

Author response to RC1

The manuscript by Šupinský et al aims is to present a comprehensive and transferable TLS dataprocessing framework for monitoring and quantifying volumetric change of ice caves, using two different terrestrial laser scanning sensors. The proposed framework is demonstrated at a Romanian ice cave.

The manuscript is interesting and well-written and huge efforts have been made to do the data acquisition. However, I am not sure about the novelty of the research and if the research fits the scope of The Cryosphere. I'll list the shortcomings and points that can strengthen the manuscript before I give specific comments.

We thank the reviewer for the detailed and thorough assessment, and for recognising the effort on data acquisition and preparation of the manuscript. The comments will help to sharpen the framing of the paper's contribution and improve its clarity and consistency. We respond to the three general concerns below and to each specific comment thereafter.

First, the novelty of the research is not clear to me. As presented here, the result of the 3-year measurement campaign is the decrease of ice volume in the ice cave. This result is given the present-day climate not surprising, but the authors do not relate their results to the processes driving the changes in the ice cave. If the processes behind the ice cave changes are assessed with, for example meteorological records, I can see that the manuscript fits the scope of The Cryosphere. Also, how is this research different from previous work of the authors in this ice cave?

The novelty of the paper is methodological rather than the observation that ice volume decreased, which we agree is expected. Its main contribution is a documented processing workflow that resolves incomplete, gap-affected data coverage due to problematic acquisition conditions including wet, semi-transparent or geometrically complex ice surfaces, which no previous study has provided. The manuscript also provides a quantified demonstration of how individual key processing choices influence the reported volume. The three-year record at Scărișoara ice cave serves to develop and validate this framework, not as the primary result. We have therefore deliberately kept the focus methodological and do not attempt a fuller interpretation of the changes in terms of meteorological forcing, which would require a dedicated process study beyond the scope of the present paper.

Earlier monitoring of this ice cave relied on point-based measurements at individual reference points (Perșoiu and Pazdur, 2011), whereas the present study is, to our knowledge, the first repeated TLS survey and quantification of the change across the entire ice surface, which is necessary given the strong spatial variability we observe. Together with its methodological focus, we believe this makes the work well suited to The Cryosphere, which also publishes measurement-technique and methodological studies of cryospheric components.

Second, the presented manuscript has a lot of technical details on the data processing, which is according to what is aimed at with this paper. However, the decisions taken on for example scanner parameters and resulting point spacing cannot be generalized to other ice caves. As presented here, the research is not directly transferable to other icy environments. I would recommend to provide a clearer guideline for other researchers that want to assess ice cave changes with TLS. If the authors manage to give this guidelines, the manuscript would be very well suitable for a remote sensing/geodesy related journal, but as presented here, the manuscript is neither suitable for a cryospheric nor a geodetic journal.

We would first clarify a point that we may not have stated sharply enough. The transferable contribution of the framework is rather the data-processing workflow and the associated decision-making, not the acquisition parameters. Of course scanner settings and the point spacing are instrument- and site-specific and cannot be generalised. What is transferable is the processing methodology: the data-driven noise assessment of each data source prior to filtering, the criteria for deciding when a second sensor or method is warranted, and most importantly, the gap-aware surface reconstruction where coverage is incomplete, the preference for full 3D over 2.5D in morphologically complex settings, and the error-propagation scheme defining the minimum detectable change. We will reformulate these transferable elements into a more explicit, generalised guideline in the conclusions, framed so that other researchers can adapt it to their own site and instrument, while making the distinction between transferable methodology and site-specific acquisition parameters clear.

Third, what bothers me is that technical jargon is not used appropriately. For example, the word surface glacier was invented, in order to distinguish between an ice cave and mountain glaciers. Other examples: cold air avalanches (?), ice cliff (wrong context) and accumulation (wrong context). Furthermore, DoD stands in a geographical context for DEM of difference, and is therefore not recommended to be used as ‘differences of distances’. Other inappropriate use of technical jargon will be highlighted in the specific comments.

