**Subject: Response to Anonymous Referee # 1 to the Manuscript titled "Permafrost Distribution Modeling in the Semi-Arid Chilean Andes" by Azócar, Brenning and Bodin.**

We would like to thank to the anonymous referee # 1 for her or his helpful comments on our manuscript. We will carefully respond to these comments and suggestions. The referee's comments are given in italics and our response as regular text in blue (and red) colors, text changes in the manuscripts are in bold.

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| R.1 | *The observational data used in this study is prone to errors and uncertainties. These errors, and their effect on the model results, should be treated in more detail in this study. For example, the data availability is sparse in the region, and hence the uncertainties regarding the predictor variable MAAT are (assumed to be) larger than in other, better equipped regions. Therefore, an estimate of the errors of the input data should be given. Issues such as the quality as well as the representativeness of the station data must be discussed. Further, an estimation of the uncertainty of the rock glacier inventory should be made (if possible, through a validation with (the existant) ground data and by providing an estimate of the miss-classification rate).*<br><br>We agree with the referee's comments about the uncertainty of the rock glacier inventory and the temperature data; however, an estimation of the uncertainty cannot be easily accomplished due to a lack of studies about the dynamic status of rock glaciers and limited availability of meteorological data in the Chilean Andes. Nevertheless, we will try to provide additional information on errors and uncertainties.<br><br>Rock glacier inventories<br><br>The rock glacier inventory cannot be easily validated with ground truth observation due to the lack of field research in the Andes. In our experience based on three rock glaciers within this study area and additional rock glaciers in the Andes of Santiago with GPS-based measurements of rock glacier dynamics and/or geophysical evidence of ground ice, the available high-resolution remote-sensing imagery is instrumental in distinguishing rock glacier activity status - in particular intact versus relict status, which is the only thing that matters in our study. However, due to our prior knowledge of these field studies of geophysical and dynamic properties, we could not use such field evidence as independent validation data.<br><br>We decided that not provide into the manuscript the classification table that we use to determine the rock glacier activity because similar classification table has been published in other research (Roer & Nyenhuis, 2007), however, to clarify this aspect, the indicator that were used to classify rock glacier in the Andes are available into the master thesis research of Azócar (2013, pages 55-56).<br><br>References:<br><br>Azócar, G. Modeling of permafrost distribution in the Semi-arid Chilean Andes, M.S. thesis, University of Waterloo, Canada, 160 pp, 2013. |

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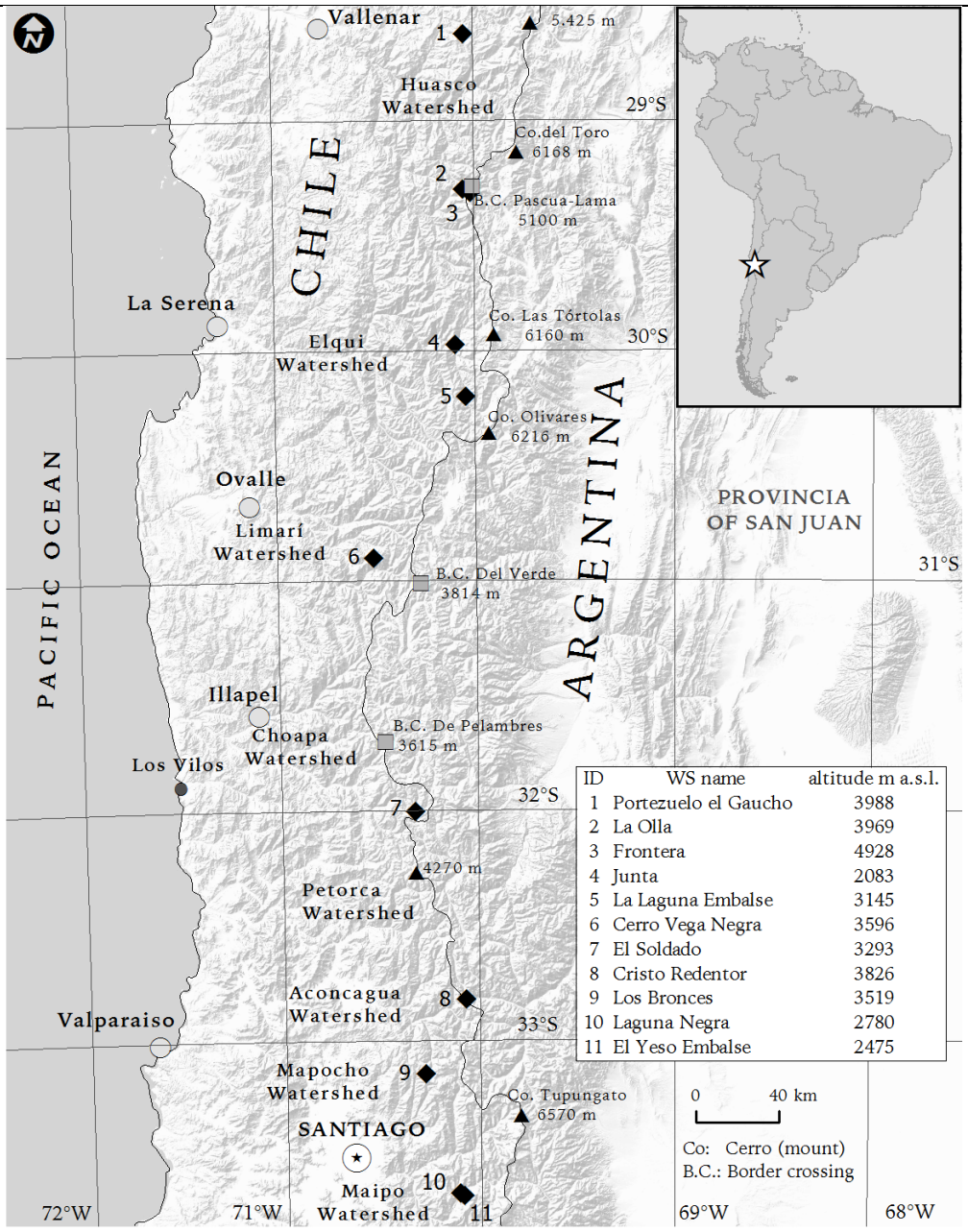
| | Roer, I., and Nyenhuis, M.: Rockglacier activity studies on a regional scale: comparison of geomorphological mapping and photogrammetric monitoring, Earth Surface Processes and Landforms, 32, 12, 1747-1758, doi:10.1002/esp.1496, 2007.<br><br>Temporal and spatial representativeness of the weather station:<br><br>Please note that our manuscript contains information on uncertainties of our MAAT regionalization. Since year-to-year variation of AAT is not relevant for MAAT regionalization, the standard deviation of 0.93°C between stations describes the precision of our MAAT regionalization (see Sect. 4.2), which is comparable to MAAT products used in the Alps for permafrost modeling (Hiebl et al., 2009; used by Boeckli et al., 2012a,b; see discussion in Sect. 5.2). Based on this information, we have no evidence that MAAT regionalization in this study region is any poorer than in the Alps with greater data availability. - We reword Sect. 4.2 to express more explicitly that the 0.93°C standard deviation can be seen as a model precision at the MAAT level, after averaging out year-to-year variation.<br><br>Long series of meteorological data in the Andes are almost inexistent. Based on our detailed knowledge of the area, we used all data available from government and academic sources as well as from the mining industry or environmental assessments. The meteorological station used in this study are distributed latitudinally throughout the study region as shown in the following map: |




