Author response to RC2 (Aurel Perşoiu)

Referee comment

Author response

First of all we would like to thank the reviewer for his thorough review and valuable comments. Please see our responses below.

7-8: this sentence is quite uninformative

We suggest to change the text as follows: "*The open period is characterised by unstable to neutral stratification which is an effect of convection during episodes when cold air can penetrate into the cave. Criteria to detect corresponding periods are investigated."*

26: "trap" would suffice

We will change "thermal trap" to "trap" in the text.

39-40: it is not clear how this sentence is linked to the case study. "Comprehensive" analysis for several caves or for this one only? It could be safely left out.

Linked to the previous sentence (line 37-39) we wanted to point out that, apart from the general lack of long-term measurements, the spatial coverage of temperature measurements in caves is usually limited to only a few loggers per cave and thus does not enable a detailed analysis of the spatial temperature patterns inside a cave.

We suggest to change the respective sentence to: "*Furthermore, the spatial distribution and temporal consistency of these measurements are mostly insufficient to allow comprehensive analyses of the full spatio-temporal characteristics."*

41: perhaps "ice level dynamics" (or similar) instead of "stake" records?

"Stake record" is often used in the glaciological literature and we find it appropriate in the context of this work, too.

We suggest to change the text to: "*We aim to fill this gap by analysing long-term data (2008 to 2021) from a network of temperature logger and ablation stakes at a sag-type ice cave in the Austrian Alps, Hundsalm ice cave*."

61: the diameters of the entrance shafts could be an important information for air circulation, please add them if available

The entrances measure about 3 x 8 m (lower entrance) and 3 x 4 m (upper entrance). This information will be added to the manuscript.

76: please give the distance between the air measurement point and the nearest ice body. It is helpful to interpret air temperature variability and role of latent heat in shaping it.

T29 was initially mounted ~1 m above the ice surface. This distance increased over the years with the decrease of the ice surface to ~2 m in 2021.

T30 is ~10 m away from the ice surface, and T36 is 1.5 m above the ice.

96: what is the altitude of the precipitation sampling site?

Buchacker station is at an elevation of 1425 m above sea level. We will add this information to the manuscript.

104: does this shoveled snow reaches areas where air temperature ad/or ice dynamics are monitored?

The snow is mainly shoveled into the main chamber (Eisdom) and below the staircase along the lower entrance. Stake A would have been influenced the most by these activities as it was in the center of the snow cone below the upper entrance but it got damaged/removed before snow was shoveled in on a regular (yearly) basis. Only a few times the shoveled snow reached stake B. In these cases the measurements were still taken at the ice surface, removing the extra snow on top. The same is true for P4. Stakes at other parts of the cave were not directly affected (see also reply to the comment to P5 L 106 of RC1).

We suggest to extend the text (L 106) as follows: "*The snow is brought in through the upper entrance forming a snow cone in the main ice-bearing chamber (Eisdom) as well as through the lower entrance where it fills the space below the staircase and feeds a secondary ice body (see Fig. 1). Although these activities are documented, proper quantification of the effect of the artificial snow input on the cave ice mass balance is not feasible. Regarding stake measurements, only stake A was directly affected by the artificial snow input and thus not used in this study.*"

Regarding the effects of the snow shoveling on temperature, we did not see any direct influence of these activities in the temperature record. As already stated in the manuscript, a more detailed assessment of the overall effect of the artificial snow input on the cave temperature can unfortunately not be made due to the lack of respective data.

105: somewhat strange, perhaps the climate is manipulated, not the entire cave?

We argue that the cave itself has been manipulated (e.g. by adding a door at the lower entrance, and an air lock at the passage to the lower (ice-free) part of the cave) and these changes as well as other activities (shoveling of snow, tourists) have some impact on the cave climate. However, we think that the main characteristics of the cave climate are largely unaffected by human interference.

122: how does this filtering influences the long-term averages calculated below?

The difference in the mean annual temperature (Table 1) compared to the unfiltered time series is < 0.01 °C. For the averages from May to October, the period most affected by the filtering, the difference is < 0.02 °C (see L 121-122).

131: this could be very useful for any subsequent studies. However, while deriving potential temperature from pressure data is quite straightforward in the free atmosphere, it might prove problematic in cave settings due to potential biases induced by pressure changes linked to movement of air inside cave passages. Did you consider these, and also potential differences between summer and winter?

