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Linkage of cave-ice changes to weather patterns inside and outside the cave Eisriesenwelt (Tennengebirge, Austria)

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Abstract

The behaviour of perennial ice masses in karst caves in relation to the outside climate is still not well understood, though a significant potential of the cave-ice for paleo-climate reconstructions could be expected. This study investigates the relationship between weather patterns inside and outside the cave Eisriesenwelt (Austrian Alps) and the ice-surface changes of the ice-covered part of the cave from extensive measurements. It is shown that under recent climate the cave ice mass balance is more sensitive to winter climate for the inner parts of the cave and sensitive to winter and summer climate for the entrance near parts of the cave. For recent climate conditions ice surface changes can be well described from cave atmosphere measurements, indicating a clear annual cycle with weak mass loss in winter due to sublimation, stable ice conditions in spring until summer (autumn for the remoter parts of the cave) and significant melt in late summer to autumn (for the entrance near parts of the cave). Interestingly, surface ice melt plays a minor role for ablation at the inner parts of the cave. Based on our measurements and other observations it is rather likely that sublimation was the major source for ice loss in Eisriesenwelt since the begin of the 20th century. Build-up of the ice in spring (as expected from theory) was not observed as a general feature of the ice dynamics. Generally, the ice body currently appears in a quite balanced state, though the influence of show-cave management on ice mass-balance could not be clearly quantified.

1 Introduction

Ice fillings are eye-catching features in several karst caves worldwide. The ice is formed mainly from refreezing of percolation water and, with much less contribution, from deposition of cave-air water vapour. If ice formation generally exceeds loss due to ice melt and ice evaporation (sublimation) a layered ice body will be formed. Today ice-caves are often used as show-caves for tourism purposes because of their impressive appearance. However, ice caves could also provide - because of the layered structure of the ice – the potential of high-resolution climate proxy information (Homlund et al., 2005). The value and the processes of both the accumulation and the ablation of cave ice, however, are still not well understood and vary between individual caves. In general static and dynamic ice-caves are to be distinguished (Luetscher and Jeannin, 2004), where the classification refers to the relationship between ice-formation and air circulation in the cave. Whereas static ice caves feature a much simpler air circulation system and related cave climate (driven from the influence of air temperature on air-density, similar to cold-air pools in sink holes), dynamic ice-caves are characterized by an interconnected system of highly structured cave passages with at least two interacting entrances resulting in a more complicated air flow system. Details on the relationship between ice cave type and cave air dynamics are to be found in e.g. Luetscher and Jeannin (2004).

Extensive investigations of ice caves are quite new (Luetscher, 2005) and in particular motivated from the perspective for paleo-climate reconstructions. Most detailed information is currently available from static ice-caves Scarisoara in Romania (Silvestru, 1999; Racovita and Onac, 2000; Persoiu et al., 2007) and Dobsinska in Slovakia (e.g. Pflitsch et al., 2007; Vrana et al., 2007). First high-quality dating of basal ice from Scarisoara yielded ages of approx. 10 000 BP (Persoiu and Persiou, 2010). Thus the Scarisoara ice cave most likely could offer a continuous Holocene temperature chronology from an ice core taken in 2003 (Persoiu and Persiou, 2010).

Eisriesenwelt (Tennengebirge, Austrian Alps see Fig. 1) is known as one of the largest ice caves of the world with an area of about 10 000 m^2 and about 33 000 m^3 in volume (Silvestru, 1999). Contrary to Scarisoara and Dobsinsky it is a dynamic ice cave, with a total length of 42 km (Pfarr and Stummer, 1988). About 700 m of the entrance-near part of the cave are covered by the ice body. The entrance of the cave is at an elevation of 1641 m in a steep rock wall of Tennengebirge facing towards Southwest. From the entrance to the most remote ice covered part of the cave there is an increase in elevation by 158 m with highest parts (1774 m a.s.l.) in between. First

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

detailed scientific studies on the cave already date back to the early 1930s (e.g. Oedl, 1922). For more than 10 years regular air temperature measurements in the cave have been performed which were summarized in Thaler (2008).

The project AUSTRO*ICE*CAVE*2100 aimed to study the relationship between ice body mass balance of Eisriesenwelt and the weather and climate patterns inside and outside the cave as well as to explore the potential for climate proxy information from an ice core taken at the site Eispalast. In this paper focus is given to the processes of ice body mass balance and related weather (and possibly climate) patterns inside and outside the cave in order to improve the paleoclimate interpretation of ice-core measurements.

2 Methodical concept and data

In order to quantify changes of the cave ice body and their linkages to atmospheric conditions both the mass balance and the energy balance at the ice surface have to be assessed. For a given location e.g. the AWS-site the specific mass balance b (mass balance per unit area) can be written as the sum of mass gain c and mass loss a:

$$b = c + a \quad \left(\mathrm{kg/m^2}\right) \tag{1}$$

with c is the specific accumulation (coming from either refreezing of percolation water or deposition) and a is the specific ablation (either by ice melt or by ice evaporation). In fact b results from temporal fluctuations of both c and a which needs to relate b to a certain period t_1 t_2:

$$b = \int_{t2}^{t1} \frac{(\partial c + \partial a)}{\partial t} \quad \left(\mathrm{kg/m^2}\right) \tag{2}$$

The ice body of Eisriesenwelt is shallow (less than 2m ice-thickness at the 2 AWS sites). Consequently, internal ice deformation and ice flow over bedrock can be neglected.

The specific ablation a is dependent on the energy balance at the ice surface:

$$R + H + L + S + M = 0 \quad \left(\mathrm{W/m^2}\right) \tag{3}$$

which means that heat for melting (M) originates from the radiation balance R, the sensible heat flux H, the latent heat flux L or the heat flux in the ice body S.

As the cave is shielded from shortwave radiation the radiation balance R includes only components of the longwave radiation at the surface, which is defined by the upward component R_U from the ice surface and the downward component R_D from the surrounding cave walls and the cave atmosphere toward the surface. Using the Stefan-Boltzmann equation R_D and R_U can be formulated as

$$R_\mathrm{U} = \varepsilon_i \, \sigma \, T_i^4 \quad \left(\mathrm{W/m^2}\right) \tag{4}$$

$$R_\mathrm{D} = \varepsilon_r \, \sigma \, T_\mathrm{r}^4 + \varepsilon_a \, \sigma \, T_\mathrm{a}^4 \quad \left(\mathrm{W/m^2}\right) \tag{5}$$

(ε_i, ε_r, ε_a are the emissivity of the ice, the rock and the air respectively, σ is the Stefan-Boltzmann constant, T_i, T_r and T_a are the temperatures of the ice, the rock surface and the air respectively). Given that ε_i, ε_r, ε_a and σ are temporally constant changes of the two radiation components R_D and R_U are defined by changes of the ice surface temperature, the rock surface temperature and the air temperature, respectively.

