Reply to referee 1

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: The simulation of recent past conditions was based on the bias-corrected ERA5 for 1950–2020 (with 10 spin-up loops in 1940–1949). By contrast, the simulation of future conditions was based on the bias-corrected CMIP6 models for 1850–2100, with 10 spin-up loops in 1850–1860 and bias-corrected ERA5 used in 1940–2022. Why did not you apply the modelling strategy used for future to recent past as well? The 100-year model initialization phase running since 1850 would likely be better than the 10 spin-up loops over 1940–1949. Moreover, this would mean better consistency and less work since you would have single time series covering the whole period 1850–2100 and both recent past and future scenarios.

Additionally, was the CMIP6 bias correction based on the bias-corrected ERA5? This is unclear to me.

Reply: In the submitted manuscript, the simulation of past evolution followed the approach adopted in Baptista et al. (2025). The simulation of future evolution was implemented as an additional step in the model implementation to the Antarctic Peninsula region. However, as pointed out, a longer spin-up period would better represent the initial thermal conditions, particularly at greater depths. It would also provide a more consistent approach. Therefore, we revised the procedure running a long-term simulation from 1850 until 2100. The analysis of both the past and future evolutions are derived from this long-term simulation.

Regarding the question, “Was the CMIP6 bias correction based on the bias-corrected ERA5 data?”, the answer is yes.

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

“For this reason, we synthesized a model forcing time series from the site-corrected ERA5 records (referred to as ERA5 in the following), from 1940 to 2020, and monthly CMIP6 output, spanning the entire CMIP6 period from 1850 to 2100.”

Point 2: Considering that you did the bias correction only in the case of air temperature, while the rest of the variables retained their uncorrected values, is the resulting dataset internally consistent? For instance, if the air temperature was corrected, while the dew point temperature remained uncorrected, this may affect outputs calculated from these two variables. Likewise, precipitation retained its uncorrected value, but solid and liquid precipitation usually occurs at some specific temperatures, which can also be affected if the temperature is corrected. I have no idea how this might affect the simulation outputs, but the issue is here obvious.

Reply: Following the adaptation of air temperature based on in situ measurements, the dew point T was also adjusted so the relative humidity stays constant, and the total precipitation is partitioned according to bias-corrected air temperature. To clarify the procedure, the explanation was extended in the methods.

Section *3.3.1 ERA5:*

“Here, the ERA5-derived air temperature at the four observatories (King Sejong, Papagal, Cierva and Amsler) was corrected following Westermann et al. (2016), in which a linear regression is used to correct the average bias and trend of model forcing (Table 2). Additionally, the 2 m dew point temperature was adapted to maintain constant the relative humidity, and total precipitation was partitioned according to bias-corrected air temperature.”

Point 3: In the methods, explain why you modelled ground temperatures specifically at a depth of 20 m. Frequently, you also present ground temperatures from a depth of 10 m, which is much closer to a maximum depth of the boreholes and might therefore have a higher validity. Was this because that is at or below the depth of zero annual amplitude?

Reply: Yes, we aimed to estimate the MAGT at a depth of zero annual amplitude and in most observatories, this is not reached at 10 m depth. The estimates at 10 m depth complement the analysis and allowed a comparison to the records in some of the observatories. We extended the explanation in the methods.

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.

These are used to calculate the MAGST and MAGT at 10 and 20 m depth. MAGT at 10 m depth provides an overview of near-surface thermal changes and their potential implications for surface and subsurface hydrology, biogeochemical fluxes, and geomorphological processes. MAGT at 20 m depth provides insight into long-term ground temperature conditions near the depth of zero annual amplitude."

Point 4: For consistency, descriptions of both recent past and future simulations should present the evolution of mean annual air temperatures, mean annual ground surface temperatures, temperatures at the base of the freeze-layer layer (TTOP under permafrost conditions), and mean annual ground temperatures at a depth of 20 m. Some of these temperature metrics are frequently missing, which makes a little sense in terms of consistency and (not only) mutual context. If mean annual ground temperatures at a depth of 10 m are shown as well, I would present them before those from 20 m. Because of heat diffusion, the temperature patterns at 10 m precede those at 20 m, so it would have more logic to proceed in this order.