On terminology, we note that the terms in question are established usage in the speleological and ice-cave literature (Perşoiu and Lauritzen, 2018) rather than invented. We fully accept, however, that the readership extends well beyond ice-cave specialists, and that these terms may be unfamiliar. We will therefore define each established and specialised term at first use, and replace ambiguous or non-standard wording.

We likewise agree with the reviewer that the acronym DoD also denotes "DEM of Difference", and we will avoid it. Where a specific computation is meant, we will use the individual method names (C2C, M2C, M3C2). Elsewhere we will rephrase to avoid the acronym.

Specific comments:

1. Title: consider adding Romania after Ice Cave.

We will add “Romania” to the title.

2. L10: consider removing the first sentence and directly focus on the monitoring of ice caves.

We will rework the abstract opening into a single coherent motivation.

3. L14: from should be including.

We will change it.

4. L26: this sentence is too generic. Of course, omitting processing steps would affect the results.

We will remove the generic closing sentence and instead quantify the biases where the respective steps are introduced (~20 % for 2.5D vs 3D already stated, and up to ~25 % for omitting gap-aware reconstruction).

5. **L30: Marzeion et al is about the global sensitivity of glaciers to climate change and the other two references are the author's work on ice caves. Either use more recent references for other cryospheric components or only focus directly on ice caves. Those references should be not only the author's own work.**

We will add recent, independent references covering the other cryospheric components, including Rounce et al. (2023) on global glacier change, Kääb and Røste (2024) on rock glaciers, Hartl et al. (2026) on Austrian glaciers, The GlaMBIE Team (2025) for a global assessment and Racine et al. (2022) on perennial cave ice.

6. **L33 and L43: surface glaciers is an invented word. Just focus on ice caves in these contexts.**

Surface glacier is not an invented term, word "surface" simply distinguishes glaciers on the surface of the Earth from those in caves. This usage appears in earlier studies, including in The Cryosphere (Perşoiu et al., 2021).

7. **L42: replace however by thus.**

We will replace it.

8. **L50: constrain should be constrains.**

We believe "constrain" is correct here, as it refers to the plural "consistent light conditions and wide scene overlaps". We will rephrase to "constraining its use...", which resolves the number agreement and improves readability.

9. **L51: I do not agree with the arguments for the unsuitability of MLS for cave mapping. With recent developments, MLS would also be a great and cost-worthy alternative for the data acquisition presented here. Please also read into the work of Goelles et al, 2022 and consider referencing.**

We would clarify that the manuscript does not present MLS as unsuitable for cave mapping. Our statement is only that the continuous platform motion results in lower single-measurement precision than TLS, so that reliable change detection with MLS requires the surface change to exceed its larger measurement error. Moreover, the precision reported by Goelles et al. (2022) for their MLS system (~1–5 cm) is coarser than the centimetre-level interannual change we aim to resolve. We do, however, agree that MLS is a rapidly developing and time-efficient method, and we will add Goelles et al. (2022) as a reference to reflect a more balanced view.

10. **L53: define what is meant by lowest spatial resolution and precision.**

Lowest is meant relative to the other methods compared (CRP and TLS). To make this concrete, current MLS systems used for cave-ice mapping are typically at the centimetre level (± 3 cm; Dušeková et al., 2024), coarser than the millimetre level of TLS and CRP. We will add this information so the comparison is explicit.

11. **L59: be consequent in the use of technical jargon. With caves, ice caves are meant here. Please check this throughout the paper.**

We will check the use of "cave" and "ice cave" throughout the manuscript and ensure consistent terminology. We will use the term "ice cave" when the presence of ice is relevant, and "cave" when we refer to the cave in general, e.g., when describing its

morphology and sectors.

