Andreas Pflitsch and Jacek Piasecki - Detection of an airflow system in Niedzwiedzia (Bear) Cave, Kletno, Poland. *Journal of Cave and Karst Studies 65*(3): 160-173.

DETECTION OF AN AIRFLOW SYSTEM IN NIEDZWIEDZIA (BEAR) CAVE, KLETNO, POLAND

ANDREAS PFLITSCH
Department of Geography, Research Group: Cave and Subway Climatology, Ruhr-University Bochum, 44780 Bochum, GERMANY
apflitsch@aol.com
JACEK PIASECKI
Department of Geography, Meteorology & Climatology, University Wroclaw, 51-621 Wroclaw, ul. A. Kosibi 8, POLAND
piasecka@iis.ar.wroc.pl

Analyses of radon gas tracer measurements and observation of the variability of thermal structures have long been thought to indicate the presence of weak air currents in Niedzwiedzia (Bear) Cave, Kletno, Poland. However, only after ultrasonic anemometers were installed could different circulation systems of varying origin and the expected air movements be observed by direct measurement. This paper presents: a) the different methods applied in order to determine the weakest air currents both directly and indirectly; b) a summary of hypotheses on the subject; and c) the first results that air indeed moves in so-called static areas and that visitors affect both cave airflow and temperature. First results show that even in so-called static caves or within corresponding parts of cave systems, the term "static" has to be regarded as wrong with respect to the air currents as no situation where no air movements took place could be proven so far within the caves. Moreover, the influence of passing tourist groups on the cave climate could unequivocally be identified and demonstrated.

Both speleometeorology and speleoclimatology differ significantly from their counterparts that deal with airflow under free atmospheric conditions: Weather conditions and climatological shaping at a specific location on the Earth's surface are mainly governed by short to medium-term (regional to global scale) changes, whereas the speleoclimate is largely or entirely dependent on local conditions (Bögli 1978). These, in turn, have an influence on openings and cavities that are interconnected. Typically, conditions in such cave systems are continuously homogenous (e.g., high relative air humidity prevails over long periods of time, temperature variations are very low, and air movements are little or absent). In combination with the total darkness inside, these factors have led to the generation of very special and fragile ecosystems.

It is a common assumption in cave climatology that air movements in caves are the results of the endogenic and exogenic factors described below. After Schuster and Novak (1999), the distinction of endogenous and exogenous factors as a cause of air circulation is made due to thermodynamic differences. For the exogenous factors, the mass transfer is contemporaneous with the transfer of energy between the cave gas phase and the outside atmosphere.

EXOGENIC FACTORS

Air movements are generated by the following processes:

- Differences between air pressure inside the cave and the outer atmosphere, which in turn are the result of the continuously changing pressure systems (Moore & Sullivan 1997).
- Pressure differences generated by the different orientation of openings compared to the actual wind direction. In such situations, the windward side shows higher values of air pressure than the leeward side (Bögli 1978).
- Temperature differences and the resulting pressure differences between the cave and outer air (Bögli 1978; Moore & Sullivan 1997). Bögli (1978) regarded the genesis of cave winds as a consequence of temperature differences between the atmosphere inside and outside the cave as an explanation valid for systems with 2 or more openings at a different height. His example of the Hölloch system shows a height difference of 500 m. The differences in pressure are governed by temperature differences between the air inside and outside the cave. During the winter, the air entering the cave system warms up, becomes lighter, ascends, and escapes through an upper opening. This loss in mass causes a very small amount of lower pressure inside the cave in comparison with the outer air pressure. During the summer, air entering the cave cools down, gains weight, descends, and flows outside through a lower opening. The amount of both effects is mostly very small and depends on the relationship between the cave volume and the number and the diameter of the openings. More recent results from Moestrof Cave, Luxembourg, show interesting relationships between the changes in pressure and differences in air density (air outside and inside the cave), air temperature outside, and the velocity of currents within the cave (Boes *et al*. 1997).

ENDOGENIC FACTORS

For the endogenous factors, no change in mass takes place; instead, transfer of energy is on a mechanical basis in a closed thermodynamic system. Air movements are generated by the following processes:

- Pressure differences inside the cave that are caused by differences of air density, which in turn are the result of temperature differences, humidity, and CO_2-content (Bögli 1978),

-Transfer of power through turbulent flow of water (Cigna 1971; Schuster & Novak 1999),
-Changes in volume caused by changes of water levels in caves (Ford & Cullingford 1976).

From the compilation of influencing factors above, it becomes fairly obvious that air temperature is one of the key factors for the generation of air currents. Temperature differences within the cave and between the cave and outer atmosphere can lead to balancing air currents, with weak air currents that are due to endogenic factors and quite high-velocity currents in the range of m/s due to exogenic effects (Schuster & Novak 1999).

The balancing currents of air into and out of a cave are normally too weak to contribute significantly to the difference of temperature between the cave air and the outside atmosphere. Thus, the temperature inside the cave is mainly governed by rock temperature, which in turn reflects the long-term mean annual air temperature of the outside atmosphere.

Moore and Sullivan (1997) report that daily fluctuations of air temperature outside the cave of an order of 30°C are reduced to an amplitude of <1°C at a depth of 57 cm inside limestone. In contrast, the same authors demonstrate that an annual amplitude of outside air temperature of 30°C is still detectable to a depth of 11 m with a variation of >1°C. Thus, caves of depths >11 m display variations <1°C. Distinct deviations from these values can only be expected where airflow is strongly oriented into the cave.

Furthermore, this shows that cave temperature can be approximately estimated based on the respective latitude and elevation above sea level at which the cave is located (Moore & Sullivan 1997). However, there are even more factors that have an influence on cave temperature, as follows:

Water: Cave rivers and smaller streams have a much higher influence on cave temperature than the weak air currents. The specific heat capacity of air and its lower density cause a much lower heat content of the air in comparison with rocks and water, causing a quick approximation of air and water temperature (Bögli 1978). The heat content of a defined volume of air is 3200x smaller than that for water and 1800x less than that for limestone. Caves that are influenced by cold meltwaters show a lower temperature than expected from the temperature outside, especially during the spring and partly during the whole year (Bögli 1978; Moore & Sullivan 1997).

Geothermal heat flux: This factor is generally regarded to have a minor effect on cave climate. Using a geothermal gradient of 0.03°C/m, an influence on cave climate can be assumed only for very deep caves. In the case of caves that belong to the active endokarst, the effect of geothermal energy can be ignored as the heat is completely masked by surface temperature effects.

Structure: For static caves (i.e., those with only one entrance–"blind"), the position of the entrance in relation to the main cavity can lead to marked differences in cave climate. If the entrance is located below the main cavity, the latter or higher areas within the cave system "collects" the less dense, light air and forms so-called "pockets of warm air". In case of an entrance above the main cavity, cold, dense air descends to lower parts of the cave forming a "pocket of cold air" that stagnates within the "hole", thus creating stable layering.

Aspect: The location of a cave with respect to the aspects of individual slopes should have some influence on the cave temperature, where the thickness of the geologic formation that covers the cave is small. This should then lead to a slight increase of cave temperature when compared to the mean annual air temperature for sunny slopes with southern aspects and slightly lower cave temperatures on northern aspects, where shadow effects are significant. These assumptions could be partly documented during our measurements in Balzarka Cave (Moravian Karst, Czech Republic); however, similar assumptions or data could not be found within the body of cave literature.

Conclusion: In general, only very low wind speeds of the order of a few cm/s can be observed, which do rarely exceed 1 m/s especially in endogenic systems. Occasionally, however, cave winds can reach gale force as, for example, 166.3 km/h in the Turkish Pinargözü Cave (Bögli 1978). These high wind speeds are generated by so-called chimney effects (Moore & Sullivan 1997). Other caves, as for example Wind Cave in South Dakota or the Cave of the Winds in Colorado, are well-known for their winds or sound that is generated when wind is pushed through narrow cavities (Conn 1966).

CLIMATIC CLASSIFICATION OF NATURAL CAVES ACCORDING TO THEIR VENTILATION

With respect to the climatic situation and ventilation, static and dynamic caves are distinguished in the literature. Both terms were introduced by Geiger (1961), using the number of cave entrances only: Caves with only one entrance are thus regarded as static systems, whereas caves with more than one entrance are referred to as dynamic caves. Although Ford and Cullingford (1976) demonstrate that static caves should only have one or no entrance, we think that this classification is not very useful, as wind speeds even in caves with only one entrance can reach high values.

Investigations of dynamically aerated caves with high wind speeds are manifold. The way of aeration of the Salzgrabenhöhle described by Schuster and Novak (1999) is one of the most recent to be mentioned in this context. Compared with Hölloch investigated by Bögli (1978), which has a height difference of 500 m between the uppermost and lowermost openings, Salzgrabenhöhle also has a very large vertical span of 640 m, which in turn causes marked pressure differences that are easy to calculate.

As wind speeds in so-called static caves are mostly low (Schuster & Novak 1999), and below the lower limit of detection of previous measurement instruments, it has to be emphasized here that the complete detection (quantification) of air currents (vertical and horizontal components) is more a technical problem of measurement. The VDI Guideline (VDI 1988) quotes a reasonable threshold value of 0.6 m/s for the use of rotational anemometers. In general, wind speeds <0.5 m/s are regarded as "situations where wind direction remains undetectable with measurement devices" (Reuter *et al*. 1991: p. 33). For situations that are known as calms, no information about wind speed or direction is available. However, recent studies that used radon gas as a tracer show that even in caves where no system of currents could be proved, a complex system of air currents could be detected though not yet quantified (Hebelka 1998; Przylibsky & Piasecki 1999). Furthermore, recent large-scale climatological investigations of Moestroff Cave, Luxemburg (Boes *et al*. 1997), and various caves of the Moravian Karst, Czech Republic (Hebelka 1998), could detect and quantify even very low wind speeds of < 0.5 m/s in a very detailed way using a hot wire anemometer. The exact detection of wind direction and wind speed is still not possible with this method.

