Detecting of Cave Floor Ice Dynamics based on Selective Cloud-to-Cloud Approach

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Abstract. Ice caves can be considered as an indicator of the long-term changes in the landscape. Dynamics in ice volume in the caves are common throughout the year, but the inter-seasonal comparison of ice dynamics indicates a change in the hydrological-climatic regime of the landscape. However, evaluating cave ice volume changes is a challenging task that requires continuous monitoring based on detailed mapping. Nowadays, laser scanning technology is used for cryomorphology mapping to record ~~a~~ status of the ice with ~~at~~ an ultra-high resolution. Point clouds from individual scanning campaigns need to be localised in a unified coordinate system as a time series to evaluate the dynamics of cave ice. ~~In order to evaluate the dynamics of cave ice, it is necessary to place individual measurements in an unified coordinate system.~~ In the presented paper, we ~~propose~~ present a selective cloud-to-cloud approach that addresses the issue of registration of single scan missions into the unified coordinate system. We present the results of monitoring ~~the~~ ice dynamics ~~monitoring~~ in the Silická ľadnica cave situated in ~~the~~ Slovak Karst, which started in summer of 2016. ~~Based on t~~The results ~~we can conclude~~show that the change ~~in~~ of ice volume during the year is continuous and we can observe repeated processes of degradation and ice formation in the cave. The ~~P~~presented analysis of the inter-seasonal dynamics of the ice volume demonstrates that there has been a significant decrement of ice in the monitored period.

1 Introduction

Ice caves are considered as the most dynamic types of caves in terms of morphology and speleoclimate changes which results from numerous processes acting inside the cave but also in its immediate exterior surroundings (Perșoiu and Lauritzen, 2018). Cave ice originates and accumulates mainly as a result of water freezing (congelation) and to a lesser extent of snow densification and diagenesis (Perșoiu, 2018). Mavlyudov (2018) articulates that cave glaciation at above freezing temperatures in the bedrock is potentially possible only at certain winter temperatures where the external air cools the cave walls to temperatures below the point of the water freezing. Besides, the quantity of ice formed depends on the quantity of water inflow. The morphology of ice is more dynamic than ~~the surface of~~ carbonate speleothems for higher plasticity and sensitiveness to cave micro-climate. Ice in the caves acts as an important archive of past atmospheric and environmental conditions in places where no icebergs or glaciers exist anymore or ever existed. The proportion of different radioactive markers in the ice can be used for calculating the absolute age of the ice formation (Kern, 2018, Kern et al., 2018). The proportion of gases trapped

Komentár od [S1]: R3C - 1: I suggest the authors to re-organize the text to better emphasize their results, rather the method (as explained below). Briefly, I suggest:
1) detail the types of ice (and rock) dynamics in ice caves;
2) present what exactly you were targeting (ice volume changes, ice movement, rocky talus movement) and
3) discuss the results in a climatic perspective.
AC - 1: Originally, we aimed to emphasize the developed method. From our point of view, the ground laser scanning method has brought enormous possibilities for monitoring ice caves, but this does not mean that having a laser scanner is the only requirement for recording the ice volume. A developed methodology of how to scan, when to scan, how to process the acquired point data, how to create surface models and evaluate it are even more important. Based on our best knowledge, we have not found a publication in which a similar approach to the presented sC2C methodology would have been used for monitoring cave floor ice. From this point of view, we believe that the presentation of the methodological procedure is also scientifically beneficial for the community focusing on the cryosphere. On the other hand, we agree that is necessary to link results to climatic conditions. This is addressed in AC – 13 of this document.

Komentár od [S2]: R3C - 2: When discussing ice dynamics, a distinction needs to be made between the dynamics of large (e.g., several meters thick) ice blocks and that of smaller, seasonal ice speleothem. The later respond to day-to-day changes in climatic and hydrologic conditions in caves, whereas the former have a much longer response time (weeks months-years). Also, the dynamics of the former has two different components: ice melting/accumulation and ice flow. The manuscript deals with the long-term melting/accumulation of large ice accumulations

Komentár od [S3]: R3C - 3: The scope of scanning should be discussed in more details, e.g., was the scope to only show that this method is suitable, or was a specific research question being addressed - dynamics in a certain area, dynamics in relationship with position of the ice within the cave, external climatic conditions, possible movement of the ice etc? Also, to improve the quality of the results, I would suggest detailing the types of dynamics and movements that were targeted and discuss the

Komentár od [S4]: R3C - 4: P1, L18: ice in caves is dynamic, rather than the caves being dynamic. The term "cave" could refer to the morphological space (walls), that space plus the air inside, the same plus the biota etc, all with a specific dynamics, on scales ranging from millions of years (walls) to seconds (biota, climate, hydrology); hence calling a cave "dynamic" is somehow incorrect
AC - 4: Accepted and in the revised paper will be replaced. Cave dynamic will be replaced to ice dynamic in the cave.

Komentár od [S5]: R2C - 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 cav

Komentár od [S6]: R3C - 5: P1, L21 delete "the surface of "
AC - 5: Accepted and it will be removed.

inside the ice indicates the composition of the atmosphere at the time of freezing. Biological remains such as pollen, fragments of leaves, and microbial life preserved in the ice provide proxies for reconstructing the palaeoenvironment. Furthermore, ice caves react differently to ~~the~~ climate change, perhaps not as rapidly as the mountain glaciers. Therefore, monitoring the change of ice morphology and ice volume in such caves can improve our understating of past climate and the concurrent climate changes.

Snow and ice formations in caves are classified by many authors by different conditions of formation in the state of origin and by their age (Mavlyudov, 2018). ~~Ice caves occurs s~~Several types of ice formations originate in caves such as icings, ice of lakes, ice in rocks, snowfields, glaciers, ice breccia and hoarfrost. These types of cave ice can be classified ~~B~~based on their age ~~is possible to classify these formations to~~as (i) ephemeral (short-term), (ii) seasonal and (iii) perennial (long-term), i.e. ~~which~~ existing more than one year (Mavlyudov, 2018). In this paper, we ~~deal with~~evaluate the change of ~~the~~ large perennial ice formations ~~that~~ revealing more about the cave environment than the short-term living formations which tend to degrad~~ing~~e after smaller fluctuation of cave temperature. In addition to the chang~~ing~~e of ice formations over time, ~~in some cases it can be~~ice movement can be observed ~~moving~~ in places where it is possible to detect the most active areas of ice flow, melting, subsiding or collapsing. Th~~us~~erefore, we ~~are also~~ focused ~~to evaluate~~on detecting possible movement of ice formations ~~through~~by monitoring objects trapped in the cave ice.

The dynamics of the cave ~~glaciers and ice accumulations~~ice formations was studied by combining various sources of data and methods. Assessment of photographic material has been the most widely used method for monitoring the extent of the ice and its change (Fuhrmann, 2007). The other methods comprise markers distributed and attached on the ice floor and/or cave walls (Pflitsch et al., 2016), geodetic surveying (Gašinec et al., 2014), absolute dating (Luetscher et al., 2007) and drilling (May et al., 2011). Complex monitoring programs of detecting dynamics of the cave ice accumulations ~~dynamics has been built in caves sporadically~~are rare, but some example can be listed, e.g. Perșoiu and Pazdur (2011), ~~(~~Kern and Perșoiu~~,~~ (2013), Kern and Thomas (2014). ~~Complex programs for monitoring the cave ice dynamics were introduced in few cases (Perșoiu and Pazdur, 2011; Kern and Thomas, 2014).~~

Quantifying the changes of ice ~~accumulations~~ formations over a certain period in high spatial resolution can improve understanding of the cave ice formation including factors affecting the accumulation or loss of ice. The challenge is in defining the method by which cryomorphological topography could be recorded fast, repeatedly and reliably. In the last decade, terrestrial laser scanning (TLS) provided opportunity to map the challenging environment of the caves in an unprecedented level of detail (Gallay et al., 2015). TLS is an active remote sensing technique allowing for contactless sampling of the 3-D point positions on the surface of the scene surrounding the scanner with a millimetre accuracy and precision (Vosselman and Maas, 2010). ~~The point density controls the spatial resolution depending on the distance of the surface to the scanner and technical settings of the scanner. It typically ranges between few millimetres at 10-metre distance. Point clouds containing millions of the 3D measurements generated from consecutive scanner positions can be merged and unified in the process of mutual registration based on a common feature in the overlapping areas.~~ Cave surface can be modelled from the point cloud as a 3-D polygonal mesh or a 2.5 raster surface, which was demonstrated in Gallay et al. (2016). Applications of TLS in non-

Komentár od [S7]: **R2C - 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.

Komentár od [S8]: **R2C - 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.

Komentár od [S9]: **R2C - 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.

glaciated caves are diverse comprising the field of geomorphology (Cosso et al., 2014; Silvestre et al., 2014; Idrees and Pradhan, 2016; Fabbri et al., 2017, De Waele et al., 2018), light conditions (Hoffmeister et al., 2014), archeology (Gonzalez-Aguilera et al., 2009, Rüther et al., 2009; Lerma et al., 2010) to increase awareness and tourism (Buchroithner et al., 2011; Buchroithner et al., 2012) ~~etc~~. 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).~~However, use of TLS in ice caves is more challenging for the slippery surface, harsh climate and reflectance of the ice~~ which ~~absorbing much of the laser energy emitted by the~~ infrared ~~scanner (Kamintzis et al., 2018).~~ Gómez-Lende and Sánchez-Fernández (2018) demonstrate potential of (TLS) technology in the mapping of ice accumulations in the caves. Repeat ~~U~~u~~sing~~e of TLS ~~, it is possible to repeat measurements and~~allows for generat~~e~~ing time-series of cryomorphological topographies easily. The suitability of using the TLS method for mapping ice is supported by many works related to monitoring of glaciers and ice~~Examples of using TLS in glaciers and ice~~ (Bauer et al., 2003; Avian and Bauer, 2006; Gašinec et al., 2012; Gabbud et al., 2015; Fischer et al., 2016; Xu et al., 2018). ~~There are also a lot of work focused to evaluate~~A plethora of research papers evaluated snow depth change with ~~different principles~~various strategies ~~of time series~~in mutual spatial registration of time-series with reference points~~and snow depth change~~ (Jörg et al., 2006; Kaasalainen et al., 2008; Prokop, 2008; Deems et al., 2013). ~~Gómez-Lende and Sánchez-Fernández (2018) demonstrate potential of (TLS) technology in the mapping of ice accumulations in the caves. Using TLS, it is possible to repeat measurements and generate time-series of cryomorphological topographies easily.~~ Avian et al. (2018) also addressed this issue with ~~terrestrial laser scanning (~~TLS~~)~~ in the glacier monitoring. Registration of single scan missions was based on 1 scan position and 6 reference points leading to generation of a time-series database. ~~In~~The registration of single scan missions without reference points remains open in case of cave cryomorphological mapping~~, some questions such as registration of single scan missions without reference points remain open.~~ ~~Avian et al. (2018) also addressed this issue with terrestrial laser scanning (TLS) in of the ice surfaces cave, but some questions of registration mutual scan positions remain open.~~

~~In order to a~~Assessment of changes of the ice accumulations ~~changes~~ based on TLS point clouds requires~~,~~ ~~adjustment~~ adjusting and re-locating ~~single~~ measurements of individual missions (point clouds) into a~~n~~ uniform coordinate system ~~is required~~in which the differences between the missions could be compared. For such a purpose, Barnhart and Crosby (2013) used a global coordinate system for TLS point clouds based on the ground control points (GCPs) acquired via Global Navigation Satellite Systems (GNSS). This approach has a~~The~~ disadvantage ~~of this approach is that it is also necessary~~ in the need of ~~to~~ scanning the parts of the cave exterior where GNSS signal is strong enough to obtain the GCPs. Traditionally, a system of stabilized GCPs located in a cave and acquired based on geodetic methods such as tachymetry is used (Gašinec et al., 2014). The placement of the GCPs on the cave floor is not possible in many caves due to the changing ice accumulations. On other ~~side~~hand, placing of the GCPs on the wall of cave at a sufficient height ~~is very demanding and risky~~poses a risk of injury to the surveyor or damage to speleothems. In ~~addition, within~~relation to a long-term monitoring program, the position of the GCPs over a longer time period ~~is~~ can become uncertain ~~due to~~for the frost, water and erosion, that ~~is,~~can move the GCPs

Komentár od [S10]: **R2C - 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.

