RC - 1: From the introduction, it is not clear why ice caves or their dynamics are important. Although authors identify the need to quantify changes in ice accumulations and appropriate techniques by which to achieve this, no case is made for why the changes in ice volume are important.

AC: Accepted. In the chapter „Introduction“, the need to quantify changes in ice accumulations will be highlighted and well-grounded. The main argument to monitor the change of ice volume in ice caves is that ice caves preserve the history of climate change in places where no icebergs or glaciers exist anymore. Furthermore, ice caves react differently to the climate change, perhaps not as rapidly as the mountain glaciers. We agree that these facts must be clearly communicated to the readers.

RC - 2: Furthermore, the aims need clarification and to reflect the contents of the paper.

AC: The main aim of our manuscript was to define a methodological framework for generating time-series of 2D/3D surfaces representing the cave floor ice from terrestrial laser scanning data collection. By monitoring the cave floor ice, we mean the surface of the ice on the cave floor and surface of rock debris covering the cave floor ice underneath. We described this goal on page 2 line 32 - page 3 line 2 and the aim was emphasized in the abstract page 1 line 11-13. To date, we have not found a publication presenting the same approach of registration single scan missions from a TLS mapping into a unified coordinate system for generating a database of 3D surface time-series. However, we will rephrase the text in order to communicate the aim and objectives clearly. We will also modify the aim in relation to the Reviewer's requirement to include interpretation of the ice change and the climate data. This interpretation will be added in the methods and results/discussion.

RC - 3: Currently, they outline that the paper will further develop the methods of detecting ice change. The paper does do this, but by using TLS, the methods that are used in the paper are already well established and are not further developed in this paper.

AC: The developed method has been perhaps not clarified sufficiently from our side but we argue that the presented method of the selective cloud-to-cloud approach (sC2C) is well established and the manuscript does not add any improvement or novelty. Our sC2C approach is novel in the way of how we achieved the transformation of individual laser scanning missions into a unified coordinate system without using reflector targets. The sC2C approach is based on several separate procedures, which are presented in the methodical part of the manuscript within chapter 3 and portrayed in Figure 5. An overview of the approaches designed to the generating a time series database from individual scan missions is described on page 2 line 20 - 30. To our best knowledge based on the review of the published research in the manuscript, a similar workflow has not been described or used in monitoring the dynamics of the ice surface on the cave floor using terrestrial laser scanning. Nevertheless, we would appreciate if the Reviewer #2 could help us with examples of published works which he or she considers similar to our method, so that we will be able to better support our argumentation.

RC - 4: Deriving complex 3d models using meshing is not novel and has been used in caves previously (eg. Silvestre et al 2015, Fabbri et al 2017, Gallay et al 2016)

AC: The presented sC2C approach enables to derive DEMs/3D mesh and to assess ice volumes changes within the cave at unprecedented spatial and temporal resolution. Generation of time series database of measurements and DEM derivation is a prerequisite for the detection of volumetric ice changes. The DEM concept is not suitable to model the full extent and complexity of cave but it is a product easy to derive and manipulate with in GIS. Therefore it was used also in cave modelling for specific purposes (). There is no universal method of creating DEM suitable for all purposes. If we wanted to model surface erosion or material deposition we would use other methods than in case of geomorphometric evaluation of landforms, possibly in solar radiation modelling or for 3D printing needs. Many of these questions are addressed in numerous of papers, e.g. Roncat et al. 2011, Hoffmeister et al., 2014. Although the methods used to derive the DEM may be the same, the modelling result is always influenced by parameters that give a degree of flexibility to the same methods, allowing better adaptation to input data and purpose of use. We cite this paper (e.g., Silvestre et al 2015, Fabbri et al 2017, Gallay et al 2016) to point it out. If the reviewer points to 3D meshes, yes, there are several papers describing the methodology of full 3D cave surface modelling. But our research in the manuscript focuses on time series of 3D meshes which pose new challenges in terms of accurate and precise registration of the source point clouds acquired from consecutive lidar surveys. This has not been addressed extensively in the published research. In the revised manuscript, we will highlight this fact.

RC - 5: Cave ice formation is briefly mentioned in page 1, line 20. This is unclear and could be expanded upon to provide the reader with an understanding of how ice-coating in caves forms and the factors controlling this.

AC: Accepted, this part will be expanded in the revised version of the manuscript.

RC - 6: Page 2, lines 7 –10 seem unnecessary –unnecessary detail in point density and number of points.

AC: Accepted, this part will be removed in the revised version of the manuscript.

RC - 7: Page 2, lines 11 –15. List of TLS applications in non-ice caves. This information does not really add to the argument for using TLS, as it simply informs the reader that TLS has been used elsewhere. Perhaps re-organising this paragraph to show what TLS is, how it has been used, and the difficulties of scanning ice and use of TLS in ice coated caves would read better. Eg. Line 26 –30 outlines the issues with tachymetric surveying. This needs to be presented up front, before presenting the argument that TLS provides an improvement on this, and then the applications of TLS elsewhere can be summarised.

AC: We structured the text deliberately as is for the following reasons. On the page 2, lines 2-4, we talk about where we see the greatest challenge in capturing cryomorhological topography in caves. Subsequently (page 2, lines 5-9), we introduce what is TLS and the basic principle of this technology. Since the paper deals with capturing the dynamics of ice in a cave using TLS, we also found it important to show an overview of cave scanning and to highlight that although caves are scanned, the purpose of scanning determines the cave mapping requirements using TLS in general, including also the non-ice caves. We also point out the main specifics of cave scanning in general (page 2, line 15-16) and examples of ice-caves scanning (page 2; line 16-19). In the next part of the text, we deal with the generation of a time series in caves (page 2; line 19-30). For time-series database creation, it is necessary to place single mappings to a common coordinate system using ground control points (GCP) - this is mentioned on the page 2; line 23-24. Subsequently, we have presented approaches to measuring GCPs, one of the approaches uses tachymetric surveying (page 2; line 26-27). We did not have intention to explain TLS is more efficient in data collection than the tacheometry.

Perhaps, this was not communicated clearly, and we will modify the text to convey the message better.

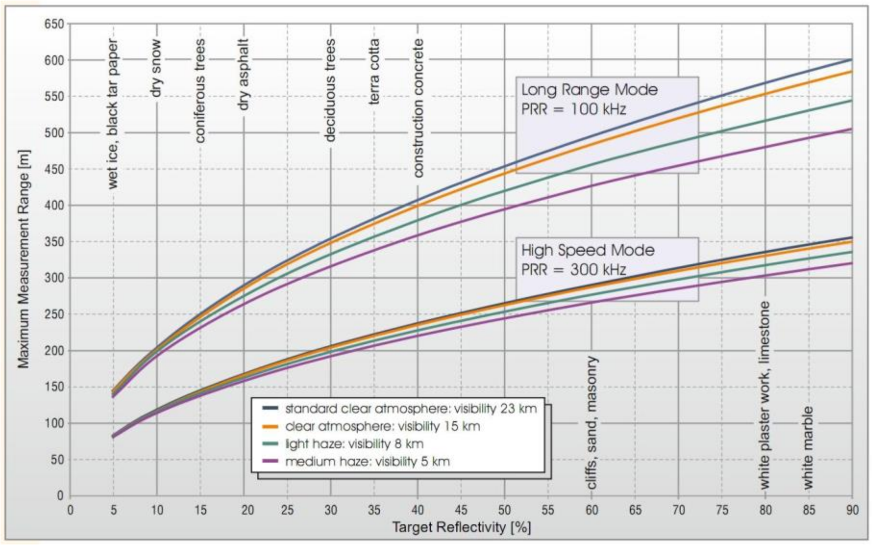
RC - 8: Page 2, line 15 –use of ‘etc.’ to end sentence is not acceptable –unprofessional use of language and assumes reader knowledge of other uses of TLS.

AC: Accepted, this part will be removed in the revised version of the manuscript.

RC - 9: Page 2, line 16 –re-write ‘reflectance of ice absorbing much of the laser energy’. This suggests that the ice is reflecting the laser beam and absorbing it at the same time – the paper cited for this shows the difficulties in scanning ice, as ice can absorb red laser beam wavelengths.