From the results compiled above, so-called "static" caves can be regarded as climatic systems that give insufficient information about a possible system of air currents that might be present within them. This lack of information could be filled in the meantime using sonic anemometers. The use of such measuring devices makes it possible to detect very low air currents down to cm/s, to record even the slightest changes in direction and velocity in intervals of split seconds and the detection of the slightest variations in air temperature, which is very useful in caves, too. The VDI guidelines quotes a lower limit of detection for air temperature of these devices as 2.2 x 10^{-2} °C (VDI 1994). The technology of sonic anemometers has been available since the mid-1960s and has been used specially in micrometeorology. But it is a fairly new instrument in East Europe, especially for cave climatologists.

The use of this thermal technique in addition to the detection of weak air currents allows for a long-term quantification of such events that, until now, could only be achieved using artificial tracers (Pflitsch & Flick 2000).

Our investigations in various cave systems in Germany, Poland, the Czech Republic, and Slovakia (Piasecki & Pflitsch 1999; Pflitsch *et al*. 1999) have shown that it appears to be more useful to classify such caves as dynamic in a climatologic sense, in which the air velocity is easily detectable and where wind speed can reach high values. In those caves, the wind plays an important role and can be regarded as the main forming agent, and air movement as the primary process for the climate of all or part of the whole cave system. Change of the other meteorologic elements, such as air temperature and relative humidity, is also clearly detectable.

Moreover, Piasecki (1996) has shown that it is useful to divide caves into different parts. During long-term investigations in the small system of Niedzwiedzia Cave, Poland, individual areas unequivocally had static climatic conditions, whereas other parts of the cave system had dynamic ones.

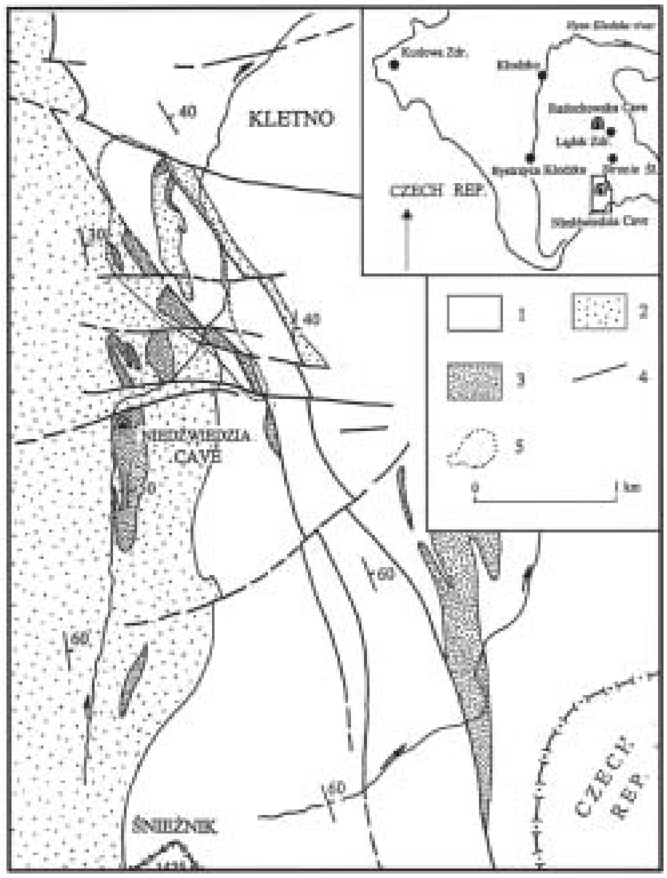


Figure 1. Overview of the Niedzwiedzia (Bear) Cave, Kletno, Poland and the geology of the surrounding area (Przybilski & Piasecki 1998, after Don 1989). Legend: 1 = Gneiss, 2 = Metamorphic Stronie Series, 3 = Marble and other carbonate rocks, 4 = Faults, 5 = Location of former uranium mine.

Thus, we revise the classification of caves into dynamic or static climatic systems, as the old classification is obsolete. The latest measurement results point to the fact that static conditions can only be claimed where little or no air movement can be demonstrated–except for areas close to entrances–and where the spatial and temporal variability of the climatic elements is small. Furthermore, within a system spatial and temporal differentiations must be applied.

INVESTIGATIONS TOWARDS A NEW CLASSIFICATION SYSTEM OF CAVES

THE STUDY AREA

Niedzwiedzia (Bear) Cave, Kletno, is within the Klesnica Valley of the Snieznik Massif in the East Sudetes Mountains at an altitude of 800 m (Fig. 1). The corridors known so far make up 3 levels built in calcite-dolomite and dolomite-marble with a total length of 2500 m–the longest cave system of the Sudetes Mountains. The marble occurs in pockets of unknown thickness, and it is not known if these are isolated pockets or if

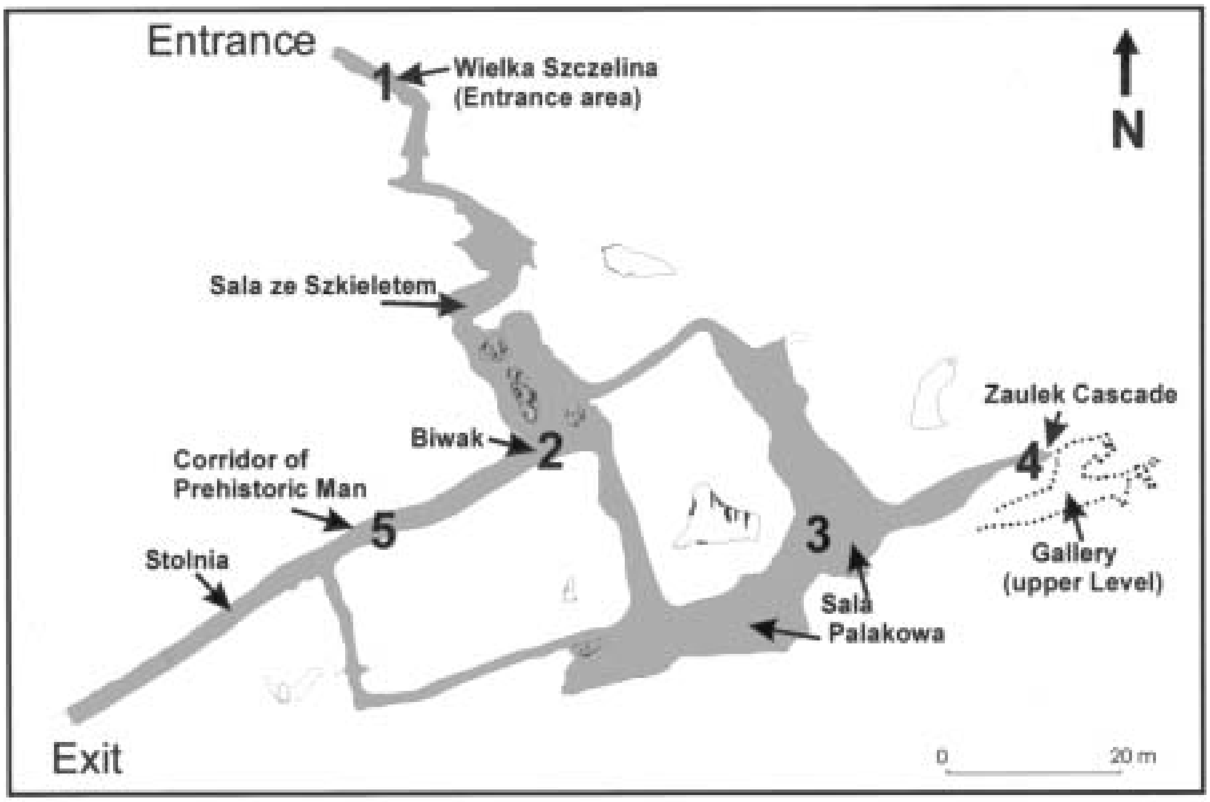


Figure 2. The part of Niedzwiedzia Cave, Kletno, Poland that is open to tourists and the study areas.

they are interconnected with one another. They are embedded in metamorphic formations of the Snieznik, which are mainly gneiss and paragneiss of the Snieznicka, Gieraltowska, and Transitory Series and micaceous schist of the Stronska Series. The massif is characterized by many joints and faults. Just north of the cave, a fault with rectangular tectonic fractures governs the morphology of the cave corridors. Hydrological and hydrochemical investigations, as well as sedimentological analyses in the water corridors, clearly point out that more cavities have to be present.

It is expected that the cave morphology has a special influence on air movements within the cave and that some characteristics of these structures are also important for the origin of the detected airflow. Morphological investigations show that from the early Holocene onward, Niedzwiedzia Cave belonged to a closed cave system, and contact to the surface only existed via ponors (Don 1989). Only as recently as 1966, an opening into the cave, which was until that date obscured by slope material and cave deposits, was cleared by an explosion in a marble quarry. In the following years, entrance and exit passages were created to the cave corridors (Pulina 1989). These are blocked by locked doors and, thus, secured against the influence of the air outside the cave. As the cave is open to tourists 5 days a week, the doors are opened only briefly many times a day.

Climatologic investigations, which were conducted after the discovery of the cave in 1966, first periodically and later in the 1990s on a regular basis, have shown that 3 climatic zones can be distinguished within the cave (Piasecki 1996). The static zone has the largest extent and includes most corridors and halls of the lower and intermediate levels, whereas the dynamic zones and those that can be regarded as transfer areas play a minor role in terms of spatial extent. The characteristics of the climatic components and the extent of the climatic zones are shown in Figures 2 and 3.

