

We sincerely thank both reviewers for their constructive feedback, which helped a lot to improve the paper. It became clear to us that the paper was not convincingly written and we carefully checked the entire manuscript trying to clarify and precise it. Please find below the answers on the individual reviewer questions and a track change version of the manuscript at the end of the document.

Answers to reviewer 1

The manuscript presents a new country-wide permafrost map over Switzerland, which is based on statistical analysis of the national borehole-data network. During the mapping process, they distinguish between ice-poor and ice-rich permafrost, where the latter normally is associated to rock glaciers or talus accumulation, spatially often detached from the more continuous permafrost zone above in elevation. They used a multiple regressions approach to map MAGT for these two different zones. The study is innovative as the permafrost types react differently on climate perturbations, and in alpine terrain ground ice has not been systematically mapped before. Thus, the study deserves attention. However, there are several issues which should be resolved before considering publication.

In general, the paper is wordy, and can be shortened substantially. Tell the reader what you have done and avoid reporting-style.

Answer: We agree

Changes: We shortened the paper and deleted some repetitions and unsubstantial phrases

There were several parts I really did not follow even reading the passages several times.

Answer: Considering the following comments, I guess this refers mainly to the method section

Changes: The methods section was completely restructured and a supporting figure was added (Figure A) See detailed remark points below.

1. Abstract. The abstract could be improved, what approach is chosen, what results are obtained which deserves attention?

Answer: We agree

Changes: We rewrote the abstract following your suggestion

2. Introduction: The introduction reads partly as a part of a discussion. An introduction should give the reader the background, not a discussion about what approach you have chosen. And it should end up

in testable hypothesis, research questions or similar. This seems a bit mixed now, and should probably be re-formulated.

Answer: We agree

Changes: We rewrote large parts of the introduction considering your remarks and removed the last discussion-like paragraph

3. Methods: This chapter needs revision. To be honest, I still do not quite understand what the authors did in all details, and in which order.

Answer: We realized that it was a major problem to follow our analyses.

Changes: We completely restructured the method section, switching to a chronological explanation of the work steps, which are now easier to follow as well as better justified.

The description is full of report-style deviations in between substantial information. Sentences like “Attributing a MAGT to each thermistor is straightforward” have nothing to do in a scientific paper. Or what was “difficult” or not.

Answer: You are right

Changes: We deleted phrases like that.

I did not follow the handling of steeper slopes than 40 deg, in relation to PR calculations.

Answer: This was not explained well.

Changes: We rewrote this and supported the understanding with two new formulae.

Maybe a flow chart helps to describe the different steps.

Answer: We renounced on a flow chart here but added a new formula.

Changes: We added a new formula.

Give justification why you used different parameters, such like the selection of explanatory variables or why you consider points “5 times minimal distance of thermistors”.

Answer: The distance threshold was optimized empirically. How, is explained in more detail now.

Changes: We gave reasons for our choice of the explanatory variables.

Eq.2: I understand you do a sort of interpolation, but I do not understand why and how you chose the factors. I do not follow p. 5, line 10 and following.

Answer & Changes: This was completely rewritten explaining better what we did and why we did it.

The sensitivity tests: Nice, but now you mentioned more parameters included in the calculation of solar radiation?

Answer & Changes: This is now coherent with the first part of the method section

Mapping of zone 2: Here you really need a flow chart, I cannot follow this, maybe some maps would help to illustrate the different steps, and a justification for e.g. the slope limits used, the size of the buffer zone around the runoff tracks etc.

Answer: The slope limit was found in (Kenner and Magnusson, 2017), which is referred to here

Changes: We insert a figure with 6 maps that represent the different work steps.

But as far as I could make out of it, you do an analysis identifying different types of mass wasting landforms (e.g. avalanche deposits, talus etc.), do some manual editing and comparison to existing data sets, and then you do what to say that the landform is part of zone 2?

Answer: We defined a narrow as possible zone in which the development of ice-rich permafrost is possible. Whether permafrost actually exists at a certain location in this zone is unknown and impossible to model as it depends strongly on the formation history of the talus ground. (Was there coverage of avalanche snow or glacier ice? Was it buried fast and deep enough to be sufficiently protected from melting? Did large scale rock fall occur which created blocky and porous ground layers which enable cooling by ventilation effects?) All this is of course unknown for the large scale.

Were there new regression for these areas, or you used only the regression values from zone 1?

Answer: We used no regression for zone 2. This is now stated more clearly.

I see you mentioned later that if including the boreholes in zone2, the performance goes down. Ok, but is there some calculation to identify zone 2 permafrost or only the mapping? Please clarify these parts. It would help if you show maps of how you classified zone 2, this does not need to be in the main text, ok within an appendix if possible.

Answer: Only the mapping approach was used to identify zone 2.

Changes: As you suggested, we added a figure showing 6 maps which represent the different working steps for creating zone 2.

4. Validation: Ok, but could be part of the methods section, does not need an own chapter.

Answer: You are right.

Changes: We included the validation part in the methods

5. Results: Ok, show a map to present the results, this is a mapping exercise, and it is good for the reader to see a map then.

Answer: We agree

Changes: We moved figure 7 into the results section

The validation is good for zone 1, does not work on zone 2. I would prefer error matrix analysis instead of the histograms (or in addition) against real observations, which also would provide a classification performance measure in addition to the regression-R2s.

Answer: I am not sure if I understand this point. An elevation-dependent analysis of real data does not make so much sense as there is hardly data available for such an analysis and the existing data is biased in their distribution, depending on the motivation of their acquisition (an overrepresentation of north facing permafrost sites at elevations between 2500 and 3000 m asl.)

I am not sure if the comparison to other modelling results (Böckli, Gruber) is a “validation”. I think, no, validation is against something we know is true or false, the other maps are also models with their biases. You also show this again in the discussion (now with maps), the comparison should be a result.

Answer: Well, this was never called a validation. We validated each of these maps using our set of validation records and the results were compared. It is a comparison of the performances of the different maps to show improvements achieved with the PGIM

6. Discussion: The first paragraph is more a result, as is the figure.

Answer & Changes: We slightly rewrote this part although we consider this paragraph as an interpretation of results

Paragraph p.14, line 10 is repetition, the same first paragraph in 5.2. Please avoid redundancies in the manuscript.

Answer: We agree.

Changes: We removed this.

Finally, the discussion is very close to the Swiss conditions, and the comparison to earlier mapping approaches. A discussion should highlight and discuss the results to general science, which turns such a study from a technical report to a scientific contribution. Therefore, I miss comparisons to other areas, a discussion of the transferability of your approach, the evaluation of the use of other statistical approaches like GLMs or similar (see e.g. Hjort et al, recently in Nature Geoscience, or Aalto et al in GRL), the comparison of your model with such approaches.

Answer & Changes: We added a section on the applicability of our approach to other regions and focused more on this issue in the entire paper. A comparison to lowland permafrost is however difficult as there are some considerable differences to (gravitational) processes taking place (or not taking place) in mountain permafrost due to the steep topography.

7. Conclusions: The conclusions states in several places that your approach is a real improvement, and this can be done in other regions. Probably, but then you need the same training data basis (which is exceptionally good in Switzerland), or are the regression coefficients universal? I do not think so. And if it so, why did you not test to transfer your approach, I guess it would be easy to transfer it at least into other areas in the Alps?

Answer & Changes: We added a section on this issue to the discussion.

What is the last conclusion point? I think you may consider reformulation of the conclusions.

Answer: We missed to discuss this point before the conclusions.

Changes: We discuss the last conclusion point before and rewrote some of the conclusions.

In summary, the paper needs major improvements to convince the reader that the presented approach includes a major step forward. I am sort of convinced that this is important, but the paper is hard to read and follow. Especially I am a bit puzzled around how zone 2 is treated in the final product. Distinguishing ground ice content is normal in Arctic permafrost regions, but little considered on mountain permafrost, and only related to clear landforms such like rock glaciers or frozen peat

plateaus. This knowledge has be part of permafrost models, which is, as far as I see, the major message from this study.

Answer: You are right: we rewrote the paper giving clearer explanations on our methods and clearer information on the relevance and improvement of the permafrost mapping in the international context.

Further changes: Some reference boreholes used to set up the PGIM zone 1 regression model were used together with the validation points to validate the permafrost maps APIM, PPDM and PGIM. They were accidentally part of the validation dataset. Using these sites for the PGIM is critically if validation and reference sites are not properly distinguished in the results. We reworked the figures showing the validation results and highlighted all reference sites in figure 4, which shows the validation of the PGIM. We furthermore highlighted all reference sites in table 2 and adapted the manuscript section.

Answers to reviewer 2

The paper presents a new mapping approach for mountain permafrost in Switzerland accounting for ground temperature and ice content. The study is based on regression analysis using borehole temperature collected in the Swiss Alps. The overall interest of this study is to propose a statistical approach to distinguish ice poor and ice rich permafrost in a mapping exercise, and to provide a more detailed and more accurate map of mountain permafrost distribution in Switzerland, representing permafrost #gaps # in its altitudinal distribution resulting of the combination of topoclimatic factors and ground ice content. The approach and objectives of the study are sounds and well-suited for the journal, but it is very hard to provide a detailed and constructive review on the scientific content at the current stage. The writting misses dreadfully conciseness and precision. The paper can only be accepted after major revisions, notably rewriting of most sections to make it easier to understand and to follow the different steps.

Answer: We agree to this general comment and made considerable changes to the paper to improve its clarity and preciseness.

I have tried to formulate general comments to in order to guide the rewriting but I finally dropped many detailed comments as it was too messy. General : One striking thing is the lack of references to the international research context : most references to previous work and knowledge focus on studies conducted in Switzerland, if not on the research team. Given that this study is submitted to an international journal of broad significance, one could expect that the international and broad significance of the paper is clearly stated and explained.

Answer: We added more international references. They are listed at the end of this document. You will find some Swiss authors there as well, these studies are however focused on different world regions.

Mapping of mountain permafrost is not carried out in many countries outside of the Alps (e.g., Norway, Iceland, Canada) and Switzerland plays a pioneer role in this field. This additionally explains the high number of Swiss references. We better embedded the study in the international context by including a section on the applicability of the method to other regions.

Changes: More international references, new section on generic use of the method

Abstract : it lacks of precise results about the predicted permafrost distribution and the improvements achieved using this innovative approach. Stating that allowed a clear improvement is inappropriate and would first need to be described. In general, the abstract is rather coarse. I suggest to rewrite It based on the following outlines (or similar, this is just a suggestion) : 1. State about the overall context, relevance and objective/research gaps and research questions of the study, 2. Briefly explain the chosen method, 3. Provide key results (as quantitatively as possible) 4. Explain the main implications of the results and main answer to research question.

Answer & changes: We rewrote the abstract based on your suggestions

Introduction : Rather badly organised also. The study is introduced as early as L15 with # The permafrost ground ice map.... #, but followed by description of the scientific background are given.

Answer & changes: We rewrote also the introduction and reordered its structure

This background is mainly based on studies from the 1st author and reference to the international context would be welcome.

Answer & changes: We substituted the mentioned references by other authors

However, the lines dedicated to introducing the study (p3 L10-15) are very poor. Try to be more straight-forward and precise in your description : what is the specific approach you choose ? Why (based on the background you described above) ? What are the main expected results to fill the research gap ?

Answer: We rewrote that considering your suggestions.

Changes: The aims and approach of the study is now introduced at the end of the section.

Methods : Here again, it is difficult to follow as the organisation of the method description is messy. Try to be more specific and more logical with the titles in order to ease the reader following the

approach. It starts with # mapping #, then with a # sensitivity analysis #, # a testing of zone 1 for zone 2 # while zone 2 is presented only afterwards.

Answer: You are right, methods were messy, see also comments to reviewer 1.

Changes: we rewrote them following a chronological order of the work steps and explained better what we did and why

Similarly, the subsections are very unequal (2.3 is very short and one can wonder about its relevance). The short paragraph introducing Section 2 (p3 L 17-22) does not reflect the main outlines of the approach as it should, it just give general information about the maps. I wish I would have found a flow chart describing the methodological approach and this should be considered in the revised version. For example, illustrate the # buffer # (P3L25), the # mapped with blue colors # or # mapped in yellow #

Answer: We agree with this remark

Changes: We restructured all this. A supporting figure was added visualizing the different steps leading to the delineation of zone 2.

(L27).P5 L19 : I wonder if the regression coefficients would rather be in the results section while the method should rather describe the statistical approach. The meaning of the regression coefficients has to be briefly expanded (results).

Answer: The regression parameters have no special meaning, they are just technical values of the linear function describing the interaction of solar radiation and MAAT regarding their effect on ground temperatures. As these technical values give no further information to the reader than that what the reader can see in Figure 1 we have the feeling it is easier to give the values in the method section rather than starting an additional paragraph for that in the result section.

Your sensitivity analysis lacks of reference to common statistical methods. It is not clear whether this # bisected# sample is a common way to test model sensitivity or if you have randomly decided it.

Answer: A common way to test the sensitivity of a model is to define critical input variables and to vary them based on a realistic assumption of their uncertainty. Bisecting the statistical population gives in our view a realistic indication of the uncertainty: The model result becomes more stable as more reference values are used to calibrate it. Stability grows however not linearly with the number of reference values but the stability decreases exponentially with decreasing reference values. This means doubling the number of reference values has a much smaller effect on model stability than bisecting the number of reference values. The bisecting method applied here will therefore rather underestimate model stability and can be considered as conservative estimate of the model sensitivity.

More technically, I think that there is a misuse of # PGIM # in Eq. 3 since the acronym refers to the map and Eq. 3 is the regression analysis.

Answer: Yes you are right

Changes: we changed “PGIM” to “MAGT(PGIM)”

Section 3. Isn't it part of the methods?

Answer: Yes it is.

Changes: We moved it to the methods

Section 4 and 5 are better written. However, in my sense, description of map features (general and more detailed at selected areas) is lacking as this study is a mapping exercise. What do your results show in term of permafrost distribution ? What is the elevation belt without permafrost for example ? Giving such information will, in my opinion, strongly broaden the significance of the results.

Answer: The permafrost-free belt has no fix elevation values but its upper boundary depends on aspect, slope and ground characteristic and its lower boundary on terrain form. We show a histogram in the supplementary material showing the permafrost distribution over elevation, including the permafrost gap.

Statistics given in 5.4 could be merge with such results (map) and therefore moved in section 4. They would be easier to get in a Table.

Answer: You are right.

Changes: We moved this to the results

Unless I missed something, the data that you use in Figure1 and 2 are not very clear also : is it annual average ? multi-year average ? others? which measurmeent years ?

Answer: It is a multiyear average.

Changes: We added the years in table 1.

Title of 5.5 is not coherent with the content, even if it deals with ground temperature and ice content, the focus is more on implication of such a map for its use.

Answer & Changes: We renamed the title to: Practical relevance of information on ground temperatures and ice content

Finally, as mentioned in the general comment, one expect that the authors place their study in an international context, at least in the discussion, and this terribly missing.

Answer: You are right

Changes: As mentioned above we inserted a section, which discusses the applicability of the methods to other regions.

Conclusions : they are poorly written. They are very general. They have to be written again with precise results and implications

Answer & Changes: We partly rewrote the conclusions

Further changes: Some reference boreholes used to set up the PGIM zone 1 regression model were used together with the validation points to validate the permafrost maps APIM, PPDM and PGIM. They were accidentally part of the validation dataset. Using these sites for the PGIM is critically if validation and reference sites are not properly distinguished in the results. We reworked the figures showing the validation results and highlighted all reference sites in figure 4 which shows the validation of the PGIM. We furthermore highlighted all reference sites in table 2 and adapted the manuscript section .

International Literature

Azócar Sandoval, G., Brenning, A., and Bodin, X.: Permafrost Distribution Modeling in the Semi-Arid Chilean Andes, 877-890 pp., 2017.

Böckli, L., Brenning, A., Gruber, S., and Noetzli, J.: Permafrost distribution in the European Alps: calculation and evaluation of an index map and summary statistics, The Cryosphere, 6, 807-820, 10.5194/tc-6-807-2012, 2012.

Böckli, L.: Characterizing permafrost in the entire European Alps: spatial distribution and ice content, University of Zurich, Mathematisch-naturwissenschaftliche Fakultät., 2013.

Davies, M. C. R., Hamza, O., and Harris, C.: The effect of rise in mean annual temperature on the stability of rock slopes containing ice-filled discontinuities, Permafrost and Periglacial Processes, 12, 137-144, 2001.

Ebohon, B., and Schrott, L.: Modeling Mountain Permafrost Distribution. A new Permafrost Map of Austria, Ninth International Conference on Permafrost, Fairbanks, Alaska, 2008, 397 - 402,

ESA: Permafrost CCI Project: <http://cci.esa.int/Permafrost>, access: 04.03.2019, 2018.