AC: Our aim was to cite Kamintzis et al. (2018) who studied the applicability of terrestrial laser scanning for mapping englacial conduits. These authors state that the quality of point cloud depends on the physical and optical properties of the surfaces within the conduit, here in comprising ice, snow, hoar frost and sediment, with their respective absorption coefficients in the shortwave infrared, reflectance type, and the complex conduit morphology determining point density and distribution. Laser returns within the englacial environment are low, typically <50% of the emitted pulse.

This argument correlates with the technology of our scanner used in the research. The manufacturer Riegl states that a different scanning range depends on the target reflectivity (various types of materials has different reflectivity) and the amount of emitted energy within a laser pulse.



Original sentence is:

However, use of TLS in ice caves is more challenging for the slippery surface, harsh climate and reflectance of the ice absorbing much of the laser energy emitted by the scanner (Kamintzis et al., 2018).

We propose to add this sentence to the revised version of the paper:

However, the use of TLS in ice caves is possible but more challenging than in non-ice or exterior environments for the slippery surface, harsh climate and physical properties of ice which absorbs considerable portion of the shortwave infrared energy typically used by the laser scanner (Kamintzis et al., 2018).

RC - 10: Page 2, line 16-18 –this is not a full sentence, just a phrase.

AC: Accepted, this part will be rephrased in the revised version of the manuscript.

RC - 11: Page 2, line 21 – what are the open questions not addressed by Avian et al 2018? Be specific, this assumes that all readers have read Avian et al 2018's paper. If these questions are addressed by the manuscript, this must be made clear.

AC: AC: Accepted, this part will be removed in the revised version of the manuscript. We propose this sentence:

Avian et al. (2018) also addressed this issue with terrestrial laser scanning (TLS) in the glacier. Registration of single scan missions was based on 1 scan position and 6 reference points leading to generation of a time-series database. In case of cave cryomorphological mapping, some questions such as registration of single scan missions without reference points remain open.

RC - 12: Figure 1 –This map does not provide much information. The text on the map is too small and blurry, particularly in the inset map showing the location of the cave in Slovakia. Providing a map that demonstrates the important geomorphological features surrounding the cave would be more useful –eg. addition of contours may add to show if cave is located in depression/high elevation, addition of notable features such as the debris cone mentioned on page 4, line 11. It would be good to overlay the planform of the cave onto the map to show it in geographical space given that no overview of the scanned cave is given. The figure caption also needs to be more explanatory –what exactly is the figure showing us

AC: Accepted and Figure 1 is redesigned - smaller scale with more contours and information. All pictures will be produced in higher resolution for final paper.

We propose a new design of the Figure 1:

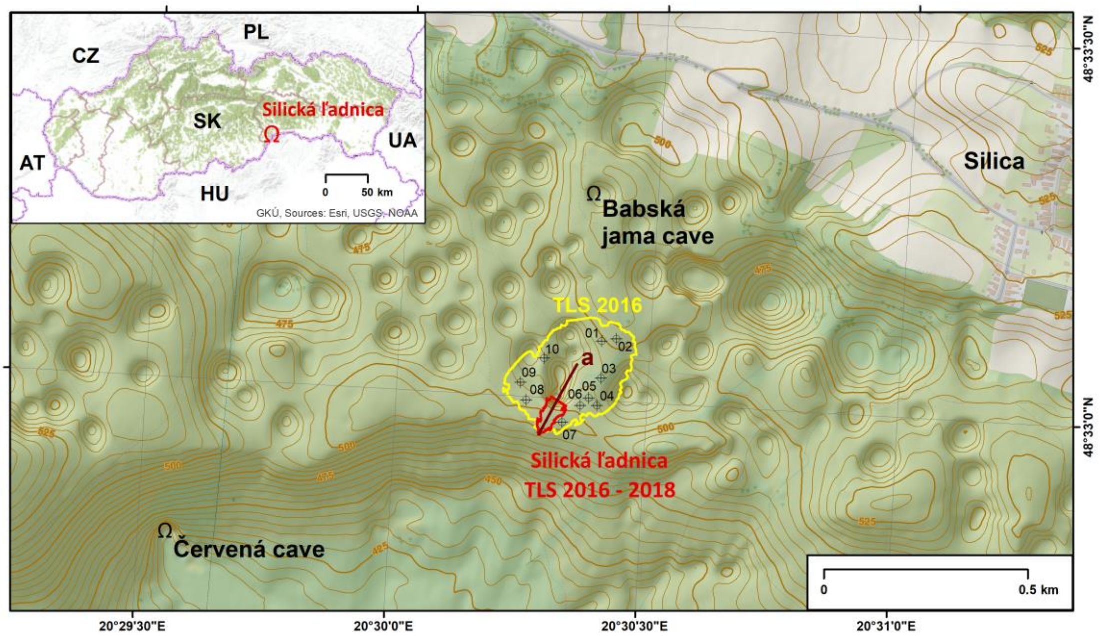


Figure 1. Location of the Silická ľadnica cave. The polygons represent the territory mapped by the TLS method - yellow outline delineates the area of the scan mission 1 in 2016, the red

outline represents the area of other scan missions used to build a time-series of TLS data. Contours and shaded relief improve the perception of numerous sinkholes on the plateau of Silická planina, which tend to have a regular funnel shape. Dark brown line denotes with „a" marks the vertical profile shown in Figure 7. Numbered black crosshairs in a circle locate the ground control points used for registration into the common global coordinate system.

RC - 13: Figure 2 –The figure caption needs to be more explanatory –is this the same view in each panel? Is the view of the cave entrance from inside the cave? Say in the caption that the figure shows decreasing ice coverage. Presumably, an object in the centre of the 2018 picture provides scale –this needs to be highlighted in the caption and readers need to know what this object is.

AC: Accepted and the Figure 2 is redesigned.

We propose a new design of the Figure 2:

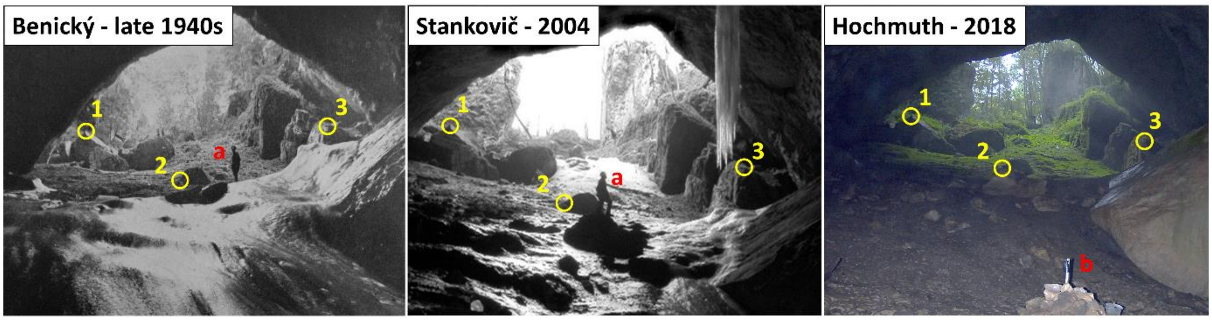


Figure 2. Photographic evidence of cave floor ice in the Silicka ľadnica cave over the last 80 years. All three photos are captured from approximately the same position (shown in Figure 3. as a red point A) from inside the cave outward and show different states of cave floor ice. Identical points are marked in yellow. As a scale, objects marked in red can be used - (a) is the figure of a speleologist and (b) a wooden stick 30 cm high. Based on the photographs we can conclude that there is a gradual loss of ice. The photographs were taken in different years but also at different periods within the year.

RC - 14: Page 3, line 13 –no need for repetition of information from introduction.

AC: Accepted and removed.

RC - 15: Page 4, line 3 -the description of the cave shape is not clear. What does an obliquely falling bag look like?

AC: Accepted and rephrased.

RC - 16: Page 4, lines 11 –15. Description of cave is unclear and does not correspond with Figure 3. Where is the debris cone? What is meant by the bottom of the iced part of the cave? It would help the reader to see these features on a map.

AC: Accepted and linked with description related with redesigned figure 3.

