Reviewer Comments for Manuscript Number egusphere-2024-269

Short-term cooling, drying and deceleration of an ice-rich rock glacier

Bast et al.

Summary

This highly relevant and interesting manuscript presents the combination of borehole temperature, piezometric pressure and geophysical data with surface meteorological and kinematic data to investigate a short-term deceleration of a rock glacier in the Swiss Alps. To the best of my knowledge, the use of borehole ERT combined with borehole temperature and piezometric pressure data in a rock glacier is a novelty and makes the manuscript very interesting.

The results of the study show that the snow cover plays a crucial role for short-term velocity changes due to its effects on the thermal state and particularly due to the water supply. According to this manuscript, snow-poor winters and dry summers are ideal for the short-term deceleration of the rock glacier under investigation. Additionally, the authors demonstrated that a summer heat wave did not play a significant role in the rock glacier movement.

The manuscript is well-written, well-structured and the figures are well designed. The Introduction provides a good overview about the relevance of the study, what has been done so far and the main objectives of the manuscript. In Material and Methods, the authors provided all information needed to understand the data collection, the processing, statistical analyses and visualizations, but a few points in the description of the ERT data processing are missing or should be revised. The results and the discussion are well presented. However, in the discussion the authors could try to focus on explaining links and the (somehow surprising) discrepancy between temperature and resistivity in the permafrost layer. These two issues together with some specific comments and technical corrections (see below) can be easily addressed. Therefore, I recommend accepting this interesting manuscript with minor revisions.

General Comments

<u>Processing of electrical resistivity data</u>

- See specific comments below

<u>Discussion of the low resistivity zone in the permafrost layer</u>

- See specific comments below

Specific comments and technical corrections

Line 9: „Long term“ -> „Long-term“ (for consistency)

Line 10: “variability of their velocity and there is still a gap in the” -> “variability of the velocity with a particular gap in the”

Line 11: “role of water in rock glaciers” Role in what? Maybe add here “in rock glacier movement”

Line 14a: “cross-borehole electrical resistivity tomography sensors.” -> “cross-borehole electrodes for electrical resistivity tomography measurements”

Line 14b: “using terrestrial” -> “using repeated terrestrial”

Line 17: “lowering of the water content in rock glaciers is crucial for” Where exactly? In general, at the shear horizon, at the surface?

Line 22: “ice/water contents” -> “ice/water content”

Line 23: “better understanding of factors affecting rock glacier kinematics” -> “better understanding of the main drivers of rock glacier kinematics”

Line 26: See also the recently published paper: Kellerer-Pirklbauer, A., Bodin, X., Delaloye, R., Lambiel, C., Gärtner-Roer, I., Bonnefoy-Demongeot, M., Carturan, L., Damm, B., Eulenstein, J., Fischer, A., Hartl, L., Ikeda, A., Kaufmann, V., Krainer, K., Matsuoka, N., Morra Di Cella, U., Noetzli, J., Seppi, R., Scapozza, C., Schoeneich, P., Stocker-Waldhuber, M., Thibert, E., and Zumiani, M.: Acceleration and interannual variability of creep rates in mountain permafrost landforms (rock glacier velocities) in the European Alps in 1995–2022, Environ. Res. Lett., 19, 034022, https://doi.org/10.1088/1748-9326/ad25a4, 2024.

Line 27: “Rock glacier kinematics are driven by common external climatic factors, and they vary over time (Delaloye et al., 2010a; Delaloye et al., 2008), with phases of acceleration, interrupted by periods of stagnation or deceleration of variable duration (Permos, 2023a).” -> “Rock glacier kinematics vary over time (Delaloye et al., 2010a; Delaloye et al., 2008), with phases of acceleration, interrupted by periods of stagnation or deceleration of variable duration (Permos, 2023a), driven by common external climatic factors.

Line 37-40: At this position, the paragraph is a bit lost and disconnected. Can you add it in the first paragraph after the first sentence?

Line 41: Can you specify the type of space-borne data?

Line 47: “rock glacier, and recent literature” -> “rock glacier. Recent literature”

Line 53: “refraction seismic” -> “refraction seismic tomography (SRT)”

Line 55: In the references, maybe you can add: Kneisel, C., Hauck, C., Fortier, R., and Moorman, B.: Advances in geophysical methods for permafrost investigations, Permafrost Periglac., 19, 157–178, https://doi.org/10.1002/ppp.616, 2008.

