Reply to referee 2

We appreciate the time and effort spent on the revision of the manuscript "Simulating the permafrost thermal regime in the Northwestern Antarctic Peninsula from 1950 to 2100". The comments and suggestions were very well received, and we have subsequently revised and improved the text and work presented. In the following, we provide point-by point replies to all issues raised. The reviewer comment appears in bold font, our replies in normal font and changes to the text which will be implemented in the revised version of the manuscript are in italics.

On behalf of all authors,

Joana Baptista

<u>Reply to the major comments:</u>

Point 1: It appears that the snowfall multipliers and some subsurface parameters were adjusted using the same ground-temperature observations later used to evaluate model performance. If so, Table 3 represents calibration performance rather than independent validation. Please specify the calibration and evaluation periods, observations, and depths used at each site. I would recommend a split-sample or leave-one-year-out evaluation, together with the parameter ranges and selection criterion. Agreement at 0.4 m should not be presented as independent model skill if that depth was used to determine the snowfall multiplier.

Reply: In our implementation of CryoGrid, subsurface parameters (mineral, water/ice and organic contents) were defined based on-site characteristics and only minor adjustments were made during model calibration through the comparison with observed ground temperatures at different depths (0.4, 1.2, 3.0 m, and the maximum depth for each borehole). MAGST (0.02 m depth) was used as the upper boundary forcing. This approach aimed at reducing potential biases associated with ERA5 forcing and at maximizing the use of the relatively short observational records available at several sites.

The snowfall multiplier was determined in a second phase using ERA5 forcing and the surface energy balance scheme. The multiplier was adjusted to reproduce the observed insulating effect of snow cover observed on ground temperature at 0.4 which was not used to force the model.

We acknowledge that the separation of the calibration and evaluation periods can improve the interpretation of the procedure. To address this, the year 2021 is now used for calibration of the subsurface parameters and snowfall multiplier, while the period from the beginning of the observational records through 2020 was used for independent model evaluation (Table 1). We have also specified in the revised manuscript (Table 1 and Section *3.2.2 Model calibration and evaluation*), for each observatory, the calibration and evaluation periods, the observations used, and the depths considered. Separate tables reporting calibration and evaluation statistics have been added accordingly (Section *4.1 Sensitivity analysis to subsurface parameterization and validation of the surface energy model*).

Point 2: The projections depend on one CMIP6 model and apparently one random realization of the monthly carrier sequence. ACCESS-CM2 was selected partly because it reproduces the ERA5 trend, although another candidate has smaller MAE and RMSE. This does not necessarily demonstrate that ACCESS-CM2 provides the most credible future regional warming. Please show how model selection and carrier sampling affect the main results. Ideally, the authors should include projections from the other candidate models and several carrier realizations. If this is not feasible, the results should be described as ACCESS-CM2-driven sensitivity experiments, and threshold crossings should be reported by approximate decade or as ranges rather than as exact years.

Section 3.5 also needs clarification. Please verify Equation (2) against the implemented code and explain whether the same sampled month was used for all forcing variables. Otherwise, covariance among temperature, humidity, precipitation, wind, and radiation may not be preserved.

Reply: The selection of the ACCESS-CM2 model based on the reproduction of the ERA5 trend is especially important considering that this is the SSP2-4.5 scenario that simulates a central pathway in which the trend continues the historical pattern without substantial deviation which is observed on the INM-CM4-8 model, despite the lower MAE and RMSE values. This deviation contradicts also the projections of Bracegirdle et al. (2020) for Antarctic. The INM-CM4-8 model also misrepresents the interannual variability. In the revised manuscript we complemented the evaluation of the CMIP6 models. Additionally, we are aware of the limitation impose by using one model but running a multi-GCM ensemble is currently not possible on the CCM. However, this is a development planned in a future study.