RC - 17: Figure 3 –This figure is too small, and the writing needs to be larger. What is meant by the mapping line and mapping points? These are difficult to see on top of the background colouring. It would be good to know how deep the cave floor is from ground level, and where the cave entrance

is. Is it necessary to show rock blocks, clay, gravel and debris on this map? Where is the icefall mentioned on page 5, line 8? I think knowing the location of ice coverage is important, but the composition of the rest of the cave does not seem to add any information/contribute to the reader's understanding of the paper –at least the importance of knowing this is not highlighted. A further thought –is the cave below ground, or above ground? Is it completely sealed off, are there any water inputs to the cave/how big are these, is there any flowing water through the cave, what is the height of the cave, what is the ambient temperature and moisture, is air circulation within the cave known/are there any openings to the outside? These sorts of information, and the locations of such detail, are useful for understanding potential causes of ice accumulation/decreases.

AC: Accepted and the Figure 3. is redesigned.

We propose a new design of the Figure 3 and we addressed the comments of the Reviewer #2:

- the terms "mapping line" and "mapping points" removed
- background colouring represented scanned part of the cave is removed
- the vertical dimension of the cave with altitude indication is included in Figure 7.
- localization of the cave forms is addressed and highlighted (simplification of map legend was performed).
- description of the cave including hydrological conditions is in chapter 2, we suggest to add 3 sentences in the revised version of paper:
  "No permanent or temporary watercourses flow through the Silická ľadnica cave. Only the rainwater infiltrated into the soil comes to the cave through the cracks of the limestone rock massif, creating ice stalagmites shown in Figure 3. This water is the source for ice formation in the cave.
- Information about entrance, temperature, precipitation and air circulation, structures of ice forms is included in chapter 2 (on page 4, line 4-6; on page 5 and page 6) and will be added to the result section of the revised paper.

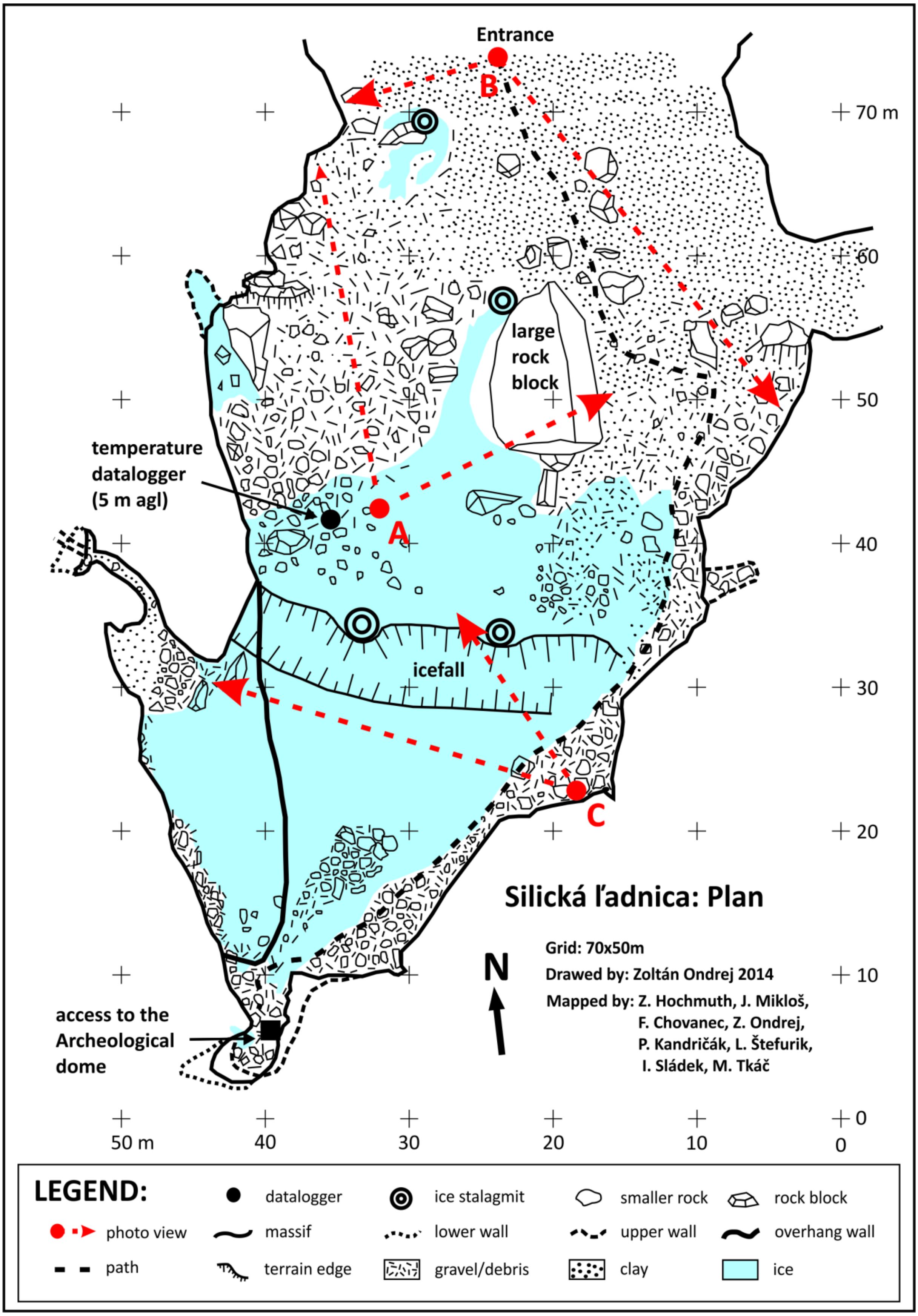


Figure 3. Map of the Silická ľadnica cave floor. The cave is an open pit cave with the entrance approximately 30 m wide and 20 m tall. It is freely accessible to the public from the north by a

concrete staircase. Gravel and debris cover the floor mainly in the upper part of the cave near the entrance. There is a large limestone boulder labeled as large rock block in the central part. The cave floor ice starts to occur from the boulder to the bottom part of the cave in the south. The are smaller blocks of rock in the ice and around the icefall. The deepest part of the Silická ľadnica cave is in the south. There is an artificial entrance to the Archaeological Dome, which is closed by a hatch and covered with rock blocks. The red points and arrows mark the field of view in the photographs in Figure 2 and Figure 4.

RC - 18: Page 4, line 6 –7 – 'large portion of floor ice situated beneath layers of sediment' -does this mean that sediment is lying on top of layers of ice, or that water has percolated downwards through the sediment and frozen in place? Ie, are these actual layers of horizontal ice, or frozen within the spaces between sediment?

AC: It means that part of floor cave ice is covered with the gravel and debris (sedimentary material deposited by gravity from upper part of the cave). This floor cave ice changes cannot be detecting directly by TLS. Our hypothesis is that if ice is melting under gravel and debris, it will be reflected on the surface by lowering the surface in these places compared to previous measurements. We will then be able to identify the extent of ice covered by sediments. At the same time, it means that water coming into a cave from melting stalagmites infiltrates into gravel and clastic sedimentary material where it freezes. We accept the comment and we will modify the text to convey the information clearly.

RC - 19: Page 6, line 3 –ice forms identified are hoar frost in the upper parts, ice coatings on the cave walls and 'others'. Surely these 'other' ice forms are important? Don't assume that the reader knows what these ice forms are. Are the authors referring to ice stalacmites and stalactites here? Or other morphological features?

AC: Accepted, it will be rephrased in the revised version of the paper.

RC - 20: Figure 4 –the picture of the icefall is not particularly clear –is that a person at the top of the ice fall to show scale? This needs to be pointed out in the caption if so. Could the rock surface be labelled to make it clearer where the ice fall is coming from? In panel A, does the cave extend at the bottom left of the photo where a head torch can be seen? Again, there is no acknowledgement of where this ice fall is within the cave. Is this at the entrance? The caption for this figure is better than the preceding figures –gives more detail. Scale would be good.

AC: Accepted, Figure 4 will be modified in the revised version of the paper. Suggested labels will be implemented to the caption and identical points and will be edge of icefall marked.

