In this paper we present the first results of our temperature measurements, which were started in autumn 2007. Due to limited access to the cave mainly from early summer to late autumn and the missing availability of electricity so far we mainly focused on the use of air temperature loggers in the different parts of the ice cave. However, the analysis of the data will show the thermal conditions of the cave and a primarily conceptual model also for the airflow regime of the cave. This temperature study is the beginning of a more interdisciplinary study on the dynamics and processes of Schellenberger ice cave. It is planned to use the results of this study with ice caves in different climatic conditions.

Site description
Untersberg (Germany) is an isolated mountain in the most Northern part of the Berchtesgaden Alps (Northern Limestone Alps) at the border between Austria and

Figure 1. Location of Schellenberger ice cave. (© GoogleMaps).

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The Schellenberger ice cave (Fig. 3) (total length: 3621 m, total depth ~260 m), which is run as a show cave since 1925, is situated at 1570 m a.s.l. on the foot of the NE-walls of Untersberg (Verein für Höhlenkunde Schellenberg e. V., 2001).

The access to the cave is marked by a 4 m high and 20 wide portal, which leads to the largest room in the cave “Josef-Ritter-von-Angermayer-Halle” with a length of 70 m and a width of 40 m. The floor 17 m below the entrance level of this hall completely consists of an approx. up to 30 m thick and 60,000 m³ ice block (Verein für Höhlenkunde Schellenberg e. V., 2001), which is surrounded by the show cave trail. Above the entrance hall the “Dohlenfriedhof” is situated - subdivided into two other floors. The two connecting parts Wasserstelle and Mörkdom are leading to the deepest point of the ice cave part, Fuggerhalle, 41 m below entrance level. From here only small fissures between the ice block and the rock give access to the deeper passages. The room below Fuggerhalle is called the “Max-Gadringer-Room”, which could be reached last time before the last World War through the “Thomas-Eder-Schacht” (Verein für Höhlenkunde Schellenberg e. V., 2001), but is today filled with ice again. 12 m above the “Lehmgang” is situated, which ends after 30 m in a choke.

Apart from the approximately 500 m ice cave part there is one major non-ice part (Fig. 2), which leads at the Northeastern end through several deep shafts to the deepest point of the cave (-221 m).

Research history

The Schellenberger ice cave is probably known for centuries to the local population because of the big entrance portal and was first mentioned in 1826 in the Bavarian ordnance map as “Schellenberger Eisloch” (Vonderthann, 2005). After 1874 the cave was explored by several speleologists of the “Landesverein für Höhlenkunde Salzburg” and later on studied by Eberhard Fugger, who published some of the most important German ice cave publications of the 19th century. He started in 1869 with a study on the ice formations of the Kolowrat cave and worked later also in the Schellenberger ice cave, where he carried out numerous ice mass measurements from 1876-1882 (Vonderthann, 2005). Since 1925 the cave is run as a show cave and to this day carbide lamps only illuminate it, as there is no access to electricity in this part of mountains. The next decades from the 1940s to the 1980s were determined by the speleologist and long-term cave guide Fritz Eigert, who carried out ice-level measurements and a temperature monitoring till the end of his activities in the cave (Ringeis et al., 2008). Starting in October 2007 the authors conducted various long-term
and mobile measurements (Grebe et al., 2008). Long-term measurements include air temperature measurements at various sites in Schellenberger ice cave (see Fig. 4) and ice temperature at one spot in the big entrance hall. Mobile Measurements include among others measurements with thermal camera, mobile temperature measurements and a study on the ice mass changes. In this paper we only discuss the results of the long-term air temperature measurements and the ice temperature in order to describe the general thermal conditions of the ice cave. In summer 2013 we installed 32 new points for ice level measurements as prolongation the study of Fritz Eigert. The results of the other studies conducted in Schellenberger ice cave may be subject to future publications.