In terms of statistical modeling we deal with the temporal and spatial representativeness and heterogeneity of data by using a Linear Mixed Effects Model (LMEM), which is specifically designed to account for nested or grouped observations such as our irregular annual measurements (Pinheiro & Bates, 2000; Twisk, 2006).

References:

Pinheiro, J., and Bates, M.: Mixed-effects models in S and S-Plus, Springer-Verlag, New York, United States, 2000

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| | Twisk, J.: Applied multilevel analysis: A practical guide, Cambridge University Press, Cambridge, United Kingdom, 2006. |
| R.2 | **Response to specific comments**<br>*Rock glacier inventory (Section 3.1):*<br><br>- *Include a definition of the rock glacier classification (intact, active, inactive, relict)*<br><br>We agree with the referee's comment and we added the following paragraphs to the first paragraph at the beginning of section 3.1.1 of the new manuscript version:<br><br>**Rock glaciers are a periglacial phenomenon widely distributed around the world, They consist of a mixture of rocks with variable or no ice content, produced during the Holocene time period (Birkeland, 1973; Haeberli et al., 2003). They have a tongue or lobe shape, with ridges and furrows on their surface that are indicative of their present or past deformation. Rock glaciers were identified following the criteria of classification proposed previously by Barsch (1996), Roer and Nyenhuis (2007) and Azócar (2013). Frequently, active and inactive rock glaciers (grouped here as intact forms) have a steep front with visual unstable rocks; in contrast, an irregular and collapsed surface due to thawing of ice commonly indicate that rock glacier is relict form (Putman & David, 2009).**<br><br>References added to new manuscript version:<br><br>Azócar , G. (2013). *Modeling of permafrost distribution in the semi'arid Chilean Andes.* Faculty of Environment, Geography Deparment . Waterloo, Canada: University of Waterloo.<br>Birkeland, P. W. (1973). Use of relative age-dating methods in a stratigraphic study of rock glacier deposits, Mt. Sopris, Colorado. *Arctic and Alpine Research, 5*(4), 401-416.<br>Haeberli, W., Brandova, D., Castelli, S., Egli, M., Frauenfelder, R., Kääb, A., . . . Dickau, R. (2003). Absolute and relative age dating of rock-glacier surfaces in alpine permafrost: concept, first results and possible applications. *EGS - AGU - EUG Joint Assembly*, (pp. 343-348). Nice, France.<br>Roer, I., & Nyenhuis, M. (2007). Rockglacier activity studies on a regional scale:comparison of geomorphological mapping and photogrammetric monitoring. *Earth Surface Processes and Landforms, 32*(12), 1747-1758. doi:10.1002/esp.1496 |
| R.3 | - *Regarding the completeness of the rock glacier inventory in the area. Please answer these questions in the manuscript:*<br>** Does a validation of the inventory of the classified rock glaciers with ground observations exist?* |

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| | We don't have ground observation to validate the inventory of rock glaciers. Therefore, the following paragraph will be added to the manuscript at the end of new section 3.1.1.:<br><br>**Due to the lack of ground observation data about the dynamic status of rock glaciers, a validation process cannot be accomplished in this research. Nevertheless, the authors have performed measurements of rock glacier dynamics and active layer status within and near the study region (UGP UC, 2010) and have knowledge of additional geophysical evidence of several rock glaciers in the dry Andes (Janke et al., 2015). Although these observations cannot be used for independent validation since they were previously known to the authors, their direct evidence of rock glacier dynamic status and ground ice presence is generally consistent with our assessment based on remote-sensing imagery.**<br><br>References added to new manuscript version:<br><br>Janke, J., Bellisario, A., & Ferrando, F. (2015). Classification of debris-covered glaciers and rock glaciers in the Andes of central Chile. *Geomorphology*(241), 98-121. doi:dx.doi.org/10.1016/j.geomorph.2015.03.034<br><br>Unidad de Gestión de Proyectos del Instituto de Geografía de la Pontificia Universidad Católica de Chile (UGP UC). (2010). *Dinámica de glaciares rocosos.* Dirección General de Aguas, Unidad de Glaciología y Nieves. Santiago: Ministerio de Obras Públicas. |
| R.4 | *How large is the fraction of miss-classifications?*<br><br>In relative terms, we do not think that miss-classification is huge because there is clear geomorphological different between the shape of intact and relict rock glaciers into the study area. As we said before, we would like to validate the data with ground truth observation but the size of the study and the large number of rock glaciers are unviable any kind of validation work. Maybe, in the future using radar image we can validate the dynamic status of major portion of rock glaciers. |
| R.5 | *Can you provide an estimate of the percentage of rock glaciers that are still missing in your classification?*<br><br>Since a detailed interpretation of high-resolution satellite imagery (finer than 2 m x 2 m resolution) was conducted using an on-screen map scale of 1: 7,000, we expect our inventory to be complete for rock glaciers > 0,01 km$^2$, probably even for substantially smaller ones. |