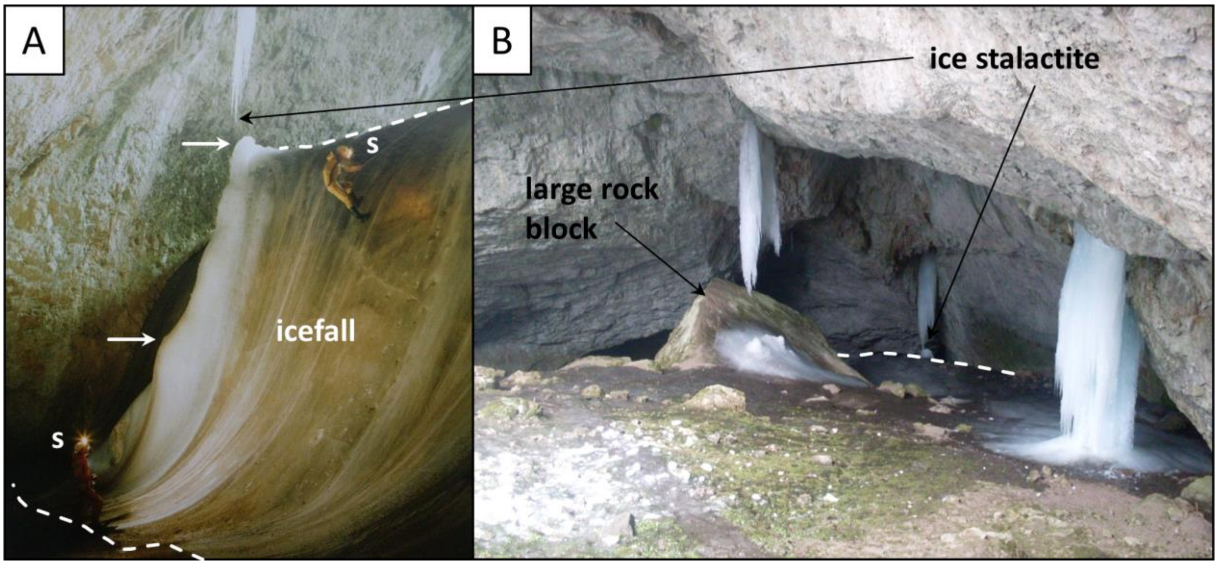


Figure 4: The Silická ľadnica cave contains different types of ice objects. The permanent ice is represented by (A) an icefall (Stankovič and Horváth, 2004) located in the bottom part of the cave. Ice speleothems (B) such as stalactites and stalagmites situated in the upper part of the cave (Ondrej, 2014) are the most dynamic objects with significant seasonal and interannually changes. Approximate size of the ice fall can be judged based in the spelunker (s). The icefall is outlined with a white dashed line. The identical location of the ice stalactite in both photographs is marked for better orientation. White arrows indicate stalagmites which tend to accumulate in dry and wet seasons or years based on the size of the stalactite marked with black arrow.

RC - 21: From Figure 4, it seems that the upper parts of the cave are separated from the lower parts by access down the ice fall. Is this correct? Does the map in Figures 3 and 6 just represent the lower level?

AC: We appreciate this comment. In Figure 3, we have inserted the position and field of view of the photos shown in Figure 2 and Figure 4.

Also, in Figure 3, we have highlighted a sidewalk (path) that can be used to reach the lower parts of the cave. Thus, access from the top of the cave to its bottom is possible without climbing equipment on the sidewalk.

RC - 22: Page 6, lines 7 –18. Most of this information regarding the cave history is redundant and does not add to the reader's understanding.

AC: We accept and in revised version of the paper the information regarding the cave history will be reduced.

RC - 23: However, the connection of the cave with the Archaelogical Dome is important –this needs to be kept but an explanation of what this dome is needed, as well as demonstrating where this link is with the Silicka ľadnica cave on a map. How did this link change the microclimate within the cave and lead to negative effects on cave ice?

AC: We appreciate this comment. This comment is addressed in Figure 3 within the caption.

RC - 24: Capitalisation of the cave name needs to be consistent throughout the manuscript– sometimes l'adnica has a capital L and sometimes it does not.

AC: We accept and we will correct it in the revised manuscript.

RC - 25: It is not clear why authors collected data over 2 years, nor is the time interval at which the cave was scanned given. This information is fundamental, given that the results show ice changes from season to season.

AC: In this paper, we present a novel methodical approach to the generation of a time series database, on which it is possible to detect changes in cave floor ice. The formation of ice and its melting is evident even during our short period. This change of the amount of cave floor ice is illustrated by Figure 8 and Figure 9.

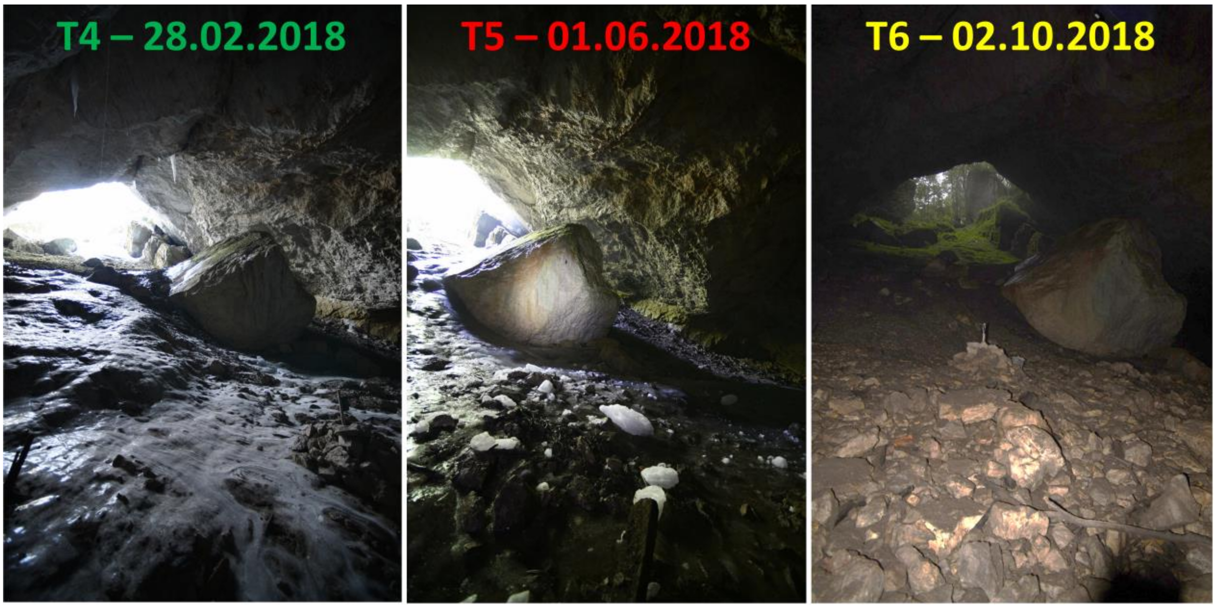
There are several research questions about the Silická ľadnica cave, e.g. Which factors are involved in the formation and melting of the cave floor ice? What role does the changing climate play? Why is the ice melting during periods of rainfall? What role does vegetation on the surface above the cave play? and many more.

In order to answer these questions in detail, the first step is to have a clearly developed and established methodology to quantify the change in cave floor ice. The change was observed by the spelunkers over decades, the advance of TLS has enabled to measure it in a high level of detail. We presented and described this methodology in detail in the presented paper. In addition, we have demonstrated that this methodology is sustainable for long-term monitoring. After 2 years of monitoring, it is more clear when is the best time for mapping. On the other side, we had no uncertainties about methodology of data collection and processing.

We will modify the related text to explain the time interval and periodicity of monitoring.

RC - 26: How did the authors come to the conclusion that ice volume may have changed at an intra-annual scale?

AC: This phenomenon is known and described in the papers citied in the "Area of interest" chapter (Page 5, lines 3 – 7; Page 6, line 15-18). To confirm this statement, we are attaching photo evidence.



This figure can be included in the revised manuscript to support its content.

RC - 27: Were scans positioned around the cave to record the entirety of the ice floored section, or just parts of interest?

AC: Accepted, Figure 6 will be redesigned in the revised version of the paper. We think this comment is addressed by changing the topographic background of Figure 6 and adding a label of the "large rock block", "icefall", "entrance and access to the Archeological dome" to the map.

RC - 28: The surveying technique could be presented in more detail/more clearly and concisely, with omission of principles such as those on page 8, lines 10-16. The Panorama mode 40 used could be summarised more succinctly.

AC: We will modify the text to present the method more concisely but exhaustively. The detailed information about parameters of scanning settings are important for repeatability of the research as different results can be achieved by using different settings, even if the deviations would probably be small. See also RC/AC -32.

RC – 29 Where were ground control points taken around the cave? Just at the entrance?