Fiddes, J., Endrizzi, S., and Gruber, S.: Large-area land surface simulations in heterogeneous terrain driven by global data sets: application to mountain permafrost, *The Cryosphere*, 9, 411-426, 10.5194/tc-9-411-2015, 2015.

Gisnås, K., Etzelmüller, B., Lussana, C., Hjort, J., Sannel, A. B. K., Isaksen, K., Westermann, S., Kuhry, P., Christiansen, H. H., Frampton, A., and Åkerman, J.: Permafrost Map for Norway, Sweden and Finland, *Permafrost and Periglacial Processes*, 28, 359-378, doi:10.1002/ppp.1922, 2017.

Gruber, S.: Derivation and analysis of a high-resolution estimate of global permafrost zonation, *The Cryosphere*, 6, 221-233, 10.5194/tc-6-221-21012, 2012.

Hipp, T., Etzelmüller, B., Farbro, H., Schuler, T. V., and Westermann, S.: Modelling borehole temperatures in Southern Norway – insights into permafrost dynamics during the 20th and 21st century, *The Cryosphere*, 6, 553-571, 10.5194/tc-6-553-2012, 2012.

Huete, A. R.: A soil-adjusted vegetation index (SAVI), *Remote Sensing of Environment*, 25, 295-309, 10.1016/0034-4257(88)90106-X, 1988.

Ishikawa, M.: Spatial mountain permafrost modelling in the Daisetsu Mountains, northern Japan, in: *Permafrost, Eighth International Conference on Permafrost, Zurich, Switzerland, 2003*, 020072388, 473-478,

Krautblatter, M.: Detection and Quantification of Permafrost Change in Alpine Rock Walls and Implications for Rock Instability, 2009.

Krautblatter, M., Funk, D., and Günzel, F. K.: Why permafrost rocks become unstable: a rock–ice-mechanical model in time and space, *Earth Surface Processes and Landforms*, 38, 876-887, 10.1002/esp.3374, 2013.

Magnin, F., Deline, P., Ravel, L., Noetzli, J., and Pogliotti, P.: Thermal characteristics of permafrost in the steep alpine rock walls of the Aiguille du Midi (Mont Blanc Massif, 3842 m a.s.l), *The Cryosphere*, 9, 109-121, 10.5194/tc-9-109-2015, 2015.

Ribolini, A., Guglielmin, M., Fabre, D., Bodin, X., Marchisio, M., Sartini, S., Spagnolo, M., and Schoeneich, P.: The internal structure of rock glaciers and recently deglaciated slopes as revealed by geoelectrical tomography: insights on permafrost and recent glacial evolution in the Central and Western Alps (Italy–France), *Quaternary Science Reviews*, 29, 507-521, 10.1016/j.quascirev.2009.10.008, 2010.

Zhang, T.: Influence of the seasonal snow cover on the ground thermal regime: an overview, *Reviews of Geophysics*, 43, 1-23, 2005.

Distinguishing ice-rich and ice-poor permafrost to map ground temperatures and **ground ice occurrence** in the Swiss Alps

Robert Kenner¹, Jeannette Noetzli¹, Martin Hoelzle², Hugo Raetzo³, Marcia Phillips¹

¹ WSL Institute for Snow and Avalanche Research SLF

² University of Fribourg, Department of Geosciences

³ Federal Office for the Environment FOEN

Correspondence to: Robert Kenner (kenner@slf.ch)

Abstract. Mountain permafrost is invisible and mapping it is still a challenge. Available permafrost distribution maps often overestimate the permafrost extent and include large permafrost-free areas in their permafrost zonation. In addition, the representation of the lower belt of permafrost consisting of ice-rich features such as rock glaciers or ice-rich talus slopes can be challenging. These problems are caused by considerable differences in genesis and thermal characteristics between ice-poor permafrost occurring for example in rock walls, and ice-rich permafrost. We therefore developed a mapping method, which distinguishes between ice-poor and ice-rich permafrost and tested it for the entire Swiss Alps. Ice-poor permafrost was modelled based on the strong correlation of ground temperature with elevation and potential incoming solar radiation. Ice-rich ground does not show such a correlation. The distribution of ice-rich ground is controlled by gravitational processes such as the relocation of ground ice by permafrost creep or by ground ice genesis from avalanche deposits or glacierets covered with talus. The zone of ice-rich permafrost was therefore defined by modelling the deposition zones of alpine mass wasting processes. This dual approach also allows the cartographic representation of permafrost-free belts, which are bounded above and below by permafrost. Indicating temperatures of ice-poor permafrost and distinguishing between ice-poor and ice-rich permafrost on a national permafrost map provides new information for users.

Gelöscht: -

Gelöscht: content

Gelöscht: A new countrywide

Gelöscht: map of Switzerland is presented, indicating ground temperatures and ice content. The new

Gelöscht: ground temperatures is achieved by distinguishing ice-poor and

Gelöscht: permafrost in the modelling process. There is a very significant

Gelöscht: temperatures

Gelöscht: in ice-poor and ice-free

Gelöscht: permafrost was

Gelöscht: and the integration of snow and ice into the ground caused by them.

Gelöscht: allowed a clear improvement in

Gelöscht: elevational

Gelöscht: bordered

Gelöscht: The reproduction of such commonly occurring permafrost gaps allowed a higher mapping accuracy and unambiguity of the mapping zones. Permafrost occurrence is represented by two clearly defined classes: Zone 1 representing modelled ground temperatures and zone 2 indicating excess ground ice outside of zone 1. 58% of 92 validation sites could be definitively classified as having permafrost or no permafrost. If only ice-poor or -free ground is considered, this value reaches 90%. The rather simple dependency

Gelöscht: on two main parameters is not only relevant for mapping but also for a wide range of scientific

Gelöscht: engineering purposes.

1 Introduction

Maps of potential permafrost distribution are useful products applied in different fields of practice and research, because permafrost is an invisible subsurface phenomenon. Such maps are used to plan construction work in alpine terrain, to evaluate local slope instability or to estimate large-scale permafrost occurrence for scientific purposes.

Mapping permafrost in the highly variable alpine landscape is however challenging, particularly on a global scale where ground temperature data or climate and terrain datasets are rare (Fiddes et al., 2015; Gruber, 2012). Developing a method appropriate to model mountain permafrost therefore requires test areas with a dense set of reference and validation data, as well as highly resolved digital terrain models. The Swiss Alps are an ideal test site, as various research activities during the last decades provide an ground temperature dataset, which is largely included in the Swiss permafrost monitoring network PERMOS (2016). Consequently, many authors have used the Swiss dataset to calibrate or validate their permafrost distribution model (Böckli et al., 2012; Deluigi et al., 2017; Fiddes et al., 2015; Gruber et al., 2006; Gruber and Hoelzle, 2001; Haeberli et al., 1996; Hoelzle et al., 2001; Keller, 1992; Keller et al., 1998).

The core of these models is a more or less simplified surface energy balance. Typically, mean annual air temperature (MAAT), represented by elevation and potential incoming solar radiation (PISR) are basic parameters (Hoelzle and Haeberli, 1995). Some authors only use MAAT (Azócar Sandoval et al., 2017) or freezing degree-days and snow cover (Gisnås et al., 2017; Ishikawa, 2003) as external forcing parameters. Fiddes et al. (2015) also consider precipitation and in particular snow cover, wind, humidity and a complete surface radiation balance in a purely physics-based method. Most other studies however used empirical-statistical approaches to convert the energy balance results to a permafrost likelihood or index, dependent on landforms, surface coverage, vegetation or topographic characteristics such as slope or curvature (Böckli et al., 2012; Deluigi et al., 2017; Gruber, 2012; Hoelzle et al., 1993).

However, the actual distribution of mountain permafrost includes phenomena which cannot be sufficiently explained using surface energy balances. This mainly concerns the existence of excess ground ice at the base of talus slopes or in rock glaciers (Haeberli, 1975), which often occur hundreds of metres below the zone of continuous permafrost and are surrounded by permafrost-free ground. This type of permafrost, hitherto referred to as ice-rich permafrost, sometimes exists at locations with higher annual surface heat fluxes than in the surrounding permafrost-free areas (Lerjen et al., 2003; Scapozza et al., 2011). The permafrost-free belts between the ice-rich permafrost at lower elevations and permafrost with lower ice contents at higher elevations are not reproduced in the existing large scale mountain permafrost maps, as was highlighted by Lerjen et al. (2003) and Scapozza et al. (2011). This is because thermally defined maps have no information on ground ice content.

Ice-rich permafrost can persist under warmer climate conditions than ice-poor permafrost due to the high heat capacity of ice (Scherler et al., 2013). Due to latent heat effects, active layer thickness deepening was less pronounced in ice-rich permafrost than at ice-poor monitoring sites in the Swiss Alps during the last two decades (PERMOS, 2016). However, if active layer thickening did occur, it was reversible in ice-poor permafrost (Hilbich et al., 2008; Krautblatter, 2009; Marmy et al., 2013), but irreversible in ice-rich permafrost due to the melt of

Gelösch: ¶

Gelösch: . They

Gelösch: An essential requirement for permafrost distribution maps is reference data to calibrate the permafrost model used. Such data are provided by monitoring networks such as

Gelösch: , which was also

Gelösch: here. Previous approaches

Gelösch: map the entire

Gelösch: in Switzerland

Gelösch: Deluigi et al., 2017;

Gelösch: Hoelzle

Gelösch: 2001; Keller, 1992; Keller

Gelösch: 1998;

Gelösch: Gruber et al., 2006;

Gelösch: are all represented by an empirical-statistical permafrost likelihood or index for different topographic settings and/or landforms. Predictor variables are typically

Gelösch: Further adjustment parameters are

Gelösch: Böckli et al.,

Gelösch: . These approaches have the advantage that uncertainties in the mapping of permafrost are clearly evident for the map user. However, the uncertainty in the prognosis of permafrost conditions are relatively high.

Gelösch: The permafrost and ground ice map (PGIM) of Switzerland presented here uses a different approach of mapping. Kenner and Magnusson (2017) and Kenner et al. (2017) highlighted the differences between ice-rich and ice-poor permafrost occurrence in terms of their development and conservation. Ice-rich mountain permafrost is considered as permafrost in talus ground containing excess ice and can therefore exist at places which do not allow the existence of ice poor permafrost. Such places refer mainly to the characteristic occurrence of ice-rich permafrost at the base of talus slopes (Haeberli, 1975). The origin of ground ice at places, unsuitable for ice-poor permafrost was explained by Kenner and Magnusson (...)

Gelösch: In contrast

Gelösch: ice-poor permafrost, the

Gelösch: of most

Gelösch: remained stable

Gelösch: occurred

Gelösch: ; Hilbich et al., 2008

considerable amounts of ground ice (Zenklusen Mutter and Phillips, 2012). This highlights ground ice as a requirement for the existence of permafrost at ice-rich, low-elevation sites. It is therefore a logical step to consider the ice content when mapping permafrost distribution, just as it is done for physics-based permafrost modelling (Hipp et al., 2012; Pruessner et al., 2018; Staub et al., 2015).

The differentiation between ice-rich and ice-poor permafrost was performed indirectly in earlier studies by including concave footslope positions in permafrost distribution models (Ebohon and Schrott, 2008; Keller, 1992). The permafrost and ground ice map (PGIM) presented here aims to reproduce the elevational permafrost gap by providing a better delimitation of the two main types of permafrost in alpine terrain. We consider the distribution of the continuous zone of ice-poor permafrost (permafrost without excess ice) as being mainly controlled by the surface energy fluxes. While negative temperatures allow small amounts of persistent ground ice in ice-poor permafrost, we assume the opposite for the ice-rich permafrost: Here, the ground ice enables the existence of permafrost, decoupled from current atmospheric conditions and often protected by coarse talus at the surface (Scherler et al., 2014; Schneider et al., 2012). The origin of this ground ice can be syngenetic due to the burial of snow and surface ice by rock debris (Haeberli and Vonder Muehl, 1996; Kenner, 2018) or epigenetic if originating from colder climate periods and displaced by long term rock glacier creep (Haeberli, 2000). To include both ice-poor and ice-rich permafrost in our map, we consider all the processes described above in our model.

2 Methods

The permafrost and ground ice map (PGIM) of Switzerland distinguishes two alpine permafrost zones: Zone 1 indicates modelled ground temperatures and is based on the parameters elevation and PISR. Zone 2 indicates areas outside of zone 1 which might be categorized as permafrost due to the existence of excess ground ice. The modelling approach for zone 2 differs fundamentally from that of zone 1; whereas zone 1 considers thermal conditions, the potential existence of ground ice is considered in zone 2; either due to superimposed rock fall and snow avalanche deposits or due to the gravity-driven relocation of excess ground ice.

2. 1 Mapping approach for zone 1

Zone 1 of the PGIM was derived from modelled ground temperatures. It includes all areas with modelled negative ground temperatures and a buffer area with ground temperatures ranging between 0°C and 1°C. This buffer of 1 K corresponds to about the double standard error of our model output. The area of zone 1 with negative ground temperatures was labelled “Permafrost” and mapped in blue colours. The buffer area was mapped in yellow and is described as “possible patchy permafrost”. The ground temperatures were calculated based on a multiple linear regression analysis using the explanatory variables PISR and elevation (as a proxy for mean annual air temperature). These are the two most important parameters for the surface energy balance (Hoelzle et al., 2001) and are used in almost all permafrost distribution models. Ground temperatures measured in 15 reference boreholes were used as predictor variables. These boreholes were chosen from areas without ice-rich permafrost in Switzerland and Italy, close to the Swiss border (upper 15 sites in table 1). Temperature is measured by thermistors in the boreholes at

Gelöscht: such

Gelöscht: Process-based permafrost modelling considers the deciding relevance of ground ice and relies on a soil stratigraphy including

Gelöscht: to reproduce accurate ground temperatures (Hipp et al., 2012; Staub et al., 2015; Pruessner et al., 2018). As ice content is typically considered for the purpose of process-based permafrost modelling it is logical to adopt this approach for permafrost

Gelöscht: well.

Gelöscht: This differentiation between ice-poor and ice-rich permafrost is moreover the key to reproduce the permafrost-free elevational belt often occurring between ice-rich permafrost in lower elevations and ice-poor permafrost in higher elevations. Scapozza et al. (2011) point out that in all available permafrost models, the permafrost probability increases upslope, which is contradicted by their observations and by many other publications. ¶ The PGIM presented here distinguishes between ice-rich and ice-poor permafrost and is therefore able to reproduce the inverse permafrost distribution described above. Furthermore, the different mapping approach of the PGIM allows the indication of modelled ground temperatures and areas with potentially high ground ice content, while existing permafrost maps represent a permafrost likelihood of occurrence instead. Our ...

Gelöscht: consists of

Gelöscht: three

Gelöscht: , potential incoming solar radiation

Gelöscht: slope

Gelöscht: completely

Gelöscht: , instead of

Gelöscht: effects

Gelöscht: was

Gelöscht: here

Gelöscht: ground ice formation by mutual superimposing

Gelöscht: gravimetrical

Gelöscht: paleo

Gelöscht: Zone 1

Gelöscht: core

Gelöscht: showing

Gelöscht: linear regression analysis using the explanatory variables potential ...

multiple depths between 15 and 100 m with a sub-daily temporal resolution. The thermistors commonly have a measurement accuracy of around 0.1°C or better, and the types of thermistor and data loggers are specified in PERMOS (2016).

The basic concept was to attribute a PISR value, an elevation value and a mean annual ground temperature (MAGT) to each of the 212 thermistors. Based on this dataset, the regression parameters a, b and c in formula 1 were determined and later used in formula 4 to calculate the ground temperatures in zone 1. The four detailed work steps involved are explained below.

$$(1) \quad MAGT = a + b \cdot R + c \cdot E$$

Where:

MAGT is the mean annual ground temperature measured by each individual borehole thermistor

R is the solar radiation value for each individual thermistor

E is the elevation value for each individual thermistor

Step 1: calculating solar radiation values for the ground surface

PISR at the ground surface around each borehole

was calculated using the ESRI tool “Area solar radiation”. The processing was based on a digital elevation model with 2 m resolution (swisstopo swissALTI3D). The input parameter transmissivity was set at 0.4, and the diffuse proportion at 0.5, which corresponds to values recommended for moist temperate climates by the software developer.

Most of the alpine ground surface is snow-covered for about 6 months and receives no insolation during that time. However, steep areas such as rock walls remain snow-free for the entire year (Magnin et al., 2015). To consider the snow cover in slopes below 40°, we only used PISR values calculated for the generally snow-free period June to November (formula 2.1).

For slopes exceeding 40° we additionally included the winter solar radiation. Solar radiation is however only one component of the radiation balance and our simplified model does not consider its counterpart, the long-wave radiation emission. This is a critical parameter during the winter period in steep snow-free areas such as rock walls.