Using a gradient approach the sensible heat flux H in Eq. (3) can be computed from the vertical temperature gradient, the density of air ρ_a, the specific heat capacity of air at constant pressurec_p and a turbulence parameter K_H which is dependent on the vertical gradient of wind speed, the ice surface roughness and the atmospheric stability:

$$H = -\rho_a \, c_\mathrm{p} \, K_\mathrm{H} \, \frac{\partial T}{\partial z} \quad \left(\mathrm{W/m^2}\right) \tag{6}$$

Similarily, the latent heat flux L in Eq. (3) can be computed from the vertical vapour pressure gradient, the density of air ρ_a, the heat of evaporation L_v and a turbulence parameter K_E which is dependent on the vertical gradient of wind speed, the ice surface roughness and the atmospheric stability

$$L = \rho_a \, L_\mathrm{v} \, K_\mathrm{E} \, \frac{\partial q}{\partial z} \quad \left(\mathrm{W/m^2}\right) \tag{7}$$

It can be concluded from Eqs. (6) and (7) that, because of c_p and L_v are constants and as long as surface roughness and atmospheric stability are temporally stable, H is well explained from the wind speed and the temperature gradient towards the ice surface and L is well explained from the wind speed and the vapour pressure gradient towards the ice surface. We argue that, because of constant ice surface conditions, surface roughness of the cave ice body varies only in a very small range (contrary to glaciers outside) and atmospheric stability is generally stable throughout the year (derived from temperature measurements of the ice surface and the atmosphere) with higher values of stability in winter compared to summer.

The heat flux S in the ice body can be formulated as:

$$S = -\lambda \, \frac{\partial T_{i(x)}}{\partial x} \quad \left(\mathrm{W/m^2}\right) \tag{8}$$

($T_{i(x)}$ is the temperature of ice at depth x below surface, λ is the thermal conductivity of ice), considering only vertical temperature gradients in the ice body. T_i was only measured at the ice surface for the location of the meteo-station and therfore S could not be quantified in this study.

Next the cave atmospheric conditions and their spatiotemporal variability have to be considered in order to assess the linkage between weather patterns and cave ice mass balance. Dynamic ice caves are known to show a clear hydrostatical behavior which enables to explain cave air flow from a simple hydrostatic model approach considering atmospheric layering inside and outside the cave. Such simple model approach was developed for Eisriesenwelt by Thaler (2008). The hydrostatic equation can be formulated as

$$\partial p = -\rho a\left(T_{\mathrm{a}(z)}\right) g\, \partial z \quad (\mathrm{hPa}) \tag{9}$$

(p is the air pressure, ρ_a is the density of air, $T_{\mathrm{a}(z)}$ is the air temperature at vertical level z and z is the vertical coordinate).

Based on the ideal gas law

$$p = \rho_a R_\mathrm{a} T_\mathrm{a} \quad (\mathrm{hPa}) \tag{10}$$

(ρ_a is the density of dry air, R_a is the universal gas constant for dry air and T_a is the air temperature)

the hydrostatic equation can be reformulated as:

$$\frac{\partial p}{p} = -\frac{g}{R_\mathrm{a}} \frac{\partial z}{T_\mathrm{a}(z)} \quad (\mathrm{hPa}) \tag{11}$$

showing that air temperature stratification is the essential parameter for the air pressure at a certain level z and thus related pressure gradients and air flow. In fact the air temperature has to be replaced by the virtual air temperature considering that the air contains a certain amount of water vapour which alters specific weight. As, however, humidity measurements from both AWSs were not reliable and are known to be temporally rather stable for cave atmosphere conditions, the influence of water vapour on specific weight was not considered.

The simple model can explain that air flow into the cave and coming out the cave are driven from air pressure gradients at the level of the cave entrances. Thus in winter, during weather patterns with advection of cold air toward the cave entrances and as long as the air outside is colder than inside the cave, the air flows into the cave. On the other hand, if the air pressure outside the cave is smaller than inside, e.g. the air is warmer outside, air flows from outward the cave. In case of an inward air flow the cave atmosphere interacts with the atmosphere outside and from the related energy balance at the ice surface inside the cave significant melting, evaporating or cooling/warming of the surface is possible. The measurement approach described below is highly motivated from the theory described above in order to capture both the air flow in the cave and to a certain degree the energy- and mass budget at the ice surface.

Consequently, the measurements in the ERW cave covered ice mass balance as well as several meteorological variables (see Table 1 and Fig. 1 for details) for the period 2007 to 2009 at two sites inside (Odinsaal and Posselthalle) as well as, for the meteorological variables only, one site outside (close to the cave entrance) the cave. Figures 2 and 3 show photographs of the two AWS installed inside ERW. As part of AUSTRO*ICE*CAVE*2100 also high resolution measurements of the ice-cave atmosphere interaction at site Eispalast were performed (see Obleitner et al., 2010). Eispalast is the remotest part still ice-covered of ERW (relative to the cave-entrance) and thus changes of ice mass and atmospheric variables are significantly smaller compared to the two AWS-sites used in this study. Such environmental conditions desire both higher resolution and higher quality sensors at site Eispalast. Combined investigation of the data set of this study together with Eispalast-data will be subject to another study.

Eisriesenwelt is characterized by a complex cave passages system and highly structured ice body. In order to cover the linkage between the meteorological conditions outside the cave with those inside and further on changes in the built-up and the loss of the ice body the following measurement approach was applied in this study:

- Measurement of the meteorological conditions outside the cave by one AWS close to the main entrance of the cave. Though other (much smaller) entrances of the cave are known from detailed cave mapping, their influence was not quantified in this study.
- Capturing of the cave atmosphere conditions at two sites, one close to the entrance and one in the middle part of the ice-covered part of the cave, considering

both demands related to show-cave management as well as the spatial representateveness of measurement.

- Estimation of changes of ice mass from both a spatially dense network of ice stakes (with non-regular manual readings) accompanied by automatic readings located at the two AWS sites, supplementing the spatially dense information of the stakes by temporally high-resolution data of ice-surface changes.
- In order to assess the energy exchange between the ice-surface and the surface-near cave-atmosphere, ice surface temperature is a key parameter to be measured in addition to atmospheric conditions and ice elevation changes. Thus ice surface temperatures were measured in order to estimate data on the sensible and latent heat flux and to characterize the ice surface with respect to melt or evaporation events.