Section *3.3.2 CMIP scenarios and models:*

"To evaluate the ability of the downscaled CMIP6 models to represent climate conditions in the northwestern Antarctic Peninsula, we compared the simulated MAATs at the Papagal observatory location with ERA5 reanalysis data for the reference period 1950–2020 (Fig. 2 and Table 3). Papagal observatory was selected as the reference site because it is located in an exposed location that is representative of regional climate conditions and provides a long-term, high-quality observational record. Among the models, ACCESS-CM2 simulated slightly warmer temperatures than ERA5, with a MAE of 1.16 ºC and a RMSE of 1.33 ºC. Its standard deviation (σ = 0.98) was close to that of ERA5 (σ = 1.01), indicating a similar representation of interannual variability. INM-CM4-8 generally reproduced the ERA5 MAATs but misrepresented the

interannual variability, as indicated by its lower standard deviation (σ = 0.78). However, it showed the lowest errors among the three models, with a MAE of 0.74 ºC and a RMSE of 0.84 ºC. In contrast, IPSL-CM6A-LR overestimated temperatures by up to 5 ºC in some years (e.g. 2011-2013) and had the highest MAE and RMSE values, at 1.37 ºC and 2.81 ºC. Its standard deviation was the highest (σ = 1.49.), suggesting that it captured the magnitude of interannual variability, despite its substantial temperature bias.

For the period 1950- 2020 linear regression showed that ACCESS-CM2 simulates a warming trajectory of 0.36 ºC dec^{-1}, closer to ERA5 (0.33 ºC dec^{-1}), while IPSL-CM6A-LR estimates a stronger warming of 0.44 ºC dec^{-1}. In contrast, INM-CM4-8 results in a much weaker warming of 0.15 ºC dec^{-1}. Additionally, INM-CM4-8 projects for the future (2020-2100) a cooling trend of -0.05 ºC dec^{-1} that contradicts the projections of Bracegirdle et al. (2020) for Antarctic and the Southern Ocean surface climate.

The difference in the air temperature simulated by each model strongly impacts the simulation of ground temperatures, leading to markedly different permafrost thermal regimes and future trajectories. ACCESS-CM2 was selected to force the simulations of future permafrost evolution as it shows the best overall performance against ERA5, combining a similar linear trend and a realistic representation of interannual variability."

Along the manuscript was stated that the future projections are based on the ACCESS-CM2 model (abstract, section *3.3.2 CMIP6 scenarios and models* and *6. Conclusions*) and we reinforced that this is an ACCESS-CM2-driven sensitivity experiment in section *4.3 Future evolution of permafrost temperature under CMIP6 scenarios (2020 - 2100)*. Additionally, the Appendix on the evaluation of the CMIP6 models was moved into the main structure and divided into the sections *3.3.2 CMIP6 scenarios and models* and *5.1 Evaluation of the forcing data*.

Regarding the "threshold crossings" we also agree that the projected threshold crossings should not be interpreted as exact dates. Accordingly, the revised manuscript reports these transitions as approximate decades or time ranges rather than as specific years.

Section *4.3.1 SSP1-2.6:*

"At 10 m depth, MAGT exhibits an average warming trend of 0.27 ± 0.01 ºC dec-1, accompanied by pronounced interannual variability (Table 8 and Fig. 6). This warming is projected to result in permafrost thawing at the low-elevation SKO Station and Amsler observatory during the 2040s."

Concerning the equation 3 (previous equation 2), the same month was used for all forcing variables to conserve the covariance. The sentence was rewritten for clarity.

"m_i^{CMIP} is equal to M_i^{CMIP} during the overlap period, while it is set to the running mean of 10-year periods for the remainder of the time series, so that short-term fluctuations can be separated from multi-annual trends (which are accounted for by the first three terms on the right-hand side). To conserve the covariance between the different model forcing variables, they were all derived from the same month. With this procedure, we ensure that the corrected CMIP6 data features the same monthly mean and standard deviation as the ERA5 data for the overlap period."

