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UNDERGROUND METEOROLOGY - "WHAT'S THE WEATHER UNDERGROUND?"

PODZEMNA METEOROLOGIJA: "KAKŠNO JE VREME V PODZEMLJU?"

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Abstract UDC 551.44:551.581
Giovanni Badino: Underground meteorology - "What's the weather underground?"
The aim of this work is to provide a synthetic outline of some of the processes of transient nature occurring in caves, focusing on poorly studied general aspects of underground physics and mainly making use of original experimental data. In the first part, the average climatic conditions of a caves, their connection to the external climate, and the general role played by rock, water, air and external morphology are discussed. The variation of the internal temperature with the altitude is a key parameter for the cave physics: the related energetic consequences are briefly discussed. In the second part, transient processes are considered, and a general overview of main meteorological phenomena occurring underground is given. The physics of thermal sedimentation, of underground temperature ranges, of infrasonic oscillations of cave atmospheres and, above all, of water vapour condensation in caves is synthetically described. The experimental study of these processes is extremely difficult, because they are time dependent and have very small amplitude; the first measurements show, however, that their variability from one cave to another, and from point to point inside a cave, is surprisingly high. To provide a more correct interpretation of underground climatic measurements, for their speleogenetic role and importance in cave environment protection, a better understanding of the processes described here is essential.
Key words: thermal sedimentation, temperature range, infrasounds, clouds in caves, cave climate, cave meteorology, cave protection.

Izvleček UDK 551.44:551.581
Giovanni Badino: Podzemna meteorologija: "Kakšno je vreme v podzemlju?"
Namen prispevka je predstaviti nekatere prehodne pojave, ki vplivajo na jamsko klimo. Pri tem izhajam iz osnovnih zakonov fizike in izvirnih eksperimentalnih podatkov. V prvem delu obravnavam povprečne klimatske pogoje v jamah in njihovo povezavo z zunanjo klimo, okoliško kamnine, podzemno vodo ter zunanjo topografijo. Pokažem pomen in vlogo temperaturnega gradienta v jamah. V drugem delu obravnavam prehodne pojave in z njimi povezane ključne meteorološke procese v podzemlju. Predstavim fiziko temperaturne sedimentacije, temperaturna območja v podzemlju, infrazvočna nihanja jamske atmosfere in kondenzacijo v jamah. Eksperimentalne raziskave teh procesov so zahtevne, saj gre za majhna nihanja časovno spremenljivih vrednosti; kljub temu se pokaže, da so spremembe vrednosti od jame do jame in tudi znotraj ene same jame presenetljivo velike. Dobra interpretacija meritev, razumevanje nekaterih speleogenetskih procesov in učinkovita zaščita jamskega okolja, bodo mogoči le na osnovi dobrega poznavanja in razumevanja osnovnih klimatskih procesov v jamah.
Ključne besede: termalna sedimentacija, območje temperatur, infrazvok, oblaki v jamah, jamska meteorologija, zaščita jam.

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INTRODUCTION

The aim of this work is to provide a synthetic outline of some of the main processes of a transient nature defined as "meteorological" processes; mainly focusing on poorly studied general aspects of underground physics.

Under the apparent stability of cave atmospheres, complex processes occur that, as a consequence of their very long time scale, can play an important role on the speleogenesis and on the constructive phenomena.

The distinction between climatology and meteorology is outlined. If referring to an outside environment, these two terms are, respectively, defined as the study of average climatic conditions – which can include regular fluctuations, as average temperature ranges and similar – and the study of transient, non-periodic processes in the atmosphere that are, since ancient times, called "meteora."

In this work, the term "climatic" is used to indicate average values of a condition, whereas "meteorological" refers to the fluctuation around it and the transient phenomena.

Inside caves, microclimates are very different from the external climate, and knowledge of these microclimates has always been very important for food seasoning and storage, medical treatments, and the use of caves as "time capsules."

The importance of cave deposits for paleoclimatic studies is nowadays increasing. Although the climate records essentially refer to hypogean deposits, the direct interest is on epigean paleoclimates. The correlation between the two is, however, not simple.

Up to about 20 years ago, microclimatic studies have been:

1) mainly observational, not considering physical models to be confirmed or refused;

2) quite local and relatively close to the surface;

3) lacking resolution and accuracy;

4) lacking long time series.

Generally speaking, measurements represented qualitative descriptions of the cave atmosphere, referring very often to too shallow layers. They showed an apparent high stability everywhere. However, note that a measure of the Earth's temperature by a thermometer with a resolution of ±50°C, would everywhere indicate the same value, leaving unexplained why here there is a desert, here a forest and there an ice cap. The old endoclimatic measures behaved in a similar way.

Now, thanks to a gigantic technological advance in the field of data acquisition and storage, in the development of physical models and to some advances in measurement techniques and data processing, the situation is quickly changing.

Cave physics studies are important:

1) to estimate paleoclimatic data reliability;

2) to understand the local adiabaticity and connect it to the occurrence of complex structures;

3) to understand the speleogenetic role of condensation;

4) to characterise caves as ecological "islands";

5) to protect caves, especially show caves, against anthropogenic impact;

Here we want to outline the main micrometeorological processes and the open problems.

The suggestion of new ideas, fields of research and eventually the growth of the interest on cave physics are, therefore, the objectives of this work.

THE CLIMATOLOGY OF CAVES

Versan le vene le fummifere acque
Per li vapor che la terra ha nel ventre,
Che d'abisso li tira suso in alto.

Every stream runs with smoke-infested waves
because of vapors hidden in the earth,
which from deep chasms rise up to the sky

Alighieri, Rime, 43

INTRODUCTION

Despite the fact that the underground temperature increases with depth, caves are usually very cold. The reason is the deep vadose zone with percolating meteoric water which equilibrates the rock mass with external temperature.

We can give a rough estimation of the involved time-scales. The water thermal capacity is around 4.2 kJ $kg^{-1}K^{-1}$, the thermal capacity of rock is five times less; the thermal capacity of water per volume unit is, therefore, about double of the rock thermal capacity. By assuming infiltration to a karst massif around 1 $m^3 a^{-1} m^{-2}$, and a rock column of 1 m^2 section and 1000 m high, it takes t_s=500 years until the thermal capacity of the water equals that of the rock column. The time t_s represents the time scale of the cooling process which, although strictly depending on the rock thickness, ranges from hundreds to thousands of years. This is also the time scale of climatic fluctuations, which are able to penetrate in the underground (Badino 2004a).

It is therefore rather important to note that the karst massifs are in thermal equilibrium with "historical" infiltrating fluids, mainly water. This explains the reason why karst massifs are quite cold and, in first approximation, unaffected by geothermal flux. As a matter of fact, the occurrence of caves in a mountain increases enormously its permeability and turns the temperature down.

The temperature of the infiltrating water changes during the year, but it is easy to observe that a fluid with a flow rate F(t), function of time t, at temperature T(t) passing a thermal capacitor C approaches a temperature T_0, at which the average thermal energy released from the fluid to the capacitor equals zero. This can be written as:

$$\int_{\tau \to \infty} F(t)\left[T(t) - T_0\right]dt = 0$$

Generally speaking, the rock behaves like a low-pass filter for the signal T(t) and it adopts the average temperature of crossing fluids. We will denote this temperature as T_R.

AVERAGE LOCAL TEMPERATURE

In a first approximation we assume that a cave has a temperature, T_C, equal to the temperature of the surrounding rock, T_R, which has the temperature of infiltrating water, T_{IW}, which is almost equal to the local yearly average temperature, T_L.

The estimation of the local average temperature T_L is then of extreme importance for understanding cave physics. T_L is a complicated function of longitude, latitude, and altitude.

The temperature variation with longitude is affected by the region macromorphology, such as the presence of seas, mountains, forests etc. and cannot be modeled. The latitude dependence is also connected to macromorphology, but more importantly, there is a regular tendency to lower the temperature going to the Poles; the latitude could therefore be roughly modeled. It is then possible to see (Fig. 1) that in Southern Europe the temperature T_L at sea level decreases by 0.7°C per latitude degree.

Quite at the opposite, the altitude dependence is very regular, the temperature decreases by about 6.5°C per kilometer of increasing elevation (this is the average "lapse rate" of International Standard Atmosphere), permitting the removal of the effect of altitude and the construction of maps of T_L's referenced to sea level (Figs. 1 and 2). Table 1 gives some more precise data in the position of main cities (WorldClimate 2010), corrected to sea level.

Table 1: Average yearly temperature of some European and Mediterranean airports (WorldClimate 2010)

St. Petersburg	4.5	Edinburgh	8.8	Mancheste	10.9
Frankfurt	10.5	Wien	10.7	Ljubljana	11.8
Lyon	12.1	Zagreb	12.3	Geneve	12.4
Trieste	13.5	Istanbul	14.1	Marseille	14.2
Roma	15.4	Barcelona	15.6	Tunis	17.7

Knowing the local temperature T_{L0} of a reference point, it is then easy to estimate the T_L in the neighborhood. For Europe we propose the formula:

$$T_L = T_{L0} - 0.7 \times \Delta Lat - 6.5 \times \Delta Alt$$

Where ΔLat is the Latitude (degrees) and ΔAlt the altitude (km) difference between the place and the reference station.

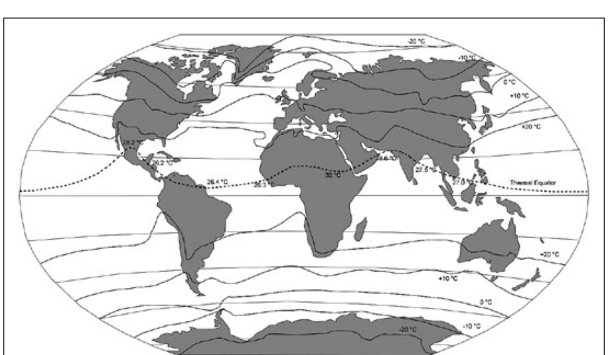


Fig. 1: World average yearly temperatures referred at sea level (Pinna 1977; WorldClimate 2010; adapted).

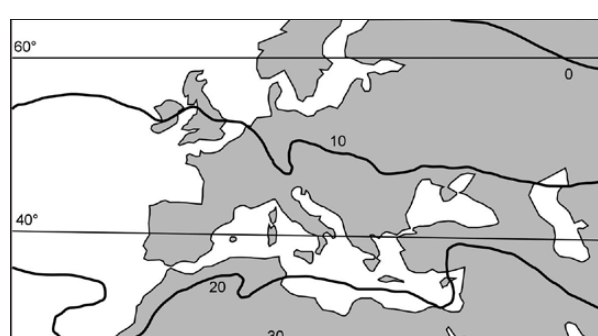


Fig. 2: European and Mediterranean average yearly temperatures referred at sea level (Pinna 1977; WorldClimate 2010; adapted).

We have stated that the cave temperature T_C is almost equal to the rock temperature T_R, which is almost equal to the temperature of the infiltrated water T_{IW}, which is almost equal to the local temperature T_L. So, the cave temperature T_C is (almost)^3 equal to the T_L ...

Let us see some of the processes capable to influence each "almost."

LOCAL AND INFILTRATION TEMPERATURES

The first "almost" that we are going to consider is connected to the differences between T_{IW} and T_L. The first reason for the temperature difference between infiltrating water and air is the local climate.

Generally speaking, it rains during cold days, and the rainfall comes from an altitude, which is higher than the local one. Therefore, the water is colder than the local air, which often cannot warm it up during the fall. The ΔT depends on many things, but in average it is assumed to be around 2°C (Celico 1986).