Komentár od [S11]: **R2C - 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. ...

Komentár od [S12]: **R2C - 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.

Komentár od [S13]: **R2C - 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** ...

Komentár od [S14]: **R2C - 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 ...

Komentár od [S15]: **R3C - 7: P4, L1 I would not stress the harsh environment as a potential factor preventing tachymetry-based studies of ice dynamics. Such methods have been used for decades, and the usage of TLS in caves is more difficult than tachymetry (as show in the introduction and in references therein: : :)**
AC - 7: Speleologists perceive the environment as unpretentious, but it is challenging deploying surveying methods such as tachymetry. For detailed ice mapping with a density of more than 1 point per ...

~~could be shifted~~to another location. For detailed mapping of the cave ice morphology, i.e. ~~mapping~~ with ~~a~~the density o~~f more than~~ver 1 point per square meter, the use of ~~classic~~standard ~~tachymetry~~tachymetric methods ~~is a much~~becomes more tedious and challenging ~~task~~ than comparing with TLS which capable of sampling the ice surface in a contactless fashion.

The presented paper builds on the published ~~experience~~ works and further develops ~~of~~ the methodology of detecting changes in ice accumulations using the TLS. We described an original framework of registration procedure based on selective cloud-to-cloud approach and generating a time~~-~~series database. The novel aspect in the presented method is in using the non-iced (i.e. rocky, exposed) cave ceiling as the stable component of the scanned scene to register the time-series. The ~~novelty~~ scientific contribution is also in the procedure ~~for~~ of deriving a complex 3D cave ~~model~~ surface from point clouds as a 3D ~~using~~ mesh surface model. ~~Based on presented methodology~~By this means, we identified and quantified cave floor ice changes in ~~the~~ ultra-high resolution and we assessed the dynamics of ~~cryomorphological~~ cryomorphology ~~topography using parameters such as~~based on vertical profiles, change of the ice area and volume ~~as well~~.

~~Proposed~~ The applied approach was demonstrated in the case study of the Silická ľadnica ice cave situated in the south margin of the Western Carpathians in Slovakia, Central Europe. The cave is world unique for its permanent ice accumulations formed at the lowest altitude in the moderate climate zone.

2 Area of Interest

The Silická ľadnica cave is one of the oldest well-explored ice caves in Slovakia (Bella and Zelinka, 2018). The cave (Fig. 1) is located in the ~~southwest of~~ eastern Slovakia, in its southwest part where several karst plateaux formed in the Slovak Karst~~on~~. The cave evolved in the Silická planina ~~(Silica p~~Plateau near the state border with Hungary~~.)~~ ~~in the Slovak Karst. The cave is unique for preserving the ice accumulations on the cave floor at the lowest altitude in the world being in moderate climate zone.~~ ~~Droppa () estimated that ice accumulations are in the cave about 2000 years.~~

Komentár od [S16]: R2C - 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.

Komentár od [S17]: R3C - 6: P3, L9 how was the age estimated?
AC - 6: Age of ice in the cave was approximated from Archeological findings by many authors such as Kunský, Roth and Bohm. Their proposal was also accepted by Droppa which mentioned that ice is in the cave 2000 years.

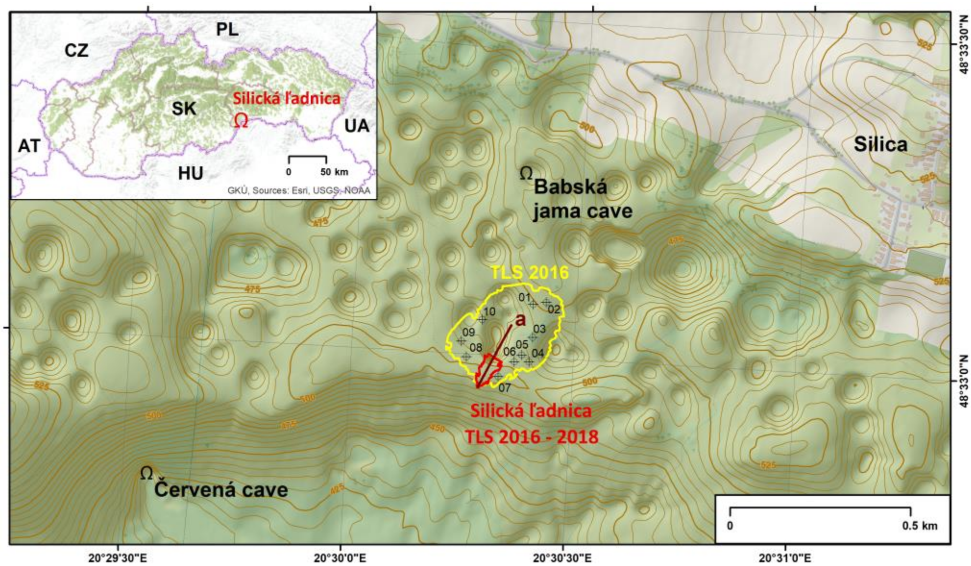


Figure 1: Location of the Silická ľadnica cave. The polygons represent the territory mapped by the TLS method - yellow outline delineates the area of the scan mission 1 in 2016, the red outline represents the area of other scan missions used to build a time-series of TLS data. Contours and shaded relief 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.

~~**Location of the Silická ľadnica cave.**~~

Over the last decades, there ~~has been~~was a significant decrease of the ice, which is particularly evident ~~on the photograph (~~(in Figure~~.~~ 2~~)~~). Ondrej (2014)~~Since 2014,~~ measure the ice surface in 2014 ~~has been measured using~~with a total station and a he generated a map of ice distribution in the cave ~~was produced by Ondrej (2014)~~ (Fig. 3). The sampling density was sparse (a point per square metre) and surveying on the icefall was dangerous. Therefore, we designed a new approach ~~Since 2016, a novel methodological approach~~ using terrestrial laser~~-~~ scanning ~~technology focusing on monitoring a~~to capture the cave cryomorhology in ultra-high resolution and to assess change of ice surface and volume over time. We have tested the method in the cave since 2016 until to date~~was proposed and tested~~.

Komentár od [S19]: **R2C – 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.

Komentár od [S25]: **R2C - 14: Page 3, line 13 –no need for repetition of information from introduction.**
AC: Accepted and removed.

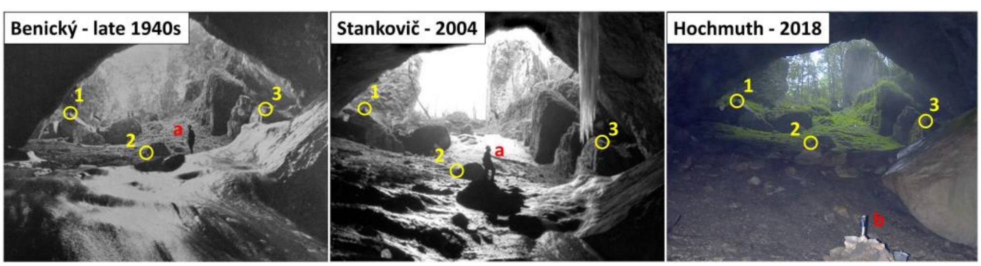


Figure 2: **Photographic evidence of cave floor ice in the Silicka ľadnica cave over the last 80 years. All three photos are captured from approximately the same position (shown in Fig. 3 as a red point A) from inside the cave outward and show different states of cave floor ice. Identical points are 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.**~~**Photographic evidence of floor environment in the Silicka ľadnica cave over last 80 years.**~~

The bottom of the ~~iced~~ glaciated part of the Silicka ľadnica cave ~~(Fig.3)~~ ~~is reachable~~can be accessed from the eastern side of ~~the~~ a debris cone (prolluvial fan) ~~, which~~ form~~s~~ed by a mixture of fine-grain~~ed~~ sediment and ~~a gravel of~~ limestone scree ~~blocks~~. Seasonal ice accumulations cover ~~The~~ the western part ~~is~~ of the cave floor ~~is covered with seasonal ice accumulations~~. The cave ceiling ~~of the cave consists mainly of bare rock~~is formed by the exposed limestone rock with seasonal occurrence of ice stalactites (Fig. 4). In the lower part of the ~~Cave~~ cave bottom, the ice continues further down by ~~passes in lower part through~~ a sharp edge into an icefall with an average slope of 70° (Fig.3). ~~Near of the lower part of the icefall~~ There is a short, 20 m long passage ~~originated~~ formed by paleo-stream near the lower part of the icefall. ~~At the~~The open pit cave closes in the south end of the iced area. ~~is a masked entrance to other cave parts that were discovered by J. Majko in 1931 (Stankovič and Horváth,~~

Komentár od [S26]: **R2C - 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.

~~2004).~~ No permanent or temporary watercourses flow through the described part~~s~~ of the Silická ľadnica cave. ~~Only t~~The infiltrated atmospheric ~~rainwater~~ precipitation is the only source of water reaching cave ~~infiltrated~~ through ~~the~~ cracks of the limestone ~~rock~~ massif~~,~~ creating cave ice formations which location is shown in Figure 3.

Komentár od [S27]: **R2C - 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.

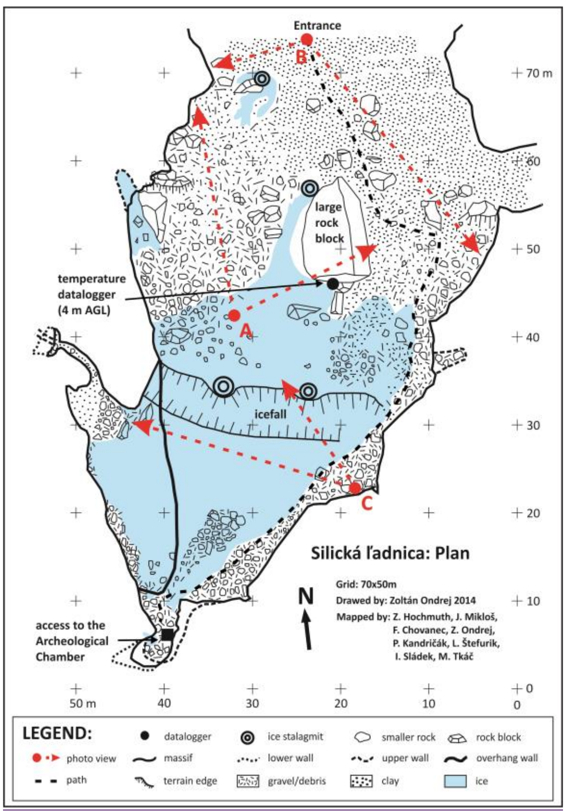
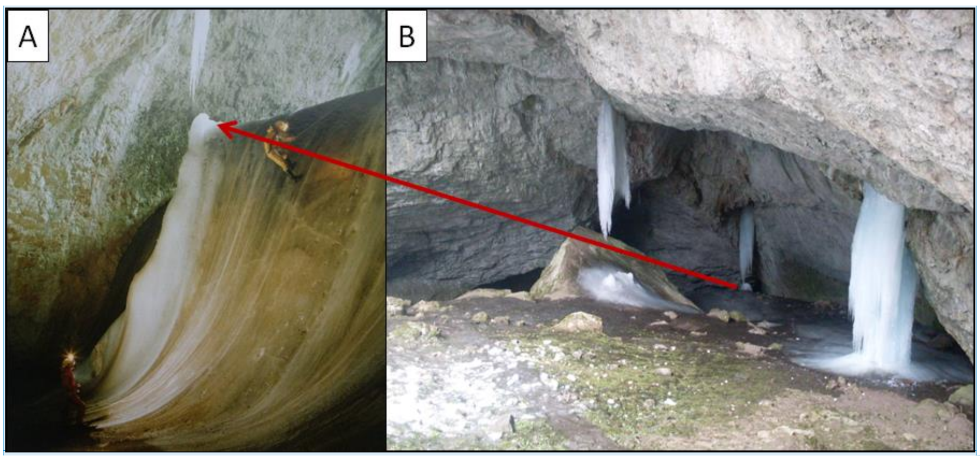


Figure 3: Map of the Silická ľadnica cave floor. The cave is an open pit cave with the entrance approximately 30 m wide and 20 m tall. It is freely accessible to the public from the north by a concrete staircase. Gravel and debris cover the floor mainly in the upper part of the cave near the entrance. 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. There 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 Chamber, 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.~~Plan of the cave modified according to Ondrej, 2014.~~

~~The ice accumulations in the Silická ľadnica cave has a different degree of degradation of vertical ice formations or their remains within the year. For optimal ice formation, the conditions of the slow spring warming are most appropriate, when~~

[illegible]

~~more mighty~~large stalactites, two over the icefall and one in the west side of the cave near the cave entrance. The Silicka l'adnica cave ~~comprise~~ contains ~~of manifold~~other ice formations such as hoarfrost located mainly in the upper parts and~~,~~ ice coatings on the walls of the cave, which usually appear in the lower most parts in the contact with non-~~iced~~ glaciated ~~places~~ parts of the cave ~~and others~~.