- 12. L63: add wavelength after 1550 nm. In the context of the different wavelengths of scanners, 1064 nm should also be mentioned, as this wavelength is also suitable for snow and ice. See research done with a Riegl VZ6000.**

We will add "wavelength" after 1550 nm and mention that 1064 nm is also suitable for snow and ice. We would note, however, that the scanner associated with this wavelength (RIEGL VZ-6000) is a long-range Class 3B instrument suitable for glacier and terrain mapping over kilometres, and is not practical for confined cave environments, both because of its ~5 m minimum range and its laser safety class (nominal ocular hazard distance of tens to hundreds of metres). We will make this distinction when mentioning the wavelength.

- 13. L71: laser scanning systemS**

We will correct this to "Laser scanning systems... penetrate".

- 14. L83: consider ending the sentence after conditions and make the text more readable.**

We will split the sentence after "conditions" to improve readability.

We suggest changing the text to: *Monitoring must therefore account for surveys conducted under suboptimal conditions. Wet, partially melted and highly reflective surfaces introduce noise, false reflections and data gaps.*

- 15. L93: cave glaciers? Please use appropriate jargon.**

Cave glacier is established usage in the ice-cave literature (Perşoiu and Onac, 2019; Perşoiu et al., 2021). To ensure clarity for the broader readership, we will define it at first use.

- 16. L95: replace the semicolon by a comma.**

We will replace it.

- 17. L97: clarify which methods are used to acquire the recent observations.**

We will specify that at Scărișoara these observations were based on ice-level measurements against fixed reference points (Perşoiu et al., 2021).

- 18. L100-L127: I got lost in the description of the ice cave. Please rewrite this section and describe all the labels from Fig. 1 in the text. For example, what is Rimaye? Is it possible to add pictures? Or place some of the pictures of Fig. 7 earlier in the manuscript?**

We will revise the section to improve clarity, define every label used in Fig. 1, including each mentioned passage, and also add photographs to orient the reader.

- 19. L101: underground glacier? Please replace by ice body or a similar term.**

Within the introductory cave description, we prefer "underground glacier" (used interchangeably with "cave glacier" in the ice-cave literature), because the ice in Scărișoara is a genuine glacier: a glacier-like ice block with a flat top and steep walls, formed by the accumulation of successive ice layers and exceeding 22 m in thickness (Bella, 2018). This distinguishes it from the great majority of ice caves, which host only

minor ice deposits orders of magnitude smaller. The term is well established for such bodies, including for Scărișoara, in this journal (Perșoiu et al., 2021). We will introduce it at first use and then, for readability, refer to it in the shortened form "ice block", which is the term used for this ice body in the same literature (Perșoiu et al., 2021; Bella, 2018).

20. L104: ice cliff? What is that? And what do you mean by ice block. Reader gets easily lost here.

An ice cliff is a near-vertical ice face, analogous to a rock cliff but formed of ice. Here it refers to the ~15 m high vertical face at the edge of the ice block facing the Little Reservation. For the ice block please see response above.

21. L105: breakdowns accumulation? Again, some invented jargon. Also remove resembling a moraine in this sentence.

We are talking about a large accumulation of breakdowns. The term is widely used in literature related to caves to indicate a pile of loose rocks that were detached from the walls/ceiling and accumulated on the cave's floor (Culver and White, 2005). In this particular case, this pile of rocks was pushed by the moving glacier and the subsequent melting of ice and retreat of the ice left behind a curved deposit of rocks, clay, wood etc. with a steep side towards the ice and a more gentle one on the outside, which resembles a moraine. We would prefer to retain the comparison to help readers unfamiliar with the cave picture the form.

22. L123: cold air avalanches? Idem.

Cold air avalanches are a common occurrence (Perșoiu, 2018; Perrier et al., 2005) in vertical caves, when temperature-induced pressure differences between the top and bottom of vertical pits result in fast transfer of air masses.

23. Fig. 1: label plan and side view with a and b and indicate in the caption that the yellow dashed line indicates the Aol and that the blue area is the area where ice occurs. Right?

The interpretation is correct, the yellow dashed line denotes the Aol and the blue area the perennial ice. Both are already annotated in the figure, with the label colours matching the respective symbols. Following the journal's guidelines, which ask for symbols to be explained within the figure, we will add a clearer legend rather than explanation in the caption. We will also label the plan and side views as (a) and (b).