Reply: We removed the TTOP metric from the analysis and focused on MAGST and MAGT. The analysis of MAGT at 10 m is now presented before the MAGT at 20 m depth. Additionally, Figure 6 (previous Figure 5) now includes the estimates for MAGT at 10 m depth that were previous located in the Appendix E.

Point 5: The discussion is relatively short and in principle deals with results of this study alone, and the context of other studies is provided to a very limited extent. While I am aware that there is currently no analogous study published for Antarctica, there are several studies that assessed short-term trends in permafrost temperatures or active-layer thickness (e.g., Guglielmin and Cannone, 2012; Ramos et al., 2017; Biskaborn et al., 2019; Hrbáček and Uxa, 2020; Hrbáček et al., 2021, 2023, 2025; Baptista et al., 2025) or some several long-term meteorological series (e.g., Oliva et al., 2017). I do not understand why you do not mention your previous study in the discussion (Baptista et al., 2025).

Reply: We agree with the comment and further developed the discussion section with respect to the studies focusing on permafrost temperature on the Western Antarctic Peninsula, especially Biskaborn et al. (2019) and Hrbáček et al. (2023), presenting the rates estimated by the authors.

Section *5.2 Past evolution of permafrost temperature (1950 - 2020):*

"At the surface, warming rates were very similar across the five observatories, ranging from 0.26 to 0.30 ± 0.04 ºC dec^{-1}, close to the rate reported by Hrbáček et al. (2023) for the South Shetlands Islands of 0.28 ºC dec^{-1} (2006-2020)."

(…)

"The cooling recorded between 2000 and 2015, together with increased snowfall that led to persistent snow cover during the thawing season that limited surface warming by increasing albedo and reducing the heat loss, produced a slight reduction in MAGT (<1 ºC) and temperature trends at 20 m depth ranging from -0.05 ± 0.02 ºC dec^{-1} to -0.01 ± 0.02 ºC dec^{-1}. Biskaborn et al. (2019), in the analysis of the global dataset of permafrost temperatures for the decade between 2007 and 2016, reported temperature trends between -0.4 to 0.8 ºC dec^{-1} for the Antarctic Peninsula region."

We mentioned the previous study (Baptista et al., 2025) along the methods since it was the first test to the approached followed. Additionally, we also include a reference in the section *5.1 Evaluation of the forcing data* discussion the limitations previous found on ERA5 reanalysis data.

Section *5.1 Evaluation of the forcing data:*

"In the case of ERA5, the comparison between reanalysis-derived air temperature and in situ measurements revealed a cold bias during the summer season, which limited surface warming and the development of the active-layer thickness observed in borehole records. A similar cold bias was also identified by Baptista et al. (2025) when modelling ground temperature at Barton Peninsula, King George Island. To reduce its impact on the simulations, the ERA5 air temperature data was bias-corrected following the approach proposed by Westermann et al. (2016)."

What I also miss in the discussion is a section devoted to the evaluation of the ERA5 and CMIP6 models used as model forcings. Consequently, I would move the Appendix C into the discussion. You may also refer to Baptista et al. (2025) or Kaplan Pastíriková et al. (2025) when evaluating the suitability of ERA5 or reananalyses for permafrost studies in Antarctica in general.

Reply: We agree with the comment and divided the Appendix C between the methods and discussion sections. Regarding the references, Kaplan Pastíriková et al. (2025) and Baptista et al. (2025) are now mentioned in the discussion.

Section *5.1 Evaluation of the forcing data:*

"In the case of ERA5, the comparison between reanalysis-derived air temperature and in situ measurements revealed a cold bias during the summer season, which limited surface warming and the development of the active-layer thickness observed in borehole records. A similar cold bias was also identified by Baptista et al. (2025) when modelling ground temperature at Barton Peninsula, King George Island. To reduce its impact on the simulations, the ERA5 air temperature data was bias-corrected following the approach proposed by Westermann et al. (2016).