Since we only have pressure measurements at the outside station we do not have the data to check whether dynamic effects on air pressure have significant influence on the results.

According to meanwhile performed measurements, air velocity at a location close to T29 hardly exceeds 0.5 m s^{-1}. Respectively induced dynamic pressure changes are negligible in this context (< 1 Pa compared to 10^3 Pa).

147: normalized?

we will change "normed" to "normalised" in the text.

161-162: the warming trend is quite interesting, and puzzling, all the same. While it is tempting to see it as a sign of a warming climate, the fact that the logger located in the non-glaciated part of the cave does not register it (nor the external one) makes one wonder if the trend is related perhaps to changing distance from ice. melting of ice would necessarily act as a heat sink, thus keeping the temperature of air in the nearby atmosphere at 0 °C as long as ice is present. Any additional hat added to the air (by, e.g., warming outside) would be used to melt additional ice and thus removing any increase. So, how far from the ice are the loggers showing the warming trend placed? Did this distance increase? Did you detect any breakpoint in the time series linked to, e.g., drop in ice level?

We show that there is also a warming trend in the non-glaciated part of the cave (0.024 °C yr^{-1}, line 166-167) which is similar to the trend at the lowest point in the ice-bearing part of the cave (T36: +0.027 °C yr^{-1}).

We explain the "missing" trend outside by the relatively short period for trend calculation with the much higher outside temperature variability compared to the cave temperature. For a longer time series at a highly correlated station (Hahnenkamm, located approx. 30 km south-east of Hundsalm at an elevation of 1794 m) a statistically significant trend was found. We address this issue in the discussion (lines 346-348).

The distance between the ice surface and the air temperature measurement at T29, where we see the strongest trend, increased from ~1 m to 2 m (which is in agreement with the measurements at stake B). As this increase is gradual, we did not detect any breakpoint in the time series.

The distance to the ice body did not change significantly at T36 and the area around T30 was always ice free.

179: how was this threshold chosen?

The threshold was chosen empirically by analysing the time series of daily standard deviation values and finding a value that was exceeded regularly during cold air intrusions at all three long-term cave monitoring sites. A similar criterion was used by Racine et al. (2022).

Racine, T., Spötl, C., Reimer, P. & Čarga, J. (2022). Radiocarbon constraints on periods of positive cave ice mass balance during the last millennium, Julian Alps (NW Slovenia). Radiocarbon, 64(2), 333-356. doi:10.1017/RDC.2022.26

189-192 (and lines above): I find the discussion on the net external cooling required to induce a net cave cooling interesting and stimulating. Especially intriguing are the values of the net differences between outside and inside which are quite high (8.5 °C!). Perhaps daily means are masking the real difference, as minima tend to occur at different times in and out of the cave? Did you try a cross-correlation analysis that would indicate the time lag between external and internal variations and thus help sustain these very large differences? Perrier et al. (2005) for instances found very short times for cold air ”avalanches„ reaching lower parts of caves

We tried cross-correlation for episodes with cold air intrusions but found that in most cases the 2h measuring interval was too coarse to see a phase shift (see lines 387-389), meaning that these "cold air avalanches" reach lower parts of the cave within the 2h interval (see Fig. 6 and related discussions). However, the amplitude of the temperature signal gets damped with increasing depth and hence for the loggers deeper in the cave to exceed the defined threshold of $\sigma > 0.1$ °C the cold air intrusion has to be correspondingly stronger (i.e. the difference between outside and inside air has to be higher).

202-203: this is an important observation, yet difficult to reconciliate with physics. Basically, the ms says that weak cooling in winter somehow results in warmer summers. Now, in any system where a heat sink is present (melting ice, in this case), temperature will be controlled by latent heat.

Further, the rock surrounding the cave has an oversized fingerprint on the overall thermal balance of the cave air+cave ice system. In the absence of the meting ice, one could imagine that weaker cooling in winter leads to warmer summer air temperatures, but the melting of ice would obliterate any such influence. Basically, you should provide a mechanistic explanation for the processes that lead from weak winter cooling to warmer summers – this would be a major point for future similar studies.

Our data clearly shows that there is a strong correlation between winter and subsequent summer air temperatures. Latent heat due to the melting of ice dampens the summer warming to some extent but in the case of HIC cannot stop the cave from warming above 0 °C (not even at the lowest logger T36 surrounded by ice). If there would be much more ice present in the cave, the impact of latent heat would possibly be higher. However, we would still expect a link between winter and subsequent summer temperature as the amount of winter cooling also influences ice accumulation and subsequently the amount of ice available for melting during summer.