In our model, any additional winter insolation on snow-free surfaces leads to a warming of the snow-free ground on an annual basis. This might be correct for steep sunny slopes, where winter insolation causes a positive feedback. Firstly, it causes snow removal due to melt or the triggering of wet avalanches and subsequently an effective heating of the bare ground above the mean air temperatures (Haberkorn et al., 2015a). In steep, snow-free shady slopes however, long-wave radiation emission largely compensates the incoming solar radiation, causing rock surface

Gelöscht: several

Gelöscht: by thermistor chains

Gelöscht: day

Gelöscht: solar radiation

Gelöscht: 3 (together with an elevation and insolation model)

Gelöscht: at

Gelöscht: single

Gelöscht: single borehole

Gelöscht: of

Gelöscht: single borehole

Gelöscht: Attributing a MAGT to each thermistor is straightforward. To attribu ...

[1] nach unten:) $R = \frac{\sum_{i=1}^n d_{i,r} \cdot k_i}{n}$

[2] nach unten: Where: ¶

Gelöscht: *R* is the solar radiation val ...

[3] nach unten: *n* is the number of ...

Gelöscht: ¶

Gelöscht: with

Gelöscht: " with the

Gelöscht: The snow cover can strongh ...

Gelöscht:

Gelöscht: at least

Gelöscht:

Gelöscht: .

Gelöscht: solar radiation

Gelöscht: July

Gelöscht: .

Gelöscht: Defining solar radiation valu ...

Gelöscht: steeper than

Gelöscht: was more difficult.

Gelöscht: just

Gelöscht: however

Gelöscht:

Gelöscht:

Gelöscht: would lead

Gelöscht:

Gelöscht: southern

Gelöscht: of warming

Gelöscht:

Gelöscht: northern

Gelöscht: the opposite occurs. Long- ...

Gelöscht: balance here

temperatures close to the air temperatures (Haberkorn et al., 2015a). To overcome this weakness in our model, the winter insolation (December to May) which affects the steep terrain parts was multiplied with an aspect-dependent factor. This factor ranges between 0 for the azimuth North (no effect of winter insolation due to similar strong long-wave emission) and 1 for the azimuth South (strongest effect of winter insolation). The winter solar radiation was then added to the summer solar radiation values and applied to slopes steeper than 40° (formula 2.2).

Gelöscht: or even below

Gelöscht: July

Gelöscht: empirically defined

Gelöscht: °

For slopes < 40°: (2.1) $r = PISR_{June-Nov}$

For slopes > 40°: (2.2) $r = PISR_{June-Nov} + PISR_{Dec-May} \cdot A$

Where:

[2] verschoben

r is the solar radiation value at a single surface point

Gelöscht: The intention of

PISR is the potential incoming solar radiation

Gelöscht: PGIM was

A is an aspect factor ranging from 0 (N) to 0.5 (E/W) and 1 (S)

Gelöscht: include almost

Step 2: attributing solar radiation and elevation values to each borehole thermistor

To attribute PISR and elevation to a thermistor we created a point cloud with 2 m resolution, representing the ground surface around each borehole. Every point contained information on its elevation and PISR. Radiation and elevation values for all surface points surrounding a thermistor influence its MAGT. To aggregate all these values into one radiation and elevation value representative for a thermistor, a spatial average was calculated (formula 3, as for elevation). The closer a surface point is to a thermistor, the stronger its influence. This was considered by an inverse distance weighting (factor d in formula 3). The larger the distance between a thermistor and a surface point, the higher the number of points lying within this distance. This increases the weight of distant surface areas when calculating a spatial average. To avoid this we categorized all points into distance classes with a 1 m increment, and included a second weighting factor considering the number of points within one distance class (factor k in formula 3). The maximal distance considered was 5 times the minimal distance of the thermistor to the ground surface. This factor was parameterised empirically by minimizing the sum of residuals between measured and modelled ground temperatures.

Gelöscht: ice-poor permafrost

Gelöscht: zone 1. To meet

Gelöscht: requirement, we had to consider the spread

$$(3) \quad R = \frac{\sum_{i=n}^{i=1} d_i r_i k_i}{n}$$

[1] verschoben

Where:

R is the solar radiation value defined for each individual borehole thermistor

n is the number of distance classes

[3] verschoben

d is a weighting factor which considers the distance between a surface point and the thermistor (inverse distance weighting)

k is a weighting factor which considers the number of surface points within one distance class

r is the solar radiation value of a single surface point

Step 3: Setting up the regression model

Gelöscht: the regression result. The temperature of single thermistors can deviate

We analysed the dataset of step 2 in a multiple linear regression corresponding to formula 1. Naturally, the measured MAGT of a single thermistor deviates from the regression line towards warmer or colder conditions. This spread indicates the occurrence of permafrost in places where the regression result indicates slightly positive temperatures. The intention of the PGIM was rather to accept permafrost free areas within permafrost zone 1 than to include permafrost areas outside of zone 1. To include deviations towards lower temperatures in zone 1, the regression analysis was carried out twice. While all thermistors were used in the first iteration, only those thermistors with a measured MAGT below the modelled MAGT in the first iteration were used in the second iteration.

Gelöscht: for reasons analysed in the discussion section.

Gelöscht: where

Gelöscht: whose

Gelöscht: lay

Gelöscht:

Step 4: mapping zone 1

To map zone 1, the defined regression parameters a, b, and c were applied to a digital elevation and insolation model with 25 m resolution (DEM25 and DIM25, based on the swisstopo DHM25). The DIM25 was produced in the same manner as in work step 1. The temperature value of each 25 m raster cell of the PGIM was defined by:

$$(4) \quad \text{MAGT}_{\text{PGIM}} = 17.275 + 4.059 \cdot 10^{-6} \cdot \text{DIM25} - 0.007015 \cdot \text{DEM25}$$

Depth-dependent 3D effects (Noetzli and Gruber, 2009), which were considered by the inverse distance weighting in our regression model, are not included in our map. In fact, such effects lose significance due to the lower resolution of the map, where insolation variations are spatially averaged within a 25 m raster cell. The temperatures on the map can therefore be interpreted as representing roughly the spatial average of mean annual ground temperatures in a cube with 25 m edge length: this corresponds to the horizontal extent of a raster cell, and the typical depths of our reference data boreholes.

2.2 Sensitivity analysis of the regression result

The regression result depends on the following parameters: PISR, elevation, and reference MAGT. Changes in these parameters will influence the regression result. Elevation is independent from external influences and therefore uncritical for the result. Reference MAGT can be influenced by environmental conditions, as well as by measurement errors, which are not considered here. Our small to medium size statistical sample of measured ground temperatures might be distorted in comparison to the total statistical population. To test the sensitivity of our result to changes in the statistical sample, we recalculated the results with a randomly bisected sample of reference boreholes. We then compared the modelled ground temperatures of all 212 thermistors based on the entire set of reference temperatures with the modelled ground temperatures based on the bisected set of reference MAGT. The calculation of PISR values, especially in steep terrain, included several other parameters such as the distance threshold, a slope threshold, an aspect-dependent weighting factor and assumptions for the timing of snow coverage. Indeed, the model was optimized by applying these parameters. The PISR values are however not an independent statistical unit of a sample of observations but are all based on the same calculation. They are therefore not the origin of random changes in the regression result.

2.3 Mapping zone 2

Zone 2 includes all forms of ice-rich permafrost such as rock glaciers or ice-rich talus slopes. Therefore, we defined areas in which the burial of ice or snow by rock fall can lead to the development of ground ice or in which epigenetic ground ice may have been relocated due to ice creep. We carried out 9 work steps, as shown in Figure A (supplementary Material):

1. Avalanche snow and rock fall deposits were assumed to accumulate at the foot of slopes steeper than 40°. Potential locations of deposits were modelled by calculating runoff tracks from such slopes using ESRI ArcGIS with a 25 m DEM. (Supplementary Figure A, a) This was done in areas above 2000 m a.s.l., as only few, azonal permafrost sites exist below in the Alps (e.g. Cremonese et al., 2011).

Gelöscht: set up

Gelöscht: model the input

Gelöscht: solar radiation

Gelöscht: elevation

Gelöscht: computed with the maximal available resolution of 2 metres around each borehole (based on Swisstopo swissALTI3D). To produce the map, the regression result was

Gelöscht: Swisstopo DHM25). Hereby, the

Gelöscht: 3) $\text{PGIM}_{\text{zone1}}$

Gelöscht: This implies that depth

Gelöscht: ,

Gelöscht: in which

Gelöscht: in

Gelöscht: 3D

Gelöscht: within one

Gelöscht: .

Gelöscht: potential incoming solar radiation

Gelöscht: ,

Gelöscht: ground temperatures and ...

Gelöscht: a well-known value which is

Gelöscht: regression

Gelöscht: ground temperatures

Gelöscht: , which are not considered ...

Gelöscht: . A

Gelöscht: therefore

Gelöscht: temperatures.¶

Gelöscht: solar radiation

Gelöscht: solar radiation

Gelöscht: as well as the distance ...

Gelöscht: Testing the mapping approach ...

Gelöscht: A second regression analysis ...

Gelöscht: The basic concept was to ...

Gelöscht: at

Gelöscht: could

Gelöscht: ground deformation ...

Gelöscht: First

Gelöscht: hydrological flow ...

Gelöscht: * were defined in ERSI

Gelöscht: on the basis of

Gelöscht: .

Gelöscht: (Cremonese et al., 2011)

2. The runoff tracks were buffered by a 120 m wide belt as shown in supplementary Figure A, b. In their upper parts, the resulting areas correspond to the main tracks of snow avalanches and rock fall. Further downslope they represent potential rock glacier creep paths. The buffer was wide enough to include particularly broad rock glacier tongues.

These areas were then reduced stepwise by excluding spatial intersections with other datasets through:

3. Removal of all areas steeper than 30° (Supplementary Figure A, c), which barely contain ice-rich permafrost (Kenner and Magnusson, 2017). Snow avalanches seldom form deposits in such steep slopes and epigenetic segregation ice in talus slopes would creep downslope.

4. Removal of all vegetated areas (Supplementary Figure A, d) because they commonly consist of fine-grained soils at relatively low elevations, where ice-rich permafrost is generally absent in the European Alps (Hoelzle et al., 1993). Vegetation cover was deduced from orthophotos ("SWISSIMAGE" provided by swisstopo) using the SAVI Index (Huete, 1988). Vegetated/unvegetated areas within the resulting 25 m grid were homogenized by iteratively applying a classic 3x3 cell erosion and dilation operation.

5. Removal of maximal extents of Little Ice Age (LIA) glaciation (Supplementary Figure A, e), because glacier coverage is known to disrupt underlying permafrost (Reynard et al., 2003; Ribolini et al., 2010). This dataset was created by Maisch (1999).

6. Removal of lakes and glaciers (based on "swissTLM3D" provided by swisstopo) (Supplementary Figure A, e)

7. Removal of flood plains, which were defined as being areas with slope < 4° and intersected by rivers (based on "DHM25" and "swissTLM3D" provided by swisstopo).

8. The remaining polygons were then aggregated to fill small gaps, simplified and smoothed. After this, all areas listed above were again excluded from the reworked polygons (Supplementary Figure A, f).

9. Zone 2 can overlap zone 1 and zone 1 was mapped with the higher priority, which implies that ice-rich permafrost can also occur within zone 1, where it is not distinguished from ice-poor permafrost.

In a final step, the resulting polygons were checked and manually edited if necessary. Some still contained areas in which surface bedrock excludes the development of ice-rich permafrost. In a few cases, parts of rock glaciers were missing due to errors in the reproduction of creep paths or due to small terrain steps steeper than 30°. Manual editing included two tasks: All areas showing a bedrock surface, infrastructure or > 50% vegetation cover (for some reason not captured by the SAVI index) were removed from zone 2. Missing parts of rock glaciers were added to zone 2 if at least parts of them were already captured by the automatic mapping approach. An exemplary editing task is shown in supplementary Figure B. The human polygon editor was not aware of the positions of the validation points during this process.

Gelöscht: (empirically optimized value) and

Gelöscht: strips

Gelöscht: , namely

Gelöscht: - All

Gelöscht: based on "DHM25" provided by Swisstopo

Gelöscht: have been shown to

Gelöscht:

Gelöscht: This might be because snow

Gelöscht: would leave steeper

Gelöscht: by the initialisation of

Gelöscht: processes

Gelöscht: - All vegetation-covered areas

Gelöscht: The vegetation coverage

Gelöscht: Swisstopo

Gelöscht: Areas of vegetation / no vegetation

Gelöscht: - Flood plains, which were defined as being areas with slope < 4° and intersected by rivers (based on "DHM25" and "swissTLM3D" provided by Swisstopo).¶
- Lakes and glaciers (based on "swissTLM3D" provided by Swisstopo)¶
- Maximal

Gelöscht: ,

Gelöscht: ;Reynard et al., 2003

Gelöscht: edited manually.

Gelöscht: of them

Gelöscht: at the surface

Gelöscht: development as described above

Gelöscht: with slopes over

Gelöscht: coverage (which was

Gelöscht: The

Gelöscht: Zone 1 and zone 2 provide two different types of information: Zone 1 indicates ground temperatures based on a simplified surface energy balance. Zone 2 indicates areas of potential ground ice existence of different sources, which can lead to the occurrence of permafrost outside the thermally based zone 1. Both zones can overlap and zone 1 was mapped with the higher priority here; firstly because it has the higher mapping accuracy and secondly zone 2 was intended as supplement to zone 1 to solve the problem of permafrost occurrence that is hard to explain thermally. This implies that ice-rich permafrost can also occur within zone 1 (...)

2.4 Validation

Using the same validation dataset, we validated the PGIM and two other permafrost maps of Switzerland in addition to compare the results: The Alpine Permafrost Index Map (APIM) created by Bockli et al. (2012), and the Potential Permafrost Distribution Map (PPDM) (Gruber et al., 2006), available online in the swisstopo web map service (swisstopo, 2018). A more detailed methodical background to the PPDM can be found in Haeberli (1975), Keller (1992) and Gruber et al. (2004). The permafrost maps were validated using a set of 98 evidence points of permafrost occurrence or absence, of which 10 represent the Swiss reference boreholes used to set up the regression model for PGIM zone 1 (Table 2). The reference boreholes are distinguished from the other records in the PGIM validation results. A more detailed verification, e.g. of modelled temperatures, was not possible due to the lack of data. The validation dataset partly consists of records collected by Cremonese et al. (2011), of which we only used direct evidence of permafrost occurrence or absence having exact coordinates. Further validation points were provided by continuous near ground surface temperature data (GST) measured at 38 automatic weather stations in the Swiss Intercantonal Measurement and Information System (IMIS) (Russi et al., 2003). To balance the number of permafrost and permafrost-free validation points, only IMIS stations above 2400 m a.s.l. were used, which mostly lie within the critical elevation belt of discontinuous permafrost. The IMIS stations measure near-surface ground temperature at 10 cm depth with a Campbell 107 temperature probe. Of these 38 IMIS stations, 33 register a constant zero curtain during winter and are therefore expected to be on permafrost-free ground (Hoelzle, 1992). The remaining 5 stations show quite constant winter GST between -3°C and -4°C and are located on active rock glaciers. They were therefore classified as permafrost sites. A few additional validation sites were added from different sources (Table 2).

All classes of the PGIM were attributed with the number of validation records lying within them indicating permafrost occurrence or permafrost absence. Additionally, zone 2 of the PGIM was validated against an inventory of 124 rock glaciers in the Albula Alps created by Kenner and Magnusson (2017).

3 Results

Predicting the ground temperatures of the ice-poor reference boreholes on the basis of elevation and PISR yields a correlation coefficient of 0.94 and a standard error of 0.57°C (Table 3, Figure 1). This highlights the strong dependency of ice-poor permafrost on these two factors and its relatively high predictability. Including ice-rich permafrost in this regression analysis causes a drastic drop of the correlation coefficient and thus in the predictability of permafrost (Table 3 and Figure 2).

[4] nach unten: . A more detailed verification, e.g. of modelled temperatures, was not possible due to the lack of data.

[5] nach unten: on permafrost-free ground (Hoelzle, 1992). The remaining 5 stations show quite constant winter GST between -3°C and -4°C and are located on active rock glaciers. They were therefore classified as permafrost sites.

Gelöscht: Furthermore, a few additional borehole sites, which are not included in Cremonese et al. (2011) were added to the validation set (Table 2).

[6] nach unten: All classes of the PGIM were attributed with the number of validation records lying within them indicating permafrost occurrence or permafrost absence.