The precipitations are concentrated in certain periods, depending on the regional climate. Let us compare, for example, climatic (not "meteorological" ...) data from Florence (Italy) and Chihuahua (Mexico) (WorldClimate 2010).

The city of Florence (44° N, 50 m asl) is quite far from the Equator, but Chihuahua (29° N, 1400 m asl) is at a relatively high altitude. The relative average local temperatures T_L are then comparable: T_L Florence: 14.6°C, TL Chihuahua: 17.8°C.

The climatic type of the two regions is very different, Florence being Mediterranean, where the rainy season occurs during intermediate seasons - mainly autumn – and the summer is quite dry. In Chihuahua, the climate is highly continental with rains concentrated during the summer season.

We have tried to estimate T_{IW} as a weighted average value from the "average monthly temperature" and "average monthly precipitation" data, which is surely inaccurate, according to the above observation about the differences between air and rain temperatures. The result is nevertheless interesting: T_{IW} Florence: 13.8°C, T_{IW} Chihuahua: 21.6°C

Indeed, not far from Florence caves have a reference temperature of about 14°C at 0 m asl (corrected with altitude) whereas a cave like Grutas Nombre de Dios, near Chihuahua, shows a temperature above 25°C.

The difference between the estimated T_{IW} and T_L is, therefore, very small in Florence – and in general in Europe - but it could be quite large in other climates. It is, then, very important to carefully make these estimations, although the effect of this error is quite small if compared to the next one we are going to describe.

The main reason for a difference between T_L and T_{IW} is what we denote as the "fluid selection", a huge class of processes that considers underground flow of water, and secondarily air. Water freezes below 0°C; therefore there is no infiltration when outside temperature is below zero. The negative parts of the sinusoid, which usually describes the average local temperature T_L, are then eliminated.

However, during the melting season the water inflows underground at temperatures not much different from 0°C; despite that the air temperature would be much higher. It is quite easy to prove that this effect cannot compensate the previous one. This means that in regions where a significant part of yearly precipitation comes as snow, the rock temperature T_R is significantly higher than the T_L and always above 0°C. The same can be stated for the cave temperatures. The selection of infiltrating water warms a rock up -especially in karstic areas - and extends the internal isothermal zero much above the external.

As an example, the Ulugh Beg cave (Hodja Gur Gur Atà ridge, Uzbekistan), at an altitude of 3750 m asl shows an estimated T_L of -6°C. The altitude of the external isothermal 0 is around 2800 m asl. The cave has important ice deposits in the first 300 meters and the measured internal temperatures are -0.8°C (3700 m asl) and 0°C (3550 m asl) (Bernabei & De Vivo 1992). This case is quite extreme (ΔT=5°C), but it is usual to measure smaller but significant temperature differences.

Another important "selection" of inflowing water is influenced by the external morphology. Cave entrances can be extremely large and deep and can concentrate large snow deposits that, during the hot season, melt and cool the cave temperature because of the presence of melting water, always at 0°C, whereas the T_L can be much higher. An example can be found in the Slovenian karst (cave Velika ledenica v Paradani), which is an ice cave at an altitude around 1000 m asl, where T_L is around 6-8°C.

There are other effects due to external morphology, which can produce large differences between T_{IW} and T_L, causing anomalies in the temperature of water infiltration. For instance, into the cave enters water coming from a lake -or slow and shallow- water fluxes highly exposed to sun, that during summer could attain temperatures significantly higher than air.

A minor fluid selection effect, but important for ice deposit formation, is the selection of air flowing inside the cave entrances. When the air density inside a vertically extended cave is lower than the external, the air flows upward (the humidity for the estimation of air density is not considered here). The surrounding cold air cannot flow into the cave; consequently the upper parts of the underground system do not freeze. Despite the cold air being unable to enter, it however contributes to the statistics that create the average local temperature T_L.

During the summer, the internal atmosphere is denser than the external, and the air falls down, inhaling the external air from the upper entrances where now enters the external air, which is warmer. The internal air, relatively cold, descends down the mountain. At the lower entrances the process is similar but inverse, and can contribute to the formation of internal glaciers; a classical example is the Kungur cave (Perm region, Russia), formed inside a relatively thin layer of gypsum, where permanent ice deposits exist near the lower entrance of this cave, and where the conduits can attain very low temperature whereas the regional average yearly temperature is around +1.6°C (Worldclimate 2010).

Caves therefore "filter" the airflows on the basis of their temperature, systematically choosing between the external and internal, the hotter for the upper entrances and the colder for lower entrances. The result is that the average temperature of airflow that goes across the entrance is not T_L, but the average local temperature during the months when the internal temperature is lower (in the upper parts) or higher (in the lower parts).

Usually, this is a minor effect because the total thermal capacity entering a cave through the air is greatly lower than the water thermal capacity, but it can be very important locally – for instance, near the entrances, forming underground glaciers - or in dry regions. This point will be thoroughly discussed later.

The T_R versus T_{IW}

We can now discuss the second "almost": the difference between the rock temperature T_R and the temperature of infiltrated water T_{IW}.

The thermal energy exchange between rock and water depends on the difference between their temperatures. As long as these two values of temperature become similar, the system tends to become adiabatic (no heat exchanges between water and rock) and it falls asymptotically to the theoretical, uniform temperature, which in fact it never attains perfectly. Moreover, the time-scale to obtain thermodynamic equilibrium between a mountain and the infiltrating water is on the order of centuries and it is difficult to assume T_{IW} as constant. Therefore, the rock temperature value is always close to the external antecedent one, which it is never exactly the present.

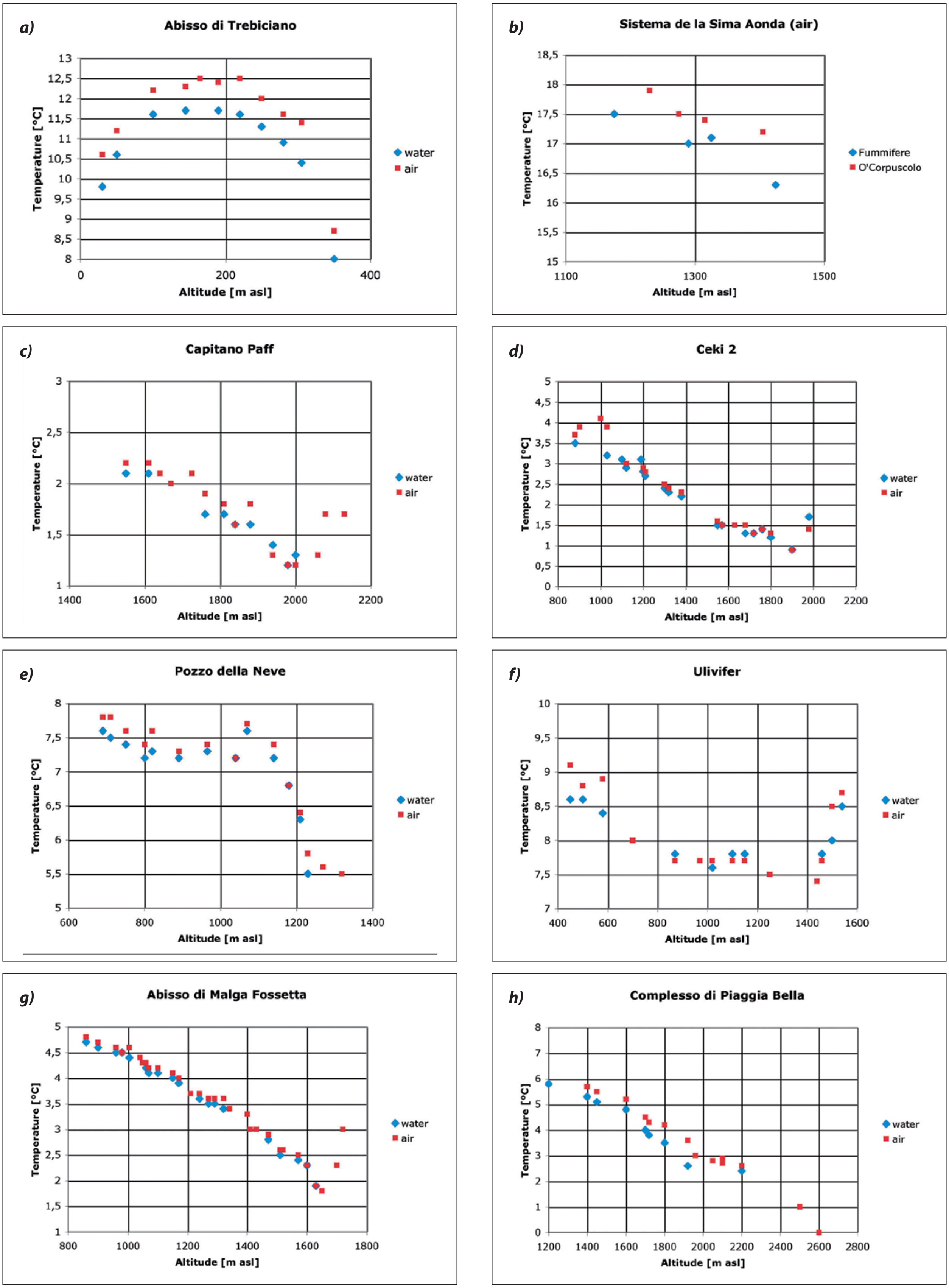
Another source of disequilibrium between the average temperature of rock and water is the airflow contribution. The specific thermal capacity of air is roughly four times less than the water one (around 1000 J $kg^{-1}K^{-1}$ –at constant pressure- against the 4200 of water; the mass flows of these two fluids are, however, highly variable in time and space, then the estimation of the total thermal capacity flux (i.e. the product of the mass flow rate multiplied by the fluid specific thermal capacity) flowing underground is complex. We need therefore to briefly discuss the relative water-air contribution.

The air flux ranges from zero (no air circulation in a deep karst: it is not unusual), to 10-40 m^3/s in large Alpine cave systems (e.g., Corchia and Piaggia Bella, in Italy, with surfaces of respectively 3 and 20 km^2), up to 100-200 m^3/s along the main conduits in some large tropical caves (e.g., Hwanseon Cave, in Korea, probably with a surface around 100 km^2). The air drainage is associated with the cave shape; the parameter "specific air drainage," indicated by the ratio between the whole flux and the whole karst surface is, then, almost meaningless yet the most significant parameter to be considered in the estimations. The specific air drainage is then around 10 kg/km^2 in Corchia and 1-2 kg/km^2 in Piaggia Bella and Hwanseon.

For developed Alpine karst, we can therefore assume as a reasonable range of specific airflow of 1-10 $kg/s/km^2$, a value comparable to the common precipitation of 500-2000 mm/a, then a water flow of 15-60 $kg/s/km^2$. If we include the high specific thermal capacity of air and water, we infer that the air usually contributes only a few percent to establishing the cave temperature. This general statement disagrees with Luetscher & Jeannin (2004) by which the air flow can play a leading role in establishing the temperature and the internal lapse rates. They estimate the same water flux, but an air flux of 150 $m^3/s/km^2$, which can be true in special cases (see below) but in our opinion this is absolutely overestimated in Alpine karst. We would have to observe exiting or entering air flows of hundredth of cubic meter per second each square kilometer of karstic area, which is too much. It is not even possible to assume that this flux takes place almost unseen along small fractures. The friction loss to air flux depends on v^2, then the flow is highly concentrated along the wider conduits: the air flow along small fracture does exist, but its contribution to the total flow rate is generally small.

In some special cases the air relative weight to the thermal capacity flow can however be much higher, for example in very dry regions, but also in rainy regions inside caves with very strong air fluxes, like in the Auyantepui, Venezuela (Photo 1). In this case the internal lapse rates are near -5°C/km (Fig. 3b) and the air is responsible for small differences between T_{IW} and T_R, causing water condensation on the cave walls.