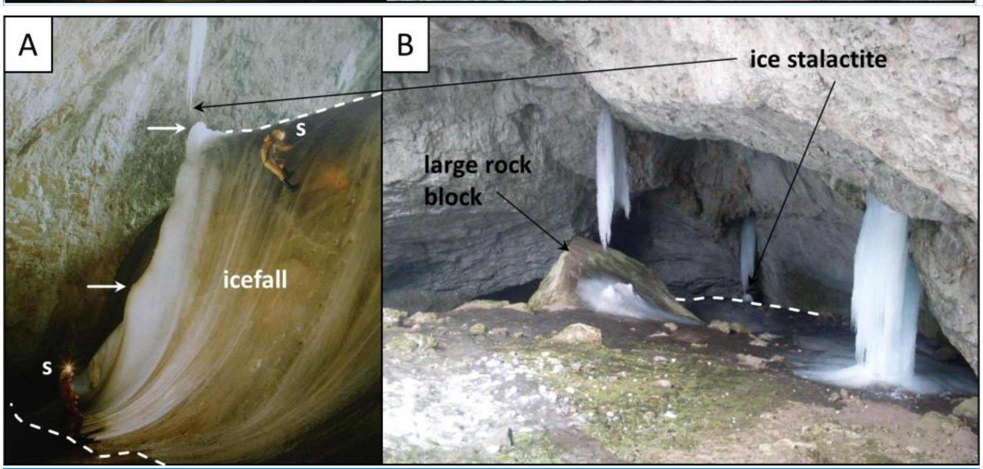


Figure 4: The Silická ľadnica cave contains different types of ice objects. The permanent ice is represented by (A) an icefall (Stankovič and Horváth, 2004) located in the bottom part of the cave. Ice speleothems (B) such as stalactites and stalagmites situated in the upper part of the cave (Ondrej, 2014) are the most dynamic objects with significant seasonal and interannually changes.

Komentár od [S30]: **R2C - 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.

Komentár od [S31]: **R3C - 10: P5, L9: "vertical gravitational ice forms" you mean stalactites?**
AC - 10: Vertical gravitation is meant as all vertical ice speleothemes such as ice stalactites, stalagmites and stalagnates. It will be rephrased in the revised manuscript.

Komentár od [S32]: **R2C - 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.

Komentár od [S33]: **R2C - 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.

R2C - 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.

Approximate size of the icefall 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.~~The Silická ľadnica cave contain 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 upper part of the cave (Ondrej, 2014) are the most dynamics objects with significant seasonal changes.~~

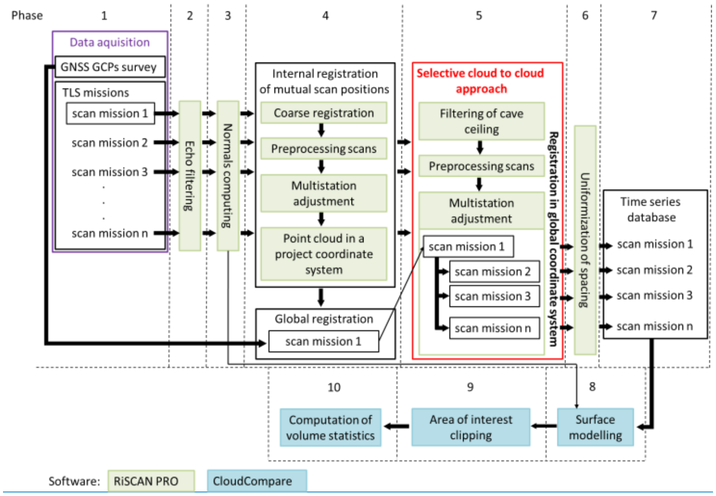
One of the negative influence ~~related~~associated with melting of the cave ice is correlated with the discover~~ing the~~y of ~~-~~Ján Majko in 1931. He found a way through collapse and he entered into the further continuation of the cave (Stankovič and Horváth, 2004). ~~connection to the Archaeological Chamber by J. Majko in 1931.~~ Many prehistoric ~~Chamber was inhabited by prehistoric man, as is evidenced by many~~ archaeological artefacts ~~findings~~ and remains of fire places ~~, whose remains have~~were ~~been~~ found in the deposits on the~~ir~~ bottom of the gallery for which it is called the Archeological Chamber. The brook of Čierny ~~Brook~~potok flows into Archeological Chamber from the south-east and it is hydrologically connected with the Gomba~~sek~~secká jaskyňa cave ~~Cave~~ (Bella and Zelinka, 2018). Gravitational shifting of the debris cone led to the closure of the natural entrance to the Archaeological Chamber blocking the prehistoric people in inhabiting the chamber, but providing ~~when occurs~~ suitable conditions for ~~creation of~~ ice formation in the cave further up towards its current open pit entrance. Nowadays, ~~is~~ the passage between these parts of the cave is kept closed with a hatch and covered by rock blocks to prevent ventilation of the cold air and degradation of the ice. ~~This prevent faster degradation of the ice and conserved cave environment to the former~~Sealed closing of the entrance into the chamber facilitates preservation of the static thermodynamic model of the cave (cold trap). The long-term monitoring revealed that extent of the ice in the Silicka ľadnica cave ~~is not constant but variable in~~varies over short~~er~~ periods ~~relatively~~ (Stankovič and Horváth, 2004). The seasonal ice formations, which are the main source of water for new layers of floor ice fills the cave usually from winter and grow until late spring, when they start~~ed~~ degrad~~e~~ing and re-icing at the lower colder parts of the cave as the floor ice. Permanent ice in the cave is kept only in the area of the icefall, which is replenished with new layers of ice during the summer ~~phase~~, when it reaches its peak volume. ~~and then~~The ice degrades ~~degraded~~ during winter ~~in cause of~~by ~~ablation~~sublimation and transfer of warm air from non-glaciated parts of the cave (Rajman et al., 1987).

~~The entrance of the cave was well-known for locals since ancient times. The first record with plan of the cave is dated to 1719 and it was created by Georg Buchholtz (Bella and Zelinka, 2018). In 1793, R. Townson with J. Teleki and other researchers performed the first temperature measurements (Zelinka, 2005). In this period, many locals were used the pieces of ice from the cave for a cooling of meat and beer. During the years 1863-1867, nearby the cave entrance a small brewery was built and operated (Bárta, 1995). Rajman et al. (1987) contend that this intervention related with brewery had negative consequences to the ice accumulations. E. Terlendayi performed the survey of ice surface in January 1892 and the ice was at the lowest value ever, what is similar to the range of current ice accumulations in the winter season. Other negative influence related with decrement of the cave ice correlated with change of the microclimatic situation of the cave after discovering the connection with the Archaeological Dome in 1931 by J. Majko. After opening the connection between the Archaeological Dome and the Silická Ľadnica cave lead to the inflow of warmer air from the lower non-iced area to the higher iced parts. This phenomenon~~

Komentár od [S34]: **R2C - 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.

is reflected in the ice melting. The long-term monitoring revealed that extent of the ice in the Silická ľadnica cave is not constant but variable in shorter periods relatively (Stankovič and Horváth, 2004).

~~Data acquisition~~The ice cave was ~~undertaken~~ surveyed by a terrestrial laser scanner VZ-1000 by ~~RIEGL~~Riegl to acquire 3D representation of its surface in ultra-high resolution~~ VZ-1000~~.~~It~~ The scanner ~~is a full waveform pulse scanner transmitting~~operates with laser beam in near infrared wavelength (1550 nm) with nominal precision of ± 8 mm at distance of 100 m and maximum scanning range up to 1400 m. It uses online processing of the full waveform enabling multi-target scanning and it improves reliability of surveying in fog dust and precipitation (Pfennigbauer et al., 2014). The ~~Minimum~~ minimum scanning distance of the scanner is 1.5 m. The device dimensions are 0.3 mx 0.2 m x 0.2 m and weigh including batteries is 10 kg (Riegl 2015).



Komentár od [S35]: **R2C - 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.

R2C - 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.

Komentár od [S36]: **R3C - 11: P5, L7-19: this historical paragraph can safely left out. I would discuss in more details the findings of StankovicÌˇN and HorvaÌA¸th, 2004**
AC - 11: Accepted and will be removed.

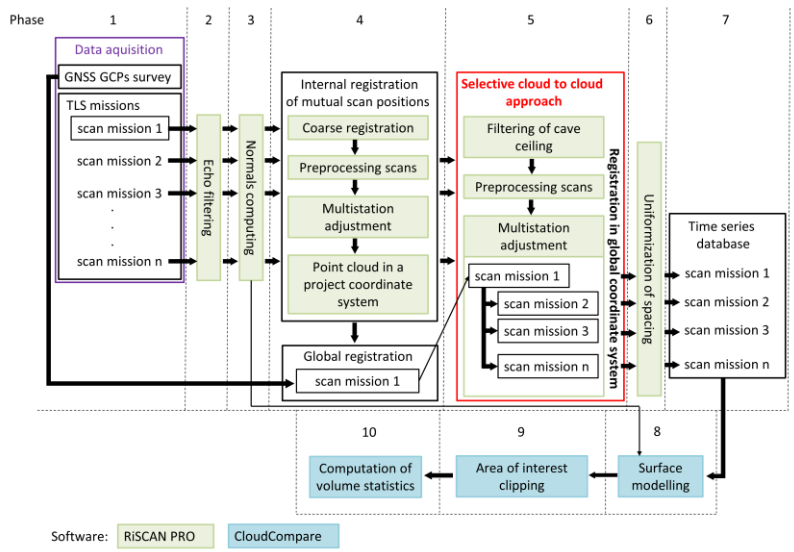


Figure 5: The workflow of generating of time series database and framework of data processing.