Gelöscht: Some of these validation points correspond to the dataset collected by Cremonese et al. (2011). Records from this database were only used if they have exact coordinates and show direct evidence of permafrost occurrence or absence; either based on observations of ice in construction work trenches and rock fall scars or based on ground temperature data measured in boreholes. Of the records in this database, 74 % indicate permafrost. To include more non-permafrost validation points we added a second validation dataset based on continuous ground surface temperature data (GST) measured at 38 automatic weather stations in the Intercantonal Measurement and Information System (IMIS) (Russi et al., 2003). To balance the number of validation points with and without permafrost, only IMIS stations

Gelöscht: The same validation process was applied to the alpine permafrost index map

Gelöscht: and the potential permafrost distribution map (PPDM) created by Gruber et al. (2006), available online in

[4] verschoben

[5] verschoben

[6] verschoben

Gelöscht: a rock glacier

Gelöscht: With 124 records, the inventory represents all rock glaciers in

Gelöscht: 4

Gelöscht: potential incoming solar radiation

Gelöscht: Fig.

Gelöscht: The regression result

Gelöscht: elevation (MAAT)

Gelöscht: solar radiation and underlines

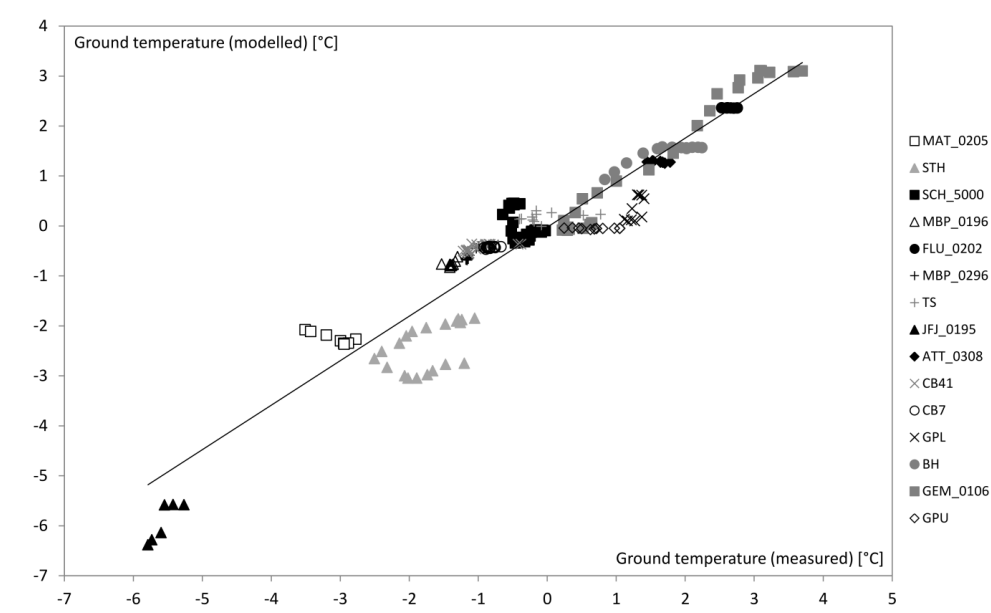
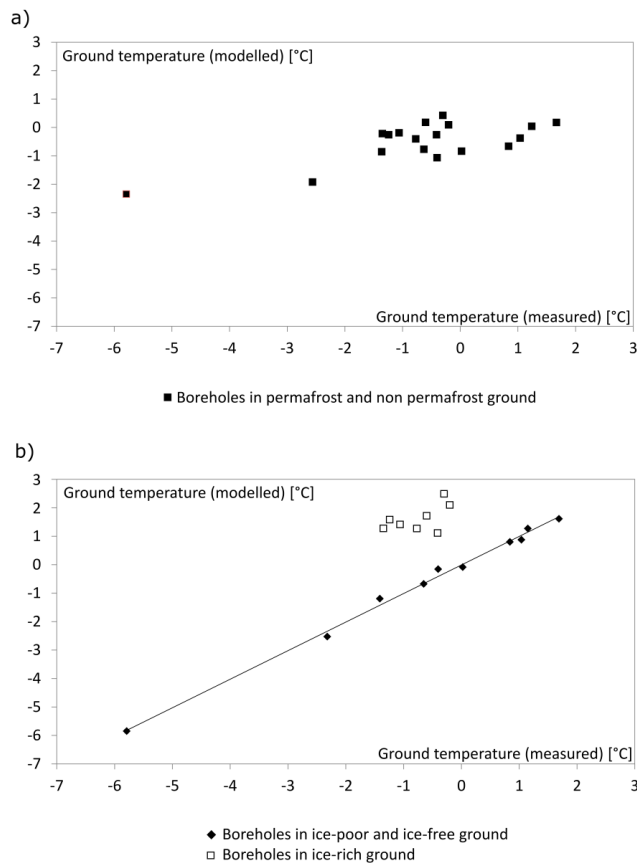


Figure 1: Measured MAGT in 15 boreholes plotted against the modelled MAGT at the same locations. The regression line corresponds to formula (4) given in section 2.1. The borehole abbreviations are explained in table 1.

[7] verschoben

[8] verschoben



[9] verschoben

Figure 2: Each data point represents a borehole and its measured and modelled mean annual ground temperatures at the depth with lowest temperatures. Included are the ice-poor boreholes 1-10 and all ice-rich boreholes in Table 2. The linear regression based on elevation and PISR shows no systematic relation between these two parameters and the ground temperatures when using both ice-poor and ice-rich boreholes for the regression (a), but a clear correlation appears when using only ice-poor or ice-free boreholes (b).

Although thermistors of individual boreholes show clear deviations from the regression line, bisecting the set of reference temperatures in ice-poor ground only had a small effect on the regression result. The differences between the modelled ground temperatures based on the entire set of reference temperatures and the ground temperatures based on the bisected sample showed a mean value of -0.11°C and a standard deviation of 0.15°C . The highest deviation found for a single thermistor was 0.51°C . The similar values for the standard deviation and the mean value suggest that the changed reference sample mainly caused a constant offset of the temperatures of slightly over -0.1°C . This corresponds to an elevation shift of zone 1 by about 12 m. Explanations for the deviations of single boreholes or thermistors are presented in chapter 4.1.

An example section of the PGIM is shown in Figure 3. The entire map is available online as a shapefile <https://doi.org/10.5281/zenodo.1470165>. Together, zones 1 and 2 indicate a potential permafrost area (area

Gelöscht: limited effects

Gelöscht: largest

Gelöscht: Transferred into the map, this

Gelöscht: discussed later. Including ice-rich permafrost in this regression analysis causes a drastic drop in the predictability of permafrost (Table 3 and Figure 2). The formerly strong correlation practically disappears.

considered by the map to potentially contain permafrost), of 2000 km² in the Swiss Alps, which is considerably less than that indicated by the APIM (3710 km² (Böckli, 2013)) and also less than on the PPDM (2550 km² (Gruber et al. 2006)). To estimate the actual permafrost area (area effectively containing permafrost), Böckli (2013) considered all areas of the APIM with an index value > 0.5. This results in an area of 2160 km² for the APIM. The PGIM includes 830 km² in the core area of zone 1 and 600 km² in zone 2, of which maximum 90% are expected to include permafrost according to the validation output. This results in an actual permafrost area of < 1400 km² in the Swiss Alps, which corresponds to < 3.4% of the area of Switzerland. For comparison, Keller et al. (1998) gave a value of 4-6 %.

[10] verschoben

[11] verschoben

[12] verschoben

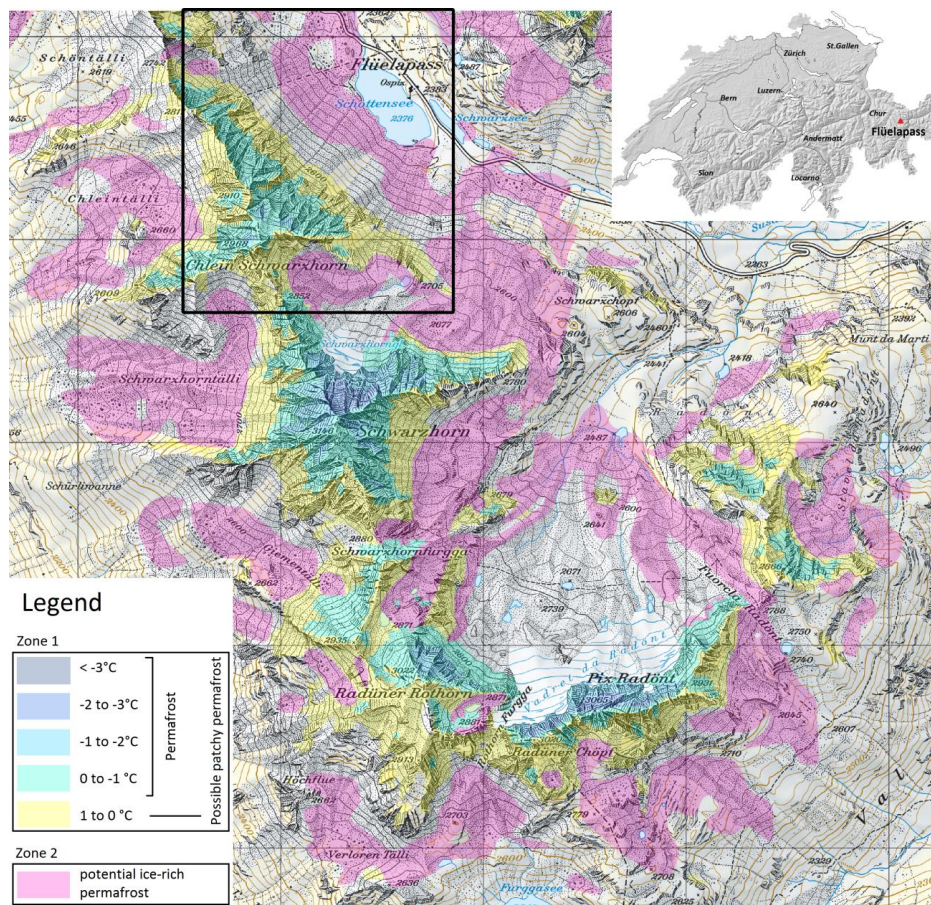
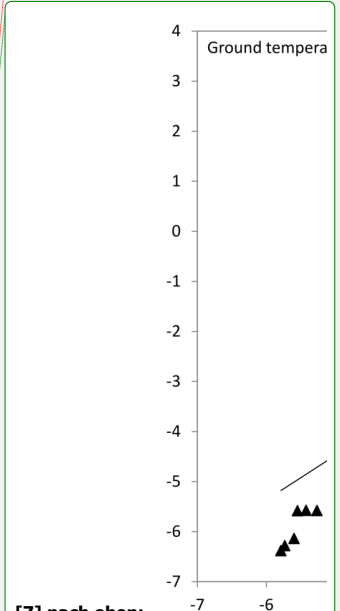


Figure 3: Map section of the PGIM close to Flüelapass in the Eastern Swiss Alps (inset map of Switzerland), showing the permafrost distribution in two zones. The black frame is the sector shown in Figure 8. The map grid has a resolution of 1 km. (Map: pixmaps © (2017) swisstopo (5704 000 000))

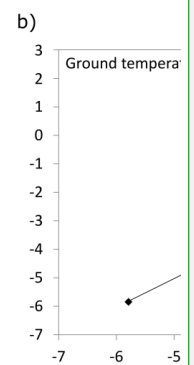
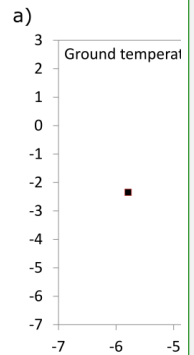
[13] verschoben

Gelöscht: 1



Gelöscht: MAGTs in 15 boreholes plotted against the modelled MAGT at the same locations. The regression line corresponds to formula (3) given in section 2.1.

[8] nach oben: The borehole abbreviations are explained in table 1. ¶



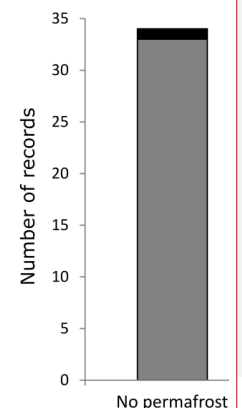
[9] nach oben: ...

Gelöscht: ¶

Gelöscht: The linear regression based on elevation and potential solar radiation shows no systematic relation between these two parameters and the ground temperatures when using both ice-poor and ice-rich boreholes for the regression

Gelöscht: 4.... The two ...ones

Gelöscht: 5.... The different probabili



Gelöscht:

The validation of the PGIM (Figure 4) confirms the high accuracy of zone 1. Only two validation sites representing ice-poor permafrost are located outside the core area of zone 1 labelled “permafrost” (Figure 4). In turn, no permafrost-free sites were located in the core area of zone 1. Zone 2 (potential ice-rich permafrost) includes 21 sites indicating permafrost and 2 indicating permafrost absence. Zone 2 furthermore includes 95.5% of the rock glacier area registered in the Albula Alps inventory (Kenner and Magnusson, 2017). This value applies to the automatically created version of zone 2 before it was manually edited.

The validation of the APIM (Boeckli et al. 2012) is shown in Figure 5. The zones with a permafrost index of 0 (no permafrost) or 1 (definite permafrost) have a similar error rate as the corresponding classes in the PGIM, but contain less validation records. The indices between 0 and 1 contain a rather homogeneous ratio of permafrost and no-permafrost sites, an increase in permafrost frequency is only visible for the very highly indexed areas (> 0.8).

The validation result of the PPDM (Gruber et al. 2006) is shown in Figure 6. The different probability ranges reflect the actual permafrost frequency quite well for the high probability classes but show larger deviations for the lower classes. Several permafrost evidence points exist outside the permafrost zonation of this map.

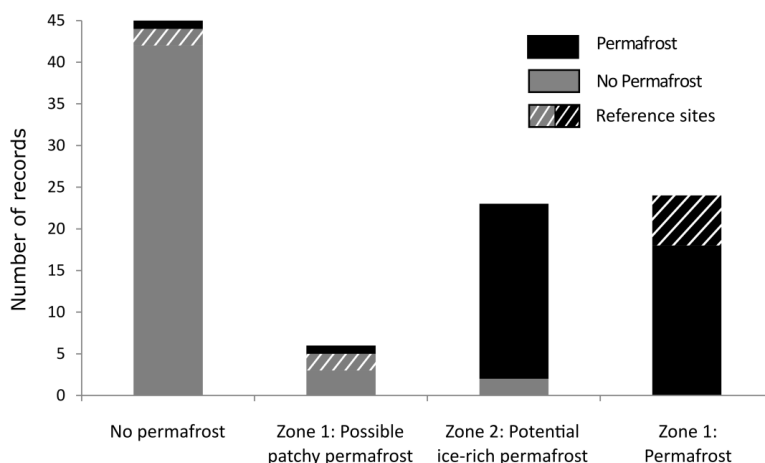
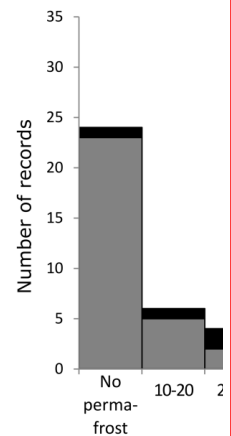
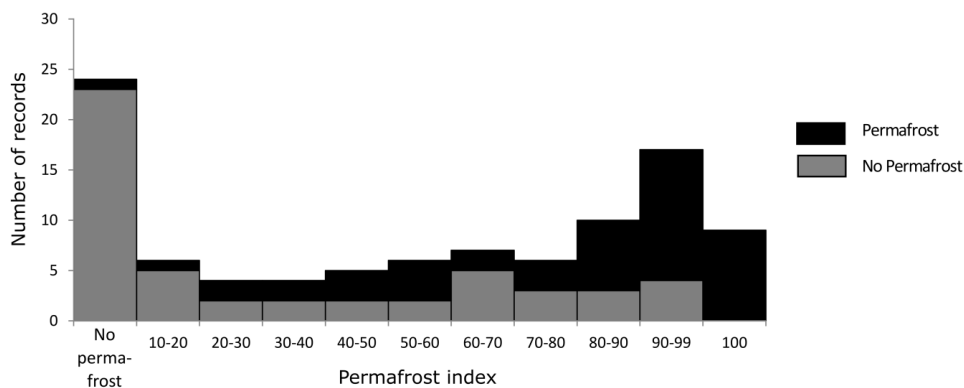
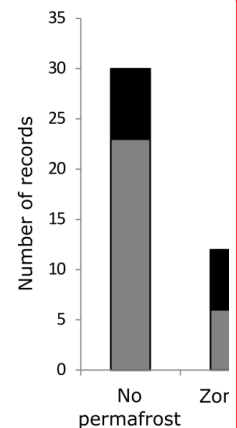
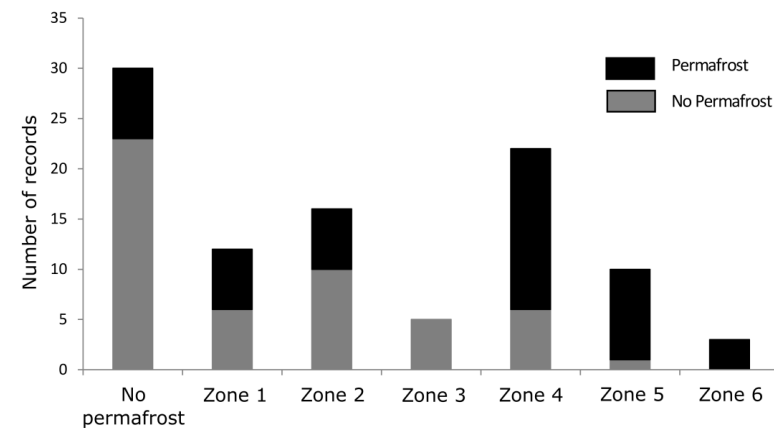


Figure 4: Validation of the PGIM showing the number of validation points with permafrost occurrence and permafrost absence in each map class. The striped sites represent the boreholes used to set up the regression model for the PGIM.