It is nevertheless very difficult to estimate the impact of airflow on cave thermal imbalance. The air flux does not depend only on an external system (the atmosphere) that behaves quite regularly, but it mainly de-


a)
Abisso di Trebiciano
Temperature [°C]
Altitude [m asl]
water
air
b)
Sistema de la Sima Aonda (air)
Temperature [°C]
Altitude [m asl]
Fummifere
O'Corpuscolo
c)
Capitano Paff
Temperature [°C]
Altitude [m asl]
water
air
d)
Ceki 2
Temperature [°C]
Altitude [m asl]
water
air
e)
Pozzo della Neve
Temperature [°C]
Altitude [m asl]
water
air
f)
Ulivifer
Temperature [°C]
Altitude [m asl]
water
air
g)
Abisso di Malga Fossetta
Temperature [°C]
Altitude [m asl]
water
air
h)
Complesso di Piaggia Bella
Temperature [°C]
Altitude [m asl]
water
air

pends on the cave structure: entrances, shape, internal impedance, verticality, and so on. The estimations can therefore change in terms of orders of magnitude for mountains with similar climate. More importantly, both water and air usually drain along different paths, locally creating elevated disequilibria.

The internal morphology can also affect the temperature, creating cold and hot traps for air, through a process that can be included in the "fluid selection" and can cause strong thermal stratification. A hermetically closed cave branch, developing upward (downward) from the main conduit, can trap the air flowing through it in a specially warmer (colder) season, thus creating air bubbles which remain untouched when the airflows become colder (warmer) than usual.

The trapping effect is mainly relevant close to the cave entrance, where the external air is still not at equilibrium, but it can create high thermally insulated branches and extreme thermal sedimentation conditions: in the Cucchiara cave (Mt. Kronio, Sicily) we have measured 36.6°C at the roof and 26.3°C at the floor, 2 meters below, whilst in the middle there was a thin mixing cloud at the contact layer (Photo 2).

Another process capable of increasing the rock temperature above the temperature of water infiltration T_{IW} is the geothermal heat flux, already discussed in detail (Badino 2005a). Generally the geothermal flux heats the rock, but in the case of highly conductive karst aquifers it is completely intercepted at the water table. Therefore, the rock masses above it remain in thermal equilibrium with the infiltrating water. In this case, the whole rock mass is not affected by the geothermal flux, as this is captured by the deep water flow and successively released at the springs, where waters have temperatures of about 1 °C higher compared to the rock temperature. It is easy to see that, in the case of a flat and homogeneous water table, the geothermal flux uniformly heats the flowing water, but this happens also where water fluxes concentrated in conduits and similar structures, as in karstic areas. Specifically, the presence of discontinuities influences the rock temperature field, refracts the geothermal flux and concentrates it on the conduits (Badino 2005a). It can be shown that the regional geothermal flux is focused on deep conduits, creating a "shadow" on the topographic surface, which is much larger than the conduit itself. The "thermal cross section" of a water body inside the rock has a size comparable to its distance from the surface; it is thus much larger than its geometrical dimension.

This process has to be taken into account for the temperature comparisons between springs and caves, but it can affect the above water cave temperature only in very special cases, mainly in extremely dry regions.

T_C *versus* T_R

We can now discuss the third "almost" and compare the temperature of cave air T_C and the rock temperature T_R.

Fig. 3: Internal temperature vs. altitude in deep caves. The accuracy of temperature absolute value is around 1°C.

a) Abisso di Trebiciano, Carso, near Trieste, Italy (entrance altitude: 350 m asl). The limited depth (328 m) does not permit detection of a regular temperature variation with altitude. The highest parts are influenced by outside, while the deepest by the flowing underground river. Water and air are far from equilibrium, ΔT_{wa}≈0.5-1°C.

b) Fummifere Acque and O'Corpuscolo, two quartzite shafts in Auyantepui, Venezuela (1475 asl). The depth is still limited, but a regular behavior, dominated by airflow, is shown.

c) Abisso Capitano Paff, Grigna Settentrionale, North of Milan, Italy (2180 m asl). Below -200 m the behavior is quite regular and the water and air near the equilibrium ΔT_{wa}≈0.1-0.2°C.

d) Čehi 2, Mt. Kanin, Slovenia (altitude 2030m asl). The regular behavior below -100 m is only interrupted for air temperature around -1000, near a big ascending shaft which probably brings an unbalanced air flux. Air and water near the equilibrium, ΔT_{wa}≈0-0.1°C

e) Pozzo della Neve, Matese, South of Rome, Italy (1360 m asl). At intermediate depths the cave morphology and water drainage change, and there are significant temperature increases. Also the equilibrium water and air seems to depend on cave shape, ΔT_{wa}≈0.1-0.4°C

f) Abisso Ulivifer, Alpi Apuane, near Lucca, Italy (1565 m asl). Measurements were taken after a big flood which blocked us for 2 days at -1100. It is interesting to note the effect of flood inflow, which had completely unbalanced the two fluids. It is, nevertheless, possible to see a quite regular lapse rate. ΔT_{wa}≈-0.2-0.5°C

g) Abisso di Malga Fossetta, Altopiano di Asiago, North of Venice, Italy (1750 m asl). The external surface is very regular and thus the internal temperatures behave in a similar way. The small lapse rate change below 1000 m asl has allowed us to notice a survey mistake, thus detected by the cave temperature profile. From the high lapse rate regularity comes also the high water-air equilibrium, ΔT_{wa}≈0-0.1°C

h) Complesso di Piaggia Bella, Marguareis, South of Turin, Italy (2525 m asl). General outline of temperatures in different cave branches of Carsena del Pa, Labassa and at the springs. The water-air equilibrium strongly depends on branches ΔT_{wa}≈0.1-1°C.

As at first, we note that T_C fluctuates around the equilibrium and the cave exchanges energy with the surface of the rock, which is never in perfect equilibrium in the deeper layers. The depth of such "boundary" layers depends on the time span of thermal exchange and the rock thermal conductivity. This is the reason why it is not possible to univocally define the concept of "heat capacity" for a cave: the cave, in fact, does not exist; what does exist is the thermal capacity of rock around the cave, but the mass involved, that of the "thermal exchanging rock layer", depends on the duration of temperature changes.

It can be shown (Lismonde 2002) that for sinusoidal temperature fluctuations of air, the amplitude ΔT_0 of thermal oscillation on surface is reducing exponentially inside rock:

$$\Delta T(x) = \Delta T_0 \, exp\left(-\frac{x}{x_p(\omega)}\right)$$

where the term:

$$x_p = \sqrt{\frac{a}{\pi}\tau}$$

is the penetration length-scale in rock of a wave with period τ, and a is the rock diffusivity, given by:

$$a = \frac{K_r}{C\rho}$$

with K_r conductivity, C specific thermal capacity and ρ density of rock. This gives us the length-scale of rock depth involved in the temperature fluctuations. We deal with daily and yearly variation and then we may obtain that the boundary layer of a compact limestone has a thickness of 0.2 m for daily and 3-4 m for annual variations. In fact, the real thickness of this thermal "boundary layer" can be much larger due to percolating water and air (Luetscher & Jeannin 2004).

The main reason for continuous disequilibrium between rock, air and water is nevertheless the different behavior of two fluids when they move along the cave. Their temperature changes due to thermodynamic transformations are different, and the two fluids are always out of equilibrium, as we will see in the next chapter.

INTERNAL TEMPERATURE VARIATIONS

The small imbalance between cave atmosphere and rock temperatures is related to the temperature variations caused by air movements.

The main temperature variation occurs with change of altitude. The temperature decreases with altitude because of the related pressure decrease. As an immediate consequence, a rising air particle expands, thus performing work against the external pressure. This process is quite fast, and the air particles (usually with size of cubic kilometers) have a very small total surface in comparison to their masses, so that the thermal exchange with the surrounding air is almost equal to zero. The thermodynamical transformation of air particles which move vertically are then adiabatic, and the work performed against the external pressure is balanced by a variation of internal energy: the temperature of a rising air particle then decreases with altitude, with a constant rate (lapse rate).

In the case of ideal gases, the internal energy depends only on the temperature, but in the case of moist air it depends on both temperature and evaporation enthalpy of water vapor. The final result is that the internal temperature of a rising dry air particle decreases by 9.7°C per kilometer of rise (dry adiabatic lapse rate G_{DA}), whereas the moist air ascent has a smaller temperature decrease because the performed work is partially compensated by the energy released by the condensation process. The cooling rate depends on both temperature and pressure (Badino 2005b). The "moist adiabatic lapse rate" G_{MA} is around -5°C/km in usual karstic conditions. In the outer atmosphere, usually quite humid, the average lapse rate (International Standard Atmosphere) is assumed to be -6.5°C/km.

The typical cave atmosphere is saturated with water vapor; thus we can expect internal lapse rates G_U very near to the moist adiabatic rate. Surprisingly, this does not happen. In fact, the usual lapse rate is between –2.8 and -4°C/km (Badino 2000), having enormous consequences for the cave energetic balances.

Although both water and air are transported through caves, it is the water which usually plays a major role in cave temperatures. Assuming adiabatic conditions, in water flowing along the conduit, the potential energy is converted into internal energy. Consequently, in this theoretical model, the water temperature increases by 2.34°C per kilometer of fall. This value represents the natural "water adiabatic lapse rate," (G_W) a fundamental parameter for cave thermodynamics.

Many measurements of internal lapse rate G_U have been gathered in very deep caves, mainly in Italy. Some results are shown and discussed in Fig. 3 and in Luetscher & Jeannin (2004). Despite many different details, a regular increase of cave temperature along a descent line of drainage is highlighted in the graph. Therefore, the most common "internal lapse rate" G_U is around 3-4°C/km, an intermediate value between the water and moist air adiabatic lapse rates. This result is absolutely reasonable; as each underground line of flow drains water and air, then it results an average lapse rate value, which is intermediate between the different air and water "natural" adiabatic law. More precisely, the average lapse rate deriving from the thermal exchanges between air and water has to be an average of the two lapse rates weighted with each thermal capacity flow F_W and F_A, products of flow rate in kg/s and the specific thermal capacity of water and air:

$$G_U = \frac{F_W G_W + F_A G_{MA}}{F_W + F_A}$$

Indeed, the lowest measured lapse rates are related to very wet caves (for instance, Čehi II, Slovenia, and other Alpine caves), whereas the highest, very near to the "moist air" lapse rate, are related or to very dry caves or very windy caves like the big shafts of Auyantepui, in Venezuela, crossed by strong air flows and relatively low water fluxes.

Along each draining branch there is a different lapse rate which depends on the ratio of air/water flux; as we will see later, disequilibria at the intersections of different branches do occur.

We can finally state that the lapse rate in cave atmospheres is significantly lower (in absolute value) than the external ones, and these experimental underground lapse rates are not adiabatic. Water and air move vertically, and their temperature change, but with different rates: this creates temperature disequilibria inside the system, therefore there is continuous energy exchange between air, water and rock. The temperature of water flowing out from deep karst is usually significantly colder than the local temperature T_L which is usually near the temperature of infiltrating water at spring elevation.

At present, the extreme case is in the deepest world cave Krubera-Vorojna (Abkhazia). The temperature at -2140 m of depth is around 6.5°C (Provalov 2010), at an altitude around 100 m asl. The average local temperature TL is around 13.5°C (WorldClimate 2010), which gives a temperature disequilibrium of 7°C!

