**Author's responses**

Dear Dr. Wickert,

On behalf of the authors, I am pleased to submit the revised version of our manuscript ID gmd-2020-5 entitled "PERICLIMv1.0: A model deriving palaeo-air temperatures from thaw depth in past permafrost regions" compiled by Tomáš Uxa, Marek Křížek, and Filip Hrbáček.

We responded point-by-point to all referee's comments and made corresponding adjustments in the manuscript, which has led to its major revisions and substantial improvements. Besides model validation/evaluation based on modern data, we also included a palaeo-air temperature reconstruction for two sites in the Czech Republic based on relict cryoturbation structures and compared its outputs with other palaeo-archives and GCMs products.

All the co-authors have read and approved the manuscript prior to its resubmission to Geoscientific Model Development. No part of the manuscript can infringe upon existing copyrights in any way. We have no conflict of interest to declare.

Thank you very much for reviewing the revised manuscript.

Yours sincerely,
Tomáš Uxa

**Author's response to comments of Referee #1**

**AC:** We thank the anonymous referee for the detailed review of our manuscript.

**RC1:** General comments
The discussion paper describes a modelling scheme to inversely estimate the near-surface atmospheric thermal states from the thaw depth information under permafrost conditions, primarily employing the idealized relationship derived from the Stefan formula, and discussed the applicability of the model to infer the past thermal conditions from the relict periglacial features, namely, active layer thickness. The authors demonstrated the efficiency of the scheme to inversely estimate the temperature characteristics, such as mean annual air temperature, and mean air temperatures of coldest and warmest months, from the active layer thickness observed at the Antarctic and Arctic sites.

The relationship expressed as the Stefan solution, Equation (1) in the text, is widely known for its useful simplicity but also tendency for biases when applied to real observations, as partly stated in the discussion paper. Still, the author proposed a new and intriguing idea to apply the relationship as a modelling framework to infer the paleo-thermal conditions at the formation time of the currently relict periglacial feature, which can be very relevant to geoscientific modelling within the scope of GMD, as well as of paleoclimatology and cryosphere-related science. In the current form of the paper, however, the explanation and evaluation of the modelling scheme are confusing, or poorly written in term of model description, and the title and the target of the paper show substantial mismatches with the current structure of the paper. Thus, the reviewer believes that the manner conducting the model evaluation, as well as overall organization of the presented text need substantial revisions (appreciating the effort that the manuscript went overall rearrangements for a model description paper), as well as the way the model application was conducted and presented in the Result section.

**AC:** We agree with the referee and admit that there is a mismatch between the title and content of the original version of the manuscript. Originally, it was meant to be a proof-of-concept study showing that the model performs well on present-day data, providing its best possible validation, which was to demonstrate that it could also reasonably derive past temperature conditions, but now we recognize that its real application on palaeo-periglacial features is necessary. Consequently, we also intend to include in the revised version of the manuscript a palaeo-air temperature reconstruction using a palaeo-active-layer thickness and to compare its outputs with reconstructions based on other proxy records and/or model products. This will also bring changes of the manuscript structure, which will be done in accordance with the referee's suggestions given here and below.

**RC1:** Two major suggestions are:
1. Move the subsection 5.4 to the Introduction section to describe the previous studies, or motivation of the study, and reconstruct the whole text to fit to a description paper of a model to be used for paleo-temperature reconstructions.

**AC:** Agreed. This subsection will be removed from the discussion and its parts will be incorporated into the introduction of the revised version of the manuscript, which will also be made less general and more related to the aims of the manuscript as suggested.

**RC1:** 2. Add a model validation case. Use only those terms and variables that would be available and used in paleo application cases (for example, seting $P$ to 365 days, and $Aa$ as described in 5.2.3, etc.), and see how the computed atmospheric thermal states compare to the observed. Also, sensitivity tests for parameters (eg, physical properties; thawing n-factor) to evaluate the range of variations in the computed temperatures would be very informative addition to discussions in 5.2.

**AC:** We intend to include in the revised version of the manuscript a palaeo-air temperature reconstruction using a palaeo-active-layer thickness and to compare its outputs with reconstructions based on other proxy records and/or model products. A section containing present-day data will be retained in the revised version of the manuscript in order to provide model validation using analogous data available for the palaeo-cases and to perform sensitivity tests.

**RC1:** Specific comments

Abstract:

The title and abstract claim that this paper introduces a presented model is to be used for paleo-temperature reconstructions. The reviewer feels that the authors' intention and the current structure and the way the model was run and evaluated have a large gap, and suspect that the current evaluation against modern temperature records could not serve properly to judge the model's ability when applied to the past periglacial features. The performed evaluation seemed to use information that could not be available for the paleo cases.

**AC:** As stated above, originally, it was meant to be a proof-of-concept study, but we intend to include in the revised version of the manuscript a palaeo-air temperature reconstruction using a palaeo-active-layer thickness and to compare its outputs with reconstructions based on other proxy records and/or model products. Still, a section containing present-day data will be retained in the revised version of the manuscript in order to provide model validation using analogous data available for the palaeo-cases and to perform sensitivity tests.

**RC1:** P. 2, ll. 46-48: This comment is related to the above one. If the paper is intended to introduce a model, it should show clear structure of the model, preferably with a simple schematic diagram, to show, for example, what are the input variables to the model; what are the parameters to be set or assumed; and what are the output variables that the model produce. The current paper appears merely to demonstrate a Stefan-based calculation scheme using the observed temperature and relevant data. Thus, if it is intended to evaluate the model to infer air temperature characteristics from past periglacial evidence, it should demonstrate the way the model would perform when applied to paleo cases (See the related comments in the "Result" section). An example of a modelling scheme for paleo application would be like:

[Input] active layer thickness

[Parameters to be determined, assumed, or deduced] thermal conductivity (thawed), wetness, thawing n-factor, length of the period (fixed at 365 days), annual air temperature amplitude

[Outputs] thermal conditions and related information (MAAT, MATW/CM, MATT/FS, Lt, Lf…)

**AC:** Please note that Table 1 in the original version of the manuscript shows what variables are inputs (upper section) and what variables are outputs (lower section) and it is incorporated in the section 2.1 describing driving parameters of the model.

As stated above, originally, it was meant to be a proof-of-concept study, but we intend to include in the revised version of the manuscript a palaeo-air temperature reconstruction using a palaeo-active-layer thickness and to compare its outputs with reconstructions based on other proxy records and/or model products, which should also clearly show how the input parameters should be chosen. Still, a section containing present-day data will be retained in the revised version of the manuscript in order to provide model validation using analogous data available for the palaeo-cases and to perform sensitivity tests.

**RC1:** P. 4, l. 84 (and others), "amplitude":

This is merely a suggestion. Use of a word "range" to denote a margin between the lowest and highest values, maybe useful to distinguish $Aa$ and $Aa/2$ in the text.

**AC:** Agreed. A collocation "annual air temperature range" will be used in the revised version of the manuscript instead of "annual air temperature amplitude".

**RC1:** P. 5, ll. 98-106: Estimation of MAAT and *Aa* appears the key, or the central part of the model when applied to the paleo settings when no a-priori thermal knowledge is available. Under the current modelling framework, when one assumes a sinusoidal annual temperature change, and has the *Ita* value as the area under the curve for the positive values, MAAT and *Aa* can be determined independently. In the current form, it is not clear if *Aa* is a parameter or an output variable in the model. So, it definitely needs more elaboration to describe how to calculate (or estimate) MAAT and/or *Aa* (with this in mind that this modelling scheme is to be used for the paleo applications).

**AC:** Please note that numerous other palaeo-air temperature reconstructions, for instance those based on glacier mass-balance modelling, also frequently utilized present-day climatology (that is, including present-day annual air temperature range) combined with MAAT and/or precipitation perturbations (though these were frequently not listed as model driving parameters) or adjusted annual air temperature range to derive most plausible palaeo-climate scenarios. Consequently, we believe that the presented scheme is meaningful.
Unfortunately, MAAT and $A_a$ cannot be determined independently because $I_{ta}$ depends on both of them, that is, $I_{ta}$ can achieve identical values for various combinations of MAAT and $A_a$. For instance, $I_{ta}$ equals 526 °C d if MAAT and $A_a$ is -4 °C and 20 °C, respectively, but also if it is -8 °C and *ca*. 29.8 °C. Consequently, $A_a$ must be a model parameter in order to estimate MAAT and other air temperature characteristics. However, please note that $A_a$ does not define their precise values. Moreover, it is believed to undergo substantially lower temporal variations than, for instance, MAAT, and thus $A_a$ for palaeo-applications may be approximated by its present-day value at a site with relict periglacial features or it may be adjusted based on other regional proxies. We will stress it more in the revised version of the manuscript.

**RC1:** P. 5, ll. 105-106, "However, potential drawbacks can be easily handled if exclusively permafrost-related features are examined.": It is not clear what is intended to say.

**AC:** Since the solution is designed to be used in permafrost environments, problems may occasionally arise in situations where seasonally frozen ground coexists under negative mean annual air temperature (MAAT) because permafrost–seasonal frost boundary rarely coincides exactly with MAAT of 0 °C. So the model should be applied on those features that indisputably formed in the presence of permafrost. Nonetheless, the statement will be changed in the revised version of the manuscript in order to be more understandable.

**RC1:** P. 6, Figure 2. It would be very user-friendly to describe how to draw relevant information from the figure, for most of the GDM reader won't be familiar with this nomogram.

**AC:** We will extend the caption and briefly describe how to draw information from the figure in the revised version of the manuscript.

**RC1:** P. 7, Table 2, and "Model validation": Please comment on the applicability to "Berry Hill slopes" in the text (other James Ross sites appear on the flat locations).
Applicability of the Stefan solution may be limited to those sites with high vertical heterogeneity, and it is mentioned in the text for the Alaskan site. Applicability to sites with large lateral flows of heat or water would also be limited.

**AC:** First of all, it should be noted that for consistency we stick to long-established site names on James Ross Island. Admittedly, the name "Berry Hill slopes" may be a little misleading because the site actually occurs on a

slightly-inclined surface in the foothills of the "Berry Hill", which has a gradient of 5–10° (Hrbáček, F., Nývlt, D., Láska, K.: Active layer thermal dynamics at two lithologically different sites on James Ross Island, Eastern Antarctic Peninsula, Catena, 149, 592–602, http://dx.doi.org/10.1016/j.catena.2016.06.020, 2017), and thus lateral flows of heat or water are supposed to be limited or small. We will mention it in the revised version of the manuscript.
We agree that the applicability of the Stefan solution may be limited at sites having high vertical heterogeneity and those experiencing a certain degree of lateral flows of water or heat. However, we believe it is necessary to test the model in various settings, including those that does not perfectly meet its assumptions, and evaluate its actual performance there. Actually, the minority of locations where the Stefan solution has been applied to estimate the thickness of the active layer can be considered as "ideal".

**RC1:** P. 7, ll. 128-129, "The Stefan equation": Does it mean Eq. (1)? If so, please add the notation (similar to p. 10, l. 212). Also, it is not clear, what are the difference between the results of what this sentence means, and what the later demonstration of the model in "Result" section.

**AC:** Yes, it means Eq. (1). The corresponding notations will be added in the revised version of the manuscript.
The sentence was to state that earlier thaw-depth estimates using the Stefan solution (not estimates of air temperatures based on active-layer thickness) were among the most accurate ever on James Ross Island, while those from the Alaskan sites were among the worst, and just for this reason we believe that these locations are well suited to evaluate the model performance. It will be changed in the revised version of the manuscript in order to be more understandable.

**RC1:** P. 8, ll. 162-163: It is curious if the results from the "successive wet and dry weighing" and the TDR probes are consistent to each other, or were independently done and not comapred (eg, Alaskan sites were solely done by the former, and the James Ross by latter). Is it possible to mention the representative of the results to be applied to the entire thawed layer?

**AC:** Only one of these methods was employed at each study site. Alaskan sites were solely done by successive wet and dry weighing, which was also applied at Abernethy Flats and Johann Gregor Mendel sites on James Ross Island, while the rest of the locations, that is, Berry Hill slopes and Johnson Mesa, was done by a calibrated TDR probe. We will consider using solely the outputs of successive wet and dry weighing in the revised version of the manuscript because it is now available from all the sites on James Ross Island.
Please note that the representativeness of the measurements was already documented by earlier publications cited in the original version of the manuscript (Zhang, 1993; Romanovsky and Osterkamp, 1997; Hrbáček et al., 2017a; Hrbáček and Uxa, 2020), which estimated active-layer thickness there.

**RC1:** PP. 8-10. Although not clearly written, it seems that the results shown in this section used some of the temperature information obtained from the observations (for example, *P* and *Aa* as shown in Table 2, which claims "model-driving" parameters). If the purpose of the paper is to demonstrate the ability to reconstruct the temperature conditions derived solely from the geomorphological evidences (that is, depth of the active layer), the evaluation should be done in the same manner as to be intended for the paleo cases. This means to run the model with the input (depth) and assumed parameters (thermal conductivity, wetness, thawing n-factor) only. Otherwise, it appears just a mere application of the calculation scheme using advantage of the present-day observations.

**AC:** As stated above, originally, it was meant to be a proof-of-concept study, but we intend to include in the revised version of the manuscript a palaeo-air temperature reconstruction using a palaeo-active-layer thickness and to compare its outputs with reconstructions based on other proxy records and/or model products, which should also clearly show how the input parameters should be chosen. The model validation based on present-day data will be

done in an analogous manner.
Please note that numerous other palaeo-air temperature reconstructions, for instance those based on glacier mass-balance modelling, also frequently utilized present-day climatology (that is, including present-day annual air temperature range) combined with MAAT and/or precipitation perturbations (though these were frequently not listed as model driving parameters) or adjusted annual air temperature range to derive most plausible palaeo-climate scenarios. Consequently, we believe that the presented scheme is meaningful.

**RC1:** Subsection “5.1 Model uncertainties,…”:
This subsection needs to restructure the organization, and clearly reformulate sentences. There are many long sentences with unclean meaning (for example, ll. 222-224, 230-233, 235-237). Also, the discussion sometimes goes back and forth, right and left, with reservation and euphemism. One suggestion for a re-organization would be to first divide the discussion to “strength of the model” and “weakness of the model”, and prioritize the issues under each of the categories.

**AC:** The discussion section in the revised version of the manuscript will be reorganized as suggested and sentences will be reformulated to make them clearer.

**RC1:** P. 10, l. 214, “Also, it assumes that the frozen layer is at 0 $^{O}$C before thaw.”: This looks pre-assumed in the derivation: that is, what is at stake is the temperature at the freezing interface between the thawed and frozen layers, which should be 0 °C.

**AC:** Please note that the Stefan equation does not consider heat conduction below the freeze-thaw plane and as such assumes that temperature is uniformly at 0 °C in the frozen zone (see e.g. Romanovsky, V.E., Osterkamp, T.E.: Thawing of the active layer on the coastal plain of the Alaskan Arctic, Permafrost and Periglacial Processes, 8, 1–22, https://doi.org/10.1002/(SICI)1099-1530(199701)8:1<1::AID-PPP243>3.0.CO;2-U, 1997; Kurylyk, B.L.: Discussion of ‘A simple thaw-freeze algorithm for a multi-layered soil using the Stefan equation’by Xie and Gough (2013). Permafrost and Periglacial Processes, 26, 200–206, https://doi.org/10.1002/ppp.1834, 2015). Nonetheless, it will be changed in the revised version of the manuscript in order to be more understandable.

**RC1:** P. 11, 225-227: It seemingly depends on whether MAAT or MATWM (or MATTS) is at question (cf. Figure 3).

**AC:** Agreed. It will be changed in the revised version of the manuscript in order to be more understandable.

**RC1:** P. 11, l. 231: It is not clear what is meant by “which”

**AC:** It should relate to “the Stefan equation tends to deviate”, but now we see that it can also ambiguously relate to “the peat-layer thickness in the active layer”. It will be changed in the revised version of the manuscript in order to be more understandable.

**RC1:** P. 11, l. 236: Not a clear sentence. Are the sites “far from being saturated” those in James Ross Island, and sites of “two-layer” those in Alaska? What (or which) does “there” actually mean?

**AC:** Rather, it was supposed to be a general statement that the model performed well on present-day data even though some of the validation sites do not perfectly meet the assumptions for the application of the Stefan formula. It will be changed in the revised version of the manuscript in order to be more understandable.

**RC1:** “5.2 Driving data”: Maybe a source of confusion in reading the discussion paper is that it is not clear what are the input (driving) data, what are the parameters or boundary conditions that set the calculations, and what are the output of the model to be applied for the paleo setting. What is discussed in this subsection is either parameters (ie, ground physical properties, thawing n-factor) or a part of the output (temperature amplitude), otherwise it does not make sense if the target temperature information is a driving data.

**AC:** Table 1 in the original version of the manuscript shows what variables are inputs (upper section) and what variables are outputs (lower section). Values of the input parameters should be obtained directly from relict periglacial structures, while those that cannot be obtained directly should be derived using empirical relations (transfer functions) or should rely on representative published data that allow a meaningful range of their values to be defined. Since we also intend to include in the revised version of the manuscript a palaeo-air temperature reconstruction, it should clearly show the above procedure.
Please note that numerous other palaeo-air temperature reconstructions, for instance those based on glacier mass-balance modelling, also frequently utilized present-day climatology (that is, including present-day annual air temperature range) combined with MAAT and/or precipitation perturbations (though these were frequently not listed as model driving parameters) or adjusted annual air temperature range to derive most plausible palaeo-climate scenarios. Consequently, we believe that the presented scheme is meaningful.

**RC1:** P. 13, l. 278, “it is possible to assess the extremes, between which the moisture likely occurred”: Not clear what is meant.