24. Sect. 3.1: for the non-experts on TLS equipment, explain the difference between time-of-flight and phase-shift scanners and elaborate a bit more on the use of these different scanners. Would it have been possible to use only one sensor?

We will add a brief explanation of time-of-flight and phase-shift measurement principles. Regarding the use of a single sensor: whether one scanner suffices is in this case determined both by the surface conditions and by the dimensions of the cave passages. The FARO was added mainly because it is more compact and has a much shorter minimum scanning range (0.6 m versus 2.5 m for the RIEGL), allowing it to capture narrow passages and confined spaces inaccessible to the RIEGL, and to provide complementary coverage in meltwater-induced data gaps.

- 25. L145: Gabbud et al used the Riegl VZ6000, which is not using a wavelength of 1550 nm. Please use references where research has been done with a Riegl VZ1000 in icy or snowy environments.**

We will correct the attribution and cite TLS studies conducted using a wavelength of 1550 nm in icy/snowy environments (Clemens-Sewall et al., 2024a, 2024b).

- 26. L146: what is the last calibration protocol?**

The value refers to the 2021 calibration protocol of the RIEGL VZ1000, which reports a ranging error of 3.1 mm at a reference distance of 100 m, within the manufacturer's tolerance of ± 5 mm. We will clarify this.

- 27. L152: what is the full scan resolution?**

We will define it in the text as the scanner's native maximum angular sampling. For the FARO, full 1/1 resolution corresponds to an angular step of $\sim 0.009^\circ$.

- 28. L155: replace 1 by up, so it reads up to 40 million points.**

We will change it to "up to 40 million points".

- 29. L158: remove the placement of.**

We will remove "the placement of" from the text.

- 30. Data acquisition: I want to compliment the authors on the huge efforts the have done for the data acquisition! 200 scan positions is a lot. Can you also indicate the scanning time of each scan position?**

We appreciate the reviewer's kind remark. We will add the acquisition time per scan position: ~ 184 s per RIEGL position, and ~ 90 – 270 s per FARO position depending on the chosen resolution.

- 31. L161: remove sub-.**

We will remove "sub-".

- 32. L164: add information about the wooden tourist path in the description of the cave. Knowing that there is a path and seeing the pictures in Fig. 7 made it more clear to me.**

We will add this information in the cave description.

- 33. L168: the points per position also depends on the number of returns per scan position, so giving these numbers here is not very useful.**

The point counts given here are the expected values for the set resolution, not the actual recorded numbers. As they also depend on the number of returns per position and scene geometry, we agree they are not informative and will remove them, keeping only the angular resolution.

- 34. L171/172: I do not see why the ice-free areas are excluded in later acquisitions, because they are the stable surface that help to register the data from year to year. Please elaborate.**

The ice-free areas omitted in later campaigns (the southern Great Reservation, Cathedral,

Coman passage, and the entrance shaft) lie outside the Aol and were not used for the registration. The interannual co-registration relies instead on the stable ceiling and walls immediately surrounding the ice block, which were retained in every campaign. Omitting these distant ice-free areas therefore removed no registration reference and only reduced the acquisition and processing load in parts of the cave that are irrelevant to ice-volume change.

35. L179: refer not only to Fig. 2 but also to Sect. 3.3.

We will add a reference to the subsections describing the following workflow. As the workflow continues beyond Sect. 3.3, we will refer to Sects. 3.3–3.5 next to Fig. 2 in the text.

36. Fig. 2: ice accumulations in the caption should be ice cave.

We will replace "ice accumulations" preferably with "cave ice", as the workflow targets the ice itself rather than the cave as a whole.

37. L186: what is the unit of the deviation threshold?

The RiSCAN PRO deviation threshold is a dimensionless (unitless) parameter, we will state this in the text.

38. L193: Laser (..) spacing should be placed before the sentence about importing in RiSCAN Pro.

The current order reflects the actual processing sequence. The FARO scans were first imported and co-registered to the RIEGL reference, and only then merged per scanner and subsampled to 1 cm. Reversing this would not match the workflow, as merging and subsampling follow registration.