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| | To clarify these point we added the following paragraphs to discussion section, and we mention the 2 m x 2 m image resolution in the modified Sect. 5.1:<br><br>**In comparison to the recent inventory of rock glaciers realized by UGP UC (2010) in the Elqui, Limarí and Choapa watersheds and Huasco by (Nicholson et al, 2009), the present inventory increases the number of known active rock glaciers from 621 to 933 (increase 60%), inactive rock glaciers from 151 to 415 (increase 275%) and intact rock glaciers from 135 to 249 (increase 184%) within these watersheds. This has been possible since to rock glaciers are recognized using high-resolution satellite imagery in comparison to previous studies.** |
| R.6 | - *Page 3, Lines 12-14: If the conditions for rock glaciers are not favorable in two of the investigated basins: how representative is the model there?*<br><br>While rock glaciers may be less abundant in the mentioned areas, there is still a substantial number of rock glaciers in these areas (e.g. several hundred rock glaciers in the smaller Limarí watershed; Sect. 4.1). Rock glacier data availability is therefore not a limiting factor here. |
| R.7 | - *Page 3, Line 29: Classification of rock glaciers: The rock glacier classification is the main input for your modelling approach and must therefore be described more in detail.*<br><br>A more detailed definition of rock glacier classes was added in response to comment R.2. With regards to rock glacier classification from remote-sensing imagery appearance, Barsch (1996) and Roer and Nyenhuis (2007) provide a general assessment of suitable criteria, which we refer to. An adaptation to the local needs of this study in a region with little to no vegetation cover was made by Azócar (2013); instead of repeating the criteria listed there, we now point the reader more explicitly to this source of detailed additional information. |
| R.8 | - *Page 4, Line 1: How do the uncertainties in the rock glacier classification (active and inactive forms) influence the statistical modeling approach? Please account for the uncertainties in your modelling approach.*<br><br>Any confounding between active and inactive landforms would not affect our model or its predictions since both active and inactive rock glaciers, i.e. intact rock glaciers in general, were treated as one single class (permafrost presence) for modelling purposes (New section 3.2 ). Non-systematic misclassification of the response labels (intact vs. relict status) are furthermore handled by the statistical model; such uncertainty reduces the AUROC performance and increases coefficient standard errors. Systematic errors would, naturally, introduce a bias. In new section 3.2.3, we introduce several possible sources of bias and explain the approaches used to eliminate or at least reduce them. |

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| R.9 | - *The section "Methods" should be restructured. A possible structure of the section could be:*<br><br>*3.1 Response and predictor variables of the statistical permafrost model*<br>*Introduction to the section: use text page 5, Line 19-26*<br>** 3.1.1 Response variable: rock glacier inventory*<br>** 3.1.2 Predictor variables:*<br>*· Regionalization of MAAT*<br>*· PISR*<br>*– 3.2 Statistical permafrost favorability model*<br>** 3.2.1 GAM*<br>** 3.2.2 Model evaluation*<br>** 3.2.3 Model adjustment*<br><br>We agree with the referee's comment and we will change the structure of the section in the manuscript version. |
| R.10 | ***Section "Regionalization of MAAT":***<br><br>*Please comment on data quality in the manuscript. Have you done any quality control previously to using the measurements?*<br><br>We agree with the referee's comment that a quality control is highly recommended. We are sure that for weather station belonging to the Directorate of Water Resources (Dirección General de Aguas, DGA; 8 weather stations), they collect the data following the World Meteorological Organization processes and standards; however, for the remaining stations (3 weather stations), it is mostly unknown how they collect the data. As usual with linear models, the distribution of model residuals was examined in order to identify any possible outliers; non were detected, and station-level and well as year-to-year variation as expressed by residual standard deviations appear to be very reasonable (Table 2), as discussed earlier in the context of MAAT precision (R.1). |
| R.11 | *What is the difference between AAT and MAAT? Please provide a proper definition of the variables. So far, it is unclear why you need both variables.*<br><br>We need both variable because in term of modeling, they have different meaning:<br><br>AAT is Annual Average Temperature for a specific year and MAAT is the mean AAT averaged over all years in the observation period (by taking the expected value of random intercepts for each year). Please refer to definitions provided in Eq. (1) and (3). |

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| R.12 | *Section 3.1.2: Stations in the Andes are often located in valley bottoms. They might therefore not reflect the conditions in high mountains. Please discuss the representativeness of the data used, and the impact on your modelling approach. For example, no station above 5000m is available, and except one all stations are below 4000m. Do you expect an error for AAT at high elevations? Please estimate or at least discuss the impact of this on your model.*<br><br>We agree with the referee in that local topoclimatic conditions will modify MAAT as well as other site characteristics that may be relevant for permafrost occurrence. In this study, weather stations located within valleys tended to have positive residuals, while more exposed sites tended to have negative residuals, indicating that valleys are "warmer" under otherwise equal conditions; however, these local variations are well described by the previously mentioned residual standard error of 0.93°C, which is provided to the reader and identified as being "typical" of comparable regionalization in high mountains. The predominance of longer AAT time series at valley locations may therefore result in an overall over-estimation of MAAT on average. Such warm bias would result in an underestimation of permafrost favorability.<br><br>To clarify this point we add the following paragraph at the end of the discussion section 5.2 into the new manuscript version:<br><br>**Considering the over-representation of station-years from valley locations, which tended to be associated with positive residuals, overall the MAAT regionalization may have a warm bias at high elevations and on the upper slopes. Such bias would, however, be substantially smaller than the residual standard error of 0.93°C due to averaging effects. As a consequence, permafrost favorability may be underestimated at the highest elevations or on the upper slopes.** |
| R.13 | *Many stations have only a few years of observations:: ï´C ˇg How does this influence the outcomes of model(Temp)? ï´C ˇg Can you exclude, for example, that the data availability is biased towards strong El Niño/La Niña years?*<br><br>The association between El Nino Southern Oscillation (ENSO) or in particular, the multivariate ENSO index (MEI) and temperature varies widely across South America, and is of weak to moderate strength in our study area and at a seasonal scale (Garreaud, 2009). Adding annually averaged MEI (based on monthly data from NOAA; http://www.esrl.noaa.gov/psd/enso/mei/index.html) to the MAAT model shows no evidence of a relationship to AAT in our study area (estimated coefficient -0.14 K, p-value 0.40). We therefore believe that we can exclude the possibility of ENSO-related bias.<br><br>Moreover, we used temperature data from a thirty year period, which from a climatological point of view is adequate for eliminating any interannual variation or anomalies (World Meteorological Organization, WMO, 2013). In our study, year-to-year variation, even in the case of stations with shorter time series, was accounted for by estimating random effects for each year and averaging these random effects out in |