Point 3: The manuscript frequently interprets positive mean annual ground temperature at 20 m as the disappearance of permafrost. I would avoid treating these as equivalent. A positive annual mean at one depth does not establish the thermal state of the full profile or whether permafrost persists above or below that level. Please define the criterion used to diagnose permafrost degradation and distinguish it from the year when MAGT at 20 m becomes positive. If possible, provide active-layer thickness and talik diagnostics from the complete simulated profile. Otherwise, "permafrost loss" should be replaced by the more precise phrase "positive MAGT at 20 m". Active-layer thickness should also be removed from the title of Section 4.3 unless the corresponding results are presented.

Reply: In the manuscript we associated positive MAGT at 20 m depth with permafrost degradation. In the revised version, we now present permafrost degradation as a possible outcome rather than as a definitive conclusion and have removed statements implying a direct relationship. Moreover, we replace some references to degradation by the word thaw. Additionally, we have added two figures with the complete simulated profile to support the analysis in the Appendix D.

<u>Reply to the minor comments:</u>

Abstract, lines 14-15: Replace "constrains trends evaluation" with "constrains the evaluation of trends."

Reply: Corrected.

Abstract: Please state clearly that the final projections are based on one CMIP6 model. Also avoid wording that equates positive MAGT at 20 m directly with complete permafrost loss.

Reply: When referring to future projections the model (ACCESS-CM2) used is identified. Regarding the permafrost loss, we adjusted the text to prevent the direct relation.

Line 50: Remove the unnecessary parentheses around "Obu et al. (2020)."

Reply: Corrected.

Lines 58-60: "Recommended Concentration Pathway" should be "Representative Concentration Pathway." More importantly, CMIP6 scenarios are SSP-based and should not be presented as predictions.

Reply: The sentences were rewritten for clarity.

Previous "Our goal is to implement a modelling approach based on the CryoGrid Community Model (CCM) (Westermann et al., 2023), which integrates site-specific characteristics to estimate ground temperature over defined time periods. Specifically, we simulate recent past conditions using reanalysis data, validate the models against observed permafrost temperature data and project the ground temperature evolution until 2100 using selected Coupled Model Intercomparison Project (CMIP) models in different Recommended Concentration Pathway scenarios (IPCC, 2014; O'Neill et al., 2016)."

New section *"Our goal is to implement a modelling approach based on the CryoGrid Community Model (CCM)* (Westermann et al., 2023)*, which integrates site-specific characteristics to estimate ground temperature over defined time periods. In the present study, the CCM was implemented for five observatories of the PERMANTAR network (http://permantar.weebly.com) distributed along the Northwestern Antarctic Peninsula, specifically, to validate the models against observed permafrost temperature data, simulate past conditions from 1950 to 2020 using reanalysis data, and project the ground temperature evolution from 2020 until 2100 under three Shared Socioeconomic Pathways (SSPs) from the Coupled Model Intercomparison Project (CMIP)* (IPCC, 2014; O'Neill et al., 2016).

In Baptista et al. (2025), the performance of the CCM was evaluated for the King Sejong permafrost observatory on Barton Peninsula, King George Island. The results of the simulation from 2020-2022 show that the model successfully represented the site conditions with correlations above 0.8 and MAE ranging from 0.1 to 0.7 ºC. Following the validation of the model, a long-term simulation from 1950 to 2022 was run showing a ground warming trend at 20 m of 0.25 ºC dec^{-1}, followed by an increase in the active layer thickness from 1.5 m in 1950 to 3.5 m in 2022."

Section 2.1: The heading uses "Western Antarctic Peninsula," whereas the rest of the manuscript refers to the "northwestern Antarctic Peninsula." Please standardize the geographical terminology and capitalization.

Reply: You are correct and it was something pending from an earlier version. Actually, the section provides a general description of the Antarctic Peninsula- Hence in the heading the word "Western" was removed.

Line 73: Replace "divided in two" with "divided into two."

Reply: Corrected.

Line 76 and elsewhere: Replace "Thomas e Tetzner 2019" with "Thomas and Tetzner (2019)."

Reply: Corrected.