39. L194/195: I don't see why this C2C approach is necessary, because this is mainly depended on the point spacing of these very dense clouds.

This C2C computation is used to quantify FARO-to-RIEGL coverage, so that only FARO points located >2 cm from the RIEGL surface are retained to fill gaps. Its dependence on RIEGL point spacing is therefore intended, as the 2 cm threshold (twice the 1 cm working resolution) marks where RIEGL coverage is insufficient.

40. L199: here a note is made about the reference surface, but no explanation has been given before that there is at stable cave ceiling. Is this enough surface area to use as reference surface?

The stable ceiling and surrounding walls used for co-registration span an area larger than the ice block itself (roughly 1.5–2×; e.g., of ~170 million floor-plus-ceiling points in 2025, ~100 million fall on the ceiling and walls and ~70 million on the floor), providing sufficient geometry with good variability in all directions and distances for a reliable alignment. We will add the explanation to the text.

41. L201: why is the latest scan used as reference and not the later scans relative to the first one (2023)?

The 2025 campaign was chosen as the reference because it provided the most favourable acquisition conditions and the most accurate and complete dataset. No total station

survey was carried out in 2023, so its errors cannot be characterised as precisely, and 2024 was affected by poor surface conditions on the ice.

42. Fig. 3b: in the legend, what is the unit of density?

The calculated density is a dimensionless value representing the sum of the weighted contributions of the neighbouring points that formed the given part of the surface at the chosen octree depth.

43. L242: remove the reference to table 2, as it is first discussed in the results.

We will remove the reference.

44. L246: is the Cloth Simulation Filter in CloudCompare? Please indicate.

Yes, the used Cloth Simulation Filter is implemented as a plugin in CloudCompare. We will indicate this in the text.

45. Eq. 2: how are the variables in this equation derived? Do they come from the software or did you calculate them? Please elaborate. Also, this E_{total} and E_v are not discussed in the results.

We will state in the text how each term is obtained: The measurement device error (E_{dev}) corresponds to the average ranging error of the laser scanners used (Sect. 3.1). The internal registration error (E_{reg}) quantifies the accuracy with which the individual scan positions of a single survey were registered into a common project coordinate system and was derived directly from RiSCAN PRO (Tab. 1). The co-registration error ($E_{\text{co-reg}}$) expresses the accuracy of aligning the TLS point clouds of the individual survey epochs to a common reference and was derived from ICP alignment on stable ceiling surfaces in CloudCompare (Sect. 4.1). The 3D modelling error (E_{model}) was calculated as the standard deviation of differences between the 3D models and the TSS control points (Tab. 2).

E_{Total} and E_v are reported in Table 2 and briefly addressed in Sect. 4.3. We will extend this part in the Results, particularly regarding the minimum detectable volumetric change.

46. Eq. 3: where does this equation come from? Does it make sense mathematically?

Eq. (3) follows from the definition of volume change as surface change integrated over an area (Wheaton et al., 2010). Similarly to Brogan et al. (2019), who computed volumetric uncertainties by multiplying the error by the pixel area and summing these, we multiply E_{Total} by the surface area of the AoI, which is equivalent for a spatially uniform error. This linear summation treats the errors as fully correlated, which is appropriate here, as the dominant registration and co-registration components affect the entire point cloud coherently. The resulting E_v is therefore a conservative, upper-bound estimate. We will clarify this in the Methods.

47. L261: here is the first time that 2.5D volume change is mentioned. Please elaborate here in the difference between 2.5D and 3D volume change.

We will define the difference between the two approaches at this first occurrence: the 2.5D method computes volume from a single-valued elevation surface (one height per planimetric position), so it cannot represent overhangs, vertical walls or ice speleothems, whereas the full 3D approach computes volume change directly from the three-

dimensional surface and captures these features.