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| | the prediction of MAAT. Interannual variations produced by the ENSO would therefore not influence our results inappropriately.<br><br>References:<br><br>Garreaud, R.D. The Andes climate and weather, Adv. Geosci., 22, 3-11, 2009. |
| R.14 | *4.3 Statistical permafrost favorability model: Please improve the structure of this section such that the reader gets a clear idea on the influence of MAAT and PISR on permafrost availability.*<br><br>*Original text:*<br><br>"According to the model results, at a regional-mean PISR, locations with a MAAT of +1°C were associated with ~33 % lower odds of permafrost occurrence compared to 0°C MAAT. At extremely sunny sites with PISR two standard deviations above the regional average, by comparison, the same MAAT contrast was associated with a ~73 % decrease in the odds of permafrost occurrence"<br><br>To clarify this point we improve the sentence at the beginning of section 4.3 in the new manuscript version:<br><br>**In order to understand the effect of the interaction between PISR and MAAT in the permafrost favorability model, it is necessary to examine the modeled effect of MAAT at sites with different levels of PISR. We will compare and contrast sites with regional-mean PISR with extremely sunny sites with PISR two standard deviations above regional-mean PISR, looking at how much less favorable sites with a MAAT of +1°C are relative to a MAAT of 0°C. At regional-mean PISR, the model predicts that locations with a MAAT of +1°C are, on average, associated with ~33% lower odds (or relative probabilities) of permafrost occurrence than 0°C MAAT sites. At extremely sunny sites, in contrast, the model predicts ~73% lower odds at +1°C versus 0°C MAAT.** |
| R.15 | *Sections 5.2 and 5.3: Please quantify the uncertainty of the permafrost favorability model outputs due to uncertainties in MAAT (and PISR), and the rock glacier inventory. Can you use a bootstrapping approach?*<br><br>We would certainly appreciate more concrete suggestions regarding the particular type of bootstrapping procedure that the reviewer would deem appropriate for this situation. The bootstrap can be used for many different purposes such as the construction of nonparametric confidence intervals or the estimation of predictive performances. In this study, the main goal of the application of the permafrost favorability model is prediction, which is why cross-validation was used to estimate predictive performance. In general it is certainly common practice to use predictors that represent somehow generalized or averaged conditions, either due to spatial averaging effects as in coarser- |

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| | resolution remote sensing, or through the use of ancillary model predictions as in this study. Any uncertainties related to these generalizations would be captured by the cross-validation estimates of predictive performance.<br><br>As far as the ancillary MAAT regionalization model is concerned (Sect. 5.2), we believe that the use of the bootstrap e.g. for the construction of coefficient confidence intervals is not justified as there is no evidence of violations of model assumptions that would perhaps encourage the use of such nonparametric technique.<br><br>We are certainly open for additional and more specific suggestions by the reviewer regarding possible bootstrapping procedures that may help to further elucidate uncertainties that are not already captured by the methods used in our study. |
| R.16 | *Conclusion: the conclusions are quite weak. Instead of giving a short summary of what you have done, it would be more interesting if you answered, for example, questions like: What are the benefits of the chosen approach, what are the drawbacks? What is the relevance and the applicability of the study, e.g., for infrastructure, water availability, etc. in the region.*<br><br>We agree with referee's comment and we improved the conclusion with the following paragraph at the end of section 6:<br><br>**Finally, the findings of this research contribute mainly to improve the general knowledge about permafrost distribution in the Andes, providing valuable information to government and economic sectors as a starting point for additional local site investigations. Considering the uncertainties inherent in regional-scale modeling, local site conditions such as surface material, snow cover duration or topoclimatic conditions should be taken into account when interpreting the present permafrost favorability index. Additional research, in particular ground-truthing using a meaningful sampling design, is necessary in order to refine the present model and eliminate possible biases.** |
| R.17 | *Figure 2 should be rearranged. The MAAT model figures as an input to the predictor variable MAAT. Please point this out in the figure: the MAAT model could figure on the right side of the PFI model, as an input to the PFI model.*<br><br>Yes we agree with the referee's comment and we made the changes.<br><br>New figure is available into the new manuscript version. |

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| R.18 | ***Technical corrections***<br><br>*The readability of the paper would improve if some more guidance in the beginning of each section/subsection was provided. Often, it is difficult to follow the storyLine of the text.*<br><br>*• Write shorter sentences (instead of comma-separated sentences).*<br>Changed as requested.<br><br>*• Be consistent in notation (semiarid versus semi-arid)*<br><br>Changed as requested. |

***Response to Comment in Manuscript revision by Anonymous referee # 1.***

***Note: First number indicate the page, second number the Line***

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| ***Page 1, Line 1*** | *Human activities such as?*<br><br>To clarify this point we modified the sentence into the manuscript in the following way:<br><br>Original text:<br><br>"Mountain permafrost and rock glaciers in the dry Andes are of growing interest due to the increase in human activities in this remote area"<br><br>Modified sentence:<br><br>**Mountain permafrost and rock glaciers in the dry Andes are of growing interest due to the increase in mining industry and infrastructure development in this remote area.** |
| ***Page 1, Line 2*** | *Sentence is too long*<br><br>Original text:<br><br>"Empirical models of mountain permafrost distribution based on the spatial analysis of intact and relict rock glaciers and mean annual air temperature (MAAT) have been established as a tool for regional-scale assessments of permafrost favorability across entire mountain ranges; however, this kind of model approach has never been applied for a large portion of the Andes"<br><br>Modified sentence:<br><br>**Empirical models of mountain permafrost distribution based on rock glacier activity status and temperature data have been established as a tool for** |