**AC:** This should mean that it is possible to determine the range of values, which moisture could reach at the time when periglacial features formed. It will be changed in the revised version of the manuscript in order to be more understandable.

**RC1:** P. 14, l. 288, “these correlations”: which correlations between what? Please describe clearly.

**AC:** This should mean correlations between thermal conductivity and other ground physical properties. It will be changed in the revised version of the manuscript in order to be more understandable.

**RC1:** “5.3 Implications for paleo-temperature reconstructions”: It would be suggested to rename the subsection title, something like “Applicability to periglacial features”.

**AC:** The subsection name will be changed or the whole subsection will be included into another one in the revised version of the manuscript, given that a palaeo-air temperature reconstruction will be added.

**RC1:** P. 15, ll. 329-331, “we hypothesize that their depth probably rather reflects the position of a transient layer where the contact between the active layer and the uppermost permafrost at the time of their formation oscillated”: It is not clear what this sentence is meant.

**AC:** Transient layer is a transition zone that alternates in status between seasonally frozen ground and permafrost over sub-decadal to centennial time scales because of natural climate variability (Shur, Y., Hinkel, K.M., Nelson, F.E.: The Transient Layer: Implications for Geocryology and Climate-Change Science, Permafrost and Periglacial Processes, 16, 5–17, https://doi.org/10.1002/ppp.518, 2005), and this is what past periglacial features likely attest to. It will be changed in the revised version of the manuscript in order to be more understandable.

**RC1:** P. 15, l. 331 “the latter”: It is not clear what is indicated.

**AC:** “the latter” was to be related to the transient layer mentioned in the previous sentence. It will be changed in the revised version of the manuscript in order to be more understandable.

**RC1:** P. 15, l. 347, "random-sampling methods": how the methods work in the context? With no information, it is not possible to judge the adequacy of the methods.

**AC:** Agreed. Random sampling will be used to generate representative sets of input parameters for a palaeo-air temperature reconstruction, which will be added into the revised version of the manuscript.

**RC1:** "5.4 Progress over previous attempts": the content of this subsection should be placed as "motivation" or "previous studies" in the Introduction, and the whole paper should be structured to "introduce and evaluate" a model to infer air temperature from the paleo-periglacial feature. It is strongly suggested that the overall organization and structure of the paper should be revised.

**AC:** This subsection will be removed from the discussion and its parts will be incorporated into the introduction of the revised version of the manuscript.

**RC1:** The authors gave proper credit to related work and clearly indicate their own new/original contribution. And the number and quality of references appear appropriate.

**Author's response to comments of Referee #2**

**AC:** We thank the anonymous referee for the review of our manuscript.

**RC2: Major**

The manuscript has a lot of jargon words in the Abstract and the Introduction. This makes it difficult to understand and follow from the beginning. The authors introduce the work from a very general perspective and do not include specific details applicable to the current study. The results section has only one figure with a lot of unnecessary discussion points, which are well-known and well-documented in the previous works. In addition, most if not all the formulas and notations can be found in Nelson and Outcalt (1987), listed in references. Note, that Nelson and Outcalt (1987) acknowledge the surface processes and do not jump straight to the Stefan's formula. I have a common criticism, which is well understood by authors, and I appreciate their effort in providing a detailed description of all the pros and cons of their model. I think that the length of the discussion should and could be reduced. Clearly, snow depth and organic peat layer are two major factors that will add a lot of bias to thaw depth calculation. Also, using a simple (one layer) formula has its significant limitations. However, for paleo-temperatures, it could be feasible.

I felt that authors are presenting the model as a proof-of-concept showing that this algorithm might work. The fact that it is performed well for homogenous soil is logical and not surprising. In addition, the model has a higher success rate for continuous permafrost regions, with minimum surface vegetation and climate-driven permafrost conditions (Shur et al., 2007). I do not think that the model will work well for the discontinuous permafrost areas. I suggest looking at early works by Clow (1992) on temperature inversion, that captures all the complexity dealing with inverse modeling studies applied to permafrost temperature reconstructions.

My major disappointment is that I was expecting to see how the model derives paleo-air temperatures on specific examples. That will be the best justification for me that high order bias can be neglected for paleo-air reconstruction. I have mixed feelings about this work. I appreciate the authors' effort and think that it can be valuable for a paleo- temperature reconstruction. I would be willing to suggest this work for publication once the authors will revise and paper, improve the flow, and get rid of jargon. Ideally, it would be nice to see some paleo-reconstructions cases. I suggest to be more specific from the beginning and clearly state the goal of this work.

**AC:** We will try to keep the number of jargon words to a minimum in the abstract and introduction in order to be more understandable, but please note that the model is intended to be used mainly by periglacial geomorphologists working in past permafrost environments, and thus some terminology may be difficult to leave. Also, we will make the introduction less general and more related to the aims of the manuscript.

Please note that we do not hide at all that some of the formulas can be already found in Nelson and Outcalt (1987), but we use them and have arranged them differently. Nelson and Outcalt (1987) introduced a scheme that is designed to decide whether permafrost is present at a given location based on air thawing and freezing index, while we seek to derive air temperature conditions using the thickness of the active layer. Definitely, snow cover and organic layer are important factors that affect the thickness of the active layer. Nonetheless, the effect of snow cover does not need to be accounted for in this case because the Stefan equation combined with thawing *n*-factor retrieves air thawing index responsible for a given thickness of the active layer, which is subsequently turned into annual as well as winter air temperature characteristics that are not affected by snow at all. Since most periglacial features develop under bare to grassy surfaces, we believe that the thawing *n*-factor, parameterizing the ground-surface–air temperature relations during the thawing season, can be reasonably estimated based on published values for analogous ground-surface covers. On the other hand, it would be a pure guess in the case of snow cover thickness and associated freezing *n*-factor. Consequently, we believe that the presented scheme, relying only on the thaw-season ground temperature conditions, is advantageous, also from that point of view that most active-layer features largely develop during the warm part of the year when snow cover is absent or very thin. As for organic layer, please note that it represents a substantial part of the Alaskan profiles included in the original version of the manuscript and indeed causes larger model scatters around the identity lines at these locations (see Figure 3 in the original version of the manuscript), but the overall accuracy is still very good if representative inputs are used, even in the case of an one-layer solution used. We will emphasize the above points more in the revised version of the manuscript and we will also trim down the discussion section.

We consider the referee's statements about the expected model failure in discontinuous permafrost areas as speculative because theoretical studies contrastingly suggested that it should fail rather in very cold locations where permafrost is supposed to be continuous (see Romanovsky, V.E., Osterkamp, T.E.: Thawing of the active layer on the coastal plain of the Alaskan Arctic, Permafrost and Periglacial Processes, 8, 1–22, https://doi.org/10.1002/(SICI)1099-1530(199701)8:1<1::AID-PPP243>3.0.CO;2-U, 1997). If the remark was to be based on the concern that in discontinuous permafrost regions the model could be applied to places with seasonally frozen ground, then we must assure you that this situation should not happen as the model should be exclusively applied on landforms and sedimentary structures indicative of the base of the palaeo-active layer, which indisputably formed in the presence of permafrost mostly during Quaternary cold stages.

We confirm that the original version of the manuscript was meant to be a proof-of-concept study, but now we recognize that real model application on palaeo-periglacial features is necessary. Consequently, we also intend to include in the revised version of the manuscript a palaeo-air temperature reconstruction using a palaeo-active-layer thickness and to compare its outputs with reconstructions based on other proxy records and/or model products.

**RC2: Minor**

L2 Not sure what are the climatic controls? Rephrase and clarify.

**AC:** It should mean the range of climatic conditions, under which individual periglacial features form. It will be changed in the revised version of the manuscript in order to be more understandable.

**RC2:** L5 Which 'flaws'?

**AC:** It is related to the still poorly understood range of climatic conditions, under which individual periglacial features form. It will be changed in the revised version of the manuscript in order to be more understandable.

**RC2:** L6 What are the relict permafrost related features? L11-12. Not sure what do you mean. Be more specific.

**AC:** It means relict (inactive under present-day climate conditions) landforms and sedimentary structures, which formed in the presence of permafrost mostly during Quaternary cold stages. We will try to be more specific in the revised version of the manuscript.

**RC2:** L14 'relict permafrost features', need to define them first.

**AC:** As stated above, it means relict (inactive under present-day climate conditions) landforms and sedimentary structures, which formed in the presence of permafrost mostly during Quaternary cold stages. We will try to be more specific in the revised version of the manuscript.

**RC2:** L17-18 'active features', 'relict periglacial assemblages' need to define them as well. L29 'periglacial features', specify.

**AC:** The sentence will be rephrased in the revised version of the manuscript in order to be more understandable.

**RC2:** L30 'geometric attributes', not sure what do you mean by that? L34 'dimension of features', specify

**AC:** It means morphology (that is, shape and size) of periglacial features. It will be changed in the revised version of the manuscript in order to be more understandable.

**RC2:** L69. Why authors did not Kudryavstsev's formula instead, which incorporates the effect of soil moisture, snow, and vegetation. Need to better explain the choice, why not use more sophisticated numerical models like GIPL or Gryogrid?

**AC:** We build on the Stefan formula because of its simplicity and reasonable accuracy at the same time. Note that the Stefan formula also incorporates soil moisture (see Eq. 1), and the effect of vegetation (~ground-surface cover) is expressed via the empirical thawing *n*-factor (see Eq. 3), which converts ground-surface thawing index into air thawing index. Advantageously, the effect of snow cover does not need to be accounted for because the solution retrieves air thawing index, which is subsequently turned into annual as well as winter air temperature characteristics that are not affected by snow at all. This is advantageous also from that point of view that most active-layer features largely develop during the warm part of the year when snow cover is absent or very thin.

The Kudryavtsev formula requires much more additional inputs as compared to the Stefan formula, such as thawed volumetric heat capacity, frozen thermal conductivity, or mean annual ground temperature at the top of the permafrost, only to derive ground surface temperatures. Numerous other extra inputs related to snow and vegetation, such as their height or thermal conductivity, are required for the conversion between ground-surface and air temperatures (this is done using only the thawing *n*-factor in our solution). Such complexity can admittedly yield better results in present-day applications where the inputs may be easily available, but a larger number of input parameters is unsuitable for palaeo-applications as more numerous assumptions would have to be made. Obviously, it is also the case of the other models, such as GIPL or GryoGrid, which are even more sophisticated and solved numerically.
Some of the above explanations will be incorporated in the revised version of the manuscript.

**RC2:** Table 1 where thermal conductivities and porosities come from? Adding the effect of the organic layer will change the results of the thaw depth (e.g. Jafarov and Schaefer 2016).

**AC:** Table 1 in the original version of the manuscript shows what variables are inputs (upper section) and what variables are outputs (lower section). Values of the input parameters should be obtained directly from relict periglacial structures, while those that cannot be obtained directly should be derived using empirical relations (transfer functions) or should rely on representative published data that allow a meaningful range of their values to be defined. Please note that we intend to include in the revised version of the manuscript a palaeo-air temperature reconstruction, which should clearly show the above procedure.
Organic layer is certainly an issue in active-layer thickness modelling and indeed Figure 5 in the original version of the manuscript nicely documents its effect. Please note that organic layer represents a substantial part of the Alaskan profiles included in the original version of the manuscript and causes larger model scatters around the identity lines at these locations (see Figure 3 in the original version of the manuscript), but the overall accuracy is still very good if representative inputs are used.

**RC2:** L105 not sure what authors mean. Rephrase and add more clarity.

**AC:** Since the solution is designed to be used in permafrost environments, problems may occasionally arise in situations where seasonally frozen ground coexists under negative mean annual air temperature (MAAT) because permafrost–seasonal frost boundary rarely coincides exactly with MAAT of 0 °C. So the model should be applied on those features that indisputably formed in the presence of permafrost. Nonetheless, the statement will be changed in the revised version of the manuscript in order to be more understandable.

**RC2:** Table 2 Again specify where thermal conductivities and porosities come from. L140 not sure why extrapolated ALT was 0.15m. it does not make sense.

**AC:** Values of the input parameters should be obtained directly from relict periglacial structures, while those that cannot be obtained directly should be derived using empirical relations (transfer functions) or should rely on representative published data that allow a meaningful range of their values to be defined. Please note that we intend to include in the revised version of the manuscript a palaeo-air temperature reconstruction, which should clearly show the above procedure.
Please note that L140 does not state that the extrapolated active-layer thickness was at most only 0.15 m, but rather that it was at most 0.15 m below the deepest ground temperature sensor available for the estimation (extrapolation) of the active-layer thickness. Since the sensor was at a depth of 0.75 m, the maximum extrapolated active-layer thickness was 0.90 m. Given the maximum vertical distance between the sensor and extrapolated active-layer thickness is as low as of 0.15 m, it is assumed that the active-layer thickness is plausible and can be used for validation in this manuscript. We feel it is necessary to assure the reader about that because active-layer thickness is sometimes extrapolated to depths well under the deepest ground temperature sensors by other papers and the resulting values may thus be of questionable validity. Nonetheless, we will slightly modify this part in the revised version of the manuscript in order to be more understandable.

**RC2:** L197. I would be super cautious with the high accuracy statements.
The rest of the discussion talks about caveats and explains when and why it fails. It is a fair discussion, but I found it rather long and not necessary. All these things are well-known and I would suggest to reduce it to a short summary of the pros and cons. I would rather see the applications as a justification of that this simple method was developed for a reason.

**AC:** We will moderate our accuracy statements and trim down the discussion in the revised version of the manuscript. Also, a palaeo-air temperature reconstruction will be added.

**RC2:** References


Clow, G.D. The extent of temporal smearing in surface-temperature histories derived from borehole temperature measurements. Global and planetary change, 6(2), 81-86 (1992)

Shur, Y. L. and Jorgenson, M. T.: Patterns of permafrost formation and degradation in relation to climate and ecosystems, Permafrost Periglac., 18, 7–19, doi:10.1002/ppp.582, 2007.

Jafarov, E. and Schaefer, K.: (2016), The importance of a surface organic layer in simulating permafrost thermal and carbon dynamics, The Cryosphere, 10, 465-475, doi:10.5194/tc-10-465-2016.

**Author's response to comments of Referee #3**

**AC:** We thank the anonymous referee for the review of our manuscript.

**RC3:** I read and totally agree with the comments from reviewers 1 & 2. The main issue is the mismatching between the title and content. From the title, as a reader, I would like to know how we can use active layer thickness to inverse palaeo-air temperature. However, the ‘inversion ’model seems not to be able to look backward for past years, decades, or centuries. Based on previous studies about this theme, the climate signal was stored in deep permafrost thermal condition (e.g., Clow (1992), Huang et al., (2000)) while the active layer is only several meters below the ground surface, which is strongly influenced by seasonal variation. The current study is only to calculate the present (rather than palaeo-) mean annual air temperature by using active layer thickness given fixed other parameters. Furthermore, assuming Aa maybe not acceptable for reconstructing palaeo-climate. P should be 365 (or 366) rather than ranges from 300+ to 400+ (in Table 2).
Thus, the current version is not able to be published but I would be willing to suggest this work for publication once the authors will show some palaeo-climate reconstructions results using active layer thickness.

References

Clow, G. D. (1992). The extent of temporal smearing in surface-temperature histories derived from borehole temperature measurements. Global and Planetary Change, 6(2- 4), 81-86.

Huang, S., Pollack, H. N., & Shen, P. Y. (2000). Temperature trends over the past five centuries reconstructed from borehole temperatures. Nature, 403(6771), 756-758.

**AC:** We agree with the referee and admit that there is a mismatch between the title and content of the original version of the manuscript. Our original intention was to show that the model performs well on present-day data, providing its best possible validation, which was to demonstrate that it could also reasonably derive past temperature conditions, but now we recognize that its real application on palaeo-periglacial features is necessary. Consequently, we intend to include in the revised version of the manuscript a palaeo-air temperature reconstruction using a palaeo-active-layer thickness and to compare its outputs with reconstructions based on other proxy records and/or model products. Still, a section containing present-day data will be retained in the revised version of the manuscript in order to provide model validation and perform sensitivity tests. Please note that the model is supposed to rely on relict permafrost features, which have formed within the active layer, and as such these features can indicate its former thickness (mostly through characteristic structures found in sedimentary profiles) at locations where permafrost occurred during Quaternary cold stages. It does not exploit temperatures measured in deep boreholes.

# PERICLIMv1.0: A model deriving palaeo-air temperatures from thaw depth in past permafrost regions

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**Abstract.** Periglacial features, such as various kinds of patterned ground, cryoturbations, frost wedges, solifluction structures, or blockfields, are among the most common relics of colder climates, which repetitively occurred throughout the Quaternary, and, as such, they are widespread archives of past ~~conditions. Climatic controls on~~ environmental conditions. Climate controls on the development of most periglacial features, however, remain poorly ~~established~~known, and thus empirical ~~palaeo-climatic~~ palaeo-climate reconstructions based on them ~~are~~ have been far from reliable. This study introduces and evaluates a new simple inverse modelling scheme PERICLIMv1.0 (PERIglacial CLIMate) that aims to overcome these flaws through deriving ~~the~~ palaeo-air temperature characteristics ~~coupled with the thickness of the palaeo-active layer~~related to the palaeo-active-layer thickness, which can be recognized ~~in many relict permafrost-related features~~ using many relict periglacial features found in past permafrost regions. The evaluation against modern temperature records showed that the model reproduces ~~the~~ air temperature characteristics ~~, such as mean annual air temperature, mean air temperature of the warmest and coldest month and of the thawing and freezing season, with a mean error of~~ with average errors ≤1.3 ~~0.5~~ °C. Besides, ~~air thawing and freezing indices both depart on average by 6 %, whereas the length of the thawing and freezing season tends to be on average underestimated and overestimated by 10~~the past mean annual air temperature modelled experimentally for two sites in the Czech Republic hosting relict cryoturbation structures was between −7.0±1.9 ~~% and 4~~°C and −3.2±1.5 ~~%, respectively. The~~ °C and its corresponding reduction was between −16.0 °C and −11.3 °C in comparison with the 1981–2010 period, which is well in line with earlier reconstructions utilizing various palaeo-archives. The relatively high model success rate is promising and suggests that it could become a ~~powerful~~ useful tool for reconstructing Quaternary palaeo-environments across vast areas of ~~mid-latitudes~~ mid- and low-latitudes where relict periglacial assemblages frequently occur, but their full potential remains to be exploited.