METHODOLOGY

In order to detect the cave climate, the following methods were used:

MEASUREMENT OF AIR TEMPERATURE

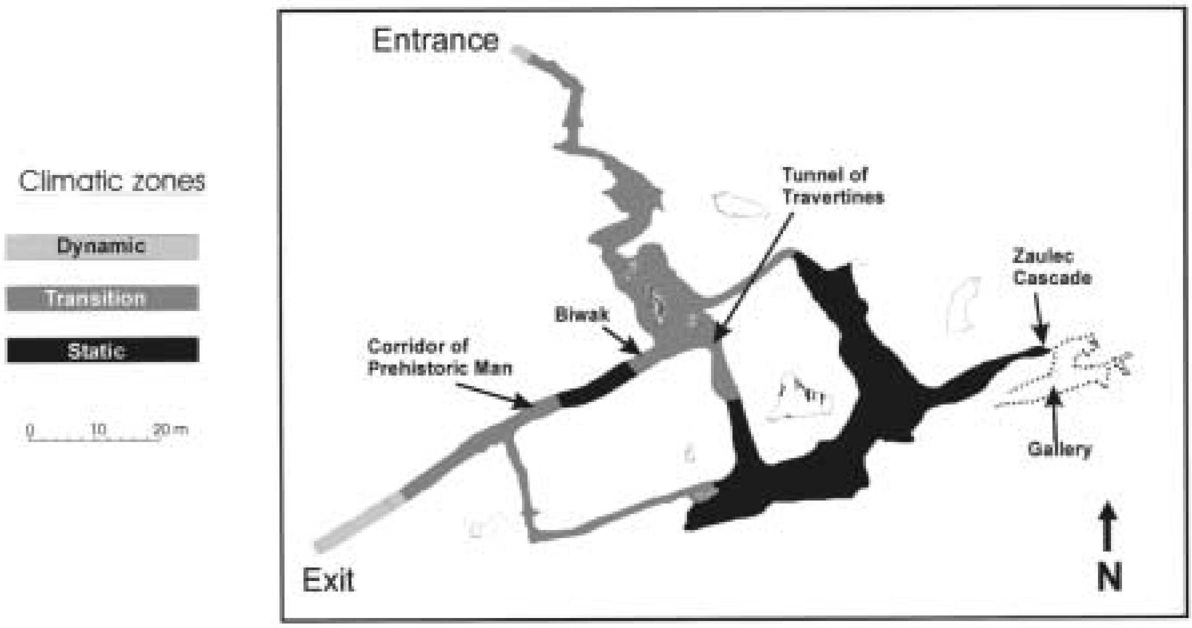
From 1991 onward, air temperature was measured at one station outside and 5 inside Niedzwiedzia Cave, ~1 m above the floor. Temperature logging was conducted using PT100-sensors (platinum resistance thermometers) with a recording interval of 1 minute and with 10 minute means. In addition, extreme values were recorded. Measurement error is ±0.2°C.

In addition to the automatic measurements, manual measurements were conducted on a regular basis; these used horizontal and vertical profiles at 16 locations within the cave with distances of 0.1, 1.0, and 2.0 m above the floor. The recording device was a DL-15 datalogger of “Thies” (Germany). In order to record the most natural, undisturbed conditions possible, only those data were used that had been recorded 3 hours after the last tourists had left the cave.

RADON MEASUREMENTS

In order to identify permanent air movement, alpha particles that are generated during the decay of radon were

Figure 3. The three climatic zones of Niedzwiedzia Cave and the locations of sonic measurements.



collected passively. The fundamentals underlying this method are based on the following physical and chemical properties of radon:

-Little chemical reactivity and a long half-life enable a reasonable detection of changes in concentration,

-The high density of radon causes an accumulation close to the floor so that gas movements are due to air movements.

In order to identify the mean trace gas concentration, 15 trace gas detectors were installed as 5 vertical profiles with 3 detectors each. Furthermore, one detector was installed in the water of the Travertine Hollows, and sediment samples were taken in order to analyze the background concentration.

For comparison of radon concentration in caves of different morphology and with different numbers of openings, additional measurements were conducted in Radochowska Cave, which is aerated via 6 openings. The period of measurement includes the 2 years 1995 and 1996, and the results can be obtained in detail from Przylibski and Piasecki (1998).

Figure 4. View of an ultrasonic anemometer at the Biwak measurement point.

MEASUREMENT OF AIR CURRENTS USING SONIC ANEMOMETERS

Investigations using a 2-D sonic anemometer were conducted in a depression in the Rashomon Gate region, Japan, by Shaw *et al*. (1996). Additional information comes with the use of 3-D sonic anemometers, which also record the vertical component.

Such investigations using 3-D sonic anemometers were conducted from March 1998 onward in Niedzwiedzia Cave (Fig. 4). The first results are presented in the following and related to the temperature and radon gas measurements (Przylibski & Piasecki 1998). The objectives of the investigation are to identify and quantify the system of air currents within the whole cave system and its seasonal variability. The measurements were conducted using METEK sonic anemometers USA-1. The measurement principle of the ultrasonic anemometer is based on the duration of ultrasonic pulses measured in 3 different directions (VDI 1994).

A sonic anemometer offers measurement opportunities that are very different from mechanical anemometers. By measuring low level winds with a mechanical device, the wind must provide enough power to overcome friction and to accelerate the mass of the moving parts (Locker 1996). On the contrary, a sonic anemometer has the following properties:

-no friction

-no inertia

These features are important for measuring very low wind speeds because of the following advantages:

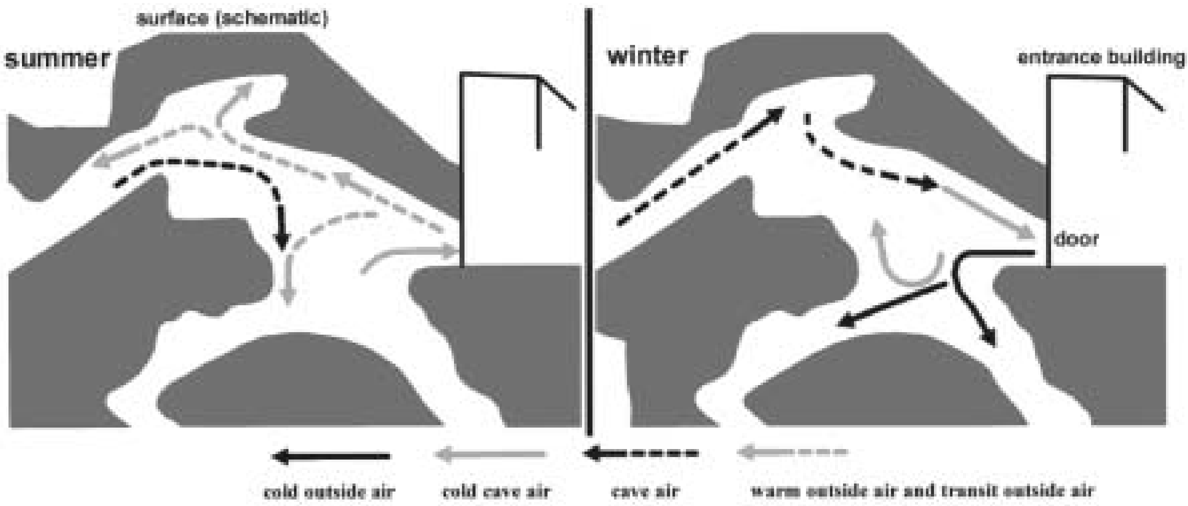


Figure 5. Schematic cross section of the air currents adjacent to the entrance area of Niedzwiedzia Cave.

-no start up phase
-useful results during short measurement intervals, for instance 1 second
-determination of very short fluctuations of wind vectors and temperature

The use of sonic anemometers makes it possible to measure current velocities with speeds of a few cm/s and the registration of finest changes of wind direction and speed in intervals of less than seconds. In addition, it is also possible to prove the finest variations of air temperature. According to the VDI guideline, the lower detection limit as well as the uncertainty of measurement for wind speeds is 0.025 m/s and for temperature 2.2 x 10^{-2} °C (VDI 1994). Based on this guideline only measurements with wind speeds >0.025 m/s are useful information. Below this limit, the information of the wind direction is not useful.

The measurements were conducted over a period of 3-5 weeks at the locations that show "static" climatic conditions; the locations of the sonic anemometers are shown in Figure 2.

Biwak	1 & 2.0 m above floor level ceiling 3 m above floor level
Zaulek Cascades	1.0 & 2.0 m above floor level ceiling 10 m above floor level
Gallery	1 m above floor level ceiling 2 m above floor level
Tunnel of Travertine Hollows	1 m above floor level ceiling 1.5 m above floor level
Corridor of Prehistoric Men	1 and 2.0 m above floor level ceiling 5.5 m above floor level

The selection of the measurement locations was influenced by the results of radon and temperature measurements that had already been conducted and by test measurement campaigns that lasted 1 day. During the analysis of the data, it was decided that the respective wind direction would not be used for analysis with horizontal air movements of ≤3 cm/s. These situations are termed "calms".

RESULTS

Using the methods listed above, 5 areas with characteristic patterns of airflow could be distinguished for the intermediate cave level. The first 2 are located within the zone of dynamic climate and the transition zone between dynamic and static climate, respectively (Figs. 2 & 3). Its climatological shaping is influenced by the air exchange between air inside and outside the cave, the conduction of heat through the ceiling rocks, and the processes of heat exchange between the cave air and surrounding rocks (Piasecki 1996).

On the basis of seasonal changes of air temperature and radon concentrations as well as the measurements of currents using sonic anemometers, the following pattern of airflow could be identified for these areas within the cave:

LOCATION 1

Closely behind the tourist entrance of the cave, different anthropogenic and natural processes lead to marked and far reaching air circulation that has an influence, especially on the air currents and temperature of the lower cave level. During the cold season between November and April, a permanent stream of cold air originating from the entrance (Fig. 5), exists close to the entrance area and leads to the floor of the Wielka Szczelina. This stream of cold air, which is due to small permanent openings, causes a reduction of the mean annual air temperature by ~0.5°C. When entering the cave, this stream of dense, cold air mixes with or completely replaces the air inside the lower level of the cave, which has the highest measured concentration of radon. As a result of this effect, the air of the lower level reaches the upper levels of the cave, which in turn leads to increased radon concentrations in the upper levels. This air then flows into the inner parts of the cave, where it can leave the cave (Fig. 5).

