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Temperature and humidity conditions of Macocha Abyss

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Abstract: The paper deals with the evaluation of temperature and humidity measurements in the vertical profile of Macocha Abyss (Moravian Karst, South Moravia, Czech Republic). The measuring profile on a rock wall is made up of seven HOBO-PRO sensors. Two other meteorological stations are installed at the bottom and near the upper edge of the abyss. The evaluation was designed separately for warm season (June 1, 2008 to August 31, 2008) and cold season (November 1, 2008 to February 28, 2009). In the warm season, distribution of inverse temperatures dominated in the abyss. Temperature differences between the bottom of the abyss and its upper edge reached about 10 °C. At the bottom of the abyss, the minimum temperatures proved to be higher than at its upper edge and in its vicinity. Thermal circulation is evident to the depth of about 60 m. The highest temperatures were observed in the deeper layers of the abyss in the warm period at around 10 a.m. of Central European Summer Time. Towards the upper edge of the abyss, the hour of daily maximum temperature shifts to 2 to 4 p.m. In the cold season, the minimum temperature was observed between 6 and 7 a.m. of Central European Time. A decrease in the accumulation of cold air (cold-air pool formation) was not found in the lower floors of the abyss. This phenomenon does not occur even during clear nights. The depth of 60 m from the upper edge of the area maintains a high relative humidity (above 95%) in the warm season. However, humidity decreases from this depth towards the top of the abyss. In the cold season, the whole abyss is filled with air with relative humidity of 90 to 95%.

Key words: air temperature, air humidity, microclimate, karst, abyss

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1. Introduction

Much less attention is paid to concave terrain shapes in terms of climate than to convex terrain shapes. Exploring microclimate of field depressions, swallow-holes, sink-holes, valleys, canyons, chasms, abysses, collapse valleys and similar forms (for a detailed specification see *Field, 2002*) is usually linked to karst or mountain areas. For deeper karst terrains, all kinds of depressions are typical e.g. Dinaric Karst (*Kranjc, 2006; Kranjc, 2004*). For example Laška Kukava and Smrekova Draga from the Dinaric karst valleys (Planinsko polje, central Slovenia) are well known due to their temperatures and vegetation. Specific conditions and temperature inversion phenomena were studied in Laška Kukava valley by *Martinčič (1977).*

Temperature regime of soil and air in deeper karst depressions with regard to elevations above the sea level and geographical orientation are studied by *Bárány-Kevei (1999). Whiteman et al. (2004b)* conducted vertical soundings and sidewall air temperature measurements in a limestone sinkhole (valley) in karst plateau on Hetzkogel (Austria).

In topographically and climatically highly specific conditions of deep vertical crevices in Poseidon Sandstone Labyrinth (vertical range of 105 m) the vertical profile of air temperatures was studied by *Růžička et al. (2010).* Significant climatic inversion occurs in this region mainly due to its vertical structure. Microclimatic conditions such as sinkholes were studied by *Whiteman et al. (2004a)*, who describe the creation of lakes of cold air at night. *Bárány-Kevei (1999)* reported the minimum radiation at minus 3 °C during night in a valley of the plateau of the Bükk Mountains where significant climatic inversion occurs mainly due to vertical structure of the valley. *Litschmann and Rožnovský (2008)* and *Litschmann et al. (2008)* describe the climatic conditions of karst narrow canyons. As opposed to sinkholes, there is limited occurrence of cold air at night and the subsequent inversion in narrow canyons. If basins and valleys are deep and narrow, sensible heat flux from daytime heat storage in the sidewalls can keep warmer nocturnal temperatures and strong temperature inversion inhibit formation *(Geiger, 1965).* It can be assumed that a similar effect in relation to the Topographic Amplification Factor *(Whiteman, 1990)* will apply also in the abysses with similarly shaped terrain (predominant vertical walls).

Within the scope of ME No. SP/2D5/5/07 project "Determination of cave microclimate depending on external weather conditions in CR show caves" monitoring of vertical temperature and humidity in Macocha Abyss in Moravian Karst (South Moravia, Czech Republic) was established in 2008. Measuring profile is a part of a special network of climatological stations located around Macocha Abyss. The stations monitor temperature and humidity, rainfall, wind speed and direction, global radiation, air pressure, humidity and soil temperature.