AC: We accept. This comment is addressed on Figure 1 within its caption.

RC – 30 Why were further scan missions after the initial scan mission only completed in areas of ice accumulation? This will skew the results and only present data on increasing ice volumes rather than presenting an overview of the whole cave. Is this due to the wording?

AC: The aims of our paper are presented on page 2 lines 31-35 and page 3 lines 1-2. Distribution of scan positions of individual scan missions are portrayed in Figure 6. Based on presented methodology and results we conclude that the presented approach does not skew the results and is a suitable methodological basis for the interpretation of changes in cave floor ice volume. We will rephrase the text where needed to make the message clear for the readers.

RC – 31 Page 9, lines 1-5. Information on scan times not necessary, unless trying to prove the point that TLS enables faster data acquisition than other survey techniques, which allows repeat scanning at increased time intervals.

AC: We wanted to emphasize that we saved a lot of time (around 25 scan positions and 12 hours of scanning versus 7-10 scan positions approximately and 3 hours of mapping) using sC2C approach within monitoring the cave floor ice. We consider this argument as one of the most important factors for long term monitoring of cave cryomorfology helping us to demonstrate the strengths of sC2C approach.

RC – 32 Table 1 –columns 4 and 5. Does 'no. of p.' refer to the number of points within the point clouds? This information does not add to the paper, as the decimation/clipping of point clouds is explained elsewhere. Column 3 –why are differing scanner modes used? This needs to be explained.

AC: Abbreviation of "no. of p." is explained within the Table 1 caption.

In initial phase of the cave floor ice monitoring, we also focused on testing various parameters of the scanner settings. We tried to find out if a higher scanning detail influences the precision of the mapping of crymorphological topography. We found that critical points such as ice have the same point density even with higher scan detail, as shown in Figure 8. Distribution of point density. By doing this, we wanted to prove / disprove the argument that higher scanning detail (Panorama 40 vs. Panorama 60) does /does not affect the detail preserved in the cave model.

In addition, there are demands for processing and storing data because of their amount. During this 2 years' period of mapping, we also identified and optimized the scan positions, which we refer to as the scan position clusters in Figure 6. Based on this testing, we know how many positions are enough to scan the cave floor ice and what scanner parameters are optimal. It is a useful information for readers, if they want to start with similar mapping.

We agree, that this argumentation is missing and in the revised version of the paper should be added. See also RC/AC – 25 and RC/AC – 28.

Table 1: Characteristics of the time series database.

Date of survey	Number of positions	Mode of scanner (mdeg)	No. of p.* after internal registration	No. of p.* after uniformization of spacing and clipping AOI	St. Dev.** of internal registration (mm)	St. Dev.** of global registration (mm)
2016 06 23	32	40	476 759 981	16 408 990	3.5	Reference
2017 04 06	7	60	57 954 146	12 260 062	3.5	4.4
2017 11 17	6	60	52 148 327	11 588 910	4.1	4.2
2018 02 28	9	40	183 997 069	22 256 625	5.0	4.2
2018 06 01	10	60	81 904 050	8 798 708	4.7	4.0
2018 10 02	8	40	175 914 550	18 278 696	4.7	4.5

*No. of p. – Number of points

** St. Dev. – Standard deviation

RC – 33 Page 9, line 9-10. Is the noise identified here the noise that was present in the laser scans, or is this comment more general about the different types of noise?

AC: Accepted, it is a general comment. In revised version of the paper the sense will be rephrased.

RC – 34 Page 9, line 19 –the points that are used are within the deviation value range of 0-20. Is this the same range as described in lines 16-18? Why have only this range of points been used? Is 20 a known threshold in the dimensionless number range of 0 –65,535?

AC: This value is recommended by the scanner producer. Accepted, it will be added in revised version of the paper.

RC – 35 Page 10, line 5 –7-this sentence is confusing, please clarify.

AC: Accepted, in the revised version will be rephrased. In case of unhomogenous distribution of points (with many empty places without points) it is more appropriate to calculate normal vectors with respect to the center of scanning position for each individual point cloud.

RC – 36 Page 10, line 10 –clarify what 'scratches' are

AC: Accepted, it will be rephrased.

RC – 37 Page 10, lines 13-23. This paragraph on the principles of cloud to cloud registration is confusing, including un-defined terms such as 'cube size' and 'search radius', which do not mean anything to the reader unless they have used the software. Brief explanation of what these are would benefit the explanation. This paragraph would perhaps be better suited to Section 3.2. It is appreciated that authors are trying to make results repeatable –but readers do not necessarily need to know the working of the algorithms used.

AC: The suggested parts could be removed, but we argue that if the readers do not need to get familiar with the software and algorithms used, they can just skip this section. Otherwise, for those who are interested in minimizing the standard deviation of registering individual scans, this can be a very useful information. The parameters are the result of multiple interactions and they are empirically determined. At the same time, these parameters were also used with the sC2C approach page 10 lines 31-32. We suggest to keep the text as is.

RC – 38 Page 10, line 27 –29. Do the areas of the cave with stable geometry have ice covering them? Are they areas of bare rock? This needs to be clarified in the area of interest section in the cave description.

AC: Accepted, the ceiling of the cave consists mainly of bare rock. This sentence will be explicitly inserted in chapter 2 and reference will be made to Figures 2 and 4.

RC – 39 Page 11, line 1 –the authors propose that the sC2C approach is more suitable, however, it is not clear which other approach this is an improvement on. Is this a wording issue and is it perhaps meant to say that this approach is the most suitable?

AC: Accepted, it will be rephrased.

RC – 40 Page 11, line 5-7 –the last sentence of this paragraph is unclear.

AC: Accepted, it will be rephrased.

RC – 41 Figure 7 –Panel C could be interpreted as a planform map, highlight which view of the cave this is in the figure caption. Check figure for spelling. Why have only scans from 23/06/2016 and 02/10/2018 been presented? Is this figure purely to demonstrate the improved registration provided by sC2C?

AC: Accepted, Figure 7 will be redesigned and caption will be rephrased as this example shows:

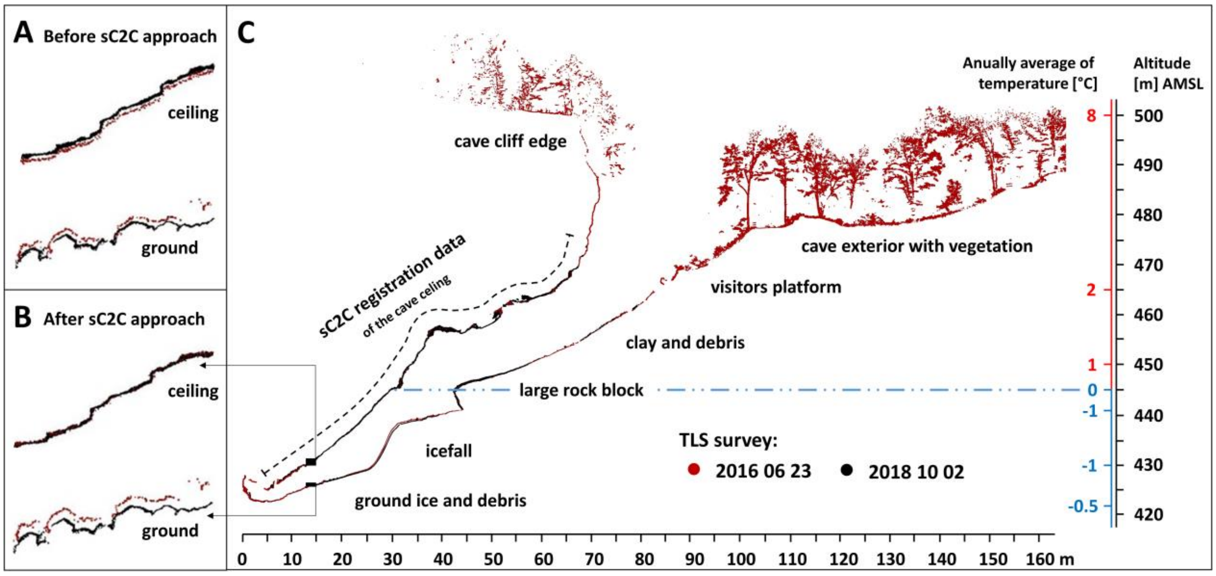


Figure 7: Demonstration of the improved registration accuracy by the sC2C method. Red dots represent the reference point cloud (surveyed on 23 June 2016). A point cloud surveyed on 2 October 2018 marked with black dots was used to demonstrate the registration result using the sC2C approach. Results of the registering the scan missions (A) before and (B) after using sC2C approach are visible in the detailed views. Stable points of the cave ceiling (C) on the bare rock were used in the sC2C approach. The horizontal and vertical range of the cave can be estimated from the horizontal and vertical axes. The annual average of air temperature of the cave interior is lowest in the icefall area. The average annual temperature of 0 degrees Celsius is nearly above the icefall. The range of the cave floor ice can also be deduced from the average annual temperature.