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| | **regional-scale assessments of its distribution; this kind of model approach has never been applied for a large portion of the Andes** |
| ***Page 1, Line 18*** | *Rephrase this sentence*<br><br>Original text:<br><br>"Especially in the Elqui and Huasco watersheds in the northern half of the study area, where a substantial surface portion (11.8 % each) was considered to be favorable for permafrost presence, while predicted favorable areas in the southern Limarí and Choapa watersheds are mostly limited to specific sub-watersheds"<br><br>Modified sentence:<br><br>**Substantial portions of the Elqui and Huasco watersheds are considered to be favorable for permafrost presence, while in the Limarí and Choapa watersheds, permafrost is expected to be mostly limited to specific sub-watersheds** |
| ***Page 1, Line 27*** | *Gruber did not explicitly mention the Andes in his work, did he? Maybe put the reference earlier in the phrase.*<br><br>We agree with the referee's comment and we will delete the reference. |
| ***Page 2, Line 14*** | *These sentences are out of context here. Provide some introductory sentences on the general approach.*<br><br>*"As a prerequisite for permafrost modeling, we assessed the regional-scale distribution of Mean Annual Air Temperature (MAAT), used as one of the predictors for the favorability for permafrost occurrence. A Generalized Additive Model (GAM) was then used to map a Permafrost Favorability Index (PFI) in debris surfaces within the study area"*<br><br>We agree with the referee's comment and we will added new sentences at the end section 1 in the new manuscript version:<br><br>**Considering the Potential Incoming Solar Radiation (PISR) and the Mean Annual Air Temperature (MAAT) as potential predictors, PISR and MAAT are model as predictor variables for the favorability for permafrost occurrence. A Generalized Additive Model (GAM) was then used to map a Permafrost Favorability Index (PFI) in debris surfaces within the study area.** |

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| ***Page 2, Line 20*** | *It would be interesting to know the total area of each watershed.*<br><br>We agree with the referee and we will add these values into the sentence:<br><br>**The study area comprises a large portion of the semi-arid Chilean Andes, covering from north to south the upper sections of the Huasco (9766 km$^2$), Elqui (9407 km$^2$), Limarí (11683 km$^2$) and Choapa (7795 km$^2$) river basins between ~28.5° S and 32.2° S.** |
| ***Page 2, Line 21*** | *Could you also give an indication of the highest point in your study region?*<br><br>We agree with the referee and we will modified the sentence in the following way:<br><br>**…with the Huasco and Elqui basins bearing the highest altitudes (i.e. Cerro de Las Tórtolas 6160 m a.s.l.)** |
| ***Page 2, Line 22*** | *Singular and plural mixed in the phrase (elevation are)*<br><br>We agree with the referee's comment and we fixed the grammar mistake:<br><br>**Their median elevations are 2995 and 2536 m a.s.l.** |
| ***Page 2, Line 26*** | *Consistency in notation: either write "semiarid" or "semi-arid" trough out the paper.*<br><br>We agree with referee's comment and "semi-arid" word will be used trough out the paper. |
| ***Page 2, Line 29*** | *During*<br><br>Changed as requested:<br><br>**Precipitation at high altitudes almost exclusively occurs as snow as it is concentrated between May and August, i.e. during austral winter (Gascoin et al., 2011).** |
| ***Page 3, Line 2 Line 5*** | *Make a new sentence*<br>*Which lie*<br><br>*Original text:*<br><br>*Most of the surface ice bodies in the study region correspond to small glaciers or "glacierets" (< 0.1 km²), while only 2 % of the glaciers in the study region are greater than 1 km2, mostly in the Elqui watershed at and near Cerro Tapado and in the upper Huasco 5 watershed (Nicholson et al., 2009; DGA, 2009; Rabatel et al, 2009).* |

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| | We will modify the sentence in the following way:<br><br>**Most of the surface ice bodies in the study region correspond to small glaciers or "glacierets" (< 0.1 km²). On the other hand, 2 % of the glaciers in the study region are greater than 1 km², mostly located in the Elqui watershed at and near Cerro Tapado and in the upper Huasco watershed (Nicholson et al., 2009; Rabatel et al, 2009; UGP UC, 2010).** |
| ***Page 3, Line 8*** | *Make a new sentence*<br><br>*Original text:*<br><br>*…and ground ice and current movement have been detected in various cases (UGP UC, 2010; Monnier, et al., 2011, 2013; Monnier and Kinnard, 2012, 2013; Janke et al., 2015).*<br><br>We will modify the sentence in the following way:<br><br>**Rock glaciers with ground ice and current movement have been detected in various cases (UGP UC, 2010; Monnier, et al., 2011, 2013; Monnier and Kinnard, 2012, 2013; Janke et al., 2015).** |
| ***Page 3, Line 18*** | *I think that it would help to provide the section numbers in the introduction to the methods. Thereby, the reader is introduced into the structure of the section, and already knows that he will obtain more information on the topic in the mentioned section.*<br><br>We agree and we will change it. |
| ***Page 3, Line 21*** | *(Sect. 3.1)*<br><br>We agree and we will change it. |
| ***Page 3, Line 22*** | *Rewrite the sentence, for example: "Further, predictor variables… were calculated (Sect. 3.2)."*<br><br>Original text:<br><br>*Predictor variables such as Potential Incoming Solar Radiation (PISR) and MAAT were furthermore calculated.*<br><br>We agree with the referee suggestion and the sentence will be modified:<br><br>**Further, predictor variables such as Potential Incoming Solar Radiation (PISR) and MAAT were calculated.** |