Other studies have also evaluated the performance of ERA5 in Antarctica. Zhu et al. (2021) assessed near-surface air temperature against observations from 41 weather stations and identified both regional and seasonal biases, including a warm bias inland and difficulties in reproducing local scale variability in areas of complex terrain. Nevertheless, ERA5 performed *better than ERA-Interim. Similarly, Jones and Lister (2015) highlighted that the extreme environmental conditions and sparse observational network of Antarctica pose significant challenges for data assimilation, contributing to uncertainties in surface temperature and precipitation estimates. Focusing on the Antarctic Peninsula, Tetzner et al. (2019) reported a seasonal cold bias in 2 m air temperature and an underestimation of wind speed in coastal areas, despite ERA5 providing a generally good representation of the prevailing wind regimes. On the eastern side of the Antarctic Peninsula,* (Kaplan Pastíriková et al., 2025) *validated ERA5-Land reconstructed air temperatures against observations from three automated weather stations (AWSs) on James Ross Island for the period 2004-2021. Their analysis showed that MAAT derived from ERA5-Land had lower interannual variability (σ=0.96 ºC) when compared to the observations (σ between 1.32 to 1.35 ºC). Moreover, the mean monthly temperatures during summer and autumn differed substantially from the observations, with ERA5-Land underestimating the air temperatures recorded, as observed at the PERMANTAR observatories. This resulted in RMSE values of approximately 3 ºC and biases ranging from -1.6 to -0.9 ºC. The authors also reported excessive snowfall in ERA5-Land, associated with an overestimation of snow accumulation that produced persistent snow depths of 3-24 m and affected ground temperatures during summer. This overestimation was also observed at the PERMANTAR observatories, requiring the adjustment of the snow factor."*

Point 6: Consider carefully whether the content of the appendices really needs to placed in them. I think that most of the appendices could be involved in the main body of the manuscript without making it fragmented.

Reply: Following your suggestions, the previous Appendix C (Evaluation of CMIP6 models) was incorporated into the main structure of the manuscript. Information related to the site characteristics and observational period from the Appendix A were also incorporated into the main structure in a summarized way. The figure presented on Appendix E was moved to the Section 4.3 and incorporated on the Figure 6 (previous Figure 5).

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

P1L13: State the period over which the mean annual air temperature increase of 3.4±1.2 °C was recorded.

Reply: The sentence was rewritten for clarity.

"a climatic hotspot of the continent where an increase in mean annual air temperature of 3.4 ± 1.2 ºC since 1950 has been recorded"

P1L18: Specify the depth for the mean annual ground temperature. Is it 20 m?

Reply: Corrected.

"Simulations forced with ERA5 reanalysis were used to reconstruct ground temperature evolution since 1950, revealing a warming trend at all depths, with mean annual ground surface temperature, and mean annual ground temperature at 10 and 20 m depth warming at rates of 0.29 ± 0.04 ºC dec^{-1}, 0.24 ± 0.01 ºC dec^{-1} and 0.18 ± 0.01 ºC dec^{-1}, respectively"

P1L20: In contrast to the above, it is unnecessary to specify the depth of 20 m here because it is a general statement.

Reply: Corrected.

"Four distinct periods are identified since 1950: early sustained warming (1950–1975), highly variable warming and cooling (1975–2000), a short cooling period (2000–2015), and intense warming after 2015 that accelerated permafrost temperature increase, resulting in mean annual ground temperatures above -2 ºC at Papagal, SKO Station and Amsler observatories."

P2L42–43: Again, state the period over which the mean annual air temperature increase of 3.4±1.2 °C was recorded. Considering that mean annual air temperature can exhibit substantial variations from year to year, is it appropriate to use a single year as a baseline value?

Reply: The sentence was rewritten for clarity and the reference to a single year removed.