- 48. L280: only 2-3% of the data is kept. This is very surprising to me and also asks the question if the amount of data acquired was appropriate. Could it have worked with less scan positions? The amount of scan positions are very high for a relatively small area. Could you give the reader recommendations on how to do the data acquisition differently?**

The 2–3 % results from three compounding steps: full-panorama scans capture large volumes outside the Aol, heavy overlaps between ~200 positions create strong redundancy, and during the processing the cloud is subsampled to 1 cm and clipped to the Aol. The high position count is driven by the need to minimise data shadows in a geometrically complex, occlusion-prone environment, not because each position is individually essential. Fewer positions would be possible in more open sections, at the cost of larger data shadows behind ice speleothems and overhangs. Such dense coverage was a deliberate trade-off favouring completeness. We will clarify this and add practical acquisition recommendations to the transferable guideline.

- 49. L295: the registration errors, are they given in the software? I also wonder if the ice cave is assumed to be stable during the two day acquisition period. If the ice cave is changing during those days, how is this affecting the registration errors?**

The reported registration errors are the software-derived residuals. Acquisition proceeds section by section, each mapped within a few hours, so ice-surface change during the mapping of a given area is negligible, comparable to the registration error itself. Moreover, registration relies on the stable ceiling, not on the ice.

- 50. Table 1: the processing error StdDev, is this the same as the registration error? And is it derived in the software?**

Yes, the processing error StdDev in Table 1 corresponds to the Internal registration processing error and is derived directly from the software.

- 51. Fig. 4: on the floor, is the yellow line, kind of shaped as a shoe, the footpath? Has the footpath been sinking? Can you give a magnitude of this, between 2023 and 2025 and between 2024 and 2025? Maybe it says something about your registration method.**

Yes, the yellow outline visible in Fig. 4 is the wooden tourist path. We would note, however, that a quantitative analysis of its lowering is not meaningful here. The tourist path rests directly on top of the ice block, so it lowers and tilts together with the melting ice surface beneath it rather than acting as an independent reference. The structure was also replaced during the monitoring period, so it is not the same object across datasets.

- 52. L308: what is ice block?**

This is a common term used in the literature to refer to massive ice bodies in caves (Perşoiu and Lauritzen, 2018).

- 53. L310: the points per m2 says something about the roughness of the surface. If the surface would be perfectly planar, there would be 10k point per m2. Is this true? Elaborate on the surface structure.**

Correct, a perfectly planar, fully covered surface at 1 cm spacing will cover 10,000 points

m^{-2} . Rougher surfaces or areas containing vertical structures or overhangs such as ice speleothems return more points per unit of planimetric area, so their apparent density may exceed $10,000 \text{ points m}^{-2}$, whereas areas with incomplete coverage or data gaps fall below it. We will elaborate this in the text.

54. L313: was more filtering or subsampling done for the combined point cloud? As these numbers do not sum up from the two data sets.

The combined cloud is not the sum of the two datasets. It comprises the filtered RIEGL data plus only those FARO points located $>2 \text{ cm}$ from the RIEGL surface (i.e., FARO points were retained only where the RIEGL reference had gaps). This is why the counts do not add up.

55. L315: why are the results of the FARO scanner better on wet surfaces? The scanners work at the same wavelength, right?

Both scanners operate at 1550 nm wavelength, so the difference does not arise from the wavelength but from the different measurement principles and their online waveform processing. Phase-shift (continuous-wave) systems such as the FARO produce denser, higher-resolution point clouds but with lower signal-to-noise ratio and retain more noise that is separated from valid returns by intensity thresholding during post-processing rather than online (Calders et al., 2020). In our acquisition the FARO recorded returns without an online intensity threshold, so weak returns from the wet ice were retained (analysed and filtered afterwards), yielding a denser but noisier point cloud. The RIEGL VZ-1000 performs echo digitisation and online waveform processing, and applies reflectance threshold during acquisition, so weak returns from the wet ice are evaluated as spurious and discarded online (Pfennigbauer et al., 2014). This yields a sparser but cleaner point cloud, in contrast to the FARO.