**Methods**

Air temperature was first measured inside the cave (Fig.4) starting from October 17, 2007 to November 7, 2013 in intervals of 10 to 15 min by using GeoPrecision data logger with PT 1000 sensors (precision ± 0.1 K, resolution 0.01°C). The specific points were chosen in order to represent the main parts of the cave and different heights starting from entrance level to the deepest point at Fuggerhalle. In the big entrance hall Angermayerhalle we selected two sites, one in the upper part close to the entrance and one at the lower end of the hall (cp. Fig. 4). The third measuring point is in the connecting passage to the lower parts of the ice cave, called Wasserstelle. The last was installed in the deepest part of the ice cave called Fuggerhalle. From June 2008 to October 2010 one temperature logger recorded also the ice temperature in Angermayerhalle. Unfortunately, somebody took out this logger without our knowledge so that we couldn’t continue these measurements. In May 2011 a third logger was also installed temporarily in a separated section of Angermayerhalle for about 14 months, but we will not include these data in this paper. Figure 3 shows the different parts of the ice cave with pictures, where air temperature loggers were installed. Except the logger in Mörkdom, which is completely surrounded by ice and the one in the upper part of Angermayerhalle, which is outside the ice, the other sites of the loggers are situated in room or passages characterized by ice and solid rock.

**Results and discussion**

In this paper we would like to present primarily results of the air temperature measurements at Schellenberger ice cave to describe the common thermal conditions inside the cave. For the basic analysis we used the air temperature data recorded between 2007 and 2013. Schellenberger ice cave has only one main entrance (Fig. 3) leading to the deepest part of the cave - Fuggerhalle via a series of descending passages. Thus the cave acts like a cold air trap with thermal conditions throughout the year closely related to external climate variations. In winter conditions the cave follows the external temperatures changes during cold air inflow (Fig. 5), by contrast in the course of the summer conditions the cave air temperatures are mostly independent from external changes. In summer the cave (Fig. 6) temperatures are specifically influenced by the thermal inertia of the ice block, the slowly warming of the overcooled walls of the cave and the direct solar radiation in the entrance hall. Additionally the melting of the snow fan takes some energy away from warming up the cave. Between these two main periods a transition time with rapid changes between winter and summer conditions takes place in April and in November. As the various parts of the cave react divergent in the different seasons, we suggest to subdivide the cave into three different zones: the entrance hall Angermayerhalle upper part (AUP) and lower part (ALP), the connecting tunnels at Wasserstelle (W) and Mörkdom (M) and the deep part at Fuggerhalle (F), which all show unlike characteristics.

The first zone at Angermayerhalle is represented by two data loggers as already described in the previous parts of this paper. The average seasonal temperatures in the upper part vary between -1.8°C and -0.03°C in winter and 1.7°C and 3.8°C in summer. Although in winter the seasonal minimum temperatures can alternate between -6°C and -2°C, AUP is the warmest measuring spot in the cave (Fig.5). Data analysis showed that AUP has also the biggest longest delay during a cold air inflow.
pile into Angermayerhalle and flows more to the left side instead of Mörkdom, which has just a small opening.

During summer ALP the average temperatures show only small variations (taverage= 0.2°C - 0.4°C) as this spot is generally situated below the inversion line. Wasserstelle and Mörkdom are representing the second zone. Here the dimensions of the passages are more tunnel like, though Wasserstelle is much higher and wider than Mörkdom. Both spots, located at the upper end of the respective cave passage, are slightly warmer than ALP in winter, peaking at minimum temperatures

Angermayerhalle lower part (ALP) in contradiction is the coldest spot of the ice cave during winter with average temperatures alternating between -3.4°C and -1°C and minimum temperatures of -6°C to -10°C. A possible reason for this fact is that the majority of the cold air inflow directly flows widespread over the snow event (Fig. 7) accompanied by a strong damping of temperature signal. This may have two reasons, which need to be proved by further detailed studies. First, the position of the logger plays an important role.

Thinking about the way such a cold airflow takes a while entering the cave through the entrance portal, the logger at AUP is located offside of the cold air inflow. And second, the damping of the temperature signal may reasoned in the fact that we do not measure the inflowing cold external air but the specifically warmer flowing out air from the deeper cave passages, which already underwent a gradual warming during the traverse of the system. As well the sensor is located mostly above the inversion we could measure by mobile measuring campaigns. In summer the whole upper part of the entrance hall especially warms up peaking at maximum temperatures at AUP up to 4.8°C due to the influence due to the effect of the outside warming. Warmer wind is pushed in by turbulences in the entrance area and warmer rain and melting water invades the caves as well. It needs to be mentioned that the logger at AUP is not directly exposed to direct solar radiation.

Figure 5. Exemplary winter conditions at Schellenberger ice cave (here winter 2011/12).

Figure 6. Exemplary summer conditions at Schellenberger ice cave (here summer 2011).