"An increase in mean annual air temperature (MAAT) of 3.4 ± 1.2 ºC since 1950 has been recorded at Esperanza Station"

P2L50: Change (Obu et al., 2020) to Obu et al. (2020).

Reply: Corrected.

P2L57–58: In the aims of the manuscript, be specific and clearly define the time frames for both the recent past and the future modelling periods.

Reply: The sentence was rewritten for clarity.

"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)*."*

P3L61–62: This previous study (Babtista et al., 2025) should be briefly described before the aims of the manuscript, so that the objectives follow logically from it. I think that, in this case, it disrupts the structure of the paragraph devoted to the aims.

Reply: The sentences were rewritten for clarity.

"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 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. 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)*."*

P3L76: Change (Thomas e Tetzner 2019) to (Thomas and Tetzner 2019).

Reply: Corrected.

P4L96: Considering the substantial warming trend, the mean annual air temperature could be reported for a shorter, more recent period to better represent current climatic conditions. Of course, this depends on your intentions.

Reply: In the revised manuscript, we now report the mean annual air temperature at Bellingshausen Station based on the climatological analysis of Turner et al. (2020), who report a MAAT of −2.1 °C for the 1981–2010 period.

"The climate is polar maritime with a MAAT of -2.1 ºC, recorded at Bellingshausen station (16 m a.s.l.) from 1981 to 2010, and annual precipitation of 534 mm, measured at King Sejong Station at 11 m a.s.l. from 2005 to 2019 (Baptista et al., 2024; Turner et al., 2020)*."*

P5L100–101: Rewrite the sentence "… the highest areas of Hurd Peninsula were deglaciated at 20 ka with most high interfluves becoming ice-free around 14-16 ka …" so that it is clear when these locations were actually deglaciated. Was it at 20 ka or around 16-14 ka?

Reply: The sentence was rewritten for clarity.

"With an ice-free area of about 20 km2, the deglaciation of Hurd Peninsula accelerated during the LGM at 20-18 ka with most high interfluves becoming ice-free around 16-14 ka. and the lower valleys around 7.5 ka."

P5L101: Change 14-16 ka to 16-14 ka.

Reply: Corrected.

P5L106: State the period for which the mean annual air temperature and mean annual precipitation are reported.

Reply: The sentence was changed based on the information published by Bañón et al. (2013).

" The climate is polar maritime, with a MAAT of -1 ºC and annual precipitation between 900 to 1000 mm, recorded at BAEJCI station (12 m a.s.l.) from 2002 to 2010 (Bañón et al., 2013; Fernández-Fernández et al., 2021).*"*

P5L115–116: State the period for which the mean annual air temperature and mean annual precipitation are reported.

Reply: Corrected.

"The climate is polar maritime, with a MAAT of -3.2 ºC, recorded at 50 m a.s.l., and annual precipitation ranging from 400 to 1100 mm from 1995 to 2013 (Wilhelm et al., 2016).*"*

P5L124–125: State the period for which the mean annual air temperature and mean annual precipitation are reported.

Reply: Corrected.

"Under a polar maritime climate, the MAAT is of -1.8 ºC at 8 m a.s.l., with annual precipitation ranging from 714 to 1410 mm from 1995 to 2013 (Wilhelm and Bockheim, 2017).*"*

P6L127–140: Move the whole section 3.1 to the section 2.2. The details on permafrost temperature and active-layer thickness at individual sites can be presented in the sections 2.2.1 to 2.2.4.

Reply: We appreciate your suggestion. We agree that the values of permafrost temperature and active layer thickness are useful for the study area description. Therefore, these values have been added to the subsections of Section 2.2. Regarding the detailed description of the permafrost network, borehole setup, and measurement depths, we prefer to keep this information in Section 3.1, as it is part of the Materials and Methods and is necessary to understand the subsequent analyses and results.