## 1 Introduction

Many mid- and low-latitude regions of the world host a number of distinctive landforms and subsurface structures collectively termed as relict periglacial features~~that have been inherited from colder~~ , such as various kinds of patterned ground, cryoturbations, frost wedges, solifluction structures, or blockfields, which developed during cold periods of the Quaternary . due to intense freeze-thaw activity taking place under seasonal-frost or permafrost conditions. Commonly, these features rest in places where other palaeo-indicators are rare or absent, or emerged at different times, which enhances their relevance as archives of past environmental conditions. So far, these assemblages relict periglacial features have been used to reconstruct former climatic conditions in two basic manners. The first searches for representative analogues in terms of composition in past climates almost exclusively on the basis of climate thresholds of their active counterparts that are mostly situated in present-day periglacial environments and associates their climates with relict features. The second assigns current climatic thresholds of active features to complex relict periglacial assemblages to deduce the most plausible palaeo-climate high-latitude periglacial environments (Ballantyne and Harris, 1994). Such empirical interpretations have, however, largely rely been largely based on flawed assumptions because suitable analogues for past periglacial environments are rare particularly due to substantial differences contrasts in solar insolation between mid and high latitudes mid- or low- and high-latitudes (Williams, 1975; French, 2017), and even if they can be found, active features present periglacial features that occur there may have developed under climatic conditions different from those which prevail different climate conditions than those prevailing at the present time (Uxa et al., 2017; Ballantyne, 2018). Climatic controls on Climate controls on the development of most periglacial features are therefore poorly establishedthus poorly known, usually implying broad ranges of climate conditions (Washburn, 1980; Harris, 1982, 1994; Karte, 1983; Wayne, 1983; Ballantyne and Harris, 1994; Huijzer and Isarin, 1997; Ballantyne, 2018), which also relates to the fact that the features partly depend on other factors, such as ground physical properties, hydrology, topography, or ground-surface cover (Ballantyne, 2018). Consequently, the inferred palaeo-climates have frequently been thought to be far from reliable, and indeed most periglacial features have been widely accepted only as indicators of seasonal frost or permafrost and ground-ice presence , but this may be dubious and rather tentative for some features as well (Ballantyne and Harris, 1994; Ballantyne, 2018). This adverse situation can largely be be largely attributed to a persistent excessive interest in the distribution patterns of periglacial features and their association with mean annual air temperature (MAATMAAT), pervading traditional palaeo-periglacial geomorphology, while their geometric attributes surface and subsurface dimensions have been widely neglectedoverlooked. Greater emphasis on the latter, closely related to the feature formation formation of periglacial features and responsible processes, could, however, advance the discipline far beyond its current frontiers (cf. Barsch, 1993; French and Thorn, 2006).

Periglacial features form through various thermally- and gravity-induced processes that mostly operate within a layer of seasonal freezing and thawing, the base of which commonly confines the subsurface dimensions of the features (Williams, 1961). The latter This zone is usually discernible in vertical cross-sections because intense ice segregation and mass displacements associated with the feature formation formation of periglacial features alter the freeze-thaw layer so that its composition and properties differ from those of the underlying ground(French, 2017). Thus, if such an interface resides relict periglacial features , it may . This contrast may be preserved long after the periglacial features have ceased to be active and, as such, it can indicate the thickness of the palaeo-freeze-thaw layer (French, 2017). Since the latter freeze-thaw depth closely couples with ground and air temperature conditions (e.g., Frauenfeld et al., 2004; Åkerman and Johansson, 2008; Wu and Zhang, 2010), its former level it retains a valuable palaeo-climatic palaeo-climate record that can be approximated based on modern air temperature–freeze-thaw depth relations (Williams, 1975) or can be retrieved through an inverse solution of the equations calculating the freeze-thaw depth (Maarleveld, 1976; French, 2008). Obviously, this idea is not new, but despite its simplicity ingenuity, simplicity, and general acceptance in a benchmark periglacial literature (Washburn, 1979; Ballantyne and Harris, 1994; French, 2017; Ballantyne, 201 (e.g., Washburn, 1979; Ballantyne and Harris, 1994; French, 2017; Ballantyne, 2018), it has never been developed into a viable tool for deriving past thermal regimes that has a sound mathematical basis, is replicable, and lacks subjectivity (see Williams, 1975; Maarlev , because computational methods have been durably underused by periglacial geomorphologists interested in reconstructions of Quaternary palaeo-environments.

This study introduces and evaluates a simple modelling scheme PERICLIMv1.0 (PERIglacial CLIMate) that is designed to infer air palaeo-air temperature characteristics associated with former relict periglacial features indicative of the base of the palaeo-active layerpalaeo-active-layer thickness, and discusses its uncertainties and applicability, inter alia, with respect to other palaeo-proxy records and/or model products. It specifically targets on palaeo-active-layer phenomena because their palaeo-environmental significance as well as preservation potential is substantially higher compared to than for seasonal-frost features. Besides, it intends to stimulate the application of modelling tools and foster the development of new quantitative methods in palaeo-environmental reconstructions exploiting relict periglacial assemblages utilizing relict periglacial features in order to raise their reputation as palaeo-proxy indicators.

## 2 Model description

The PERICLIMv1.0 model principally builds on an inverse solution of the Stefan (1891) equation, which has originally been developed to determine the thickness of sea ice, but it also well describes the thaw propagation in ice-bearing grounds, and lately it has become probably the most commonly used analytical tool to estimate for estimating the thickness of the active layer (e.g., Klene et al., 2001; Shiklomanov and Nelson, 2002; ?)over permafrost (e.g., Klene et al., 2001; Shiklomanov and Nelson, 2002; Hrba . It assumes that the thawed-zone temperaturedecreases linearly with depth, while , which is controlled by the ground-surface temperature at the surface boundary, decreases linearly towards the bottom frozen zone that is constantly at 0 °C and latent heat is the only energy sink associated with its thawing. , that is, heat conduction below the thaw front is not accounted for (Kurylyk, 2015). As such, the Stefan equation tends to deviate inversely proportional to the moisture content in the active layer as well as the active-layer temperature at the onset of thawing (Romanovsky and Osterkamp, 1997; Kurylyk and Hayashi, 2016) , but its accuracy is still reasonable (e.g., Klene et al., 2001; Shiklomanov and Nelson, 2002; Hrbáček and Uxa, 2020). Besides, its simplicity and low requirements for input data as compared to more complex analytical or numerical models (e.g., Kudryavtsev et al., 197 is highly advantageous for palaeo-applications as fewer assumptions have to be made. Here, it is solved for a uniform, non-layered ground while ignoring any of its thaw-related mechanical responses.

The PERICLIMv1.0 deduces the thawing-season temperature conditions in the above way, which it further converts into annual as well as freezing-season air temperature attributes as detailed below. Please note that its code is implemented and disseminated as R package.

**Table 1.** List of the model input and output parameters, their symbols and units/classes.

| Parameter | Symbol | Unit/Class |
|---|---|---|
| **Inputs** | | |
| Palaeo-active-layer thickness | $\xi$ | m |
| Volumetric ground moisture content | $\phi$ | – |
| Dry ground bulk density | $\rho$ | $\mathrm{kg\,m^{-3}}$ |
| Ground quartz content | $q$ | – |
| Ground grain-size class | $f/c$ | 'fine' or 'coarse' |
| Ground-surface thawing $n$-factor | $n_\mathrm{t}$ | – |
| Annual air temperature range | $A_\mathrm{a}$ | °C |
| **Outputs** | | |
| Mean annual air temperature | MAAT | °C |
| Mean air temperature of the warmest month | MATWM | °C |
| Mean air temperature of the coldest month | MATCM | °C |
| Mean air temperature of the thawing season | MATTS | °C |
| Mean air temperature of the freezing season | MATFS | °C |
| Air thawing index | $I_\mathrm{ta}$ | °C d |
| Air freezing index | $I_\mathrm{fa}$ | °C d |
| Length of the thawing season | $L_\mathrm{t}$ | d |
| Length of the freezing season | $L_\mathrm{f}$ | d |
| Ground-surface thawing index | $I_\mathrm{ts}$ | °C d |

### 2.1 Driving parameters

The ~~model~~ PERICLIMv1.0 is driven by the ~~thaw depth~~ palaeo-active-layer thickness $\xi$ (m), the ~~bulk thermal conductivity of the thawed ground $k_\mathrm{t}$~~ volumetric ground moisture content $\phi$ (−), the dry ground bulk density $\rho$ ($\mathrm{kg\,m^{-3}}$), the ~~volumetric ground moisture content $\phi$~~ ground quartz content $q$ (−), the ground grain-size class $f/c$ ('fine' or 'coarse'), the ground-surface thawing $n$-factor $n_\mathrm{t}$ (−), ~~the annual amplitude of air temperature oscillations~~ and the annual air temperature range $A_\mathrm{a}$ (°C) ~~or, alternatively, the~~ (Table 1), which corresponds to the difference between the mean air temperature of the warmest ~~month~~ MATWM and coldest MATCM month (°C)~~, and the period of the air temperature oscillations $P$ () (Table 1)~~. The ground physical parameters are assumed to characterize the entire modelling domain (∼active layer) and ~~they are~~ are treated as constant over time.

### 2.2 Ground-surface and air thawing index

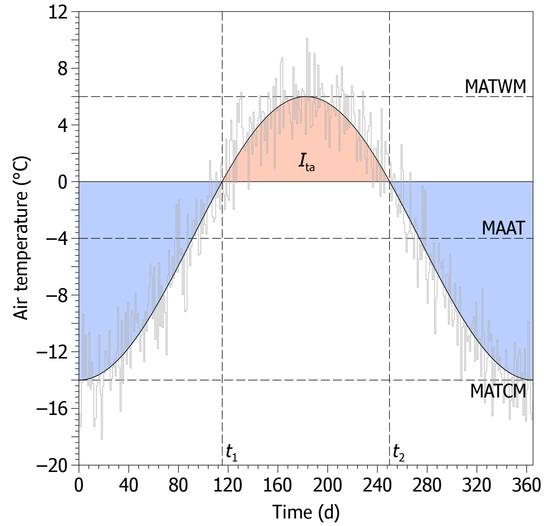


**Figure 1.** An idealized course of air temperature during the year described by a sine function with a mean of –4 °C and a range of 20 °C (black solid line) superimposed on the annual air temperature curve with daily variations (grey solid line). The air thawing index is shown in red, while the blue areas depict partial air freezing indices of the preceding (left) and subsequent (right) freezing season, respectively. See text and Table 1 for abbrevations.

~~The simplest scheme of the Stefan solution~~ The Stefan equation for calculating the ~~thaw depth in~~ active-layer thickness in a homogeneous substratum with constant physical properties has the following form (Lunardini, 1981):

$$\xi = \sqrt{\frac{2k_\mathrm{t} I_\mathrm{ts}}{L\phi\rho_\mathrm{w}}}, \tag{1}$$

where $k_\mathrm{t}$ is the thermal conductivity of the thawed ground ($\mathrm{W\,m^{-1}\,K^{-1}}$) calculated here as a function of its dry bulk density and volumetric moisture content using the Johansen's (1977) thermal-conductivity model (Appendix A), $I_\mathrm{ts}$ is the ground-surface thawing index defined as a sum of positive daily ground-surface temperatures in the thawing season ($\mathrm{°C\,d}$) (Fig. 1), $L$ is the specific latent heat of fusion of water ($334\,000\,\mathrm{J\,kg^{-1}}$), and ~~$\rho_\mathrm{w}$~~ $\rho_\mathrm{w}$ is the density of water ($1\,000\,\mathrm{kg\,m^{-3}}$). Please note that $I_\mathrm{ts}$ must be multiplied by the scaling factor of $86\,400\,\mathrm{s\,d^{-1}}$ in Eq. (1) to obtain the ~~thaw depth~~ active-layer thickness in meters. Besides, the product of $\phi$ and $\rho_\mathrm{w}$ can be alternatively substituted by that of the gravimetric ground moisture content and ~~the dry bulk density of the ground because~~ dry ground bulk density as their results are identical.

The ground-surface thawing index required to reach the specific ~~thaw depth~~ active-layer thickness can be obtained if Eq. (1) is rearranged such as:

$$I_\mathrm{ts} = \frac{\xi^2 L\phi\rho_\mathrm{w}}{2k_\mathrm{t}}. \tag{2}$$

The ground-surface thawing index can then be converted into the air thawing index $I_\mathrm{ta}$ ($\mathrm{°C\,d}$) through the ~~so-called~~ ground-surface thawing $n$-factor (Lunardini, 1978), which is a simple empirical transfer function that has been widely used to parametrize the thawing-season air–ground temperature relations across permafrost landscapes (e.g., Klene et al., 2001; Gisnås et al., 2017):

$$I_{\mathrm{ta}} = \frac{I_{\mathrm{ts}}}{n_{\mathrm{t}}}. \tag{3}$$

~~List of input and output variables, their symbols and units. Variable Symbol UnitThaw depth $\xi$ Thawed ground thermal conductivity $k_{\mathrm{t}}$ Volumetric ground moisture content $\phi$ Thawing $n$-factor $n_{\mathrm{t}}$ Annual air temperature amplitude $A_{\mathrm{a}}$ Period of~~ Note that the effect of snow cover on ground-surface temperatures does not have to be accounted for because the air thawing index is later used only to calculate other air temperature characteristics, and these are not affected by snow in any way. Such a scheme is particularly advantageous because it keeps the number of inputs low. However, it should be borne in mind that it is suitable especially for locations without long-lasting snow cover, which might disrupt the coupling between the air ~~temperature oscillations $P$ Mean annual air temperature MAAT Mean air temperature of the warmest month MATWM Mean air temperature of the coldest month MATCM Mean air temperature of the thawing season MATTS Mean air temperature of the freezing season MATFS Air thawing index $I_{\mathrm{ta}}$ Air freezing index $I_{\mathrm{fa}}$ Length of the thawing season $L_{\mathrm{t}}$ Length of the freezing season $L_{\mathrm{f}}$~~ and ground temperatures during the thawing season (e.g., Gisnås et al., 2016).

### 2.3 Air temperature characteristics

The temporal evolution of air temperature over ~~a~~ the year $T_{\mathrm{a}}(t)$ (°C) can be well described by a sine wave (Fig. 1) such as:

$$T_{\mathrm{a}}(t) = \mathrm{MAAT} + \frac{A_{\mathrm{a}}}{2}\sin\left(\frac{2\pi t}{P}\right), \tag{4}$$

where $t$ is the time (d) and $P$ is the period of air temperature oscillations (365 d). Note that ~~here the amplitude corresponds to the difference between MATWM and the mean air temperature of the coldest month MATCM and, as such, it~~ the annual air temperature range must be halved in Eq. (4) and the subsequent equations in order to characterize the annual temperature ~~variation~~ variations around MAAT ~~. Unconventionally~~(Fig. 1). Besides, the range of annual air temperature oscillations can also be ~~expressed through~~ alternatively expressed using MATWM ~~(cf. Williams, 1975) if its difference from MAAT is substituted for $\frac{A_{\mathrm{a}}}{2}$ in Eq. (4)and elsewhere~~(Appendix B).

The air thawing index represents ~~the~~ positive area under the annual air temperature curve (Fig. 1) and can be calculated by integrating Eq. (4) over the thawing season ~~:~~ as follows:

$$I_{\mathrm{ta}} = \int\limits_{t_1}^{t_2} T_{\mathrm{a}}(t)\,\mathrm{d}t, \tag{5}$$

with

$$t_1 = \arcsin\left(-\frac{\mathrm{MAAT}}{\frac{A_{\mathrm{a}}}{2}}\right)\frac{P}{2\pi}, \tag{6}$$

$$t_2 = \left[\pi - \arcsin\left(-\frac{\mathrm{MAAT}}{\frac{A_{\mathrm{a}}}{2}}\right)\right]\frac{P}{2\pi}, \tag{7}$$

where $t_1$ is the time when the air temperature curve crosses the zero-degree Celsius level from below (∼thawing season begins), while $t_2$ is the time when it crosses this level from above (∼thawing season ends) (e.g., Nelson and Outcalt, 1987).

An idealized course of air temperature during the year expressed by a sine function with a mean of −4 and an amplitude of 20 superimposed on the annual air temperature curve with daily variations. The air thawing index is shown in red, while the blue areas depict partial air freezing indices of the preceding (left) and subsequent (right) freezing season, respectively. See text and Table 1 for abbrevations.