Figure 7. Cold air inflow event during winter 2010: air temperature in °C inside Schellenberger ice cave and at outside station Geiereck (30 min interval).
of -8.3°C (W) resp. -8.6°C (M). Average temperatures underwent already a gradual warming on the rather short way through Angermayerhalle and alternate equally between -2°C to -3°C. In summer both measuring points show strong daily variations depending on the number of tourists visiting the cave (Fig. 6). Occasionally this leads to an interruption of the summer stratification. Thus, this difference in air temperature with the other measuring points triggers air movement between the deepest part (F) and Mörkdom resp. Wasserstelle. It can be assumed that the airflow follows the same way as under typical winter conditions.

The third zone, Fuggerhalle (F) shows the same characteristic with only small amplitudes during summer times. Here summer average temperatures vary between -0.03°C to -0.13°C, while maximum temperatures can peak at ≈ 2°C. Under winter conditions Fuggerhalle, though the deepest ice cave part is always warmer than the upper parts. This fact needs to be studied in further details in the future. Minimum temperature are then between -6.1°C and -2.3°C, maximum temperatures alternate between -0.4°C and 0.4°C. That shows that even under winter conditions with cold air inflow Fuggerhalle does not cool down as much as the upper parts of the cave, regularly reaching temperatures around the melting point. One reason is surely the gradual warming of the cold air inflow while its way through the whole cave. Another aspect, which we would like to study with airflow measurements, is a possible influence of chimney effects from of the deeper parts of the caves, which are connected just by cracks to the non ice-parts of the cave versus the deeper cave passages of the Kolowrat-System, which are assumed to be connected to the ice cave (cp. Fig. 3), too.

**Conceptual Model of the airflow regime**

The analysis of the air temperature measurements gives us also a first impression of the airflow regime inside the ice part of Schellenberger ice cave, which shall be validated by future airflow measurements. Thus we use for the primarily conceptual model only the air temperature measurement to extrapolate the air movements. Due to the fact that the cave has only one entrance, which is naturally open and not sealed by any door, the ice part mainly acts as a cold air trap depending on the external air temperature. In general the cave shows three main types of air exchange, a winter situation (Fig. 8) and a summer situation (Fig. 9) and the related transition period between the both extremes. The winter situation is limited to external temperatures below 0°C causing intensive inflow of cold air from outside into the cave caused by specific density differences mainly occurring from November to April. The cold external air flows currents through the whole entrance portal and then subdivides in Angermayerhalle into two subsequent streams, which are both directed to the deepest part of the ice cave, “Fuggerhalle”. While the one stream current flows down the left side of “Angermayerhalle” through “Wasserstelle”, the other stream equally descends to “Mörkdom” (cp. Fig. 8). At the crossing point of both passages, these streams reunite and descend further down until they reach the deepest part. The specific colder air replaces the warm air at the bottom and pushes it out along the ceiling towards the entrance of the cave into Angermayerhalle.
For the warm outflowing air two possibilities exist: either a major outflow of warm air at Wasserstelle due the larger dimensions of this passage or the major outflow takes place at Mörkdom. For the second possibility the wavy structures and scallops at Mörkdom are a hint that this part might react like a chimney because it leads more direct to the higher surface in Angermayerhalle. In the transition period in April, when the external air temperature strongly varies around 0°C, the airflow regime is controlled by the changes between winter and summer conditions. In addition, the change between night and day is another factor that influences the thermal conditions, because nightly cold air inflow interrupts the stratification occasionally (Fig. 9), but also these short events don’t stop the slowly warming of the cave (Fig. 8). With a delay of several weeks the cave reaches finally the summer static conditions with air temperatures around 0°C around May. From May to October air exchange between the internal and external air is severely limited and a distinct inversion develops, which vertical location alternates depending on the daytime and the external weather conditions. In the inner parts of the ice cave some small-scale until the first cold air inflow events around air movement can be suspected but need to be proved. October the ice cave remains in the summer condition and slowly transforms again to the transition period, before reaching the winter conditions finally around November.

Outlook

The presented results are the first step of a more interdisciplinary study on the dynamics and processes of Schellenberger ice cave. It is planned to work out the specific microclimatological characteristics in more detail in order to define the locality factors of the processes and dynamics. If possible, we will use the results of this study with ice caves in different climatic conditions. The central focus of this study is the interdisciplinary, for this reason we will also conduct a series of investigations on the processes and dynamics of the ground ice in Schellenberger ice cave.

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