Infiltrating water on top of the mountain is colder than that at low altitudes due to the external lapse rate of 6.5°C/km. On the other hand, while percolating down to the springs the water attains only 3.5°C/km, then is "too cold" in comparison with the local climate. Thus, the usual impression at a spring "this water is very cold, therefore it comes from very far" could be quite correct!

Note that the lapse rate of the water is still higher than the adiabatic lapse rate (2.34°C/km). Therefore, water also receives heat from the air, which appears to be the main energy supply for the deep karst.

Water subtracts energy form karst, air supplies it, then in speleogenesis, water looks to be the chisel, and air the hammer ...

It is obvious that thermal exchanges between the two fluids are possible only if the two fluids bear different temperatures. This has a very important implication, impossible to discuss more deeply here: in general the underground systems are not at the maximum entropy state and, as a consequence, complex structures can appear.

In conclusion, the general water-air energy exchange along a vertical transfer is very complex, is season-dependent, and is probably also responsible for local condensation, thermal stratification and temperature differences between the two fluids and different cave regions. A lot of work has still to be done to understand these processes.

HUMIDITY

The term "humidity" indicates the water vapor content in air. The water vapor pressure in the air above a flat surface increases until the number of molecules leaving the surface (evaporation) equals the number of those coming back to the surface. In these conditions evaporation carries on, but the vapor partial pressure remains stable at the "equilibrium pressure," often incorrectly called "saturation" pressure. We shall hereafter use the term "saturated" air parcel, for simplicity, paying attention to the inaccuracy of using the word "saturation" in place of "equilibrium" (Bohren & Albrecht 1998). The value of the vapor equilibrium pressure depends essentially on the temperature of the system, as described by the Clausius-Clapeyron equation. It must be noted that although the system temperature is univocally defined because water and vapor must be at the same temperature and because thermodynamic equilibrium is assumed, in general, this is not true inside caves. The equilibrium pressure also depends on the radius of curvature of free water surfaces (Kelvin equation). Finally, it depends on water purity, because dissolved salt or gases reduce the equilibrium pressure, the so-called Raoult's law (Fleagle & Businger 1980).

As we are going to see, each of these dependences can cause speleogenetic processes on very long time scales.

The humidity of a cave atmosphere is generally at the equilibrium level, due to the close contact among water surfaces and air in these quasi-closed systems. It is very interesting to understand what happens when the vapor pressure is slightly below or above the equilibrium level (from now on: under- and super-saturated), because in these cases evaporation and condensation occur.

In general, closed systems bearing free water surfaces reach thermal equilibrium- uniform and constant temperature- and vapor pressure equilibrium (relative

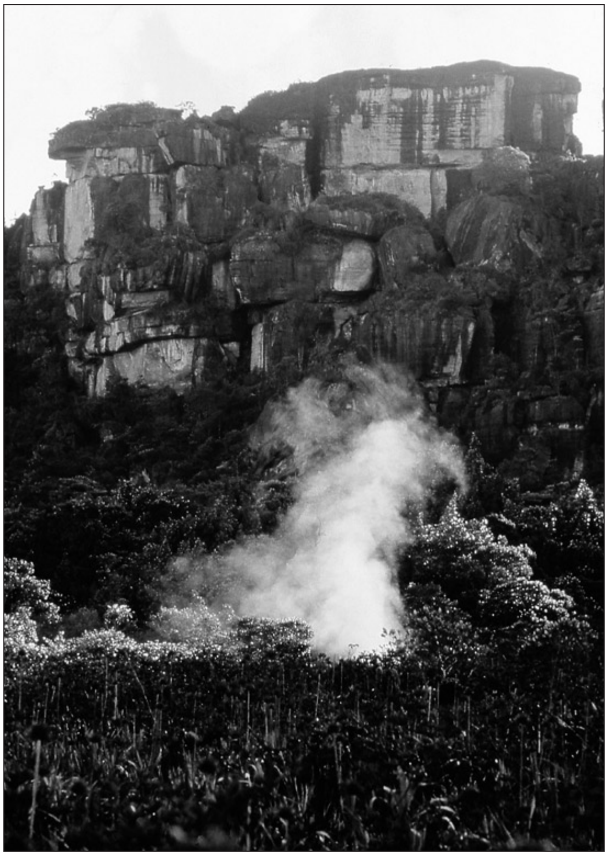


Photo 1: The mixing clouds at the entrance of the 330 m shaft of Fummifere Acque, Auyantepui, Venezuela. The air flow dominates the thermal exchanges in these very wide shafts.

humidity H_R=100%). These are the (almost) usual cave atmosphere conditions and, also, the reason why the hygrometers do not work inside caves.

Table 2 shows the water vapor density (mass of water per cubic meter of air) above a flat surface at equilibrium (H_R=100 %) in environmental conditions we have experienced underground. The extreme lower temperatures are in ice caves in Antarctica and, at the opposite extreme, in Cucchiara cave (Mt Kronio, Sicily) and Cueva de los Cristales (Naica, Mexico). It is possible to notice that there is a factor of 50 for water content at the extremes, which corresponds, and is probably more important, to a comparable factor in the energetic content of the cave atmospheres. We can note a very simple rule, very useful in usual karstic conditions (5-25°C): the water vapor density in g/m^3 is numerically close to the temperature in degree centigrade.

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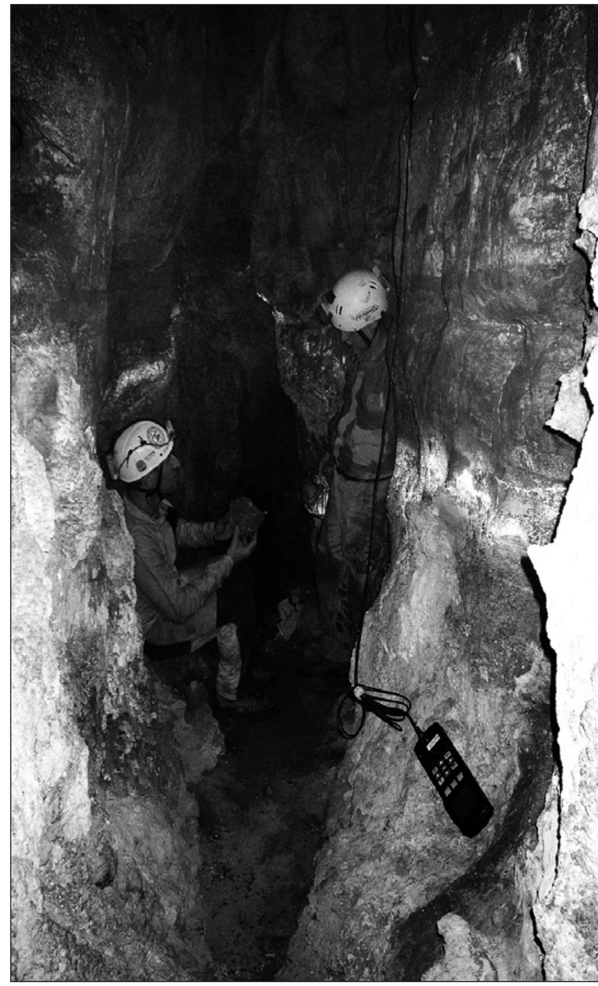

Photo 2: Extreme thermal sedimentation in Cucchiara cave, Sicily, Italy. The lower part of conduit is around 22°C, the upper at 37°C. It is possible to see the sudden transition of condensation on the walls, but also in air there is a narrow layer of a permanent mixing clouds.

Table 2: Water vapor density in common and uncommon cave conditions.

Cave	***Temperature (°C)***	***Water vapor density (g m^{-3})***
Campbell 1, Antarctica	-17	1.37
Piaggia Bella, Italy	5	6.8
Angelica, Brasil	22	19.5
Cucchiara, Italy	37	44
Cristales, Mexico	46	69

AIRFLOW: CONVECTIVE CIRCULATION

Underground air fluxes are driven by external meteorological conditions (instantaneous pressure, temperature and winds). They are essentially transient phenomena. A discussion about underground air fluxes should refer to meteorological phenomena; here we briefly discuss their global phenomenology.

Internal air density is almost constant, whereas the external is denser during winter and less dense during summer. There is a general trend of the internal air column to sink during summer and to rise during winter. The resulting winds can be surprisingly strong, usually 5-10 m/s but up to 50 m/s in Pinargozu, Turkey (Bakalowicz 1972), although the theoretical quantitative estimation of speed is not easily determined. In fact, the difference of density between the external and internal atmospheres creates a buoyancy force on the internal air column, but this does not uniquely establish the wind velocity.

Let us consider a cave with two entrances, at different altitudes H, and suppose we stop the air flow with a door which closes the lower entrance. On the two sides appear –after some time from closure- different pressures. It can be shown that the difference of pressure is proportional to H and to the average air density difference along the two paths from one entrance to the other, one external and the other internal. This means that, roughly, the pressure difference on the closed door ("moving pressure") is proportional to H and to the average difference of temperature ΔT between the cave temperature and outside temperature T_{ext}. Then, the static pressure on the door does not depend on the cave shape. It is easy to find an accurate formula for the moving pressure ΔP_m, which take into account the temperature and density variations with altitude (for instance in (Badino 1995)), but it is possible to use average values and the simple formula:

$$\Delta P = \rho_{in}\left(\frac{\Delta T}{T_{ext}}\right)gH$$

Where ρ_{in} is the average cave atmospheric density.

If we open the door, the air starts flowing through with an increasing velocity -transient flux- until the speed becomes constant –stationary flux-, what happens when the total moving force determined by the buoyancy becomes equal to the friction force due to air movement inside the cave. The flow therefore becomes stationary when the pressure drop along the cave, which depends on the whole air velocity field, equals the moving pressure. Unfortunately the relation between air velocity and friction is nonlinear and also depends on the geometry of the conduit; it is therefore essentially impossible to estimate the stationary air speed under given conditions.

We may nevertheless state that the friction in a conduit depends roughly on the square velocity of fluid then, at constant discharge, on the inverse of conduit cross-sectional area. The internal airflow is, therefore, usually determined by points where the conduits cross-section is smaller.

Notably, this fact has huge consequences for cave protection, because relatively small works to widen small passages can deeply affect the whole cave, changing dramatically the airflow and the cave energetic balance.

Our main conclusion is that there has to be proportionality between air velocity and the square root of ΔT.

AIRFLOW: BAROMETRIC CIRCULATION

The other main reason for air circulation inside caves is the variability of atmospheric pressure. Its variations create a continuous unbalance with the internal air masses, forcing airflows through the entrances. The general behavior of this air circulation is quite obvious and quantitatively similar to the convective circulation, but in this case the buoyancy pressure difference is substituted by the internal-external pressure difference. The main difference is that the air discharge is not constant along the cave but changes with position, being maximal at the entrance and zero at the cave bottom. The friction term then becomes very complex and concentrated in the part near the entrance, but we send the reader to the literature on this issue (Lewis 1992; Pflitsch *et al.* 2010).

In Alpine karsts, usually characterized by many cave entrances, relatively small volumes and large altitude differences, this process is relatively small, but it can dominate the air circulation where these conditions are not true, as in the giant caves in the United States.

Anyway, this circulation can be very important for caves with one entrance or with extremely small entrances, because it can be the only process capable of connecting internal and external atmospheres and, therefore, the chemical composition of cave air.

TEMPERATURE METEORA

Già mi parea sentire alquanto vento:
per ch'io: «Maestro mio, questo chi move?
Non è qua giù ogne vapore spento?»

Still it appeared to me I felt some wind;
Whence I: My Master, who sets this in motion?
Is not below here every vapour quenched?