Unfortunately, Eq. (5) has no analytical solution for MAAT. The latter can be derived from a nomogram (Fig. 2), but here it is calculated numerically using the bisection root-finding method applied on the right-closed interval $(-A_\mathrm{a}, 0\rangle$. searching for MAAT such that $-A_\mathrm{a} < \mathrm{MAAT} \leq 0$. This condition ensures that both positive and negative air temperatures have occurred during the annual periodyear, which is an essential prerequisite for the active layer to form. The same procedure can be applied in calculations based on the MATWM, but MAAT has to be searched within the interval $(-\infty, 0\rangle$ in their case because the amplitude is to be determined later. Admittedly, these assumptions are Admittedly, it is simplistic because air–ground temperatures are modulated by surface and subsurface offsets so that permafrost–seasonal frost boundary rarely coincides with usually occurs at slightly negative MAAT of 0. Instead, it usually occurs where MAAT is somewhat lower (?Smith and Riseborough, 2002)(Smith and Riseborough, 2002). Consequently, there might be a risk that the model is incorrectly applied to seasonal-frost conditions. However, potential drawbacks this can be easily handled if exclusively permafrost-related features prevented if periglacial features that have indisputably developed in the presence of permafrost are examined.

Once MAAT is known, the air freezing index $I_\mathrm{fa}$ ($^\circ\mathrm{C\,d}$) can be simply computed as:

$$I_\mathrm{fa} = \mathrm{MAAT}\,P - I_\mathrm{ta}. \tag{8}$$

Furthermore, MATWM and MATCM , respectively, is calculated as:

$$\mathrm{MATWM} = \mathrm{MAAT} + \frac{A_\mathrm{a}}{2}, \tag{9}$$

$$\mathrm{MATCM} = \mathrm{MAAT} - \frac{A_\mathrm{a}}{2}. \tag{10}$$

Mean air temperature of the thawing MATTS () and freezing MATFS season ($^\circ\mathrm{C}$) season, respectively, is defined as:

$$\mathrm{MATTS} = \frac{I_\mathrm{ta}}{L_\mathrm{t}}, \tag{11}$$

$$\mathrm{MATFS} = \frac{I_\mathrm{fa}}{L_\mathrm{f}}, \tag{12}$$

where $L_\mathrm{t}$ () and $L_\mathrm{f}$ () is the duration of the thawing and freezing season, respectively (d), which is expressed from Eq. (6) and (7) as:

$$L_\mathrm{t} = t_2 - t_1 = \left[\pi - 2\arcsin\left(-\frac{\mathrm{MAAT}}{\frac{A_\mathrm{a}}{2}}\right)\right]\frac{P}{2\pi}, \tag{13}$$

$$L_\mathrm{f} = P - L_\mathrm{t}. \tag{14}$$

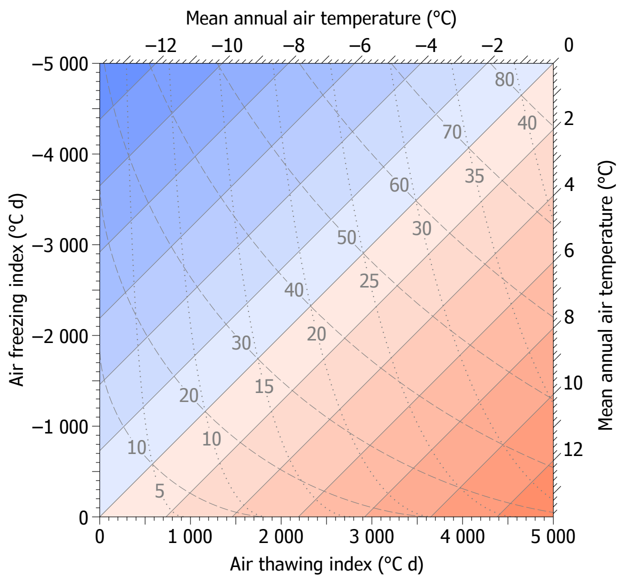


**Figure 2.** A nomogram showing relations between the air thawing and freezing index, mean annual air temperature (solid diagonal lines), annual air temperature ~~amplitude~~ range (dashed curved lines), and mean air temperature of the warmest month (dotted curved lines). Note that the value of the mean annual air temperature (read diagonally) and the air freezing index (read horizontally) is obtained at the intersection of the air thawing index (read vertically) and the annual air temperature range or the mean air temperature of the warmest month (both read curvilinearly).

Unsurprisingly, but importantly, solutions based on alternate driving parameters, as suggested above, produce identical outcomes, allowing the model adaptations to specific situations and available data.

## 3 Model validation

~~The PERICLIMv1.0 performance was tested against mostly previously published modern temperature data obtained in the period 20092010 to 20172018 at four bare permafrost sites located on the northern, unglacierized tip of~~ Performance of the model was tested using the same simulation schemes as for palaeo-applications detailed in the next section (see Sect. 4.2.5), but on the basis of data from modern permafrost environments of the James Ross Island ~~, north-eastern Antarctic Peninsula, between 6349′–6353′ S, 5750′–5757′ W, and 10–340 (e.g., Hrbáček et al., 2017a, b; ?), and data collected by the Geophysical Institute Permafrost Laboratory at the University of Alaska Fairbanks in the period 20012002 to 20162017 at three vegetated permafrost locations on the coastal plain of the Alaskan Arctic adjacent to the Beaufort Sea, between 6940′–7022′ N, 14828′–14843′ W, and 3–111 (, access: 28 June 2019; Romanovsky et al., 2009; Wang et al., 2018) (Table 2). The Stefan equation has been used to calculate the active-layer thickness at some of these sites before, but with contrasting success. While on James Ross Island the thaw-depth estimates were among the most accurate ever, those from the Alaskan sites were among the worst (Romanovsky and Osterkamp, 1997; ?). Given that both regions also differ in their climatic and environmental settings, we~~

thus believe that they are highly suitable for PERICLIMv1.0 validation and evaluation of its limits. The stations measured air and ground temperatures with thermistor sensors installed in solar radiation shields 1.5 or 2 above ground surface and at six to fifteen various depth levels ranging from or near from the ground surface to 0.75 or around 1 below, and their records were averaged to daily resolution (Romanovsky et al., 2009; Hrbáček et al., 2017a, b; Wang et al., 2018; **?**). Overall, we had 61 annual periods of data available for model validation (Table 2).

Active-layer thickness, which corresponds to the maximum annual depth of the 0 isotherm (Burn, 1998), was mostly determined by linear interpolation between the depths of the deepest and the shallowest sensors with the maximum annual temperature $> 0$ and $\leq 0$ , respectively. Alternatively, it was established by linear extrapolation of the maximum annual temperatures of two deepest sensors if both were positive. The extrapolated active-layer thickness was at most 0.15 below the deepest available temperature sensor, and thus we assume that the accuracy of the obtained values is analogous to the interpolated ones.

Number of annual periods ($N$) along with means and ranges of the model-driving parameters at the James Ross Island (upper section) and Alaskan Arctic (lower section) validation sites. Site $N$ $\xi$ () $k_{\mathrm{t}}$ the Alaskan Arctic () $\phi$ () $n_{\mathrm{t}}$ () $A_{\mathrm{a}}$ () $P$ () Abernethly Flats 6 0.57 (0.39–0.68) 0.61 0.265 2.55 (1.60–3.21) 20.1 (17.6–21.8) 363 (350–402)Berry Hill slopes 6 0.87 (0.85–0.90) 1.03 0.312 2.98 (2.15–4.48) 18.9 (16.0–22.2) 360 (329–403)Johann Gregor Mendel 5 0.58 (0.51–0.65) 0.17 0.160 3.95 (2.42–6.21) 20.1 (18.4–23.0) 365 (344–403)Johnson Mesa 6 0.58 (0.49–0.65) 0.61 0.211 3.98 (2.01–8.63) 19.4 (16.5–21.5) 360 (318–403)Deadhorse 10 0.73 (0.68–0.78) 0.77 0.515 0.97 (0.75–1.22) 40.2 (35.9–47.5) 366 (327–422)Franklin Bluffs 14 0.70 (0.64–0.79) 0.82 0.583 0.58 (0.43–1.24) 43.5 (40.3–49.2) 366 (350–378)West Dock 14 0.35 (0.26–0.42) 0.60 0.725 0.49 (0.41–0.60) 37.3 (32.5–45.8) 366 (336–404)

Thawing and freezing seasons were defined by a continued prevalence of positive and negative mean daily temperatures at the shallowest ground temperature sensor and, for consistency, these time-windows were also applied to air temperatures. Consequently, MATTS, MATFS, $I_{\mathrm{ta}}$, $I_{\mathrm{fa}}$, $L_{\mathrm{t}}$, and $L_{\mathrm{f}}$ were computed. Since the model assumes that air temperatures are solely positive and negative during the thawing and freezing season, respectively (Appendix C). Comparisons of the modelled and observed data showed relatively good agreements and clear trends along the identity lines for most air temperature characteristics (Fig. 1), positive and negative air temperatures alone were used to determine the respective seasonal means. Likewise, MAATs were calculated as length-weighted averages of the seasonal means for periods composed of the thawing seasons and their preceding freezing seasons, which are thought to be more representative for the active-layer formation than calendar periods (**?**), but on average, they differ by only a few days from the standard length of a year at individual stations (Table 2). Annual air temperature amplitudes were defined by an annual range of a 31-day simple central moving average of mean daily air temperatures, with its extremes being considered to substitute MATWM and MATCM. Finally, thawing *n*-factors were derived as ratios of the thawing indices at the shallowest ground temperature sensors and air thawing indices. Hence, for modelling, the active-layer thicknesses had to be reduced by the depth of the shallowest ground temperature sensors in order to ensure consistency since the model presumes that the *n*-factors transfer between air and ground surface temperatures (cf. **??**).

Ground physical properties for the James Ross Island sites were determined in situ or from intact samples collected near the temperature monitoring stations at a depth of 0.2–0.3 during the thawing seasons of 20132014, 20162017, and 20182019

(Hrbáček et al., 2017a; ?), while those for the Alaskan sites were adapted from Zhang (1993) and Romanovsky and Osterkamp (1997) who taken samples to a depth of about 0.6 during the thawing season of 1991 and then averaged their characteristics over the full active-layer thickness. Thawed ground thermal conductivity was determined through replicate measurements with needle thermal-conductivity probes, whereas volumetric ground moisture content was established by successive wet and dry weighing or through replicate measurements with time-domain reflectometry probes (Zhang, 1993; Hrbáček et al., 2017a; ?). The obtained ground physical parameters (Table 2) entered the model as time-independent constants that describe the entire active-layer profile.

The model accuracy was evaluated by comparing the modelled and observed data for all sites individually and together through a simple error statistics and common error measures such as mean error (ME) and mean absolute error (MAE):

$$\mathrm{ME} = \frac{1}{N}\sum_{i=1}^{N}(m_\mathrm{i} - o_\mathrm{i}),$$

$$\mathrm{MAE} = \frac{1}{N}\sum_{i=1}^{N}\mid m_\mathrm{i} - o_\mathrm{i}\mid,$$

where $m_\mathrm{i}$ and $o_\mathrm{i}$ is the modelled and observed value, respectively, and $N$ is the total number of model–observation pairs.

## 4 Results

Comparisons of the model outputs against the observed data showed that PERICLIMv1.0 reproduces the air temperature characteristics with a high accuracy at most stations, though its outcomes from 3), which suggests that the model might also work well over a wider range of climates. Generally, however, the outcomes tended to be slightly underestimated, with those from James Ross Island are somewhat more precise being somewhat more accurate and less scattered than those from Alaska (Fig. 3).

MAAT was slightly underestimated and exhibited a site-weighted exhibited an average mean error and a site-weighted an average mean absolute error of −0.51.3 °C and 11.3 °C, respectively (Fig. 3). The Mean absolute error was ≤ 1 °C and ≤ 2 °C in at 57 % and 7986 % of casesthe validation sites, respectively, and the maximum absolute error did not exceed 4.3maximally was 2.4 °C.

Observed versus modelled air temperature characteristics. Acronyms ME and MAE under the plot labels correspond to the site-weighted mean error and the site-weighted mean absolute error, respectively, while those at the bottom right of the plots indicate the station names: Abernethy Flats (AF), Berry Hill slopes (BHS), Johann Gregor Mendel (JGM), Johnson Mesa (JM), Deadhorse (DH), Franklin Bluffs (FB), and West Dock (WD).

MATWM and MATCM evenly scattered around the identity lines and showed almost identical biases as they both attained a site-weighted mean error of −0.1showed slightly lower bias as their average mean errors attained −1.0 °C and a site-weighted mean absolute error of −0.9 °C, respectively, and average mean absolute errors achieved 1.1 °C for both characteristics (Fig. 3). Likewise, the absolute deviation was Their mean absolute deviations were ≤ 1 °C in 46at 43 % of cases, in 84 % and 82 % it

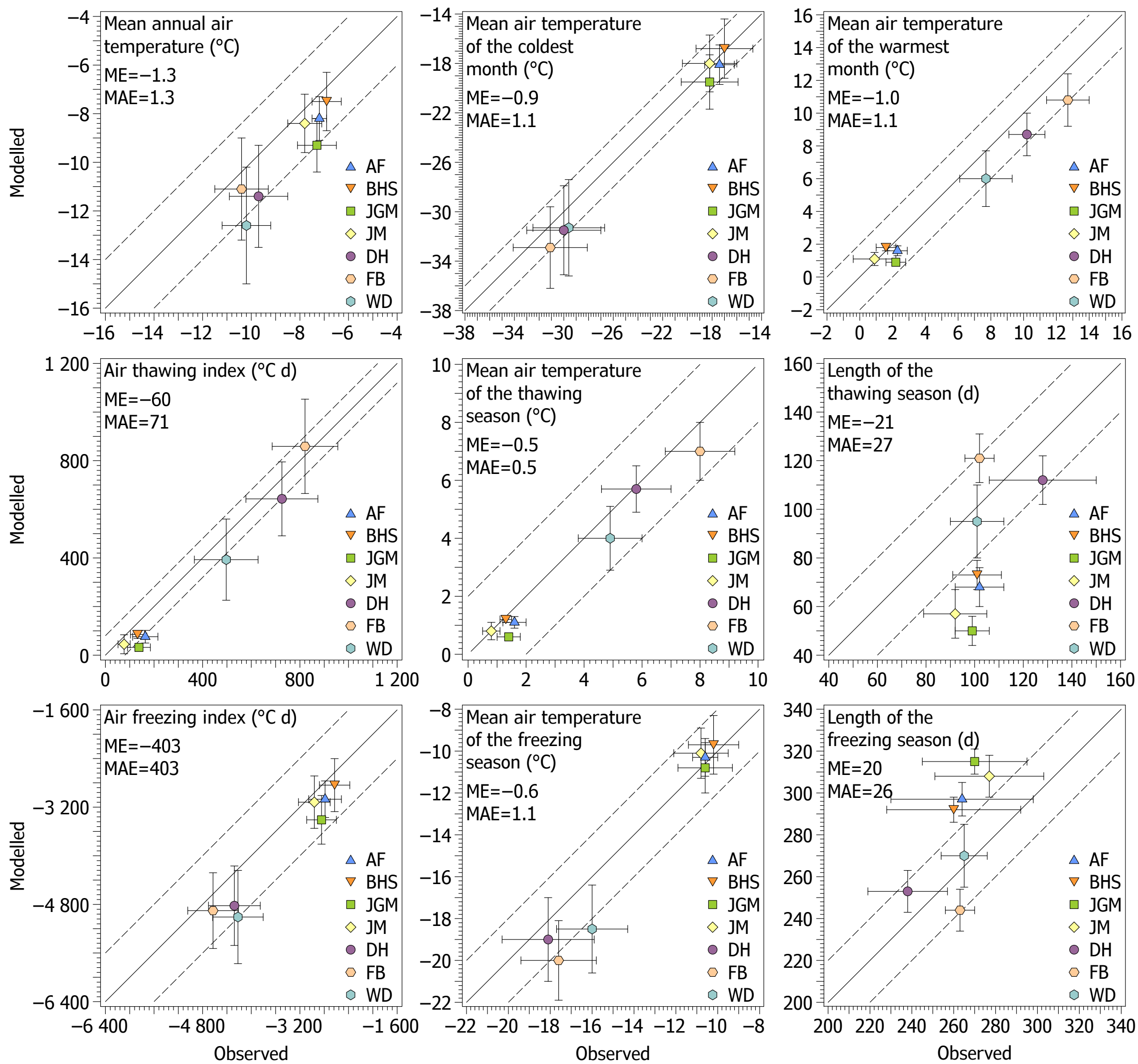


**Figure 3.** Observed versus modelled air temperature characteristics at the James Ross Island and Alaskan Arctic validation sites. Acronyms ME and MAE under the plot labels correspond to the site-weighted mean error and the site-weighted mean absolute error, respectively, while those at the bottom right of the plots indicate the names of the validation sites: Abernethy Flats (AF), Berry Hill slopes (BHS), Johann Gregor Mendel (JGM), Johnson Mesa (JM), Deadhorse (DH), Franklin Bluffs (FB), and West Dock (WD).

was the validation sites and $\leq 2\,^{\circ}$C for at 100 % of them. Mean absolute MATWM and MATCM , respectively, and the error was at worst 3.4errors were at worst 1.9 °C for both characteristicsand 1.8 °C, respectively.

$I_{ta}$ was rather uniformly distributed around the identity line, while and $I_{fa}$ tended to be slightly underestimated (Fig. 3). The indices showed a site-weighted mean error of 22were modelled with average mean errors of −60 °C d and −199403 °C d, respectively, which corresponds to about 6–16 % and −12 % of the observed site-weighted average mean values, and their site-weighted mean absolute error was 91average mean absolute errors reached 71 °C d and 314403 °C d, respectively (Fig. 3). $I_{\mathrm{ta}}$ biased by ≤ 2040 °C d in 23at 29 % of cases, and in 38 % the validation sites and by ≤ 4080 °C d at 43 % of them. $I_{\mathrm{fa}}$, which achieves one order of magnitude larger values, deviated by ≤ 200400 °C d in 41at 57 % of cases the validations and by ≤ 400800 °C d in 66at 100 % . The maximum of them. Maximum mean absolute departures of $I_{\mathrm{ta}}$ and $I_{\mathrm{fa}}$ reached 473achieved 106 °C d and 1789 512 °C d, respectively.