Surface changes were measured by two different methods, manual stake reading und ultrasonic sensor (US) range sounding, respectively. For manual stake readings plastic stakes were drilled by a steam drill at eight locations into the ice (see Fig. 1 for location). The stakes were measured at each visit of the cave, with a total of 18 readings available within the period 16 October 2006 and 24 November 2009. All stake readings are summarized in Fig. 4. Ultrasonic sensors range measurements were performed at two sites (see Fig. 1: Meteo "Posselthalle" and Meteo "Odinsaal") offering permanent measurements of ice surface changes. US-Sensor data were stored with Campbell CR200 data loggers. Both US-Sensors and Campbell loggers worked well without any data loss within the entire period starting October 2007 and ending September 2009. Whereas the weather station at site Odinsaal is situated at a plane part of the cave, weather station Posselthalle is very near to the cave entrance with surface inclination of the ice body about 20°. Additionaly, there is another significant discrepancy between the two measurement sites. Compared to Posselthalle the site Odinsaal is a narrower part of Eisriesenwelt so that significant differences in air flow are to be expected from the differences in cross sectional area.

Meteorological measurements were performed inside and outside the cave using both standard mobile automatic weather station (enterprise Kroneis, Austria) of the Austrian weather service (ZAMG) for the outside station as well as automatic weather station specifically adapted for measurements inside the cave (see Table 1 for details).

3 Results

3.1 Spatial and temporal changes of the cave ice body

Results from the manual readings of the ice stakes of ERW are shown in Fig. 4. It is evident from this Figure that a clear spatiotemporal pattern of ice built-up and ice loss is hard to derive. In particular expected built-up of ice in spring from refreezing of draining snow-melt water as well as ice loss from melt in summer cannot be identified. Most distinct changes of ice mass were measured for cave-entrance near stakes with clear ice loss in summer and strong ice increase (of up to about 25 cm) in late autumn 2008. The general picture, however, is that ice changes are rather small and spatially inhomogeneous. Additionally, it was observed that the temporal variability of ice surface changes decreases with distance from the cave entrance, which is in agreement with the spatial variability of the cave climate to be shown later. In overall the ice body seems to be in a rather stable state over the period of observations, with the exception of stake “Posselthalle unten” which lost about 20 cm of ice.

More detailed information on ice changes can be seen in Figure 5 from the continuous ice surface measurements using the US-Sensors. Over the entire period the US-measurements are in fairly good agreement with parallel measurements from stakes with exception of one observation for site “Posselthalle unten”, which maybe resulted from an error during manual observations. Though the observed changes for the two sites are rather small, in particular for the site Odinsaal, a clear temporal structure can be derived from the measurements. For both sites the series started with a rather weak mass loss in winter in the order of about 1–2 cm which happened between about the end of November until about April of the subsequent year. After this period of weak mass loss the ice body remained stable until approx. begin of August (for the entrance near site) respective November (for the site in the middle of the ice-covered part of the cave). Whereas the site in the middle section of the cave experienced no ice loss in summer the entrance-near site showed a clear loss in late summer and early autumn. For late autumn 2008 the entrance-near site showed a significant mass gain. The temporal cycle of ice surface elevation changes can be summarized as:

- weak mass loss in winter
- stable conditions in spring for the entrance near parts of the cave and from spring until autumn for the inner parts of the cave
- mass loss in late summer and autumn for the entrance near parts of the cave

Additionally, there appears a period of significant ice increase in Fig. 5 for late autumn for the entrance near parts of the cave which counteracts general rules of cave ice dynamics.

Measurements of long-term changes of the ice body in Eisriesenwelt are not available. There are, however, a large series of photographs of the cave back the begin of the 20th century. Comparison of these old photographs with recent one clearly indicates a mass loss in particular for the site Eispalast, where comparisons are advantageous because of the flat structure of the ice surface.

3.2 Linkage between atmospheric conditions inside and outside the cave

The existence of linkages between atmospheric conditions inside and outside a cave is not new and was discussed in e.g. Hauser and Oedl (1923) for the Eisriesenwelt cave. However, earlier studies were often based on simpler meteorological measurements and underlying concepts. Additionally, it has to be kept into mind that each cave has its own cave air flow dynamics highly dependent on the structuring of the cave as well as on the number and the location of entrances. In comparison to karst-caves without ice filling ice caves have additional significant influence on air flow dynamics from the hygro-thermal conditions of the ice body.

Figure 6 gives a rough overview on atmospheric conditions inside and outside the cave Eisriesenwelt from monthly means of air temperature and wind speed. The Figure clearly shows that average atmospheric winter conditions were colder in 2008/2009 compared to 2007/2008 for both inside and outside the cave and that the average wind speed during winter was higher in 2008/2009 compared to 2007/2008, too. This finding agrees with the theory from equation 11 as colder temperatures outside the cave induce larger pressure gradients between outside and inside the cave and consequently higher wind speeds in the cave. Additionaly, it can be also seen from Fig. 6 that the wind speed outside the cave is not linked to the wind insdie the cave.

A more detailed picture of the interaction between the atmosphere inside and outside the cave in the winter period can be seen from Fig. 7 for the period 1 December 2007 to 31 May 2008. Whenever the air temperature outside the cave dropped below the air temperature inside the cave the air moved into the cave (triggered from the air pressure gradient described by Eq. 11). This air flow into the cave is not only reflected in the clear temperature drop inside the cave, which delays from the entrance towards the inner parts of the ice cave by 1 h or even more, but also from the significant increase of the wind speed inside the cave during such events. As soon as the temperature level outside the cave returned to warmer temperatures than inside the pressure gradient levelled out and the inward air flow stopped or even reversed. It can be clearly seen from Fig. 7 that the typical winter inward air flow was not stable throughout the winter season but was interrupted in many cases by advection of warmer air masses outside the cave. In the middle of April the predominate inward air flow significantly decreased and levelled out at the begin of May 2008. The same general picture as for winter-spring-autumn 2007–2008 was observed for the year 2008–2009 (not shown here).

During summer the cave air temperature was rather stable at the level of 1–2 °C at the two sites Odinsaal and Posselthalle (see Fig. 8). A striking feature of summer temperature behaviour can be seen from Fig. 10. Both measurement sites show a clear diurnal cycle of the air temperature which is quite independent from the air temperature outside the cave. In particular, every day the air temperature quickly increased after 07:00 a.m. by about 0.5 to 0.8 °C approaching the maximum at about 01:00 p.m. Thereafter the air temperature decreased to the next minimum phase during the night. The daily cycle was well established and stable during summer and autumn. Most probably the cycling has something to do with the management of the cave which starts with the first activities and opening of the entrance in the morning and ends up with the closure of the cave-entrance in the evening. The intermittent opening of the door during the day in summer initiate on outflow of the cold and dense air from the cave and increases the temperature from warmer and adiabatically warmed-up air masses from the inside-parts of the cave. During night, however, the outflow of cold air is blocked from the door generating a cold air pool in the lowest part of the cave close to the entrance.

