CLIMATIC SYSTEM OF THE DOBŠINSKÁ ICE CAVE

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Abstract: The paper presents the most important characteristics of the Dobšinská Ice Cave climate. To determine the cave climate, the time and spatial changes of several meteorological parameters as well as the in-cave ice processes were studied. To resume, six cave climate-ice complexes were distinguished. They reflect interactions and interdependencies between individual factors which form Dobšinská Ice Cave climate and also they can characterize the state of climatic system of the cave in a given time.

Keywords: Dobšinská Ice Cave, cave climate, air exchange, thermal conditions, humidity conditions, ice conditions

INTRODUCTION

In case of caves open for tourists, the environmental processes and conditions of the caves as well as of any other underground cave-like system are extremely important factors to know. A good knowledge of the factors mentioned above allows us to explore and to exploit the caves properly; it is also necessary to protect their environmental, cultural and historical values. The climatic factors influence environment a lot and, if we want to preserve it in a good way, we need a good knowledge of these factors (Christoforou *et al.* 1996; Cigna 2002; Deacon 2006; Fajmon *et al.* 2006; Fernández-Cortés *et al.* 2006; Russel & MacLean 2008).

The paper presents selected results of climatological studies carried out in the Dobšinská Ice Cave the aim of which was to define typical characteristics of time-space changeability of air temperature and humidity, air exchange and ice conditions inside the cave. The second step in the studies was to determine the factors that drive the changes of climatic conditions inside the cave and the third one was to provide a complex description of the cave climatic system. As an instrument to describe particular states of the system, determined by specific meteorological conditions, both inside the cave and in its surroundings, the classification of climate-ice complexes has been devised. Its construction has based on the analysis of the cave environment "behaviour" in the model meteorological situations which may be observed in the cave surroundings (freeze and warm periods, periods with and without snow cower, periods with and without precipitation etc.).

STUDY AREA

The Dobšinská Ice Cave is situated in the karst area of Spiš – Gemer, in the Stratena nature reserve which, in turn, is a part of the Slovak Paradise National Park. The cave opens for tourists mid May and closes end of September. The number of tourists visiting is estimated to be at 100,000. Since 2000 the Dobšinská Ice Cave figures on the UNESCO World Heritage List.

The entrance of the cave is situated on the NW slope of the Duča karst massif, 969 m. a. s. l. and 130 m above the bottom of fhe Hnilec river valley. The cave's origins date back to the Neogen, when the paleo – Hnilec eroded the limestones of the Duča massif (Tulis & Novotný 1989). As to the genesis, the Dobšinská Ice Cave is a part of the Stratenská Cave system; however, the two cave systems are

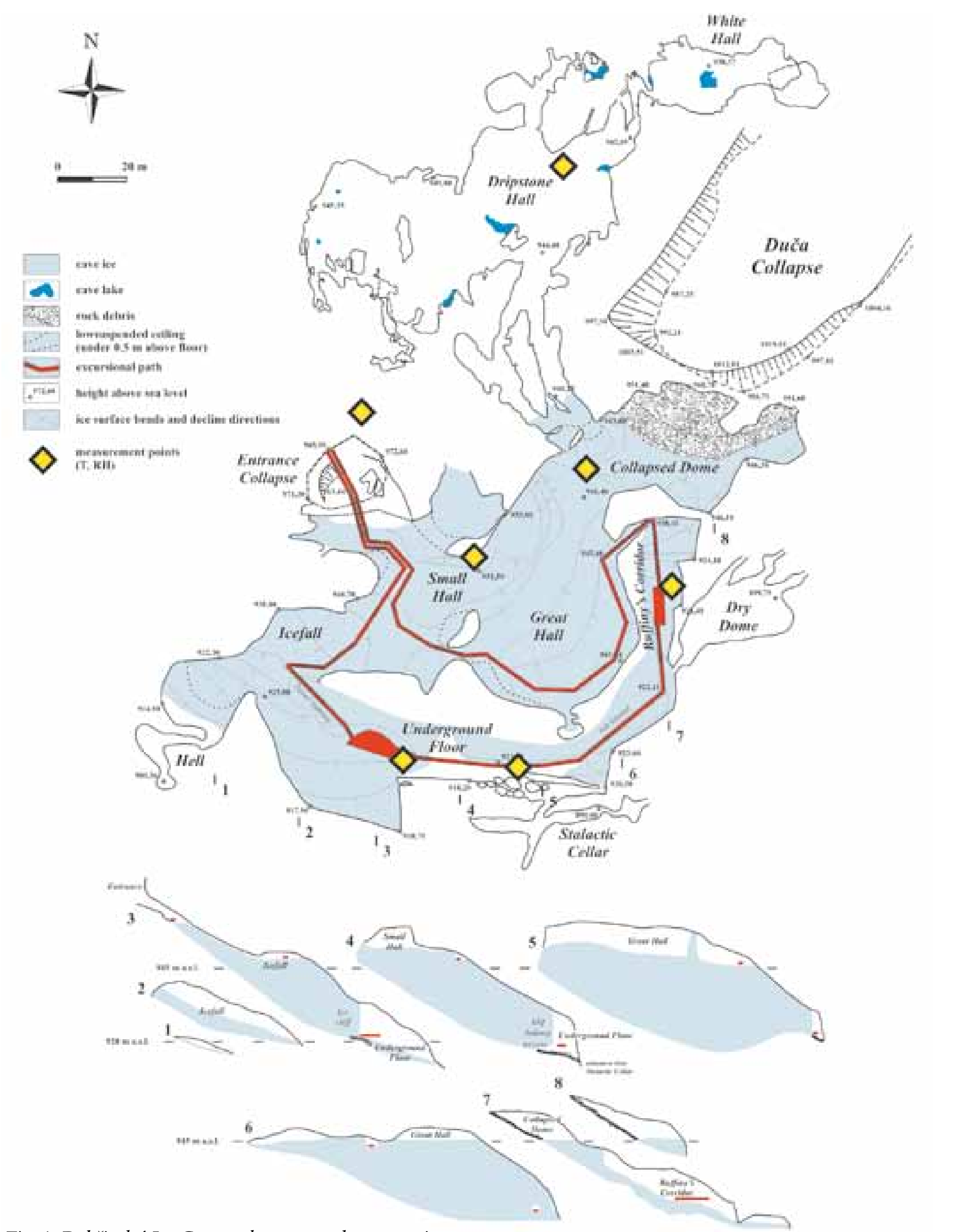

Fig. 1. Dobšinská Ice Cave – the map and cross-sections.

now separated. The caves lost the connection probably in Pleistocene after the ceilings of the cave collapsed (Novotný 1995). As a result of that phenomenon the Duča collapse arose and separated both the Dobšinská and the Stratenská Cave.