This paper analyzes in detail the measured values of temperature and humidity in the vertical profile of Macocha Abyss over two periods: June–August 2008 (warm period of the year) and December–February 2008/2009 (cold period of the year).

2. Material and methods

The locality studied

Macocha Abyss probably came to being by collapse of the dome of an underground vault, under which the river Punkva flows. Fusion of karst depressions on the surface with the cave created a vertical cavity. Depth of the abyss (measured up to the lake level at the bottom) is 138.4 m, maximum length is 281 m, and maximum width is 126 m, length of his own esophagus is 114 m. Mighty dimensions of the abyss allow daylight enlightenment of its entire precinct ("light hole" in the karst classification). This fact is reflected in both climate and vegetation. With regards to cross section it is possible to recognize almost perpendicular rock wall, facing the northeast, the opposite side is composed of at first gradual slope, which again passes into an almost perpendicular cliff.

Measuring device

The vertical profile for temperature and humidity measurements consists of seven series of HOBO-PRO (Onset, USA). The sensors are located under covers made of stainless steel with a double wall placed on the vertical rock wall with north-eastern orientation. Distance of the measuring devices from the wall is 40 cm. Download of the data is performed using a laptop and climbing equipment. At the bottom of the abyss, there are weather stations installed to monitor the microclimate of the bottom of the abyss. There is a meteorological station located near the upper edge of the abyss that measures and records conditions in the plateau surroundings. The meteorological data is registered in fifteen-minute intervals as instantaneous values. Figure 1 shows a photo of Macocha Abyss with marked location of individual sensors.

Fig. 1. Positions of individual sensors along the abyss wall.

Evaluation of data

Two seasons were chosen for the purposes of evaluation as follows:

– 1.6.2008 to 31.8.2008 marked as the "warm period". Macocha Abyss is characterized by higher air temperatures and direct sunlight penetration to the bottom of the abyss (at least during short episodes) in the warm period.
– 1.12.2008 to 28.02.2009 marked as the "cold period", during which mostly low temperatures occur. Direct solar radiation illuminates only the upper part of the wall of the abyss. Separate processing of these two parts allows a better understanding of the processes taking place in the air filling the space between the walls of the abyss. The average daily temperature and humidity were determined as the arithmetic average of all fifteen-minute data of the day. The maximum and minimum values represent the highest and the lowest value of a fifteen-minute measurement interval of a day given.

Statistical evaluation (analysis of variance and Fisher LSD test) of air temperature and air moisture performed using STATISTICA software (ver. 7.0).

3. Results and discussion

Dynamics of air temperature and vertical profiles of average temperature are shown in Fig. 2. Inverse distribution of air temperature dominates in the warm period. The temperature difference between the bottom of the abyss and its upper edge reaches about 10 °C. In the first few dozen meters from the top edge, the temperature changes only very little, as a result of turbulent heat transfer. Increasing depth causes almost linear temperature drop up until the bottom of the abyss. *Gabrovšek and Mihevc (2009)* state that if the abyss is connected with underground areas, the inversion of temperature is more pronounced in summer time when bottom temperatures do not exceed the cave temperatures in a great extent. The cold season brings apparent increase in average temperature with increasing depth. This dependence is almost linear. The difference in average temperature between

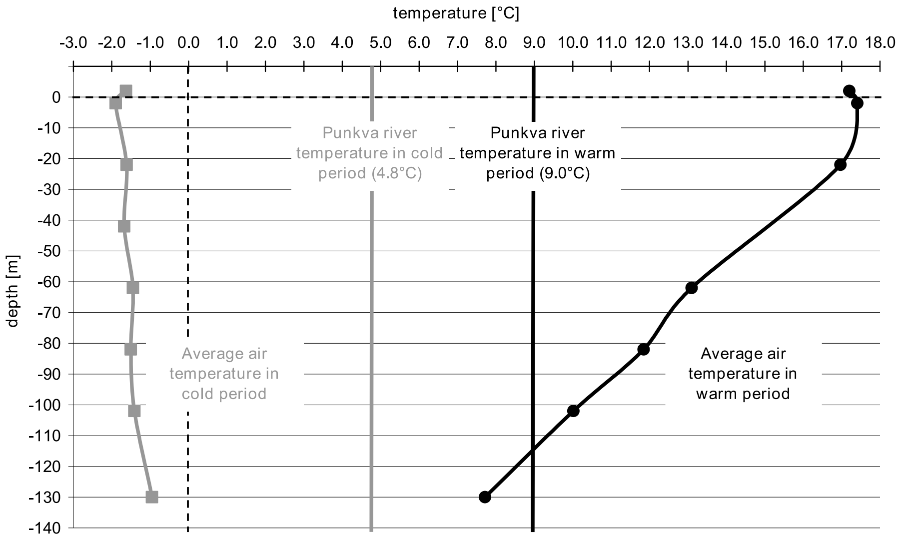

Fig. 2. Vertical profile of air temperature and average temperature of Punkva river.