Inferno, XXXIII

FLUCTUATIONS

The concept of "temperature" is unambiguously defined for systems in thermodynamic equilibrium; nevertheless the concept can be also extended to systems in local, quasi-equilibrium, but with intrinsic low accuracies. The measurements of epigean temperature, therefore, show an intrinsically low precision, because of the presence of strong energy exchanges, which indicate that the system is far from equilibrium.

A very high-resolution temperature measurement (0.001°C) of an outside temperature would therefore have no physical meaning. However, this does not apply to caves, where very small energy exchanges as well as temperature differences between fluids (air, water and radiation) can be observed. Being in a near-equilibrium condition, it is possible to reach theoretically significant accuracies on the order of 1 mK.

This can be attained also experimentally, with an approach which is quite usual in experimental physics but adapted and used underground for the first time in the Rio Martino laboratory (Piedmont, Italy), then in the Cueva de los Cristales (Naica, Mexico) it is better a brief discussion of this method. Each temperature point was measured by a set of 7 sensors PT-100, each hour, then was firstly calculated the average $Tave_0$ of the seven measured temperatures T_j, and finally the time dependence of fluctuation of each difference T_j-$Tave_0$. It was then possible to exclude the sensors which showed instrumental drift. With this exclusion, was re-calculated the average $Tave_1$ and then the distribution of each "good" sensor around it, to have a direct measure of intrinsic accuracy of each sensor. With these, was easy to calculate the accuracy of $Tave_1$, which was around 5 mK.

To this level of resolution, cave atmospheres show thermal exchanges and transient processes, then their meteorological processes appear.

Temperature variations have been already discussed above, when considering the origin of temperature imbalances inside a mountain. We can now consider some additional details.

THERMAL SEDIMENTATION

In the upper part of a conduit, the air is often warmer than the air in the bottom, then the air temperature changes with the height (temperature sedimentation). We note that this always implies energy exchanges, instabilities and, in general, that the system is not thermodynamically closed, but in contact with some time-dependent external processes. In a closed system, these temperature differences would be wiped out in a short time.

Temperature gradients do exist also in ventilated conduits and usually are around 0.1°C/m. Extreme values have been measured, as in the above cited grotta Cucchiara (Mt Kronio, Sicily), with gradients above 5°C/m. Nevertheless this value represents a very special case, really extreme, but the usual, smaller thermal sedimentation can complicate a lot the interpretation of the underground temperature and airflow measurements and are surely a very important parameter for show caves protection (Fig. 4).

There are evidences that temperature gradients are actually seasonal effects (Fig. 5), connected to the main underground air flow; this time dependence suggests that temperature gradients are related to the heating of air parcels, which are falling down in the warm season. As air parcels are still in contact with the water masses at the bottom of conduits, the relatively heated and dried air tends to concentrate near the conduit roof. This effect can probably create a systematic temperature difference between the floor and the roof, then seasonal processes of condensation appear when the airflow direction is reversed.

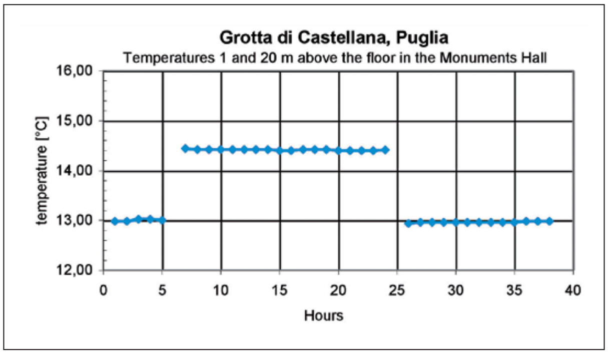

Fig. 4: Thermal sedimentation measured in the Sala Monumenti, in the Grotta di Castellana, Puglia, Italy. The thermometer was held for 5 hours near a monitoring station, on the floor, then moved to the upper part in the hall, then moved again to the previous position.

It is necessary to note, that a lot of work has to be done to understand the complex phenomenology of thermal sedimentations, which can be extremely important to understand the cave atmosphere physics.

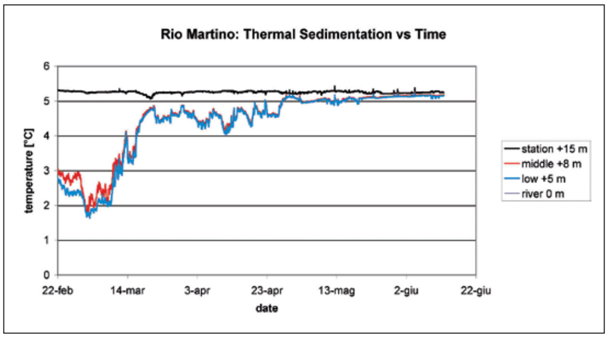

Fig. 5: Thermal sedimentation at the Rio Martino meteorological station. It is possible to see a seasonal dependence of its structure, that it tends to disappear during summer.

TEMPERATURE RANGES

The more obvious sources of temperature fluctuations are the external daily and seasonal temperature variations.

The rock layer near the surface is directly involved in the external temperature fluctuation by conduction, affecting only the very first meters of rock.

The main reason for internal temperature fluctuation is surely to be found in the inflow of external waters and, secondarily, the inflow of air. We have already discussed their relative weight, showing that usually the water flux dominates the thermal exchanges thanks to its larger heat capacity.

We can try to quantify the intensity of coupling between a particular place in a cave and the external meteorology. For that we introduce the concept of temperature range, which is the peak-to-peak amplitude (T_{max}-T_{min}) of daily and seasonal temperatures.

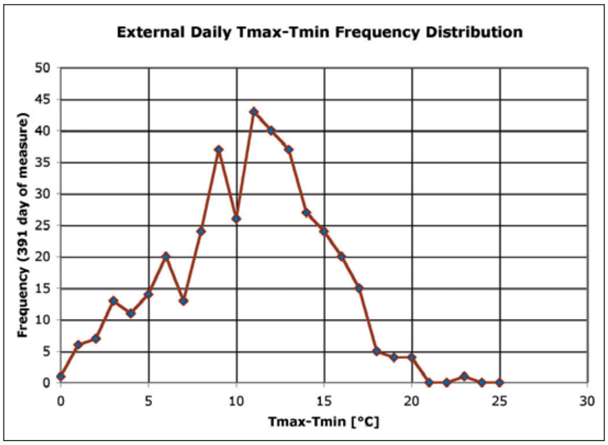

Fig. 6: The frequency distribution of daily temperature ranges (daily Tmax-Tmin) at a meteorological station near the Rio Martino cave, Piedmont, Italy (Courtesy ARPA-Piemonte).

The frequency distribution of temperature amplitudes is a bell-shaped curve (Fig. 6) around the most usual temperature difference T’, showing a very low probability of reaching 0 value - i.e. absence of fluctuations during the day or the season- to a maximum (T_{max}-T_{min}) around 2T’, because very large fluctuations are rare.

We can then assume that during the day or the season, temperatures can be approximated by a sinusoid with period τ of 24 hours or 365 days; the average value equal to the average temperature T_L and amplitude T_A, which is half of the previous defined T’. In formula:

$$T = T_A \sin\left(\frac{2\pi}{\tau} t\right).$$

The value T_A characterizes the climatic types. Table 3 shows yearly temperature ranges for different climates.

Table 3: Average extremes of temperature and ranges in various climatic types

	T_{ave} January	T_{ave} July	T_A
Ulan Bator	-19.4	15.1	17.2
Ushuaia	9.2	1.5	3.8
Roma	7.2	24.4	8.6
Berlin	-0.9	18.6	9.8
Tromso	-3.3	11.6	7.4

From the above table, it is possible to infer that the temperature ranges on Earth are quite similar everywhere, because a factor lower than 5 occurs between the climatic extremes, super-oceanic (Ushuaia, Argentina) and super-continental (Ulan Bator, Mongolia).

Although the T_A amplitudes of each location need to be correctly estimated, it is possible to say that, on average, typical values in Europe of yearly temperature amplitudes are around 10-12°C, and the daily temperature variations are about half of that, i.e. 5-6°C.

Now we can consider the problem of underground temperature range, not only including seasonal but also daily ranges, which can be detected with statistical techniques applied to multiple sensors, as above discussed.

As a first approximation we return to our first model assuming the cave as a thermal capacitor C crossed by a flow F of a fluid with a temperature which fluctuates sinusoidally with an amplitude T_A and period τ. The cave as a whole behaves as a low-pass filter, and it is easy to show that the temperature fluctuation of C shows the same period, but with reduced amplitude and a different phase:

$$T = \Delta T \sin\left(\frac{2\pi}{\tau} t + \alpha\right)$$

As in the physics of oscillators, where is called "quality factor", we can introduce the attenuation factor Q given by:

$$Q = 2\pi\left(\frac{C}{\tau F}\right)$$

Where C is the system thermal capacity and F the total inflowing thermal capacity during a specific period. This gives:

$$\Delta T = \frac{T_A}{\sqrt{1+Q^2}} \approx \frac{T_A}{Q}$$

The middle part of equation is valid if Q>>1, which is usually valid for caves. Attenuation of the temperature oscillations rise with increasing frequency of the signal and the ratio between the heat capacity of the massif and heat flow given to the system.

MEASURE OF THERMAL INSULATION

The ratio Q between the external temperature and the local internal range ($T_A/\Delta T$) indicates a direct measure of the thermal insulation (or the "thermal coupling" with the outside) of each sector in the cave.

A lot of research has been done in the past both in the field of seasonal temperature variation in caves and on temperature spatial variation along the cave. The amplitudes range from 2°C (Jernigan, 2001) to 0.10°C (Gadoros 1989), but the most common values are around 0.15-0.3°C. If we compare this value to the typical external temperature range (10°C), we see that the seasonal Q is usually around 30-50.

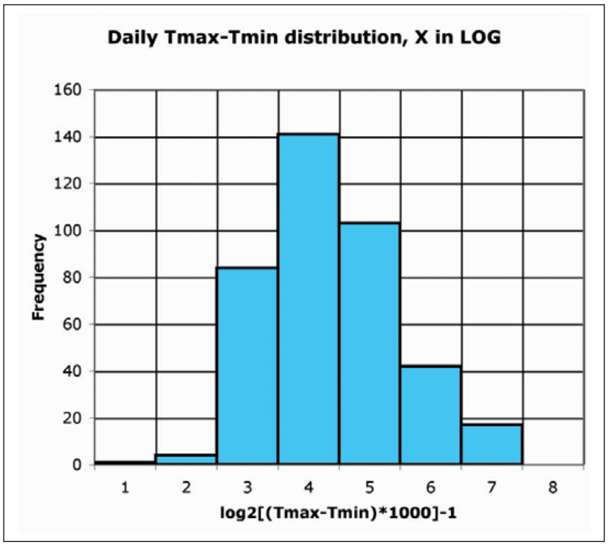

Fig. 7: The frequency distribution of daily temperature ranges inside the Rio Martino cave, Piedmont, Italy.

To measure daily temperature variations is very difficult, yet possible, with parallel sensors and special data analysis as above described. Figs. 7, 8 and 9 show the internal daily temperature range of two very different caves, Rio Martino (Piedmont), and San Giovanni Domusnovas (Sardinia, Italy). The first is a typical Alpine cave, crossed by a small river and a strong airflow. The yearly amplitude of temperature variation is 0.12°C (Q≈90), but the daily variation is much smaller, 0.012°C. This corresponds to a Q≈5/0.012=400. The second is a huge, natural hydro-geological tunnel, crossed by a small river and intense airflow; its daily temperature range is 1.8 °C, which corresponds to a Q=2.8, about two orders of magnitude less than Rio Martino. The two can be considered "high energy" caves.