RC – 42 Page 11, line 22 – both points explaining why a heterogeneous distribution of points occurs in TLS point clouds need to be clarified. The explanations of high densities of points in some areas and low densities in others on page 12 could be clearer.

AC: We will modify the text to explain the issue more clearly.

RC – 43 Page 12, line 8 –this sentence does not make sense.

AC: This sentence will be revised or omitted.

RC – 44 Figure 8 –this figure is not needed. It shows that the point cloud spacing has been homogenised; the reader does not need to see this to understand the explanation given in the text. Although this figure demonstrates where cave geometry is possibly more intricate, requiring more scans to be conducted around these features, this does not add to the reader's understanding of the paper.

AC: Accepted, Figure 8 will be removed.

RC – 45 Page 12, line 14-15 –the authors introduce a result of the paper here. As this section should just outline the methods used, this sentence would be better placed as part of an introduction to the results section.

AC: We think this sentence belongs here. It is linked with figure 5. The generation of time series database is a part of the methodology. Throughout Chapter 3, the steps are described and explained. At the same time, we argue that the main result of the paper is the evaluation of cave floor ice changes in the cave. We structured the text on methodology and on the results accordingly. The abstract on page 1 (lines 10 to 16) describes what can be expected in the results. The generation of a time series database is a prerequisite for evaluating changes in floor cave ice.

RC – 46 Page 12, line 16 –this sentence does not fit here and is unnecessary.

AC: Accepted, it will be removed in the revised version.

RC – 47 Page 12, line 20 -'classical bivariate functions' needs to be explained or defined. It is unclear whether this means that certain parts of the cave have not been modelled.

Page 12, line 21 –equation for modelling terrain needs components to be defined.

AC: Accepted, we will explain it in more details.

RC – 48 Page 12, line 22 –page 13, line 2 -bivariate functions needs to be defined –currently this does not make sense despite the example of using a cube with a defined side length.

AC: This is one of the reason why the presented approach of this interpolation method is interesting. Space of input data is temporarily voxelized and bivariate functions are used to find a suitable surface. The result is a complex 3D surface of the cave.

In the revised version, this section will be modified to explain the issue more clearly.

RC – 49 Page 13, line 6 –19 –the authors provide an explanation of PSR principles. An explanation of why this interpolation method was selected would be more useful than the detailed principles, together with maybe one or two sentences on how this interpolation method works.

AC: Accepted, we consider this part crucial to prove that we have created a highly detailed 3D model of the cave surface. This method was published in Kazhdan et al., 2013, which we citied. The choice of the method used will be mentioned and text expanded in the revised version of the paper.

RC – 50 Page 13, line 21 –authors say that ice is expected to occur on the floor of the cave –previously, they have inferred that ice covers the floor of the cave. Is this an issue with wording? This suggests that the ice coating the walls of the cave and features extending between the floor and ceiling have not been included in the analysis of ice volume change.

AC: Accepted, it will be rephrased in the revised version.

RC – 51 Page 13, line 29 –the authors need to clarify what is meant by 'gradual' change. Quantify. What is the 'difference of distance' approach? Is this finding the difference in floor height between each scan mission?

AC: It is not exactly the difference in floor height between the scan missions but a 3D difference calculated based on normal vectors. More details about the M3C2 method can be found in Lague et al. (2013), which we cited in the paper on page 13 line 27. We will add more information into the text to convey the message clearly.

RC – 52 Page 13, 28 –30 –again, this sentence should not be in the methods section but would be better situated in the results section.

AC: This sentences are a part of the section related with Fig. 5 Phase 10 Computation of volume statistics. In Chapter 3, there is a step-by-step description of the procedure how we achieved the results. Volume calculation and surface distance difference are an integral part of the whole procedure for detecting cave floor ice changes.

RC – 53 Page 14, line 5 –authors should be careful in using the word 'significant'. This should be used only to refer to statistical testing, and the relevant test and significance values should be presented, otherwise, the word 'considerable' may be better. Significant is also used on page 17, line 7.

AC: Accepted, the word "significant" will be replaced by " considerable”

RC – 54 Section 4.1 -how was the cross-section location decided upon? Was only one cross-section assessed and why? Although the cross-section encompasses three areas of different cave floor types, it cannot be concluded from this that ice accumulations are decreasing (as indicated by page 15, line 14) as changes in ice surface are also governed by local factors. More cross-sections demonstrative of these three floor types are needed to reach these conclusions.

AC: We think that one cross-section is sufficient for demonstration of the proposed methodology in the text but an original output of the research is the interactive web interface where cross-sections can be created arbitrarily by the user in any direction (https://geografia.science.upjs.sk/webshared/Laspublish/Ladnica/Silicka%20ladnica_All.html

). The web interface does not require the installation of any add-on modules and is freely available. Data can be also exported. In addition, the changes of the cave floor ice can be read from Figure 10. The presented cross-section is led across the floor of the cave.

RC – 55 Page 14, lines 11-12, 18 –these sentences explaining what each panel shows are repeating information from the caption of Figure 9.

AC: Accepted, it will be removed.

RC – 56 Figure 9, line 14 -'vertical' cross-sections imply that a cross-section was taken from the cave ceiling to the floor.

AC: In the description of the figure 9 it is explicitly stated that the cross-sections represent the cave floor colored by date of TLS survey.

RC – 57 Figure 9, line 15 –the cross-sections show the floor surface morphology, not the dynamics. The dynamics of the ice typically imply ice motion/change and the processes causing this, and can be inferred from looking at changes in ice volume/morphology.

AC: Accepted, it will be corrected.

RC – 58 Figure 9, line 16, (b)–see previous comment with regard to ice dynamics. This panel seems to show the greatest change in elevation rather than the most visible dynamics.

AC: Accepted, it will be corrected.

RC – 59 Page 14, line 21 –page 15, line 1 –this sentence does not make sense. Cross-section 'convergence' is also a confusing term –does this mean areas where the lines become closer together (ie little change in floor elevation)?

AC: Accepted, the sentence will be rephrased. The term of "cross-section convergence" will be replaced by "the convergence of profile lines".

RC – 60 Section 4.2 and Figure 10 –it is unclear what the differences of distance method shows –in the figure, it appears that the panels show areas of increasing/decreasing ice elevation, representing literally the difference in height elevation between each survey, as shown from the scale bar unit of 'm'. However, the authors then talk about the figure showing changes in volume in the figure caption. Does this figure show changes in volume or changes in elevation?

AC: Accepted and the caption will be corrected.

Figure 10: Differences of distances (DoD) between the individual cave floor surface models. The blue color represents decrease and red color indicates increase of the surface elevation.

RC – 61 It may make more sense to present the DEMs of difference (figure 10) first, and then use the cross-sections to examine the changes in areas of transitions between floor materials. The cross-sections basically demonstrate the same data as the DEMs of difference, but using a different viewpoint (ie long profile of the floor across the ice fall, rather than the planform view of the entire cave floor), and therefore it cannot be said that these two methods of analysis are difference –they are presented as such in the manuscript.

AC: Figure 9 shows just point clouds of the generated time series database. This will be explicitly stated within the description of Figure 9.

Comparing the cave floor ice changes using vertical profiles illustrates a clear evidence that cave floor ice changes have occurred and that we were able to record the changes using the presented approach. Moreover, in the paper the assessment of volume changes was also presented. This is a more complex issue. Figure 10 demonstrates the difference of surfaces based on which the volume changes were derived. Figure 9 and Figure 10 are not similar and portray different data. Point clouds were the input for creating 3D surface models as is presented in chapter 3 in detail. 3D mesh surface model is continuous representation of the surface while the point cloud is discrete/discontinuous. Thus, Figure 9 shows the point clouds; Figure 10 shows the 3D surface model. We consider the structure of presenting the results appropriate and corresponding with the methodological workflow and its description.