Section *2.2.1 Barton Peninsula, King George Island*:

"*In 2020, the King Sejong permafrost observatory, located at 127 m a.s.l., had an active-layer thickness (ALT) of 3 m and a mean annual ground temperature (MAGT) of −1.5 °C at 13 m depth.*"

Section *2.2.2 Hurd Peninsula, Livingston Island*:

"*In 2020, the Papagal permafrost observatory, located at 147 m a.s.l., had an ALT of more than 4 m and a MAGT of −0.7 °C at 4 m depth. The SKO Station, located at 25 m a.s.l., had an ALT of more than 8 m and a MAGT of 0 °C at 8 m depth.*"

Section *2.2.3 Cierva Point, Antarctic Peninsula*:

"*In 2020, the Cierva permafrost observatory, located at 187 m a.s.l., had an ALT of 6 m and a MAGT of −1.2 °C at 15 m depth.*"

Section *2.2.4 Amsler Island, Palmer Archipelago*:

"*In 2020, the Amsler permafrost observatory, located at 67 m a.s.l., had an ALT of more than 9 m and a MAGT of −0.2 °C at 9 m depth.*"

P7L151–152. This sentence on the calibration strategy is difficult to understand. Rewrite it even though it is partly obvious from the following text.

Reply: The sentence was rewritten for clarity. Additionally, in response to comments from Reviewers 2 and 3 regarding the division of the observational period for calibration and evaluation, it was updated accordingly.

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

P7L156: What is the geothermal heat flux of 50 mWm^-2 based on? Please cite the source.

Reply: Thanks for pointing this out. In the initial simulations, we used a geothermal heat flux value of 50 mW m^{-2}, following the implementation described by Westermann et al. (2023). We have re-run the long-term simulations used to derive the past and future estimates and used the geothermal heat fluxes derived from An et al. (2015) for each observatory, which are now described on the methods. The final result changes were minimal, but it is an important point for improved accuracy.

Section *3.2.2 Model calibration and evaluation:*

"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."

P7L157: What does the phrase "With the structure set, …" mean?

Reply: The structure relates to the employed configuration of the CryoGrid model, but we very much agree that it is not a good term and have rephrased the sentence for clarity.

"1D simulations were run with different configurations of mineral and water/ice relative volumetric content for each of the five boreholes."

P7L160: Is the supplement "… using a probe." necessary?

Reply: The supplement was removed.

P7L164: What do you mean by "relative volume fraction" here?

Reply: The term "relative volume fraction" was removed from the manuscript and replaced simply by the term "volumetric mineral/water/ice content". This value goes from 0 to 1, which is the same as 0-100%, expressing the percentage of the total volume occupied by each component.

"1D simulations were run with different configurations of mineral and water/ice volumetric content, that goes from 0 to 1, with correspondence to 0 and 100%, for each of the five boreholes."

P7L171: Indicate that Fub(t) is the energy flux into the uppermost grid cell. The rest of the variables (radiation and heat fluxes) would be better to describe after Eq. (1).

Reply: The sentence was rewritten following the suggestion.

"The energy flux into the uppermost grid cell ($F_{ub}(t)$) is calculated through Eq. (1):

$$F_{ub}(t) = S_{in}(t) - S_{out}(t) + L_{in}(t) - L_{out}(t) - Q_h(t) - Q_e(t) \tag{1}$$

where S_{out} and L_{out} are the outgoing short- and longwave radiation and Q_h and Q_e the sensible and latent heat flux."

P7L175: "The heat conduction based on Fourier's law is the main mode of heat transport in the subsurface." is too brief description of the subsurface heat transfer.

Reply: The sentence was further developed.

"The heat conduction based on Fourier's law is the main mode of heat transport in the subsurface and is calculated as:

$$j_{hc} = -K_h \frac{\partial T(e)}{\partial z} \tag{2}$$

where K_h [$Wm^{-1}K^{-1}$] is the thermal conductivity and temperature T is a function of enthalpy e."

P8L183: Change "phenomenologically" to "phenomenological".

Reply: Corrected.

P8L186: State also that you calculated p-value.

Reply: Corrected.