The scanner rotates along its vertical axis establishing a full 360 degrees of the horizontal field of view. ~~parameters that allow using the scanner in ice caves despite of dimensions and weight easily.~~ The vertical scanning angle is limited to 100 degrees. ~~disadvantage of using this type of scanner in caves is incomplete vertical scanning range limited to 100 degrees.~~ This means, that from a single scanner position, it is not possible to capture a portion of the view under the scanner in the nadir direction and a part of the ceiling above the scanner in the zenith direction. The data shadows ~~are~~ were eliminated by ~~more frequent~~defining a proper configuration of positions ~~of~~ during the ~~scanner~~ scanning ~~during scanning mission~~in which overlapping point clouds are generated. ~~The horizontal field of vision view has a range of 360 degrees.~~ The ~~D~~data collection by TLS in Silická ľadnica commenced in ~~started since~~ June ~~of~~ 2016. The ~~First~~ first ~~mapping with TLS was~~ campaign ~~focusing~~ focused on ~~the~~ testing the capability of the technology to capture ~~an~~ the cave ice ~~in the cave~~surface. There were six scanning mission accomplished ~~Until~~ by October 2018~~, the sixth series of scanning mission was accomplished~~. The formation of ice and its melting ~~is evident~~was recorded even ~~during~~in this relatively ~~this~~ short period. The ~~change~~ice dynamics was observed by ~~the~~ spelunkers over decades but the advance of TLS ~~has enabled to~~opened capabilities for measuring the change of ice morphology ~~measure it~~ in an ~~high~~unprecedented level of detail. After 2 years of monitoring, it is clear when is the best conditions for mapping. On the other side, we have no uncertainties about the methodology of data collection and processing. The number of scan positions was not unified ~~because a~~ for a ~~placement~~ placing ~~of~~ the scan positions

Komentár od [S37]: **R2C - 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.
R2C - 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.

was determined ~~by~~ mainly by the extend of the floor ice ~~in the cave~~ and ~~(ii)~~ sufficient overlaps to ~~eliminating~~ eliminate shadows in the final point clouds (Fig. 6).

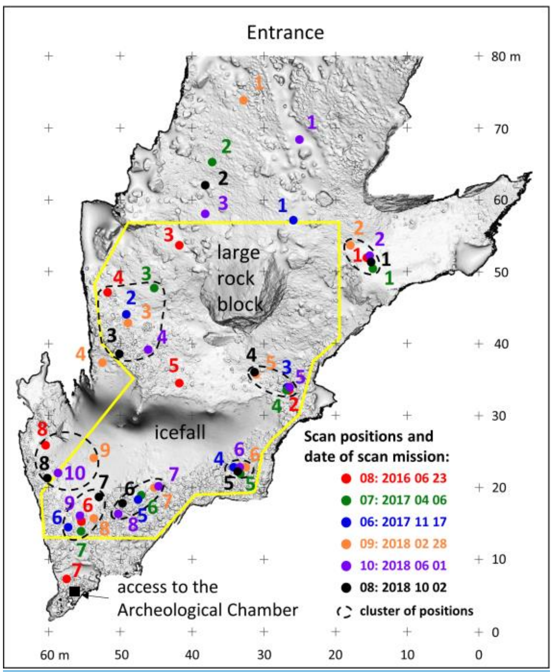


Figure 6666: Distribution of scan positions of individual scan missions located within the S-JTSK (EPSG:5514) coordinate system presented on the plan of the cave derived from TLS mapping. Yellow polygon shows defined AOI for computation of changes in ice accumulation.

There were ~~first mapping mission contains~~ 32 individual scan positions used in the first mapping mission.~~,~~ ~~because of t~~The GCPs were placed in the close ~~, immediate~~ exterior ~~surroundings~~ of the cave ~~were captured as well~~therefore several scan positions were located also in this area (Fig. 5 phase 1). The scan mission 1 ~~have~~ used 10 GCPs for registration in global coordinate systems (Fig. 5 phase 4). Data from ~~All~~ all scanning mission data sets ~~are~~ were registered ~~initial~~ in the national coordinate system S-JTSK (Systém jednotnej trigonometrickej siete katastrálnej ~~– in Eng. System of the Unified Trigonometrical Cadastral Network~~), EPSG code 5514. The GCPs were measured by the global navigation satellite systems (GNSS) ~~methods~~ using the TOPCON HiPER II ~~device~~ receiver with a reference connection to the Slovak observation service - SKPOS. Point measurements were performed for 30 seconds using the real time kinematic positioning (RTK) ~~method~~ via weighted averaging with overall accuracy of the fixed solution between 1-2 cm. The coordinates of the points were calculated by TopconLink software. The standard deviation error of transformation of scan mission 1 in global coordinate system based on the GCPs ~~is~~ was 5.3 cm.

The setting of scan parameters is ~~expressed~~reported differently by individual scanner manufacturers. We worked with 0.04 and 0.06 degrees of angular increment in horizontal and vertical rotation, respectively. ~~During the scan missions, we used the settings of scanning~~These modes are termed Panorama 40 and Panorama 60~~. Using a scanning mode are enable to set some parameters of scanning detail.~~ in ~~The~~ the Riegl VZ-1000 scanner. The increment defines the level of spatial detail captured by the scanner. ~~distributes laser pulse by a rotating mirror. In the mode of Panorama 40, the scanner emits a pulse in the ambient environment every 0.04 degrees of mirror rotation in the vertical direction and 0.04 degrees in the~~ ~~and~~ ~~horizontal direction.~~ The smaller the ~~angle~~increment the shorter is the spacing between the recorded laser pulse echoes at the same range from the scanner.~~,~~ ~~more detailed and higher the number of recordings in the resulting point cloud is captured (~~Table~~.~~ 1~~).~~ summarizes the generated datasets in terms the amount of data and accuracy based on the scanning parameters. ~~Precision of scan mission is dependent on the number of scan positions as well. The most points were recorded within the first scan mission, where we scanned the surroundings of cave. Further scan missions have already been carried out only in the cave in the places of ice accumulations. Therefore, the number of scan positions as well as the number of points are lower compared to the first scan mission. Duration of the scanning at one position with scanner settings of range 450 metres, frequency of 300 kHz and mode of Panorama 60 takes 3 minutes and 50 seconds and with mode of Panorama 40 takes 5 minutes for and 20 seconds respectively. The total scanning time of the first scan mission was approximately 12 hours due to the challenging terrain and the surrounding forest. Using sC2C approach enabled us to perform The second timefollowing scan missions only inside the cave, the thus scanning time did not exceed 3 hours. This Shorter time and less amount of data is acceptable for repeating scanning to capture the ice accumulation dynamics and generation of time series database for long term monitoring of cave cryomorfology. In initial phase of the cave floor ice monitoring, we were 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. 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 (Fig. 6). Based on this testing, we know that in our case minimum of 7 positions with panorama 60 mode are sufficient to scan the cave floor ice.~~

Table ~~1~~1: Characteristics of the time series database.

Date of survey	Number~~o.~~ 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

Komentár od [S39]: R2C - 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.
R2C – 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.

Komentár od [S40]: R2C – 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.

Komentár od [S41]: R2C – 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.

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

Precision of scan mission also depends on the number of scan positions. The largest point cloud was recorded within the first scan mission, where we scanned the surroundings of cave. Subsequent scan missions were focused on acquiring data in the cave in places where the ice formation. Therefore, the number of scan positions and the number of points is lower in comparison with the first scan mission. Scanning at one position with scanner settings of range 450 metres, frequency of 300 kHz and mode of Panorama 60 took almost 4 minutes while the duration of scanning was 5 minutes and 20 seconds with Panorama 40. The total scanning time of the first scan mission was approximately 12 hours due to the challenging terrain and the surrounding forest. Using sC2C approach enabled us to perform following scan missions only inside the cave, thus scanning time did not exceed 3 hours. Shorter time and less amount of data is acceptable for repeating scanning to capture the ice accumulation dynamics and generation of time series database for long term monitoring of cave cryomorfology. In initial phase of the cave floor ice monitoring, we tested various parameters of the scanner settings. The aim was in finding 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. In addition, there are demands for processing and storing data because of their amount. During the two years mapping period, we also identified and optimized the scan positions, which we refer to as the scan position clusters (Fig. 6). Based on this testing, we learned that in our case minimum of 7 positions with panorama 60 mode are sufficient to scan the cave floor ice.

Komentár od [S42]: R2C – 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.

3.1 A framework of registration procedure using TLS data

Data processing consisted of several steps. We used the RiScan Pro software for primary data processing. After importing the individual scan positions into the project, we removed the noise points from ~~single~~ each single scan position. ~~that are problematic for registration.~~The ~~In general, these are points referred to as a noise.~~ ~~N~~noise points occur~~s~~ during scanning in many situations. Ones of them are the impact of a laser beam on water level, or in case of false reflections in places where the laser beam traces the objects inter face. By removing the noise from point clouds of single scan positions in this phase, we improved the registration result based on automatic cloud-to-cloud approach. As noted in Gómez-Lende and Sánchez-Fernández (2018), the noise can be removed manually or automatically. In our approach, we suggest automatic noise filtration using parameters of the order of reflection and deformation of the shape of laser pulse trace. The scanner emits a laser pulse and distributes it to the ambient environment. A laser pulse has a certain shape ~~of trace~~ when it ~~comes to~~hits the surface. The scanner Riegl VZ-1000 is capable ~~to~~ of recording the pulse deformation ~~of the pulse trace~~owing to the online waveform processing of the pulse. This parameter is termed deviation. It is a dimensionless number with values ~~of range~~from 0 to 65,535.

Komentár od [S43]: R2C – 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.

The value 0 indicates that the track has circular (ideal) shape, the value 65,535 represents the shape of the elongated ellipse of the pulse track. we filtered out less accurate measurements caused by the deformed shape of scanner pulse track. In addition, we used only points that represent the first and unique echoes. In this phase, we removed about 35-40% of the points from the point clouds of single scan positions.

The next step was to calculate the normals for points (Fig. 5 phase 3). We recommend performing this step before internal registration of mutual scan positions. The reason is that the direction of normals could be erroneously determined for cave after internal registration because of complexity of shape geometry of the cave. Derivation of normals is required for the generation of 3D model of cave surface (Fig. 5 phase 8). The direction of the normals was calculated to the scanner position. In case of ~~unhomogenous~~irregular distribution of points it is more appropriate to calculate normal vectors with respect to the center of each scan~~ning~~ position than ~~In this step, we eliminated the erroneous estimation of normals of points that could arise within methods based on calculating normals regard to the geometric centre of the point cloud as well as with determination of normals~~ using algorithms ~~via the~~based on ~~analysis of~~ neighbourhood analysis. ~~Finally, the normals of all points are oriented inside the cave.~~

After filtering the points and calculating the normals, ~~there was a phase of internal registration of the~~ mutual orientation of the scan positions followed (Fig. 5 phase 4). It is termed the internal ~~R~~registration ~~of mutual scan positions~~and it was ~~performed within 2~~in two steps. First, the scans acquired within a single mission were coarsely ~~registration~~ registered ~~approach~~ via identical points ~~was used~~identified in the area of the scans overlap. We chose ~~The~~ edges of ~~the~~ rocks on the ceiling and well-recognizable sharp objects ~~such as~~e.g. ~~scratches~~ fault edges ~~were chosen as identical points~~. The ~~Second~~second step involved iterative closest point (ICP) adjustment which is implemented in~~,~~ the RiSCAN Pro software ~~has an integrated~~as the ~~multi~~Multi-station adjustment (MSA) module. The procedure ~~that allows registration of mutual scan position based on~~uses cloud-to-cloud approach to find the closest match of two or more scans (Ullrich et al., 2003). This approach ~~is built on the~~ automatically searches and extract~~ion~~ groups of points ~~of areas defined~~ based on certain parameters. ~~In our case, w~~We used ~~a~~ the method based on filtering planar patches ~~of planes~~. The minimum number of points to define a planar patch ~~Planes were calculated at least from~~was set to 5 ~~points.~~and the ~~Minimum~~ minimum search cube size was 0.128 m. Only ~~areas whose minimum plane error was~~the patches from which the points deviated by less than 0.02 m were used for registration of ~~mutual~~ overlapping scan ~~position~~s. Subsequently, centroids of the planes and the normals derived for them were determined. The registration of two scan positions is based on the assumption that the same areas with the same or very similar ~~normals~~ characteristics of normals ~~planes~~ to the planar patches will be identified as identical within scenes being registered ~~scenes~~. The tolerance of the normals deviation is defined by the parameter of maximum tilt angle which was set to ~~value of~~ 1 degree. Search radius was set to ~~value of~~ 0.5 m. ~~In other words, the identical planes~~Planar patches from two scans are considered identical if their centroids~~to be those that~~ are within 0.5 m ~~far~~ distance from each other (after coarse registration in the first step) and ~~the similarity~~difference of the direction of their normal ~~direction of their~~at centroids does not exceed~~are~~ 1 degree. ~~This way, individual scan positions were registered and a point clouds were generated and located in the local coordinate system. In order to evaluate the increase~~

Komentár od [S44]: **R2C – 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.