MATTS exhibited a site-weighted an average mean error and a site-weighted an average mean absolute error of 0.1–0.5 °C and 0.60.5 °C, respectively, while for MATFS the errors showed site-weighted means of −0.4mean errors averaged −0.6 °C and 1.21.1 °C , respectively (Fig. 3). The agreement between the modelled and observed MATTS was better than or equal to ≤ 1 °C in 75at 100 % of cases, and the maximum absolute error was 2the validation sites, with maximum mean absolute error of 1.0 °C. In contrast, the bias in MATFS was deviated by ≤ 1 °C in 46at 71 % of cases, ≤ 2 in 79 %, the validation sites, and at worst, it was 4.12.5 °C.

Because Since $L_{\mathrm{t}}$ and $L_{\mathrm{f}}$ inherently counteract, their characteristics mirror each other . The former if the values are not rounded. $L_{\mathrm{t}}$ tended to be a little underestimated by a site-weighted average of 10underestimated by an average of 21 d, while the latter $L_{\mathrm{f}}$ was overestimated by the same duration an average of 20 d (Fig. 3), which comprised 10–20 % and 48 % of the site-weighted mean observed observed average mean $L_{\mathrm{t}}$ and $L_{\mathrm{f}}$, respectively, and the site-weighted their average mean absolute errors achieved 2127 d . The and 26 d. Mean underestimation or overestimation was ≤ 20 d in 54at 43 % of cases, the validation sites and ≤ 40 d in 85at 86 %, and the maximum deviation did not exceed 55. Maximum mean deviation was up to 49 d.

## 4 DiscussionModel application

### 4.1 Model uncertainties, limitations and potential adjustments

The model exhibited a high accuracy and clear trends along the identity lines for most air temperature characteristics (Fig. 3) , which suggests that it is also likely to work well over a wider range of climatic conditions. The overall success rate of the model is remarkable because active-layer thickness commonly exhibits rather moderate to low correlations with annual or winter air and ground temperature parameters, but on the other hand it mostly strongly couples with summer air and ground temperature indices (e.g., Frauenfeld et al., 2004; Åkerman and Johansson, 2008; Wu and Zhang, 2010). Since PERICLIMv1.0 inherently builds on thaw depth–summer temperature relations, which it further converts into annual or winter air temperature characteristics through $A_{\mathrm{a}}$ or MATWM, this scheme gives rise to its high accuracy. It should be noted that it is successful despite the ground physical parameters used have certainly experienced at least slight changes since sampling or over the validation period and show vertical variations in the As a feasibility study, the model was utilized experimentally for derivation of palaeo-air temperature conditions on the basis of relict cryoturbation structures. Cryoturbations (∼periglacial involutions) are characterized by folded and/or dislocated strata of unconsolidated sediments caused by recurrent freeze-thaw-induced processes operating within the active layer over permafrost, which limits the vertical extent of the cryoturbations from below and also acts as an impervious boundary that provokes well saturated conditions. As such, cryoturbations are thought to

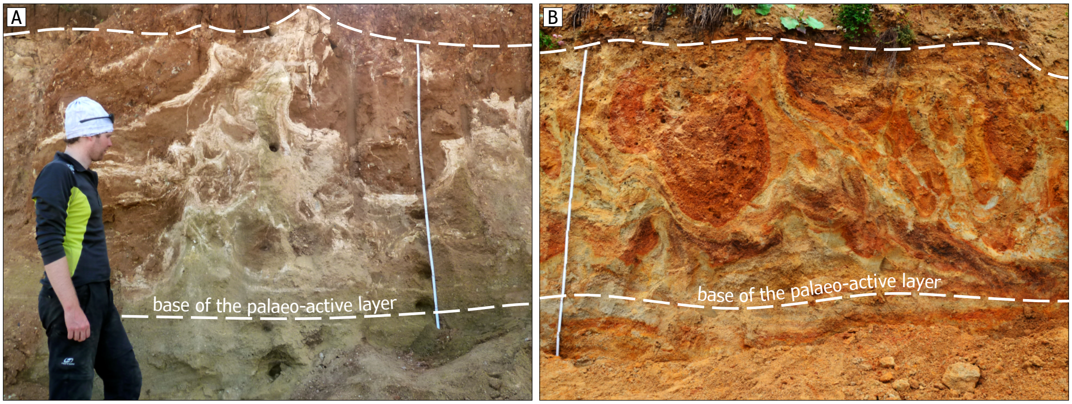


**Figure 4.** Cross-sections through cryoturbation structures at the (A) Brno–Černovice and (B) Nebanice site with the white dashed lines indicating their vertical extent and thereby the thickness of the palaeo-active layer.

indicate the thickness of the active layer as well (Zhang, 1993; Hrbáček et al., 2017a; ?). Besides, the model parameterizes air temperature behaviour with a sine wave defined by annual amplitude, which simplifies the actual evolution of air temperature and completely ignores its sub-annual variations. Finally, the Stefan equation assumes stationary conditions, and thus it well represents multi-annual averages that moderate the energy imbalances introduced by natural climatic variations, but it tends to fail at capturing inter-annual transient departures from the equilibrium state (?), which are involved in the validation dataset. Some scatter in the model estimates is therefore inevitable, and may be considerable, but it is important that the averaged outputs are close to those of the observed data as the presence of permafrost at the time of their development. Also, MAAT thresholds of <−8 °C and <−4 °C have been suggested for their formation within coarse- and fine-grained substrates, respectively (Vandenberghe, 2013; French, 2017), the validity of which can be assessed with the model as well.

### 4.1 Study sites

We consider two study sites in the Czech Republic where vertical cross-sections through cryoturbated horizons, portraying the palaeo-active layers (Fig. 3)4), were exposed and sampled for those attributes that allowed to define the most plausible ranges of the model driving parameters.

The Stefan equation in its simplest form (Eq. 1) presumes that the latent heat of phase-changing ice-water is much larger than the sensible heat required to raise the ground temperature, and thus it accounts only for the former, while the latter is completely ignored. Also, it assumes that the frozen layer is at 0

The Brno–Černovice site (49°10′43″ before thaw. These simplifications cause that it tends to overestimate the thaw depth inversely proportional to the moisture content in the active layer and its temperature at the onset of thawing (Romanovsky and Osterkamp, 19 . A number of correction factors can overcome these flaws. However, although simple corrections exist, besides complex implicit solutions (Kurylyk and Hayashi, 2016), they all require additional inputs such as frozen thermal conductivity and thawed and frozen volumetric heat capacity or active-layer temperature at the start of its thawing.Hence, the corrections are frequently difficult to implement even in many present-day situations and definitely are much less viable for palaeo-reconstructions. Moreover, their inverse solution is not straightforward and would probably require the application of iterative techniques. N, 16°38′56″ E, 240 m asl) is an active sand–gravel pit situated about 3 km southeast of the centre of Brno, South Moravia. The mine is embedded within sands and gravels of the Tuřany terrace of the Svitava River, in reality a highly flattened alluvial fan, tentatively attributed to the Günz glaciation (∼Marine Isotope Stage [MIS] 22–11), which is located about 1.5 km east of the present channelized river bed and ∼40 m higher. The material tends to coarsen down to a depth of 6–13.5 m, under which the Neogene clayey sands and gravels emerge (Musil et al., 1996; Musil, 1997; Bubík et al., 2000). The cryoturbations mostly consist of sands to gravels that constitute ∼80 % and ∼14 % of the substrate, respectively, and are deformed by numerous injection tongues (Fig. 4). Currently, the cryoturbations rest ∼1.6–3.6 m under the ground surface, but we suppose they were just below it when they developed.

The associated uncertainties in the ground-surface thawing index estimation are likely to produce somewhat smaller errors at higher temperatures and at higher thawing *n*-factors because the derived air temperature characteristics are increasing or decreasing functions of mostly concave-down or concave-up shapeThe Nebanice site (50°07′13″ N, 12°27′09″ E, 430 m asl) is a currently inactive sand–gravel pit about 1.5 km west of the centre of Nebanice, West Bohemia. It is set in sands and gravels of the Nebanice terrace of the Ohře River, which is thought to have originated during the Mindel–Riss glaciations (∼MIS 10), and now is situated about 200 m north of the river bed at a relative height of ∼10 m (Šantrůček et al., 1994; Balatka et al., 2019). The terrace sediments have a thickness of 1.7–3.8 m (Balatka et al., 2019) and are underlain by the Pliocene–Lower Pleistocene clays, sands, and gravels (Špičáková et al., 2000). The cryoturbations are mostly composed of sands and gravels that comprise ∼67 % and ∼29 % of the material, respectively, and thus are less sloped under these conditions take the form of festoons and ball-and-pillow structures (Fig. 4) . By contrast, at higher temperatures the model estimates are much more sensitive to emerging in the uppermost part of the terrace ∼1.1–2.8 m below the modern ground surface as they were overlaid by younger sediments and soils as well.

Cryoturbations, like other permafrost-related features, in the area of the Czech Republic have been tentatively attributed to the last glacial period (Czudek, 2005) and arose at the choice of thawing *n*-factor and temperature amplitude (Fig. 4) . These rules partly explain why the model outputs from James Ross Island are more accurate and less scattered than those from Alaska ends of the major cold events when permafrost started to degrade (sensu Vandenberghe, 2013). We believe that the studied relict cryoturbations indicate past environmental conditions similar to those at the end of the Last Glacial Maximum (LGM) when analogous features formed in the nearby regions (Kasse, 1993; Huijzer and Vandenberghe, 1998; Kasse et al., 2003; Bertran et al., 2014) .

## 4.2 Model set-up

### 4.2.1 Palaeo-active-layer thickness

The palaeo-active-layer thickness was considered to be represented by the vertical extent of the cryoturbated horizons (Fig. 3). Much more, however, is this contrast due to differences in 4), which was determined in horizontal steps of 0.2 m along the

**Table 2.** Driving parameters used to model palaeo-air temperature characteristics related to the cryoturbations at the Brno–Černovice and Nebanice site. Note that the parameters described by means and standard deviations ($\xi$, $\rho$, $n_t$, $A_a$) had normal distributions, while those defined by simple ranges were assumed to be beta- ($\phi$) or uniformly distributed ($q$).

| Site | $\xi$ (m) | $\phi$ (−) | $\rho$ (kg m$^{-3}$) | $q$ (−) | $f/c$ | $n_t$ (−) | $A_a$ (°C) |
|---|---|---|---|---|---|---|---|
| Brno–Černovice | 1.58±0.28 | 0.088–0.394 | 1635±120 | 0.30–0.56 | coarse | 1.03±0.12 | 23.2±2.4 to 33.2±2.4 |
| Nebanice | 1.40±0.13 | 0.114–0.391 | 1645±116 | 0.30–0.57 | coarse | 1.03±0.12 | 20.9±2.6 to 30.9±2.6 |

See Table 1 for abbrevations.

entire length of each cross-section (4.0–8.2 m), and attained 1.58±0.28 and 1.40±0.13 m at the Brno–Černovice and Nebanice site, respectively (Table 2).

### 4.2.2 Ground physical properties

Ground physical properties were chosen using intact samples collected at four representative positions along four vertical profiles within each cross-section (16 samples per cross-section) into 100 cm$^3$ stainless steel cylinders, which were then weighted in wet and dry states as well as sieved to assess their volumetric moisture content, dry bulk density, and texture. The current volumetric moisture content averaged 8.8 % and 11.4 % at the Brno–Černovice and Nebanice site, respectively, but because cryoturbations require well saturated conditions for their development (Vandenberghe, 2013; French, 2017), these values were assumed to be the lower moisture thresholds, while the upper moisture thresholds were supposed to be given by average ground porosity, which was calculated as a function of the ~~distribution of ground physical properties within the active layer, which is rather homogeneous at the James Ross Island sites (Hrbáček et al., 2017a; **?**), but has a two-layer structure with a thick surface layer of peat at the Alaskan locations (Zhang, 1993).Overview of published data implies that the Stefan equation tends to deviate proportionally to the peat-layer thickness in the active layer (Fig. 5), which contradicts the theoretical assumptions of the Stefan equation (Romanovsky and Osterkamp, 1997; Kurylyk and Hayashi, 2016) as the presence of peat is commonly associated with high moisture contents, but it is also consistent with the present model outcomes~~ dry bulk density (Eq. A4), and achieved 39.4 % and 39.1 %, respectively. Moisture, however, usually tends to be close to saturation for at least part of the thawing season (Woo, 2012), and thus we further skewed its values leftwards using a beta distribution as follows:

$$\phi(x) = \phi_0 + f(x;\alpha,\beta)\,(n - \phi_0)\,, \tag{15}$$

where $\phi_0$ is the current average volumetric ground moisture content (−), $f(x;\alpha,\beta)$ expresses the probability density function of the beta distribution for $0 \le x \le 1$ with shape parameters tentatively assumed to be $\alpha = 5$ and $\beta = 2$ that yield a mode of 0.8, and $n$ is the average ground porosity (−). The resulting values are thus bounded by the lower and upper moisture thresholds (Table 2), but show left-skewed distributions peaking at ∼33.3 % and ∼33.6 % at the Brno–Černovice and Nebanice site, respectively, which corresponds to the degree of saturation of ∼84.5 % and ∼85.8 % (Fig. ~~3). This is probably due to complications in obtaining representative input parameters for peaty active layers because physical properties of peat extremely~~

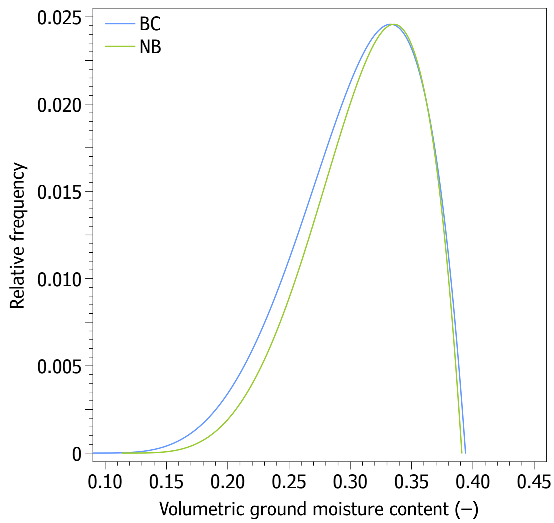


**Figure 5.** Modelled mean annual air temperature as a function Probability distributions of volumetric ground moisture contents assumed for the ground-surface thawing index, thawing *n*-factor, Brno–Černovice (BC) and annual air temperature amplitudeNebanice (NB) site.See Table 1 for abbreviations.

Mean absolute percentage error of the Stefan equation in relation to the surface peat-layer to active-layer thickness ratio (PL/ALT) and the volumetric moisture content in the active layer (VMC) based on data published in Romanovsky and Osterkamp (1997), Klene et al. (2001), and ?.

differ from those of any other underlying materials. Still, the model evaluation showed that it is capable of acceptable results, despite the active layer at some of the test sites is far from being saturated or is two-layer 5). Since the vast majority of moisture in sands and gravels tends to undergo phase changes (Andersland and Ladanyi, 2004) and its unfreezing portion is supposed to influence the calculations negligibly if its ratio to the total moisture content is at levels up to several tens of percent (Uxa, 2017) , the moisture contents were not further adjusted for an unfrozen moisture. Slightly lower moisture content of the eastern site in Brno–Černovice as compared to Nebanice in the west (Fig. 5) is likely to be reasonable because it can be understood as including the continentality and elevation effects as well as the thicker palaeo-active layer (Table 2) and permafrost there is rather cold (Hrbáček et al., 2017a, b; Wang et al., 2018)in which the same amount of water has a lower volume fraction.

Sometimes, stratified profiles may also be associated with relict periglacial features, which is mostly due to post-formation pedogenic or depositional processes (French, 2017). However, if they are related to the feature formation itself, the Stefan equation can be adapted to calculate the thaw depth in multi-layered grounds (e.g., Nixon and McRoberts, 1973; Kurylyk, 2015) , and its inverse solution can be easily derived as well (Contrarily, the other ground physical properties were supposed to be representative for former conditions as such. The dry ground bulk density was 1635±120 kg m$^{-3}$ and 1645±116 kg m$^{-3}$ at the Brno–Černovice and Nebanice site, respectively. The ground quartz content was estimated at 30–56 % and 30–57 %, respectively, on the basis of the proportions of clay–silt and sand fractions (see Appendix A). On the other hand, the internal composition of most periglacial features is usually too complicated to be discretized into multiple clearly distinguishable and laterally homogeneous sub-layers. Such complex structures are advisable to be described by a homogeneous domain rather than by layered schemes since the former is less computationally demanding and requires fewer ground physical parameters but at the same time is likely to yield accurate outcomes if a representative set of driving data is provided. Given the low proportion of clay–silt fraction and the presence of gravel (see Sect. 4.1), the substrates were treated as coarse-grained (sensu Johansen, 1977) at both sites (Table 2).