Gelöscht:

Gelöscht: 4



Gelöscht:

Gelöscht: 5

Figure 5: Validation of the APIM (Boeckli et al. 2012) showing the number of sites with permafrost occurrence and permafrost absence for different permafrost probability ranges. As the map does not define classes but gives unique index values for each cell of the map, ranging from 0.1 to 1, these values were classified in 10 permafrost classes and a “No permafrost” class including all records outside the permafrost zonation.

Figure 6: Validation of the PPDM (Gruber et al. 2006) showing the number of sites with permafrost occurrence and permafrost absence in each map class. The zones were originally defined as follows: Zone 1 – local permafrost possible, patchy, discontinuous; Zone 2 – local permafrost possible, frequent patchy distribution; Zone 2 – local permafrost possible, patchy to extensive; Zone 4 – Extensive permafrost likely; Zone 5 – Extensive permafrost likely, increasing thickness; Zone 6 – Extensive permafrost likely, very thick in places, to over 100 m. The class “No Permafrost” includes all records outside the permafrost zonation.

4 Discussion

4.1 Permafrost predictability

While the permafrost modelling based on the regression analysis was successful for ice-poor permafrost, it is not applicable for ice-rich permafrost (table 3). This makes ice-poor permafrost much better predictable than ice-rich permafrost. The high correlation coefficient achieved by the regression analysis is remarkable, because the borehole temperatures represent different landforms with strong differences in substrate and snow coverage. These factors, which influence ground temperatures (Haberkorn et al., 2015b; Hoelzle and Gruber, 2008; Schneider et al., 2012; Zhang, 2005), are represented in the regression result by rather small deviations of less than 1 K (Figure 7).

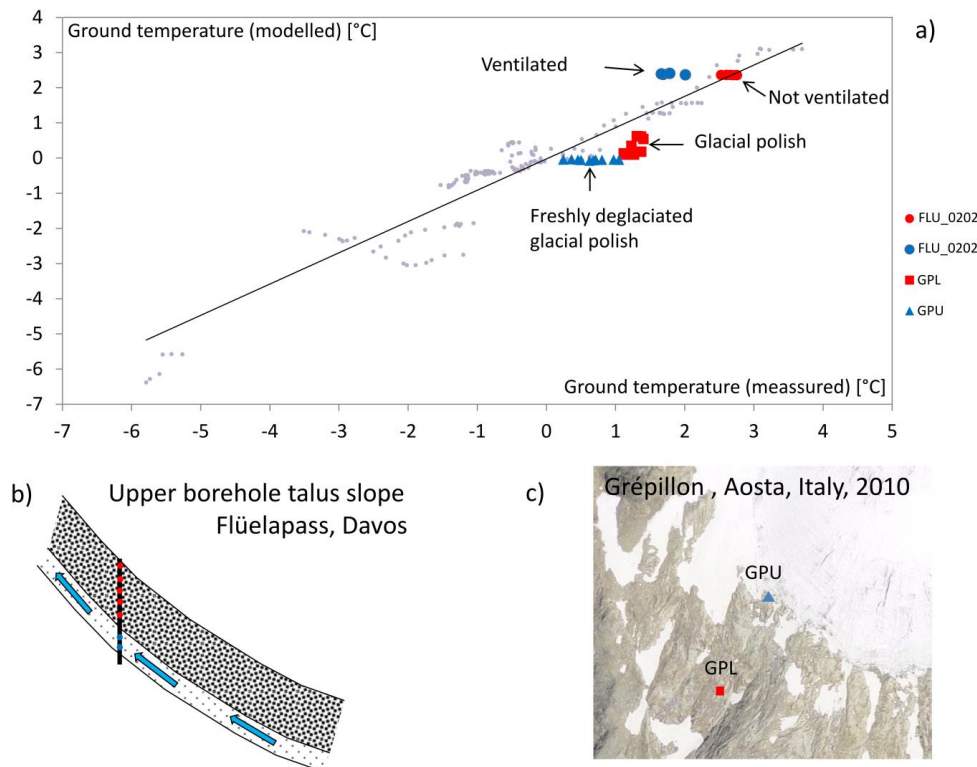
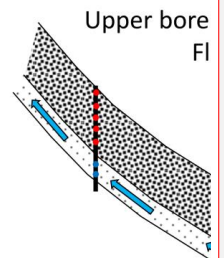
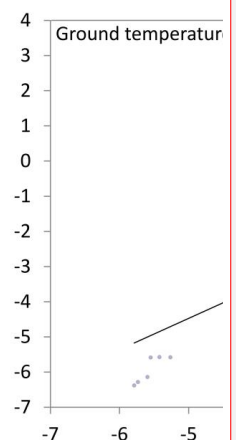


Figure 7: The Flüela- (Eastern Swiss Alps) and Grépillon (Italian Alps) boreholes show examples of thermal disturbances. The lowermost 3 thermistors in Flüela (FLU_0202) are ventilated (Phillips et al., 2009) and thus deviate from the regression line. The Grépillon boreholes are drilled in a glacial polish, which can warm more efficiently than the talus surfaces at most of the other boreholes. The upper Grépillon borehole (GPU) was only recently deglaciated: whereas the uppermost thermistors have adapted to the new thermal conditions, there is a clear temperature gradient towards lower temperatures at greater depth. Here, the temperatures are still close to 0° C as a consequence of the former glaciation.

Gelöscht:Seitenumbruch.....
1
Gelöscht: :
Gelöscht: 5
Gelöscht: The large deviations of
Gelöscht: temperature data acquired in
Gelöscht: within our regression model
Gelöscht: , column 4) highlights the importance of distinguishing between
Gelöscht: and ice-poor
Gelöscht: when using only ice-poor permafrost in
Gelöscht: model
Gelöscht: in particular when taking into account that
Gelöscht: are known to
Gelöscht: Zhang, 2005;
Gelöscht: 6



Gelöscht:
Gelöscht: 6
Gelöscht: nice
Gelöscht: loose rock
Gelöscht: just

Nevertheless, deviations exist due to advective cooling (Flüelapass; Figure 7a & 7b; (Phillips et al., 2009)), substrate characteristics (relatively warm glacial polish at the lower Grépillon borehole; Figure 7a % 7c) or temperature disturbances due to former glaciation (upper Grépillon borehole; Figure 7a & 7c).

Ice-rich permafrost cannot be satisfactorily predicted based on surface energy fluxes and requires the consideration of mass wasting processes such as rock fall and avalanche activity as well as creep rates and varying glaciation during the Holocene. As these processes are often not known in detail, the accuracy of the cartographic representation of ice-rich permafrost is limited, as discussed in section 4.3.

4.2 Map uncertainty and accuracy

The uncertainty of a map can be quantified by the validation points, which are clearly mapped as being permafrost or not. In the PGIM, definitive permafrost is indicated by the core area of zone 1. In the APIM definitive permafrost is indicated by a permafrost index of 1 (for validation, values higher than 0.994 were rounded to 1). The PPDM does not have a zone of definitive permafrost. Definitive permafrost absence is indicated on all three maps for areas outside the permafrost zonation. The PGIM could attribute 69% of the validation points to a definitive class, while the APIM reached 33% and the PPDM 23% (Figures 4-6).

Accuracy can be measured by the number of validation points wrongly attributed to a definitive class or by the plausibility of the description of a class. In the PPDM, 7 permafrost sites occur outside the permafrost zonation. The definitive permafrost classes of the APIM and the PGIM predict all validation points correctly - with the exception of one site (Emshorn-Oberems), which is wrongly attributed on both maps. A weakness of our accuracy analysis is that the landforms and geographical locations of the validation sites do not represent the natural variability. Terrain- or region related errors of the permafrost zones, which are not captured in this accuracy analysis are therefore possible.

The APIM includes almost all areas in Switzerland in which permafrost will occur and is therefore a useful tool to exclude permafrost at a certain location. However, similar to the PPDM it shows weaknesses in the reproduction of permafrost-free areas, while the PGIM performs better here. This might be caused by the 'elevational permafrost gap' phenomenon introduced in section 1. Figure 8a shows the example of the research site Flüelapass (Kenner et al., 2017), with a permafrost-free belt between the ice-poor and ice-rich zones.

Mapping solely based on thermal influences is not able to reproduce the permafrost gap and either neglects the ice-rich permafrost at the base of talus slopes (Figure 8b) or overestimates the permafrost further upslope (Figure 8b and 8c). This problem leads to a high number of permafrost-free validation points in the zones of medium permafrost probability on the comparison maps. For example, the 60-70 % probability zone on the APIM or the zone "local permafrost possible, patchy to extensive" on the PPDM (Figures 5 and 6). This may also cause the rather random distribution of permafrost-free validation points over the remaining probability classes of the APIM. In the PGIM the permafrost gap becomes visible when plotting the mapped permafrost area against elevation as shown in Figure 9.

Gelöscht: such disturbing effects are clearly visible in some cases. Figure 6 shows examples of thermistors which deviate from the regression line...eviat...

Gelöscht: The high predictability of ice-poor permafrost is insufficiently exploited when ice-rich permafrost is not treated separately in the data analysis (Table 3 and Figure 2). ...ce-poor and ice-rich

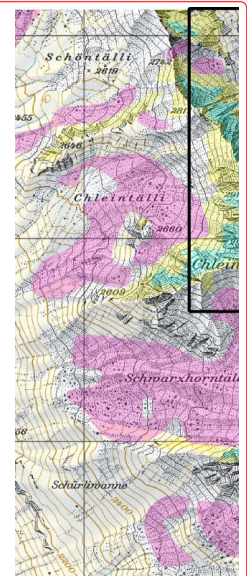
Gelöscht: 5....2 Map interpretation,

Gelöscht: In contrast to other maps, the PGIM only has 2 zones, which are simple to interpret: Zone 1 represents modelled ground temperatures and zone 2 specifies areas with potentially high ground ice content caused by mass movement

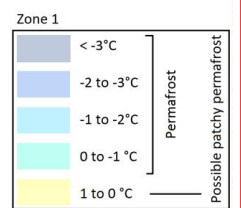
Gelöscht: contained within them

Gelöscht: . In the Alps permafrost distribution is commonly characterised by thermally induced permafrost...introdu...

[13] nach oben: The map grid has a resolution of 1 km. (Map: pixmaps © (2017) swisstopo (5704 000 000))



Legend



Gelöscht:

Gelöscht: does...s not able to reprodu

(supplementary material). A more accurate identification of this permafrost gap is an important step because it enables a better planning of ice-sensitive infrastructure in alpine terrain.

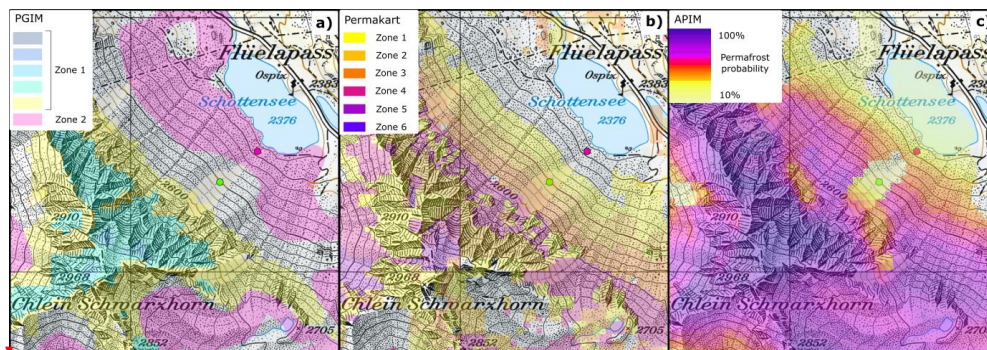


Figure 8: Comparison of three permafrost maps at the research site Flüelapass (a: PGIM, b: PPDM (Gruber et al. 2006), c: APIM (Boeckli et al. 2012)). This example shows typical alpine permafrost distribution, with ice-rich permafrost at the base of a talus slope, a permafrost gap further upslope and permafrost in the rock wall above the talus slope. A borehole without permafrost (green dot (FLU_0202)) is located in the permafrost gap, another with ice-rich permafrost (pink dot (FLU_0102)) is at the base of the slope. (Map: pixmaps © (2017) swisstopo (5704 000 000))

4.3 Challenges and possible future approaches in mapping ice-rich permafrost

Zone 2 of the PGIM has a relatively high uncertainty. The low number of permafrost-free validation points wrongly attributed to this zone (2 out of 33, see Figure 4) might rather overestimate the accuracy of the zone due to a general lack of permafrost-free validation points in talus slopes. However, there is very little ice-rich permafrost outside this zone, as indicated by the 95% representation of the Albula rock glacier inventory within the automatically created raw version of zone 2. Accordingly, zone 2 should not be interpreted as a reliable representation of ice-rich permafrost but rather as a best-guess including most of the ice-rich permafrost in Switzerland, with some bycatch of permafrost-free ground. The greatest challenges in mapping ice-rich permafrost are the correct representation of rock glaciers and the differentiation between loose rock sediments which can contain ice-rich permafrost and bedrock which cannot. Merging existing, manually created rock glacier inventories in Switzerland to a nationwide inventory would improve zone 2 as the model approach could be focussed on ice-rich talus slopes.

Kenner and Magnusson (2017) highlighted the influence of the combined effect of lithology and precipitation on the occurrence of ice-rich permafrost. Ice-rich permafrost is less frequent in sedimentary rock areas with high precipitation rates and relatively abundant in drier areas with crystalline or metamorphic lithology. These regional climate- and lithology induced differences are difficult to implement in a map and must be carefully interpreted by the user.

Gelösch: construction projects

Gelösch: The typical azonal permafrost found at low elevations (<2000 m), at sites like Creux du Van (Delaloye et al., 2003) or Dreveneuse (Delaloye and Lambiel, 2007) is not included on any of the permafrost distribution maps for the Swiss Alps discussed in this paper. The presence of azonal permafrost is possible due to a constellation of processes involving unusually effective advective cooling. These are difficult to implement in a large-scale map.¶

Gelösch: located

Gelösch: 5

Gelösch: The ice-rich permafrost in zone

Gelösch: Fig. 3) here

Gelösch: this

Gelösch: possible one

Gelösch: This area needs to be narrowed down in a common effort by the permafrost community and improved updates of the map are planned in future. This has certain challenges, which are discussed below.

Gelösch: Rock glaciers are a clearly visible indicator of ice-rich permafrost but are also the most critical ice-rich permafrost features to map, as the creep process has to be considered. Creep paths are sometimes hard to reproduce, as rock glaciers change the terrain morphology in such a way that the runoff tracks, which are the basis of zone 2, run laterally to the convex rock glacier body and their buffer zone does not incorporate the whole rock glacier. Additionally, in some cases rock glaciers creep over terrain steeper than 30° and these parts of rock glaciers are missing in zone 2. A further problem is caused by rock glaciers mapped as LIA glaciers by Maisch (1999), which are thus not included in the map. The manual editing of zone 2 has largely solved these problems. However further improvements would be possible by merging the existing rock glacier inventories in Switzerland and completing a nationwide inventory by mapping hitherto uninvestigated areas. In this way, rock glaciers could be excluded from the automatic mapping of ice-rich ground, allowing to focus on ice-rich tal...

Gelösch: . As ice

Gelösch: , zone 2 will contain more or less permafrost in the respective regions.

