

Responses to Reviewer 1

Overview of the manuscript

This manuscript investigates the changes of ice thickness of five ice-filled caves (Scărișoara, Chionotrypa- Falakro, Chionotrypa-Olympus, Crna Ledenica and Velika ledena jama v Paradani), as well as the area changes of two mountain glaciers (Snezhnika and Banski Suhodol), all of them in Eastern Europe, during the hydrological year 2018-2019. The relatively large changes observed are associated to an anomaly in the weather (both summer and winter weather). The observations of ice changes are carried out based on in situ length measurements for the ice within caves, and with a drone for the two mountain glaciers. Weather parameters are obtained from the following datasets: E-OBS (Cornes et al., 2018), NCEP/NCAR (Kalnay et al., 1996) and MODIS/Terra Snow Cover Monthly L3 Global (Hall et al., 2006).

The authors have done substantial modifications of the manuscript, which has, in my opinion, improved significantly. They have also adequately addressed the majority of the questions from the first review. However, there are still a couple of aspects where the reply from the authors still raises some questions. This concerns mainly (1) the lack of error bars when presenting the results, (2) missing explanations in the methodology and (3) content of the abstract and conclusions in comparison to the actual content of the manuscript.

Thank you for the detailed work on the manuscript and the appreciations. The responses and manuscript modifications are detailed below.

General comments:

Error bars:

Although the revised manuscript has improved in this regard, showing some kind of errors in the observations, still none of the results shows error bars. For the rigor of the study, this should be adequately addressed and there should be some sense of uncertainties in all the numbers, i.e. volumes and areas, should be provided in the results.

In the “Results” chapter, we added the values of the errors to the estimated volume changes for each cave glacier and surface glacieret.

Methodology:

The revised manuscript shows a descriptive figure of the type of measurements done with tape. However, the authors do not explain how the measurements are carried out in Chionotrypa Falakro and Crna Ledenica, where the Table 1 shows the measurements as "Photogrammetry". This needs a better explanation. Also, the drone survey data is now better presented, and a Digital Elevation Model (DEM) is shown for each survey, as well as a map of elevation difference. However, it should be straight-forward to present a volume change from their comparison (as well as the uncertainties associated), in the same way as volume changes are presented for the cave ice.

The following section of the “methods” describes the methodology (photo) for Chionotrypa Falakro and Crna Ledenica: “In Chionotrypa Falakro, Chionotrypa Olympos and Crna Ledenica annual ice level fluctuations were intermittently recorded at the end of the ablation period over the past five years. Photographs of the upper surface of the ice and snow body taken intermittently from the same spot at the end of the ablation periods were compared in order to visually estimate the ice level changes. The errors associated with these measurements are less than 0.3 cm in Scărișoara Ice Cave and Velika ledena jama v Paradani, and are estimated to be between 20 and 50 cm in Chionotrypa Falakro, Chionotrypa Olympos and Crna Ledenica (Table 1). The errors for the 2019 ice level changes are estimated between 1 and 25 % (Table 1), lower where rulers were used and higher where the presence of snow precluded precise measurements and/or estimates.”

The volume changes for the two Bulgarian glacierets were calculated and the following line was added to the main text: “The loss of ice at the surface of these glaciers (excluding thus basal melting) between 2018 and 2019 amounts to 10045 (± 241) m³ (Banski Suhodol) and 2933 (129) m³ (Snezhnika).”

Abstract and Conclusions:

As pointed out in the first revision, there are some strong statements made in the abstract and conclusions that are not supported by the data and methods presented in this study, and they should not be presented in the abstract or in the conclusions, only as part of the discussion.

Specific comments

- L20-21: The role of changing atmospheric circulation patterns and distribution of precipitation in glacier changes is not studied as such in this manuscript. The atmospheric conditions are presented as observations but there is no strong link or model carried between these observations and the glacier changes. For this reason, I find this sentence outside the scope of the abstract.

We removed the reference to atmospheric circulation patterns and kept that on the distribution of precipitation, as this is what we have studied.

“While increasing air temperature is the main factor behind glacier mass and volume loss, variable patterns of precipitation distribution also play a role, though these are not as well understood.”

• L29-30: Same as in the previous comment, this work does not analyze any climate model prediction, and therefore this should not be included in the abstract.

We did not analyze climate model predictions, as this was beyond the scope of the paper. We 1) presented and discussed the response of glaciers to extreme precipitation events and 2) present data (lines 373-385 of the revised ms) from previous studies that discusses model predications to contextualize our findings.

• L57: Throughout the manuscript the authors refer to "cave glacier", "ice cave" and "cave ice". This needs consistency.

Depending on context, we used these as follows:

Ice cave – refers to a rock cave hosting perennial ice deposits. We used “ice caves” when discussing the caves themselves.

(e.g., “Ice caves occur in mountain regions across the Northern Hemisphere...”).