Komentár od [S45]: **R2C – 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.

Komentár od [S46]: **R2C – 36 Page 10, line 10 –clarify what 'scratches' are**
AC: Accepted, it will be rephrased.

[illegible] ~~Such a procedure was used~~ [illegible] system.

3.2 Selective cloud-to-cloud approach

The final point clouds from different missions required transformation into a common coordinate system to allow for the assessment of morphologic changes in ice accumulations. ~~We~~ For this propose, we designed an innovative ~~a~~ selective cloud-to-cloud (sC2C) approach to register scan missions into a unified coordinate system (Fig. 5 phase 4). ~~The proposed approach is built on identification of the stable parts of the cave, where there is no increase or decrease in mass. The first step, it is necessary to identify surfaces whose geometry is constant over a time. In the Silická ľadnica cave, the surfaces that are stable~~ [illegible]

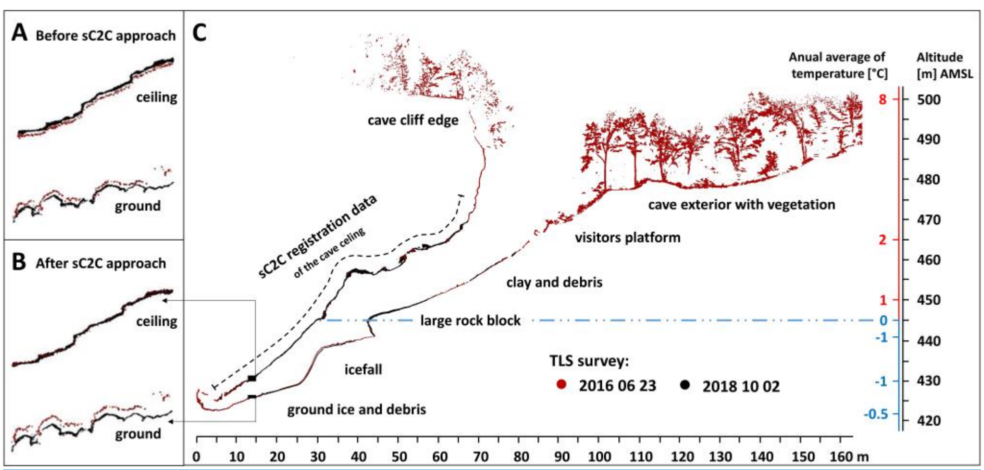


Figure 7: Demonstration of the improved registration accuracy by the sC2C method. Red dots represent the reference point cloud ~~(~~surveyed on 23 June 2016~~)~~. ~~A~~The point cloud surveyed on 2 October 2018 marked with black dots was used to demonstrate the registration result using the proposed sC2C approach. The ~~R~~results of ~~the~~ registering the two scan missions in the detailed views show the performance of (A) ~~before~~the standard C2C approach and (B) after ~~using~~applying sC2C approach ~~are visible in the detailed views. S~~in which stable points of the cave ceiling (C) on the bare rock were used~~, in the sC2C approach.~~ The size of the cave can be estimated from the vertical and horizontal ~~and vertical range of the cave can be estimated from the horizontal and vertical~~ axes which units are in meters. The left side of the vertical axis shows mean annual ~~average of~~ air temperature ~~of~~ inside the cave. The mean temperature is the ~~interior is~~ lowest in the area of the icefall ~~area~~. The ~~average~~mean annual temperature of 0 degrees Celsius is ~~nearly~~just above the icefall indicating the approximate maximal vertical range of the cave floor ice. ~~The range of the cave floor ice can also be deduced from the average annual temperature.~~ ~~Result of registration of scan mission (A) before and (B) after using sC2C approach. For sC2C approach has been used stable points of the cave celling (C).~~

~~The floor ice dynamics in a cave using the TLS method can be captured with a certain degree of accuracy, which is determined~~ [illegible]

Komentár od [S47]: R2C – 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.

Komentár od [S48]: R2C – 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.

Komentár od [S49]: R2C – 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.

Komentár od [S50]: R2C – 40 Page 11, line 5-7 –the last sentence of this paragraph is unclear.
AC: Accepted, it will be rephrased.

Komentár od [S51]: R2C – 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

in the first step. In the Silická ľadnica cave, the ceiling of the cave was considered as the morphologically stable part of the cave where no change of the mass is expected (Fig. 7 C). Certain stable surface features were extracted and they were used to transform the final point clouds for the individual scan missions into a common coordinate system with the using MSA tool. Selecting the points after representing of the ceiling of the cave, we derived the planes and normals of their centroids were determined according to the same parameters as in the phase 4. We argue that for generating a time series of point clouds, this kind of sC2C approach (Fig. 7 B) based on cave ceiling performs better in the automatic registration of individual scan missions than a C2C approach in which the entire scan is used for registration with another member of the time series (Fig. 7A). The point cloud of the reference scan mission was locked and the propagation of errors of identical planes were distributed only at locations that we considered as morphologically stable parts of the cave. By this means, in the registration of time series, we avoided the use of moving objects which did not change their geometry but changed their position or orientation, such as stones floating on the ice surface (Fig. 7 A and B). Thus, the residuals of normals were not dispersed into places that could had been considered similar in shape but not identical in the position. Such approach facilitates surface change detection. Finally, all final point clouds of individual missions were placed in the S-JTSK global coordinate system to enable comparison with other older geodetic measurements.

Laser scanning point clouds typically have~~A~~ heterogeneous spatial distribution of points. ~~is one of the main characteristic of TLS point cloud~~~~technology~~ ~~what is resulting from (i) t~~The first reason is in the very ~~methodology~~ principles of data acquisition for which the point spacing increases with growing distance from the scanner, i.e. the point density per unit area decreases. ~~and (ii) the necessity of registration of mutual scan positions.~~ ~~Both factors are linked because~~Another reason is in the need of spatial overlap ~~s are necessary for registration of~~to perform the mutual registration of scan~~s positions what causes in many redundancies~~. ~~At locations near to the scanner position, the density of the points is higher in comparison to the farter parts from the scanner~~~~. This is because, at the same scanning angle, the spacing of points changes with increasing distance from the scanner.~~ . ~~In addition, higher~~The point density ~~of points is mainly situated in places that are visible from~~increases in the area of overlap causing data redundancy in places that were in the scanner field of view from multiple position~~s, lower density of the points is located in places visible only from one position~~. ~~High~~ The marked variability spatial distribution of the points ~~spatial distribution~~ within point clouds ~~causes problems especially for~~complicates interpolation ~~functions~~ of digital surface models and modelling ~~of~~ derived surface parameters (Gallay et al., 2016). This ~~problem~~ complication can be solved by making the distances between points more uniform~~ization of point spacing – the distances between points~~ (Fig. 5 phase 6). We used 0.005 m of spacing ~~for reduction~~to decimate original point clouds which reduced~~. It leaded to decrement of~~ 60 % of points without ~~impact to~~marked decrease of spatial ~~resolution of~~detail captured in the final surface model~~ (Fig 8)~~. Homogenization of the point distribution was performed using Octree tool implemented in RiSCAN Pro software. ~~IIn the places with a lower point density is the same distribution of points in comparison with original input dataset. On other side in places with high point density (more than 7000 points per square meter) we reduced the number of points and we homogenized spatial distribution of the final point cloud.~~ By removing redundant points, we obtained a spatially homogenized input point cloud for the calculation of cave surface models.

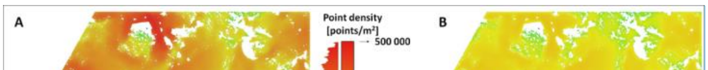
Komentár od [S52]: R2C – 38 Page 10, line 27 –29. Do the areas of the cave with stable geometry have ice covering them? Are they areas of bare rock? This needs to be clarified in the area of interest section in the cave description.
AC: Accepted, the ceiling of the cave consists mainly of bare rock. This sentence will be explicitly inserted in chapter 2 and reference will be made to Figures 2 and 4.

Komentár od [S53]: R2C – 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.

Komentár od [S54]: R2C – 40 Page 11, line 5-7 –the last sentence of this paragraph is unclear.
AC: Accepted, it will be rephrased.

Komentár od [S55]: R2C – 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.

Komentár od [S56]: R2C – 43 Page 12, line 8 –this sentence does not make sense.
AC: This sentence will be revised or omitted.



3.3 Deriving complex 3D cave model from point clouds using mesh model

Comparison of the cave floor ice over time requires a time series of surface models derived from point clouds representing floor of the cave. The cave has a very complex geometric structure with floor, ceiling and perpendicular walls and therefore some classical bivariate functions hit to their limits and cannot be fully applied for modelling of the cave morphology. Common used classical bivariate functions in GIS ~~Traditionally, functions~~ designed for modelling terrain, which general formulation is $z = f(x, y)$ working only in 2D space, ~~are widely used~~when only one z coordinate for repeating pairs of coordinates (x, y) can be computed. ~~.~~ On other side, for surface modelling it is only possible to use bivariate functions, but with a local search radius in 3D space (Gallay et al., 2016) what allow us to generate complex 3D surface models. Space of input data is temporarily voxelized and bivariate functions are used to find a suitable surface. The result of proposed modelling approach is still a ~~two-dimensional~~2D surface (plate) which is located in ~~three-dimensional~~3D space. Thus, the bivariate functions with general form $z = f(x, y)$ does not apply to the whole dataset in 2D space ~~-~~but only locally in 3D space fragmented to e. g. for a cube with defined side length which allow us to avoid conflicts in computation of z coordinates. There for, we used a vector-based mesh modelling approach to create the surface of the cave floor, which makes it possible to model such complex shapes. Ones of the key input for calculation of mesh are vector ~~-~~normals of the points that have been derived in phase 3 for each scan position individually. We used the Poisson surface reconstruction (PSR) interpolation method (Kazhdan et al., 2013) implemented in the open-source software CloudCompare (Girardeau-Montaut, 2018). This global method using B-spline was chosen because it combines the advantages of global and local surface reconstruction methods without creating jagged polygons in phase of segments joining. Using the coordinates of input points in the form of control vector fields and normal vectors, PSR defines an indicator function to solve Poisson equation at multiple octree levels. Which result to derivation of iso-surfaces for individual fixed depths, their values are used in last step to reconstruct resulting 3D watertight surface. The generated cave surface model by PSR is dependent on several parameters. Spatial resolution of the 3D cave surface model is controlled by Octree parameter. It is a dimensionless number used for fragmenting the space defined by the range of input data. Octree 1 means that the space of input data range is fragmented to 8 cubes, which is identical with the bounding box cube of input data. Octree 2 means that each cube from the previous step is divided into 8 smaller cubes. Thus, 64 smaller cubes are generated. In general, for calculation of the resulting fragmentation of input data range is valid the formula $8^{(\text{Octree Parameter})}$. In our case we used the value of Otree 13, where by the whole space of input data range was fragmented to 8^{13}(549.755.813.888) cubes, which represents a spatial resolution of 0.0054 m. At the respected point spacing resolution of generated point clouds (Fig. 5 phase 6) without additional generalisation of the 3D cave model. We were used a high resolution of Octree parameter, because other parameters such as samples per node and point weight did not have a significant effect on a quality of final 3D cave models. The parameter of full depth, we set the value of 8, which represents a cube with an edge size of 0.1714 m. By this parameter, the spatial resolution of triangles for parts of the 3D cave model in places with lower density of point distribution is set ~~(Fig.~~

Komentár od [S57]: R2C – 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.