Gelösch: 5.4 Permafrost area in Switzerland¶
The PGIM indicates a potential permafrost area

4.4 Relevance of information on ground temperatures and ice content

The PGIM is the first large scale permafrost map indicating permafrost temperature and ground ice content. The ice-rich permafrost in Zone 2, located in lower elevations than zone 1, typically has temperatures at or slightly below

0°C (PERMOS, 2016). The distribution of ice-rich and/or warm permafrost is particularly important for engineering purposes as it affects the ground stability and bearing capacity strongest (Bommer et al., 2010). Permafrost in rock walls is very sensitive to climate fluctuations (Noetzli and Gruber, 2009) and rock temperatures influence rock slope instability (Davies et al., 2001; Gruber and Haeberli, 2007; Krautblatter et al., 2013). In general, permafrost requires adapted construction materials to prolong the service-life of infrastructure (Bommer et al., 2008).

4.5 Application to other regions

The mapping approach of zone 1 can probably be adapted to other mountain regions or future climate scenarios without requiring any local ground temperature reference data. Formula 4 in section 2.1 defines the distribution of ice-poor permafrost solely by the parameters PISR and elevation as a proxy for MAAT. PISR can be calculated globally based on digital elevation models. By setting radiation to 0, Formula 4 represents a direct conversion between elevation and MAAT. If the elevational MAAT distribution is known, elevation models for other climate regions can be adapted using this conversion and can then be used in the regression formula defined in this study. The same applies for future scenarios of air temperatures. This approach should be tested in a future study using the validation dataset of worldwide borehole temperatures, and is currently in preparation (ESA, 2018). This universal application of our method would only be feasible for mapping ice-poor permafrost. Our approach for modelling ice-rich permafrost can only be used for regions very similar to the Swiss Alps, as it is designed for non-arid, vegetated areas and requires special datasets such as information on past glaciation.

5 Conclusions

This study presents a new approach to map permafrost distribution in the Swiss Alps based on the differentiation of ice-poor and ice-rich permafrost. The new approach highlights i) the high predictability of ice-poor, thermally induced permafrost based on a simplified surface energy balance and ii) the need for a different mapping approach for ice-rich permafrost, typically formed at the base of slopes by alpine mass wasting. This is important for mapping and local modelling, but also to develop scenarios of present, past and future permafrost evolution.

We conclude that:

- Using a simple linear regression analysis of solar radiation and elevation, ground temperature profiles of 15 boreholes in ice-poor or ice-free ground could be modelled with a clearly sub-Kelvin accuracy.

- The regression result that zone 1 of the map is based on can easily be adapted to different climate conditions: either spatially for different mountain regions in the world, or temporally for future climate scenarios in Switzerland.

[10] nach oben: of 2000 km² in the Swiss Alps, which is considerably less than that indicated by the APIM (3710 km² (Böckli, 2013)) and also less than on the PPDM (2550 km² (Gruber et al. 2006)).

[11] nach oben: This results in an area of 2160 km² for the APIM. The PGIM includes 830 km² in the core area of zone 1 and 600 km² in zone 2, of which maximum 90% are expected to include permafrost according to the validation output.

Gelöscht: This results in an area of ≤ 1400 km² of permafrost terrain in the Swiss Alps, which corresponds to 3.4% of the area of Switzerland.

[12] nach oben: For comparison, Keller et al. (1998) gave a value of 4-6 %.

Gelöscht: To estimate the true permafrost area, Böckli (2013) suggested to consider all areas of the APIM with an index value > 0.5.

Gelöscht: 5.5 Ground temperatures and ice content¶
The advantages of the PGIM are not only its relatively high accuracy and low uncertainty. The zonation allows an estimation of the permafrost temperature, as zone 1 indicates ground temperatures and the ice-rich permafrost in Zone 2, located in lower elevations than zone 1, has typically a temperature a few degrees below to

Gelöscht: localisation

Gelöscht: Warm permafrost in rock walls is very sensitive to climate fluctuations and can contribute to rock slope instability (Davies et al., 2001; Krautblatter et al., 2013; Gruber and Haeberli, 2007). In cold rock permafrost, specially adapted construction materials are required

Gelöscht: Furthermore, the distinction of ice-rich permafrost can be the basis for a more accurate estimation of the potential water resources stored as ground ice in mountains (Jones et al., 2018; Böckli, 2013)

Gelöscht: map for the Swiss Alps but also further corroborates

Gelöscht: to distinguish it from

Gelöscht: .

Gelöscht: for developing

Gelöscht: - Ground temperatures can be mapped

Gelöscht: at a national scale at several depths in ice-poor or ice-free ground. It is likely

Gelöscht: similar results can be obtained in other

Gelöscht: regions using the method presented here

- A major improvement has been achieved in defining permafrost-free areas (referred to as a permafrost gap in this study), which can be of particular interest for construction projects involving ice-sensitive infrastructure.

Gelöscht:

- The distribution of ice-rich permafrost outside the continuous zone of permafrost is better predicted by the analysis of mass wasting processes than by thermal influencing factors.

Gelöscht: of

Gelöscht: 1

Gelöscht: ones

- The permafrost and ground ice map PGIM presented contributes towards an improvement in the accuracy of permafrost mapping in Switzerland.

Gelöscht: here

- The two zones on the map provide clear information on their meaning (i.e. ground temperatures versus the potential occurrence of excess ice permafrost) rather than a probability value, and are thus easy to interpret.

Gelöscht: 2

Gelöscht: give the reader

Gelöscht: resp.

Gelöscht: enable

While the distribution of ice-poor permafrost is predictable with a high accuracy, there is a relatively large uncertainty referring to ice-rich permafrost. To improve the mapping result here, a more detailed dataset on surface characteristics (talus vs. bedrock) and manually mapped rock glacier inventories are required. An improved data base is needed as well for the validation of permafrost maps in general. Currently available datasets are biased regarding aspect, elevation and landforms. In addition, evidence of permafrost absence in the belt of discontinuous permafrost is clearly lacking.

Gelöscht: interpretation with a low uncertainty

Gelöscht: - The future adaptation of the map to higher ground temperatures induced by climate warming in the reference boreholes is easily possible.¶

Table 1: Reference boreholes provided by 1 - PERMOS (2016), 2 – WSL Institute for Snow and Avalanche Research SLF, 3 - Swiss Federal Office for the Environment FOEN, 4 - University of Lausanne, 5 - ARPA Valle d'Aosta. The uppermost 15 were used for the calculation of ground temperatures in zone 1 of the PGIM. The lowermost 8 were used to demonstrate the failure of this calculation if ice-rich and ice-poor boreholes are not distinguished (Table 3).

Line	Site name & provider	Abbreviation	Ground ice content	Elevation [m a.s.l.]	Longitude (WGS 84)	Latitude (WGS 84)	Time series
1	Breithorn ³	BH	Ice-free	2865	7.81785	46.14010	2016 – 2017
2	Flüela 0202 ²	FLU_0202	Ice-free	2501	9.94314	46.74687	2003 – 2005; 2009
3	Tsaté ¹	TSA_0104	Ice-poor	3040	7.54844	46.10904	2009 – 2012; 2015
4	Schilthorn 5200 ¹	SCH_5000	Ice-poor	2910	7.83442	46.55828	2006 – 2009; 2013 – 2015
5	Stockhorn 6000 ¹	STo_6000	Ice-poor	3410	7.82419	45.98678	2011 – 2012; 2014 – 2016
6	Les Attelas 3 ⁴	ATT_0308	Ice-free	2741	7.27492	46.09659	2009 – 2010
7	Jungfrau ¹	JFJ_0195	Ice-poor	3590	7.97316	46.54617	2010 – 2015
8	Gemsstock ¹	GEM_0106	Ice-free	2940	8.61043	46.60125	2009 – 2010; 12; 15; 16
9	Cima Bianchi 41 ⁵ (Italy)	CB41	Ice-poor	3094	45.91906	7.69249	2010 – 2011; 2014 – 2017
10	Muot da Barba Peider 0196 ¹	MPB_0196	Ice-poor	2946	9.93109	46.49639	1997 – 2010; 2015 – 2016
11	Muot da Barba Peider 0296 ¹	MPB_0296	Ice-poor	2942	9.93143	46.49657	2000 – 2011; 2015; 2016
12	Cima Bianchi 7 ⁵ (Italy)	CB7	Ice-poor	3098	45.91920	7.69277	2010 – 2011; 2013 – 2017
13	Grépillon, upper ⁵ (Italy)	GPU	Ice-free	3047	7.05690	45.90990	2013 – 2017
14	Grépillon, lower ⁵ (Italy)	GPL	Ice-free	3000	7.05638	45.90919	2013 – 2017
15	Matterhorn ¹	MAT_0205	Ice-poor	3288	7.67605	45.98232	2006 – 2007; 2009 – 2013
16	Flüela 0102 ¹	FLU_0102	Ice-rich	2394	9.94516	46.74792	2005 – 2009; 2014
17	Attelas 0108 ¹	ATT_0108	Ice-rich	2661	7.27307	46.09677	2009 – 2010; 12; 15; 16
18	Attelas 0208 ¹	ATT_0208	Ice-rich	2689	7.27368	46.09674	2009 – 2010; 12; 15; 16
19	Corvatsch 0200 ¹	COR_0287	Ice-rich	2672	9.82185	46.42878	2001; 2003 – 2008; 2010; 2011; 2013 – 2017
20	Lapies 1208 ¹	LAP_1108	Ice-rich	2500	7.28435	46.10611	2010; 2012; 2014
21	Muragl 0299 ¹	MUR_0299	Ice-rich	2539	9.92735	46.50722	2010 – 2013; 2016; 2017
22	Schafberg 0290 ¹	SBE_0190	Ice-rich	2754	9.92631	46.49737	2001 – 2016
23	Ritigraben 0102 ¹	RIT_0102	Ice-rich	2690	7.84983	46.17469	2003; 2004; 2006; 2007; 2009; 2012; 2014; 2016

Eingefügte Zellen

Gelöscht: 0287

Gelöscht: 1108

Gelöscht: 0190

Gelöscht: 11

Seitenumbruch

Table 2: Validation sites and the zones assigned to them in the permafrost maps PGIM, APIM (Boeckli et al. 2012) and PPDM (Gruber et al. 2006). The bold typed sites at the bottom were used to set up the regression model for PGIM zone 1. Type: IMIS - IMIS station, BH - borehole, CS - construction site, RF - rock fall. Data providers: 1 – WSL Institute for Snow and Avalanche Research SLF, 2 - Cremonese et al. (2011), 3 - University of Lausanne, 4 – Swiss Federal Office for the Environment. 5 – University of Fribourg. Zones and probability classes of the maps: see Figures 3-5.

Type ^{provider}	Name	Permafrost	PGIM/ Temp. (mod)	APIM	PPDM	Elevation [m a.s.l.]	Longitude (WGS 84)	Latitude (WGS 84)
IMIS ¹	Boveire - Pointe de Toulès	No	Zone 2	43	Zone 4	2687	7.23722	45.98480
BH ³	Lapir2	No	Zone 2	76	Zone 2	2559	7.28345	46.10526
IMIS ¹	Saas - Seetal	No	No perm.	No perm.	Zone 1	2477	7.87895	46.17137

Gelöscht:

IMIS ¹	Trubelboden - Trubelboden	No	No perm.	No perm.	No perm.	2459	7.58558	46.37096
IMIS ¹	Lukmanier - Lai Verd	No	No perm.	63	No perm.	2554	8.78352	46.60416
IMIS ¹	Fully - Grand Cor	No	No perm.	46	No perm.	2602	7.08964	46.19469
IMIS ¹	Bernina - Puoz Bass	No	No perm.	50	No perm.	2629	9.91588	46.44007
IMIS ¹	Gandegg - Gandegg	No	No perm.	72	No perm.	2710	7.76060	46.42926
IMIS ¹	Kesch - Porta d'Es-cha	No	No perm.	66	Zone 1	2727	9.89813	46.62132
IMIS ¹	Gornergrat - Gornergratsee	No	No perm.	98	Zone 5	2952	7.78359	45.98718
BH ²	Barthélemy les Rochers (Zinal)	No	No perm.	35	Zone 2	2519	7.59812	46.13660
BH ²	Neue Monte Rosa Hütte (Zermatt)	No	No perm.	93	Zone 1	2866	7.81233	45.95795
IMIS ¹	Zermatt - Alp Hermetje	No	No perm.	No perm.	No perm.	2409	7.70238	45.99799
IMIS ¹	Goms - Treichbode	No	No perm.	No perm.	No perm.	2428	8.22856	46.48912
IMIS ¹	Julier - Vairana	No	No perm.	No perm.	Zone 1	2426	9.69231	46.47850
IMIS ¹	Oberwald - Jostsee	No	No perm.	No perm.	No perm.	2432	8.31595	46.54522
IMIS ¹	Piz Martegnas - Colms da Prasonz	No	No perm.	No perm.	No perm.	2429	9.53739	46.58009
IMIS ¹	Bedretto - Cavanna	No	No perm.	No perm.	Zone 2	2420	8.51112	46.53268
IMIS ¹	Bernina - Motta Bianca	No	No perm.	No perm.	No perm.	2447	10.02920	46.42057
IMIS ¹	Davos - Hanengretji	No	No perm.	No perm.	No perm.	2456	9.77400	46.78885
IMIS ¹	Goms - Bodmerchumma	No	No perm.	10	Zone 2	2439	8.23251	46.42045
IMIS ¹	Taminatal - Wildsee	No	No perm.	59	No perm.	2468	9.39093	46.96836
IMIS ¹	Eggishorn - Flesch	No	No perm.	No perm.	No perm.	2500	8.09170	46.41680
IMIS ¹	Bever - Valetta	No	No perm.	No perm.	No perm.	2512	9.83713	46.53953
IMIS ¹	Samnaun - Ravaischer Salaas	No	No perm.	No perm.	No perm.	2512	10.33833	46.95637
IMIS ¹	Weissfluhjoch	No	No perm.	34	No perm.	2536	9.80911	46.82955
IMIS ¹	Les Attelas - Lac des Vaux	No	No perm.	No perm.	No perm.	2550	7.26988	46.10529
IMIS ¹	Davos - Barentalli	No	No perm.	No perm.	Zone 2	2557	9.81941	46.69890
IMIS ¹	Les Diablerets - Tsanfleuron	No	No perm.	65	No perm.	2584	7.23939	46.31445
IMIS ¹	Anniviers - Tracuit	No	No perm.	No perm.	No perm.	2589	7.65639	46.12116
IMIS ¹	Arolla - Breona	No	No perm.	No perm.	No perm.	2602	7.56205	46.08742
IMIS ¹	Anniviers - Orzival	No	No perm.	No perm.	Zone 4	2641	7.53536	46.18828
IMIS ¹	Zermatt - Triftchumme	No	No perm.	19	Zone 4	2753	7.72738	46.04217
CS ²	Speichersee Totalpsee (Davos)	No	No perm.	26	Zone 2	2501	9.81109	46.83724
CS ²	Herrenabfahrt Corviglia (St. Moritz)	No	No perm.	14	Zone 2	2829	9.80023	46.50610
BH ²	Catogne (Bovernier)	No	No perm.	21	No perm.	2331	7.10474	46.06012

BH ²	La Montagnetta (St. Jean/Grimentz)	No	No perm.	0	No perm.	2270	7.55943	46.19472
BH ²	Barthélemy les Rochers (Zinal)	No	No perm.	0	Zone 2	2519	7.59812	46.13660
BH ²	Barthélemy les Rochers (Zinal)	No	No perm.	0	Zone 1	2519	7.59812	46.13660
BH ²	Emshorn (Oberems)	No	No perm.	16	Zone 1	2506	7.67602	46.26670
BH ²	Emshorn (Oberems)	No	No perm.	0	No perm.	2506	7.67602	46.26670
BH ²	Felskinnbahn (Saas Fee)	No	No perm.	68	Zone 2	2585	7.91784	46.08137
BH ²	Illsee	No	No perm.	0	Zone 2	2359	7.63472	46.25945
BH ²	Lapires	No	No perm.	97	Zone 4	2650	7.28345	46.10526
IMIS ¹	St. Niklaus - Oberer Stelligletscher	No	Zone 1: 0.4°C	86	Zone 2	2915	7.75054	46.16782
BH ³	Attelas 3	No	Zone 1: 0.7°C	69	Zone 4	2741	7.27493	46.09660
IMIS ¹	Arolla - Les Fontanesses	No	Zone 1: 0.9°C	83	Zone 4	2857	7.44542	46.02967
IMIS ¹	Finhaut - L'Ecreuleuse	Yes	Zone 2	18	No perm.	2252	6.96409	46.10076
IMIS ¹	Simplon - Wenghorn	Yes	Zone 2	46	No perm.	2424	8.04516	46.17802
IMIS ¹	Piz Lagrev - Tscheppa	Yes	Zone 2	72	Zone 1	2727	9.74488	46.45112
IMIS ¹	Vinadi - Alpetta	Yes	Zone 2	82	Zone 5	2729	10.44286	46.93178
IMIS ¹	Saas - Schwarzmies	Yes	Zone 2	91	Zone 5	2799	7.97436	46.12436
CS ²	Gruobtagfeld (Turtmantal)	Yes	Zone 2	21	No perm.	2375	7.71797	46.20474
CS ²	Wasserscheide (Davos Parsenn)	Yes	Zone 2	56	Zone 4	2620	9.80255	46.83391
BH ²	Gentianes	Yes	Zone 2	87	Zone 5	2894	7.30226	46.08383
BH ²	Mont Dolin (Arolla)	Yes	Zone 2	49	Zone 4	2597	7.46188	46.02634
BH ²	Mont Dolin, (Arolla)	Yes	Zone 2	30	No perm.	2574	7.46330	46.02634
BH ²	Ritigraben (Grächen)	Yes	Zone 2	51	Zone 4	2639	7.84983	46.17470
BH ²	Seetalhorn (Grächen)	Yes	Zone 2	92	Zone 5	2862	7.85911	46.17642
BH ²	Stafel-Seetalhorn (Grächen)	Yes	Zone 2	36	Zone 4	2457	7.86022	46.18694
BH ²	Flüelapass (Davos)	Yes	Zone 2	29	No perm.	2500	9.94317	46.74688
BH ²	Lapires	Yes	Zone 2	61	Zone 2	2505	7.28435	46.10612
BH ²	Schafberg I	Yes	Zone 2	74	Zone 4	2752	9.92701	46.49655
BH ²	Schafberg II	Yes	Zone 2	61	Zone 1	2729	9.92387	46.49909
BH ²	Murtèl-Corvatsch	Yes	Zone 2	83	Zone 1	2666	9.82186	46.42879
BH ²	Muragl I	Yes	Zone 2	60	Zone 4	2536	9.92784	46.50757
BH ²	Les Attelas I	Yes	Zone 2	47	Zone 4	2661	7.27308	46.09677
BH ²	Les Attelas 2	Yes	Zone 2	55	Zone 4	2689	7.27369	46.09675
BH ²	Emshorn (Oberems)	Yes	No perm.	0	Zone 2	2506	7.67602	46.26670

Gelöscht: BH²

...