A second airflow, which is again oriented downward, is due to natural processes. Prior to the beginning of the cold period, a layer of warm air hangs directly below the ceiling, with the highest temperatures having been detected during October and November. During the course of the winter,

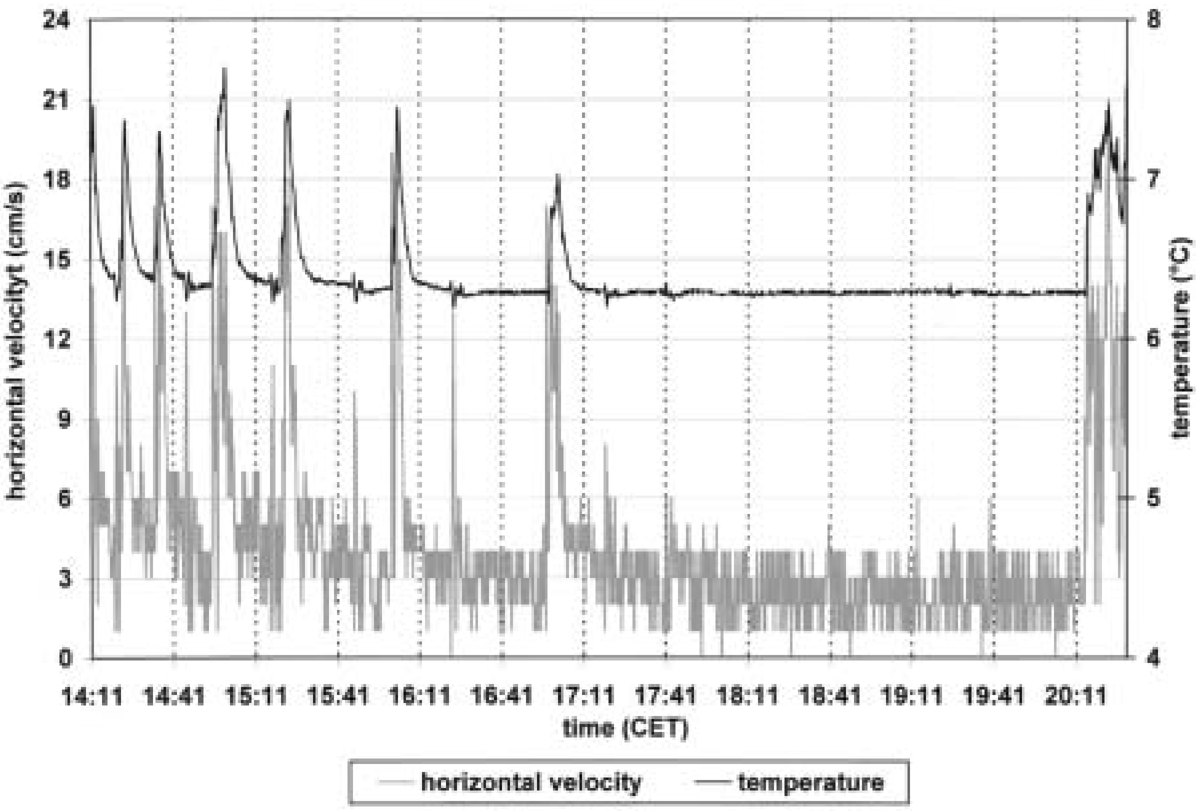


Figure 6. Air temperature and horizontal velocity of air flow in Niedzwiedzia Cave at Biwak, 28th of March 1998 (measured by sonic anemometer, average time: 10 s).

cooling of the rocks leads to a descent of this now cooler air mass. This phenomenon reaches its maximum intensity during the end of the cold period (Piasecki & Pflitsch 1999).

For the warm season from June to September, the mechanisms of air movement cannot yet be completely explained and identified for the area around Wielka Szczelina. The change of air temperature indicates air movement toward the outer cave areas, but this assumption is not supported by high radon concentrations and their little variability. In order to clear this issue, measurements with sonic anemometers are being planned for the future.

LOCATION 2

The second location represents the central or intermediate cave level, respectively. In our hypothesis brought forward at the beginning, we assumed that warming air moved upward from the lower level under the ceiling (Sala Lwa, Sala ze Szkieletem). This hypothesis was supported by temperature measurements that showed increased mean air temperature at Biwak. As static as well as transitional conditions could be proved for this area, the climatic boundaries are not clearly defined here. During consecutive measurements, 2 sonic anemometers were located at the crossing of 2 corridors (Fig. 2).

During the first experimental measurements in March 1998, air currents could be clearly proved. Surprisingly, and contrasting with the long-term temperature measurements, the influence on cave climate of tourist groups that visited the cave could be proved as well. The results presented here show impressively the tourist group influence and how the short-term opening of the doors changes the cave climate.

Figure 6 shows the course of air temperature and wind speed for a period of 6 hours. The average calculated by the sonic anemometer is 10 s. Two different situations are clearly visible: The first part of the period shown here displays a more or less periodic increase and decrease of wind speed, which also shows a clear relation to the air temperature values. After ~17:30 h, these conditions change significantly. The variations of both parameters stop rather abruptly with variations remaining within the measurement error.

The explanation for this pattern is simple: The first part of the figure shows the conditions during the time of the day when tourist groups are being led through the cave and pass the sonic anemometer at a distance of about 5 m. The second part shows the undisturbed period of time.

Beginning with the undisturbed situation, one can see that the air temperature is constantly 6.3°C, with a wind speed between 1-4 cm/s. As the lower limit was set to 3 cm/s (see above), the velocity is largely below the lower limit of detection. In stark contrast to this pattern is the period of time where tourist groups are being led through the cave. Wind speed with values of 3-6 cm/s is largely above the lower limit of detection with peaks of up to 20 cm/s, but again, 2 different patterns are distinguished within this period of time. Firstly, 7 larger increases in wind speed to 15-20 cm/s that last some minutes and secondly, short-term changes with lower values of 9-12 cm/s that are characterized by markedly lower increases in wind speed. This distinction can also be made using air

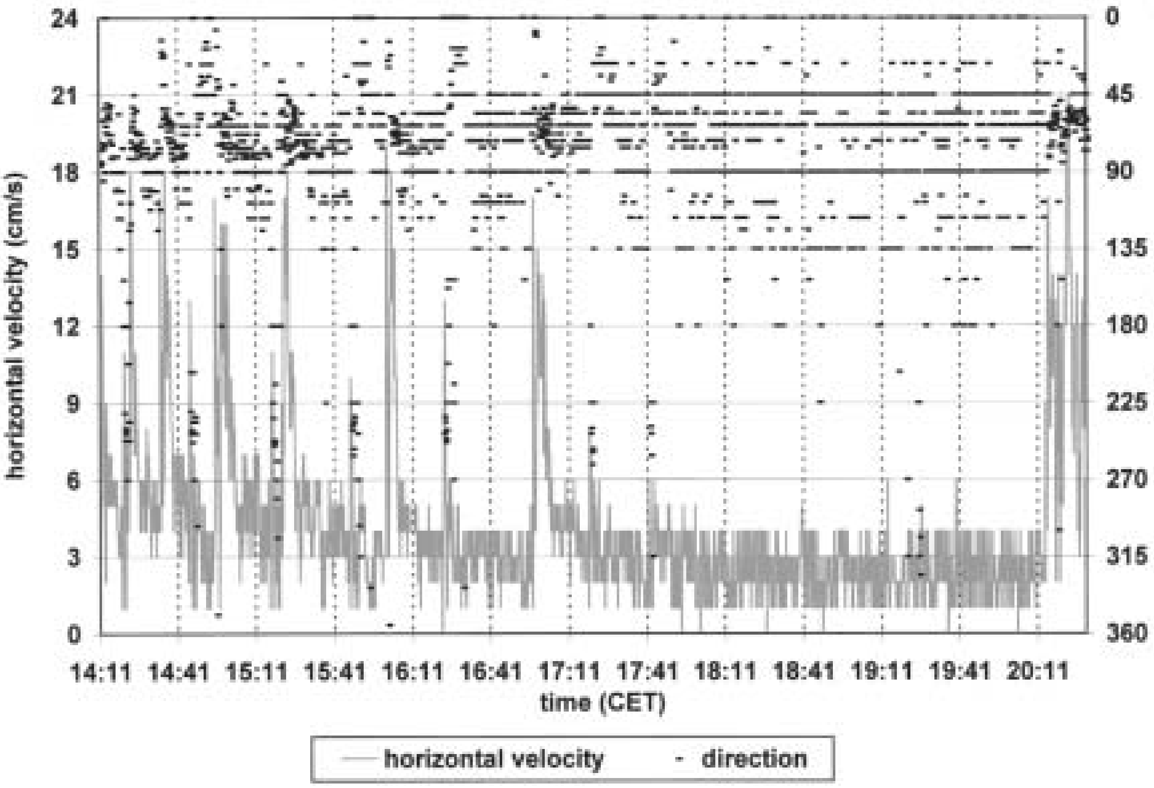


Figure 7. Direction and horizontal velocity of air flow in Niedzwiedzia Cave at Biwak, 28th of March 1998 (measured by sonic anemometer, average time: 10 s).