The main part of the cave is a large chamber that appeared as a result of a collapse of ceiling that separated the two main morphological cave levels. The chamber is fulfilled with the ice monolith, the volume of which is estimated at 110,000 m³ (Tulis & Novotný

1995). The monolith – by contact with the chamber's ceiling – separates the chamber into two main parts (Fig. 1). The difference in altitude of these two parts is about 30 m. In the upper part, the chamber divides into three halls: Small Hall, Great Hall and Collapsed Dome and they are all situated in the north and central parts of the chamber. The ice floor of the halls is the upper level of the cave glaciation. Underground Floor and Ruffiny's Corridor are situated in the south of the halls mentioned above and below of them and make the lower part of the cave. 20 m high ice cliffs, which limits these halls from north and north-west (Fig. 1) make theirs peculiar feature. The surface of halls floor consisted of ice and rock debris indicates the lower level of the cave glaciation. Halls of the upper and of the lower cave parts are connected one with another with the Icefall area (which join Small Hall and Underground Floor). Adequate connection between Ruffiny's Corridor and Great Hall is provided by opening, located under the ceiling of the Corridor in its north part (Fig. 1).

The halls of the upper and lower cave parts are still connected with the remains of primary, pre-collapse corridors and halls system, which are Hell, Stalactic Cellar and Dry Dome (in the lower level) and Dripstone Hall as well as other neighbour halls (the upper level). These parts of the cave are ice-free and it is only in Stalactic Celar where one may find ice.

The cave is connected with its external surroundings by the main entrance hole situated in the north-west part of the cave, about 20 m above the ice surface of the near-entrance area (Small Hall), as well as by fissures that give to the Small Hall and Icefall. The complex of fissures developed in the rock debris in between the Collapsed Dome and the bottom of the Duča Collapse also connect the cave with the outside. The Collapsed Dome is about 40 m below the Duča Collapse and the above position of the complex makes the air exchange caused by chimney effect.

DATA SOURCES AND MEASUREMENTS

The air temperature (T_{AIR}) and the air humidity (RH) were the main data used in the cave climate investigation. Both quantities were measured inside and outside of the Dobšinská Ice Cave for several years (from February 2001 to October 2007) and they were recorded by the cave climate monitoring network.. The measurements were taken automatically with the data loggers L3120 and L0141 "Black Box" manufactured by Comet System: five of them were situated in the icy part of the cave, one in the free-of-ice part of the cave (Dripstone Hall) and the last one was situated outside the cave (Fig. 1.). The accuracy of the recorded data was: 0.2 °C for the T_{AIR} and 2 % for the

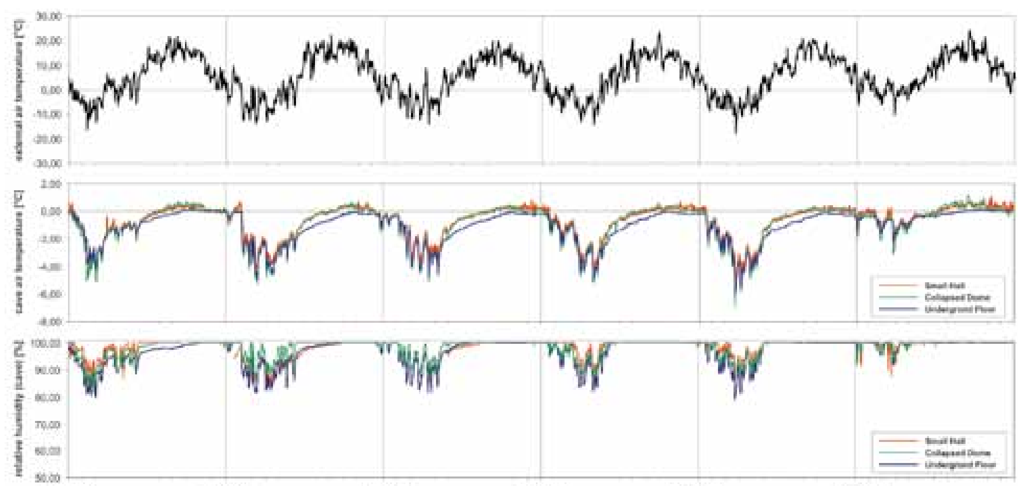

Fig. 2. The course of the air temperature and the relative humidity changes at the selected measurement points inside and outside the cave in the hydrological years 2001 – 2007.

RH, respectively. The frequency of data recording depended on the period of a year: from October to May the data were recorded every hour; from May to September, when the cave opens for tourists, the data were recorded every 10 minutes. The process of air exchange in the cave was an investigation subject in the years of 2002 – 2007 (Pflitsch *et al.* 2007; Piasecki *et al.* 2004, 2005, 2008). Here, the data were recorded with frequency of 1 minute by ultrasonic anemometers USA-1 made by METEK GmbH, which accuracy was 1° for wind direction and 0.01 ms^{-1} for wind velocity. In the years of 2002 to 2007 the periodical observations and measurements of the ice phenomena were also taken. The mass balance of ice monolith and the processes of development and degradation of the sublimation ice crystals were studied with the intervals of 2 to 3 months, and so we were given a great piece of valuable information on the spatial diversity and dynamics of the in-cave climatic processes that depend on the phase transitions of water (Strug *et al.* 2004; Pflitsch *et al.* 2007; Strug *et al.* 2008; Strug & Zelinka 2008). As a completion of the climatological data obtained in present surveys archival data of rock temperature (monthly averages) were also used. These were recorded in the years of 1980 – 1984 and published by J. Halaš (1985, 1986).

