

Author response to RC2

The manuscript 'A comprehensive TLS-based framework for cave ice monitoring under adverse surface conditions: application at Scărișoara Ice Cave' by Šupinský et al. presents a detailed multi-year LiDAR survey of the Scărișoara Ice Cave with a careful assessment of the uncertainties of various methods to derive the point clouds and volumes. I found this work to be very interesting and informative, with some key take-home messages for the survey of ice caves. This is a relevant and very complete study that will make a nice contribution to The Cryosphere.

We thank the reviewer for the positive and constructive review, and for recognising the relevance of the work for cave ice monitoring. We address the two general comments first and then respond to each line-by-line comment.

General comments

Level of details: The level of detail is impressive, to a point that I find it sometimes a bit too much as it impacts on the readability of the whole work. Particularly the results and some of the attached tables and figures would benefit to be streamlined to highlight the main observations, with the rest being shifted to Supplementary Material for the readers who want to delve into the technical aspects.

We agree that clarity is important. To improve readability, we will move Table 1 (summary point-cloud statistics) and Fig. 4 (co-registration results) to the Supplementary Material, keeping key values in the main text. We will also foreground the key observations and tighten the surrounding text so the main messages stand out more clearly. The remaining figures and table each support a distinct step of the core processing workflow that is the aim of the paper, and we would prefer to retain them.

Co-registration evaluation: Upon reading the manuscript, I am not entirely sure how was the co-registration evaluated and the corresponding uncertainties quantified? I was wondering if just using the ceiling for co-registration may lead to some systematic biases? I think it would also be useful to explain how the scan positions are obtained as well as more specifically the functionalities of the total station and how they are used for this work.

The interannual co-registration was evaluated as the residual standard deviation of C2C distances over the stable ceiling and ice-free limestone surfaces after alignment (3.7 mm for 2023 and 3.5 mm for 2024 relative to the 2025 reference). These residuals are consistent with the declared accuracy of the scanners and enter the error budget as the co-registration term ($\sigma_{\text{Co-reg}}$) in Eq. 2. The co-registration was additionally verified against independent total-station control points on the ice located outside data shadows ($n = 221$ in 2024). The TLS-to-TSS residuals yielded a standard deviation of 4.6 mm, confirming a consistent alignment of the ice surface with the ceiling-based co-registration. We will add this evaluation to the revised manuscript.

Regarding the scan positions and the total station, data acquisition with TLS involved about 200 scan positions, spaced up to 10 m apart, with a higher density in occlusion-prone areas to minimise data shadows in such geometrically complex environment. The total station (TOPCON GT) served to measure tie points to place all annual datasets in a common local

coordinate system, and to provide independent control points on the ice for accuracy assessment since 2024. We will expand and highlight these aspects in the text.

Line-by-line comments:

L2, 15: Several different adjectives are used to characterize the acquisition, such as ‘adverse’ or ‘suboptimal’, which makes things vague as we don’t know what these refer to.

We will define these conditions explicitly at the early mentions in the text and use more consistent terminology. By "adverse"/"suboptimal" acquisition conditions we mean wet, partially melted, semi-transparent or highly reflective ice surfaces that reduce return quality and cause noise and data gaps within the TLS datasets.

L24, 567: This sounds like a lot but is difficult to interpret as such. Would be worth adding what it represents relative to the total cave volume, and to the average thinning rate.

We will contextualise the cumulative loss by expressing it relative to the total perennial ice volume of the cave ($>120\,000\text{ m}^3$; i.e., on the order of $\sim 1.3\%$ over three years) and as a mean surface-lowering rate. We would, however, add a note of caution: the interannual loss was strongly uneven ($\approx -300\text{ m}^3$ in 2023–2024 versus $\approx -1200\text{ m}^3$ in 2024–2025), reflecting the year-to-year hydrometeorological conditions. We will therefore report an approximate mean rate for the monitored period while emphasising that a robust mean annual melting rate would require a longer monitoring series, which is one of the motivations for establishing this standardised framework.

L33: It would be worth defining what an ‘ice cave’ is here. I tend to think of ice caves as cavities that form at the glacier base, which obviously is not the case here. Also note that some small glaciers also have accumulation and ablation occurring at the same place - Mott, R., Wolf, A., Kehl, M., Kunstmann, H., Warscher, M., and Grünwald, T.: Avalanches and micrometeorology driving mass and energy balance of the lowest perennial ice field of the Alps: a case study, *Cryosphere*, 13, 1247–1265, <https://doi.org/10.5194/tc-13-1247-2019>, 2019.

We will add a definition of ice caves as rock-hosted caves in which snow and ice accumulate to form perennial ice masses, distinct from glacier caves, which form within glacier itself. Ice in caves can form either through snow diagenesis or water freezing (or a combination of the two). The vast majority of cave ice deposits are formed in single-entrance, descending caves, in which snow is trapped and subsequently metamorphosed to ice and/or inflow of cold air leads to water freezing. The perennial ice masses can reach well over $100\,000\text{ m}^3$ and more than 20 m in thickness, being able to flow under their own weight in a manner similar to surface glaciers. We will also rephrase the text to acknowledge that some surface glaciers (and glacierets) have their accumulation and ablation zones in the same place (Mott et al., 2019).

L42, L54: Some references missing here

We will add supporting references at both locations: At L42 we will cite the freezing/melting and sublimation processes governing cave ice dynamics (Perşoiu, 2018; Luetscher, 2005). At L54, to support the lower precision of mobile relative to terrestrial laser scanning, we will add a controlled comparison of SLAM-based mobile and terrestrial laser scanners which reported higher noise and lower single-measurement precision for the SLAM systems, with static scanners yielding superior accuracies by Chrbolková et al., 2025, complementing the already-

cited Dušeková et al. 2024, who compared measurement technologies directly in an ice cave setting with same results.

L98: It would be useful to give some numbers that quantify this ‘rapid’ loss

We will add a concrete value: Perşoiu et al. (2021) reported a ~35 cm drop in ice level in 2019, corresponding to a loss of 1050 (± 90) m³ of ice from the ~3000 m² ice-block surface, which we will cite to quantify this recent rapid loss.

L104: ‘massive’ is unclear, can you be more explicit?

We will replace 'massive' with an explicit value: the ice at this location reaches a thickness of ~22–25 m.

L111-113: sentence structure needs revision.

We will rewrite the passage as: *"The ice block has formed through the accumulation of successive ice layers (Perşoiu and Pazdur, 2011). Each layer results from the freezing of infiltration water during the cold season (November–March), which forms a shallow lake on top of the existing ice block that subsequently freezes, adding a new layer of ice each winter."*

References

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