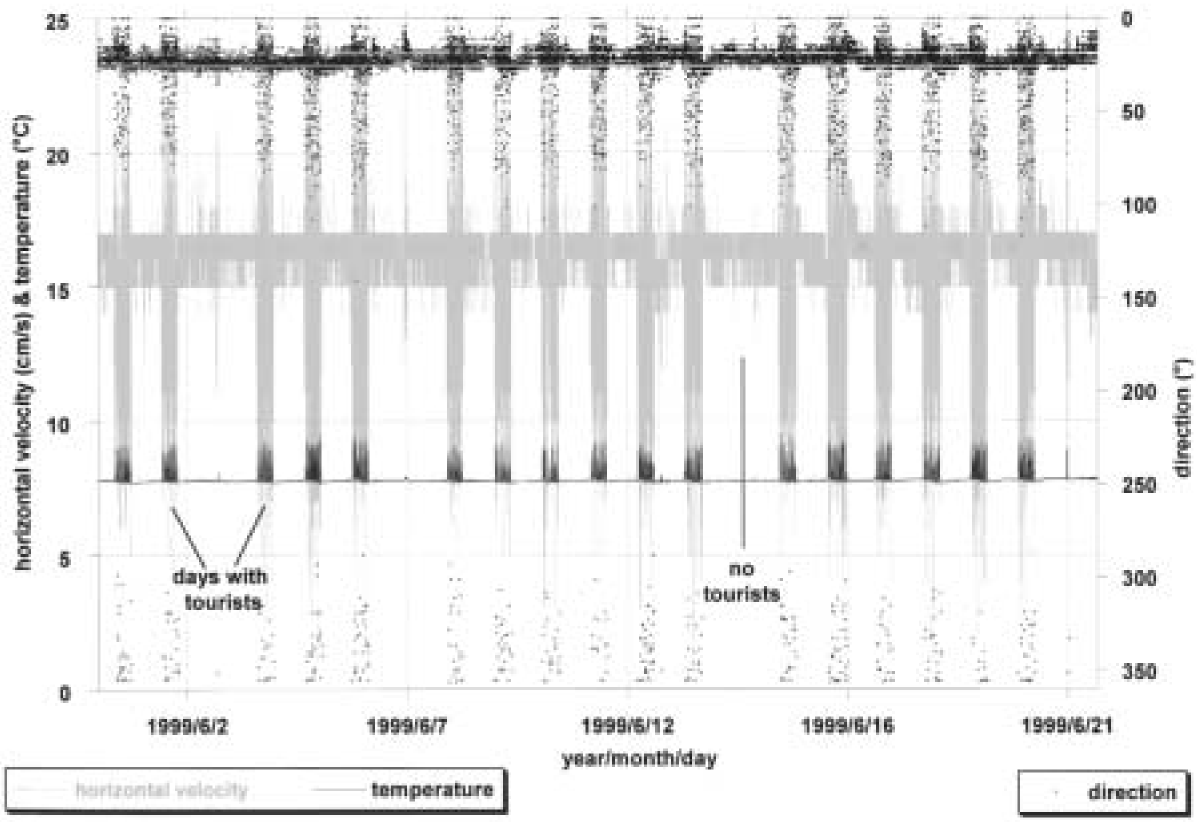


Figure 8. Direction and horizontal velocity of air flow and air temperature in Niedzwiedzia Cave at Biwak, at 2.0 m above ground level, 1st to 21st of June 1999 (measured by sonic anemometer, average time: 1 min).

temperature: The 7 peaks that are clearly identifiable also show marked increases in temperature (by 1.4°C), whereas the short-term changes correspond only to very little variation in air temperature of the order of 0.1°C (although even these small variations can be easily detected due to their characteristic pattern).

Using the information on wind speed as well as the conditions described above can also be seen here (Fig. 7). For the undisturbed situation, one can see that the background current is predominantly from northeasterly directions but that the direction can change for shorter periods of time to about southeast (again, only wind directions were used where wind speed was >3 cm/s). During those periods of time where wind speed increased, wind direction is from the NE. Contrasting with this pattern, wind direction changes for ~60-90 seconds to SW directions (i.e., toward the respective axis of the corridor with the corresponding smaller peaks). The vertical component shows no change for the short-term changes of the climatic conditions described above apart from an increase in vertical velocity from 1-2 cm/s to 8-11 cm/s during the increase in velocity and air temperature. The temporal distribution of both structures has shown that they are caused by completely different processes. The strong changes are due to the influence of tourists who are standing in front of the instrument, whereas the less strong variations are due to the opening and closing of the entrance doors.

That these phenomena have not resulted from chance on individual days can be seen from Figure 8. The results shown here have been obtained from a measurement location just 2 m away from Location 1. The results stem from measurements conducted over a period of 2 weeks during June 1999 and clearly show that the patterns are highly constant and due to the influence of tourist groups. The first 3 days show a period of time where tourists disturb the current followed by 1 day when the cave was closed, again followed by 6 days with tourist groups being led through the cave, again 1 day off, and another 3 days with tourist groups at the end of this measurement period. Measurements used an averaging time of 1 minute. Although the level of velocity is markedly higher due to seasonal variability (compared to the first example at ~10 cm/s) and although the mean wind direction is oriented northward, the results show similar patterns of disturbance as already described in the first example.

For the nocturnal hours and for the days with no tourist groups inside the cave, a mean velocity of 14-18 cm/s and a constant azimuth of airflow from 15°-30° can be observed. Both represent the situation during undisturbed periods of time at this location, which is characterized by highly constant conditions. Completely varying from this pattern are the days when tourist groups are being led through the cave: wind speed is highly variable with decreases down to ~2 cm/s and increases in velocity up to 27 cm/s. With respect to these observations, wind direction loses its constant characteristic and deviates to easterly directions to ~110° and to westerly directions to 270°, thereby increasing the range of directions from ~15°-200°.

Using the first example as a comparison, it can be seen from Figures 6-8 that during days with tourist activity, in addition to the situation of airflow, significant changes in air temperature can be observed. During the nights and days off, air temperature shows a highly constant course, whereas the presence of tourist groups is, again, characterized by a marked increase in air temperature up to 1.5°C. Corresponding to the situation of airflow, the temperature adjusts to its normal level quite quickly after the influence of the tourists has ceased.

LOCATION 3

The third location includes the Sala Palacowa and areas of corridors close by with strongly developed static, climatic characteristics. Based on the variations in air temperature that now have been observed for many years, it was assumed that only air currents that are weakly developed would be present and that these could, perhaps, be due to heat exchange with the surrounding rocks. Every deviation from the background current would, thus, be related to the influence of tourists and not to any natural causes.

The respective radon measurements showed seasonal alterations in concentration in the vertical profile from Sala Palcoea toward Zaulek Cascade. In the winter, the highest radon concentration was (against our assumptions) measured 2 m above the floor of the hall, and this in turn can be used to conclude that a comparatively high vertical current must be present that prohibits the accumulation of radon close to the floor. For the summer and the transition to autumn and winter, the increase in radon concentration both close to the floor and ceiling seems to be due to 2 seasonally present currents (Przylibski & Piasecki 1998). In order to test these controversial hypotheses, detailed measurements of the airflow are necessary and planned.

LOCATION 4

Both seasonal changes in air temperature and the differences in radon concentration in the Sala Palacowa show the interdependencies of the respective characteristics in the fifth zone, which includes the area of Zaulek Cascade and the adjacent corridor (eastern end of Sala Palacowa). Of special importance for the cave structure are vertical fractures below the hall. Both the corridor that leads downward to the lower level of the cave and the upper corridor of the gallery end blind. The axes of the Sala Palacowa and the Zaulek Cascade cross tectonic fault zones. Using the long-term measurements of the air temperature, characteristic short-term temperature anomalies could be proved (i.e., a temperature inversion that happened irregularly between November and May). Investigation of radon concentrations indicated the variable nature of air movements within the course of one year (Przylibsky & Piasecki 1999).

Using the temperature distribution and the radon concentration, we concluded that a complicated, periodically variable system of airflow had to be present in the Zaulek Cascade and the Galleria. In the Zaulek Cascade, contrary to the normal conditions, inverse temperature profiles could not be observed between 1 and 2 m above ground. This example again (e.g., the temporally altered radon distribution) hints at airflow that is only present periodically between Zaulek Cascade and the gallery directly above it. The origin of this airflow, which we accept here, can be attributed to the heat flux and exchange with the rocks in the ceiling. Furthermore, the

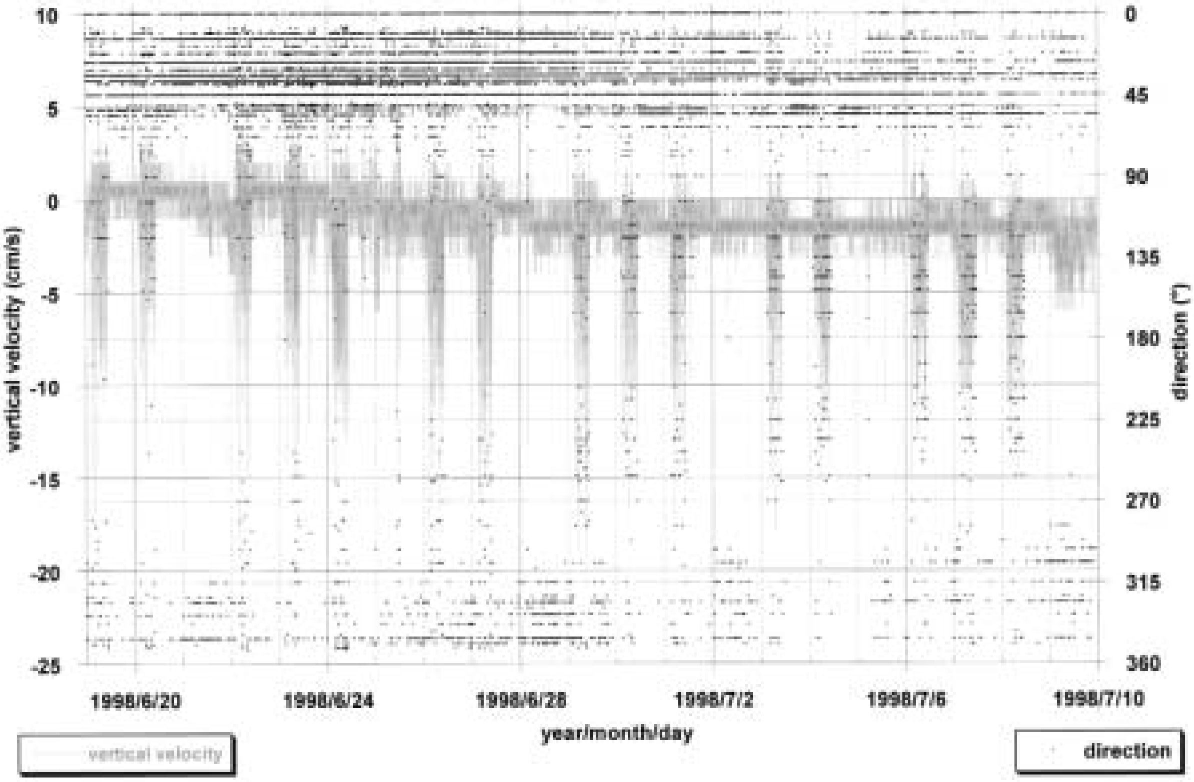


Figure 9. Direction and vertical velocity of air flow in Niedzwiedzia Cave at Zaulek Cascade I, at 2.0 m above ground level, 23rd of June to 14th of July 1998 (measured by sonic anemometer, average time: 1 min).