Line 52-62: Could you try to restructure the paragraph? Maybe you start with the direct method (borehole temperature sensors), their limitations and present the geophysical methods with their advantages over the direct methods as alternatives? What about the spatial coverage/resolution? That would make it clearer why you use a geophysical method in your study.

Line 60-62: “Cross-borehole geophysics are a means to distinguish ice and water in ice-rich permafrost and to monitor their volumetric variation and distribution over time (Musil et al., 2006; Phillips et al., 2023).” Geophysical methods do not provide direct information about ice and water content, you still need a model linking a geophysical variable, like resistivity, to ice or water content. Please add that here.

Line 73: I would remove the apostrophe in the elevation numbers.

Line 77-81: The description of the boreholes and their location is a bit confusing. For example: Are there also boreholes B1 and B2? What is the depth of the boreholes? Did you reach the bedrock in boreholes B4 and B5 as well or just in B3? What Please try to improve the structure.

Line 83: “relative ice-/water contents” The ERT method does not provide ice-/water contents directly, just a physical parameter.

Fig. 1: I would recommend to merge c and d, remove e, and add the scale bars and symbologies in the accompanying subplot. Additionally, the borehole names B2-B4 are missing. And I guess the north arrow is not valid for all subplots, right?

Fig. 2: “Syscal system” In the caption of the Figure, the type of electrodes would be more relevant than the instrument name.

Line 110: Please add that the Table is in the Supplementary Material.

Line 118: “These delivered” -> “They deliver”

Line 122a: “icing days” -> “number of icing days”

Line 122b: “15 °C days” -> “15 °C-days

Line 126-127 and 130: Please add the information about the boreholes in section 2.1. What is in B1 below 15.2 m? Is it broken?

Line 134-136: Why B1 for the annual variations and B5 for the short-term variations?

Line 135: “the evolution” -> “short-term evolution”

Line 138: The abbreviation ERT has been already explained.

Line 139: “ERT soundings” -> “ERT measurements”

Line 140: “in total 23 ERT measurements” -> “in total 23 time steps”

Line 146a: Please remove the apostrophe in “1494”

Line 146b: “data points” -> “data”

Line 146c: “ERT sounding” -> “time step”

Line 147: Please describe what dipole-dipole and skip-two means.

Line 138-147: please add some information about contact resistances and their change over the whole year. I guess they are not constant over the time and might affect the data quality, particularly during winter months. Which type of electrodes did you use and how are they connected to the subsurface material?

Line 149a: Please explain what reciprocal counterpart means.

Line 149b: “positive values of measured apparent electrical resistivities” -> “positive apparent electrical resistivities”

Line 148-150: How many quadrupoles did you keep for the inversion? Did you filter for every time step the same quadrupoles? If not, the combination of different quadrupoles might result in different sensitivities increasing the generation of time-lapse artifacts.

Line 150-152: 10 m mesh extension is a bit too small and might influence the inversion.

Line 152: “ResIPy’s” For inversions, ResIPy calls the R2 code – maybe you can add that here.

Line 154: What means “according to the reciprocal check”? Could you specify the error model here? Is your error value (10%) similar to the one estimated from the normal-reciprocal analysis and is the error constant over all time steps? And why is your used error parameter (10%) much higher than your filtering threshold (25%)?

Line 156a: Could you explain what is the reference model in this context?

Line 156b: “It converged” -> “The inversion converged”

Line 157: Did you use an error-weighted RMS? If yes, you could add that here.

Line 168: “systemic” -> “systematic”

Line 171-179: Could you shift the paragraph with the description of the Figure to the results section?

Line 176: “entire layer” What do you mean with entire layer?

Line 180: “differences of the variables” Which variables?

Fig. 3: The temperature and precipitation data look very similar between the different stations. Could you try to present every parameter only for one station and shift the data of the other stations to the Supplementary material? That would make the statement of the Figure more concise.

Line 211: “(ERT) soundings” -> “(ERT) measurements”

Line 241: “thickness of the active layer (ALT)” -> “”depth of the active layer”

Line 248: “from the surface to ~ 10 m depth” -> “from the surface on the left hand side to ~ 10 m depth at the right hand side”

Line 249a: “low and high resistivity segment” Please add the range of the values.