Cave ice – refers to presence of ice in a cave, regardless of volume, mass, type etc (e.g. “Various proxies in cave ice have been used to reconstruct temperature variability”)

Cave glacier – we used it when referring to the cave ice as affected by different processes (e.g., “average summer precipitation might play an important role in the overall volume changes of cave glaciers”).

As these examples show, the three terms cannot be used interchangeably.

• L149: Does the metal ruler allow sub-millimeter precision? (most rulers only allow measuring to one millimeter). This is contradicted in Table 1.

Typo, thanks for spotting it! We mean “cm”, not “mm”.

• L161-162: “Photographs of the upper surface of the ice body (...) to visually estimate the ice level changes”. How exactly is this measure taken and how is it possible to obtain a precision of 0.3 cm with this method? See general comment nr2.

The <0.3 cm precision refers to Scărișoara Ice Cave and Velika ledena jama v Paradani caves, only. For Chionotrypa Falakro, Chionotrypa Olympos and Crna Ledenica caves, the errors are 20 cm (Crna Ledenica), 30 cm (Chionotrypa Falakro) and 50 cm (Chionotrypa Olympos). These are the values given in table 1 and we have corrected the text for consistency (also deleted a duplicate part of the sentence). The full sentence reads:

The errors associated with these measurements are less than 0.3 cm in Scărișoara Ice Cave and Velika ledena jama v Paradani, and are estimated to between 20 and 50 cm in Chionotrypa Falakro, Chionotrypa Olympos and Crna Ledenica (Table 1).

• L214: Mass balance vs volume change: The authors explained in their first author response that the dimension of "mass balance" yields a fundamental question and they decided to continue using this term at several occasions through the manuscript. I kindly disagree with this response, and in the revised manuscript I have not found a clear clarification of this, which still makes this concept misleading. I suggest either adding a sentence to clarify what the authors define as mass balance, or replace expressions as “positive mass balance” for “volume gain”.

While we used volume changes in the text, this was not done in a consistent manner throughout the manuscript. We corrected this and now the text reads volume gain/loss/change, as appropriate.

• L226-230: Since the volume change is reported for the cave ice, why not reporting the volume change for the two glacierets too? This is straightforward to calculate from the map of elevation difference from the subtraction of the two DEMs.

The volume changes for the two Bulgarian glacierets were calculated and the following line was added to the main text:

The loss of ice at the surface of these glaciers (excluding thus basal melting) between 2018 and 2019 amounts to 10045 m³ (Banski Suhodol) and 2933 m³ (Snezhnika).

• L343: Please provide a more updated reference for the accelerated warming of the Arctic.

Cohen et al., 2020

• L353: This is still a very strong statement in the conclusions that is not supported by your material and methods. Therefore, it only should be mentioned in the discussion.

We expanded the discussion with a new paragraph to support this inference.

• L360-361: The Rossby waves have only been mentioned twice before in this manuscript and I also think this should not be a conclusion of your study. It needs to go to discussion.

We stand behind this sentence, as it stems from our article.

Figures

• Fig. 5: As pointed out in the first round of comments, this figure showing changes in snow is heavily influenced by the seasonal differences of each picture. The authors argued that the pictures were taken at the end of the melting season, but this is not the case by looking at the date of acquisition. The snow field can change dramatically between July and October. This needs to be properly addressed or otherwise this figure should not be presented. Also, the “green” outline does not match with the “yellow” color in the legend. There seems to be a “green” line in the middle of the snow patch in the 2019 image.

The caves were (and are) regularly visited, during spring-autumn (risk of avalanches in winter prevents access to the surface of the ice). We take photos at each visit and use them to assess the dynamics of the upper face of the ice and snow body. The caves where these observations were made are located in Greece and S Croatia, where summers are dry, with only occasional rains (or, as was the case in 2019, prolonged periods of heavy thunderstorms). Thus, depending on meteorological conditions, the ablation periods can be longer or shorter. For example, a very dry summer will shorten the ablation period, as 1) no warm rain water reaches the ice and 2) in the deep (~50 m) entrance shaft, the thermal inversion prevents the advection of heat to the surface of the ice while conduction through the air column results in limited warming. As a result (while present), ablation in dry summers can be extremely reduced, amounting to a few cm per several weeks, not discernable in visual/photogrammetric observations. We thus used those images that “signaled” the end of the ablation period for a specific year.

- Fig. 7: For the soundness of the UAV work, it would be needed to show the comparison between the two DEMs in the entire overlapping area, and not just in the glacier itself. The color scale could also be improved: due to the high level of detail and accuracy in the DEMs, the scale bar could have more discrete steps in order to discern smaller changes in elevation.

We made a new figure 7, according to the suggestions (comparison for the entire area covered by DEM, improved color scale)

Tables

- Fig. 5: Table 1: The uncertainties given here do not correspond to the values shown in the text. “Photogrammetry”. Can you provide additional information on how the photogrammetric measurements are done in Chionotrypa Falakro and Crna Ledenica?