3.3 Cave atmospheric conditions and ice mass changes

Now we use the atmospheric measurements inside and outside the cave from the AWSs in order to asses the major components of the energy balance at the ice surface and to relate them to the measured ice changes. In Sect. 3.1 an annual cycle of ice surface changes were described with a clear ice loss in winter/spring and summer (the latter for the entrance near parts only) as well as, for the entrance near sites, distinct ice accumulation in late autumn 2008. Obviously, ice body loss has to come from either sublimation or melt whereas accumulation is to be expected from freezing of percolation water (liquid precipitation or snow-melt water) on the ice surface.

Though measurements of relative humidity were done at both sites Odinsaal and Posselthalle, the data were not accurate enough to be used for computation of vapour pressure gradients inside the cave. However, assuming total saturation (relative humidity 100%, which is realistic for Alpine caves) vapour pressures both over the ice surface as well as for the atmosphere (approx. 1 m over ground) can be computed from temperature measurements (of ice and air respectively) using empirical approximations (e.g. the Magnus formula), which estimates water vapour pressure E_a (for air) as:

$$E_{a(t)} = E_0 \exp\left(\frac{17.62\,t}{243.12 + t}\right) \quad \text{(hPa)} \tag{12}$$

and E_i (for vapor pressure over ice) as:

$$E_{i(t)} = E_0 \exp\left(\frac{22.46\,t}{272.62 + t}\right) \quad \text{(hPa)} \tag{13}$$

and for $E_0 = 6.112$ hPa (t is the air temperature in °C).

Using Eqs. (12) and (13) vapour pressures were computed from air temperature and ice temperature for Odinsaal and Posselthalle, respectively (Fig. 10). Analysis of the results shows that during the winter/spring period between December and April the vapour pressure over the ice body was generally larger than the vapour pressure of the cave atmosphere at the level of temperature sensors, indicating ice evaporation (to be derived from Eq. 7). As the wind speed was significantly increased during periods with vapour pressure gradients from the ice surface towards the cave atmosphere, the turbulence was increased during these periods, too, thus enforcing the latent heat flux. Though, this is only limited information on the latent heat flux, as computation of latent heat flux would need much more precise meteorological measurements, it is a clear indication on the sign and the dimension of energy balance at the cave-ice surface.

Importance of sublimation for ice ablation in Eisriesenwelt is further supported by the existence of well established cryogenic carbon layers in the ice wall at Mörkdom. These layers, described by Spötl (2008), were built due to freezing of calcium-rich surface melt layers and later were enriched by sublimation (and melt) forming white-brown horizontal layers in the ice body. The large number of cryogenic carbon layers covering the entire ice wall at Mörkdom underlines the improtance of sublimation for mass balance of Eisriesenwelt ice body since its formation. A high contribution of sublimation to ice melt in an ice cave was also shown by Rachlewicz and Szczucinski (2004) from extensive measurments in Janskinia Lodowa w Ciemniaku (Tatra Mountains, Poland). However, additional to the strong ice loss due to sublimation in winter (30% of the total loss) this cave also experiences high loss from ice melt in summer and autumn (70 of the total loss).

Whereas ice loss in winter can be well explained from sublimation, ice ablation in summer can be only associated to surface melt, as vapour pressure gradients did not allow sublimation. In fact, the begin of the ablation period in autumn agrees well with the time when the ice surface temperature approached the threshold of 0 °C (see Fig. 9) for site Posselthalle (whereas it took significant longer for site Odinsaal to approach 0 °C ice surface temperature). At the same time air temperatures at site Posselthalle were high enough to generate melt from sensible heat flux, although turbulence was rather weak because of low wind speed. Additional entry of energy could be expected from increased longwave radiation balance as the upward component is limited by the 0 °C threshold of ice surface, whereas the downward component could further increase with increasing rock- and air temperature.

During the period of increasing air temperatures in May 2009 the level of 0 °C was approached quite fast. This is shown in Fig. 9 for the period 1 April to 1 October 2009 for both AWS sites, Odinsaal and Posselthalle, and was observed very similar for the spring 2008, too (not shown here). It is however a clear feature of Fig. 9 that, compared to air temperature, ice temperature needed much longer to reach the level of 0 °C, indicating that the ice did not melt before approx. the begin of August in 2009 (again this finding is in good agreement for summer 2008, not shown here), with a clear increasing time-shift towards the more inner part (Odinsaal) of the cave.

Both Figs. 4 and 5 show a period of distinct ice accumulation in late autumn 2008. This accumulation period, however, can not be associated to single weather patterns inside or outside the cave. Ice accumulation would need significant refreezing of percolation water at the ice surface which originates from precipitation or snow melt. Measurements from the weather station outside the cave, however, do not support this reason.

A final synopsis of Figs. 5, 9 and 10 now enables to derive a clear picture of ice body changes in the Eisriesenwelt and related atmospheric conditions inside and outside the cave. In particular significant periods of ice surface changes from Fig. 5 can be well explained from atmospheric conditions shown in Figs. 9 and 10:

- December–March: Whenever in the winter period the atmosphere outside the cave entrance is significantly colder than inside, a pressure gradient into the cave is established and the cold air moves from outside into the cave. This inward air flow is quite well reflected from a significant cooling of the air in the cave and a significant increase of the wind speed inside the cave. Additionally the wind direction in the cave during such periods is clearly inward. As the approaching air is significantly colder than the ice surface a vapour pressure gradient from the ice towards the air is established and the ice body looses mass from evaporation, enforced from the increased turbulence due to the higher wind speeds. As soon as the air outside the cave warms up (e.g. from advection of warmer air masses) the inward air flow and the ice evaporation stops

- April–July (AWS Posselthalle), April–November (AWS Odinsaal): In spring the air temperature outside the cave increases and air pressure gradients between inside and outside the cave levels out. Wind speeds are now much weaker compared to the winter period. The air temperature in the cave increases to about 1–2 °C and evaporation from the ice surface is no longer observed. Contrary to air temperatures ice temperatures remains below 0 °C until summer. Thus the ice surface experiences a balanced state without any accumulation or ablation. In particular a significant accumulation from refreezing of percolating snow-melt water is not observed.

- August–November (AWS Posselthalle only): During late summer until autumn the behaviour of the ice body is characterized by significant ice loss for the entrance near parts of the cave. The different behaviour of the entrance near and the remote parts of the cave is well reflected in the ice and air temperature measurements, respectively, which are both significantly higher for the entrance near parts of the cave. Obviously, the mass loss is triggered from increased air temperatures and related sensible heat flux. The period of clear mass loss happens until the end of November when the door of the cave will be opened and winter conditions starts again.