It can be assumed that the model may fail in situations when substantial warming events take place after the maximum thaw depth had been reached because air or near-surface ground temperature andactive-layer thickness clearly decouple during these episodes. Besides, active layer may occasionally develop even though air temperatures remain negative throughout the summer. This is characteristic for cold permafrost regions, such as Victoria Land or Dronning Maud Land, Antarctica, where bare surfaces are highly irradiated (??). Unfortunately, PERICLIMv1.0 cannot address such behaviour adequately as it assumes that MATWM is positive for both air and ground surface because

#### 4.2.3 Ground-surface thawing *n*-factor

Since the coupling between the air and ground-surface temperatures is principally governed by ground-surface cover and its properties themselves (Westermann et al., 2015), the ground-surface thawing *n*-factors cannot convert between positive and negative temperatures. Still, were estimated on the basis of values published elsewhere for bare (excluding bedrock and debris) to little vegetated (sparse lichens, mosses, or grasses) surfaces, which are assumed to have existed at the study sites when the cryoturbations originated because treeless landscapes dominated in South Moravia and West Bohemia at that time (e.g., Kuneš et al., 2008). We took over a total of forty-one ground-surface thawing *n*-factor values reported from mid-latitude and mostly permafrost regions of Central-Eastern Norway (Juliussen and Humlum, 2007) and British Columbia/Yukon and Labrador, Canada (Lewkowicz et al., 2012; Way and Lewkowicz, 2018) that are believed to be representative for the study sites as those locations also occur outside the Arctic Polar Circle and, as such, have comparable insolation budgets owing to the absence of polar-day periods, which might impose an undesirable growth of the ground-surface thawing *n*-factor values (e.g., Shur and Slavin-Borovskiy, 1993). Overall, the collected *n*-factors averaged $1.03\pm0.12$, which was assigned to both study sites (Table 2).

#### 4.2.4 Annual air temperature range

As a starting point, we used the annual air temperature ranges based on monthly air temperatures measured in 1981–2010 at meteorological stations located about 4 and 7 km southeast and southwest of the Brno–Černovice and Nebanice site, respectively, at elevations of 241 and 475 m asl (Czech Hydrometeorological Institute, 2020), which averaged $23.2\pm2.4$ and $20.9\pm2.6$ °C, respectively (Table 2). Additionally, we also assumed stepwise perturbations of 2 °C to these annual air temperature ranges up to $33.2\pm2.4$ and $30.9\pm2.6$ °C, respectively, which is within the range of 28–36 °C suggested by previous regional estimates for the end of the LGM (Huijzer and Vandenberghe, 1998) and at the same time maintains the contrasts between the study sites (Table 2).

#### 4.2.5 Simulations

The model was solved by the Monte Carlo simulation with Latin hypercube sampling (LHS) (McKay et al., 1979) using *lhs* R package (Cannel, 2020), which discretizes the probability density functions of the individual driving parameters (Table 2) into $N$ non-overlapping intervals of equal probability $1/N$ and then randomly selects one value from each. Subsequently, these samples are randomly matched and used as uncorrelated inputs for $N$ model runs (McKay et al., 1979). LHS is computationally more efficient than simple random sampling because its sampling scheme adapts to the probability density functions of the driving parameters, and thus it requires fewer simulations to achieve stable outputs if $N$ is large enough.

We realized 1 000 model runs for six scenarios of the ~~model provides reasonable outputs on an annual basis if the annual air temperature oscillations are defined by $A_{\mathrm{a}}$. By contrast, it fails completely if the~~ annual air temperature ~~oscillations are to be characterized by negative MATWM. Another pitfall of the MATWM-based reconstructions is their high sensitivity to variations of $I_{\mathrm{ta}}$ andMATWM itself~~ ranges at each study site, of which 78.1–91.1 % produced physically feasible combinations of the driving parameters and provided the most plausible palaeo-air temperature characteristics that account for the uncertainty as well as natural temporal variability of the inputs.

### 4.3 Modelled palaeo-air temperature characteristics

Most modelled palaeo-air temperature characteristics changed in various extents depending on the scenarios of the annual air temperature ranges, the higher values of which generally caused colder and/or more continental conditions as well as larger scatters of the model outputs. This was especially true for MAAT and the freezing-season characteristics, whereas the changes were comparatively milder for the thawing-season attributes (Fig. ~~2), which may result in major errors if the input parameters are defined inaccurately. Unfortunately, the deviations are expected to be larger at lower $I_{\mathrm{ta}}$ and MATWM~~ 6).

MAAT was modelled at −6.6±2.7 to −3.3±2.0 °C and −7.0±1.9 to −3.2±1.5 °C at the Brno–Černovice and Nebanice site, respectively (Fig. ~~2~~6), which ~~are typical for permafrost regions, and thus it should be highlighted that the MATWM-based solution should be employed cautiously.~~

~~If desired, the PERICLIMv1.0 can also be utilized to derive air temperature characteristics~~ corresponds to its average decline of −16.0 to −12.7 °C and −15.1 to −11.3 °C, respectively, in comparison with the 1981–2010 period. The average contrasts between the warmest and coldest MAAT scenarios based on the ~~seasonal frost depth. However, snow cover is an efficient insulator that, if present, alters the ground thermal regime substantially, which in turn influences the frost depth as well. Importantly, the thickness and density of snow, which are the principal controls on ground-surface–air temperature offset in winter (Smith and Riseborough, 2002), vary enormously over time and ,~~ current and assumed past annual air temperature ranges, respectively, were 3.3 °C and 3.8 °C at the Brno–Černovice and Nebanice site, respectively, which means that MAAT changed by 33 % and 38 % of the change in the annual air temperature range.

The thawing seasons had MATTS of 5.4±1.2 to 6.5±1.6 °C and 4.7±0.8 to 5.5±1.0 °C at the Brno–Černovice and Nebanice site, respectively, and culminated with MATWM of 8.4±1.9 to 10.1±2.6 °C and 7.3±1.3 to 8.5±1.6 °C (Fig. 6), which suggests that MATTS changed on average by 11 % and 8 % of the magnitudes of the annual air temperature range perturbations,

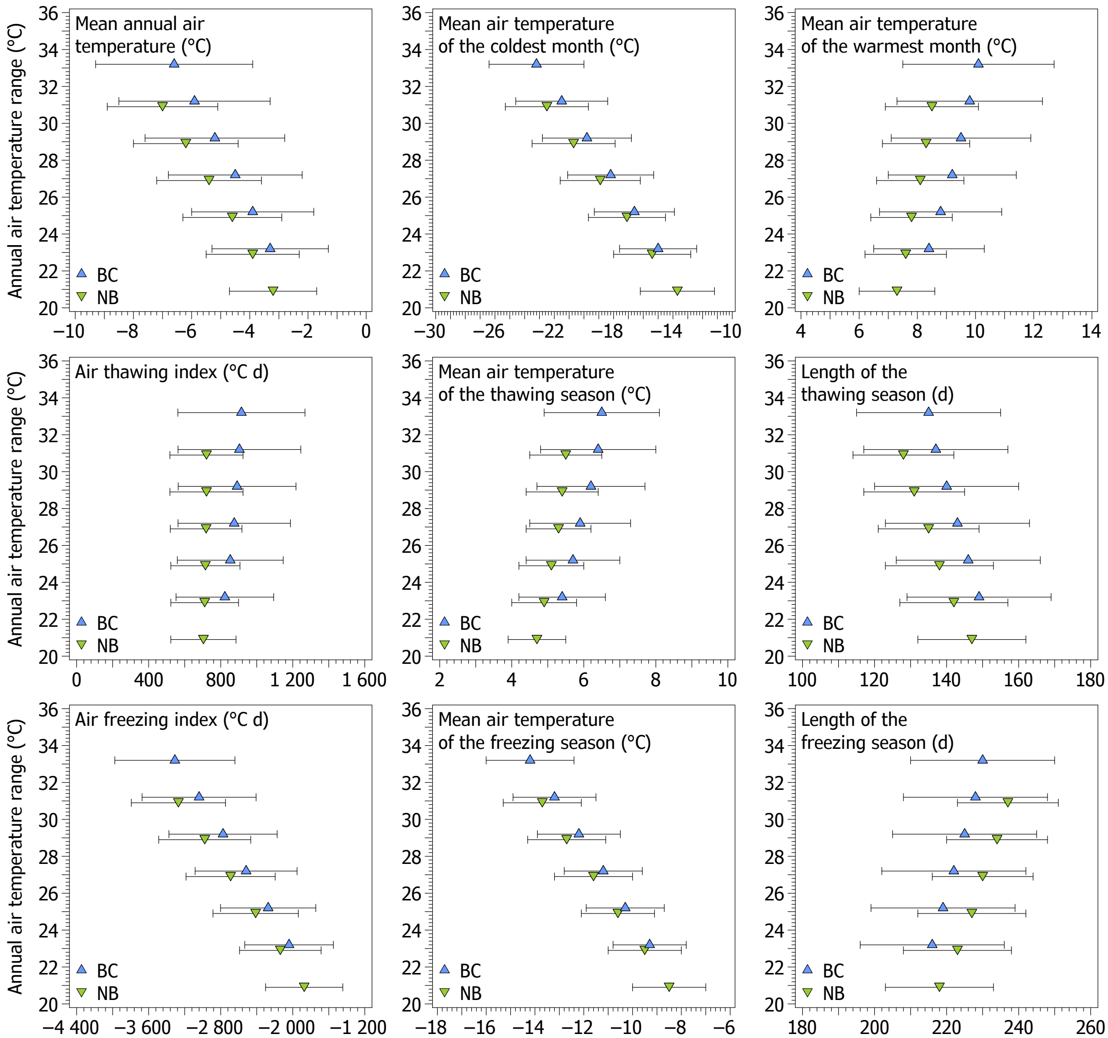


**Figure 6.** Modelled palaeo-air temperature characteristics at the Brno–Černovice (BC) and Nebanice (NB) site for six scenarios of the annual air temperature ranges.

while MATWM varied on average by 17 % and 12 %. $I_{ta}$ showed even more consistent outputs as it attained 823±271 to 915±353 °C d and 704±181 to 721±203 °C d at the Brno–Černovice and Nebanice site, respectively (Fig. 6), and, as such, ~~their buffering effects cannot be easily estimated via freezing $n$-factors. The associated uncertainty can lead to a considerable inaccuracy of the model outputs, the magnitude of which is proportional to the freezing-index value.~~it varied by as low as ∼1.1 % and ∼0.2 % per 1 °C change in the annual air temperature range. Likewise, $L_t$ was modelled at 135±20 to 149±20 d and 128±14 to 147±15 d (Fig. 6), which yields the respective changes of ∼1.0 % and ∼1.5 %.

### 4.4 Driving data

It may be argued that the present exercise is impossible to replicate for relict periglacial features because of complications associated with the choice of plausible driving parameters. Undoubtedly, the ability to obtain precise forcing data from relict features is limited. At the same time, there is also little information on ground physical properties and thermal regimes of active features, which could provide a baseline for Obviously, the freezing seasons exhibited the largest scatters of the model outputs as well as the highest variability among the scenarios with MATFS of −14.2±1.8 to −9.3±1.5 °C and −13.7±1.6 to −8.5±1.5 °C at the Brno–Černovice and Nebanice site, respectively, and MATCM as low as −23.2±3.2 to −15.0±2.6 °C and −22.5±2.8 to −13.7±2.5 °C (Fig. 6). It thus follows that their variations were close to the modelling.However, any palaeo-environmental reconstruction includes some uncertainty because of many unknowns involved. Probably the best that can be done is therefore to specify a reasonable range of environmental constraints, under which the features could have developed, and then estimate the most probable palaeo-air temperature based on random-sampling methodsmagnitudes of the annual air temperature range perturbations, which generated them, reaching on average 49 % and 52 % of the perturbations for MATFS and as much as 82 % and 88 % for MATCM. $I_{fa}$ spanned −3309±667 to −2041±492 °C d and −3270±523 to −1873±429 °C d at the Brno–Černovice and Nebanice site, respectively (Fig. 6), which corresponds to average variations of ∼6.2 % and ∼7.5 % per 1 °C change in the annual air temperature range. On the other hand, $L_f$ was modelled at 216±20 to 230±20 d and 218±15 to 237±14 d, respectively, and thus it varied on average by as low as ∼0.6 % and ∼0.9 % of the magnitudes of the annual air temperature range perturbations.

#### 4.3.1 Ground physical properties

Unfortunately, thermal conductivity is the least available ground physical parameter for most periglacial features, while ground moisture content highly varies both locally and temporally, which substantially complicates the selection of their representative values. Sometimes, however, periglacial features may be well preserved despite their considerable age, and in these situations, some of their ground physical properties can be established based on in situ observations. Bulk density, which in most mineral grounds exhibits a relatively limited range of values (?), can be used to estimate saturated moisture content, and then it is possible to assess the extremes, between which

## 5 Discussion

### 5.1 Model performance and limitations

Generally, the moisture likely occurred. Numerous periglacial features are, moreover, composed of frost-susceptible sandy-clay-loam mixtures that are prone to compaction (?) and, as such, they tend to have a high bulk density, which in turn means a lower water-holding capacity and hence a reduced uncertainty in the moisture-content estimation. In addition, the moisture involved in the phase change is typically up to a few percent lower than the total moisture content as its part always remains unfrozen at freezing temperatures (Andersland and Ladanyi, 2004) and proportionally reduces the amount of latent heat required to be absorbed for thawing. The maximum moisture content may therefore be lowered correspondingly because the unfrozen moisture content alone is, by default, not included as a model input parameter.At the same time, it should be borne in mind that unfrozen moisture likely affects the thaw-depth calculations negligibly if its ratio to the total moisture content is at levels up to tens of percent (Uxa, 2017). Contemporary measurements of ground thermal conductivity would probably be misleading because it is controlled by other ground physical parameters that may also have changed substantiallymodel validation showed its relatively high success rate for most air temperature characteristics if appropriate driving parameters are available. It is remarkable, though, given that active-layer thickness commonly exhibits rather moderate to low correlations with annual or freezing-season air and ground temperature attributes, but on the other hand, it mostly strongly couples with thawing-season air and ground temperature indices (e.g., Frauenfeld et al., 2004; Åkerman and Johansson, 2008; Wu and Zhang, 2010). Since PERICLIMv1.0 builds on active-layer thickness–thawing-season temperature relations, which it further converts into annual and freezing-season air temperature characteristics, this scheme gives rise to its rather high accuracy. It also needs to be stressed that the model was successful regardless the ground physical properties used have certainly undergone at least slight changes since sampling and varied over the validation period. More accurate and less scattered outputs on James Ross Island than in Alaska were largely due to differences in the distribution of the ground physical properties within the active layer, which is rather homogeneous at the James Ross Island sites (Hrbáček et al., 2017a; Hrbáček and Uxa, 2020), but has a two-layer structure (Appendix D) with a thick surface layer of peat at the Alaskan locations (Zhang, 1993). Besides, the model parameterizes the air temperature behaviour with a sine wave, which simplifies its actual evolution over a year and completely ignores sub-annual variations.

Overall, however, the model underestimated most air temperature characteristics to various extents (Fig. 3). Firstly, it is attributed to intrinsic shortcomings of the Stefan equation (Eq. 2) that tends to deviate inversely proportional to the moisture content in the active layer as well as the active-layer temperature at the onset of thawing (Romanovsky and Osterkamp, 1997; Kurylyk and H . Secondly, it is associated with the Johansen's (1977) thermal-conductivity model (Appendix A), which tended to produce too high thermal conductivity values at the James Ross Island sites. Surely, the Stefan equation (Eq. 2) might be improved by a number of correction factors. However, these correlations can be reasonably used to estimate the ground thermal conductivity through transfer functions building on such characteristics as moisture content and dry bulk density of the ground (e.g., ?Zhang et al., 2018) . Definitely, it is highly advisable to assume also published data for modern analogous as they may help keep the inputs within realistic limits.

Ground physical properties could also be alternatively combined into a compound edaphic term (Nelson and Outcalt, 1987, Eq. 18) , which describes the entire profile by a single value given by $E = (2k_\mathrm{t}/L\phi\rho_\mathrm{w})^{1/2}$ or $E = (2k_\mathrm{t}n_\mathrm{t}/L\phi\rho_\mathrm{w})^{1/2}$. Its simplicity seems extremely advantageous for palaeo-climatic reconstructions. Besidesalthough simple corrections exist, besides complex implicit solutions (Kurylyk and Hayashi, 2016), these require additional inputs, such as frozen thermal conductivity, thawed and frozen volumetric heat capacity, or active-layer temperature at the start of its thawing. As such, the corrections are frequently difficult to implement even in many present-day situations and definitely are much less viable for palaeo-applications. Moreover, their inverse solution would not be straightforward and would probably demand iterative techniques. Similarly, the Johansen's (1977) thermal-conductivity model is advantageous in that it requires fewer inputs as compared with other solutions while having comparable accuracy (e.g., Dong et al., 2015; He et al., 2017; Zhang et al., 2018). As such, it is ~~capable to suppress the intrinsic flaws of the Stefan equation. However, the edaphic parameter is currently difficult to implement as it has commonly been determined empirically based on correlations between the thaw depth and thawing index (**??**Shiklomanov and Nelson, 2002 , and thus its transferability to other locations is limited. Moreover, it has not yet been established for any specific periglacial features.~~ also difficult to replace by another thermal-conductivity schemes.