the top and bottom edge of the abyss is 0.94 °C. Vertical gradient reaches 0.72 °C per 100 m. It is almost identical to the value of dry adiabatic lapse rate. Figure 1 contains the average water temperature in Punkva river. Especially in the cold season, the difference between the air temperature of and water temperature at the bottom of the abyss is significant. Temperature of Punkva river is influenced by its flow trough the rock massif. Its annual temperature variation is therefore strongly limited. However, especially in the winter the air temperature inside the abyss is mainly influenced by cold air flowing from upper part of the abyss.

Statistical analysis of daily air temperature differences in warm period for individual sensors is shown in Table 1. Table for cold period is not included because all differences are significant.

Figure 3 shows average daily amplitude of the air in the profile of the abyss. The highest amplitudes were measured at the station located on the upper edge of Macocha Abyss in the warm period. At this point, the largest heat exchange with the active surface takes place and the temperature variance is the highest. The amplitude decreases by about 5 °C in the area of the abyss from its top edge to the depth of 20 m. Towards the bottom of the abyss, the amplitude of air temperature decreases and reaches values smaller than 1 °C at the very bottom of the abyss.

In the cold season, the difference in amplitude between the surface station and the air at the top of the abyss is less than 1 °C. This is due to lower input of solar radiation in this part of the year. Towards the bottom of the abyss, the amplitude does not decrease significantly. The amplitude

Table 1. Statistical analysis (significance level, p–value) of daily air temperature differences for individual sensors, warm period

	{1} 17.411	{2} 16.971	{3} 13.094	{4} 11.845	{5} 10.017	{6} 7.7164	{7} 17.202
Mac1 {1}		*0.097*	0.000	0.000	0.000	0.000	*0.431*
Mac2 {2}	*0.097*		0.000	0.000	0.000	0.000	*0.382*
Mac4 {3}	0.000	0.000		0.000	0.000	0.000	0.000
Mac5 {4}	0.000	0.000	0.000		0.000	0.000	0.000
Mac6 {5}	0.000	0.000	0.000	0.000		0.000	0.000
Mac7 {6}	0.000	0.000	0.000	0.000	0.000		0.000
Surface station {7}	*0.431*	*0.382*	0.000	0.000	0.000	0.000	

Note: statistically insignificant differences are marked by italics font; $p < 0.05$ significant difference, $p < 0.01$ high significant difference.

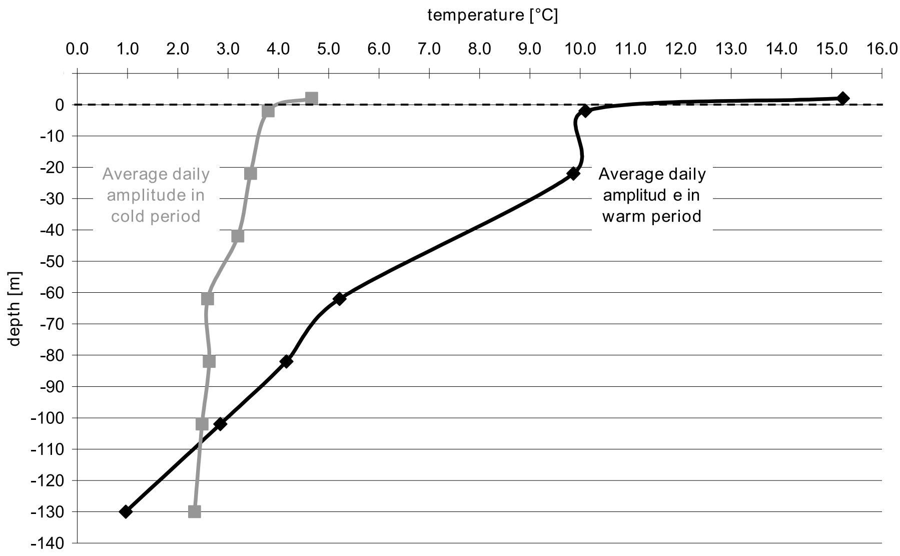

Fig. 3. Average daily amplitude of air temperature.

in the deepest parts of the abyss is higher in the cold period than in the warm period. This shows greater exchange of air in this period.