As described earlier ice bodies from ice caves are currently discussed as a valuable source for proxy data for paleo-climate reconstructions. For climate interpretation of proxy data its sensitivity to the climate is essential. In particular the sensitivity of the proxy data to single climate elements and to a particular season of the year has to be known. From our two-year measurements it can be clearly seen that under the actual climate the inner parts of the Eisriesenwelt ice cave are only sensitive to winter conditions whereas the entrance-near parts of the cave are sensitive to both the winter and summer/autumn conditions. Colder winters increase ice loss due to increased ice evaporation, which can be derived from comparison of Fig. 3 with Fig. 4 (the winter 2007/2008 was significantly warmer and experienced less ice loss in winter compared to the winter 2008/2009) and which is in agreement with the formulation of latent heat flux of Eq. (7), too. However, all results on climate sensitivity have to be put into perspective of possible influence from cave-management activities on ice dynamics.

4 Conclusions

In this paper the ice dynamic of the Austrian ice cave Eisriesenwelt was quantified from analysis of extensive meteorological and glaciological measurements for the period 2007–2009. Focus was given to the linkage between weather patterns inside and outside the cave as well as resulting effects on ice surface changes. From the evaluation of observations we conclude that:

- Eisriesenwelt clearly shows the typical behaviour of a dynamic ice cave, with, at the lower main entrance, well established episodic inward air flow during cold weather types in winter and rather weak outward air flow during warm weather types for both winter and summer. Inward air flow in winter is triggered from air-pressure gradients between the outside and the inside atmosphere and air flow always starts from the entrance towards the inner parts of the cave.

- In spite of the current increasing temperatures outside the cave the ice body of Eisriesenwelt appears at a quite stable state. It is, however, unclear to which degree the stable state results from the influence of show-cave management on ice changes or from climate variability.
- Continuous measurements of ice surface changes of the ice body show clear temporal patterns with ice loss in winter, stable conditions in spring until summer and clear melt in late summer and autumn for the entrance near parts of the cave. The ice mass changes are in fairly good agreement with energy fluxes at ice surface derived from cave atmosphere measurements and the hydro-thermal structure of the cave ice body indicating weak ice-evaporation in winter, melt-free conditions in spring until summer and melt conditions in late summer and autumn for the entrance-near parts of the cave.
- Accumulation of ice in spring from refreezing of percolating snow-melt water, as expected from general theory for ice cave formation, was measured only at single stakes and for certain periods for Eisriesenwelt. Largest amount of ice accumulation was observed for the entrance near stakes in November 2008 (exceeding 20 cm for a stake close to the cave entrance) during a period without significant precipitation or snow-melt.
- Sensitivity of cave ice mass balance to the outside climate is complex and various with location inside the cave and with season. Cold winters generally decrease mean air temperature and increase mean wind speed inside the cave and thus increase ice evaporation from enforced latent heat flux from the ice body surface. In summer, however, the linkage between the outside air temperature and the

ice mass balance is highly damped because of the long-distance pathway for air parcels through the cave forced from the outward flow summer circulation. Whereas the inner parts of the ice body show stable mass balances over the summer season, the entrance near parts of the cave experience significant ice loss due to melt during summer/autumn.

- On the long term perspective ice changes in Eisriesenwelt can be well derived from comparison of photographs back to the begin of the 20th century, documenting a clear mass loss. Most likely this ice loss originates primary from sublimation in winter, as, even under the actual warm climate, sublimation appears as the major component of ablation for the inner parts of the cave. This hypothesis is further supported from the occurence of clear cryogenic carbon layers in the ice body, which need significant sublimation at the time of formation. Interestingly, contribution of surface melt to ablation is of minor influence for the inner parts of the ice cave. This, however, does not mean that the ice surface is not melting in summer, but that the melt water layer on the surface can not drain and refreezes as soon as temperature drops below 0 °C. In fact clear ablation was measured for the entrance near inclined part of the cave.

- For air temperature inside the cave a clear daily cycle was observed during late spring until autumn. This cycling increases with time approaching a maximum value in summer and appears to be independent from the weather outside the cave. Additionally, it is not simply related to the activities of the operator running the show-cave (opening of the door and visits from groups of cave tourists). Further measurements are needed to understand this striking feature of Eisriesenwelt cave climate.

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Table 1. List of meta-information on meteorological sensors used in the study.

Site	Air temperature	Ice surface temperature	Wind direction	Wind speed	Luftfeuchte	Precipitation	Air pressure	Ice surface change
AWS Outside	Kroneis 430 HC		Kroneis 263 PR	Kroneis 263 PR	Kroneis 430 HC	Kroneis AP22	Kroneis 315	
AWS Posselthalle	HOBO U12-013	HOBO U12-013	Gill/Mursch Propeller Anemometer	Gill/Mursch Propeller Anemometer	HOBO U12-013			Judd
AWS Odinsaal	HOBO U12-013	HOBO U12-013	Gill/Mursch Propeller Anemometer	Gill/Mursch Propeller Anemometer	HOBO U12-013			Judd

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

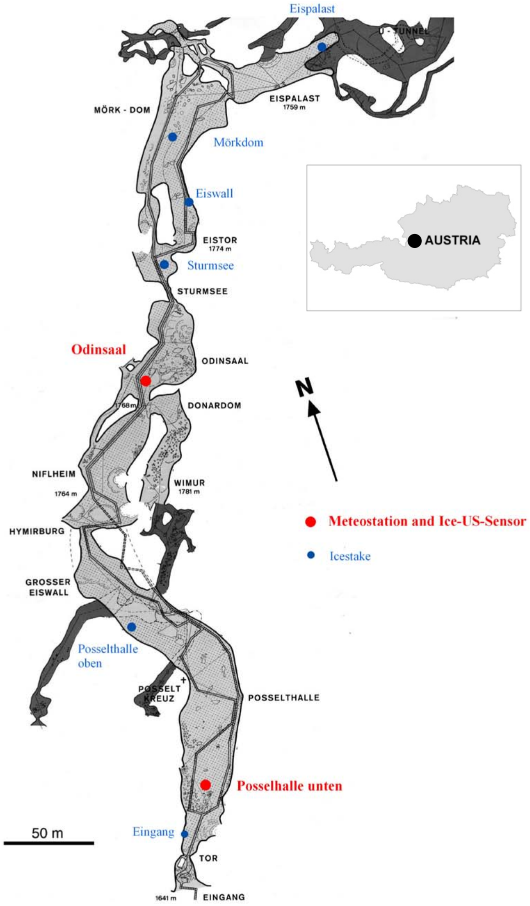

Fig. 1. Map of Eisriesenwelt and location of ice stakes (blue) and weather-stations (red) for this study.

Fig. 2. The automatic weather station AWS close to the cave entrance at site Posselthalle (see Fig. 1 for location of the AWS).