This coefficient of local thermal insulation is probably a fundamental parameter to understand many de-

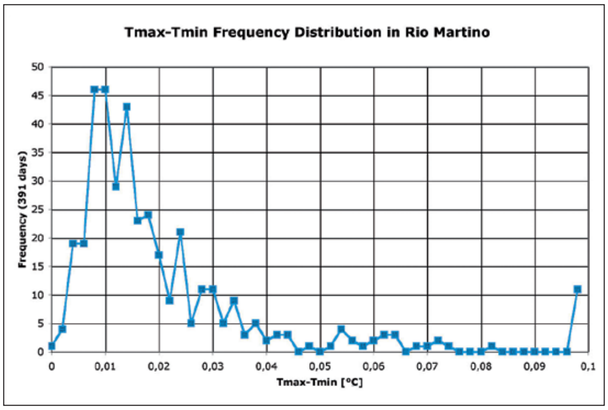

Fig. 8: The Log-plot of daily temperature range frequency distribution in the Rio Martino cave. The distribution appears to be Log-normal.

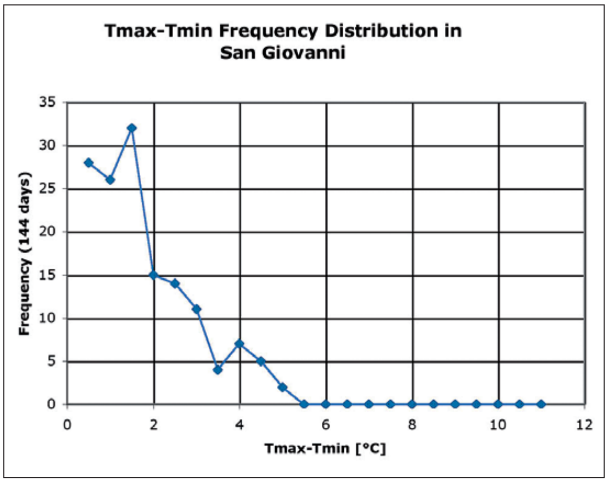

Fig. 9: The frequency distribution of daily temperature ranges inside the San Giovanni Domusnovas cave, near Iglesias, Sardinia, Italy.

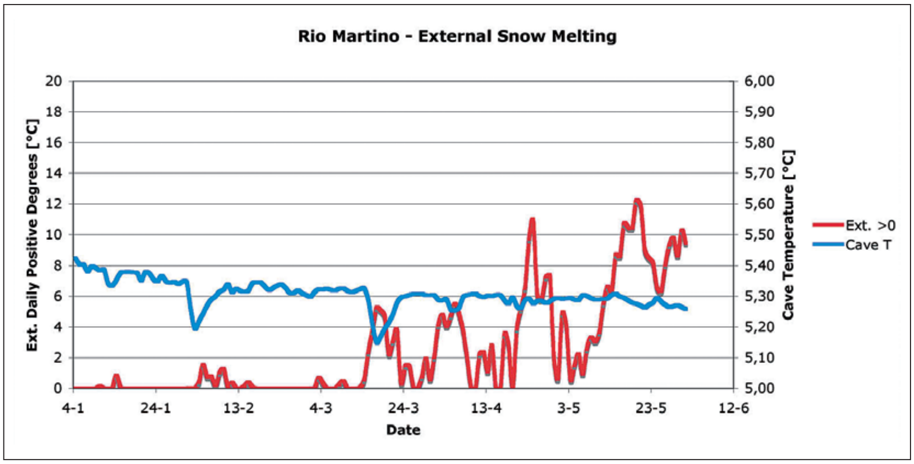

Fig. 10: Temperature variation induced by cold inflowing water from snow melting in Rio Martino. Red line gives the daily external Positive-Degree function, which gives a measure of melting.

tails about the cave morphology, as well as speleothemes formation, condensation, and so on.

It can be noted that it is possible to make a different model for temperature range "fading" inside caves (Badino 2004b), assuming a cave behaves like a conductive wall where a sinusoidal temperature fluctuation propagates by diffusion. This physical model can also suggest the use of the same parameter Q for adiabaticity, although this will provide different values for the phase shift. It is interesting to note that while the first model has no "memory" about the previous fluctuation (all the inflowing flux is mixed inside C), the wall model maintains memory of past cold or warm waves inside the system.

We can conclude with a detail. The general rule that refers to external heating inducing an internal temperature increase, usually with reduced amplitude -and the opposite for external cooling-, is reasonable and generally true, but it is here necessary to carefully consider the above-mentioned concept of "fluid selection." Fig. 10 shows the underground behavior of the cave Rio Martino at an altitude of 1450 m asl, when a warm front arrived during the winter, causing snow to melt above the cave and a resulting in water inflow with a temperature around zero, which cooled down the cave.

In general, we can say that if the cave temperature is above zero and the region of infiltration is covered by snow, a warm climatic episode during winter could provoke a cave cooling.

Similarly, warming or cooling of external air can result in airflow changes and, possibly, in cooling or warming of parts exposed to airflow.

WATER VAPOR METEORA

Ben sai come ne l'aere si raccoglie
quell'umido vapor che in acqua riede,
tosto che sale dove 'l freddo il coglie.

Well knowest thou how in the air is gathered
That humid vapour which to water turns,
Soon as it rises where the cold doth grasp it.

Purgatorio, V

INTRODUCTION

Water vapor phenomenology surely plays a key role in speleogenesis. The cave walls are very often covered by water films that play an important role in rock corrosion. The speleogenetic role of condensation is highlighted by the insoluble inclusions, which outcrop from the limestone. In this case the rock is usually uniformly corroded around the inclusion, by some isotropic process which is able to corrode in the same manner above and below the inclusion. Also the enormous quartzite shafts in the Venezuelan Tepui (Piccini & Mecchia 2008) have the walls uniformly covered by condensation, which seems the main cause of their very typical rock surface weathering throughout the "dissolution" of the quartzite cement for the first few centimeters of thickness. The result is a compacted sand rock surface. Finally, the position of many speleothemes at the bottom of convex surface on the roof, suggest a possible formation due to local rock solution and deposition -without water infiltration- driven by condensation processes.

For a caver, a cave is usually perceived as "active" when a water film covers the walls.

It is therefore important to analyze the condensation processes occurring in caves, because in a closed system at the equilibrium -maximum entropy- there would not be condensation, and the temperature would strictly be homogeneous.

We need now to analyze the small terms, which are able to open a cave system, and create disequilibria.

SUPERSATURATION PROCESSES

The main reason for disequilibrium is a sudden cooling of a fluid -air or water- when this penetrates underground. In general, the difference of temperature between fluids and rock creates an imbalance. This can also happen at large depths, but it is mainly a process at the "interface" between the epi- and hypogean environments.

This process can also affect the energy balance of most shallow areas of a cave as well as the stability of internal glaciers. It can generate a net water flow into a cave -usually very small- but it is typically a local and low depth process. We are instead going to focus our attention on global processes that are due to the continuous fluctuation of fluids around equilibrium and that are active at large depths too (Badino 2005b).

Inside a cave system, essentially five processes can create condensation, all connected to the presence of airflow:

1) upward movements of air parcels (adiabatic cooling)
2) mixing of air fluxes
3) air expansion in throttles
4) condensation from hazes
5) "Raoult" mixing.

UPWARD MOIST AIR MOTION

Outside, the cooling generated by the upward movement of air parcels is the main reason for cloud formation. Underground, the situation is rather similar but it is always very difficult to observe the clouds there. We have already seen that in the free atmosphere, the average air cooling along an upward external rise is around 6.5°C/km, very near to the moist adiabatic lapse rate. This means that each cubic meter of air cools 6.5°C in 1 km of rise, therefore: i) it does not release thermal energy to the surrounding environment and, ii) it condenses 6 grams of water vapor.

Inside caves the situation is slightly different, because the lapse rate is usually around -3.5°C/km. The transformation is not adiabatic, and this means that the rise of an air particle underground subtracts thermal energy, cooling the environment, and releases only 3.5 grams of water per kilometer of rise. Haze, clouds and "rain" appear: the cave walls get wet. It is easy to see the haze in suspension, looking at a distant light in large grottos, or watching the bright droplets in suspension in the few centimeters of air in front of a strong light.

The "rainy season" then happens during the upward transfer of air parcels, generally when the external temperature drops below the internal temperature. This explains why large temperature fluctuations of the external atmosphere directly affect the underground energetic balance and condensation, even if the net air inflows into the cave are very small.

Descending branches in a globally ascending cave obviously show an opposite phenomenology, as can be easily detected by looking at the hazes in suspension along ascending and descending conduits.

As previously noted, there are evidences that these seasonal processes affect the thermal stratification inside the conduits.

Let us focus on the specific deposition points on the cave walls.

Condensation causes a local energy release that stops the condensation process, unless the energy excess is removed inside the rock and to the air. At the equilibrium, the condensation processes are therefore driven by the efficiency of these two processes of energy removal, which depends on the rock thermal diffusivity, the surface morphology, its orientation and so on (Dreybrodt *et al.* 2005). It is quite common to observe that, in a regular conduit, the condensation is usually quite uniform, but this can be an interesting field of research.

Unfortunately, caves are far from being regular, and water deposition usually tends to concentrate at specific points. To start, the development of a droplet always needs a condensation nucleus. Inside an air particle flowing upward, the condensation nuclei -impurities- are quickly captured by droplets and eventually transferred to the walls. This is, by the way, the reason for the usual extreme air purity inside caves, although it depends on the direction of the airflow motion.

Becoming poor in nuclei, depleted from the air by droplets formation, the air can locally become supersaturated, and water condenses on the cave walls as soon as it reaches them. The deposition is thus concentrated on the relatively narrow passages following a wide area.

This is the first process that indicates that relatively narrow passages are preferred points of condensation, and therefore preferred points of rock dissolution.

AIR FLUXES MIXING

The condensation created by adiabatic cooling of moist air particle is, by far, the most common in the free atmosphere, but in the caves atmosphere other processes become important. The most common to be observed is the condensation due to the mixture of two saturated air particles at different temperatures. The resulting "mixing clouds" are so common underground, to the point that cavers do not observe them: the clouds created by breathing or moist cloths are typical examples of mixing clouds.

The scientific literature has plenty of references about the mixing clouds formation mechanism and its common misinterpretation; the opinion that they form "because the warm breath is cooled...", and so on, is not true. "Heating and cooling itself are irrelevant... mixing clouds are formed by mixing of different air parcels... because of the shape of the saturation vapour pressure curve two parcels can mix to form a supersaturated parcel" (Bohren & Albrecht 1998). Their role in cave atmospheres has been only recently considered (Lismonde 2002).

This is, in fact, a mechanism connected to the non-linearity of the Clapeyron curve (Badino 2005b), and essentially the same as the so-called "Bögli's mixing corrosion" (Bögli 1965).

Temperature drops in caves are commonly due to different "histories" of water and air columns flowing along different branches, often characterized by different temperature gradients along the flow, but mainly by different temperatures at the entrance (Badino 1995), especially in the presence of very steep external topographies.

It is easy to see that super-saturations are low and not directly measurable, some 0.01-0.1% of relative humidity. These values, nevertheless, correspond to a total release of some milligrams per cubic meter of air reaching the mixing point. A flow rate of 10 m^3/s, quite usual underground, can release 10^3 kg of unsatured water per year in the mixing region. The areas of confluence of different conduits, where different airflows are mixed, often present supersaturated atmospheres. There, we can expect to find a sudden conduit dimension increase and observe water films around us.

This process depends on the airflows strength and direction and therefore it is dependent on the external temperature. It is then another seasonal effect.