56. L318: introduce the Rimaye passage in the introduction of the ice cave.

We will introduce the Rimaye passage in the cave description, e.g.: The retreat of the vertical side of the ice block from the cave wall left a narrow gap, named "Rimaye" by its first explorers (as it resembles a rimaye).

57. Fig. 5: in the combined point cloud, is the FARO data overlayed on the RIEGL data? Because the percentage of FARO data seems to be higher than indicated. Also, and especially for 2023, there doesn't seem to be a lot of data gaps that have to be filled with FARO data. Is this a matter of visualization?

This is a visualisation effect as a larger point size was used for better visibility, so in 2023 the gaps appear filled, and the FARO points, plotted on top of the RIEGL points, appear more extensive than their actual share. The reported percentages reflect the true proportions of each dataset.

58. L327: how are the incidence angles derived?

They were computed in a dedicated script after export, from the point normal and the scanner position, following Nováková et al. (2022). We will add this reference.

59. Fig. 6d: What is meant with scan position? Is this the right legend?

The legend denotes the index (order) of the scan position ($1 \dots n$); we will clarify it in the text.

60. L347: is ice fall a correct term in an ice cave?

"Icefall" is an established speleological term (Bella, 2018) for steep to moderately inclined, massive descending ice. At this site it is a massive ice body ~17 m long descending ~11.5 m towards the Great Reservation at ~45°.

61. Fig. 7: this figure is too small and almost unreadable. Maybe focus on 4 instead of 8 surfaces and make the labels bigger/better readable.

As this figure is one of the paper's main outputs, we would prefer to retain the full comparison, but we will substantially improve readability.

62. L354: ice fall, see above.

As in our response to comment 60, "icefall" is an established term, which we will define at first use and apply consistently.

63. L376: what is high incidence angle degradation? Please rewrite this sentence.

We will rewrite the sentence. The increased dispersion of residuals observed at high incidence angles occurs for both scanners, confirming that it is caused by the acquisition geometry (the oblique angle between the laser beam and the surface) rather than by the specific instrument.

64. Fig. 8b: in the FARO point cloud residual on the left, a cyclic pattern is visible with outliers every (approx.?) meter. Please explain where this comes from. This figure is also too small and barely readable.

The periodic pattern is a known systematic effect of phase-shift scanners, namely a cyclic range error, which produces a sinusoidal error as a function of distance (Dorninger et al., 2008). This error is always present but becomes clearly visible here because of the low signal-to-noise ratio of returns from the wet vertical ice wall, where it is no longer masked by strong returns. The pulse-based RIEGL system does not exhibit this effect. We will enlarge the figure and add this explanation.

65. Fig. 9: add a scalebar to the figure.

We will add the scalebar.

66. L417: ice accumulations monitoring? Use a different term than accumulations.

We will use "cave ice monitoring" instead.

67. L418: the definition of 2.5D and 3D should have been given before.

We will add the definition earlier in the text.

68. L427: because of not uniform point cloud coverage within the Aol. Please rewrite this sentence.

We will rewrite the sentence for clarity, e.g.: Because point cloud coverage within the Aol was non-uniform, reaching 85 % in 2023 and 93 % in 2025 but only 70 % in 2024 owing to the mapping conditions, 3D modelling was required to interpolate data gaps and compute relevant differences of distances across the entire Aol in all years.

69. Table 2: I don't understand why 2025 is reference. The DeltaV and Deltah are negative, relative to 2025. So does it mean that the volume of the ice increased over time?

The negative values indicate ice loss, not an increase. The differences of distances were computed against the 2025 reference model, and the resulting values were sign-adjusted (multiplied by -1) to follow the chronological order (2023 to 2025 and 2024 to 2025), so that ΔV and Δh represent the change from the given year to 2025, as also shown in Fig. 10 and the following text. We agree that this convention was not explained, and we will revise the caption of Table 2 accordingly.

Table 2: Evaluation of 3D modelling. ΔV and Δh values are chronologically oriented towards 2025.