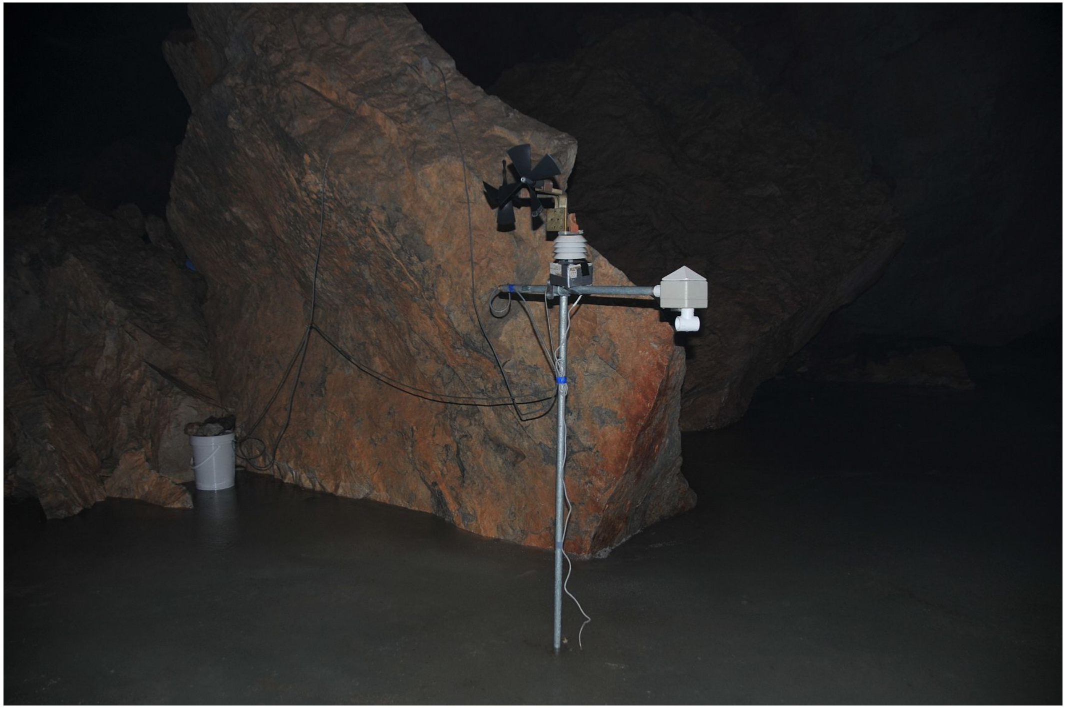

Fig. 3. The automatic weather station AWS in the central part of Eisriesenwelt at site Odinsaal (see Fig. 1 for location of the AWS).

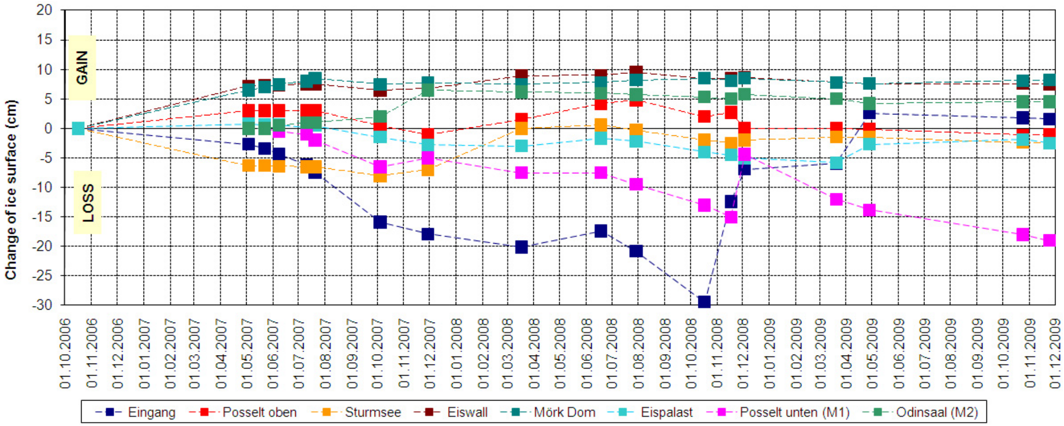

Fig. 4. Time series of ice surface changes of Eisriesenwelt ice body measured by manual stake readings within the period 1 October 2006 and 29 October 2009.

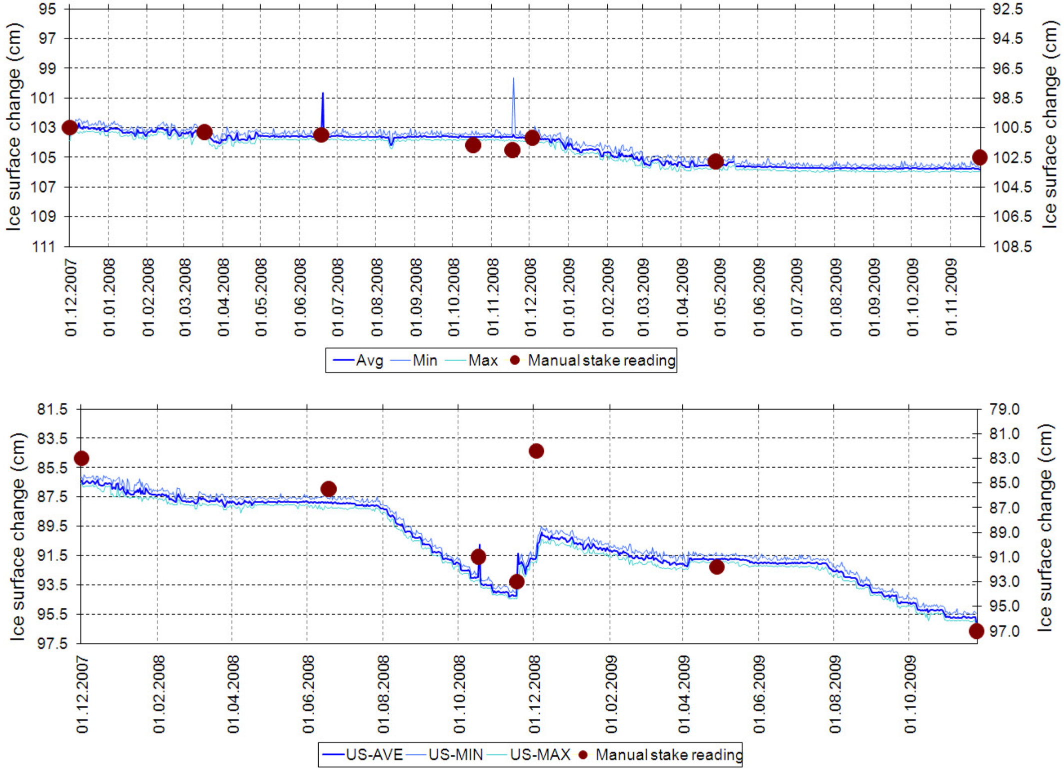

Fig. 5. Time series of ice surface changes of Eisriesenwelt ice body measured by ultrasonic range sensors at two sites Odinsaal (above) and Posselthalle (below) for the period 1 December 2007 and 29 Ocotber 2009.

