöhle extends 15 m into E entrance. Below the entrance pitch, diurnal variations were not detectable. In CSB passage, a multi-day effect (temperature depression associated with a storm) was visible.
- Condensation in Steinbrückenöhle occurs near E entrance, in Crowning Glory passage, and at CSB. Between 49.0 and 228.6 litres are visible at peak times, implying a value for Q_L of -555.6 kJ day^{-1} if the condensation is replaced daily.

This study provided a first look at the likely relative magnitudes of component processes in diurnal heat transfer at Rundreisehöhle and Steinbrückenhöhle. Confirmation that condensation occurs near entrances in accordance with the ”chimney effect“ (Bögli, 1980) is of interest to the exploration aims of the expedition as well as its scientific aims. Often new entrances to cave systems can be discovered from below. If condensation can be treated as a reliable indicator that an entrance is nearby, then explorers hunting for entrances (such as CUCC in Tunnockschacht (1626/117), a cave of which 3km has been explored via a single entrance) can increase their chances of success by keeping an eye out for water droplets.

Because this is a multi-year project, annual cycles as well as the diurnal timescale will be observed. At the end of Summer 2007 data collection, a datalogger was installed attached to a four-thermistor transect with 50 m spacing between thermistors in CSB. The datalogger will record the temperature at four points, once an hour, until the memory fills up in July 2008. CSB did not show coherent diurnal temperature variation. If it does demonstrate an observable annual cycle of temperature variation, this will support the ”frequency filter“ theory that longer periodicities are observed further into the cave, which would allow researchers to select speleothem for analysis from favorable locations.

Another interesting possibility is that the 12-month dataset will suggest entirely different processes are dominant in the winter. Luetscher (2008) found that at Monlesi cave, Switzerland, there is a seasonal shift between ”open“ and ”closed“ regime with seasons. Most of the entrances to Steinbrückenhöhle are partially or entirely closed by snowfall during the winter, reducing airflow. If Q_S is a major factor, then we would expect to see a ”flattened“ curve and less overall subsurface-surface heat transfer.

Future investigations in these caves should seek to quantify the chimney effect and Q_S during the expedition period using anemometry at multiple entrances. Now that condensation in Steinbrückenöhle's most accessible areas has been mapped, photographed, and initial estimates of condensate volume produced, the 2009 expedition can observe those areas in more detail, and expand the map to other sections of the cave, such as entrance 204a. The important questions regarding the mechanism responsible for removal of condensation droplets and how completely they are removed on a diurnal scale could be answered with the use of automated timelapse photography.

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