RC – 62 Page 15, line 20 and 24 –the term 'glacier' has a very specific definition and is not what the authors are suggesting here; this seems to be a misunderstanding in translation which has implications for the content that are not necessarily correct.

AC: Accepted, the term 'glacier' will be replaced by 'ice'.

RC – 63 Page 15, line 24 –although the collapse of an ice stalactite does not change the ice volume of the cave, the authors have only examined the changes in cave floor volume and, thus, this collapse does contribute to this change.

AC: The ice stalactites hanging from the ceiling are not part of the cave floor ice. If the ice stalactite falls on the cave floor, it becomes part of the floor ice. In this section, we are explaining why there is an increase in floor ice volume in certain places of the cave.

Original text page 15 line 24-27:

It is interesting to study the increment of the stalagmite on the icefall (Fig. 4A), the volume of which has increased during the whole period (Fig. 10 gradual). The increment is related with a crevice in the rock ceiling, which is fulfilled with the ice stalactite. Because of the dry seasons, the stalactite has been melted and its shape was reduced. Thus, dripping water dropped to another location and a new stalagmite was formed just below.

We will rephrase the text as follows:

There is an interesting formation of a stalagmite on the icefall (Fig. 4A) which is related with a crevice in the rock ceiling filled with an ice stalactite (Fig. 4). We empirically observed over the last decade that in dry years the stalactite above the stalagmite melts and its shape reduces. In case of a dry spring the stalactite does not grow to a significant size to contribute with melt water to the grow of the stalagmite right below it. When the stalactite is smaller, the dripping melt water flows further down along the ceiling to another location and a new stalagmite accumulates just below the original one (Fig. 4A, red arrows). The change of volume of the ice stalagmites was recorded by monitoring with TLS. The lower stalagmite grew while the upper stalagmite generally decreased during the whole surveying period (Fig. 10).

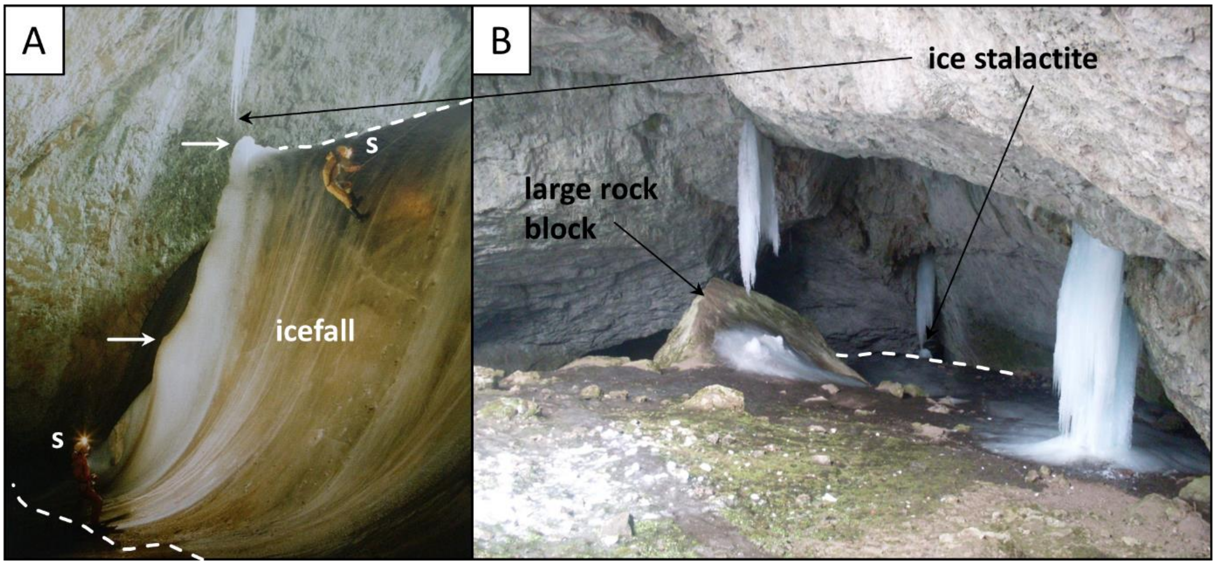
RC – 64 Page 15, line 25 –sentence needs to be revised to make it clear when melting occurs and when seasonal minimums are observed.

AC: Accepted, the sentence will be rephrased. See response to RC – 63.

RC – 65 Page 15, line 27 –it is not clear what the 'increment of the stalagmite on the icefall' refers to, and whether the volume of the ice fall has increased over the whole period, or the volume of the stalagmite.

AC: The sentence will be rephrased, see response to RC – 63.

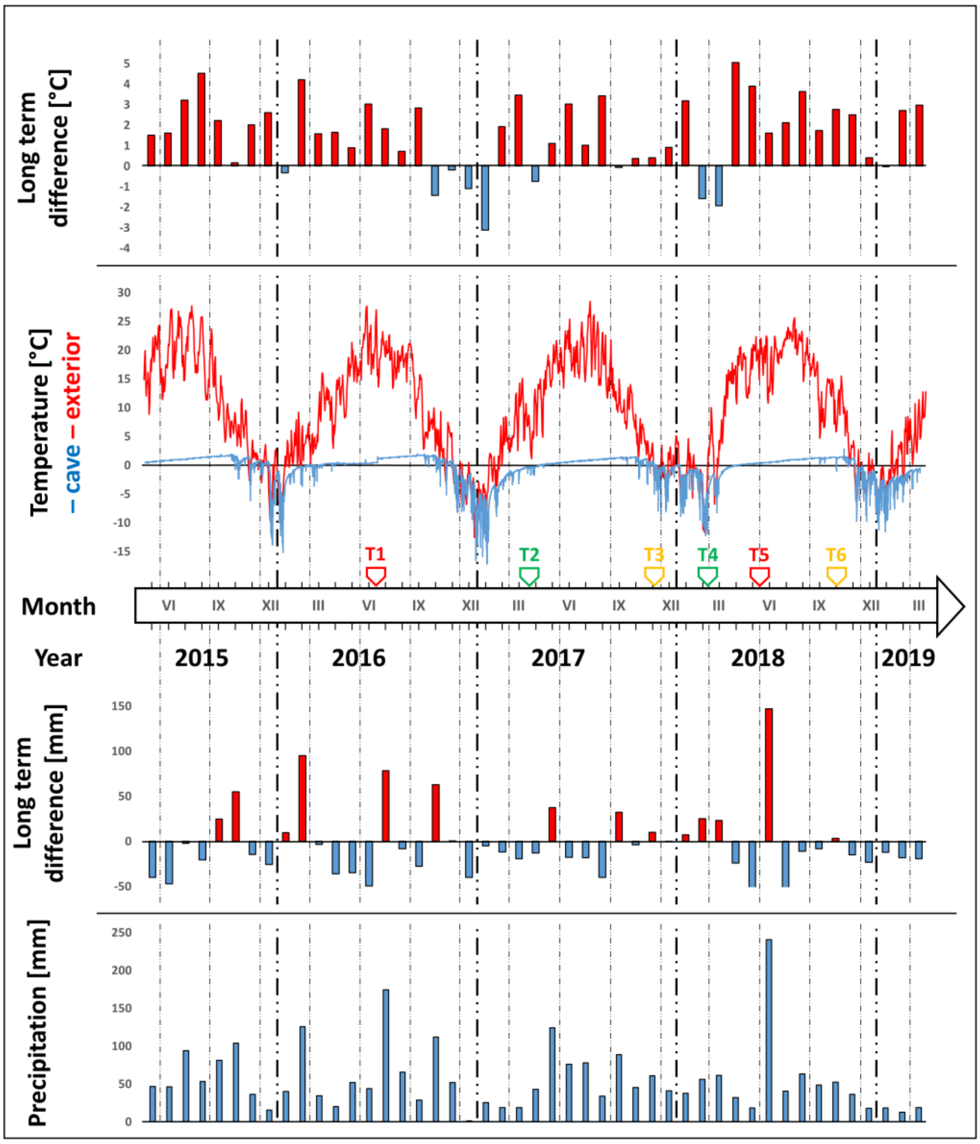
Fig 4A.