AIR EXPANSION IN BOTTLENECKS

The clouds that sometimes appear leeward large peaks are called "banner clouds." Their phenomenology is not completely understood, but they appear to be the result of a sudden (i.e. adiabatic) air expansion that locally cools the gas below the dew point (Friedlander 2000).

Let us now consider the airflow in a cave system. The flux through a mountain, as a whole, can be considered a Joule-Thomson expansion because the air parcel is de facto "throttled" through the cave. The general transformation is isenthalpic.

The actual process seems extremely complex, showing energy dissipation by friction, temperature and flow periodicities, thermal exchanges on the cave wall. The whole transformation results in a small temperature increase due to the dissipation of mechanical energy (air pressure drop at the passage ends), but in the proximity of the downstream end the cooling generated by the adiabatic expansion can prevail, as in the case of external banner clouds.

The pressure drop at the edge of a narrow conduit can be measured with an altimeter. In Corchia (Tuscany, Italy) we have measured values around 100 Pa for an air speed of 5 m/s, which is roughly equivalent to an upward movement of some 10 m for the air particle. It has been stated above that the adiabatic rise of an air particle causes 5°C of cooling per kilometer of rise, then flowing through the throttle with this pressure drop, the air has a rapid cooling of some hundredths of a degree, and the related water condensation (some hundredths of gram per cubic meter of flowing air) represent the result of this process.

The air throttling down bottlenecks creates stationary and invisible clouds, downstream of the narrow passages ("banner clouds").

This is a second process indicating preferred condensation on relatively narrow passages.

CONDENSATION FROM HAZE

The Clapeyron law describes the equilibrium pressure above a flat water surface. If the surface shows a radius of curvature comparable to the intra-molecular interaction length -a small droplet- then a molecule on the surface is less bound to the liquid than to a flat surface, resulting in a strong tendency to evaporate. The equilibrium pressure, described by the Kelvin equation, is then higher (Fletcher 1969; Rogers & Yau 1989).

Incidentally, we note that the very common presence of a stable aerosol (or haze) in a cave atmosphere is a direct evidence of supersaturation of moist air around droplets: in a simple "saturated" atmosphere the haze would quickly evaporate.

In the case of a negative radius of curvature – a concave surface - the surface needs a smaller vapor pressure to reach equilibrium and becomes a preferred condensing point for the surrounding air in equilibrium with a flat surface. This means that small rock fractures tend to be filled up with aggressive condensed water. This process of a preferred point of condensation is very evident on the giant gypsum crystals of the Ojo de la Reina cave in Naica, Mexico (Photo 3) (Badino *et al.* 2010).

A droplet produced by mechanical fragmentation, as happens at the base of a waterfall, is able to create a local super-saturation; the water is transferred from the waterfall to relatively distant walls not only by direct droplet deposition but also by condensation, because

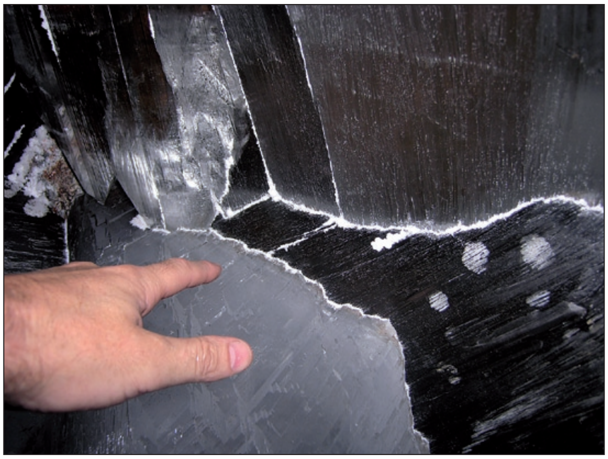

Photo 3: Ojo de la Reina, Naica, Mexico. Micro-crystals formation on the surface of gypsum megacrystals due to condensation in microfractures.

the water vapor around droplets is always supersaturated relative to flat rock surfaces.

RAOULT CONDENSATION

Raoult's Law describes the decrease of vapor pressure for saline water. Practically, salty water evaporates with lower rates than pure water, and if pure salt is exposed to moist air, some water will condense on the crystal surfaces. This happens because the water vapor in the air becomes supersaturated in comparison to the salty solution.

A typical carbonate concentration value in karst water is around 100 mg/l, which corresponds to a mole fraction X_s=2x10^{-5}; the equilibrium pressure above karstic water is some 0.001% lower than above pure water. The correction is very small, but does exist.

The global effect is the water transfer from a less to a more salty water surface and therefore, for instance, to soak the conduit walls if the water flowing inside has a lower salt content than the water film on the rock.

The water exchange between internal waters with different salt concentrations commonly happens and it represents again a speleogenetic process occurring at the intersections of different water and air drainages.

AIRFLOW METEORA

Io venni in loco d'ogne luce muto,
che mugghia come fa mar per tempesta,
se da contrari venti è combattuto.

I came into a place mute of all light,
Which bellows as the sea does in a tempest,
If by opposing winds 't is combated.

Inferno, III

INTRODUCTION

We have seen that convective air circulation in caves depends on the buoyancy and friction of internal air, and that wind velocities would depend on the square root of ΔT, the difference between the instantaneous internal and external temperatures. If we plot the wind velocity versus the square root of the difference of temperature, we expect to obtain a straight line.

We made this measurement at the entrance of the Su Bentu cave system (Sardinia, Italy) obtaining the plot as shown (Fig. 11)- not exactly a straight line ...

Plotting the ratio (wind velocity)/(square root of ΔT) versus time (Fig. 12), it is possible to see that the anomalies are actually concentrated; in fact, the general trend does not generally differ from a straight line; however, during two short periods of time the system has not behaved as expected in case of convective circulation. A similar, more precise measurement, made in coincidence between two different entrances of the same huge cave (Corchia, Tuscany, Italy), shows a similar behavior (Fig. 13). Why?

OSCILLATION PHENOMENOLOGY

Cave atmospheres are essentially quasi-closed air masses very close to thermodynamic and buoyancy equilibrium, connected by relatively small conduits to the

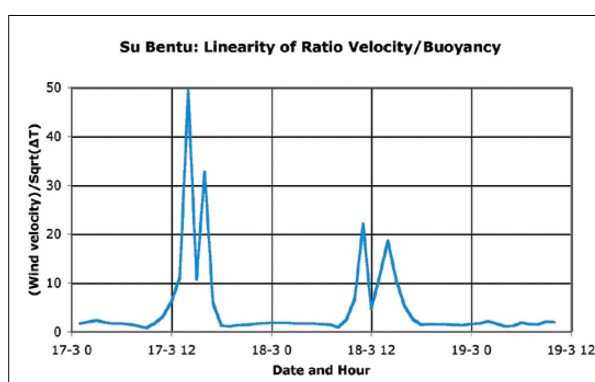

Fig. 11: Su Bentu cave, near Nuoro, Sardinia, Italy. In the convective model of air circulation, the wind velocity and the square root of the difference between internal and external temperature are proportional, then plotting one vs. the other would give a straight line. It looks far to be true.

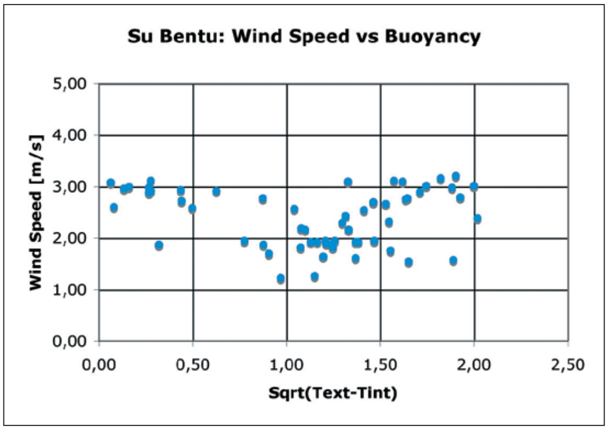

Fig. 12: Su Bentu cave, near Nuoro, Sardinia, Italy. The ratio between wind velocity and the square root of the difference between internal and external temperature has to be constant. In fact, it is quite constant except during definite periods.

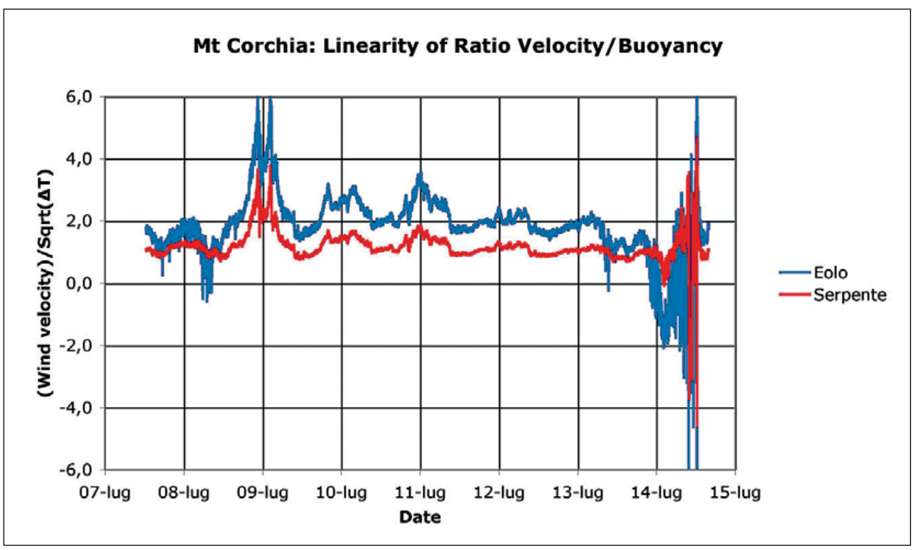

Fig. 13: The ratio between wind velocity and the square root of the difference between internal and external temperature vs. time, measured in coincidence at the two main entrances, Eolo and Serpente, of the Corchia cave system (Tuscany, Italy). Sometimes the airflow has the opposite direction than expected by the convective model.

variable external atmosphere. This causes a continuous energy transfer between the outside and the inside (Badino 1995).

A quasi-closed air mass is able to store energy because of the difference of pressure between itself and the air masses connected to it.

On the other hand, a moving air parcel has some inertia and cannot stop immediately when the driving pressure is switched off.

When an internal-external imbalance occurs, an energy release to the system takes place, and the energy flows and oscillates between the different internal kinetic and pressure energy "reservoirs", like a moving swing. The whole mass of internal air atmosphere starts oscillating back and forth.

It has been well known for a long time that cave winds are sometimes periodic (Plummer 1969).

In the field, observation of these air fluctuations is only possible when the average wind speed is very small, nearly equal zero. The theory has, however, shown that the oscillations must also occur in presence of strong winds, and that every cave atmosphere contains its intrinsic harmonics and "timbre" that depend on the cave morphology (Badino 1995).

It is therefore expected that an underground wind measured at the cave entrance should contain information on both the internal and external atmosphere dynamics, as well as on the geometry of the underground system (Plummer 1969; Lismonde 2002).

In fact, it can be theoretically shown that the shape of each single conduit has effects everywhere inside the cave, therefore the air movement in each contains information about the whole cave.

Elementary acoustical models can describe the origin of infrasound harmonics; however, cave morphology is usually very complex, and the harmonic spectra of its "voices" are extremely complex.

CAVES HARMONICS AND NOISE

The presence of rhythmic behavior of airflow at the entrance of caves has usually been associated with very big caves, located at intermediate altitude.

This could be fairly true in general, although such events can be noticed - without the instrumental support (anemometer) - only if a complete reversal of flow occurs, meaning an average flow around zero -intermediate entrances - and only if the period of oscillations is comparable with the time that usually cavers spend in the windy conduit.

