The Cryosphere Discussions

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Comment on tc-2021-337

Anonymous Referee #2

Referee comment on "Geophysical measurements of the southernmost microglacier in Europe suggest permafrost occurrence in the Pirin Mountains (Bulgaria)" by Gergana Georgieva et al., The Cryosphere Discuss., https://doi.org/10.5194/tc-2021-337-RC2, 2022

The study entitled `Geophysical measurements of perennial snow patches in Pirin Mountain, Bulgaria`, by Kisyov, A., Tzankov, C and Georgieva, G. presents interesting results in a region still poorly investigated so far. The paper brings valuable knowledge from a small glacier in the Pirin Mountains (Bulgaria), but should be highly improved to be published in this journal. The authors should address several important problems before the paper can be accepted. The paper is clearly structured and well-illustrated, but requires some supplementary explanations regarding the study site and the methodological approach. In addition, interpretations should be improved, new figures inserted and confusion regarding the inappropriate usage of some concepts should disappear. The English needs some smoothing in places.

After careful consideration, I recommend that the paper be published only after the authors address the issues listed below.

General comments

- In several previous papers, the ice bodies assessed in this paper in the Pirin Mountains are called `glaciarets` (Gachev et al., 2016) or `microglaciers` (Grunewald et al., 2006) (even you mention in the paper Snezhnika as being a microglacier!). In addition, they are considered the southernmost glaciers in Europe by Hughes (2008), Grunewald and Scheithauer (2010) and other authors. Gachev (2017) mention typical glacial processes associated with these glaciarets, such as: striations and initiation of small moraines, suggesting that these ice bodies display motion and play a role in the present-day morphodynamics in the proglacial area. Moreover, the drillings performed by Grunewald in 2006 in Snezhnika revealed the presence of ice (Grunewald and Scheithauer, 2010). These glaciarets are probably several hundred years old (at least

from the XIXth century). In this context, I think the authors should consider changing `perennial snow patches` with `glaciarets`.

- According to the title and objectives, the approach deals with geophysical measurements of perennial snow patches. However, the article would have a broader impact if the achieved results are used to gain knowledge regarding e.g., the evolution of these small glaciers, present-day changes/behaviour of glaciaret, glacial-periglacial processes at this site, hydrological significance etc. In the present form, the article focused on identifying several different layers on GPR radargrams/ERT profiles, but the considerations regarding these layers' geomorphological/hydrological importance are lacking almost completely. Therefore, I suggest going further with the analysis and interpretations than only identifying the bedrock depth, the permafrost, etc., but trying to explain the relevance of these findings for the mountain cryosphere. Otherwise, I am afraid that the paper seems to make an impact only locally.
- I have some concerns regarding the design of the approach.

- First, I didn`t understand why the authors performed geophysical measurements on different alignments in different years? In the beginning, I thought that the authors would like to compare the results and quantify the changes, but it seems that was not the case. Because the profiles were not conducted on precisely the same lines, quantifications are not possible.
- Second, the distribution of the profiles is not adequate. Most of the profiles were performed in the downslope part of the glacier, where the glaciaret is thin. It would have been good to have at least 1-2 transversal profiles in the upper part of the glaciaret (in this case, you could have calculated the glacier volume and then the water equivalent etc.).
- Third, you used a simple handheld GPS, which can have low accuracy in this type of environment. Therefore, the profiles' exact position might be different from what appears on your map.
- You used ERT to investigate the lower part of the glaciaret, but as far as I know, ERT is problematic when the electrodes are fixed in the snow. Please refer to similar studies using ERT on snow patches/small glaciers and highlight the capabilities/limitations of ERT on snow/ice surface. In addition, I didn`t understand why setting the electrodes distance at only 1.5 m? Because the distance between electrodes was small, the penetration was not enough to estimate `frozen areas` thickness in some profiles. Generally, the measurement protocol in this environment uses a 5 m electrode distance.
- It would also be helpful to mention the precise date of geophysical measurements each year.
- The radargrams have no topography, and because of this is difficult to interpret the reflections.

- A recent study (Persoiu et al., 2021) showed that significant changes might occur at Snezhnika between different hydrological years (e.g., 2018 vs 2019). Therefore, please consider the interannual changes of this glaciaret when interpreting the results of profiles performed in different years. From the pictures, it seems that in 2018 was much more snow than in the following years. Do your GPR profiles tell you anything about ice-thickness changes between 2018 and 2020? Because according to Persoiu et al., significant variations in the surface may occur at this site.
- Because this site is unknown to most readers, you should give more details about this site. First, please include a map with the localization of the study area. Then, please

add a short description of the evolution of glaciers in the Pleistocene and Holocene in this area supported by the morphology of this valley (e.g., moraines). Because karstic rocks occur here, please also refer to the presence of karstic features in this cirque. You did measurements in the proglacial area of the glacier, but you didn`t describe it: type of surface, vegetation, clasts dimensions, presence of soil, water etc. It is also essential to describe the climate in the Pirin Mts.