Gelöscht: BH⁴

...

BH ²	Muot da Barba Peider, lower shoulder	Yes	Zone 1: -0.1°C	81	Zone 4	2791	9.92891	46.49583
RF ²	Gemsstock (Andermatt)	Yes	Zone 1: -0.2°C	99	Zone 1	2911	8.61043	46.60125
RF ²	Chrachenhorn (Davos Monstein)	Yes	Zone 1: -0.4°C	91	Zone 5	2830	9.81226	46.68836
BH ²	Pointe du Tsaté	Yes	Zone 1: -0.4°C	94	Zone 5	3028	7.54696	46.10995
BH ²	Lagalp (Berninapass)	Yes	Zone 1: -0.4°C	97	Zone 2	Restricted	Restricted	Restricted
RF ²	Kärpf (Elm)	Yes	Zone 1: -0.6°C	74	Zone 4	2654	9.08917	46.91611
CS ²	Scex Rouge (Les Diablerets)	Yes	Zone 1: -0.6°C	93	No perm.	Restricted	Restricted	Restricted
CS ²	Diavolezza (Berninapass)	Yes	Zone 1: -0.6°C	98	Zone 5	2993	9.96948	46.40975
BH ²	Schilthorn 51/98	Yes	Zone 1: -0.7°C	100	Zone 4	2910	7.83462	46.55828
CS ²	Cabane des Vignettes (Arolla)	Yes	Zone 1: -0.9°C	89	Zone 1	3164	7.47555	45.98865
CS ²	Rothornhütte (Zermatt)	Yes	Zone 1: -0.9°C	98	Zone 4	Restricted	Restricted	Restricted
CS ²	Rifugio Camosci (Pizzo Cristallina)	Yes	Zone 1: -0.9°C	94	No perm.	2903	8.53667	46.46444
BH ²	Arolla, Mt. Dolin	Yes	Zone 1: -1.0°C	99	Zone 5	2862	7.45473	46.02663
BH ²	Wisse Schijen (Randa)	Yes	Zone 1: -1.2°C	89	Zone 4	3039	7.74832	46.09635
BH ²	Stockhorn 61/00	Yes	Zone 1: -2.7°C	100	Zone 4	3412	7.82420	45.98679
CS ²	Cabane Dent Blanche (Ferpècle)	Yes	Zone 1: -3.3°C	100	Zone 2	Restricted	Restricted	Restricted
BH ²	Jungfrauoch South	Yes	Zone 1: -3.9°C	100	Zone 2	3574	7.97306	46.54548
BH ²	Jungfrauoch North	Yes	Zone 1: -5.2°C	100	Zone 4	3602	7.97319	46.54611
BH ²	Eggishorn (Fiesch)	Yes	Zone 1: 0.6°C	88	Zone 1	2847	8.09365	46.42638
BH ²	Flüelapass 0202	No	No perm.	18	Zone 2	2500	9.94317	46.74688
BH ²	Gemsstock	No	Zone 1: 0.4°C	97	Zone 2	2940	8.61043	46.60125
BH ²	Les Attelas 3	No	No perm.	73	Zone 4	2741	7.27492	46.09659
BH ⁴	Breithorn	No	Zone 1: 0.7°C	81	Zone 2	2864	7.81785	46.14010
BH ²	Muot da Barba Peider I	Yes	Zone 1: -1.0°C	99	Zone 6	2938	9.93092	46.49647
BH ²	Tsate	Yes	Zone 1: -1.0°C	96	Zone 2	3040	7.54844	46.10904
BH ²	Schildhorn 5200	Yes	Zone 1: -0.3°C	100	Zone 4	2910	7.83442	46.55828
BH ²	Stockhorn 6000	Yes	Zone 1: -2.8°C	100	Zone 5	3410	7.82419	45.98678
BH ²	Jungfrau	Yes	Zone 1: -5.3°C	100	Zone 6	3590	7.97316	46.54617
BH ²	Hörnigrat (Matterhorn, Zermatt)	Yes	Zone 1: -2.0°C	100	Zone 6	3288	7.67605	45.98232

Gelöscht: BH²

Gelöscht: BH²

Gelöscht: 60

Gelöscht: ¶
¶

Gelöscht: potential solar radiation

Table 3: Results of the regression analysis on ground temperature in dependency of elevation and **PISR**. Left: Regression analysis used to map the PGIM. Centre: Regression analysis using only the 'coldest thermistor' in boreholes in homogeneous terrain (no ridges). Right: Same approach as in the central column but including the ice-poor boreholes shown in table 1.

	Ice-poor permafrost (213 thermistors in 15 boreholes)	Ice-poor permafrost (coldest thermistor of 10 boreholes)	Ice-poor and ice-rich permafrost together (coldest thermistor of 10 ice-poor and 8 ice-rich boreholes)
Correlation coefficient	0.944	0.998	0.523
Standard error	0.57° C	0.16° C	1.02° C

Acknowledgements

The authors sincerely thank all persons and institutions who supported this work by providing data. A major part of the reference ground temperatures was provided by the Swiss Permafrost Monitoring Network PERMOS. Paolo Pogliotti (ARPA Valle d’Aosta) and Christophe Lambiel (University of Lausanne) contributed valuable borehole temperature data to the study. Ilja Burn is thanked for checking and manually editing the polygons representing zone 2 of the PGIM. Martin Schneebeili, the Editor Moritz Langer and two anonymous reviewers kindly provided constructive comments to the manuscript.

Gelöscht: that

Gelöscht: and

Gelöscht: and

References

- Azócar Sandoval, G., Brenning, A., and Bodin, X.: Permafrost Distribution Modeling in the Semi-Arid Chilean Andes, 877-890 pp., 2017.
- Böckli, L., Brenning, A., Gruber, S., and Noetzli, J.: Permafrost distribution in the European Alps: calculation and evaluation of an index map and summary statistics, *The Cryosphere*, 6, 807-820, 10.5194/tc-6-807-2012, 2012.
- Böckli, L.: Characterizing permafrost in the entire European Alps: spatial distribution and ice content, University of Zurich, Mathematisch-naturwissenschaftliche Fakultät., 2013.
- Bommer, C., Keusen, H.-R., and Phillips, M.: Engineering solutions for foundations and anchors in mountain permafrost, 9th International Conference on Permafrost, Fairbanks, Alaska, 2008, 159-163,
- Bommer, C., Phillips, M., and Arenson, L. U.: Practical recommendations for planning, constructing and maintaining infrastructure in mountain permafrost, *Permafrost and Periglacial Processes*, 21, 97-104, 10.1002/ppp.679, 2010.
- Cremonese, E., Gruber, S., Phillips, M., Pogliotti, P., Boeckli, L., Noetzli, J., Suter, C., Bodin, X., Crepaz, A., Kellerer-Pirklbauer, A., Lang, K., Letey, S., Mair, V., Morra di Cella, U., Ravel, L., Scapozza, C., Seppi, R., and Zischg, A.: Brief Communication: "An inventory of permafrost evidence for the European Alps", *The Cryosphere*, 5, 651-657, 10.5194/tc-5-651-2011, 2011.
- Davies, M. C. R., Hamza, O., and Harris, C.: The effect of rise in mean annual temperature on the stability of rock slopes containing ice-filled discontinuities, *Permafrost and Periglacial Processes*, 12, 137-144, 2001.
- Deluigi, N., Lambiel, C., and Kanevski, M.: Data-driven mapping of the potential mountain permafrost distribution, *Science of The Total Environment*, 590, 370-380, 2017.
- Ebohon, B., and Schrott, L.: Modeling Mountain Permafrost Distribution. A new Permafrost Map of Austria, Ninth International Conference on Permafrost, Fairbanks, Alaska, 2008, 397 - 402.
- ESA: Permafrost CCI Project: <http://cci.esa.int/Permafrost>, access: 04.03.2019, 2018.
- Fiddes, J., Endrizzi, S., and Gruber, S.: Large-area land surface simulations in heterogeneous terrain driven by global data sets: application to mountain permafrost, *The Cryosphere*, 9, 411-426, 10.5194/tc-9-411-2015, 2015.
- Gisnås, K., Etzelmüller, B., Lussana, C., Hjort, J., Sannel, A. B. K., Isaksen, K., Westermann, S., Kuhry, P., Christiansen, H. H., Frampton, A., and Åkerman, J.: Permafrost Map for Norway, Sweden and Finland, *Permafrost and Periglacial Processes*, 28, 359-378, doi:10.1002/ppp.1922, 2017.
- Gruber, S., and Hoelzle, M.: Statistical modelling of mountain permafrost distribution: local calibration and incorporation of remotely sensed data, *Permafrost and Periglacial Processes*, 12, 69-77, 2001.
- Gruber, S., Hoelzle, M., and Haeblerli, W.: Rock-wall temperatures in the Alps: modelling their topographic distribution and regional differences, *Permafrost and Periglacial Processes*, 15, 229-307, 2004.
- Gruber, S., Haeblerli, W., Krummenacher, B., Keller, F., Mani, P., Hunziker, G., Hölzle, M., Vonder Mühll, D., Zimmermann, M., Keusen, H.-R., A., G., and Rätz, H.: Erläuterungen zur Hinweiskarte der potentiellen Permafrostverbreitung in der Schweiz 1:50'000, Swiss Federal Office for the Environment (FOEN), 2006.
- Gruber, S., and Haeblerli, W.: Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change, *Journal of Geophysical Research: Earth Surface*, 112, 10.1029/2006JF000547, 2007.
- Gruber, S.: Derivation and analysis of a high-resolution estimate of global permafrost zonation, *The Cryosphere*, 6, 221-233, 10.5194/tc-6-221-2012, 2012.

Gelöscht: Delaloye, R., Reynard, E., Lambiel, C., Marescot, L., and Monnet, R.: Thermal anomaly in a cold scree slope (Creux du Van, Switzerland), Eighth International Conference on Permafrost, Zurich, 2003, 175-180, ¶ Delaloye, R., and Lambiel, C.: Drilling in a low elevation cold talus slope (Drevenouse, Swiss Prealps), *Geophysical Research Abstracts*, 9, 10907, 2007.¶

- Haberkorn, A., Hoelzle, M., Phillips, M., and Kenner, R.: Snow as a driving factor of rock surface temperatures in steep rough rock walls, *Cold Regions Science and Technology*, 118, 64-75, 10.1016/j.coldregions.2015.06.013, 2015a.
- Haberkorn, A., Phillips, M., Kenner, R., Rhyner, H., Bavay, M., Galos, S. P., and Hoelzle, M.: Thermal Regime of Rock and its Relation to Snow Cover in Steep Alpine Rock Walls: Gemsstock, Central Swiss Alps, *Geografiska Annaler: Series A, Physical Geography*, 97, 579-597, 10.1111/geoa.12101, 2015b.
- Haerberli, W.: Untersuchungen zur Verbreitung von Permafrost zwischen Flüelapass und Piz Grialetsch (Graubünden). *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich, Zurich*, 221 pp., 1975.
- Haerberli, W., Hoelzle, M., Dousse, J. P., Ehrler, C., Gardaz, J. M., Imhof, M., F., K., Kunz, P., R., L., and E., R.: Simulation der Permafrostverbreitung in den Alpen mit geographischen Informationssystemen, *Schweizerischer Nationalfonds zur Förderung der wissenschaftlichen Forschung*, 58, 1996.
- Haerberli, W., and Vonder Mühl, D.: [On the characteristics and possible origins of ice in rock glacier permafrost, *Zeitschrift für Geomorphologie*, 104, 43-57, 1996.](#)
- Haerberli, W.: Modern Research Perspectives Relating to Permafrost Creep and Rock Glaciers: A Discussion, *Permafrost and Periglacial Processes*, 11, 290-293, doi:10.1002/1099-1530(200012)11:4<290::AID-PPP372>3.0.CO;2-0, 2000.
- Hilbich, C., Hauck, C., Hoelzle, M., Scherler, M., Schudel, L., Völsch, I., Vonder Mühl, D., and Mäusbacher, R.: Monitoring mountain permafrost evolution using electrical resistivity tomography: a 7-year study of seasonal, annual and long-term variations at Schilthorn, Swiss Alps, *Journal of Geophysical Research*, 113, 10.1029/2007JF000799, 2008.
- Hipp, T., Etzelmüller, B., Farbro, H., Schuler, T. V., and Westermann, S.: Modelling borehole temperatures in Southern Norway – insights into permafrost dynamics during the 20th and 21st century, *The Cryosphere*, 6, 553-571, 10.5194/tc-6-553-2012, 2012.
- Hoelzle, M.: Permafrost occurrence from BTS measurements and climatic parameters in the Eastern Swiss Alps, *Permafrost and Periglacial Processes*, 3, 143-147, 1992.
- Hoelzle, M., Haerberli, W., and Keller, F.: Application of BTS-measurements for modelling permafrost distribution in the Swiss Alps, 6th International Conference on Permafrost, Beijing, China, 1993,
- Hoelzle, M., and Haerberli, W.: Simulating the effects of mean annual air-temperature changes on permafrost distribution and glacier size: an example from the Upper Engadin, Swiss Alps., *Annals of Glaciology*, 21, 399-405, 1995.
- Hoelzle, M., Mittaz, C., Etzelmüller, B., and Haerberli, W.: Surface energy fluxes and distribution models of permafrost in European mountain areas: an overview of current developments, *Permafrost and Periglacial Processes*, 12, 53-68, 2001.
- Hoelzle, M., and Gruber, S.: Borehole and ground surface temperatures and their relationship to meteorological conditions in the Swiss Alps, 2008.
- Huete, A. R.: A soil-adjusted vegetation index (SAVI), *Remote Sensing of Environment*, 25, 295-309, 10.1016/0034-4257(88)90106-X, 1988.
- Ishikawa, M.: [Spatial mountain permafrost modelling in the Daisetsu Mountains, northern Japan, in: *Permafrost, Eighth International Conference on Permafrost, Zurich, Switzerland, 2003*, 020072388, 473-478.](#)
- Keller, F.: Automated mapping of mountain permafrost using the program PERMAKART within the Geographical Information Systems ARC/INFO, *Permafrost and Periglacial Processes*, 3, 133-138, 1992.
- Keller, F., Frauenfelder, R., Gardaz, J. M., Hoelzle, M., Kneisel, M., Lugon, R., Phillips, M., Reynard, E., and Wenker, L.: Permafrost map of Switzerland, Seventh International Conference on Permafrost, Yellowknife Canada, 1998, 557-562,

Gelöscht: Jones, D. B., Harrison, S., Anderson, K., Selley, H. L., Wood, J. L., and Betts, R. A.: The distribution and hydrological significance of rock glaciers in the Nepalese Himalaya, *Global and Planetary Change*, 160, 123-142, 10.1016/j.gloplacha.2017.11.005, 2018.¶