Komentár od [S58]: R2C – 46 Page 12, line 16 –this sentence does not fit here and is unnecessary.
AC: Accepted, it will be removed in the revised version.

Komentár od [S59]: R2C – 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.

Komentár od [S60]: R2C – 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.

~~8)~~. The lower density of point distribution is located in the icefall, where the highest point-to-point distances reaching 0.15 m. Thus, parameter of the full depth helps us to regulate and limit creation of longitudinal triangles.

Creating after the 3D cave model, it was necessary to cut the area of interest (AoI) (Fig.5 phase 9). The area of interest we considered places on the floor of the cave, where we expect the occurrence of visible and buried floor ice. Seasonal ice coating on the walls and hanging from the ceiling were not included to the computation. We argue that all seasonal ice coating in the cave degraded and replenished cave floor ice. ~~The~~ For better visualisation and understanding of ice dynamics, we have extended the polygon to the nearest surroundings. Area of AoI polygon projected orthogonally to the flat defined by x and y axes is 1.2~~,0~~00 m^2. This step is necessary to do after 3D cave modelling (Fig. 5 phase 8), because due to the interpolation function there is deformation on the model at the border of AoI (border effect). We used a segment tool implemented in CloudCompare software to cut the models based on AoI polygon.

The resulting truncated 3D floor cave models were subtracted from each other and calculated volume changes (Fig. 5 Phase 10). To calculate volume of changes, we used the M3C2 tool (Lague et al., 2013) implemented in the CloudCompare software. This tool using normal vectors and compute oriented differences of distances between 2 datasets which was used to calculate volume change. Differences between 3D floor cave models within time series database were expressed by ~~profile cartographic method~~ cross sections and arrows representing movement of objects (~~Fig. 9~~Fig. 8), ~~gradual~~ seasonal and ~~inter-seasonal~~annual changes via surfaces derived from the differences of distances approach (~~Fig. 10~~Fig. ~~9~~10) and numerically (Tab. 2).

4 Results and Discussion

In this paper we introduce a new approach of time series creation using TLS missions using the sC2C approach. This approach is characterized by the fact that no targets, markers or stabilized points are needed in the research area to place individual scan missions in a single coordinate system. As detailed in the methodology of this article, those parts of the cave that are stabilized are used to place the individual scan missions in a common coordinate system. In our case it is the ceiling of the cave.~~Using TLS and sC2C approach leading to generation of time series database of measurements, cave floor ice dynamics could be evaluated.~~ We decided to analyse then by two methods such as overlapping cross sections (Fig. 8~~Fig. 9~~~~Fig. 8~~) and calculating volume changes based on differences of distances using 3D floor cave models (Fig. 10) with interpretation due to precipitation and temperatures during monitored period (Fig.9)~~. Based on the profiles of the cave floor, we can conclude that the dynamics of surface in the monitored period was~~ considerable ~~significant~~.

4.1 Detection of floor ice dynamics and analysis of its movements~~Detecting cave floor ice dynamics using cross sections~~

One of the easiest options for detecting floor cave ice dynamics is to overlay the cave floor cross-sections as shown in Figure ~~9~~8. This approach for analysing the change in ice cave requires the location of individual measurements in a common coordinate system. ~~In this paper we introduce a new approach of time series creation using TLS missions using the sC2C approach. This approach is characterized by the fact that no targets, markes or stabilized points are needed in the research area to place individual scan missions in a single coordinate system. As detailed in the methodology of this article, those parts of~~

Komentár od [S61]: R2C – 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.

Komentár od [S62]: R2C – 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.

Komentár od [S63]: R2C – 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.
R2C – 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.

Komentár od [S64]: R2C – 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"

Komentár od [S65]: R2C – 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 ...

We evaluated the quality of the placement of individual scan missions in a common coordinate system based on (1) the calculation of the standard registration error and (2) the visual check on the overlapped vertical cross sections that represent point clouds from each scan missions.

The calculation of the standard deviation error of registration was presented in Table 1. The internal registration of scan po~~s~~sitions within individual scan missions ranged from 3.5 mm to 5.0 mm. To compare the quality of internal registration, we used the same parameters in the plane patch filter for all scan missions. We reached the lowest standard deviation error of internal registration in the summer of 2016. This was because up to 24 positions were located in external parts around the cave, where the reflectivity of objects was higher, thus achieving better scanning quality. Although the number of scan po~~s~~sitions was higher, the internal registration error was lower because the higher errors achieved in the cave at ice locations are masked by the lower errors achieved in the exterior parts of the cave, thus the overall standard deviation error is lower. This consideration can also be supported by the measurement of 06/04/2017, where there was a significant loss of ice. Thus, the reflectivity of the objects was higher, which resulted in a lower internal registration error. On the other hand, the highest internal registration error was achieved in the measurement in which new ice increments were recorded. It was a measurement from 20/02/2018. However, during all measurements, we achieved satisfactory results with internal registration. Using the sC2C approach, we have achieved an acceptable Standard deviation of global registration, which ranges from 4.0 to 4.5 mm (Tab. 1).

The floor ice dynamics in a cave using the TLS method is captured with a degree of uncertainty, which is determined by the device error ($E_{instrument}$) and the error of registering individual scan positions ($E_{registration}$). One of the advantage of the proposed sC2C method is that there is no accumulation of errors due to errors in other measurements, such as GNSS (E_{GNSS}) measurements and Global Coordinate System registration error (E_{GCS}). The total error (E_{Total}) of the proposed method can be calculated using a modified equation (1) by Collins et al. (2012):

$$E_{Total} = \sqrt{E_{instrument}{}^{2} + E_{registration}{}^{2}} \qquad (1)$$

In our case, we used the Riegl VZ-1000 for mapping, whose $E_{instrument}$ is defined by the manufacturer and is 0.008 m. The highest standard deviation error of global registration has been reached for the measurement of 02/10/2018 and has a value of 0.0045 m. The total error E_{Total} is ± 0.0092 m, which is a threshold for recognizing the changes between measurements. Thus, changes in point clouds of less than 0.0092 m cannot be interpreted as a change in the cave ice, as this may be an error propagation of the device and registration.

We also evaluated the quality of registration of the scan missions in the common coordinate system by visual inspection. The best way to evaluate registration quality is through visual inspection on profiles where the cloud points from each scan missions are rendered by unique colour. During the check we observe the course of point clouds, whether double surfaces of identical objects arise. In Figure 7 (B) it can be seen that the registration of scan missions by applying the sC2C approach achieves excellent ceiling performance, but there are larger variations on the floor of the cave. Based on a more detailed view of the cave floor presented in Figure 8 (B), we conclude that the use of the sC2C approach is equally successful on the cave floor, except that the cave floor has changed in some places due to ice loss or accumulation. Ice dynamics is not the same in all locations. The biggest ice dynamics can be seen in the middle of the profile, which is related to the shape of the icefall.

The convergence of profile lines (areas where the lines become closer together) is not as observable as in a foot of the icefall (Fig. 8 a), because there is a mechanically conditional movement of the material by cavemen walk. On Fig. 8 c, it is possible to observe a random arrangement of the cross sections above a flat stone with converging character. We argue that based on profile lines analysis is possible to detect area of ice occurrences in the cave. The locations of cross sections divergence (areas where the lines are farther apart) can be considered as the occurrences of cave floor ice, which may be cover by the sediment of a clastic unsorted material. This indicate the occurrences of buried ice.

A virtual tour of the cave as well as a visual inspection of the quality of registration of individual scan missions can also be done through a Potree-based web application (Schuetz, 2016), which enables interactive work with scan point clouds of scan missions, for example creating vertical profiles in optional direction, measurement of distances or changing amount of rendered points. This web application contains time series database, which will be continuously updated by newer scan missions aiming to document the cryomorphologic changes of the cave floor in the long term perspective. The web-based interactive application is available through this **link**. For demonstration, we selected cross-section passing through identical cave sites and across the cave floor. The line crosses different types of morphological structures such as stone debris, icefall, subsurface floor ice, and stable elements such as large rocks attached to the subsoil structure (Fig. 8 A).

~~All cross sections were led through identical cave sites and passed across the cave floor to represent different types of morphological structures such as stone debris, icefall, subsurface floor ice and stable elements such as large rocks attached to the subsoil structure (Fig. 9 A). A unique colour was assigned to each cross section by mapping dates (Fig. 9 B). The floor cave ice dynamics are demonstrated in selected details of cross sections showing three parts of the cave floor. The first part (Fig. 9 a) represents a foot of the icefall located in the lowest part of the cave, where a transition between the rocks connected with the subsoil structures and the stone debris with subsurface floor ice is situated.~~

Komentár od [S66]: **R2C – 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.

Komentár od [S67]: **R2C – 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.

R2C – 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.
R2C – 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.

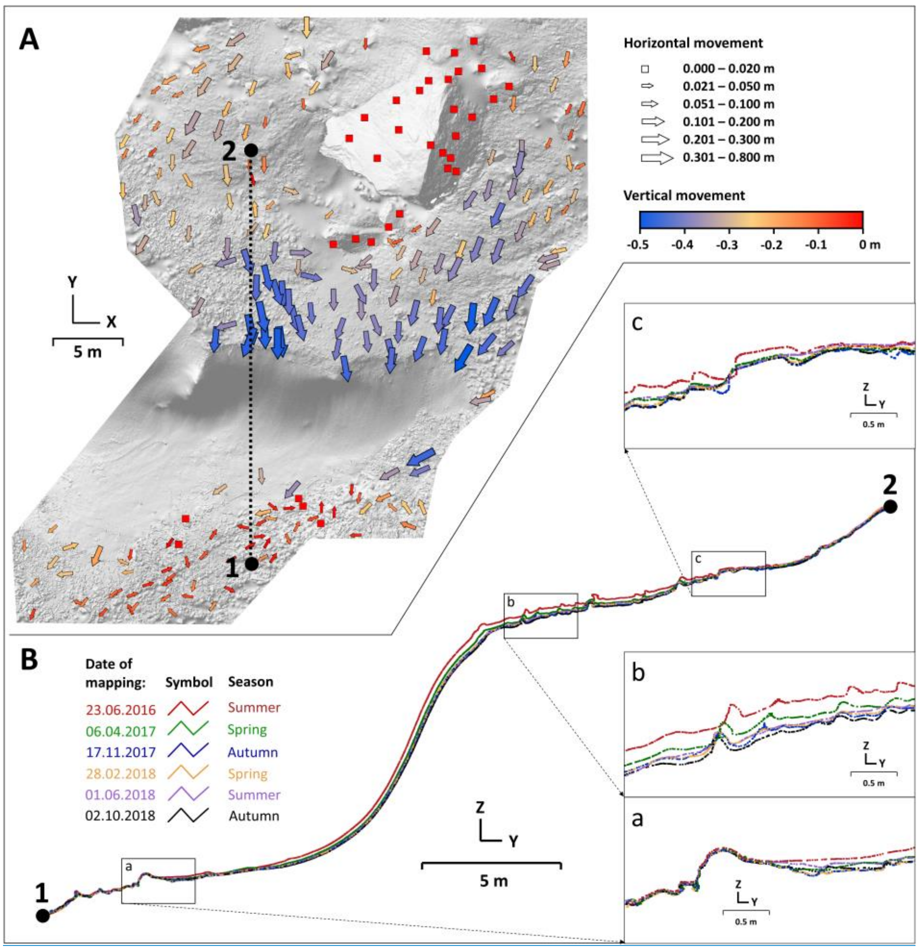


Figure ~~88~~89: (A) Top view of the AoI portraying cave floor model with the dotted line indicates the place of vertical cross section. The arrows indicate the direction of ice movement. The size of the arrow reflects the length of movement in the horizontal direction and the colour expresses the length of movement in the vertical direction. Squares represents the places with no detected movement. (B) The overlaid cross sections represent the cave floor coloured by date of TLS mappings. Changes of the iced part of the cave floor are visualised in selected details. The details represent (a) a foot of the icefall, (b) a place of the most visible changes of the cave floor ice and (c) the highest occurrence of the floor ice in the cave in contact with stone debris.~~Top view of the AoI portraying shading 3D cave floor model with the red line indicated vertical cross sections. (B) Dynamics of the cross sections representing the cave floor coloured by date of TLS survey. Details of selected parts of the cross sections representing (a) a foot of the icefall, (b) a place of the most visible dynamics of the cave floor ice and (c) the highest occurrence of the floor ice in the cave in contact with stone debris.~~