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| ***Page 3, Line 30*** | *Provide a definition of the classes of your classification: e.g., define: active, inactive, intact and relict*<br><br>Please see response to comment R.2. |
| ***Page 4, Line 4*** | *minuscule "a"*<br><br>Changed as requested |
| ***Page 4, Line 9*** | *Does AAT refer to:*<br>*annual average air temperature (or, for example, surface temperature). Please define.*<br><br>See answer in R.11. |
| ***Page 4, Line 10*** | *The difference between MAAT and AAT is unclear.*<br><br>See answer in R.11. |
| ***Page 4, Line 11*** | *Please include an additional sentence to make the transition to the following section more understandable.*<br><br>We clarify it adding the following sentence:<br><br>**Detail about response and predictor variables and MAAT model structure are presented in the following sections.** |
| ***Page 4, Line 12*** | *Include an introductory sentence.*<br><br>Where it said:<br><br>*"The response variable AAT was calculated using data from eleven weather stations for a time period of between 1 and 30 years (1981-2010), depending on data availability"*<br><br>We modified the sentence at the beginning of section 3.1.2.1.1 in the new manuscript version:<br><br>**To build a response variable representing air temperature conditions, AAT was calculated using…** |
| ***Page 4, Line 14*** | *Is the difference between AAT and MAAT that AAT is calculated from monthly means, and MAAT from daily values? It is quite confusing that you use a different* |

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| | *notation for these two. It they differ substantially, then you should define each variable when they appear, and motivate why you need these two variables.*<br><br>See answer in R.11. row |
| ***Page, 5 Line 2*** | *for some years, you have only one observation, is that correct? Is the estimate for u_{0j} then reliable?*<br><br>u is a random effect for year, not for station. There is only one year (2007) with only one observation; removing it from the data set leads to no appreciable change in model results. |
| ***Page 5, Line 3*** | *The notation model (Temp) looks strange. Could you maybe find another notation?*<br><br>We agree and we deleted the annotation "Temp" to be clearer in the notation model. |
| ***Page 5, Line 11*** | *Do you mean model (Temp)?*<br><br>Yes, and we changed the sentence to be more clear. |
| ***Page 5, Line 19*** | *Better: the probability of permafrost presence/absence*<br><br>Since the response variable is not a probability but a dichotomous variable, we prefer to keep the text as is. |
| ***Page 5, Line 22*** | *Unclear: rephrase the sentence*<br><br>Original text:<br><br>*"Annual PISR was preferred over PISR for part of the year such as the snow-free period since detailed information on snow cover duration was not available and seasonal PISR values are highly correlated"*<br><br>We changed the sentence at the beginning of second paragraph into section 3.2 in the new manuscript version:<br><br>**Due to the lack of snow cover information, annual PISR was preferred over PISR because seasonal PISR is highly correlated with snow cover periods.** |
| ***Page 5, Line 27*** | *I think the calculation of PISR should have an own section.*<br><br>Yes, we agree and we added it to a new section (section 3.1.2.2 in the new manuscript version) |

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| ***Page 6, Line 6*** | *Please define the PFI based on equations 4 and 5.*<br><br>We define PFI equation in page 6, line 6. |
| ***Page 6, Line 20*** | *smoothing?*<br><br>We agree that smoothing terms is more adequate and used in the literature https://stat.ethz.ch/R-manual/R-devel/library/mgcv/html/smooth.terms.html |
| ***Page 6, Line 22*** | *rephrase the sentence*<br><br>*In this method local linear regressions are fitted to subsets of data falling within a moving window in order to construct a function that describes a smoothly varying relationship between predictor and response*<br><br>We change the sentence at the end of section 3.2.1 in the new manuscript version:<br><br>**In this method local linear regressions are fitted using a moving window that describes a smoothly varying relationship between predictor and response variables.** |
| ***Page 8, Line 6*** | *How reliable is the model in the Choapa basin, if rock glaciers are mainly absent there?*<br><br>We fixed the sentence at the beginning of section 4.1 in the new manuscript version:<br><br>**Rock glaciers are most abundant in the Elqui (n=681), Limarí (n=486) and Huasco (n=r24) watersheds, in contrast, they are less abundant in Choapa watershed (n=324).** |
| ***Page 8, Line 8*** | *Make two sentences.*<br><br>*Original text:*<br><br>*"The majority of rock glaciers (~60-80 %) are located below the present ZIA obtained in this study from the LMEM of temperature, and 37 % of active, 21 % of inactive, 26 % intact and 15% of relict rock glaciers are located above the ZIA"*<br><br>We changed the sentence at the beginning of section 4.1 in the new manuscript version:<br><br>**The majority of rock glaciers (~60-80 %) are located below the present ZIA obtained in this study from the LMEM of temperature. On the other hand, 37 % of active, 21 % of inactive, 26 % intact and 15% of relict rock glaciers are located above the ZIA** |

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| ***Page 8, Line 10*** | *New sentence, for example: in contrast in the Limari and Choapa watersheds…*<br><br>*Original text:*<br><br>*"In the Huasco and Elqui watersheds, nearly 50% of all active rock glaciers are located at negative MAAT compared to less than 20 % in the Limarí and Choapa watersheds in the southern part of the study area (Fig.3)"*<br><br>We changed the sentence at the beginning of section 4.1 in the new manuscript version:<br><br>**In the Huasco and Elqui watersheds, nearly 50% of all active rock glaciers are located at negative MAAT; in contrast, in the Limarí and Choapa watersheds in the southern part of the study contain less than 20 %.** |
| ***Page 8, Line 29*** | *This chapter contains the most important results of your study. The structure of the text should be strongly improved.*<br><br>*You could give an example of the meaning of the "odds" such that a reader that is not so familiar with statistics understands the word. Further: explain (in words) the meaning of "33% lower odds".*<br><br>See answer in row. R.14 |
| ***Page 9, Line 12*** | *rephrase, for example: favorable conditions for permafrost were inferred for 6.8% of the study area*<br><br>*Where said:*<br><br>"Considering a PFI ≥ 0.5 and excluding steep bedrock and glacier surfaces, site conditions favorable for permafrost occurrence were inferred for ~6.8 % of the study area, or 2636 km²"<br><br>We changed the sentence as requested at the beginning of section 4.3.1 in the new manuscript version:<br><br>**Considering a PFI ≥ 0.5 and excluding steep bedrock and glacier surfaces, favorable conditions for permafrost were inferred ~6.8% of study area, or 2636 km$^2$.** |
| ***Page 9, Line 19*** | *This is because the watersheds in the South are at lower elevations, no? There is no direct relation with being "southwards", which, in the Southern hemisphere, would be equal to being colder, no?*<br><br>Right, because these watershed are at lower elevations into the study area and we don't evaluate in this work if most of these surface are south-*facing* slope |