THE DOBŠINSKÁ ICE CAVE MICROCLIMATE

Thermal conditions

In the 2001 – 2007 investigation period the air temperature of the icy part of the cave was about 0 °C in summer to a few Centigrade above zero in winter. In winter period the course of T_{AIR} changes inside the cave was in correlation with the corresponding characteristic outside the cave and the amplitude of changes of in-cave temperature reached a few of Centigrade (Fig. 2). In the summer half-year only the temperature of the Collapse Dome was influenced by the outside air temperature, however, the daily difference in the T_{AIR} did not exceed 1.0 °C. The air temperature measured in the Dripstone Hall (fragment of the free-of-ice parts of the cave) was about 3.0 °C all year and the amplitude of seasonal changes of T_{AIR} in this area did not exceed 0.5 °C (Fig. 2).

The mean annual air temperature indicates the coldest parts of the cave, which are Underground Floor (lower part) and Collapsed Dome (upper part of the cave); Small Hall and Ruffiny's Corridor are warmer than the parts of the cave mentioned above. This untypical temperature distribution (Luetsher & Jeannin 2004; Mavlyudov 1997; Wirgley & Brown 1976), results from cave's icy part configuration as well as from the course of air exchange in winter period (November to April). In the contrary to the winter period, the temperature distribution in the summer period can be qualified as typical. The cold zone with the T_{AIR} below 0 °C appeared in the halls of the lower level of the cave, the upper level of the cave was warmer and the T_{AIR} here was slightly above 0 °C. Presented patterns of air temperature distribution occur every year despite the outside weather condition. And so, one may compare here the distribution of the T_{AIR} in the cold year (2006) with the distribution of T_{AIR} in the warm one (2007) (Fig. 3).

The course of changes of the air temperature inside the cave is different in each season of the year. In the free-of-ice part of the cave (Dripstone Hall) we observe only seasonal changes of air temperature and they are not significant. However, the icy part of the cave is a place where the dynamic of air temperature changes is much more visible and where we may observe the seasonal as well as the short-term variations of air temperature. For this part of the cave three types (patterns) of air temperature changes were distinguished. Each time, the dynamics as well as the scale of changes are different.

Type-1. The first type of air temperature changes appears in winter. Here, the in-cave T_{AIR} changes result from the ones from the outside of the cave (Fig. 4). These are short-term changes and their range can reach several Centigrade, however, the amplitude of those changes is always lower than the one of the outside of the cave. As to the spatial distribution of this quantity, Collapsed Dome and Underground Floor are the two places of the highest amplitude; its value is lower in Small Hall and the lowest in Ruffiny's Corridor area.

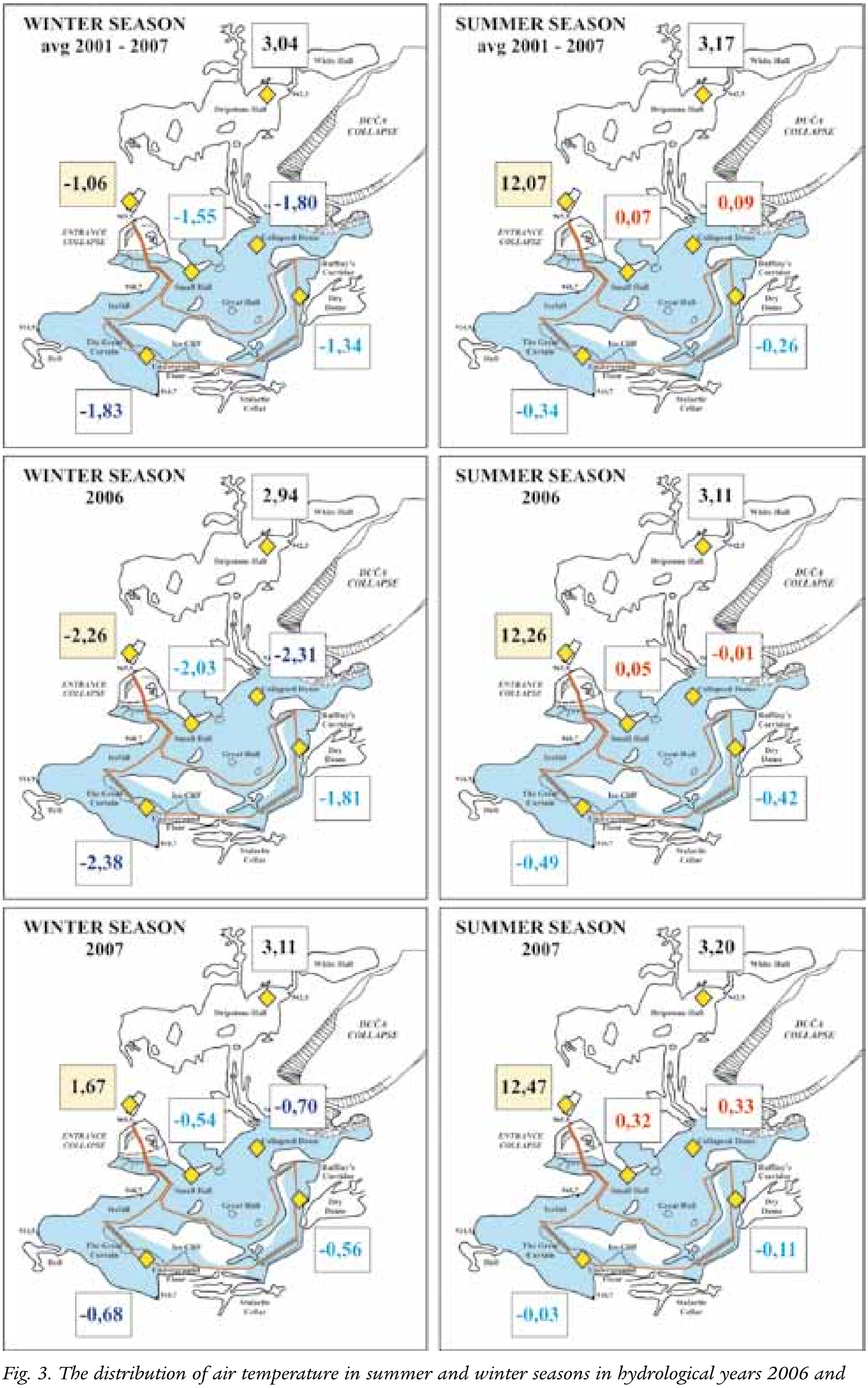

Fig. 3. The distribution of air temperature in summer and winter seasons in hydrological years 2006 and 2007 against mean long-term seasonal air temperature in the 2001–2007 period.