Daily minimum air temperatures are shown in Fig. 4 (warm period) and Fig. 5 (cold period). For greater clarity, only values from surface stations and the lowest and highest sensors in the abyss are used in the graphs. The air mass at the bottom of the abyss has relatively constant temperature in the warm period. The change of its temperature occurs only when a significant cooling occurs, i.e. when the minimum air temperature at the surface station reaches less than 6 °C. Cold air from the plateau begins to flow down to the bottom of the abyss and fills it. The values of minimum temperatures at the bottom and top of the abyss are almost identical in these cases. However, they are always higher than the minimum measured at the surface station.

In the cold period (Fig. 4), these situations are quite numerous. For this reason, the link between the minimum temperatures on the surface, at the bottom and top of the abyss are closer than in the warm season. The minimum air temperatures at the bottom of the abyss are almost always higher

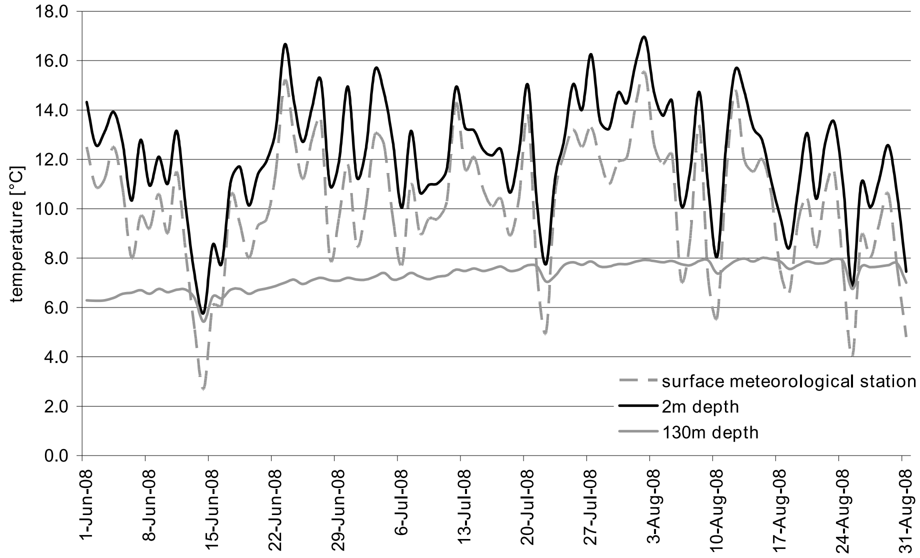

Fig. 4. Minimal air temperatures in the warm period.

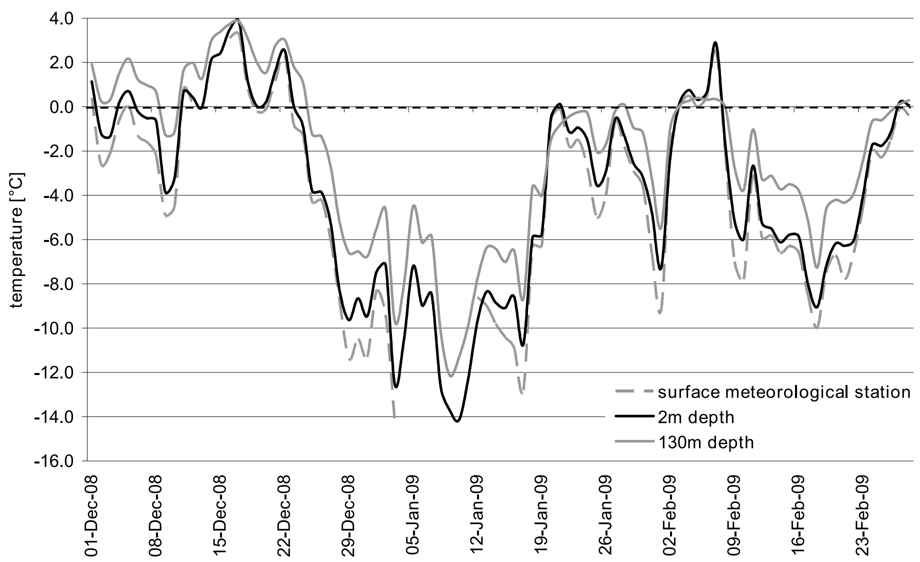

Fig. 5. Minimal air temperatures in the cold period.