~~The convergence of profile lines (areas where the lines become closer together) is not as observable as in a foot of the icefall (Fig. 8 a), because there is a mechanically conditional movement of the material by cavemen walk. On Fig. 8 c, it is possible to observe a random arrangement of the cross sections above a flat stone with converging character. We argue that based on profile lines analysis is possible to detect area of ice occurrences in the cave. The locations of cross sections divergence (areas where the lines are farther apart) can be considered as the occurrences of cave floor ice, which may be cover by the sediment of a clastic unsorted material. This indicate the occurrences of buried ice.~~

~~The second part (Fig. 9 b) shows the location with cave floor ice accumulations. On the cross section it is possible to identify rocks that seem to float on the ice surface. Their shape does not change, only their positions. The tendency of the rocks movements is in the direction of gravity to the lower parts of the cave. The third part (Fig. 9 c) there is again a stone debris passage of transitions between iced and not iced parts of the cave. A convergence of the cross sections is not as pronounced as in a foot of the icefall (Fig. 9 a), because there is a mechanically conditional movement of the material by cavemen walk. On Fig. 9 c, it is possible to observe a random arrangement of the cross sections above a flat stone with converging character.~~

The results of the repeated terrestrial laser scanning based on the sC2C approach revealed changes of the ice surface and defined areal and volumetric changes. When evaluating and interpreting ice formation and dynamics of ice accumulations, it is necessary to support results by meteorological measurements of temperature and precipitation (Fig. 9). The meteorological data were recorded by the official meteorological station in the Silica village located about 5 km east from the cave. The data on air temperature from the interior of the cave is from an automated datalogger, which is located in Figure 3.

The mean daily air temperature from the Silica weather station ranged from -15° C to + 28° C throughout the monitored period. The highest temperatures were in summer, when the daily mean temperature did not drop below 12° C. The lowest mean air temperatures occurred in winter, when their values oscillated around 0° C and only sporadically rose above 5° C. The monitored period was above the long-term average in comparison with the mean daily temperatures of the previous 30 years. Below-average daily temperatures occurred in two instances. It was the autumn 2016 and the subsequent winter 2017 and winter 2018 during the winter-spring transition.

Komentár od [S68]: **R2C – 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".

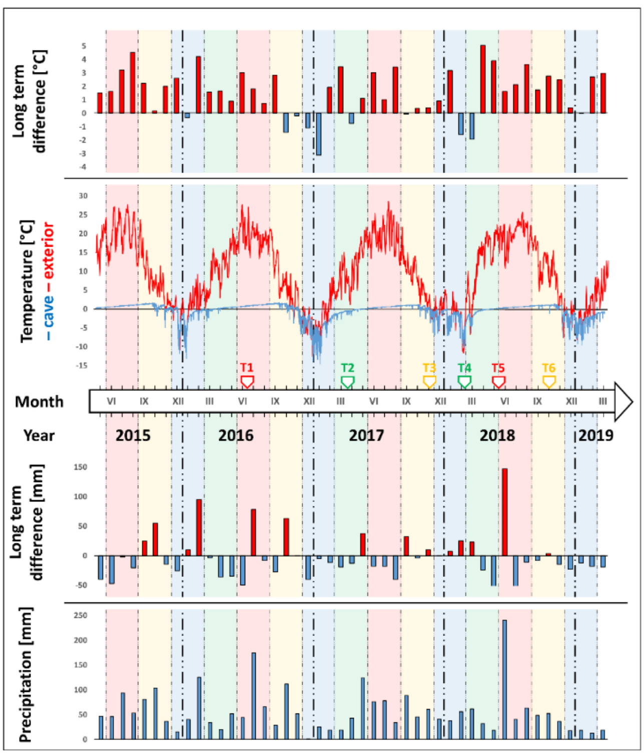


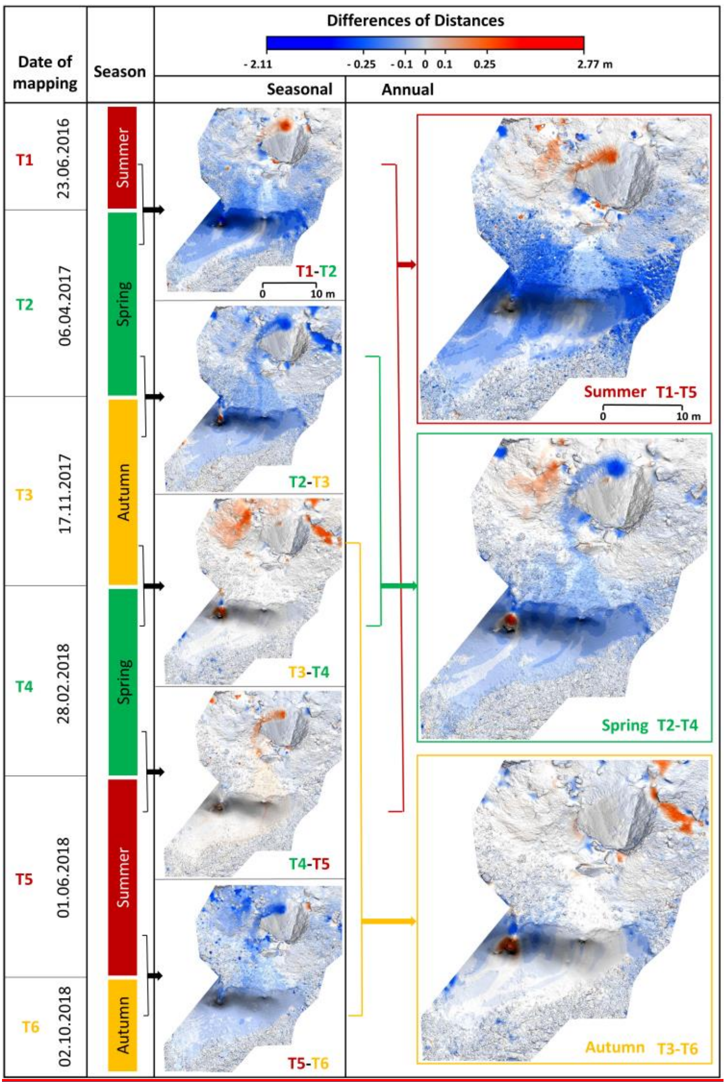
Figure 9: The figure shows the long-term running of daily mean temperature (above the timeline) and precipitation (below the timeline) and their deviations from the long-term average. The timeline shows the dates on which TLS mapping was performed. The background colours of the graph show the season (red - summer, yellow - autumn, blue – winter, green – spring). The bold dashed lines are the separator of years. Source: Data supplied by SHMÚ (2019) and own measurements.

Based on the analysis of mean daily temperatures inside the cave we can identify the 3 phases described by Rajman et al. (1987) following the annual cycle of ice formation in Silická ľadnica: the winter, transitional and summer phase. The winter phase occurs at a time when the ambient air temperature drops below 0° C and the temperature in the cave decreases until it reaches a warm minimum. In the case of the Silická ľadnica cave, the first cold air enters the cave from mid-autumn, when the first ground frosts occur. Although minus temperatures do not appear on daily averages, short-term fluctuations are evident in the cave. However, due to the temperature of the rock, this cold air is not maintained for a long time. In the later autumn period, the ambient air temperature is already approaching 0° C, which is also reflected in the gradual lowering of the temperature in the cave, because cold air inlets of daily temperature lows are more frequent. In the winter months the cave cools and freezes.

Since the water is in a solid state during this period, the ice in the cave is not renewed but the sublimation of the ice occurs. At the end of winter with the onset of spring, there is a transitional phase in which the greatest amount of ice is formed. The temperature of the cave is low after winter, but water in the surrounding environment is in a liquid state and flows into the cave where it freezes. The onset of the summer phase of the cave occurs in the second half of spring, when the internal temperature of the cave gradually rises above 0° C, mainly due to higher temperatures of the external environment and due to the penetration of warm water from precipitation into the cave. Thus, the formation and ablation of cave ice is influenced by precipitation, which is a source of water (Perşoiu and Pazdur, 2011). The graph of monthly cumulative precipitation (Fig. 9) indicates that the precipitation was mostly below average during the whole monitoring period. Precipitation in June 2018 seems to be a significantly above average. However, there were only two precipitation events with a short-term but intensive precipitation (summer storms). The situation was similar in July 2016.

For the formation of ice in the cave, the inflow of water into the cave during the transition phase (the end of winter and the first half of spring) is important. The rock and ice in the cave are cooled enough below 0°C during this period. If the inflow of water is sufficient, it has a significant effect on the increase of the amount of cave ice. Most of the ice mass in Silická ľadnica is found on the icefall. However, the recovery of ice on the icefall is gradual. The first stage involves formation of vertical ice stalactites (Fig. 4B). After melting, degradation or collapse the stalactites become the source of water for the formation of ice accumulations on the icefall. The equilibrium between the ice accumulation rate during different climate conditions is controlled by a complex interplay between the climatic factors that control the mass balance of ice, i.e., wet vs. dry summers and/or winters and cold vs. warm summers and/or winters (Perşoiu and Pazdur, 2011). Ice increments in the Silická ľadnica occur mainly during the transition phase. During the summer and winter phases, there is a loss of ice. In the summer phase, the melting of ice is due to the higher temperature of the ambient air and warm penetrating water into the cave. Ice degradation in winter is mainly caused by ice sublimation. It is precisely this principle of ice formation and ablation in the Silická ľadnica that can be better described based on the time series of the TLS scan missions using the differences in the distances (DoD) (Fig. 10 and Tab. 2). Seasonal comparison of surface dynamics (Fig. 10 Seasonal) demonstrates that there is a constant change in ice volume (Tab. 2). Thus, the ice in the cave is constantly increasing or decreasing between time periods.

The biggest ice volume was recorded at the beginning of the monitoring in June 2016, as much water entered the cave due to above-average precipitation from the end of winter and early spring of 2016 (Fig. 9). Interestingly, the temperature in the cave at the turn of winter and spring 2016 was higher compared to the same period in spring 2017, but there was less ice in the cave (Fig. 9 and Fig. 10). A similar meteorological situation was repeated at the turn of winter and spring 2018, although the amount of precipitation in this period was less than in spring 2016. Between summer 2016 and spring 2017 (Fig. 10, T1-T2) on icefall, while ice increment can be seen on large stone block in middle of cave, where water dripping from vertical ice hanging from ceiling formed ice accumulations (Fig. 4B). This phenomenon always occurs in the spring when the water from the melting snow and spring rains passes through the cracks into the frozen part of the cave. ~~Volume changes can be better evaluated based on differences of distances method (DoD) (Fig. 10). Gradual comparison of surfaces dynamics (Fig. 10 Gradual) demonstrates that there is a constant change in ice volume. Thus, the ice in the cave constantly increases or decreases between time periods.~~



Differences of Distances
- 2.11
- 0.25
- 0.1
0
0.1
0.25
2.77 m
Date of mapping
Season
Seasonal
Annual
T1
23.06.2016
Summer
T2
06.04.2017
Spring
T3
17.11.2017
Autumn
T4
28.02.2018
Spring
T5
01.06.2018
Summer
T6
02.10.2018
Autumn
T1-T2
0
10 m
T2-T3
T3-T4
T4-T5
T5-T6
Summer T1-T5
0
10 m
Spring T2-T4
Autumn T3-T6

Figure ~~910~~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.~~Differences of distances (DoD) between the individual cave floor surface models. The blue colour represents decrease and red colour indicates increase of the volume.~~

A similar phenomenon can be seen in Fig. 10 T4-T5. Another phenomenon is the collapse of the glacial stalactites that we caught before the autumn (Fig. 10 T3-T4). So it is not in the true sense of increment of cave ice volume, but the destruction of the original ice drops hanging from the ceiling. During the summer and autumn ice degradation and winter it is possible to observe the seasonal minimum in the volume of cave ice (Fig. 10 T2-T3 and Fig. 10 T5-T6).