RC – 66 Page 17, line 1-6 –it would be nice to see the authors' interpretation of events causing the loss of ice using the data sets mentioned (temperature, precipitation). Without this, the manuscript is just a report of ice change and does not present any concepts or ideas for this. If the manuscript presented a novel technique for obtaining such a great dataset, and explored its potential uses, this would be more acceptable. However, the techniques used have already been established.

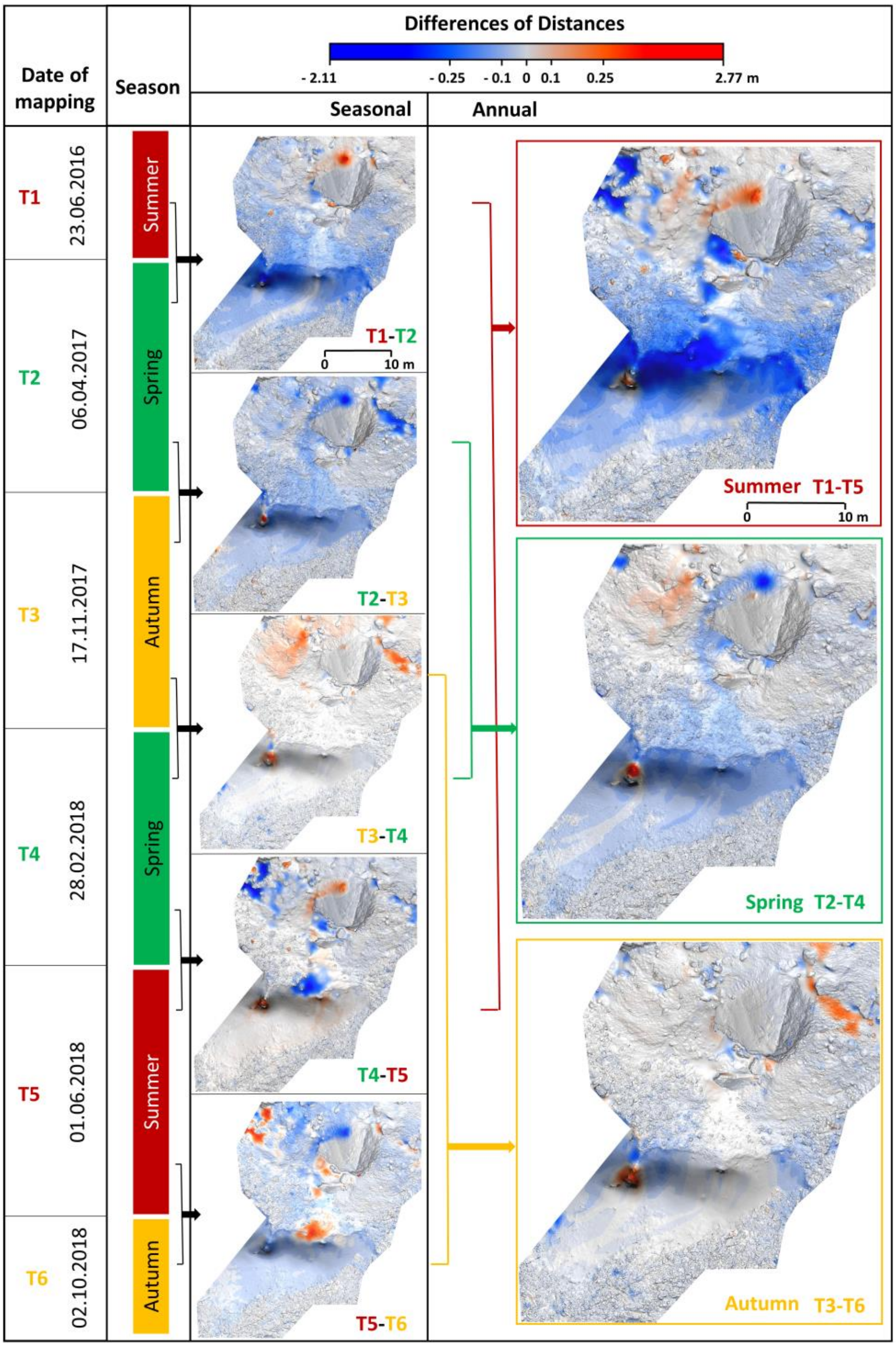
AC: As we emphasized in the previous comments, the manuscript focuses on presenting a new method for monitoring the cave ice change. Adding interpretations to the findings would considerably extend the text. Nevertheless, we implemented our concise interpretations based on meteorological data and data acquired from our own temperature sensors in the cave. In the revised version of the paper, we will add separate section within the chapter 4.

We will also add a new figure. The new section will be focused on interpretation of events causing the loss of ice using the time series database and linked with temperature (interior and exterior) and precipitation. New figure will be designed as follows:



RC – 67 Figure 10 –this is a good figure and is perhaps the only figure of appropriate size in the manuscript. The scale bar text could be larger. A scale with more than two colours could be used to show more subtle differences in elevation, as currently the changes from light to dark blue/red are hard to correlate with the scale bar. Also, the labelling of 'gradual' and 'seasonal' is incorrect –it appears that the 'gradual' column reflects seasonal change (change from one season to another), and the 'seasonal' column reflects annual change (change from one summer/spring etc to the summer/spring of the following year). However, caution must be taken in that the top panel of this column shows summer change over 2 years (2016 –2018).

AC: Accepted. The recommendations are addressed in the redesigned version of the figure.



RC – 68 Page 17 –ice accumulation means addition of ice. Authors should alter wording to reflect whether ice has increased/decreased. For example, 'the loss of ice accumulations' in line 1 suggests that there is no further increase in ice, whereas I think that the authors mean that ice is decreasing.

AC: Accepted, we will rephrase the text to communicate the meaning clearly. In general, we consider ice accumulations as forms on the floor of the cave such as cave floor ice or parts of destructed ice speleothems not as a process of growing/increasing mass of ice.

RC – 69 Page 18, lines 1-2 –the volumetric error calculation appears to be derived by multiplying the total error by the area of observation –I am unsure that this is correct. Furthermore, errors for each DEM should be reported.

AC: It is possible to calculate volumetric error for each observation in different ways which can be simple or complex, e.g. based on geostatistics and randomized error on each lidar point drawn from a normal distribution. We used the simple approach with but conservative (worst case) scenario (largest error). However, this error is much smaller than we report in the paper. The error must be calculated based on the precision parameter specified in the scanner calibration report (the error was calculated based on the parameter of accuracy). The new recalculation will be implemented in the revised version but the constant is different. The calculation procedure is simple/straightforward but we consider it correct to demonstrate the volume change and its uncertainty.

RC – 70 Page 18, line 14 –the content of this sentence should also be in the introduction and expanded upon to explain why ice caves are important and what they can tell us about changes in the landscape. Furthermore, the whole point of the paper seems to be on detecting changes in ice volume –if these changes are dependent on the surrounding landscape/climate, the decreasing ice volumes can infer changes to these factors and should be discussed in the manuscript.

AC: Accepted and the sentence will be moved to introduction. The issue of surrounding climate and its impact to the ice volume changes will be addressed in a new section (see RC - 66).

RC – 71 The conclusion implies that using sC2C has not been accomplished in caves before and presents the advantages of this. These advantages could be made clearer within the rest of the paper.

AC: Accepted and the advantages of using sC2C approach will be emphasized in the other parts of paper.

RC – 72 The dynamics of ice cave changes have not been explored fully in this paper with only brief suggestions for causes of change. If only the datasets and basic analysis are to be presented, the paper needs to acknowledge the uses of such a dataset and present the paper in such a way as to show that this dataset is available for further use. This style of data presentation would be expected if the manuscript was improving a method or ascertaining its applicability.

AC: As we mentioned in previous short AC the mechanism of ice change in the ice caves is based on various factors and we were focused in the paper to detect only change of cave floor ice and showing whole methodology from data acquisition to the results based on sC2C approach. The data sets can be accessed freely and interactively in 3D via the Potree online web portal generated in LAStools. The link will be included in the revised manuscript.

RC – 73 Without the inclusion of temperature or rainfall datasets, it is impossible to conclude that ice losses are related to dry years, and even more difficult to determine whether these ice losses are related to climate warming.

AC: Accepted and with regard to the RC/AC 66 and the included picture and added text we will explain the impact of precipitation and temperature to the ice loss.