- Please refer to other similar studies regarding the interpretation of the GPR measurements. For example, you interpreted a pattern of reflections in the substrate as a' frozen zone'. Based on what characteristics of the reflections do you make this interpretation? Are there similar findings in other studies? The same observation for the second layer where the `voids are filed with ice and water`. How do you be so sure that the voids between blocks are filled with ice and water? If the voids are filled with ice in this layer, then this is also permafrost. Then, what is the difference between layer 2 and 3? You should interpret all the other reflections by comparing them with similar findings elsewhere. Have you noticed any hyperbola in the radargams? You can use it to calculate velocities and see whether you have ice/permafrost/rocks or a mixture (most probably). What about internal coarse layers embedded in the ice? Grunewald and Scheithauer (2010) found such layers in the drillings done in 2006. Please also discuss the transition between snow/firn/ice.
- One of the most interesting findings in the geophysical profiles is the so-called `frozen zone`. Unfortunately, the interpretation based on the presented results is partly vague. For example, it is not clear if there is a lens of massive ice in the substrate or a mixture of ice and rocks (ice-cemented materials). The term `frozen zone` is problematic and I suggest replacing it with ground ice/permafrost. First, you should clarify if you have periglacial or glacial ice in the substrate and discuss the origin of the ground ice/permafrost. Then you should describe the mechanisms involved in forming the permafrost at this site below the glacier and the non-frozen bedrock and whether it is ice-rich permafrost or massive ice is missing. Finally, try to explain processes that control permafrost occurrence at this site below an unfrozen/frozen ?? (this is not clear) bedrock and what happens with water below the glacier. Since this is a region with karstic rocks, please also refer to the hydrogeology in the Discussions and the presence/absence of caves/dolines etc. in the region.

Specific comments

Abstract

Line 7: `in order to evaluate changes in the snow patches size and thickness`…replace with `in order to assess glaciaret thickness and its internal structure`. You haven`t cuantified changes of size/thickness.

Line 8: Maximum thickness of ice can be higher than 8 m in the upper part of the glaciaret where there are no transversal profiles. Please add that maximum thickness of 8 m or even higher occur in the upper part of the glaciaret.

Line 10: replace `frozen zone` with permafrost/ice-cemmented sediments.

Line 11: the presence of permafrost in the Pirin was also indicated by Onaca et al., (2020, 2022).

Introduction

Please write a paragraph on the importance of knowing the ice thickness, internal structure for glaciology/hydrology/geomorphology.

Line 18: add a citation after `global changes than glacier`.

Line 19-20: What do you want to say with `permafrost is the last stage of glacial life cycle?` This doesn't seem right. The occurrence of permafrost is not necessarily conditioned by the presence of a glacier. For example, in never-glaciated regions in Canada permafrost exists for several hundred of thousand years. In mid-latitude mountains, in regions without glaciers in the last 10 ka, permafrost still exists due to favourable topo-climatic conditions. In the Pirin Mts., permafrost probably also occurred at sites free of ice in the last 10 ka.

Line 21: This is wrong! During LIA the only glaciarets in Bulgaria were very small (see Gachev, 2000, Holocene glaciation in the mountains of Bulgaria, Mediterranean Geoscience Review, 2, 103-117). Large glaciers occurred in Bulgaria only in the Pleistocene. Please refer to this (see Kuhlemann et al., 2013, QI).

Line 32: please see this recent study (Onaca et al., 2022) in which geophysical measurements on Snezhnika are presented.

Line 36: it is not clear if you are talking about permafrost or air temperature?? Please also add a citation here.

Line 36: not only `mountain slopes with permafrost are significantly vulnerable to climate change`; flat permafrost terrain is also vulnerable (see, Biskaborn et al., 2019).

Line 41: you are right that snow acts as a shield for radiation, but on the other hand it also may hamper the aggradation of permafrost.

Lines 74-75: `The polar ice….` - this is irrelevant here.

Line 84: `ERT can successfully be applied for studying glacial structures` - What types of structures? Please be explicit and add citations.

Line 92: You didn`t present any results from Banski Suhodol Valley and since is not the subject of this paper you should avoid referring to this site when presenting the aim of the paper.

Methods

Line 98: You didn`t present any DEM in the paper. Please delete this sentence.

Line 99: 2.1. Study site description – please give more details on this site. A localization map + a detailed map of the topography of this cirque is also necessary. Please indicate on this map: Dzhamdziev ridge and all the other peaks.

Line 103: replace `snow patch` with `glaciaret`.

Line 112: `They were formed during the final phase…`. It is not clear who?

Line 131: What about mean velocities of snow? And permafrost? You mention that this glaciaret is a snow patch, but using the velocities for ice. In other studies ice is 0.16 m/ns. How can affect the thickness estimation of the glaciaret?

Line 134: I have serious doubts regarding such a low error of the GPS in this shaded cirque. What about the vertical error? Topography is extremely important for the interpretation of geophysics profiles. When doing geophysics in such a rough terrain the protocol says that differential GPS is mandatory!