### 5.1.1 ~~Thawing *n*-factor~~

~~Similarly, thawing~~ Besides, it should be highlighted that for the model validation cases the active-layer thickness was trimmed by the depth of the shallowest ground temperature sensor, which was used to determine the ground-surface thawing *n*~~-factor has also been determined for a limited number of periglacial features (e.g., **??**). However, it is principally controlled by thawing-season~~ -factor, to ensure consistency of the calculations (Appendix C). However, if this treatment was not done, the model outputs improved, with MAAT, MATWM, MATCM, MATTS, and MATFS showing average errors ≤1 °C, $I_{\mathrm{ta}}$ and $I_{\mathrm{fa}}$ deviating on average by −1 % and −8 %, respectively, and $L_{\mathrm{t}}$ and $L_{\mathrm{f}}$ by −16 % and 6 %, respectively, because this compensated the effects described in the previous paragraph. Since the published ground-surface ~~characteristics alone (e.g., Westermann et al., 2015), although it may also be slightly altered by winter snow cover (Gisnås et al., 2016). Hence, it varies within a rather narrow range for specific ground-surface covers across most regions of the northern hemisphere (e.g., Lunardini, 1978; **?**; Shur and Slavin-Borovskiy, 1993; Gisnås et al., 2017), but exhibits a somewhat larger span over Antarctica (e.g., **?**Hrbáček et al., 2017b). Because most periglacial features develop under bare to grassy surfaces, we believe that thawing~~ thawing *n*~~-factor can be reasonably estimated based on published values for analogous ground-surface covers. The values should be adopted circumspectly though due to their potential latitudinal variations (Shur and Slavin-Borovskiy, 1993) as they have commonly been reported from high-latitude locations, around or far beyond the polar circles, where seasonal cycles outweigh daily variations and, as such, the energy balance there substantially differs from that in mid-latitudes where, by contrast, relict periglacial features predominate.~~ -factors used (Juliussen and Humlum, 2007; Lewkowicz et al., 2012; Way and Lewkowicz built on various depths of ground temperature sensors, we did not adjust the active-layer thickness for the palaeo-applications, and the modelled palaeo-air temperature characteristics could thus have a slightly increased accuracy as well.

### 5.1.1 ~~Annual amplitude of air temperature oscillations~~

~~The initial estimate of the annual air temperature amplitude can be based on its present-day variability that may additionally be enlarged slightly. Also, it is advisable to consider available palaeo-climatic~~

## 5.2 Comparison to previous palaeo-air temperature reconstructions

The modelled MAAT between −7.0±1.9 °C and −3.2±1.5 °C and its corresponding reduction between −16.0 °C and −11.3 °C in comparison with the 1981–2010 period is relatively well consistent with earlier reconstructions utilizing various relict periglacial features in Central European lowlands that suggested MAAT depressions mostly between −17 °C and −12 °C

(Poser, 1948; Büdel, 1953; Kaiser, 1960; Frenzel, 1967; Goździk, 1973; Huijzer and Vandenberghe, 1998; Marks et al., 2016). By contrast, it disagrees with slightly milder MAAT reductions of at least −7 °C and −13 to −6 °C derived from groundwater data (Corcho Alvarado et al., 2011) and borehole temperature logs (Šafanda and Rajver, 2001), but these may not necessarily correspond to the lowest temperatures because groundwater cycling has been slowed or interrupted by permafrost, while ground temperature history may have partly been masked by latent-heat effects. Similarly, the modelled MAAT differs rather highly from simulations of three Global Climate Models (GCMs), namely Community Climate System Model 4, Model for Interdisciplinary Research on Climate–Earth System Model, and Max Planck Institute Earth System Model Paleo, capturing the LGM at ∼22 ka, which were originally released by the Coupled Model Intercomparison Project 5 in coarse resolutions, but later downscaled to 2′30′′ and made available via the WorldClim 1.4 dataset at https://www.worldclim.org (Hijmans et al., 2005) . The GCMs suggest that MAAT was between −4.5 °C and −0.4 °C at the study sites, which corresponds to its reduction between −12.6 °C and −9 °C. Such relatively high temperatures, however, contrast with many proxy records and are thus suspected to be unrepresentative of the coldest LGM conditions when continuous permafrost presumably occurred there (Vandenberghe et al., 2014; Lindgren et al., 2016).

The modelled MATWM of 7.3±1.3 to 10.1±2.6 °C is well in the range of proxy-based reconstructions and model simulations, which commonly provide MATWM of 5 to 13 °C that has been reconstructed for Central European lowlands (Huijzer and Vandenberghe, 19 . By contrast, it deviates greatly from the GCMs outputs being as high as 11.1 to 18 °C. The modelled MATCM ranged widely from −23.2±3.2 to −13.7±2.5 °C, which, however, also pertains to other proxy records that show somewhat lower values of −27 to −16.5 °C (Huijzer and Vandenberghe, 1998; Marks et al., 2016). The GCMs-based MATCM exhibits less variability of −21.6 to −17.7 °C, but its average is generally well consistent with that modelled by this study. Unfortunately, other modelled palaeo-air temperature characteristics cannot be validated directly because no reliable proxy records or GCMs outputs are available for them. However, as they are closely related to MAAT, MATWM, or MATCM, we believe that those attributes have similar plausibility.

Lastly, the modelled MAAT range between −7.0±1.9 °C and −3.2±1.5 °C is relatively well consistent with the MAAT threshold of <−4 °C commonly suggested for the range of which may indicate $A_a$. As such, these data sources could be seemingly used for standalone reconstructions because the arithmetic mean of the monthly air temperature extremes also corresponds to MAAT. The problemformation of cryoturbation structures within fine-grained substrates (Vandenberghe, 2013) . At the study sites, however, is that they may be asynchronous with the examined periglacial features. Moreover, they usually reconstruct the palaeo-temperature in coarse temporal and /or spatial resolutions. Nonetheless, we hypothesize that $A_a$ undergoes comparatively lower temporal and spatial changes than MAAT, the cryoturbations consist of coarse-grained materials, for which the MAAT threshold as low as <−8 °C has been proposed (Vandenberghe, 2013). Although the distinction between fine- and thus the proxy-based reconstructions and model simulations can be utilized to constrain the range, in which the amplitude likely fluctuated during the feature formation. coarse-grained substrates may not be clear, it definitely raises questions about the validity of the previously suggested MAAT thresholds for cryoturbation structures that have been widely utilized in reconstructions of past temperatures, and calls for their thorough revision.

Since the PERICLIMv1.0 assumes that periglacial features develop under quasi-steady-state conditions (see Sect.??),

### 5.3 Sensitivity analysis

Global sensitivity analysis using multiple regression and resulting standardized regression coefficients (SRCs), which indicate how many standard deviations an output parameter changes in response to one standard deviation change in an input parameter, with all other inputs being constant, suggested that the palaeo-active-layer thickness and annual air temperature range had a major impact on the modelled palaeo-air temperature characteristics at the Brno–Černovice and Nebanice site (Fig. 7). The palaeo-active-layer thickness importantly showed the highest SRCs especially for the annual and thawing-season air temperature attributes. Similarly, the annual air temperature range also highly influenced MAAT and, in particular, it had the utmost control over the freezing-season air temperatures as its SRCs even tended to outweigh those for the palaeo-active-layer thickness at that time of the year. It thus follows that the freezing-season characteristics may have limited accuracy if the annual air temperature range is uncertain, which indeed translates into their higher variance (Fig. 6). On the other hand, the annual air temperature range negligibly affected the thawing-season air temperature attributes (Fig. 7), and these are thus assumed to be the ~~period of the air temperature oscillations should be fixed at the standard annual period of 365~~ most plausible. Ground-surface and subsurface driving parameters, such as volumetric ground moisture content, ground dry bulk density, and ground-surface thawing *n*-factor, had considerably lower, albeit stable, effects on most modelled palaeo-air temperature characteristics. Ground quartz content was the weakest of the driving parameters as it was responsible only for a minor variability in the model outputs (Fig. 7).

### 5.4 ~~Implications for palaeo-temperature reconstructions~~Applications to other periglacial features

~~The PERICLIMv1.0~~ Besides cryoturbations, the model is thought to be ~~applied on~~ utilized for deriving palaeo-air temperature characteristics on the basis of any other relict periglacial features that ~~may~~ can indicate former active-layer thickness, such as some ~~types~~ kinds of patterned ground, ~~large cryoturbations,~~ some solifluction structures, frost-wedge tops, autochthonous blockfields, mountain-top detritus, active-layer detachment slides, up-frozen clasts, indurated horizons, or frost-weathering microstructures (Ballantyne and Harris, 1994; Matsuoka, 2011; Ballantyne, 2018)~~, which dominated mid-latitude landscapes in cold-climate periods in the past. Commonly, their relics rest in places where other palaeo-indicators are rare or absent, or emerged at different times, which enhances their palaeo-environmental significance. But since~~. However, it can also be easily adapted for seasonal-frost features.

Since most periglacial features develop on at least decadal or centennial timescales (e.g., Karte, 1983; Matsuoka, 2001; Ballantyne, 2018), inherently involving ~~climatic~~ natural climate as well as active-layer thickness variations, we hypothesize that their ~~depth probably rather reflects the position of a~~ vertical extent probably also includes the bottom transient layer where the ~~contact~~ boundary between the active layer and ~~the uppermost permafrost at the time of their formation oscillated (cf. Shur et al., 2005). Besides, the latter~~ permafrost has fluctuated when periglacial features formed (cf. Shur et al., 2005). This implies that the palaeo-active-layer thickness ~~usually tends to~~ may appear as a dispersed rather than a sharp boundary in many vertical cross-sections.

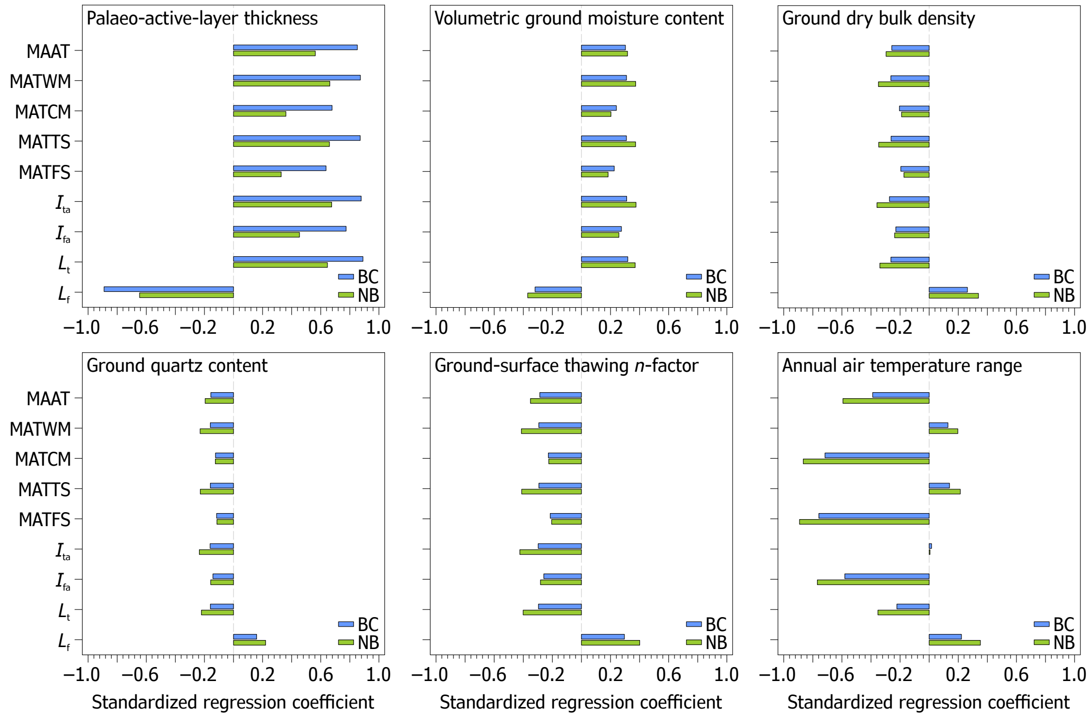


**Figure 7.** Sensitivity of the modelled palaeo-air temperature characteristics at the Brno–Černovice (BC) and Nebanice (NB) site to individual driving parameters expressed by standardized regression coefficients. See text and Table 1 for abbrevations.

Special attention must ~~therefore~~ thus be paid to avoid ~~potential ambiguities in~~ any ambiguity in both the identification of ~~both the~~ relict periglacial features and the determination of the palaeo-active layer ~~. Indeed, this can be tricky because fossil features~~ that may be severely degraded. ~~Moreover, some of them~~Indeed, some periglacial features, such as small patterned-ground features, small cryoturbations, some solifluction structures, up-frozen clasts, indurated horizons, or frost-weathering microstructures, may be produced by seasonal frost alone, while some look-alike features may even have a non-periglacial origin (Ballantyne and Harris, 1994; Ballantyne, 2018). Nonetheless, even if identified correctly, problems may arise in places where ground-surface level has changed over time due to ~~deposition of sediments~~ sedimentation or erosion. ~~Moreover, highly imprecise reconstructions~~ Besides, high uncertainty can probably be expected especially for ~~features consisting of very coarse to blocky substrates~~ periglacial features composed of pebbly to bouldery materials, such as blockfields or mountain-top detritus, in which the vertical variability of ground physical properties is extremely ~~large (Ballantyne, 1998) , and thus it is problematic to describe it~~ high (Ballantyne, 1998) that is difficult to describe by single-value parameters. On slopes, ~~they~~ these materials may also provoke non-conductive heat-transfer processes, which give rise to high-magnitude ~~short-distance~~ variations in ground temperatures over short distances that cannot be addressed by simple heat conduction models (Wicky and Hauck, 2017).

Given the above considerations, the model should be ideally applied to utilized for co-occurring permafrost features of the same age, which may allow periglacial features that allow for a more robust estimate of the range, in which the active-layer thickness and other model driving variables probably were at the time of the feature development. The most plausible values of air temperature characteristics at that time can then be assessed through random-sampling methods. Of coursepalaeo-air temperature estimates. Surely, it can capture only a short snapshot of the temperature history, but this is no different from a number of numerous other palaeo-indicators, such as various glacial deposits. Moreover, if relict periglacial assemblages of different ages exist in a given region, they may eventually provide a more complete record of former temperaturestemperature conditions. Undoubtedly, dating of periglacial features is still challenging, because they may can have a highly complex formation history, which partly devaluates their palaeo-environmental importance. Nonetheless, this shortcoming also becomes increasingly is also increasingly being suppressed by improved dating methods that bring more reliable chronologies (e.g., ?Andrieux et al., periglacial chronologies (e.g., Andrieux et al., 2018; Nyland et al., 2020; Engel et al., in print).

### 5.5 Progress over previous attempts

Similar attempts to infer former temperature conditions have actually been made much earlier. Williams (1975) determined the palaeo-active-layer thickness of 2.0–2.3 from the vertical extent of cryoturbation structures, and based on air temperature–thaw depth relations in present-day permafrost environments he deduced the corresponding $I_{ta}$ of 900 . Subsequently, Williams (1975) assumed MATWM of 10 , on the basis of which he derived MAAT of ca. −8 and MATCM of ca. −25 . This approach has been legitimately appreciated for its ingenuity, but the reconstruction itself has been subject to criticism especially for some doubtful palaeo-environmental assumptions (see Ballantyne and Harris, 1994). Its main shortcoming, however, is that it is hardly replicable as it is purely empirical. It is also unclear how MAAT of ca. −8 was established because the value corresponding to $I_{ta}$ of 900 and MATWM of 10 is ca. −5.9 if sine air temperature curve is assumed (Fig. 2), while MATCM equals ca. −21.8 . Moreover, MAAT corresponding to the alternatively determined $I_{ta}$ of 1500 and the same MATWM of 10 is ca. 3.5 , which contradicts the permafrost presence presumed by Williams (1975).

Likewise, Maarleveld (1976) derived the palaeo-frost depth of 2.5 m based on the depth of seasonal frost-cracking fissures, but he advanced further by applying the Stefan equation to estimate $I_{fa}$ of −2230 . On the other hand, he provided no other temperature characteristics, but merely suggested that the obtained $I_{fa}$ is inconsistent with modern permafrost occurrences. Many criticisms can also be made for this approach regarding the validity of frost-cracking features as frost-depth indicators, the equality of air and ground-surface freezing index, which ignores the snow-cover effects, or vague selection of input parameters.

Yet, the two publications (Williams, 1975; Maarleveld, 1976) definitely were original and stimulating attempts, which unfortunately have never been developed further, despite being broadly cited in recognized review publications (Washburn, 1979; Ballantyne and Harris, 1 . PERICLIMv1.0 aims to fill this gap by combining their strengths, but advances far ahead as it has a sound mathematical basis and, importantly, provides solution that itself is replicable and lacks subjectivity.

## 6 Conclusions

The PERICLIMv1.0 is a novel easy-to-use model that derives the palaeo-air temperature characteristics coupled with related to the palaeo-active-layer thickness identifiable in relict permafrost-related features . The that can be recognized using many relict periglacial features found in past permafrost regions. The model evaluation against modern temperature records demonstrated that the model reproduces the it reproduces air temperature characteristics, such as MAAT, MATWM, MATCM, MATTS, or MATFS, with a mean error of as low as average errors $\leq$ 0.51.3 °C. Besides, $I_{\mathrm{ta}}$ and $I_{\mathrm{fa}}$ both depart deviates on average by 6–16 % , and −12 %, respectively, while $L_{\mathrm{t}}$ and $L_{\mathrm{f}}$ tends to be on average underestimated and overestimated by 1020 % and 48 %, respectively. This is well above expectations and indicates that PERICLIMv1.0 is able to perform reasonably accurately if representative driving data are supplied. Yet, there is an urgent need to further test the model in various environmental settings. The palaeo-MAAT modelled for two sites in the Czech Republic hosting relict cryoturbation structures was between −7.0±1.9 °C and −3.2±1.5 °C and its corresponding reduction was between −16.0 °C and −11.3 °C in comparison with the 1981–2010 period, which is relatively well in line with earlier reconstructions utilizing various palaeo-archives, and the same importantly holds true for other modelled palaeo-air temperature characteristics as well.