Line 97: "measured at King Sejong Station."

Reply: Corrected.

Table 1: "Measurement height/depth" combines height above the surface and depth below it. Please separate these quantities or use a clear signed convention.

Reply: The table was updated. Now exists one column for the height and another for the depth.

Lines 193-196: Air temperature appears to be missing from the ERA5 variable list. Dew-point temperature is listed, whereas CryoGrid uses specific humidity; please explain the conversion.

Reply: The 2 m temperature was missing from the previous version, being now identified on the variables listed.

Table 2: Please provide units for MAE and RMSE and specify the sampling frequency and evaluation period. The meaning of the reported p-value should also be defined, considering temporal autocorrelation.

Reply: The table was updated with the required information.

Lines 246-250: Please clarify whether monthly CMIP6 data were used and standardize the variable names and units. Specific humidity should be reported in kg kg⁻¹ rather than as dimensionless.

Reply: The sentence was rewritten for clarity and the unit added.

Section *3.3.2 CMIP6 scenarios and models:*

"Data was downloaded from the Climate Data Store (Copernicus Climate Change Service, 2021) *for the historical, the SSP1-2.6, the SSP2-4.5 and the SSP5-8.5 scenarios. The variables at monthly resolution used to force the simulation were:"*

Line 257: The description of the vertical model resolution is unclear. Please state explicitly the grid spacing above and below 5 m depth.

Reply: The sentence was rewritten for clarity.

Section *3.4 Long-term simulation of the past and future evolution of permafrost temperatures:*

"In the simulation's output we provide estimates of ground temperatures for a profile of 20 m depth, with vertical resolution varying with depth: 0.05 m from the surface to 1 m, 0.1 m from 1 to 2 m, 0.2 m from 2 to 5 m, and 0.5 m below 5 m depth."

Section 3.5: In addition to the issues raised above, all symbols in Equations (2) and (3) should be defined consistently, and the ERA5 and CMIP6 terms should be distinguishable.

Reply: We reviewed the terms to ensure the distinction.

Table 3: Please define whether mineral and water/ice contents are volume fractions and provide units, sample sizes, and evaluation periods for the performance statistics.

Reply: The table was updated with the information required. Additionally, information on the mineral and water/ice contents type of unit is provided on the methods section. As previously mentioned, we will split the calibration and evaluation periods and update the table accordingly.

Section *3.2.2 Model calibration and evaluation:*

"Following Baptista et al. (2025), the model calibration for each borehole was performed in two phases: i. the simulations were run for 2021 forced with ground surface temperature, being subsurface parameters (i.e. mineral and water/ice content) adjusted to obtain the best configuration through a sensitive analysis, ii. the best configuration scheme was then used when forcing the simulations with ERA5 data of the same year, but using the CCM surface energy balance scheme, in order to define

the snowfall multiplication factor. The model performance was evaluated for each borehole by comparing the results from the beginning of the observational period until 2020 (Table 1).

For the adjustment of the subsurface parameters, a class representing a ground column with temperature boundary condition at the surface (GROUND_freeW_ubT, Westermann et al., 2023) was selected, for which water phase change occurs at 0 ºC and the sum of water and ice contents remain constant (Baptista et al., 2025). *Measured ground surface temperature from the PERMANTAR monitoring sites was used as upper boundary input while a geothermal heat flux value obtained from An et al. (2015) and applied as the lower boundary. Geothermal heat flux values for King Sejong, Papagal and SKO Meteo were 73 mWm^{-2}, for Cierva were 61 mWm^{-2}, and for Amsler were 58 mWm^{-2}. The thermal conductivity was obtained from thermophysical analysis performed on the rock cores. For this, the cores were sliced, and the conductivity was measured with an ISOMET 2104. 1D simulations were run with different configurations of mineral and water/ice volumetric content, that goes from 0 to 1, for each of the five boreholes. From each simulation, estimated daily average ground temperatures at 4 depths (0.4, 1.2, 3.0, and maximum depth of borehole) were extracted and compared with the observational records. The metrics used for the assessment of model performance were bias, correlation coefficient (r), the p-value associated with the correlation coefficient which was considered statistically significant when $p < 0.05$, mean absolute error (MAE) and root mean square error (RMSE).”*

Figure 2: The caption should define the box, whisker, and outlier conventions and give the observation period for each site.