Lines 135-140: it is not clear if there are GPR profiles repeated exactly on the same line in 2020 compared with 2018. From fig 3 it seems that GPR in 2020 is different than those performed in 2018. It means that you can not actually compare the radargrams, by means of changes.

Line 140: why didn`t use topography when creating the radargrams? Topography is extremely important for interpretation. Without topography how can you interpret if reflections are parallel with the surface etc?

Line 142: It would have been good to try at least 1 or 2 GPR profiles in the upper part of the glaciaret in 2018 (when the glacieret size was the greatest in the last years) and where the thickness is probably greater.

Figure 3: Give more details about the picture in the background (when it was taken?). If possible, would be good to overlap the contour of glaciaret (or at least of the front) in 2018, 2019,2020 to see if it was ice in 2019 and 2020 where you did some profiles. Please replace Glacier Snezhnika with glaciaret Snezhnika on the picture. In the caption replace the Golyam Kazan area with Snezhnika glaciaret.

Line 155: Why setting the distance between electrodes at 1,5 m? Following the protocols in permafrost environments a distance of 5 m between electrodes allows you to measure 120 m profile length and probably around 20 m penetration depth. The moraine looks a bit challenging, but it would have been so interesting to make at least a profile on it, to see its internal structure!

Line 159: It is not clear if some profiles/parts of the profiles cross the glacieret. It seems that ERT 3 and 2 cross the glacieret and in this case, you should interpret the ERT values with extreme caution, since ERT in the snow is extremely tricky. Write a phrase about the contact between the electrodes and the ground?

Line 162: `real geoelectrical section` - what do you mean (inversion from apparent to true resistivity?)

Results and Discussion

Line 170: `which are horizontal relative to the slope`…how do you know, since your profile has no topography?

Line 170: replace `snowfield` with `glaciaret`.

Line 171: `The uppermost layer represents the microglacier`. What do you mean? The ice?

Less 173: you identified some discontinuities in the ice. Vey nice…can you say something about these?

Lines 175-175: is not very clear here. Please rephrase.

Line 177: `The second layer lies under the ice`…you are not referring to GPR2018-1, GPR2018-2 and GPR2018-3, right?

Line 178. You say that the voids are filled with water and ice in layer 2, but is not clear based on what you affirm this? Please, give references to similar findings. If this layer is draining the melted glacial water, why are some voids filled with icer? And how do you explain the presence of water in the so-called `meltwater zones`, which are between the glacier front and the LIA moraine? Here is a possible scenario, but it might be wrong: the melting water may infiltrate layer 2, but because layer 3 is permafrost (impermeable), it follows the permafrost table downslope and accumulates in the proglacial area where ERT reveals a high concentration of water. Maybe if you agree with this scenario, you can make a simple model in which to represent the primary circuit of glacial melting water and the role of permafrost for drainage.

Line 186: This is very important. Can you comment on the large differences in the velocity between layers 2 and 3? Ice lenses mean massive ice (pure ice)? It is hard to believe…only if a thick mantle of debris-covered old glacial ice. I think here might be rather an ice-rich permafrost (usually around $10^5\Omega m$).

Line 194: replace `snowfield` with `glaciaret`.

Lines 199-200: It is not clear which figure is the frontal moraine? If it`s 5a it means that the frontal moraine is well below the ice because GPR1 ends somewhere in the middle of the glacieret? Please clarify!

Line 210: according to Onaca et al., 2022 the maximum dept was 12 m. You should also refer to this finding.

Line 222: apparent resistivity? Why not true resistivity?

Line 231-233: please be more precise: ground ice/permafrost (avoid `frozen zone`).

Line 238: Interesting finding! Can you explain why the active layer has thickened so much in only 1 year?

Line 256: How can you explain the occurrence of `frozen zones` only in the lowest part of the glaciaret?

Lines 274-275: Not clear. Rephrase this.

Please write a paragraph on the methodological uncertainties (mainly the limitations of GPR and ERT) and where the interpretations should be treated with cautions.

Conclusions

Line 278: replace `snow` with `ice`.

Line 280: `…the ice body it reaches 8 m`, but the maximum thickness may exceed this value in the upper part of the glacieret.

Line 286 (and within all the manuscript): you are using rock blocks in many cases, but please refer to a classification of clasts based on the size of individuals (e.g.,pebbles, cobbles, boulders etc.).

Line 287: Please check again if ice occurs in layer 2.

Line 299: Indeed, shading is essential, but is not acting alone. You should consider the other controlling factors of permafrost in the Discussions.

Line 300: I suggest to delete the last phrase. It is not a conclusion of this study.

References:

Biskaborn et al., 2019. https://doi.org/10.1038/s41467-018-08240-4

Gachev et al., 2020. DOI: 10.1007/s42990-020-00028-3

Kuhlemann et al., 2013. 10.1016/j.quaint.2012.06.027

Onaca et al., 2022. https://doi.org/10.1016/j.catena.2022.106143

Persoiu et al., 2021. https://doi.org/10.5194/tc-15-2383-2021