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| ***Page 9, Line 15*** | *is the inventory publicly available or not?*<br><br>Yes, the data are available in www.andespermafrost.com and through Pangaea server: https://doi.pangaea.de/10.1594/PANGAEA.859332 |
| ***Page 10, Line 25*** | *Include an estimate of the uncertainty of the method. Can you estimate the percentage of rock glaciers that could still not be detected (due to various possible reasons), or that were miss-classified?*<br><br>PFI is a "soft" classification, i.e. a score and not a yes/no decision. The AUROC is therefore the most appropriate measure of model fit or overall predictive skill; its cross-validation estimate is reported in the Results. Depending on the particular PFI threshold used (e.g., 0.5), the fraction of detected rock glaciers (i.e. sensitivity) would vary. In addition, due to the bias adjustment (related to altitudinal bias of rock glaciers; Sect. 3.3.4), a fair number of intact rock glaciers would be expected to be found at relatively low PFI values. We are afraid that such information would therefore be rather confusing to the reader and would require a fair amount of explanation in order to put these values into perspective. |
| ***Page 10, Line 4*** | *Add a reference to earlier statements regarding rock glacier presence.*<br><br>The following references were added: Brenning (2005), Azócar & Brenning (2010). |
| ***Page 10, Line 12*** | *delete the "somewhat"*<br><br>Changed as requested. |
| ***Page 10, Line 15*** | *This is higher (almost double) than the temperature offset you account for in the model. What is the influence on your results? Can you quantify the uncertainty of your results?*<br><br>We would like to remind the reviewer that the residual standard error is a non-systematic error. Since the residuals have mean zero, this residual standard error is unrelated to any bias corrections and should not compared to those. Since there is no "one" uncertainty but various types and levels of uncertainty and error, we made an effort in our paper to separate these into, for example, year-to-year variation (averaged out in moving to MAAT), station-to-station variation (as expressed by the residual standard deviation mentioned here), and PFI model prediction uncertainty (as expressed by the AUROC). |

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| ***Page 10, Line 19*** | *Very long sentence. Please rephrase.*<br><br>Where said:<br><br>"Compared to other studies that had only very limited access to high-elevation weather data from the high Andes, our approach focused on incorporating all available high-elevation data into a locally calibrated regionalization in order to avoid an over-reliance on assumed or extrapolated lapse rates. Still, the available temperature data over-represented non-permafrost altitudes, underlining the need for increased weather observation efforts at high elevations"<br><br>We changed the sentence as requested in section 5.2 of the new manuscript version:<br><br>**Even though our research approach focused on incorporating all available high elevation temperature data available into a hierarchic regression model, the limited availability of temperature data can affect permafrost prediction**. |
| ***Page 10, Line 21*** | *Yes, this is an important point. Do you have an estimate of the error that arises due to this data lack?*<br><br>See answers in row R.8 |
| ***Page 11, Line 8*** | *no "therefore" needed*<br><br>*Original text:*<br><br>*"Additional systematic ground-truthing is therefore required for a quantitative assessment of permafrost extent and to reduce model uncertainties (Lewkowicz and Ednie, 2004). Model-model comparisons are therefore currently the only means for assessing uncertainties in permafrost distribution"*<br><br>Changes as requested |
| ***Page 11, Line 15*** | *Model against model*<br>*did you do a model-against-model evaluation of your PFI?*<br><br>That is right. We evaluated the results of our model against the permafrost zonation index (PZI) of Gruber (2012). |
| ***Page 11, Line 16*** | *Can you estimate the uncertainty of the estimated area by your model (based on uncertainties in MAAT and PISR)?*<br><br>As mentioned previously, we would like to differentiate the various types of uncertainty, which is very important in order to recognize that errors may be random or systematic, and may occur at different scales. Once this important differentiation is made, it may become clear that there is no simple number or map that would highlight model uncertainties. As far as MAAT uncertainty as expressed by the |

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| | residual standard error is concerned, we would clearly expect these to average out to 0 when considering the area of PFI > 0.5 based on different realizations of a spatial MAAT residual random field over such a large area. This should also hold true for PISR.<br><br>Interestingly, any systematic error in MAAT (or PISR, for that matter) would not affect PFI modeling results since the PFI model is calibrated to rock glacier data; the PFI model's intercept would take care of a bias in MAAT, just like a conversion from °C to K would not change PFI model output.<br><br>Other than that, the reader is carefully pointed to the need to interpret PFI maps considering local site characteristics that may be related, in particular, to unobserved confounders such as topoclimatic conditions or substrate properties. |
| ***Page 11, Line 27*** | *Rephrase the sentence*<br><br>*Original text:*<br><br>*"However, in logistic regression such high AUROC values may result in numerical difficulties in the estimation of logistic regression coefficients (Homer and Lemeshow, 2000), and in the case of Sattler et al. (2016) the high value may be explained by the omission of inactive rock glaciers as a permafrost landform located in topographic conditions between active and relict ones"*<br><br>We change the sentence at the end of section 5.4 in the new manuscript version:<br><br>**It is worth to mentioning that excessively high AUROC values in logistical regression may results in difficulties in the estimation of logistic regression coefficients (Hosmer and Lemeshow, 2000), and in the case of Sattler et al. (2016) the high value may be explained by the omission of inactive rock glaciers as a permafrost landform located in topographic conditions between active and relict ones.** |
| ***Page 12, Line 5*** | *Is there any important infrastructure that could be damaged? It would be interesting to have an example here.*<br><br>There are some records about damage of infrastructure in the mining industry. See Brenning & Azocar (2010) |