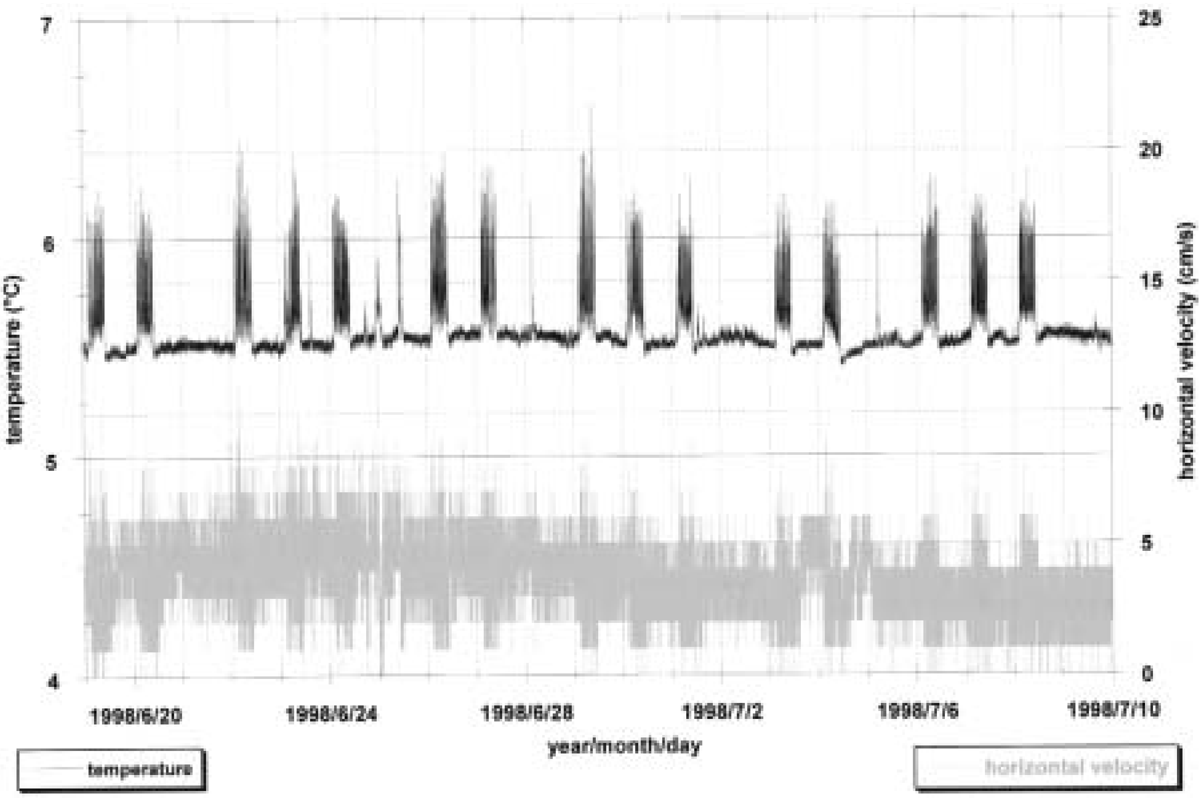


Figure 10. Direction of air flow and air temperature in Niedzwiedzia Cave at Zaulek Cascade I", in 2.0 m above ground level, 23rd of June to 14th of July 1998 (measured by sonic anemometer, average time: 1 min).

air movements appear to be related to the air exchange between different cave levels, which is also periodic (Piasecki 1996).

A downward-oriented current could be observed during short-term measurements in the area around Zaulek Cascade at 2 m above the floor, which was directed toward the axis of the Sala Palacowa (Fig. 9). This current is normally weak (5-10 cm/s) and has a constant nature, but it is heavily disturbed by tourists. Under the influence of tourist groups, turbulent airflow moves with extreme (in relation to the size of the cave)

Figure 11. Direction and vertical velocity of air flow in Niedzwiedzia Cave at Zaulek Cascade II, at 0.5 m above ground level, 23rd of June to 14th of July 1998 (measured by sonic anemometer, average time: 1 min).

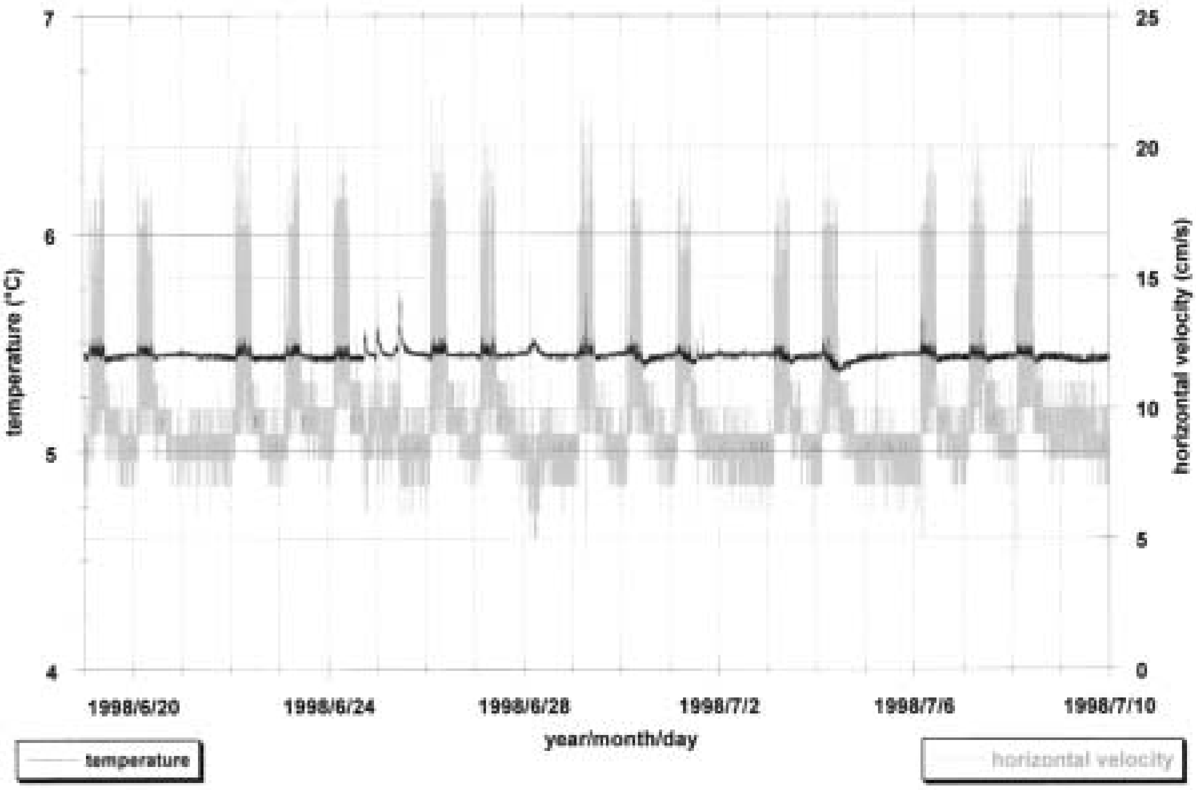
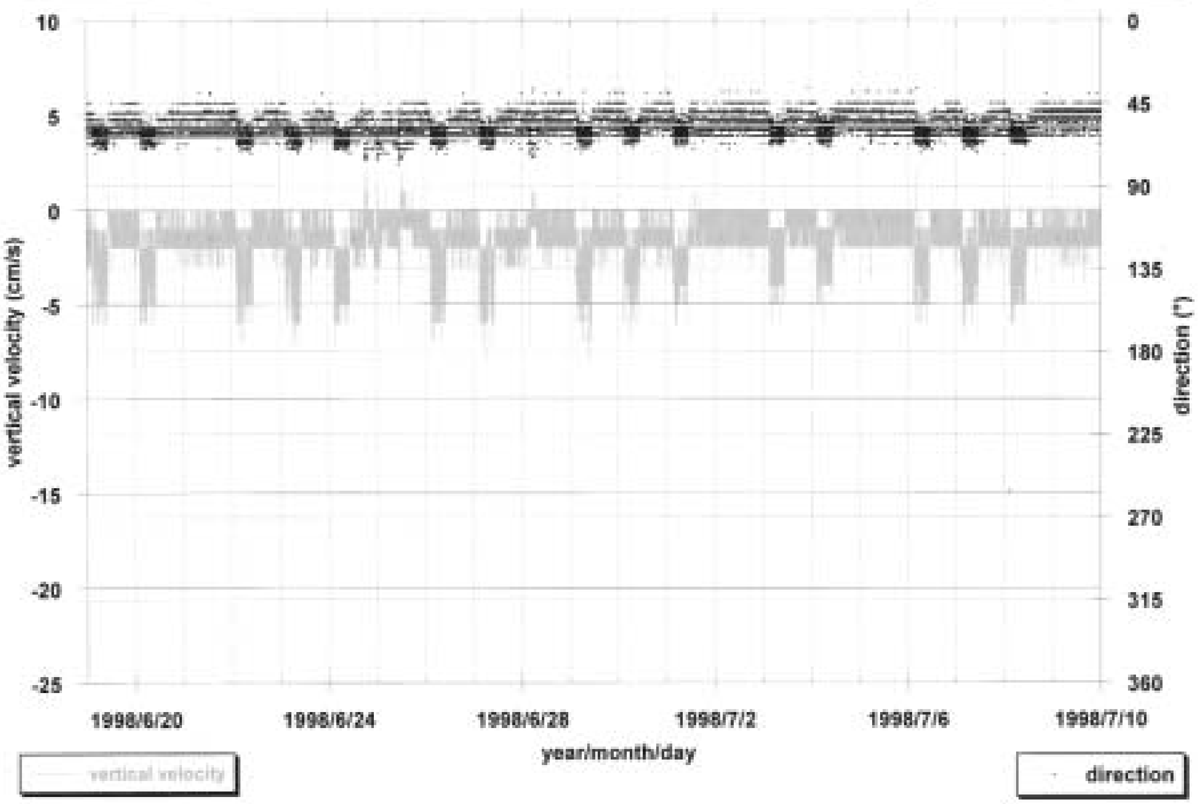


Figure 12. Direction of air flow and air temperature in Niedzwiedzia Cave at Zaulek Cascade II, at 0.5 m above ground level, 23rd of June to 14th of July 1998 (measured by sonic anemometer, average time: 1 min).



downward movements of up to 23 cm/s. The horizontal direction of airflow changes quickly and strongly, moreover we could observe increases in temperature of >1°C (Fig. 10).