- Kenner, R., and Magnusson, J.: Estimating the effect of different influencing factors on rock glacier development in two regions in the Swiss Alps, *Permafrost and Periglacial Processes*, 28, 195-208, 10.1002/ppp.1910, 2017.
- Kenner, R., Phillips, M., Hauck, C., Hilbich, C., Mulsow, C., Bühler, Y., Stoffel, A., and Buchroithner, M.: New insights on permafrost genesis and conservation in talus slopes based on observations at Flüelapass, Eastern Switzerland, *Geomorphology*, 290, 101-113, 10.1016/j.geomorph.2017.04.011, 2017.
- Kenner, R.: Geomorphological analysis on the interaction of Alpine glaciers and rock glaciers since the Little Ice Age, *Land Degradation & Development*, doi:10.1002/ldr.3238, 2018.
- Krautblatter, M.: Detection and Quantification of Permafrost Change in Alpine Rock Walls and Implications for Rock Instability, 2009.
- Krautblatter, M., Funk, D., and Günzel, F. K.: Why permafrost rocks become unstable: a rock-ice-mechanical model in time and space, *Earth Surface Processes and Landforms*, 38, 876-887, 10.1002/esp.3374, 2013.
- Lerjen, M., Käb, A., Hoelzle, M., and Haeberli, W.: Local distribution of discontinuous mountain permafrost. A process study at Flüela Pass, Swiss Alps, *Eighth International Conference on Permafrost, Zurich, 2003*, 667-672.
- Magnin, F., Deline, P., Ravel, L., Noetzli, J., and Pogliotti, P.: Thermal characteristics of permafrost in the steep alpine rock walls of the Aiguille du Midi (Mont Blanc Massif, 3842 m a.s.l.), *The Cryosphere*, 9, 109-121, 10.5194/tc-9-109-2015, 2015.
- Maisch, M.: Die Gletscher der Schweizer Alpen: Gletscherhochstand 1850, aktuelle Vergletscherung, Gletscherschwund-Szenarien ; [Projektschlussbericht im Rahmen des Nationalen Forschungsprogrammes "Klimaänderungen und Naturkatastrophen", NFP 31], vdf, Hochsch.-Verlag an der ETH, 1999.
- Maisch, M., Haeberli, W., Frauenfelder, R., Käb, A., and Rothenbühler, C.: Lateglacial and Holocene evolution of glaciers and permafrost in the Val Muragl, Upper Engadin, Swiss Alps, in: *Permafrost*, edited by: Phillips, M., and Springman, S., A.A. Balkema Publishers, Lisse, 717-722, 2003.
- Marmy, A., Salzmann, N., Scherler, M., and Hauck, C.: Permafrost model sensitivity to seasonal climatic changes and extreme events in mountainous regions, *Environmental Research Letters*, 8, 035048, 2013.
- Noetzli, J., and Gruber, S.: Transient thermal effects in Alpine permafrost, *The Cryosphere*, 3, 85-99, 2009.
- PERMOS: Permafrost in Switzerland 2010/2011 to 2013/2014, PERMOS, 85, 2016.
- Phillips, M., Zenklusen Mutter, E., Kern-Luetsch, M., and Lehning, M.: Rapid degradation of ground ice in a ventilated talus slope: Flüela Pass, Swiss Alps, *Permafrost and Periglacial Processes*, 20, 1-14, 10.1002/ppp.638, 2009.
- Pruessner, L., Phillips, M., Farinotti, D., Hoelzle, M., and Lehning, M.: Near-surface ventilation as a key for modeling the thermal regime of coarse blocky rock glaciers, *Permafrost and Periglacial Processes*, 29, 152-163, 2018.
- Reynard, E., Lambiel, C., Delaloye, R., Devaud, G., Baron, L., Chapellier, D., Marescot, L., and Monnet, R.: Glacier/permafrost relationships in forefields of small glaciers (Swiss Alps), *Proceedings 8th International Conference on Permafrost, Zurich, Switzerland, 2003*, 947-952,
- Ribolini, A., Guglielmin, M., Fabre, D., Bodin, X., Marchisio, M., Sartini, S., Spagnolo, M., and Schoeneich, P.: The internal structure of rock glaciers and recently deglaciated slopes as revealed by geoelectrical tomography: insights on permafrost and recent glacial evolution in the Central and Western Alps (Italy-France), *Quaternary Science Reviews*, 29, 507-521, 10.1016/j.quascirev.2009.10.008, 2010.

- Russi, T., Ammann, W., Brabec, B., Lehning, M., and Meister, R.: Avalanche Warning Switzerland 2000, in: Early Warning Systems for Natural Disaster Reduction, edited by: Zschau, J., and Küppers, A., Springer Berlin Heidelberg, Berlin, Heidelberg, 569-577, 2003.
- Scapozza, C., Lambiel, C., Baron, L., Marescot, L., and Reynard, E.: Internal structure and permafrost distribution in two alpine periglacial talus slopes, Valais, Swiss Alps, *Geomorphology*, 132, 208-221, 10.1016/j.geomorph.2011.05.010, 2011.
- Scherler, M., Hauck, C., Hoelzle, M., and Salzmann, N.: Modeled sensitivity of two alpine permafrost sites to RCM-based climate scenarios, *Journal of Geophysical Research: Earth Surface*, 118, 780-794, 10.1002/jgrf.20069, 2013.
- Scherler, M., Schneider, S., Hoelzle, M., and Hauck, C.: A two-sided approach to estimate heat transfer processes within the active layer of the Murtèl–Corvatsch rock glacier, *Earth Surf. Dynam.*, 2, 141-154, 10.5194/esurf-2-141-2014, 2014.
- Schneider, S., Hoelzle, M., and Hauck, C.: Influence of surface and subsurface heterogeneity on observed borehole temperatures at a mountain permafrost site in the Upper Engadine, Swiss Alps, *The Cryosphere*, 6, 517-531, 10.55194/tc-6-517-2012, 2012.
- Staub, B., Marmy, A., Hauck, C., Hilbich, C., and Delaloye, R.: Ground temperature variations in a talus slope influenced by permafrost: a comparison of field observations and model simulations, *Geogr. Helv.*, 70, 45-62, 10.5194/gh-70-45-2015, 2015.
- Zenkhusen Mutter, E., and Phillips, M.: Active layer characteristics at ten borehole sites in Alpine permafrost terrain, Switzerland, *Permafrost and Periglacial Processes*, 23, 138-151, 10.1002/ppp.1738, 2012.
- Zhang, T.: Influence of the seasonal snow cover on the ground thermal regime: an overview, *Reviews of Geophysics*, 43, 1-23, 2005.

Supplementary material

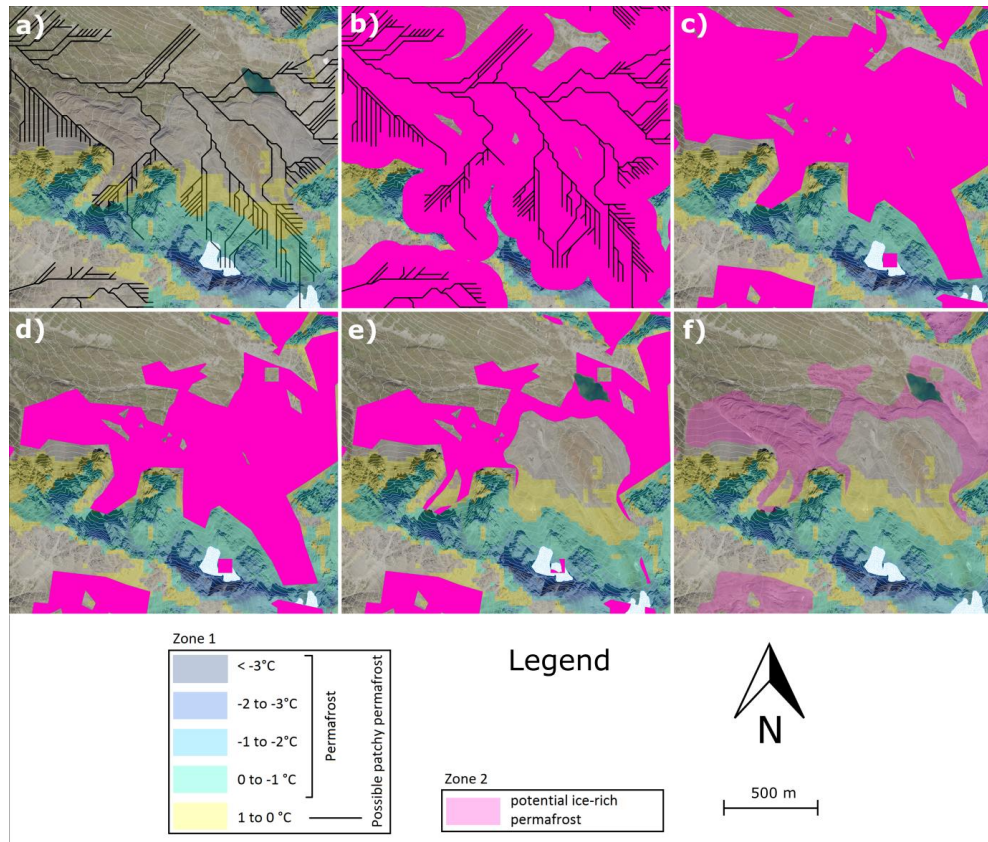


Figure A: Parts a-f show the individual work steps described in section 2.3 to create zone 2 representing ice-rich permafrost. The example shows the area around rock glacier Muragl (Kenner, 2018; Maisch et al., 2003). In short: a) Step 1: runoff tracks; b) Step 2: Buffered runoff tracks; c) Step 3: erase areas steeper 30°; d) Step 4: erase vegetated areas; e) Step 5+6: erase LIA glaciation & Lakes; f) Step 8: Simplifying and smoothing

Gelöscht: Appendix 1

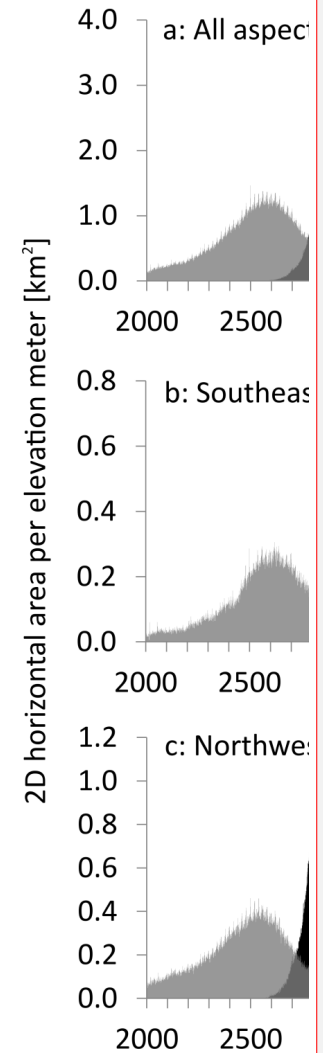


Figure A

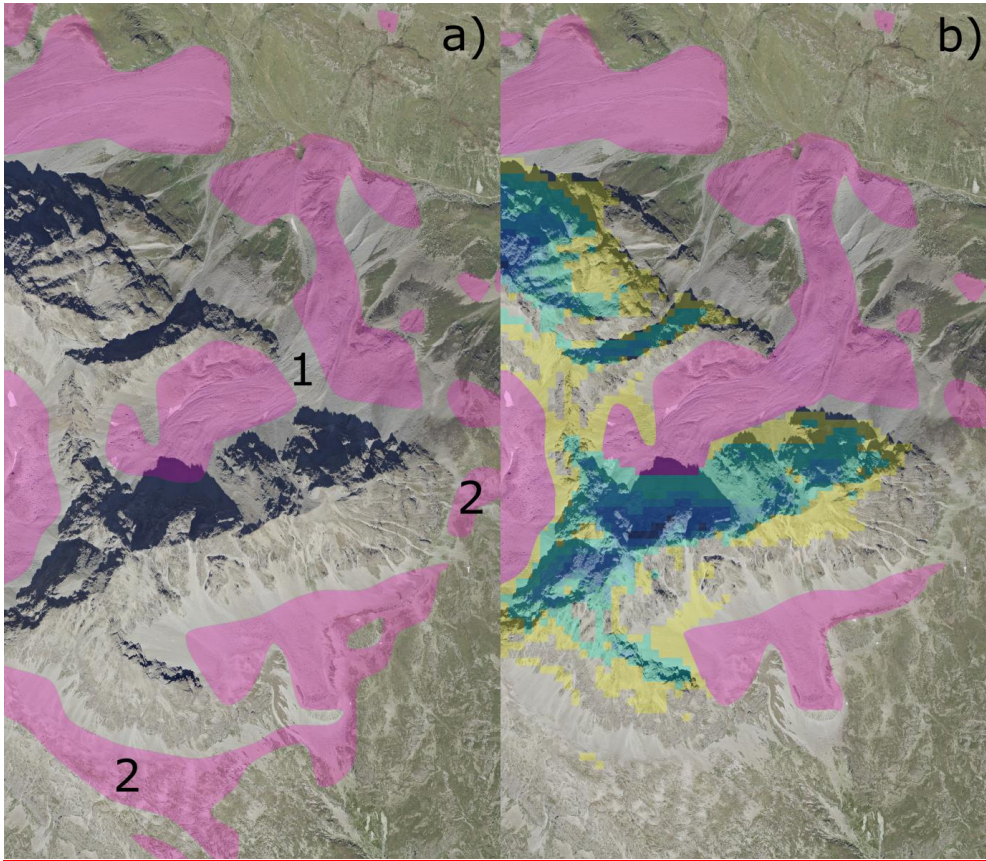


Figure B: Part a shows the raw model output for zone 2. Part b shows the edited zone 2 together with zone 1. Index 1 shows a part of the rock glacier which was not captured by the model due to a terrain step steeper than 30° and included manually. Index 2 shows zones which were manually removed as they mainly include bedrock or vegetation-covered ground.

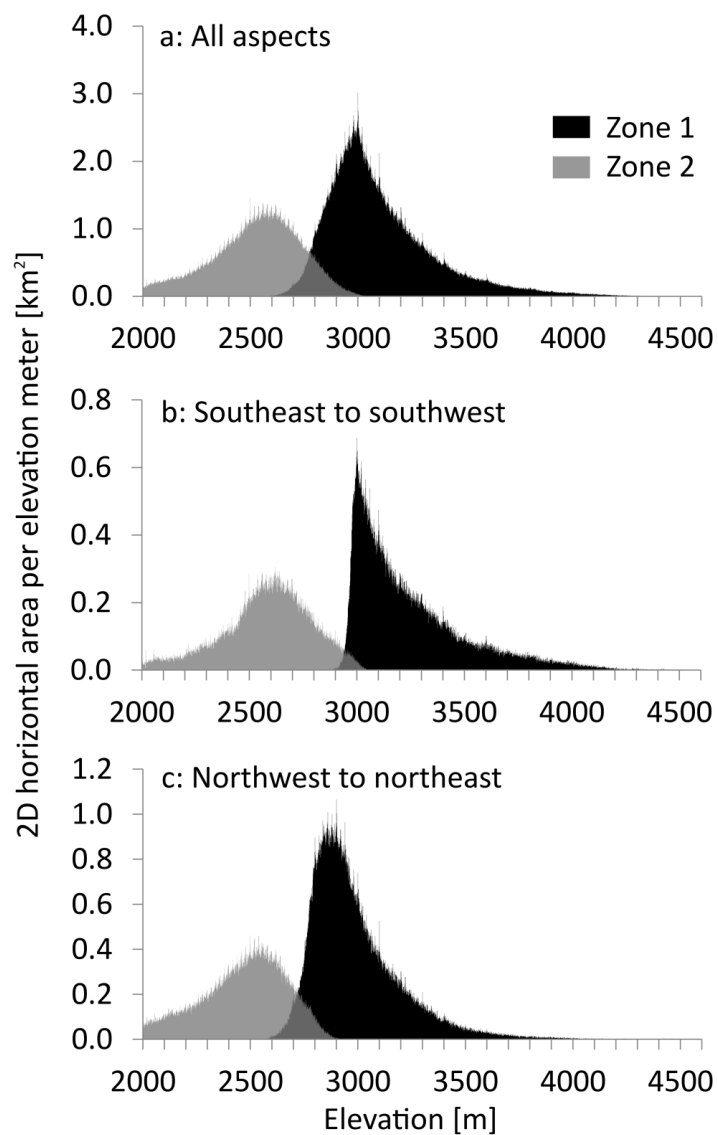


Figure C: Distribution of the PGIM zones 1 (only negative ground temperatures) and 2 over elevation. Part a shows the permafrost zonation over all aspects, part b for the aspects southeast to southwest and part c for aspects ranging between northwest and northeast. The permafrost gap appears between the two map zones. ▼

Gelöscht: 1