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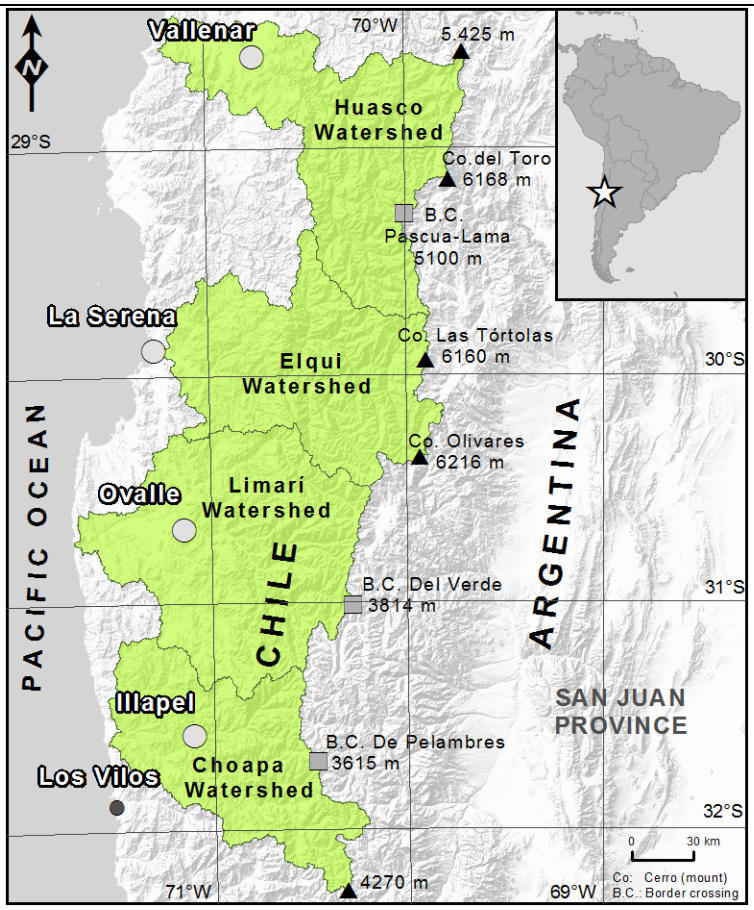
| ***Page 12, Line 8*** | *These sentences are very general and do not relate to your study area.*<br><br>*Where said:*<br><br>*Moreover, an increase 5 in debris flow and rockfall activity would be expected and has been reported elsewhere (Haeberli et al., 1993; Gruber and Haeberli, 2007). In this context, PFI maps can serve as a first resource to assess permafrost conditions and uncertainties in mountain research and practical applications such as infrastructure planning (Boeckli et al., 2012b).*<br><br>We agree and we will deleted the sentences. |
| ***Page 18, Line 3*** | *It would be preferable to write the years (or a range of years) for which data is available, instead of "record n years". For example: 2004-2006*<br><br>*That would provide an overview of the data used. Is it clear that the availability of the data is not biased towards for example El Niño events?*<br><br>We prefer to keep as record number of year to make more easily to the reader see the number of year with data. In regard to the Niño years see answer in row R.13 |
| ***Page 20, Line 3*** | *Should the numbers not sum up to the total area in the watershed?*<br>*Otherwise, is the remaining area classified as "not permafrost"? Would that not mean the PFI = 0? Maybe you should include PFI = 0 in the first Line?*<br><br>Not necessarily because we did not run the model for the entire watershed but only above a particular altitudinal threshold defined by rock glacier distribution<br><br>*And: what is about the percentage of the region that was excluded (bedrock)?*<br><br>The data show in the table are just for debris surface areas because bedrock surface were excluded into the analysis. |
| ***Page 21 Figure 1*** | *Include a map of Chile (or at least a part of it including some major cities). Thereby, the reader more easily sees where the study is located. is Santiago on the map (33°S)?*<br><br>We agree with the referee's comment and we changed the map: |


Vallenar
70°W
5.425 m
Huasco
Watershed
29°S
Co.del Toro
6168 m
B.C.
Pascua-Lama
5100 m
La Serena
Co. Las Tórtolas
6160 m
Elqui
Watershed
30°S
PACIFIC OCEAN
Co. Olivares
6216 m
Ovalle
Limari
Watershed
CHILE
ARGENTINA
B.C. Del Verde
3814 m
31°S
Illapel
SAN JUAN
PROVINCE
B.C. De Pelambres
3615 m
Los Vilos
Choapa
Watershed
32°S
0
30 km
71°W
4270 m
69°W
Co: Cerro (mount)
B.C.: Border crossing

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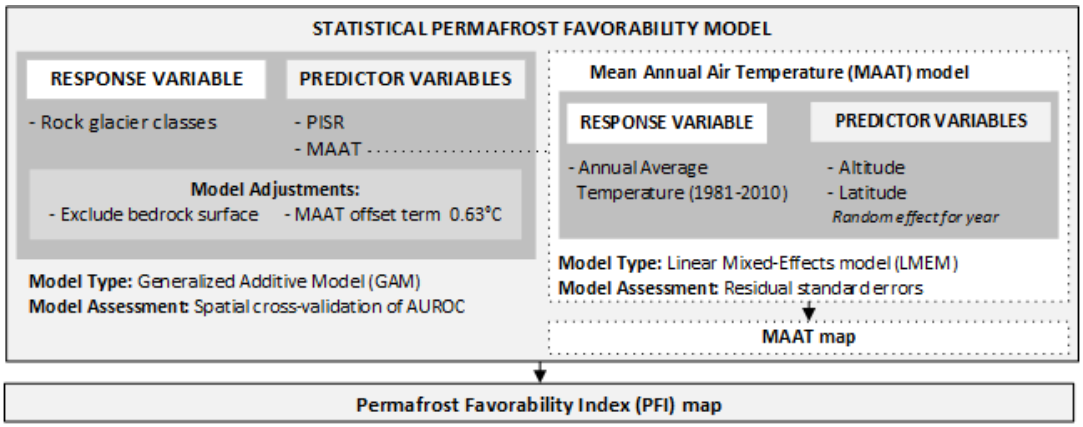
| ***Page 22***<br>***Figure 2*** | *Was bedrock not excluded?*<br>*this figure is confusing. Please rearrange the boxes:*<br><br>*-> the square including the MAAT model should be placed as a sub-model where the predictor variables are explained*<br><br>We fixed the mistake and we arranged the MAAT box:<br><br>  |
| ***Page 24***<br>***Figure 4*** | *Could you visualize the annual variability for the stations with more than one year of observations?*<br><br>*Do the point represent the mean AAT over all years?*<br><br>The purple dots represent the number of Annual Air Temperature (AAT) records for weather stations used to run the model, and they do not represent the annual variability for stations. |