Line 249b: “Below the AL” Please add here the depth of the AL.

Line 249c: “existed” -> “exists”

Fig. 6: What about the sensitivity in the different time steps and in your model domain? To be more concise, you could merge Fig. 6 with Fig. 7 and keep the absolute values only for the reference time step or one image per season. In the colorbar please write Ωm instead of ohm.m.

Line 256: “cross-borehole electrical resistivity tomography (ERT)” -> “cross-borehole ERT”

Line 259-260: “The ERT multi-core cables with 24 electrodes per borehole (indicated by the light grey short lines) and a vertical spacing of 0.5m are installed the boreholes B3 and B4.” You wrote that information already in the Methods. You can change that to: “Electrode positions are indicated by light grey short lines.

Line 262: “See Fig. 1 for borehole locations, Fig. 2 for further details and stratigraphy, and Fig. 7 for relative electrical resistivity changes.” Not necessary here.

Line 277-278: “See Fig. 1 for borehole locations, Fig. 2 for further details and stratigraphy, and Fig. 7 for inverted resistivity tomograms.” Not necessary here.

Fig. 8: “kohm.m” -> “kΩm”

Line 04: “fastest” -> “highest”

Line 309a: “TLS were collected” -> “TLS data were collected”

Line 309b: “each year” -> “each year from 2018 to 2023”

Line 328: “Changes in temperature T” -> “Changes in air temperature TA”

Fig. 10: In these Figure you use different colors for two different categories which makes it confusing. It would be easier to understand the plot, if you directly write down which column presents winter and which one summer and you keep the bars in the same color.

Line 343: I think “SZC” has not been introduced before.

Line 355a: “electrical resistivity tomography (ERT)” -> “ERT”

Line 355b: “revealed relative phase changes in water and/or ice content” -> “revealed relative changes in electrical resistivity related to phase changes in water and/or ice content”

Line 356-357: Did you measure the contact resistances? Did they change over time? And if yes, how strong? Did you have a look in the change of apparent resistivities over time?

Line 359: “Further, our modelled resistivities are in line with recent surface geophysical soundings near B3 and B4” Geophysical sounding means 1D survey. I guess you used a configuration for sounding and profiling, right? If yes, I would remove the term “sounding”.

Line 361-362: The resistivities in Fig. 6 suggest that, even the temperature is <0°C below a depth of 4m, the material between 4 and 10 m depth is not frozen or there is only a little amount of ice. Could you try to give some possible explanations?

Line 364: “fines” -> “fine”

Line 365a: “ice from snow melt” -> “ “ice from the time of the snow melt”

Line 365b: “presence of suprapermafrost water” The low resistivity anomaly is not only in the layer above 4 m depth. If you define the upper boundary of the permafrost layer by the temperature curve in Fig. 4, the water is not only suprapermafrost but also in the permafrost layer.

Line 366: “resistivities were highest through all seasons” Could you add the depth here please.

Line 367-69: Maybe you can refer here to the temperature profile in fig. 4. Maybe the water does not freeze until a depth of 10 m because the temperature is too high for freezing (-0.2°C) at the given salinity/Gibbs-Thomson effect? Or is there a preferential flow path?

Line 367: “permafrost resistivities” -> “resistivities”

Line 371: “temperature decrease and the” -> “temperature decrease in spring and the”

Line 373: What do you mean with striking here?

Line 383: “catalysor” -> “catalyst”

Line 393: “amount of unfrozen water” -> “amount of unfrozen water even in the permafrost layer”

Line 393-394: “The stratigraphic recordings and ERT data depict the small-scale heterogeneity within the rock glacier and the low resistivity anomalies throughout the ERT images.” This sentence sounds confusing.

Line 399: “From 1991 to 2000, the depth of the shear zone in borehole B1 on rock glacier Ursina III was between 16.4 m and 11.4 m” -> “From 1991 to 2000, the shear zone in borehole B1 on rock glacier Ursina III was in a depth between 16.4 m and 11.4 m”

Line 414: “observe the relative water content changes” -> “observe the relative resistivity changes associated to water content changes”

Line 415-420: Could you try to make the paragraph a bit more clear?

Line 422: “permafrost temperatures below the active layer remained low.” -> “temperatures in the permafrost layer remained low.”

Line 428: What about vertical water flow?