Our measures (more than 3 million in 12 entrances of 5 cave systems) have shown that apparently very regular airflows can have a complex structure (Fig. 14) and that every cave is able to emit infrasounds.

The "cave player" is obviously the external atmosphere, which, during windy and perturbed days, can excite the main cave harmonics. The energy is stored and the air masses start to oscillate, releasing energy to other harmonics and to distant cave regions. Although a short period of stimulation can result in hours of oscillations, the general rule is that under common atmospheric conditions only noise signal is acquired, which on average overwhelms the harmonics.

Although the data analysis is extremely complex and we are still "tuning" our experimental approach, we can however already make some observations based on the available measurements.

The first observation is that caves emit infrasounds with frequencies around 10^{-2} and 10^{-3} Hz, on discrete (quantized) harmonics. Low frequencies seem to characterize the whole system, whereas "high" frequencies are emitted only "locally," i.e. by surrounding conduits. For instance, the Mt. Corchia cave system was recently studied by placing two identical anemometers on the two far system entrances (Eolo and Serpente). Spectra show a significant common low frequency ("Deep harmonic"? "Fundamental harmonic"?) of 0.000295 Hz, which corresponds to a period of 3400 s. It would represent the note emitted by a 280 km tube, closed at one side...

The second result is about the noise spectrum.

The power spectra of sampled signals show an overall decay at increasing frequencies, following a power law f^{-n}, often with n=2.3-2.7, but which depends on the frequency scale.

Depending on the value of the exponent of the power law, different scenarios can be drawn: in the 1/f regimen (pink or flicker noise) the energy decreases linearly with frequency, then each octave contains the same energy. Pink noise is intermediate between the $1/f^0$ noise (white noise), where the system has no memory of previous states and the energy is equally distributed among frequencies, and the $1/f^2$ noise (Brownian noise), where the system has no memory of previous increments. We then show that the overall power spectra of large underground systems usually tend to behave as pink noise (Fig. 15).

Pink noise is rather ubiquitous and occurs in very different natural systems. It has been shown to appear in complex systems with superposition of dynamic processes that relax exponentially with different characteristic times (Milotti 2002).

These results are very interesting because from the infra-acoustic point of view, complex caves can be considered as systems of many different damped and coupled oscillators, and this could probably be considered the origin of the pink noise.

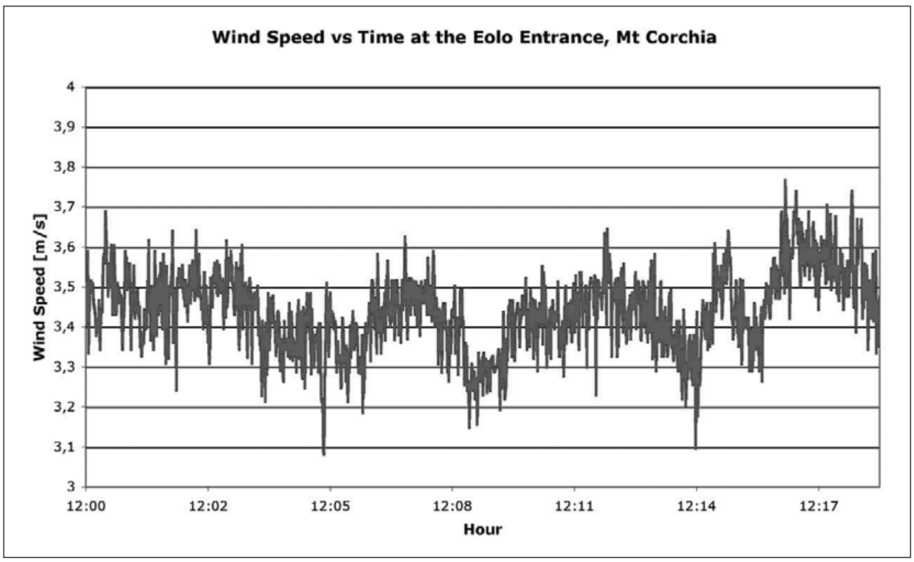

Fig. 14: Corchia cave complex (Tuscany), Eolo entrance. The apparently constant airflow has in fact an extremely complex structure connected with the cave morphology.

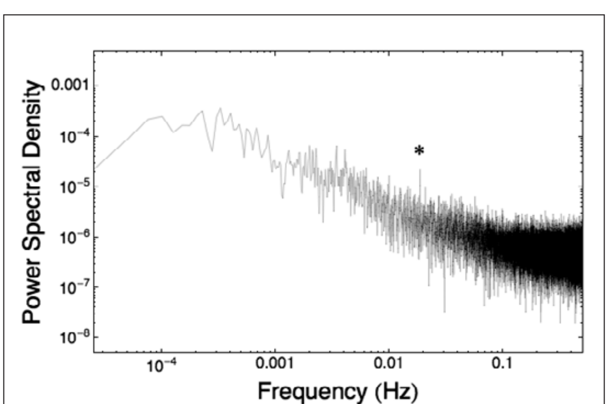

Fig. 15: Corchia cave complex (Tuscany), Eolo entrance. A typical air flow spectral power. The intrinsic harmonics are usually submerged by a pink noise.

CONCLUSIONS

A cave is commonly considered to be a nearly-invariable environment: daily or seasonal climatic cycles cannot infiltrate, the weather stays perfectly stable, and meteorological fluctuations are absent.

Furthermore, this stable condition would homogeneously occur anywhere inside a cave; the temperature would not change along the year, also maintaining constant along the entire cave length.

Caves appear to be the realm of "invariability".

This belief is mainly generated by the observation of relatively small amplitude variations for both internal temperature and humidity, if compared to the external variations. The variations of amplitude inside caves are in fact fairly small; however, this does not justify the common thought that, in a cave, either climatic or meteorological processes do not actually take place.

In the real world, external cycles will appear underground in the form of: variations of airflow direction and intensity; imperceptible variations of seasonal and daily temperature; local air and water temperature disequilibria; local thermal air sedimentation, and water film condensation on the cave walls.

The best way to highlight these processes is to carefully analyze the subtle parameters responsible of underground meteorology: the spatial and temporal temperature variations; the energy exchanges, that will always locally happen if small differences in temperature occur; the condensation-evaporation processes, which cover walls with thin films of water and create internal clouds; the air fluxes, with their imperceptible but continuous changes of speed.

The phenomenology of the two main flowing fluids in a cave -water and air- is completely different.

Water can only flow downward and on the lowest part of conduits; due to its enormous thermal capacity, water generally has the leading role in establishing the underground temperature. Nevertheless, its flow is not adiabatic and water normally subtracts energy from the underground systems.

Air can flow everywhere, reverse its flowing direction and, consequently, the thermal exchanges; air can make the rock surfaces wet; by its water vapor content air can smooth the temperature variations and dominates the energy exchanges. More importantly, along the cave length the nature of thermodynamic transformations of air is not adiabatic. This means that a thermal exchange between air and water will continuously take place.

Finally, airflow generally releases energy to the cave as a whole.

Measurements suggest that the meteorological variability among caves, and also among different points within a cave, is relatively high, and probably can explain many details of their structure. These variations from one cave to the other are relatively much larger than the variability of the external environment, where the astonishing changeable Earth landscape are created by relatively small differences in precipitation, temperature ranges and absolute humidity.

The characterization of these micro-meteorological variations is, probably, the key for a better understanding of the underground world.

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REFERENCES

Badino, G., 1995: Fisica del Clima Sotterraneo - Memorie IIS, 7, II, pp. 137, Bologna

Badino, G., 2000: I Gradienti di Temperatura nei Monti, un Indicatore Esplorativo.- Talp-FST, 21, 72-80.

Badino, G., 2004: L'Influenza del Clima Esterno sulle Terre della Notte. - Memorie IIS, II, XVIII, 2004

Badino, G., 2004:Cave temperature and global climatic chnages.- Int. J. Speleol., 33,103-114.

Badino, G., 2005: Underground Drainage Systems and Geothermal Flux. - Acta Carsologica, 34/2, 1, 277-316.

Badino, G., 2005: Clouds in Caves.- Speleogenesis and Evolution of Karst Aquifers.- Speleogenesis and evolution of karst aquifers, 2/2, [Online] Available from http://www.speleogenesis.info [Accessed 30th .11.2010].

Badino, G., Calaforra, J., Forti, P., Garofalo, P. & L. Sanna, 2010: The Present Day Genesis and Evolution of Cave Minerals inside the Ojo de la Reina Cave (Naica, Mexico) - IMA 2010, submitted to Int. J. Speleology.

Bakalowicz, M., 1972: La Riviére Souterraine de Pinargozu - Annales de Spéléologie, 27/1, 93-103.

Bernabei, T. & A. De Vivo (ed.), 1992: Grotte e Storie dell'Asia Centrale - Centro Editoriale Veneto, 310 pp., Padova.

Bögli, A., 1965: The Role of Corrosion by Mixed Water in Cave Forming - in: Stekl O. (ed.), Problems of the Speleological Research. Czechoslovak Academy of Science, pp. 125-131, Prague.

Bohren, C. & B. Albrecht, 1998: Atmospheric Thermodynamics.- Oxford University Press, pp. 402, New York.

Celico, P., 1986: Prospezioni Idrogeologiche.- Liguori, pp. 736, Napoli.

Fleagle, R. & J. Businger, 1980: An Introduction to Atmospheric Physics.- Academic Press, pp. 432.

Fletcher, N., 1969: The Physics of Rainclouds - Cambridge University Press, pp. 389, Cambridge.

Friedlander, S., 2000: Smoke, Dust, and Haze - Oxford University Press, pp. 408, New York.

Gadoros, M., 1989: The Physical System of Speleoclimate.- In Proceedings of 10th international conference of Speleology, Vol 3, 752-754, Budapest.

Jernigan, J. & R. Swift, 2001: A Mathematical Model of Air Temperature in Mammoth Cave.- Journal of cave and karst studies, 63(1), 3-8.

W.C. Lewis, 1991: Atmospheric pressure changes and cave airflow: a review.- National Speleological Society Bull., 53, 1–12.

Lismonde, B., 2002: Aérologie des Systèmes Karstique.- CDS Isére, pp. 361, Grenoble.

Luetscher, M. & P.Y. Jeannin, 2004: Temperature distribution in karst systems: the role of air and water fluxes.- Terra Nova, 16, 344–350.

Milotti, E., 2002: A Pedagogical Review of 1/f Noise.- Arxiv preprint physics/0204033 [Online] Available from arxiv.org [Accessed November 30th, 2010].

Pflisch, A., Wiles, M., Horroks, R., Piasecki, J. & J. Ringeis, 2010: Dynamic Climatologic Processes of Barometric Cave Systems Using the Example of Jewel Cave and Wind Cave in South Dakota, USA.- Acta Carsologica, 39/3, xx-xx.

Piccini, L. & M. Mecchia, 2008: Solution Weathering Rate and Origin of Karst Landforms and Caves in the Quartzite of Auyan-tepui (Gran Sabana, Venezuela).- Geomorphology, 106, 15-25.

Pinna, M., 1977: Climatologia.- UTET, pp. 442, Torino.

Plummer, W., 1969: Infrasonic Resonances in Natural Underground Cavities - Journal of the Acoustical Soc. of America, 46 (5), 1074-1080.

Provalov, D., private communication, 2010.

Rogers, R. & M. Yau, 1989: A Short Course in Cloud Physics.- Pergamon Press, pp. 227, Oxford.

WorldClimate, 2010: [Online] Available from: http://www.worldclimate.com [Accessed 24 February 2010]