Notwithstanding that, the high The model success rate is definitely promising and suggests that it could become a powerful useful tool for reconstructing Quaternary palaeo-environments across vast areas of mid-latitudes mid- and low-latitudes where relict periglacial assemblages frequently occur, but their full potential remains to be exploited. It is the very first viable solution that seeks to interpret former relict periglacial features quantitatively and in a replicable and subjectivity-suppressed manner and, as such, it may can provide much more plausible periglacial-based palaeo-temperature reconstructions than ever palaeo-air temperature reconstructions than before. Hopefully, it will be a springboard for follow-up developments of more sophisticated modelling tools that will further increase the exploitability and reliability of relict periglacial features as palaeo-climatic proxiesindicators of palaeo-climates.

*Code and data availability.* The latest version of PERICLIMv1.0 is available as R package from https://github.com/tomasuxa/PERICLIMv1.0 under the GPLv3 license. The exact version of the model used to produce this paper is archived at https://doi.org/10.5281/zenodo.4057202. The validation datasets from James Ross Island are available upon request from FH (hrbacekfilip@gmail.com), whereas those from Alaskan Arctic can be retrieved from https://permafrost.gi.alaska.edu/sites_list.

## Appendix A: Ground-surface and air thawing index in a two-layer Thermal conductivity of the thawed ground

If two distinct ground layers are present and the base of the bottom one is supposed to indicate the thickness of the Thermal conductivity of the thawed ground is calculated as a function of its dry bulk density and volumetric moisture content using the Johansen's (1977) thermal-conductivity model. This empirical transfer scheme requires less parameterizations than its derivatives, but still provides reasonable and consistent estimates of thermal conductivity for a wide range of substrates having the degree of saturation of >5–10 to 100 % (e.g., Dong et al., 2015; He et al., 2017; Zhang et al., 2018). Basically, it interpolates between dry $k_{\mathrm{dry}}$ and saturated $k_{\mathrm{sat}}$ thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$) of a material as follows:

$$k_{\mathrm{t}} = k_{\mathrm{dry}} + (k_{\mathrm{sat}} - k_{\mathrm{dry}})K_{\mathrm{e}}, \quad \text{(A1)}$$

where $K_{\mathrm{e}}$ is the dimensionless Kersten number ($-$) used to normalize the contrast between $k_{\mathrm{sat}}$ and $k_{\mathrm{dry}}$ based on the degree of saturation.

The dry ground thermal conductivity is defined by the following semi-empirical relationship (Johansen, 1977):

$$k_{\mathrm{dry}} = \frac{0.135\rho + 64.7}{2700 - 0.947\rho}, \quad \text{(A2)}$$

where the constant of $2\,700\,\mathrm{kg\,m^{-3}}$ represents the typical density of solid ground particles that is, for consistency, used throughout the thermal-conductivity scheme.

The saturated ground thermal conductivity is calculated by a weighted geometric mean based on the thermal conductivities of individual ground constituents and their respective volume fractions (Johansen, 1977):

$$k_{\mathrm{sat}} = k_{\mathrm{s}}^{1-n} k_{\mathrm{w}}^{n}, \quad \text{(A3)}$$

where $k_{\mathrm{s}}$ and $k_{\mathrm{w}}$ is the thermal conductivity of solid ground particles and water, respectively ($\mathrm{W\,m^{-1}\,K^{-1}}$), and $n$ is the ground porosity ($-$), which is expressed as a function of the dry bulk density and the typical density of solids:

$$n = 1 - \frac{\rho}{2700}. \quad \text{(A4)}$$

The thermal conductivity of water is set at $0.57\,\mathrm{W\,m^{-1}\,K^{-1}}$, while that of solids is computed as:

$$k_{\mathrm{s}} = k_{\mathrm{q}}^{q} k_{\mathrm{o}}^{1-q}, \quad \text{(A5)}$$

where $k_{\mathrm{q}}$ and $k_{\mathrm{o}}$ is the thermal conductivity of quartz and other minerals, respectively ($\mathrm{W\,m^{-1}\,K^{-1}}$), and $q$ is the quartz fraction of the total content of solids ($-$). Quartz is assigned the thermal conductivity of $7.7\,\mathrm{W\,m^{-1}\,K^{-1}}$, while for other minerals it is as follows (Johansen, 1977):

$$k_{\mathrm{o}} = \begin{cases} 3, & \text{for } q < 20\,\% \land \text{coarse-grained} \\ 2, & \text{otherwise} \end{cases}. \quad \text{(A6)}$$

Note that materials having more than 5 % of clay should be considered as fine-grained, while others should be treated as coarse-grained (sensu Johansen, 1977).

Since the quartz content is usually unknown, it can be estimated as a weighted average of its empirically obtained percentages for clay, silt, and sand fraction, having 0, 15, and 45 %, respectively, which is thought to have an uncertainty $< 30\,\%$ (Johansen, 1977). Alternatively, it can also be drawn from a nomogram using the ground texture (Fig. A1).

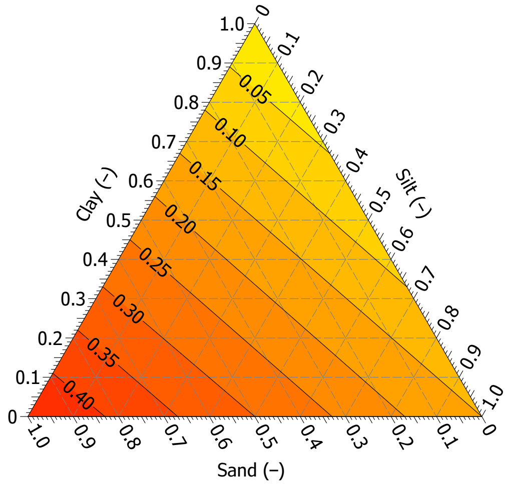


**Figure A1.** A nomogram for estimating the quartz content using the ground texture based on Johansen (1977). Note that the quartz content (black solid diagonal lines) is obtained at the intersection of the contents of clay, silt, and sand (grey dashed three-way lines) that are read in the direction of their respective tick marks and labels.

The Kersten number for thawed fine- and coarse-grained ground with the degree of saturation $S\,(-)$ larger than $10\,\%$ and $5\,\%$, respectively, is expressed as (Johansen, 1977):

$$K_\mathrm{e} = \begin{cases} \log S + 1, & \text{for } S > 10\,\% \wedge \text{fine-grained} \\ 0.7 \log S + 1, & \text{for } S > 5\,\% \wedge \text{coarse-grained} \end{cases}, \quad \text{(A1)}$$

where

$$S = \frac{\phi}{n}. \quad \text{(A2)}$$

Clearly, the values of the calculated ground thermal conductivity increase exponentially and logarithmically with rising input values of the dry bulk density and volumetric moisture content, respectively, and thus the conductivity tends to change more sharply if the inputs are higher and lower, respectively (Fig. A2).

## Appendix B: Solution using MATWM to define the range of annual air temperature oscillations

Unconventionally, the range of annual air temperature oscillations can also be defined using MATWM (cf. Williams, 1975) if its difference from MAAT (i.e., MATWM − MAAT) is substituted for $\frac{A_\mathrm{a}}{2}$ in Eq. (4) and elsewhere. Likewise, MAAT is then calculated numerically using the bisection root-finding algorithm, but is searched for $-\infty < \mathrm{MAAT} \leq 0$ because the actual value of the annual air temperature range is to be determined by the calculation itself. This solution can be advantageously

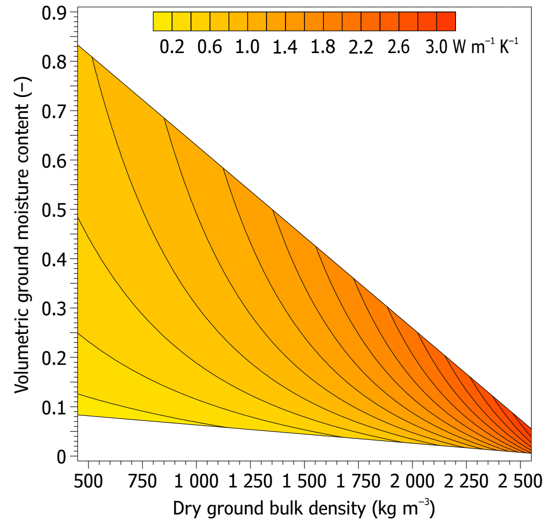


**Figure A2.** Thermal conductivity of the thawed ground as a function of its dry bulk density and volumetric moisture content calculated using the Johansen's (1977) thermal-conductivity model for thawed fine substrates with the degree of saturation of >10 to 100 % and the quartz content of 40 %. Please note that the white areas are outside the saturation limits.

combined with other palaeo-indicators that allow to estimate MATWM. However, it should be employed cautiously because it is highly sensitive to variations of $I_{\mathrm{ta}}$ and MATWM itself (Fig. 2), which can result in major errors if the input parameters are defined inaccurately. Unfortunately, the deviations are expected to be higher at lower both $I_{\mathrm{ta}}$ and MATWM (Fig. 2) that are characteristic for permafrost regions. Please note that this alternate solution is also implemented in the PERICLIMv1.0 R package.

## Appendix C: Validation data

The PERICLIMv1.0 validation was based on mostly previously published data obtained in the period 2011/2012 to 2017/2018 at four bare permafrost sites located on James Ross Island, north-eastern Antarctic Peninsula, between 63°49′–63°53′ S, 57°50′–57°57′ W, and 10–340 m asl (e.g., Hrbáček et al., 2017a, b; Hrbáček and Uxa, 2020), and data collected by the Geophysical Institute Permafrost Laboratory at the University of Alaska Fairbanks in the period 2001/2002 to 2016/2017 at three vegetated permafrost locations on the coastal plain of the Alaskan Arctic adjacent to the Beaufort Sea, between 69°40′–70°22′ N, 148°28′–148°43′ W, and 3–111 m asl (https://permafrost.gi.alaska.edu/sites_list, access: 28 June 2019; Romanovsky et al., 2009; Wang et a ) (Table C1). The stations measured air and ground temperatures with thermistor sensors installed in solar radiation shields 1.5 or 2 m above ground surface and at six to fifteen depth levels ranging from or near from the ground surface to 0.75 m or around 1 m below, and their records were averaged to daily resolution (Romanovsky et al., 2009; Hrbáček et al., 2017a, b; Wang et al., 2018; Hrbáč .

**Table C1.** Driving parameters used to model air temperature characteristics at the James Ross Island (upper section) and Alaskan Arctic (lower section) validation sites. Note that the parameters described by means and standard deviations ($\xi$, $n_\mathrm{t}$, $A_\mathrm{a}$) had normal distributions, while others were assumed to be uniformly distributed ($q$) or were treated as constants ($\phi$, $\rho$).

| Site | $\xi$ (m) | $\phi$ (−) | $\rho$ (kg m$^{-3}$) | $q$ (−) | $f/c$ | $n_\mathrm{t}$ (−) | $A_\mathrm{a}$ (°C) |
|---|---|---|---|---|---|---|---|
| Abernethly Flats | 0.57±0.04 | 0.250 | 1380 | 0.18–0.34 | fine | 2.30±0.55 | 19.7±1.6 |
| Berry Hill slopes | 0.83±0.02 | 0.290 | 1850 | 0.22–0.40 | fine | 2.68±0.44 | 18.6±2.5 |
| Johann Gregor Mendel | 0.55±0.06 | 0.147 | 1460 | 0.25–0.46 | fine | 3.38±0.72 | 20.4±2.2 |
| Johnson Mesa | 0.54±0.06 | 0.197 | 1435 | 0.18–0.46 | fine | 3.05±0.93 | 19.1±2.3 |
| Deadhorse | 0.72±0.04 | 0.515 | 980 | 0.06–0.11 | fine | 0.97±0.18 | 40.2±3.5 |
| Franklin Bluffs | 0.63±0.04 | 0.583 | 1125 | 0.07–0.13 | fine | 0.53±0.09 | 43.7±3.1 |
| West Dock | 0.29±0.06 | 0.725 | 413 | 0.00–0.00 | fine | 0.49±0.06 | 37.3±3.6 |

See Table 1 for abbrevations.

Active-layer thickness, which corresponds to the maximum annual depth of the 0 °C isotherm (Burn, 1998), was primarily determined by a linear interpolation between the depths of the deepest and the shallowest sensors with the maximum annual ground temperature $>0$ °C and $\leq 0$ °C, respectively. Alternatively, it was established by a linear extrapolation of the maximum annual ground temperatures of the two deepest sensors if both were positive. Thawing and freezing seasons were defined by a continued prevalence of positive and negative mean daily temperatures, respectively, at the shallowest ground temperature sensor and, for consistency, these time-windows were also utilized for air temperatures. Since the model assumes that air temperatures are solely positive and negative during the thawing and freezing season, respectively (Fig. 1), positive and negative air temperatures alone were taken to determine MATTS, $I_\mathrm{ta}$, $L_\mathrm{t}$ and MATFS, $I_\mathrm{fa}$, $L_\mathrm{f}$. Likewise, MAAT was calculated as a length-weighted average of the seasonal air temperature means for a period composed of the thawing season and its preceding freezing season, which is thought to be more representative for the active-layer formation than a fixed calendar period (Hrbáček and Uxa, 2020). Annual air temperature range was defined by an annual spread of a 31-day simple central moving average of mean daily air temperatures, with its extremes being considered to substitute MATWM and MATCM. Finally, ground-surface thawing $n$-factor was derived as a ratio of the thawing index at the shallowest ground temperature sensor and air thawing index. Consequently, for modelling, the active-layer thickness had to be trimmed by the depth of the shallowest ground temperature sensor to ensure consistency because the model presumes that the ground-surface thawing $n$-factors transfer between air and ground-surface temperatures (cf. Hrbáček and Uxa, 2020).

Ground physical properties for the James Ross Island sites were determined in situ or from intact samples collected near the temperature monitoring stations at a depth of 0.1–0.3 m during the thawing seasons 2013/2014 to 2018/2019 (Hrbáček et al., 2017a; Hrbáče , while those for the Alaskan sites were adapted from Zhang (1993) and Romanovsky and Osterkamp (1997) who took samples from a depth of up to about 0.6 m during the thawing season 1991 and then averaged their characteristics over the full active-layer thickness. Volumetric ground moisture content was established by successive wet and dry weighing or through replicate measurements with time-domain reflectometry probes. Similarly, dry ground bulk density was determined using dry weighing (Zhang, 1993; Hrbáček et al., 2017a; Hrbáček and Uxa, 2020). Ground quartz content was estimated on the basis of the proportions of clay, silt, and sand fractions (see Appendix A), which were ascertained through a wet sieving and X-ray diffraction (Hrbáček et al., 2017a; Hrbáček and Uxa, 2020) or assessed visually via soil type (Zhang, 1993). All the substrates were considered as fine-grained owing to their relatively high clay–silt contents.

## Appendix D: Ground-surface and air thawing index in a two-layer ground

If two distinct ground layers can be distinguished within the palaeo-active layer, the Stefan equation for calculating the thaw depth active-layer thickness in two-layer ground can be applied. It has been proposed in the following form (Nixon and McRoberts, 1973; Kurylyk, 2015):

$$\xi = -Z_1 \frac{k_{\mathrm{t}_2}}{k_{\mathrm{t}_1}} + Z_1 + \sqrt{\frac{Z_1^2 k_{\mathrm{t}_2}^2}{k_{\mathrm{t}_1}^2} + \frac{2k_{\mathrm{t}_2} I_{\mathrm{ts}}}{L\phi_2\rho_{\mathrm{w}}} - \frac{Z_1^2 k_{\mathrm{t}_2}\phi_1}{k_{\mathrm{t}_1}\phi_2}}, \quad \text{(D1)}$$

where $Z_1$ is the thickness of the top sub-layer $(\mathrm{m})$, the physical parameters of which are subscripted by 1, while the bottom sub-layer is denoted by the subscripts 2. The ground-surface index can then be simply expressed from Eq. (A1): D1):

$$I_{\mathrm{ts}} = \frac{\left[(\xi + Z_1 \frac{k_{\mathrm{t}_2}}{k_{\mathrm{t}_1}} - Z_1)^2 - \frac{Z_1^2 k_{\mathrm{t}_2}^2}{k_{\mathrm{t}_1}^2} + \frac{Z_1^2 k_{\mathrm{t}_2}\phi_1}{k_{\mathrm{t}_1}\phi_2}\right] L\phi_2\rho_{\mathrm{w}}}{2k_{\mathrm{t}_2}}. \quad \text{(D2)}$$

As in Eq. (1 and 2), the product of $\phi$ and $\rho_{\mathrm{w}}$ can be substituted by that of the gravimetric moisture content and the dry bulk density of the ground, but note that the fraction on the far right of Eq. (A1D1) and at the corresponding place of Eq. (A2D2) is simplified because the density of water in its numerator and denominator is the same. Subsequent procedures to derive the air temperature characteristics are analogous to those for the one-layer solution (Eq. 3 to 14).

*Author contributions.* TU came up with an initial idea with feedbacks from MK, developed the model, evaluated it against data from James Ross Island and Alaskan Arctic, which were processed by FH and TU, respectively, and tested it for derivation of palaeo-air temperature characteristics using data sampled collectively with MK in the Czech Republic. TU draw figures and wrote the manuscript with inputs from MK and FH. All authors reviewed and approved the final version of the paper.

*Competing interests.* The authors declare that they have no conflict of interest.

*Acknowledgements.* The PERICLIMv1.0 development and evaluation was supported by the Czech Science Foundation, project number 17-21612S. The validation datasets from James Ross Island were collected thanks to the Ministry of Education, Youth and Sports of the Czech Republic, project number LM2015078. We thank Tereza Dlabáčková for her assistance at the Nebanice site and with sample analysis. The

Geophysical Institute Permafrost Laboratory at the University of Alaska Fairbanks is acknowledged for its continuous effort in collecting temperature data across Alaska and their online dissemination.

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