Only a few meters behind Zaulek Cascade in the corridor that leads to the upper cave level, very constant airflow with respect to nearly every parameter was recorded at 0.5 m above the floor. The current moved toward Sala Palacowa with a mean velocity of 5-10 cm/s (Fig. 11). Contrasting with other currents (e.g., at Biwak and Zaulek Cascade), this current, which is clearly oriented downward again, remains virtually

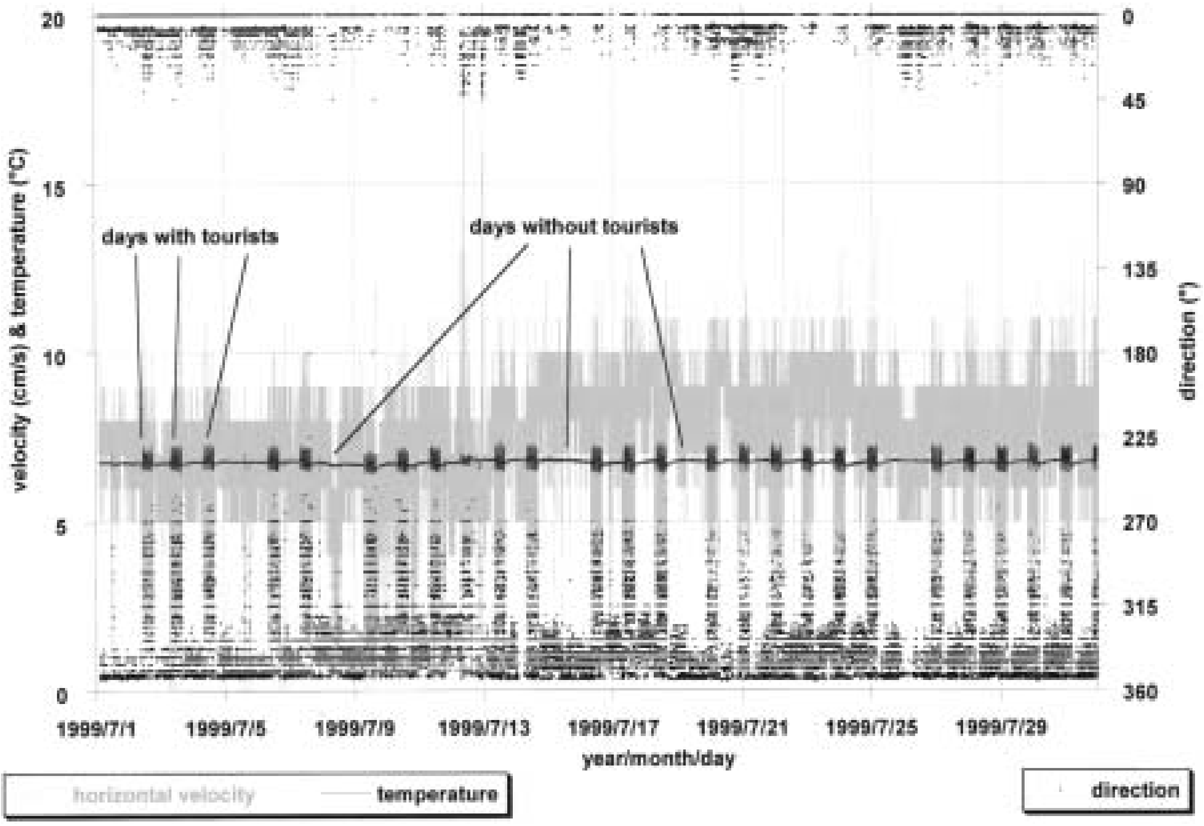


Figure 13. Direction and horizontal velocity of air flow in Niedzwiedzia Cave at Corridor of Prehistoric Man in 2.0 m above ground level, 1st of July to 1st of August (measured by sonic anemometer, average time: 1 min).

unaltered by tourist groups with respect to both air temperature and wind direction. The variability of direction is only of the order of a few degrees, and temperature fluctuations are of ~0.1°C at a maximum.

It is interesting to note that contrasting with this pattern, characteristic increases in the downward component and the horizontal wind speed have been observed during the passage of tourist groups. Here, the vertical component increases from ~3-8 cm/s and the horizontal velocity from 18-23 cm/s or 100-200%. These observations are clear indications that the vertical circulation induced by tourists in the area around Zaulek Cascade reaches up to the gallery of the upper cave level, and that the air masses that cool down there descend into the lower levels using the same corridor. These patterns lead to increased general current activity (Fig. 12). The existence of this pattern as predicted by theory could be verified by measurements of the airflow patterns in the gallery above the Zaulek Cascade.

LOCATION 5

The fifth location includes the exit gallery and part of the Corridor of Prehistoric Man (Fig. 2). Here, the highest air temperatures and radon concentrations were recorded just below the ceiling of the corridor ~10 m above the floor. Both values are clear evidence of permanent air movement toward higher areas of the corridor. In the meantime, the floor of the corridor and the galleries both show changing air currents between cave and outside air on a seasonal time scale (Fig. 12). Although doors and galleries pose a barrier to the airflow and hamper it significantly, the high amplitude of air temperature and its frequent fluctuations clearly show their presence.

The measurements with sonic anemometer conducted continuously since March 1999 have proved the presence of a well-developed and normally constant air current, which is heavily disturbed by tourist groups. In this context, Figures 13 and 14 show a similar situation to that at Biwak. In addition to clear currents, the constant temperature conditions and a well-developed northern direction of currents, the modifications of the velocity of air currents are striking. While the current is between 6-9 cm/s for days where tourists groups do not visit the cave, visitor days reach values between 1 and 11 and, in peak times, up to 17 cm/s (Fig. 13). In addition to the horizontal component of air currents, the vertical one is strongly modified (Fig. 14). For the days without tourist use, an upward air movement of 5-6 cm/s can be seen, whereas the heat produced by tourists gives rise to strong turbulence and, thus, to a perpetual change between upward and downward airflow. It is interesting to note in this context that the vertical component does not switch back to the original situation during the nocturnal quiescence period, but that this only happens during the few days when no tourists are allowed to enter the cave. Using air temperature and currents as indicators for a comparison of days with and without tourists, it becomes obvious that every group of tourists can be identified with these measurements variables (Fig. 15).

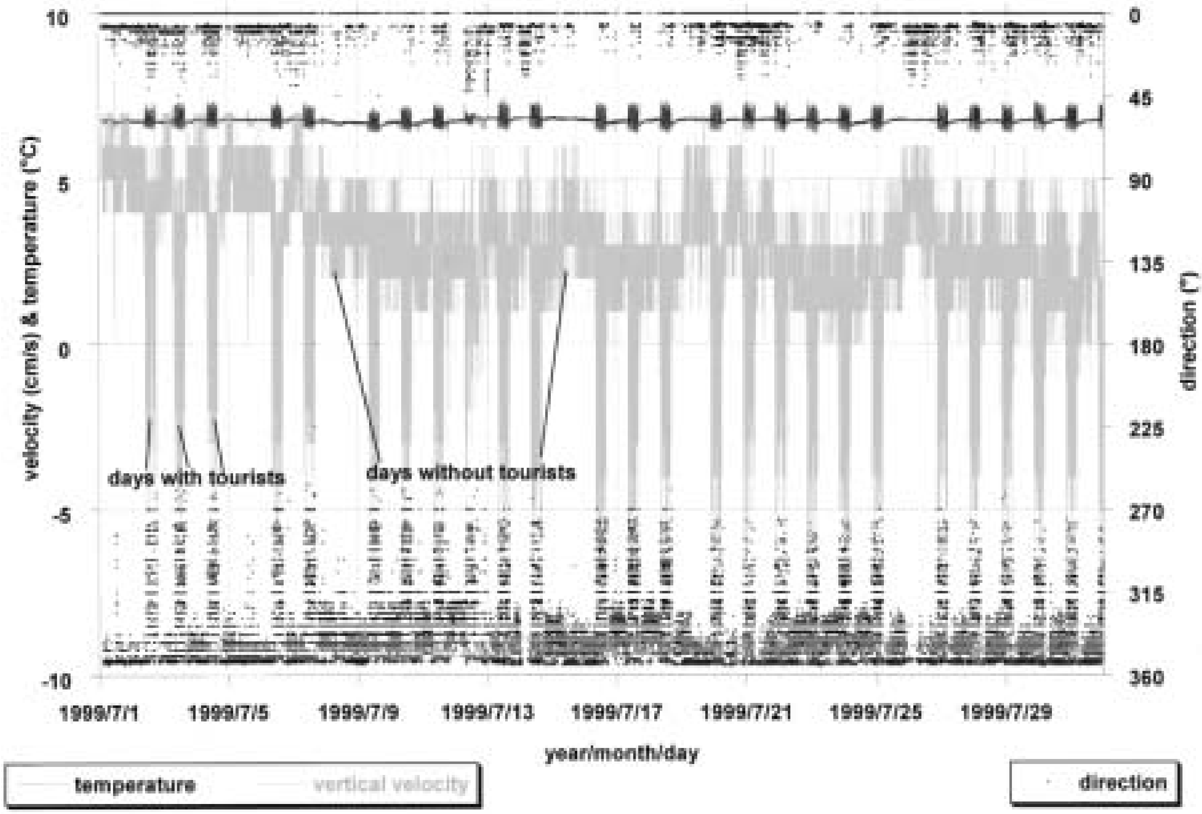


Figure 14. Direction and vertical velocity of air flow in Niedzwiedzia Cave at Corridor of Prehistoric Man at 2.0 m above ground level, 1st of July to 1st of August (measured by sonic anemometer, average time: 1 min).