We corrected the errors in the main text.

Responses to reviewer 2

Overview and general comments:

I have read the revised version of the manuscript, previously entitled,

“Unprecedented loss of surface and cave ice in SE Europe related to record summer rains in 2019”, now entitled “Record summer rains in 2019 led to massive loss of surface and cave ice in SE Europe”

The new version of the manuscript has improved substantially with respect to the first one.

The authors provide a new figure about the morphology of the caves, which helps to have an idea about the ice location. In relation to the ice measurements in caves and glacierets, the authors include two new tables summarizing the place, the method used, the measurement uncertainty, the resolution, and the errors. This helps the reader to have a quick summary about the methods used to conduct the study. Moreover, the authors add a new digital elevation model of the glacierets studied showing the changes in ice surface elevation. They also provide a new fig. 3 to explain how the basal and superficial ice thaw is measured. Although these measurement methods are known in the ice caves community, this figure provides a visual example for non-expert readers. Does figure 3 show a real cave cross-section of the cave? if not, I suggest reducing the figure to a schematic illustration, something similar to the one attached below. The authors can use this or generate a new one if they want.

Thank you for the comments and for the nice work behind the suggested figure, will use it.

Line 186: To add space between the number and percentage (80% or 80 %) to be consistent.

Done.

In the figures, use the same letter source (e.g Fig 12 and Fig 11 have different letter sources). Also use parenthesis-letter-parenthesis (a), (b)... to numbering the figures. Some of them appear with/out parenthesis.

All figures have been corrected where required to match the journal style.

Responses to Reviewer 3

Dear Authors, Dear Editor,

Thanks for the opportunity to read the revised version of the original manuscript. I appreciate the Authors' effort how they revised their original work. I think the introduction and the discussion improved a lot. The extension of the methodological section gives much better insight to the technical details of the applied methods which is a crucial requirement for the potential repeatability of the study. I like also the modified title of the study because it catches better the key message of the study. Since glacierets and cave ice deposits are currently the main representatives of the cryosphere in the studied region (SE Europe) I think the topic can be interesting to the readership of the journal.

As written above the study improved a lot compared to the original version, however some minor revisions are still needed before the publication of the study:

line 73: I think Munroe 2020 could be a more pertinent reference here than Kern and Persoiu 2013

Munroe, J. S.: First Investigation of Perennial Ice in Winter Wonderland Cave, Uinta Mountains, Utah, USA, The Cryosphere Discuss. [preprint], <https://doi.org/10.5194/tc-2020-152>, in review, 2020.

Added (it has since been published as Munroe (2021)).

line78: I suggest replacing “Most of” with “Many”

Changed to “ Numerous caves hosting perennial ice”

lines 145,177: Please change “table” to “Table” in the brackets.

Done.

lines 307-308: Can you provide any evidence supporting the statement “The thermal inversion layer inside this shallow entrance shaft was easily destroyed during the prolonged warm spell,...”?

We noticed positive temperatures close to the surface of the ice during visits in summer. The text now reads: “The thermal inversion layer inside this shallow entrance shaft was easily destroyed during the prolonged warm spell (as observed during visits to the cave),”

lines 327-328: Needs revision. You probably wish to say that the climatic snowline (or TP-ELA) is above highest peaks in SE Europe, so these small glacierets are strongly controlled by topoclimatic conditions, and their mass balance is extremely affected by extreme events.

Yes, thank you for the clarification, we amended the text.

lines 331-332: Please consider replacing “glacierets we investigated” with “studied Bulgarian glacierets,” I think it is more understandable.

Indeed. Done.

line 353: “unraveled unprecedented” Sorry, the meaning is unclear to me.

We have investigated [...] and [have] unraveled unprecedented

line 364: I suggest inserting “by the calibration-in-time approach” between the word “reconstructions” and “it”

We decided to keep sentence as it is now, its second part describes the ‘calibration approach’ (we have avoided repetition)

line 366: I think “measured” should be written instead of “measure”

Indeed, thank you.

Figures

Fig2: This multipanel figure needs a careful checking. The cross section in panel 'e' seems to be Paradana however this cave is listed as 'd') in the caption. Similarly, panel 'b' seems to be Chionotryopa Falakro, however it is listed as 'c') in the caption. In addition, please check the name in the brackets after Paradana Cave. As far as I know the right spelling of the first surveyor is Pavel Kunaver.

Thank you for the sharp eye. We have corrected the references in the panels.

Fig7: In the caption “glaciarets” should be replaced with “glacierets”

Yes.

Fig8: Panel code should be 'e' instead of '3' in the caption.

Yes.

Fig12: in panel 'b' the histogram seems to be the same as in panel 'a' suggesting that the "no. of observations" were not tuned to the past 30years. Please check and correct it if needed.

We retained panel (a) only, as panel b does not bring new information.