"As for the first phase, the validation of the surface energy model and snow factor were performed through the comparison between the estimated and measured ground temperatures for 2021 at 4 depths and the analysis of the four statistical measures (bias, r, p-value, MAE and RMSE)."

P9L219: I guess there should be "SPPs" in "The RCPs are used to represent 4 pathways…"

Reply: The sentence was complemented for clarity.

"The RCPs are used to represent 4 pathways of GHG emissions and atmospheric concentrations driven by population size, economic activity, lifestyle, energy used, land use patterns, technology and climate policy associated to SSPs (IPCC, 2014).*"*

P10L230: Note that the SPP5-8.5 scenario is now considered an extreme case that is rather implausible. You should point this out in the manuscript (here and in the discussion).

Reply: A reference was added to the sentence.

"SSP5-8.5: predicts a trend of human development with substantial investments in education and health, rapid economic growth, and functioning institutions, but based on intensive energy consumption and a fossil-based economy, in which global warming will range from 3 to 5 ºC. It is worth notice that this scenario has been recently consider as implausible due to the trends in the costs of renewables, the emergence of climate policy and recent emission trends (Van Vuuren et al., 2026)*"*

P10L235: Remove the word "models".

Reply: If it is the word "models" on line 232, we are referring to the models from CMIP6 designated as this on the documentation.

P10L243–245: Place this paragraph at the end of the whole section 3.3.2.

Reply: Corrected.

P10L253: I would remove "…in the selected PERMANTAR monitoring sites." because it is redundant here.

Reply: Corrected.

P11L258: The vertical resolution of the model is unclear from this: "… from 0.05 to 0.5 m, below 5 m depth." Revise it.

Reply: The sentence was rewritten for clarity.

"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."

P11L259: Specify the depths at which you calculated the mean annual ground temperature.

Reply: Corrected.

"These are used to calculate the MAGST and MAGT at 10 and 20 m depth. MAGT at 10 m depth provides an overview of near-surface thermal changes and their potential implications for surface and subsurface hydrology, biogeochemical fluxes, and geomorphological processes. MAGT at 20 m depth provides insight into long-term ground temperature conditions near the depth of zero annual amplitude."

P11L266–269: Rewrite this so it is more clear that you bias-corrected the period 1850–2100 from CMIP6 using the statistical relationships with ERA5 for the sub-period 1940–2020.

Reply: The sentence was rewritten for clarity.

"For this reason, we synthesized a model forcing time series from the site-corrected ERA5 records (referred to as ERA5 in the following), from 1940 to 2020, and monthly CMIP6 output, spanning the entire CMIP6 period from 1850 to 2100."

P12L300: Remove the sentence "In the figures, the x-axis spans the period 2000-2100."

Reply: Corrected.

P13L326: In Table 3, you should indicate that the thermal conductivity relates to the rock.

Reply: Corrected.

P14L354: In Fig. 2, the range seems to be somewhat smaller than -5 to 5 °C.

Reply: The range was presented in more detail.

"Temperatures fluctuate between positive (4 ºC) and negative (-3 ºC) values during DJF and MAM, and remain negative (0 to -5 ºC) during JJA and SON."

P16L364–380: In addition to the trends, present also the temperatures or their ranges. This is only done at three stations for TTOP and at all of them for MAGT. Report also the values and trends from the mean annual air temperature (and maybe snowfall if both are shown in Fig. 3).

Reply: The sentences were completed with estimated values for 1950 and 2020. References to the TTOP were removed.

"The simulation of ground temperatures since 1950 enabled the reconstruction of past permafrost temperature evolution, revealing a general warming trend in ground temperatures at all depths that follows the warming trend of air temperature (Fig. 4 and Table 7). Air temperature ranged from -5 to -3 ºC during 1950-1960, with a warming rate varying from 0.25 ± 0.03 ºC dec^{-1} to 0.36 ± 0.05 ºC dec^{-1}, reaching values between -3 to -1 ºC during 2010-2020. At the surface, most observatories showed a warming rate of 0.30 ± 0.04 ºC dec^{-1}, except for SKO Station, where a warming rate of 0.26 ± 0.04 ºC dec^{-1} was obtained. MAGST during 1950-1960 was estimated to range from -4 to -3 ºC, while during 2010-2020 it ranged from -3 to 1 ºC."