70. Fig. 10: please add labels a, b, etc to the subplots. Is it correct that the combined point cloud C2C gives positive results and the other ones show negative results? Is it ice loss or gain? Also, the sum of volume change between 2023 to 2024 and 2024 to 2025 should be the volume change between 2023 and 2025. Especially for M3C2, this deviates a lot. Please elaborate.

We will add a/b labels to the subplots and clarify the sign and colour convention in the caption. C2C returns unsigned nearest-neighbour distances and therefore cannot indicate the direction of change, whereas M3C2 and M2C compute signed distances. This is why C2C shows positive values while the signed methods show ice loss. We will state explicitly in the caption that the C2C results represent unsigned absolute distances and should not be interpreted as ice gain.

Regarding additivity, the cloud-based methods evaluate a different common-coverage area for each pair of years because of the data gaps ($\approx 7786 \text{ m}^2$ for 2023–2024, $\approx 6424 \text{ m}^2$ for 2024–2025 and $\approx 8745 \text{ m}^2$ for 2023–2025). Their estimates are therefore not additive, as each comparison covers a different part of the ice surface. For M3C2, the sum of the 2023–2024 and 2024–2025 changes ($\approx -971 \text{ m}^3$) is $\sim 445 \text{ m}^3$ lower than the 2023–2025 change ($\approx -1417 \text{ m}^3$), reflecting both the reduced area and the different ice-surface portions evaluated in the gap-affected 2024 dataset. By contrast, the MeshFix M2C results, evaluated over a consistent Aol of $\sim 9000 \text{ m}^2$, are nearly additive and differ by only $\sim 11 \text{ m}^3$. We will explain this explicitly in the revised manuscript, as it demonstrates the benefit of the gap-aware 3D modelling approach.

71. L520: reference to the several published ice cave studies is missing.

We will add the relevant citations: Blatnik et al. (2022) and Pukanská et al. (2024) used 2.5D volume computation, whereas Buchroithner and Gaisecker (2020) used a full 3D approach. These studies are already cited in the Introduction, we will now also reference them here to support the statement.

72. L524-528: please reconsider this statement. With the gap filling, artificial surfaces are created and you can never be sure that volume change is happening here.

We agree that reconstructed surfaces in gap areas carry higher uncertainty. We would, however, retain the conclusion that the gap-filled 3D model is preferable overall, on two grounds: it was validated against independent TSS control points and against an

independent enclosed-volume computation, and it enables evaluation over the full ~9000 m² AoI rather than only the ~6423 m² covered without gap filling in 2024, which, as shown above (comment 70), is what makes the multi-year results internally consistent (agreement within ~15 m³). We will align this with our existing statement that the method improves areal completeness but does not fully replace missing geometric information.

73. L571: I like the listing of recommendations, but please rephrase and refrain from using DoD evaluation.

We will rephrase the sentence and avoid using the DoD acronym.

74. L573: what is a well-characterized laser scanner? The choice of scanner should be elaborated better earlier in the manuscript.

We will define this as a scanner whose noise behaviour has been assessed for the surface types of interest, and we will elaborate the rationale for scanner choice earlier in the Methodology.

75. Data availability: I was happy to see that there is a web interface, however this page is not working in different browsers. I can see the labels of the sections of the ice cave, but no point cloud is visible.

The problem was most likely caused by the external-access protection of our university server, which blocked the loading of the 3D models for foreign users. We have contacted the server administrator to resolve the issue. If this is not possible, we will migrate the interface to a different server accessible to external users. In either case, we will verify that the 3D models render correctly across common browsers before resubmission and update the link in the Code and data availability section accordingly.

76. Author contributions: with investigation, is the data acquisition meant?

Yes. According to the CRediT contributor roles taxonomy recommended by Copernicus, "Investigation" covers data/evidence collection, which includes the data acquisition.

77. References: the doi or link to Buchroithner and Gaisecker is missing, but I found it here: https://www.zobodat.at/pdf/Hoehle_71_0062-0070.pdf

We will add the provided link as the DOI is not available.

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