in comparison with the temperatures measured at the surface station and the temperature measured at the upper edge of the abyss. The reason dwells in absence of radiative cooling of the air and flow of the cold air down to the bottom. There were not found significantly lower temperatures at the bottom of the abyss than in the surrounding flat terrain. The descending air is warmed dry adiabatically. Consequently, the minimum temperatures proved to be higher at the bottom of the abyss than at its top edge or in its vicinity. In accordance with the above statement, a few days with the advection of warmer air occurred during the cold period (the temperature at the bottom of the abyss was lower than in its upper part and on its surface). Such situations occurred on 21. 1. 2009 and 7. 2. 2009.

Daily continuance of air temperatures in the abyss is influenced not only by the inflow of cold air from the surrounding terrain in the time before sunrise but also by gradual heating of the walls and subsequent heating of the air in the abyss after sunrise. Ascent of the air is terminated after reaching the negative energy balance on the surrounding terrain and is followed by a decrease of colder air to the bottom edge of the abyss. Topographic parameter seems to have a correlation with air temperature development with the amount of sky visible from the bottom of the basin (*Steinacker et al., 2007*). The daily course of meteorological elements in the field depression affects the character of vegetation and nature of the substrate.

Daily course of air temperatures in cold and warm periods is shown in Fig. 6 and Fig. 7.

In the warm period, the lowest temperatures were observed in the whole profile across the abyss around 5 a.m. *Zängl (2005)* reveals that during undisturbed clear nights, the air in closed sinkholes cools very rapidly around sunset, followed by a more gradual cooling at night. After sunrise, the upper part of the abyss is illuminated first. The rays are parallel to the longitudinal axis of the abyss around 10 a.m. of Central European Summer Time (CEST). The highest temperatures are observed in deeper layers at this time. Towards the top edge, where turbulent air exchange is predominant, the maximum is observed at around 2-4 p.m., when the maximum temperatures are also observed on the surface. *Bárány-Kevei (2011)* introduces the influence of slope orientation and in particular time of the day on the formation of vertical stratification of temperatures in the karst terrain depression.

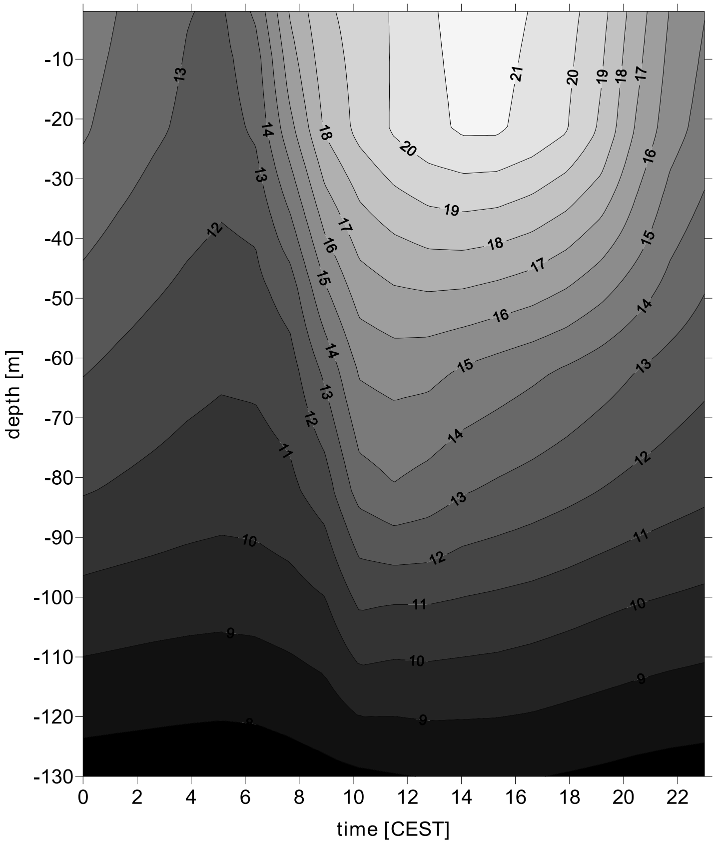

Fig. 6. Daily course of temperatures in the warm season.