Reply: Corrected. Previous Figure 2 is now Figure 3.

“Seasonal variation (DJF, MAM, JJA and SON) of simulated and observed ground temperatures on the PERMANTAR observatories at 0.4 m, 3 m and maximum borehole depth. Boxes indicate the interquartile range, the central line indicates the median, whiskers extend to 1.5 times the interquartile range. The record covers 2020 for King Sejong, 2011-2020 for Papagal, 2012-2020 for SKO Station, 2014-2020 for Cierva and 2018-2020 for Amsler.”

Section 4.2 and Figure 3: These give different historical periods. More generally, please check all analysis periods, as the manuscript alternates among 1950–2020, 1950–2022, 2020–2100, and 2022–2100.

Reply: The analysis periods were standardized.

Figure 3: Please define the SWE statistic. For example, whether it represents an annual mean, maximum, or another quantity. The caption should also be revised because it groups air temperature and snowfall under "ground temperatures."

Reply: Corrected. Previous Figure 3 is now Figure 4.

"Long-term simulation (January 1950 to December 2020) for the PERMANTAR observatories: annual snowfall (mm water equivalent), mean annual air temperature - MAAT (ºC); mean annual ground surface temperature - MAGST (ºC); mean annual ground temperature at 10 m - MAGT (ºC); mean annual ground temperature at 20 m - MAGT (ºC)."

Figure 4: This appears to show five point simulations rather than a spatially continuous estimate. Please revise the figure or caption accordingly. The use of the single year 1950 as a baseline should also be justified, particularly if it was exceptionally cold.

Reply: We understand the reviewer's concern. Figure 5 (previous figure 4) is intended as a spatial comparison. We agree that would be more appropriate to present the estimate for a period, as suggested. Therefore, we have calculated averages for the corresponding decades. This means that the value previously shown for 1950 now represents the average for the period 1950-1960, the value for 2020 represents the average for 2010-2020, and the value for 2100 refers to the period 2090-2100.

Results and Discussion: Please distinguish clearly between total temperature changes in °C and trends in °C decade^{-1}. Each value should have a clearly defined reference period.

Reply: To uniformize, we replaced the temperature change by trend per decade.

Results, Discussion, and Conclusions: Several threshold years differ among the abstract, Results, Discussion, and Conclusions. I suggest generating all threshold years from one summary table and using them consistently throughout.

Reply: The thresholds were uniformized among the sections.

Section 4.3: Active-layer thickness should be removed from the section title unless the corresponding results are presented.

Reply: It was removed from the section title.

Figure 8: Figure 8 is cited, but no Figure 8 is included. Please identify the intended figure.

Reply: Corrected.

Table 5: The caption should reflect that the table includes MAAT and MAGST as well as MAGT at 20 m. Please also use uppercase "SSP" consistently.

Reply: Previous Table 5 is now Table 6. The caption was updated with the missing information and the SSP acronym corrected.

"Change rates from the simulations of future temperature evolution on the PERMANTAR observatories from 2020 to 2100: mean annual air temperature - MAAT (ºC/ decade); mean annual ground surface temperature - MAGST (ºC/ decade); mean annual ground temperature at 10 m depth - MAGT (ºC/ decade); mean annual ground temperature at 20 m depth - MAGT (ºC/ decade)."

Figure 5: Please identify the transition from ERA5 to synthesized ACCESS-CM2 forcing and define the line colors in the caption.

Reply: Previous Figure 5 is now Figure 6. The description of the dotted line was added to the legend of the figure.