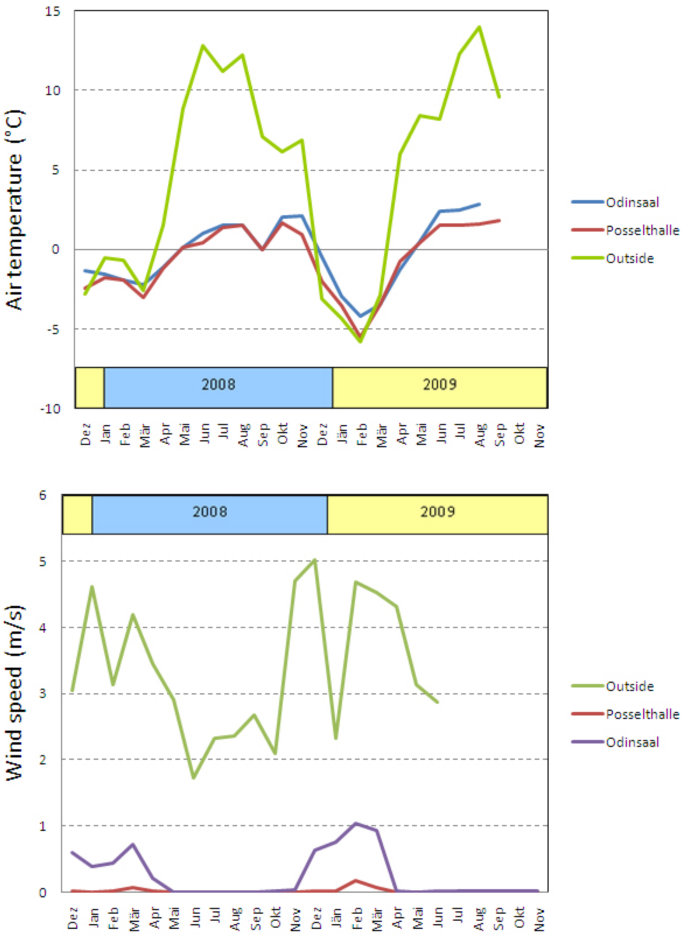

Fig. 6. Monthly averages of air temperature (above) and wind speed (below) at two AWS sites in cave Eisriesenwelt and one site outside the cave close to the entrance for the period December 2007 to October 2009.

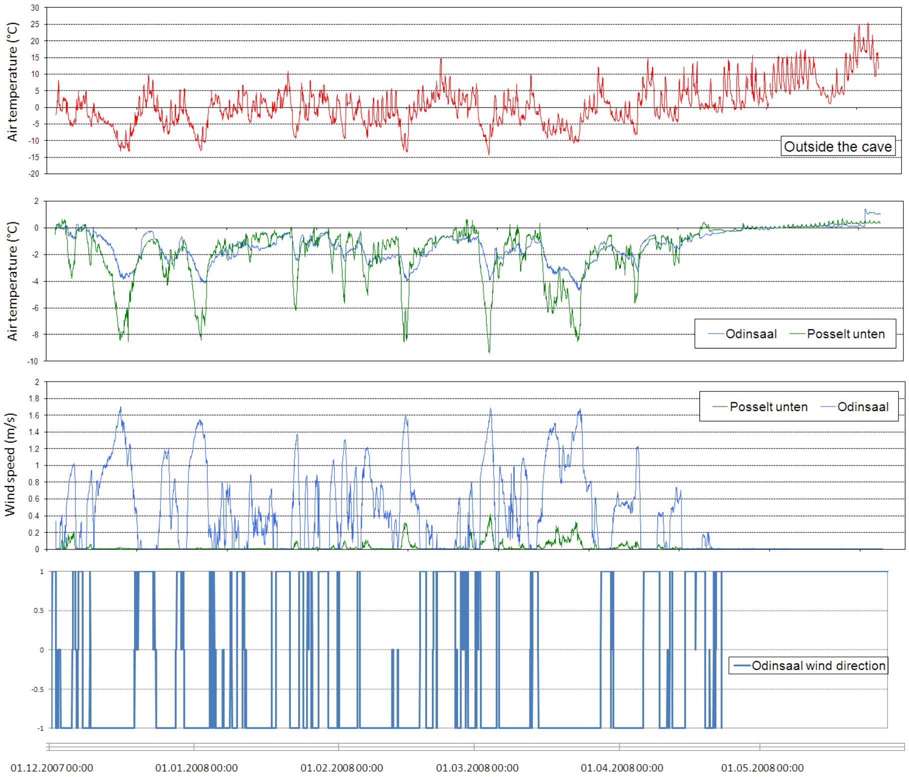

Fig. 7. Hourly values of air temperature (upper 2 graphs, red line = AWS outside, green line = AWS close to the entrance, blue line = AWS in the middle part of the cave), wind speed (third graph from above) and wind direction (bottom, AWS in the middle part of the cave only) in the cave Eisriesenwelt and outside the cave close to the entrance for the period 1 December 2007 to 31 May 2008. For wind direction values of +1 means outward flow, values −1 means inward flow.

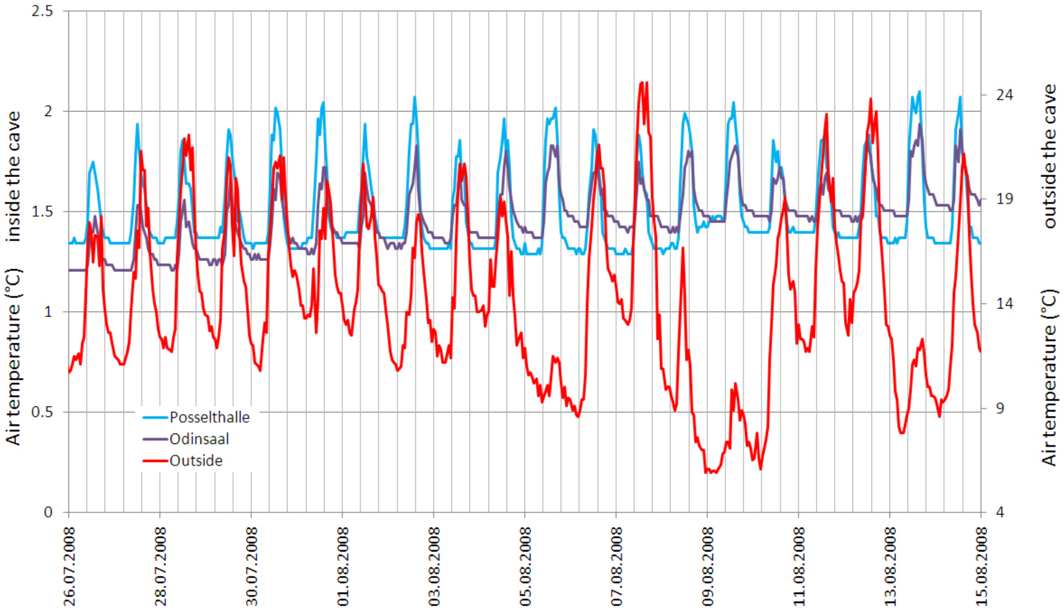

Fig. 8. Daily cycle of air temperature (hourly values) for the two AWS-locations Posselthalle and Odinsaal as well as the weather-station outside the cave Eisriesenwelt for the period 26 July 2008 to 15 August 2008.