In the cold season (Fig. 7), the minimum temperature was achieved between 6 and 7 a.m. of Central European Time (CET). Unlike in the warm season, the lowest temperature was observed at the upper edge of the abyss. Temperatures at the bottom of the abyss are about 1.2 °C higher (due to adiabatic warming of decreasing cold air). Warming of the air in the abyss due to heat flow from the rock massif or from the Punkva river possibly arises mainly during the daylight hours. These physical processes occur also in the night and in the morning, but are probably covered by cold air flowing from the upper parts. At this time the air heated by Punkva river and by rock massif rises up and is adiabatically cooling. So that the tem-

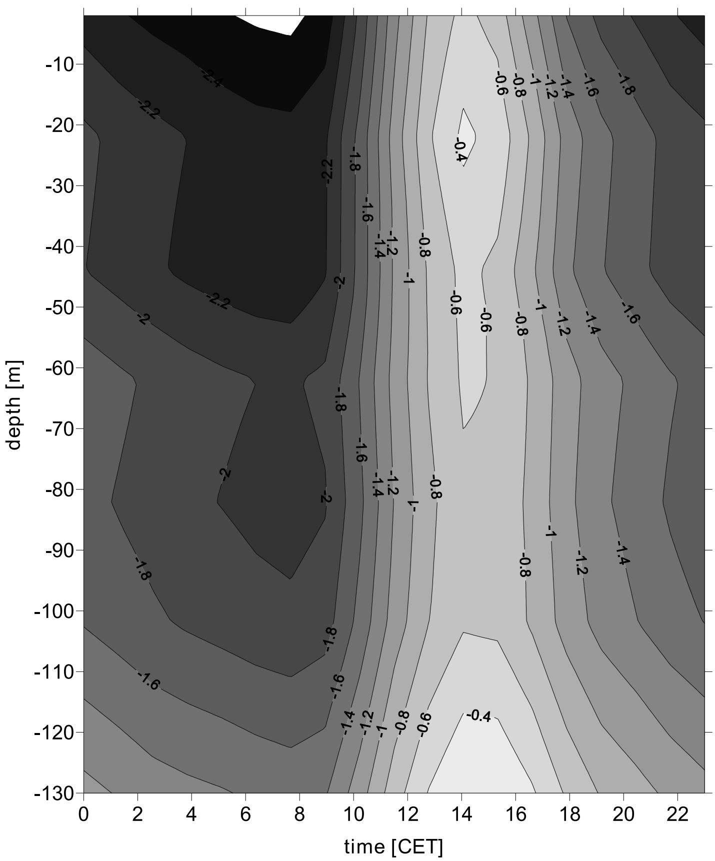

Fig. 7. Daily course of temperatures in the cold season.

perature course is identical as when cold air fall down into the abyss and is adiabatically warming.

The highest temperatures occurred between 1 and 2 p.m. At around 10 a.m., isotherma occurs throughout the whole profile of the abyss, similarly as between 4 and 6 o'clock in the afternoon. Increase in the temperature throughout the whole profile across the abyss in the afternoon can be caused by inflow of heat from the rock massif. There can occur significant transfer of heat through water penetrating the cracks, as well as through air flow from the underground space in karstic rocks (*Luetscher and Jeannin,* *2004*). Changes in temperature during the cold period in the day at the bottom of the abyss are significant. In absolute terms it reaches around 1 °C. In the warm season, the temperature of the rock massif is lower and therefore the heating effect of the mass does not apply.

Dynamics of humidity

Average daily values of relative humidity of both periods are shown in Fig. 8. In the warm season, the area with high relative humidity (above 95%) was observed from the depth of 60 m below the surface. However, humidity decreases from this depth towards the surface. Just below the surface it reaches around 74%, on the surface it decreases by 5% or less. In the warm period, more intensive change of air occurs in the depth to 60 m. This fact is caused, among others, by thermal circulation in the rock walls brought about by access of sunlight to greater depths. For this reason, the values of humidity to the depth of 60 m are relatively high and unchanged with increasing depth. At greater depth (i.e. 60 meters or more) the air exchange with the surrounding atmosphere is limited – air is mixed with steam from the surrounding water areas at the bottom of the abyss and wet rock walls during precipitation.