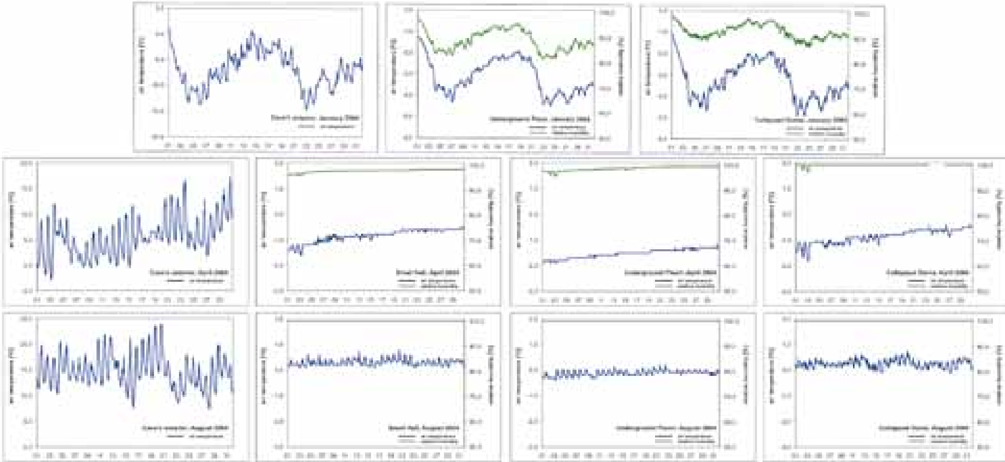

Fig. 4. The types of the course air temperature changes and relative humidity changes at the selected measurement points in Dobšinská Ice Cave against the air temperature changes outside the cave (hourly means). Type-1 on the top, Type-2 in the middle, Type-3 on the bottom of the graph.

Type-2. This pattern of the air temperature changes appears in spring and in warm periods of winter. The short-term changes of the T_{AIR} that are typical for winter does not exist in this pattern. The increasing trend in the air temperature is well visible here; however, the rate of increase does not exceed 0.1 °C / 24 h (Fig. 4). This pattern of air temperature changes persist until the T_{AIR} stabilize at 0 °C, which can differ in time: T_{AIR} of halls of the upper level of the cave gets stabilized at the beginning of summer (June/July) while the T_{AIR} of lower level of the cave stabilizes much later – depending on the cave temperature. It is quite possible that, in case of extreme events, the T_{AIR} in this part of the cave does not reach 0 °C in the warm period.

Type-3. Type 3 represents a typical pattern of summer changes of air temperature. The T_{AIR} gets stabilized at around 0 °C; however diurnal changes are well visible because of tourism. Only the Ta variation of the Collapsed Dom was marked with the daily rhythm of changes of the external air conditions (Fig. 4).

As to the spatial distribution, both air and rock temperature (T_{ROCK}), have similar annual distribution. The zone of cold of the halls of the lower level of the cave is well visible in the rock temperature distribution; as well as thermal privilege of the Small Hall and the Ruffiny's Corridor areas. In a summer half-year the temperature of rock massif of the lower level of the cave is below 0 °C, while the rock temperature of the halls of the upper level of the cave may be above 0 °C. The T_{ROCK} exceeds 0 °C in about a month after the relevant T_{AIR} increase (Tab. 1). The difference between T_{AIR} and T_{ROCK} indicate the heat transfer direction. The energy flux is from rock to air ($T_{ROCK} > T_{AIR}$) from November to February: the rock massif cools down and the cave air warms up (Tab. 1). The above air and rock temperature changes are explicable and confirmed. Thus, the genesis of the January anomalies of the upper level of the cave, when the air temperature is higher than the rock temperature, is still not clear. In spring as well as during the whole warm period of a year, the energy flux is from air to rock ($T_{ROCK} < T_{AIR}$).

Humidity conditions

The annual course of relative humidity changes inside the cave is similar in dynamics to the dynamics of the changes of air temperature. In winter, the RH value in the icy part of the cave varies form 80 to 95 % (Fig. 2 and 4). The lowest RH values were observed in Underground Floor and Collapsed Dome, which are the coldest parts of the cave. In the halls of the upper level of the cave (Small Hall and Great Hall) as well as in the Ruffiny's Corridor both, T_{AIR} and RH have greater values and so the amount of water

Table 1. The mean monthly temperature (T) of cave air (AIR) and rock surface temperature (ROCK) and the temperature difference between air and rock surface (Δ) at the selected measurement points inside the Dobšinská Ice Cave in the years of 1980 – 1984 (on the basis of Halaš 1986).

Measurement point	**T**	**Months**											
		I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
Small Hall	Air	-2.28	-2.85	-1.93	-1.08	-0.53	-0.13	0.08	0.18	0.23	0.18	-0.60	-1.36
	ROCK	-2.33	-2.63	-2.00	-1.23	-0.78	-0.30	-0.15	0.03	0.13	0.10	-0.58	-1.20
	Δ	0.05	-0.23	0.08	0.15	0.25	0.18	0.23	0.15	0.10	0.08	-0.02	-0.16
Great Hall/ Collapsed Dome	Air	-2.40	-3.10	-1.95	-1.08	-0.58	-0.20	-0.08	0.03	0.15	0.10	-0.66	-1.54
	ROCK	-2.60	-2.80	-1.88	-1.28	-0.75	-0.35	-0.23	-0.03	0.10	0.06	-0.52	-1.36
	Δ	0.20	-0.30	-0.08	0.20	0.18	0.15	0.15	0.05	0.05	0.04	-0.14	-0.18
Ruffiny‘s Corridor	Air	-2.55	-2.83	-1.93	-1.50	-0.78	-0.38	-0.10	0.05	0.05	-0.04	-0.70	-1.68
	ROCK	-2.40	-2.75	-1.90	-1.55	-1.08	-0.78	-0.60	-0.25	-0.13	-0.06	-0.70	-1.52
	Δ	-0.15	-0.08	-0.03	0.05	0.30	0.40	0.50	0.30	0.18	0.02	0.00	-0.16
Icefall	air	-3.63	-3.93	-2.58	-1.90	-0.90	-0.48	-0.38	-0.25	-0.13	-0.16	-1.12	-2.18
	ROCK	-3.38	-3.40	-2.70	-2.05	-1.20	-0.70	-0.53	-0.35	-0.25	-0.34	-0.92	-2.08
	Δ	-0.25	-0.53	0.13	0.15	0.30	0.23	0.15	0.10	0.13	0.18	-0.20	-0.10

vapour contained in the air is more significant in those areas. As the spring comes, the type nr 2 of the air temperature changes appears and RH value stops changing. The relative humidity inside the cave increases and the cave air quickly becomes almost saturated (RH > 95 %). The abovementioned conditions are the typical ones for spring and summer; after the first autumn freeze appears relative humidity inside the cave drop down (Fig. 2 and 4). In the free-of-ice part of the cave (Dripstone Hall) the humidity conditions do not change – the air is always almost saturated.