We are currently working on a more physically based explanation for this relationship that is planned to be submitted elsewhere.

Chapter 3.3. This is a long chapter with very detailed discussion of the data that seems to result in a loss of focus. Perhaps the data description should be shortened and the discussion focus on the interaction between cold air intrusion, distance of air measurements points from ice and the role of internal air circulation. These are all linked and the presence of ice acts as a strong modifier of air circulation/temperature. This could/should perhaps merged with the subsequent chapter 3.4 (which I will not discuss further down).

We think that this chapter is an important part of this manuscript as it gives detailed insights into the vertical air temperature profile, its temporal and spatial variability and implications for cave ventilation.

Chapter 3.5. The discussion of rock/ice temperatures could be used to support/reject the inferences made on lines 202-203 (see above).

We will consider adapting the discussion.

Chapter 3.6. I miss a discussion of the links between PDD outside the cave and ice dynamics – this would help understand the role of external air temperature variations on ice dynamics – see also the opening line of the discussions (L343)

We found that there is no significant correlation between PDD outside the cave and ice dynamics. This can be explained by the fact that the outside air is largely decoupled from the cave atmosphere during the ablation period due to the strong stable stratification that prohibits air exchange. This is why we used the FDD outside the cave for the model, as the cave atmosphere mainly interacts with the outside atmosphere during cold air intrusions in the accumulation period.

We will adapt the corresponding text in the manuscript to make this clearer.

12 – well, this lack of correlation is somehow normal. Dripping water, direct snowfall and snow shoveling by cave managers result in a complex and possibly impossible to understand link between snow accumulation and precipitation amount.

We agree with this comment.

315-319: I am not sure a model that excludes outside temperature would help understand the ice dynamics, this should be included.

The third model in this list uses outside temperature (freezing degree days during the accumulation period) as the predictor. Since there is no correlation of ablation or mass balance with outside PDD we did not include such a model.

335 – this density refers to ice at maximum density. Is this the case here? I would expect lower density, based on how ice forms.

This is a good point. We repeated our calculations using the density value of 870 kg m^{-3} found in a study in Eisriesenwelt (May et al, 2011) and will adapt the text accordingly.

May, B., Spötl, C., Wagenbach, D., Dublyansky, Y., and Liebl, J.: First investigations of an ice core from Eisriesenwelt cave (Austria), The Cryosphere, 5, 81–93, https://doi.org/10.5194/tc-5-81-2011, 2011.

338 – these are extremely high values. What are the errors associated to the measurements?

The error of the ice measurements is expected to be ± 1 cm .

344-346 – this is extremely interesting, but perhaps it should be moved after the discussion of the data.

351-358 – this section somehow does not fit well in here, especially given the strong opening statement of the section (344-346)

We agree with these two comments and will rearrange this part of the discussion.

372 and subsequent: again, apart from correlation, which can be the result of artifacts in statistical analyses, an explanation is required. Basically here, the results are presented again but no discussion follows.

We will move parts of the discussion, including Fig. 10, to the results section and expand the discussion on this subject. However, we do not think that the correlation between winter and subsequent summer temperature is a statistical artifact. As a test we tried to do the same correlation the other way around (with summer and subsequent winter temperatures) and found no correlation at all.

412-415: again, see my comments above. Melting in summer has to be the result of warm temperatures and/or the sum of low winter accumulation and (high) summer melting, rather than warm winters only. Also, the unquantified snow shoveling must play an (oversized) role.

The summer melt rate is related to the respective available energy during melting and thus is related to the summer conditions which are influenced by the preceding winter conditions. We think our data provides sufficient evidence to support this conclusion.

General observation for the “discussions” section: this study can be broken down on a climate analysis and links between ice dynamics and climate. The first part is nicely done, however, the links with ice dynamics are somehow weakly supported by the observations and hampered by the anthropic influence. I suggest reducing the entire discussion to the discussion of 1) cave climate and 2) links with ice, but with the later stating from the beginning the fact that snow shoveling inside the cave strongly masks the natural processes.

Apart from the suggested changes mentioned in the previous comments (i.e. moving Fig. 10 to the results section and rearranging chapter 4.1), we want to keep the structure of the rest of the discussion as it is now. Furthermore, we already pointed out the potential influence of snow shoveling in the discussion (line 416-422).