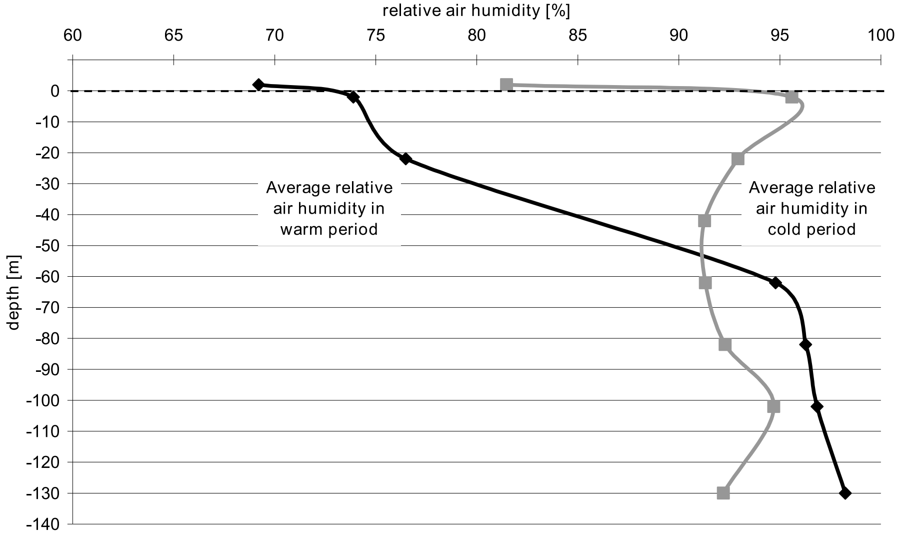

Fig. 8. Vertical profile of average relative humidity.

In the cold period, the abyss is filled with air with relative humidity of 90 to 95%. It is characterized by a significant difference (14%) between the upper edge of the abyss and the surface station. This difference is greater than the difference between the same points in the warm period.

Statistical analysis of daily air humidity differences in warm period and for individual sensors is shown in Table 2 – warm period and in Table 3 – cold period.

In the cold period, more frequent descent of cold air masses to greater depths occurs in the moisture regime of the abyss. The air is warmed adiabatically and saturation does not occur. Less moisture was measured in the cold period than in the warm period at the bottom of the abyss. In the

Table 2. Statistical analysis (significance level, p-value) of daily air humidity differences for individual sensors, warm period

	{1} 73.891	{2} 76.485	{3} 94.780	{4} 96.273	{5} 96.838	{6} 98.239	{7} 69.205
Mac1 {1}		0.004	0.000	0.000	0.000	0.000	0.000
Mac2 {2}	0.004		0.000	0.000	0.000	0.000	0.000
Mac4 {3}	0.000	0.000		*0.093*	0.021	0.000	0.000
Mac5 {4}	0.000	0.000	*0.093*		*0.524*	0.027	0.000
Mac6 {5}	0.000	0.000	0.021	*0.524*		*0.115*	0.000
Mac7 {6}	0.000	0.000	0.000	0.027	*0.115*		0.000
Surface station {7}	0.000	0.000	0.000	0.000	0.000	0.000	

Note: statistically insignificant differences are marked by italics font; $p < 0.05$ significant difference, $p < 0.01$ high significant difference.

Table 3. Statistical analysis (significance level, p-value) of daily air humidity differences for individual sensors, cold period

	{1} 94.684	{2} 92.410	{3} 92.022	{4} 92.763	{5} 93.567	{6} 95.643	{7} 93.748	{8} 84.450
Mac1 {1}		0.017	0.005	0.044	*0.242*	*0.315*	*0.327*	0.000
Mac2 {2}	0.017		*0.684*	*0.711*	*0.225*	0.001	*0.161*	0.000
Mac3 {3}	0.005	*0.684*		*0.437*	*0.106*	0.000	*0.071*	0.000
Mac4 {4}	0.044	*0.711*	*0.437*		*0.399*	0.003	*0.302*	0.000
Mac5 {5}	*0.242*	*0.225*	*0.106*	*0.399*		0.030	*0.849*	0.000
Mac6 {6}	*0.315*	0.001	0.000	0.003	0.030		0.047	0.000
Mac7 {7}	*0.327*	*0.161*	*0.071*	*0.302*	*0.849*	0.047		0.000
Meteostation {8}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	