Air exchange

The studies on the air exchange in the Dobšinská Ice Cave proved the chimney effect to be the one that forms the process of cave ventilation. There is the complex of fissured debris that separates the cave interior from the Duča Collapse that play a role of a cave "chimney" (Pflitsch *et al.* 2007; Piasecki *et al.* 2004, 2005, 2008). The course of air exchange depends on the flux variation of the value and direction of the air temperature gradient between the inside and the outside of the cave. Thus, the seasonal variation of the air exchange is observed in the cave and one may distinguish here two air exchange types: the winter and the summer one.

Winter type of the air exchange appears when: the air temperature in the cave surroundings is below 0 °C and, in the same time, lower than in-cave air temperature. The difference in the air density makes the cold air flow into the cave via the entrance hole. In the entrance zone (Small Hall) the main air stream divides into two sub-streams, one of which passes on ice floor – through the halls of the upper level of the cave (Small Hall, Great Hall), than it goes to the Collapsed Dome and to the cave "chimney" (fissured debris complex in Collapsed Dome). The second sub-stream goes down to the halls of the lower level of the cave – it passes through the Icefall and Underground Floor in its way to the Ruffiny's Corridor (Fig. 5). The rock massif warms the two air streams up which process activates sublimation of cave ice. As a result the water vapour content in the cave air increases. Because of the longer way to go,

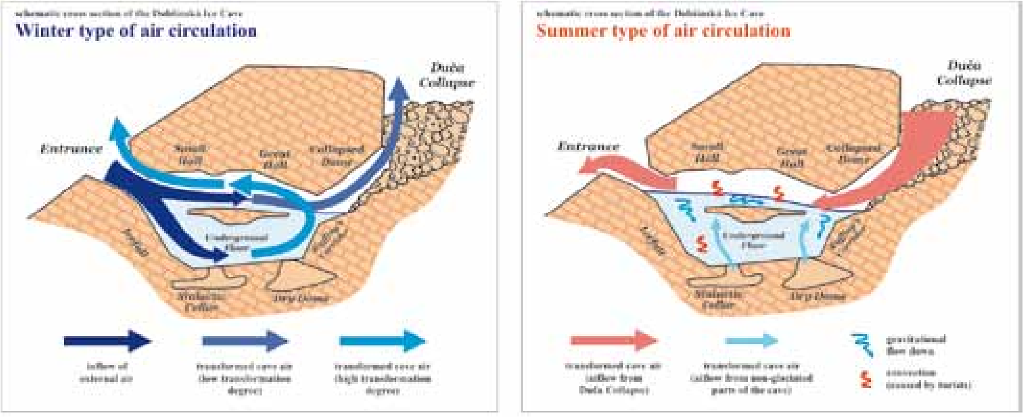

Fig. 5. The patterns of air exchange in the Dobšinská Ice Cave.

the air of the lower sub-stream is much more transformed than the air of the sub-stream which flows through the upper cave part (see Fig. 1 and 5). And so, the T_{AIR} in the Ruffiny's Corridor is higher than the T_{AIR} in the Great Hall (sometime the air temperature difference of these areas may increase up to 3 °C). In the cases like that the convective outflow of relatively warm and moist air stream from the Ruffiny's Corridor is observed. In Great Hall the stream moves under the cave ceiling in its way to Small Hall, and next it flows out the cave through entrance hole and near-entrance fissures. The relevant warm air flow that would be expected here (from Ruffiny's Corridor in a way to Collapsed Dome and cave "chimney") does not exist, because of the low ceiling that separates the Collapsed Dome from the Great Hall.

The under-ceiling flow of air in the halls of the upper part of the cave diversifies the air-flow structure in the area, which is particularly visible in the entrance zone. Two air streams are observed here and each of these two streams is in the opposite to the other. The above-floor stream is a stream of external air which flows into the cave and the under-ceiling stream of air lead the transformed in-cave air out of the underground system (Fig. 5).

The second type of air exchange is a summer type. This type appears when the external air temperature is higher than the in-cave temperature. Here, this is the difference in temperature, that makes the relatively heavy air, that accumulates in the chimney, go down (summer phase of the chimney effect). Then, the air passes through the halls of the upper level of the cave (Collapsed Dome, Small Hall and Great Hall) in their way to the cave entrance. Permanent air leakage from chimney fissures is compensated with the air sucked in its upper part, what causes intensive exchange of heat between air and rock inside the chimney. The in-flowing external air warms the chimney up, in the contrary, the air cools down and its relative humidity increases. The overall processes make the relatively warm and moist air flow into the icy part of the cave. According to the investigation results, the temperature of the flowing-out air was at 1.0 ° to 1.5 °C in July and August and its RH value was about 100 %.

In the lower part of the cave and during the summer air exchange phase, the outflow of air is observed, that comes from the holes connecting the Underground Floor and Ruffiny's Corridor with the free-of-ice parts of the cave (Stalactic Cellar and Dry Dome), as well as from the fissures developed under the ice monolith (Piasecki *et al.* 2008). The above outflow needs the same conditions to be active as the summer air flow of the upper cave part. This fact indicates that the genesis of the two air flows is exactly the same and the lower parts of the cave must be connected with the surface by chimney-like joining system. The air that flows out the fissures of the lower level of the cave is colder than the air that flows into the Collapsed Dome; in this case, the T_{AIR} may be above 0 °C but only at the end of the summer half-year. The difference results probably from the greater cooling of the lower part of the cave and from the less intensive air outflow there.

The summer air exchange appears mostly in the summer period. However, it was also observed in warm periods of winter. Both types of the air exchange may occur in turn in spring and autumn in a form of episode. The episodes take from several hours to a few days and they depend on the outside weather conditions.