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, white 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).

~~Naturally, the question arises as to what is causing the loss of ice accumulations in the cave and whether there is irreversible year-on-year loss of ice accumulations. To be able to qualified answer this question, it is necessary to continue in monitoring of cave ice and other factors such as temperature, precipitation as well.~~ However, based on the presented analysis, we can conclude that the assessment of floor cave ice dynamics in terms of overall trends is only possible to observe through a season-on-season comparison between the same periods, e.g. between summer or spring seasons over a longer time period (Fig. 10 Seasonal).

A ~~significant~~ considerable loss of ice ~~accumulations~~ formations volume has been seen in Fig. 10 T1-T5, which demonstrates the rapid decrement of ice between summer 2016 and summer 2018. DoD was calculated with respect to the z-axis, so there is a ~~significant~~ considerable drop in surface, even more than 2 m. However, it should be interpreted that if the ice on a steep icefall with a slope more than 70 ° falls 0.2 m in a direction perpendicular to the slope of the profile, the difference in z-axis (height) for a place with the same x and y coordinates can reach 2 m, which is visible from the comparison of individual cross sections (Fig. 8~~9~~ B and Table 2 Max. Decrease).

The red colour shows the increment in two places, which were demonstrated in Fig. 4. The increment in the massive rock in the middle of the cave was caused by the destruction of the glacial stalactite. The second distinctive height increment is located on the icefall in the form of stalagmite, which is formed from dripping water from the shrinking stalactite hanging from the crevice in the cave ceiling, as described above. Another inter-seasonal comparison between spring 2017 and spring 2018 (Fig. 10 T2-T4) indicates a year-on-year loss of ice. In the case of DoD between autumn 2017 and autumn 2018 (Fig. 10 T3-T6), there is no ~~significant~~ considerable decrement or increment of ice accumulations. We can conclude that the ice volume is comparable between these periods, so, it is stabilized.

Komentár od [S76]: **R2C – 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.

Komentár od [S77]: **R2C – 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.

Komentár od [S78]: **R2C – 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:

Komentár od [S79]: **R2C – 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.

The biggest benefit of the created time series database of complex 3D surface model is also in the quantification of the volume changes of the cave floor ice and its expression through summary numerical statistics (Table 2).

Given the total error of E_{Total} 0.0092 m and the area of observation of 1,200 m^2, it should be emphasized that a volume of up to 11.04 m^3 may be the result of a measurement error. The highest difference in ice volume was observed at the beginning of the monitored period between summer 2016 and spring 2017 (Fig. 10 T1-T2) and spring 2017 and autumn 2017 (Fig. 10 T2-T3), when a total ice loss was approximately 70 m^3 in both cases (Tab. 2).

Table 2: Summary statistics of volumetric and vertical changes of the selected cave floor extent during the monitored period.

Differences of distances (DoD)	**Type**	**Total vol. change [m^3]**	**Increment of volume [m^3]**	**Decrement of volume [m^3]**	**Avg. change of surface [m]**	**Max. increase [m]**	**Max. decrease [m]**
T1-T2	~~gradual~~Seasonal	-73.20	13.76	86.96	-0.060	1.20	1.59
T2-T3	Seasonal ~~gradual~~	-67.03	07.18	74.21	-0.054	2.52	1.38
T3-T4	Seasonal ~~gradual~~	32.35	41.57	09.22	0.027	1.30	0.96
T4-T5	Seasonal ~~gradual~~	~~05~~31.~~70~~74	~~32~~39.~~75~~99	~~27~~08.~~04~~25	0.~~003~~026	2.14	0.89
T5-T6	Seasonal ~~gradual~~	-~~42~~66.~~85~~03	~~16~~03.~~46~~45	~~59~~69.~~31~~48	-0.~~031~~054	2.77	2.11
Summer T1-T5	~~seasonal~~ Annual	-~~102~~75.~~13~~79	~~15~~17.~~17~~91	~~117~~93.~~31~~70	-0.~~085~~062	1.34	0.89
Spring T2-T4	~~seasonal~~ Annual	-34.69	16.68	51.37	-0.028	1.75	1.33
Autumn T3-T6	~~seasonal~~ Annual	-04.68	20.51	25.19	-0.001	2.50	1.33

Komentár od [S80]: **R2C – 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. Error of measurement for 1 cell of computation is 0.0092 m = 0.92 cm and if we compute volume change in cells of 1x1 cm then volumetric error for one cell is 0.92 cm^3 and in area of 1200 m^2 we multiplied error by number of cells which gives us resulting error.

~~Given the total error of E_{Total} 0.0092 m and the area of observation of 1,200 m^2, it should be emphasized that a volume of up to 10.04 m^3 may be the result of a measurement error.~~ ~~The highest difference in ice volume was observed at the beginning of the monitored period between summer of 2016 and spring of 2017 (Fig. 10 T1-T2) and spring of 2017 and autumn of 2017 (Fig. 10 T2-T3), when a total ice loss was approximately 70 m^3 in both cases (Tab. 2).~~ ~~Significant~~ Considerable **loss of ice in these periods can also be identified from the average change of surface, which in this period reaches a loss of about 0.06 m. The highest increase was recorded between autumn ~~of~~ 2017 and spring ~~of~~ 2018, when new ice from spring rains is usually formed in the cave. The increase in ice should culminate in summer, but in 2018 there was little rainfall and relatively warm.** ~~Thus, during the spring and summer of 2018, the new ice did not form.~~ **The loss of ice between summer and autumn ~~of~~ 2018 is already a natural phenomenon. The inter-seasonal comparison suggests that there is a ~~significant~~ considerable loss of ice due to the lack of water flowing into the cave during the monitored period, as evidenced by the comparison between the summer ~~of~~ 2016 and the summer ~~of~~ 2018, when about ~~100~~ 75 m^3 of ice were lost in the cave.**

5 Conclusions

Ice caves can be considered as an indicator of the long-term changes in the landscape. Hydrological and climatic dynamics of the landscape are manifested in the ice caves and it is well-recognizable because of the caves are evidently linked with immediate surroundings. The interpretation of the dynamics in the ice cave accumulations is a challenging task that should be based on long-term and regular monitoring. In the paper we presented the analysis of the floor ice dynamics in the Silická ľadnica cave.

Our research was based on several observations of ice formation and ablation in the Silická ľadnica cave, which have been published in several works (e.g. Roda et al., 1974, Rajman et al., 1987, Stankovič and Horváth, 2004) and began in the mid-20th century. According to the described thermodynamic regime and process of ice formations in Silická ľadnica is Grotta del Gelo (Maggi et al., 2018) a good example of the similar cave as well as many other cold traps e.g. Ledenica u Čudinoj uvali, Ledenica cave (Buzjak et al., 2018) or Stojkova ledenica (Nešić and Ćalić, 2018) but most of these caves contain only seasonal ice formations. We also undertake international research on other ice caves and present new results in the methodology of TLS data collection and processing, generation of time series database, floor ice dynamics evaluation using object movement analysis and quantification of ice mass dynamics based on complex 3D cave models.

We used terrestrial laser scanning to map dynamics of cave sediments containing ice accumulations. In order to evaluate the changes in the cave ice accumulations, it was necessary to register the individual mappings into a uniform coordinate system. For this purpose, we have proposed an innovative method based on automatic registration of the individual scan positions using stable objects of the cave such the ceiling of the cave. The presented selective cloud-to-cloud approach reduces the overall registration error of the data time series into a unified coordinate system by avoiding the repeated positioning of GCPs by GNSS. ~~The presented selective cloud-to-cloud approach brings several advantages. Using the sC2C approach, the mapping time is a shortening because it is not necessary to map the exterior surroundings of cave within repeating scan missions because of GCPs. This approach also reduces the overall registration error to the unified coordinate system as it eliminates measurement errors through GNSS.~~ We argue that the presented methodological framework of sC2C approach has potential to be used in

Komentár od [S81]: **R2C – 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. Error of measurement for 1 cell of computation is 0.0092 m = 0.92 cm and if we compute volume change in cells of 1x1 cm then volumetric error for one cell is 0.92 cm^3 and in area of 1200 m^2 we multiplied error by number of cells which gives us resulting error.

Komentár od [S82]: **R2C – 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).

Komentár od [S83]: **R2C – 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.

other applications where it is necessary to identify landscape dynamics, such as mountain glacier assessment and sediment accumulation dynamics analysis.

Finally, ~~proposed~~ the developed methodological framework of data processing ~~unable~~ enables to generate a time series 3D database of interior cave surface at ultra-high~~-scale~~ resolution. We also presented a procedure for the modelling of complex 3D surfaces from the point clouds. Presented data and the methods ~~serve us to~~provided means for ~~evaluate~~ evaluating the dynamics of the cave floor ice. ~~Cave floor ice~~We detected the dynamics ~~has been detected~~of the ice based on cross sections method and via differences of 3D distances analysis. Complex 3D models of cave floor ~~have also been~~were used to quantify the volumetric changes. ~~which we have expressed numerically.~~

~~The presented r~~Results of the quantitative assessment of cryomorphological changes showed that there was a ~~significant~~ considerable loss of ice in the cave during the monitored period. The 3D mapping over the two-year period was coupled with continuous monitoring of air temperature inside and outside the cave and monitoring of rainfall. ~~Temperature monitoring is also carried out in the cave and rainfall stations are located around the cave. Results from these monitoring stations were not included into the presented paper.~~ Linking the findings on the dynamics of the cryomorphology and the meteorological monitoring shows well known fact that a cold but dry winter will lead to less ice accumulation as a warmer, but wetter one, while a warm but dry summer will lead to less melting than a cold, but wet one.~~However, based on our observation as well as presented analysis of the cave floor ice dynamics, we can conclude that the loss of ice is not related with warming climate but with extremely dry years.~~ Naturally, the question arises if there is irreversible year-on-year loss of ice mass or only longer cycle of perennial ice accumulation replenishment. To be able to qualified answer this question, it is necessary to continue in monitoring of cave ice and to analyse other factors such as temperature of precipitation, air circulation, evapotranspiration, tectonics and geological structure of massif, morphology of the cave and immediate surrounding, connection with other part of the cave system.~~In the presented paper, we focused mainly on the presenting the methodological approach of the high-detailed mapping of the cave ice accumulations, data processing and generation of time series database. We argue that the presented methodological framework of sC2C approach has potential to be used in other applications where it is necessary to identify landscape dynamics, such as mountain glacier assessment and sediment accumulation dynamics analysis.~~

Komentár od [S84]: **R2C – 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.

Acknowledgement

~~With support~~ The results achieved in the presented research originated thanks to the financial support by the grant of the Ministry of Education, Science, Research and Sport of the Slovak Republic within the projects~~s~~ VEGA 1/0963/17: Landscape dynamics in high resolution, ~~APVV-15-0054: Physically based segmentation of geodata and its geoscience applications,~~and VEGA 1/0839/18 Development of a new v3.sun module designed for calculation of the solar energy distribution for digital geodata derived from a point cloud using adaptive triangulation methods~~.~~; and by the Slovak Research and Development Agency for the financial support within the project APVV-15-0054: Physically based segmentation of geodata and its geoscience applications.

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