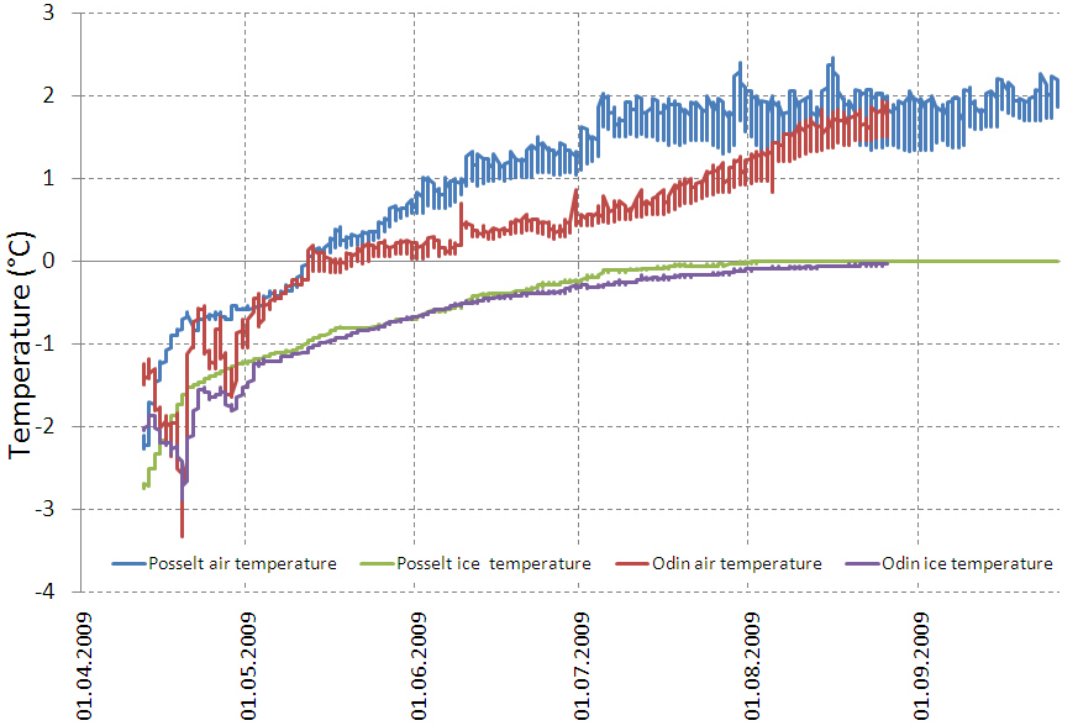

Fig. 9. Hourly values of air temperature and ice temperature at two sites (Odinsaal and Posselthalle) in the cave Eisriesenwelt for the period 1 April 2009 to 30 September 2009.

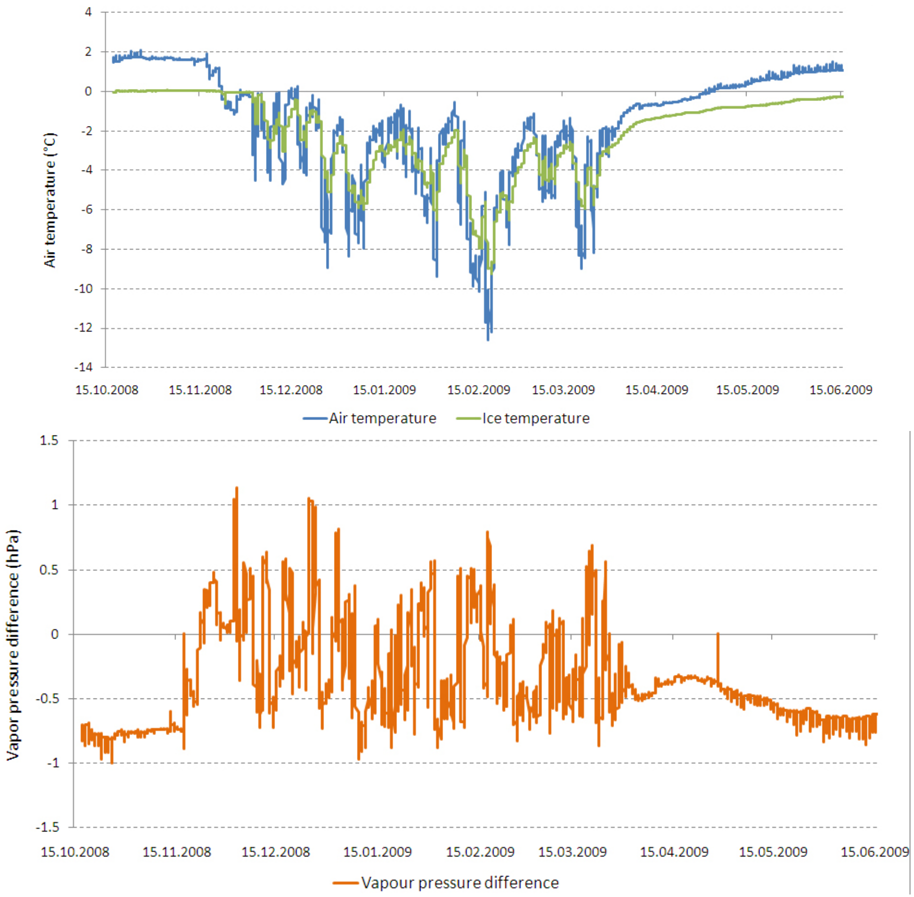

Fig. 10. Hourly values of air temperature, ice temperature (above) and computed vapour pressure difference (ice surface minus air) for AWS-location Posselthalle in the cave Eisriesenwelt for the period 1 April 2009 to 30 September 2009. Vapour pressure was computed under the assumption of saturation using the empirical Magnus-formula.