Ice conditions

The dynamics of the ice processes of the Dobšinská Ice Cave and development of ice forms depend on the water conditions, on the ventilation processes and on the heat transfer between: the cave air, the rock massif, the cave ice and the infiltration water (Halaš 1980, 1986, 1989; Strug *et al.* 2004; Pflitsch *et al.* 2007; Strug & Zelinka 2008). All around a year, the ice forms of the cave can result from freezing of the infiltration water (which, in this case are the ice monolith and the ice speleothems) or from the development of the re-sublimation ice (ice crystals sediment). All the ice forms develop in a three-phase process which includes: winter phase, ice creation phase and ice degradation phase.

In winter phase, most of the precipitation water is accumulated in the snow cover and there is a lack of infiltration water in the winter phase. As the cold air flows into the cave (the outside temperature is below 0 °C) the rock massif, as well as the ice monolith, cool down (winter type of the air exchange). Because of the heat exchange, the cave air warms up. The increase in air temperature causes the increase of saturation deficit in the air, in turn; the sublimation process on the ice floor becomes very intensive. The influence of thermal and humidity conditions and also the airflow may result in lost of the ice volume in the monolith surface, which may be from a few to as many as several of millimetres (Strug & Zelinka 2008). At the entrance zone of the cave, the re-sublimation ice crystals appear. These crystals develop as a result of the air stream that passes through Ruffiny's Corridor in its way to the cave entrance. The air is relatively warm and moist, and with the contact with the cold rock in the near-entrance zone it cools down until the dew point temperature. The above conditions activate the re-sublimation processes and the ice crystals development (Strug *et al.* 2004; Pflitsch *et al.* 2007).

Ice creation phase. This phase is a typical one for spring, when the snow cover in the cave surroundings melts in a fast way. The cave interior is cold (the in-cave air and rock temperature is below zero) so the snowmelt water which infiltrates from the surface freezes inside. The above conditions make the ice speleothems appear; this is also a phase of the ice monolith increase (the increase in the ice monolith volume may be up to several of cm). The increase in the air temperature outside the cave makes the summer type of the air exchange begin: warm and moist air flows into the cave. As the rock massif is cold, the air cools down and the intensive growth in ice crystal cover is well visible overall the cave.

The phase of the ice creation may appear also in warm periods of winter, when snow cover melts. As the warm period of winter ends and the air temperature is low again, the water infiltration stops and soon after that the winter ice-phase reactivates (Strug *et al.* 2004; Pflitsch *et al.* 2007; Strug & Zelinka 2008).

The third phase is the **phase of the ice degradation**. The phase processes begin if the rock massif temperature is 0 °C or higher and the amount of cold accumulated in the ice monolith is not enough to freeze water. In the same time the covers of ice crystals and the ice speleothems on the cave ceiling disappear. The loss in ice volume may result from the heat supply caused by: the air exchange, the infiltration of water after a period of precipitation and the heat transfer from the rock massif. The anthropogenic heat is another factor that contributes to the ice mass loss. The phase of the ice degradation of the upper part of the cave begins in June/July. As to the lower level of the cave it may happen, that the ice mass may not loose its volume and, which is also possible, the ice mass may increase until the next winter ice-phase begins (Strug *et al.* 2004; Pflitsch *et al.* 2007; Strug *et al.* 2008; Strug & Zelinka 2008).

DOBŠINSKÁ ICE CAVE CLIMATIC SYSTEM

The Dobšinská Ice Cave climatic system is a system where the air exchange, the heat transfer (to and from the rock massif), the water infiltration as well as the ice mass development and degradation (which depend from actual weather conditions and from a season of a year) play a main role. The relationships and the dependencies between the above processes were crucial to distinguish six cave climate-ice complexes (from C-1 to C-6; see Tab. 2), that can describe the variable state of the cave climatic system. All the complexes were based on the characteristics of the typical meteorological situations which may be observed in the cave exterior (autumn and winter freezes, winter warmings, deep spring warmings, spring freezes, dry summer periods and summer periods with precipitations). The external meteorological conditions are the most important ones here and influence on the dynamics and on the climatic conditions of the cave interior a lot. Morphology of the cave, local tectonics and geology, cave sediments, ways and places of the water infiltration are constant factors and they are much less important for the cave climate, because they do not influence directly on the dynamics of climatic processes in short-time periods.

The cave climate-ice complexes C-1 and C-4 are the ones, where the cave cools down systematically as the cold air form the outside flows into the cave (this situation corresponds with Type-1 of air temperature changes). The above complexes may take as long as 100 days a year. While C-2 or C-3 activate, the air temperature of the cave system goes up (Type-2 of the air temperature changes). When C-3 is active, one may observe the most intensive development of the ice mass inside the cave. The C-5 and C-6 complexes are the ones with the important degradation of the ice volume (it is even much more evident when the 6^{th} complex is active). In this time air temperature inside the cave is around 0 °C (this is the Type-3 of air temperature changes).

In the above typology the anthropogenic heat supply (caused by visitors and the cave lights) is not included. The amount of this heat is estimated at 83,965,016 – 89,781,316 kJ/year (Halaš 1986, 1989) and it is used for ice melting as well as for the cave ceilings heating (because of convective lifting of relatively warm air). The Dobšinská Ice Cave is opened for tourists for six months and so the anthropogenic heat income is limited in time.

The 1980' the studies on the cave energy balance revealed that these are the C-1 and C-4 complexes that play a key role in the cave climate. In the cold periods of a year, when the air temperature in the cave surroundings is below 0 °C, the cave system looses about -186,751,872 kJ, while the mean heat value that enters to the cave system in warm periods is estimated to be at 54,330,048 kJ (plus the anthropogenic heat). The cold that had been stored in the cave in winter allows the ice mass balance to be positive and the annual increase in the ice mass is estimated to be at 11 – 13 mm (Halaš 1986, 1989). The analysis of thermal conditions of the 2006 and the 2007 years (year 2006 was the coldest year of the investigation period and the year 2007 was the warmest one; Fig. 2) prove that this is the length of a particular weather pattern than influences the most the energy balance. Short-term periods of cold in winter (2006/2007) and relatively high air temperature made the cave not cool down. What's more, after the winter period in the whole icy part of the cave (including its lower part) the air temperature rapidly arose up to 0 °C (Fig. 6). As a result the phase of the ice degradation was 1.5 month longer than its mean annual length. Energy equilibrium in the cave system was also disturbed – not all the energy was used in the process of ice melting and its excesses did cause noticeable growth of temperature in the cave upper part (Fig. 6).