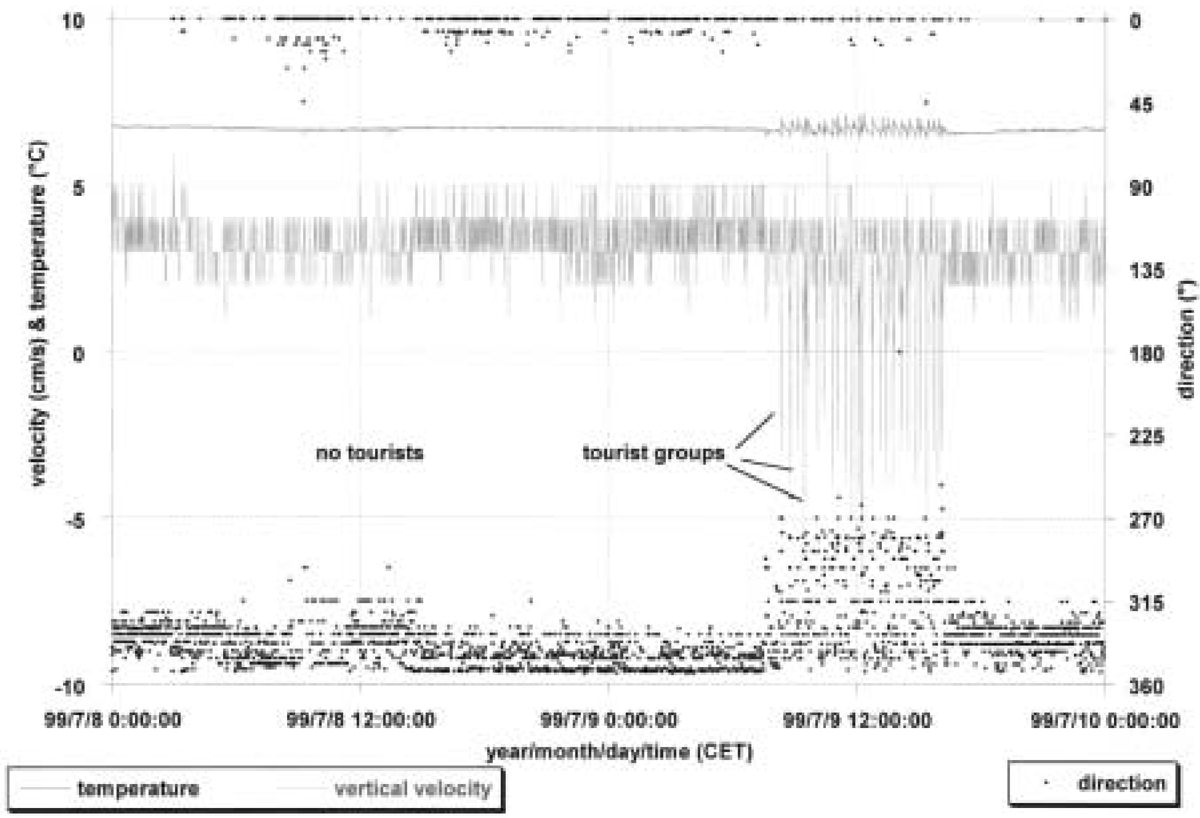


Figure 15. Direction and vertical velocity of air flow in Niedzwiedzia Cave at Corridor of Prehistoric Man at 2.0 m above ground level, 8th to 9th of July (measured by sonic anemometer, average time: 1 min).

SUMMARY

The investigations of variability of air temperature, radon concentration, and current velocity in Niedzwiedzia Cave, Kletno, Poland, that used sonic anemometers, unequivocally proves the existence of a complex system of airflow. The hypotheses made so far can only account to a limited extent for the origin and the flow of air within the selected parts of the cave (static areas). The opportunity of direct measurement of air movement presented here enabled us to verify the results obtained from other methods. Furthermore, in addition to the seasonal differences, we could identify those short-term differences that are due to the influence of tourists. It has also become possible to look at different aspects of the detection and recording of the climate system within the cave. Here, the investigation of long-term (seasonally induced) changes and the evaluation of short-term variability have the same priority. The differentiation and quantification of the causes of these changes (natural and anthropogenic) are of equal importance.

First results show that even in so-called static caves or within corresponding parts of cave systems, the term "static" has to be regarded as wrong with respect to the air currents. No situation where no air movements took place could be proved so far within caves. This observation is in agreement with the results of measurements that are now being conducted in the Czech Republic and Germany.

Moreover, the influence of passing tourist groups on the cave climate could unequivocally be identified and demonstrated. Depending on the location and distance of the measurement location from the stopping points of these groups, different degrees of alteration of all climatic variables could be shown. The modification of the air temperature and the situation of the air currents are partly short-lived, but long-term alterations also could be observed, and conditions only returned to normal after a quiescence period of at least 1 day. Further investigations are needed here to yield new information about the extent and influences that these modifications have on the cave climate.

REFERENCES

Boes, C., Ek, C., Faber, S., Kies, A., Massen, F., Schintgen, G., Sinner, E., & Waringo, G., 1997, The Moestroff Cave: Centre de Recherche Public Centre Universitaire, Luxemburg, 199 p.

Bögli, A., 1978, Karsthydrographie und physische Speläologie: Springer, Berlin, 292 p.

Cigna, A., 1971, An analytical study of air circulation in caves: International Journal of Speleology, v. 3, p. 41–54.

Conn, H.W., 1966, Barometric wind in Wind and Jewel Caves, South Dakota: National Speleological Society Bulletin, v. 28, p. 55-69.

Don, J., 1989, Geologic evolution of the Snieznik Massif and the cave: - Jaskinia Niedzwiedzia w Kletnie, *in* Jahna, A. (ed.), Polska Akademia Nauk Odzial We Wroclawiu: Kozlowskiego, St. & Wiszniowskiej, T., Wroclaw, p. 58-79

Ford, T.D., & Cullingford, C.H.D., 1976, The science of speleology: Academic Press Inc., London, 593 p.

Geiger, R., 1961, Das Klima der bodennahen Luftschicht: Braunschweig, Vieweg & Sohn, 640 p.

Hebelka, J., 1998, Zavedeni jednotneho monitoringu mikroklimatickych pomeru zpristupnenych jeskyni: Zaverecna Zprava, Praha (CD-Rom)

Locker, R., 1996, A sonic anemometer for general meteorology: Sensors, the Journal of Applied Sensing Technology, v. 13, p. 12-18.

Moore, G.W., & Sullivan, N., 1997, Speleology - Caves and the cave environment: St. Louis, Cave Books, 176 p.

Piasecki, J., 1996, Warunki termiczne w Jaskini Niedwiedziej, w: Masyw OnieOnika (Thermic conditions in the Bear Cave): Masyw OnieOnika, zmiany w Orodowisku przyrodniczym, Wydawnictwa PAE, rozdz. 11 Warzawa, p. 207-218.

Pflitsch, A., Piasecki, J., & Kleeberger, M., 1999, Impact of tourists on the climate of static cave systems, *in* De Dear, R.J. & Potter, J. (eds.), Proceedings of the 15th International Congress of Biometeorology & International Conference on Urban Climatology, ICB 24.3, Sydney (on CD-Rom).

Pflitsch, A., & Flick, B., 2000, Proof and characterization of slowest air currents using sonic anemometers in urban and topographical climatology research: Sensors, the Journal of Applied Sensing Technology, v. 17, p. 75-82.

Przylibski, A., & Piasecki, J. 1998, Radon as a natural radioactive tracer of permanent air movements in Niedzwiedzia Cave: Snieznik klodzki, Sudety Mts., Kras I speleologia, T. 9 (XVIII), Katowice, p 180-193.

Pulina, A., 1989, Historia Odrkrycia I Badan: Jaskinia Niedzwiedzia w Kletnie, Polska Akademia Nauk Odzial We Wroclawiu, Wroclaw, p.11-20

Reuter, U., Baumüller J., & Hoffmann, U., 1991, Luft und Klima als Planungsfaktor im Umweltschutz: Expert Verlag, Ehningen (Germany), 170 p.

Schuster, R., & Novak G., 1999, Die Wetterführung der Salzgrabenhöhle (1331/29) bei Berchtesgaden: Sonderveröffentlichung der Höhlenkundlichen Arbeitsgemeinschaft Rosenstein/Heubach e.V. 42 p.

Shaw, R.H., Maitani, T. & Miayashita, K., 1996, Micrometeorology of a depression and the influence of cave airflow: 12th Symposium on BLT, American Meteorological Society, p. 502-503.

VDI, Verein Deutscher Ingenieure (Association of German Engineers), 1988, Meteorologische Messungen für Fragen der Luftreinhaltung, Wind: Düsseldorf, VDI-Richtlinie 3786, VDI-Handbuch Reinhaltung der Luft, v. 1.

VDI, Verein Deutscher Ingenieure (Association of German Engineers), 1994, Meteorologische Messungen, Turbulenzmessungen mit Ultraschall-Anemometern: Düsseldorf, VDI Richtlinie 3786, v. 12.