"Long-term simulation of air and ground temperature (2020 - 2100) on PERMANTAR observatories: mean annual air temperature - MAAT (ºC); mean annual ground surface temperature - MAGST (ºC); mean annual ground temperature at 10 m depth - MAGT (ºC); mean annual ground temperature at 20 m depth - MAGT (ºC). Vertical line represents the transition from the ERA5 series to the synthesized CMIP6 series as forcing of the long-term simulation."

Figure 6: Please use the complete scenario names SSP1-2.6, SSP2-4.5, and SSP5-8.5.

Reply: The complete scenario name is now used on the figures.

Discussion: Some explanations involving the Amundsen Sea Low, sea-ice changes, and snow effects are presented causally without direct supporting analysis. Please provide the relevant diagnostics or present these mechanisms as possible explanations.

Reply: We have developed further the discussion section to incorporate the explanations associated with the ASL and sea-ice changes.

"Following the historical trend, the SSP2-4.5 scenario estimates a much stronger MAAT warming rate of 0.31 ± 0.02 ºC dec⁻¹. Consequently, MAGT at 20 m depth exhibits a more accelerated warming, leading to positive MAGTs at 20 m depth at all five observatories in the 2080s, with values ranging from 1 to 2 ºC in 2100. In contrast to the SSP1-2.6 scenario, SSP2-4.5 displays a distinct spatial pattern in MAAT warming rates, with increased warming at the more southerly observatories which may be related to the sea ice loss on the Bellingshausen Sea and consequent deepening of the ASL that strengthens north-northwesterly flow towards the Antarctic Peninsula, favouring advection of warm, maritime air and raising surface air temperatures, especially during the winter (Abram et al., 2010; Clem et al., 2017; Hosking et al., 2013; Turner et al., 2013)*."*

Conclusions: Please verify statements such as "most observatories" against the site-specific results. Wider implications involving thermokarst and slope instability should also be presented as possible consequences rather than direct model results, particularly because most sites are represented as bedrock with little ground ice.

Reply: The sentences were rewritten to remove the direct relationship.

"Our results for bedrock sites indicate that the future projected warming across the Northwestern Antarctic Peninsula, independently of the CMIP6 scenario will very likely lead to the thawing of permafrost from coastal areas and low elevation sites. Although extrapolation to non-bedrock settings is subject to limitations, our results provide an important indication of regional warming trends that are likely to influence permafrost conditions across a range of ice-free environments. Such substantial changes in the ground thermal regime may modify surface and subsurface hydrology, biogeochemical fluxes and geomorphological processes, with implications for the sensitive terrestrial (and potentially also to nearshore) ecosystems. They may also increase the vulnerability of human infrastructure (research stations, roads, and airstrips) to degradation. Similarly to what is recorded in comparable regions in the Arctic, in non-consolidated deposits, thermokarst and landslide activity will likely increase. In the steep rocky slopes, so typical of the coastal areas of the Northwestern Antarctic Peninsula, as bedrock warms and thaw propagates along joints, rockfalls and landslides may become more frequent, increasing hazards in areas that are experiencing growing tourist visitation during the austral summer."

Appendix C: The text refers to Table A1, but this appears to be Table C1.

Reply: Corrected.

Table C1: Please use the official CMIP6 model identifiers consistently. The IPSL model appears in different forms, including IPSL-CM6A, IPSL-CM6-A, and IPSL-CM6A-LR.

Reply: Corrected to IPSL-CM6A-LR.

Appendix E: Its title gives 2022–2100, whereas the associated analysis also uses 2020–2100. Please standardize the period.

Reply: The figure presented on Appendix E was incorporated in Figure 6.

Code and data availability: Please provide the exact CryoGrid version, release, or commit used. The processed forcing, parameter files, carrier realization or ensemble, and relevant scripts should also be made available in a persistent repository to ensure reproducibility.

Reply: The CryoGrid version was provided in the section "Code availability" (Westermann et al., 2026). The parameter files, forcing data and simulation outputs are available at Zenodo(Pedro Baptista et al., 2026b, a).

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