SUMMARY

These are the Dobšinská Ice Cave location and configuration formed by collapse event that made the great ice monolith appear. The monolith is an important component of the cave climatic system. The processes of development and degradation of cave ice moderate the cave microclimate and they are in close relation with the other in-cave climatic processes.

Table 2. The characteristics of the cave climatic-ice complexes in the Dobšinská Ice Cave in dependence on the weather type outside the cave.

weather type outside the cave	cave climatic-ice complexes	course of air exchange	characteristic of water infiltration process	ice conditoins	characteristic of thermal and humidity conditions inside the cave	characteristic of energy exchange
autumn and winter freezes	**C-1**	winter type	lack of infiltration or limited infiltration	ice sublimation on the ice monolith surface; development of the re-sublimation ice (ice crystals sediment) on the cave ceiling	T_{AIR} below 0 °C, significant variations of T_{AIR}; RH value varies form 80 to 95 %; **Type-1** of air temperature changes	direction of heat transfer – from rock surface to cave air (T_{ROCK}>T_{AIR}) – the rock massif cools down and the cave air warms up; the cave cooling is intensified by latent heat absorbing (sublimation process); part of the latent heat is returned in re-sublimation process
winter warmings	**C-2**	summer type	limited infiltration (lack of infiltration also possible)	development of the re-sublimation ice (ice crystals sediment) in the whole cave area	T_{AIR} below 0 °C, constant increase of T_{AIR}; RH value stops changing and increases rapidly to 100 %; **Type-2** of air temperature changes	heat supply caused by air flowing into the cave and by latent heat from (re-sublimation process); heat supply caused by infiltration water and latent heat (freezing processes) also possible; direction of heat transfer – from air to cold rock surface (T_{AIR}>T_{ROCK})
deep spring warmings	**C-3**	summer type	intensive infiltration	freezing of infiltration water; development of the re-sublimation ice (ice crystals sediment) in the whole cave area	T_{AIR} below 0 °C, constant increase of T_{AIR}; RH value stops changing and increases rapidly to 100 %; **Type-2** of air temperature changes	heat supply caused by air flowing into the cave, by infiltration water and by latent heat (re-sublimation process, freezing process); direction of heat transfer – from air to cold rock surface (T_{AIR}>T_{ROCK})
spring freezes	**C-4**	winter type	limited infiltration (possible with high snow-melt water resources in ground and rock massif)	if infiltrations occurs – intensive freezing of water; lack of infiltrations – ice sublimation on the ice monolith surface; development of the re-sublimation ice (ice crystals sediment) possible	T_{AIR} below 0 °C, significant variations of T_{AIR}; RH value varies form 80 to 95 %; **Type-1** of air temperature changes	direction of heat transfer – from rock surface to cave air (T_{ROCK}>T_{AIR}) – the rock massif cools down and the cave air warms up; the cave cooling is intensified by latent heat absorbing (sublimation process); part of the latent heat is returned in re-sublimation and water freezing processes
dry summer periods	**C-5**	summer type	limited infiltration or lack of infiltration (drought)	low intensive ice melting on the ice monolith surface; intensive degradation of ice crystals sediment (air flowing impact)	T_{AIR} around 0 °C; RH around 100 %; **Type-3** of air temperature changes	heat supply caused by air flowing into the cave; this heat is absorbed in ice melting process and is used in rock heating (T_{AIR}>T_{ROCK})
summer periods with precipitations	**C-6**	summer type	water infiltration into the cave (infiltrations depends on intensity of precipitations)	intensive degradation of the cave ice	T_{AIR} around 0 °C; RH around 100 %; **Type-3** of air temperature changes	heat supply caused by air flowing into the cave and by infiltration water; this heat is absorbed in ice melting process and is used in rock heating (T_{AIR}>T_{ROCK})

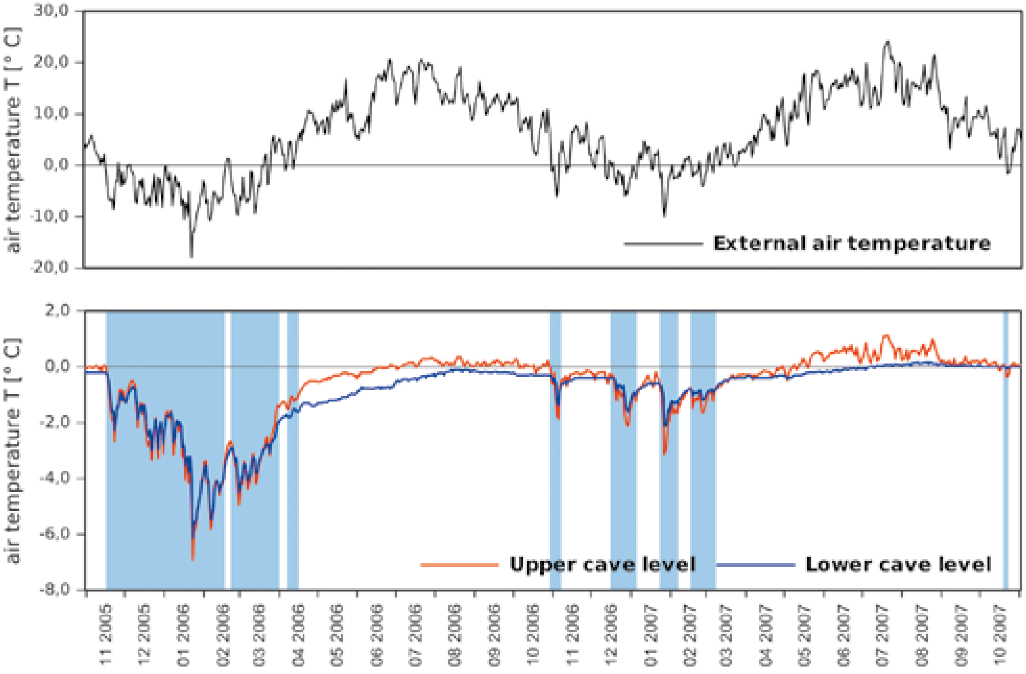

Fig. 6. Comparison of thermal conditions inside and outside the cave in the hydrological years 2006 and 2007. The grey colour indicates periods when the first (C-1) and the fourth (C-4) climate-ice complexes (CWC-3) occurred.