Note: statistically insignificant differences are marked by italics font; $p < 0.05$ significant difference, $p < 0.01$ high significant difference.

midday and afternoon hours, slight upward flow caused by the fluctuating heat from the surrounding rock mass occurs. Rising air cools in this case and humidity rises. Therefore, the value of humidity in the whole profile across the abyss does not change much and reaches high values even at its upper edge, where they reach values higher by 30% in the cold season as compared with the warm season. The presumption of increased moisture in the outcoming air was confirmed by low average daily amplitude of humidity in the cold season (Fig. 9). In the warm season, this flow does not take place and the amplitude of humidity rises towards the upper edge of the abyss.

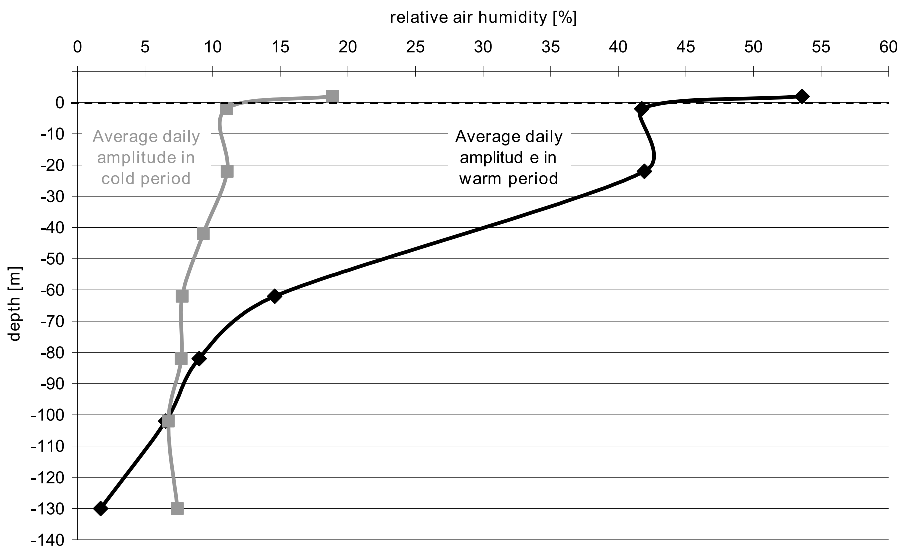

Fig. 9. Average daily amplitude of humidity.

4. Conclusion

Using a detailed long-term monitoring of temperature and humidity basic features of mode of these elements were determined in Macocha Abyss and its surrounding area.

In the warm period, the determining factor of temperature and moisture regime proved to be heating of the walls of the abyss by solar radiation and thermal circulation to the depth of approximately 60 m. In case of lower depths, heat transfer by turbulent air exchange with the surroundings of the plateau is also apparent. From the depth of 60 m below the abyss is filled with cool and rather humid air. Exchange of the air in this depth occurs only sporadically. In this part of the abyss, the air is cooled by the surrounding walls and air exchange with underground precinct. It is carbonated by water areas on the bottom of the abyss and humidity on the surface of rocks.

In the cold period, the scheme of temperature and humidity is determined by descending colder air masses from the surrounding terrain. The air warms, and as a result, its relative humidity decreases. It is very important that at the bottom of the abyss no accumulation of air that is cooled by radiation at night occurs. This phenomenon does not occur even during clear nights. The area where this air could create, namely on the vertical and inclined walls of the abyss, is relatively small. A convenient place for creation of a bigger amount of air cooled by radiation processes is the surrounding of the plateau. In the event that this air flows over the edge of the abyss, it begins to warm. Once it fills the entire capacity of the abyss, the lowest temperatures are not observed at the bottom but at the upper edge of the abyss. Once the cold air stops descending down into the abyss (after sunrise), it is possible to observe a slight increase in temperatures, probably due to the influx of heat from the surrounding rock mass. This influx is most intense at the bottom of the abyss. This phenomenon causes a slight upward flow. The rising air cools and its relative humidity increases – the average value of relative humidity in the whole profile is relatively high.

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