According to the cave climate studies, the seasonal changes in the air exchange between the cave and its surroundings as well as the in-cave air exchange are the main climatogenic factors in the cave climate system. Spatial distribution of the air temperature and humidity and energy balance of the cave depend on them and also (in indirect way) the cave ice development and degradation. There are two types of air exchange: the winter one and the summer one. Each of them dominates in a particular season of a year. However, it happens quite often, that both of them may appear in turns, especially in spring and autumn. The first type of air exchange cools the cave system down while the second is an important component in the process of development (in spring) and in degradation (summer) of the cave ice. As an effect of interaction between ice processes and air exchange processes one can point the characteristic patterns of air temperature and humidity changes which can be observed inside the cave.

Cave climate-ice complexes distinguished in the paper result from the overall changes and dependencies of the cave microclimate. The main characteristics used in the complexes description are: external meteorological conditions, in-cave meteorological conditions, air exchange, simple characteristics of energy exchange and course of ice processes. Definition of the complexes is an attempt to comprehensive description of the climatic conditions of the Dobšinská Ice Cave.

References

Christoforou, Ch. H., Salmon, L. G. & Cass, G. R. 1996: Air exchange within the Buddhist cave temples at Yungang, China. Atmospheric Environment, 30, 23, 3995 – 4006.

Cigna, A. A. 2002: Modern trend in cave monitoring. Acta Carsologica, 31, 1, 35 – 54.

Deacon, J. 2006: Rock art conservation and tourism. Journal of Archeological Method and Theory, 13, 4, 379 – 399.

Fajmon, J., Štelcl, J. & Sas, D. 2006: Antropogenic CO_2 flux into cave atmosphere and its environmental impact: A case study in the Cisařská Cave (Moravian Karst, Czech Republic). Science of the Total Environment, 369, 231 – 245.

Fernández-Cortés, A., Calaforra, J. M., Jiménez-Espinosa R. & Sánchez-Martos, F. 2006: Geostatistical spatiatemporal analysis of air temperature as an aid to delineating thermal stability zones in a potential show cave: Implications for environmental managment. Journal of Environmental Managment, 81, 371 – 383.

Halaš, J. 1980: Vplyv fyzikálnych veličín ovzdušia na genézu ľadových útvarov v Dobšinskej a Demänovskej ľadovej jaskyni. Slovenský kras, 18, 139 – 145.

Halaš, J. 1985: Novše poznatky z merania teploty horninového plášťa. Slovenský kras, 23, 69 – 88.

Halaš, J. 1986: Tepelná bilancia Dobšinskej ľadovej jaskyne. Kandidátska dizertačná práca, Vysoká škola technická – Banícka fakulta, Košice, manuskript, archív Správy slovenských jaskýň, 119 p.

Halaš, J. 1989: Tepelná bilancia Dobšinskej ľadovej jaskyne. Slovenský kras, 27, 57 – 71.

Luetscher, M. & Jeannin, P.-Y. 2004: A process-based clasification of alpine ice caves. Theoretical and Applied Karstology (Special Issue on Ice Caves), 17, 5 – 10.

Mavlyudov, B. R. 1997: Caves climatic systems. *Proceedings of the 4th International Congress of Speleology, Symposium 7: Physical Speleology,* La Chaux-De-Fonds, 191 – 194.

Novotný, L. 1995: K veku jaskynného systému Stratenskej jaskyne. *Ochrana ľadových jaskýň, Zborník referátov z odborného seminára,* Dobšinská Ľadová Jaskyňa, 21. – 22. 9. 1995, Liptovský Mikuláš, 37 – 41.

Pflitsch, A., Piasecki, J., Sawiński, T., Strug, K. & Zelinka, J. 2007: Development and degradation of ice cristals sediment in Dobšinská Ice Cave (Slovakia). In Zelinka, J. (ed.): *2nd International Workshop on Ice Caves, Proceedings,* 38 – 49.

Piasecki, J., Sawiński, T. & Zelinka, J. 2005: The spatial differentiation of air temperature in the entrance collapse of Dobšinská Ice Cave as a contribution to the recognition of air exchange between the cave and its environment. Slovenský kras, 43, 81 – 97.

Piasecki, J., Sawinski, T. & Zelinka, J. 2008: The structure of air flow inside the lower part of the Dobšinská Ice Cave (the Underground Floor – Ice Cliff area). Slovenský kras, 46/1, 127-141.

Piasecki, J., Zelinka, J., Pflitsch, A. & Sawiński, T. 2004: Structure of air flow im the upper parts of the Dobšinská Ice Cave. *Výskum, využívanie a ochrana jaskýň, Zborník referátov zo 4. vedeckej konferencie,* 113 – 124.

Russel, M. J. & MacLean, V. L. 2008: Management issues in a Tasmanian tourist cave: Potential microclimatic impacts of cave modifications. Journal of Environmental Management, 87, 474-483.

Strug, K., Piasecki, J., Sawiński, T. & Zelinka, J. 2004: The ice crystals deposit in the Dobšinská Ice Cave. *Výskum, využívanie a ochrana jaskýň, Zborník referátov zo 4. vedeckej konferencie*, 125 – 133.

Strug, K., Perşoiu, A. & Zelinka, J. 2008: Preliminary results of ice temperature measurements in the Dobšinská Ice Cave (Slovakia) and Scărişoara Ice Cave (Romania). *3rd International Workshop on Ice Caves, Proceedings*, 16 – 22.

Strug, K. & Zelinka, J. 2008: The influence of extremely different external thermal conditions on the ice forms occurrence in slovak ice caves in the 2005 – 2007 period. *3rd International Workshop on Ice Caves, Proceedings*, 74 – 84.

Tulis, J. & Novotný, L. 1989: Jaskynný systém Stratenskej jaskyne. Osveta, Martin, 464 p.

Tulis, J. & Novotný, L. 1995: Čiastková správa o morfometrických parametroch v zaľadnených častiach Dobšinskej ľadovej jaskyne. *Ochrana ľadových jaskýň, Zborník referátov z odborného seminára*, Dobšinská Ľadová Jaskyňa 21. – 22.9.1995., Liptovský Mikuláš, 25 – 28.

Wigley, T. M. L. & Brown, M. C. 1976: Cave Meteorology. In Ford, T. D. & Cullingford, C. H. D. (eds.): *The Science of Speleology*, Academie Press, 329 – 344.