P16L381: In Table 4, specify the depth for the mean annual ground temperature.

Reply: Corrected.

P17L385: Fig. 3 has a misleading caption because snowfall and air temperature cannot be referred to as ground temperatures.

Reply: The words "of ground temperatures" were removed. 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)."

P18L388: In Fig. 4, I think it is a bit misleading to present the temperature for a single year 1950 because it was exceptionally cold. Is it appropriate to use a single year here, at least for the mean annual ground surface temperature, which has an instantaneous response to air temperature?

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.

P18–19L391–416: Check that it is clearly stated everywhere what temperature the reported trends refer to.

Reply: The sentences were reviewed accordingly.

P18L409: Rewrite the sentence "Despite continued interannual air temperature variability, MAGST fluctuated between -4 to -1 °C." which does not make complete sense.

Reply: The sentence was rewritten for clarity.

"During this period, MAGST ranged between -4 and 0 ºC, with a cooling rate around -0.47 ± 0.04 ºC dec-1. MAGT at 10 m depth, showed very small variations with values around -3 ºC at Cierva, -2ºC at Amsler, King Sejong and Papagal, and -1 ºC at SKO Station, experiencing a cooling rate of around -0.21 ± 0.06 ºC dec-1. At 20 m depth, the colling rate was minimal (-0.02 ± 0.02 ºC dec-1) with MAGT remaining constant."

P19L412: It is unclear what temperature the trend of 2.10±0.60 °C refers to.

Reply: Corrected.

"The final years of the series were marked by intense and rapid warming of air temperature (2.14 ± 0.12 ºC dec^{-1}) and a general decrease of snowfall, when compared to the previous period."

P19L423: You should rather write for 2020–2100. Trends should always refer to a period, not a single year. Additionally, it is unclear what the temperature trend of 0.59±0.22 °C refers to.

Reply: The sentence has been clarified, and the trends are now presented per decade for consistency.

"Under the SSP1-2.6 scenario, an average warming on air temperature of 0.07 ± 0.03 ºC dec^{-1} is projected for the Northwestern Antarctic Peninsula for the period 2020-2100."

P20L427: Change "… being the warming more pronounced at the …" to "… with more pronounced warming at the…"

Reply: Corrected.

P20L429: Remove "For most of the observatories, " Then, the sentence will make more sense.

Reply: Corrected.

P20L434–437: Maybe move this paragraph before the previous one. Definitely, it is better to start with the statement that all stations host permafrost at present, and then describe that it will warm and likely degrade or disappear at some of them.

Reply: Done as suggested.

P20L439: Again, it is unclear what the first trend of 2.59±0.20 °C refers to.

Reply: Corrected. All trends are now presented for the decade for consistency.

"Following the historical trend, the SSP2-4.5 scenario estimates a much stronger MAAT warming rate of 0.31 ± 0.02 ºC dec^{-1}."

P21L469–470: Change "At Cierva despite a warming rate of 0.51 ± 0.01 °C.dec-1 positive MAGT is projected…" to "At Cierva, despite a warming rate of 0.51 ± 0.01 °C.dec-1, positive MAGT is projected…"

Reply: Corrected.

P21L476: Table 5 has a misleading caption because it presents other temperature variables in addition to the mean annual ground temperature at 20 m.

Reply: The caption was changed.

"Change rates from the simulations of future temperature evolution on the PERMANTAR observatories from 2020 to 2100."

P22L480: Fig. 5 has a misleading caption because air temperature cannot be referred to as ground temperature.

Reply: The caption was changed.

"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)."

P24L505–509: The interpretation that ground temperature warming in the periods 1950–1975 and 2015–2020 was favoured by decreased snowfall and shorter duration of the snow cover contradicts former explanations that thicker and longer snow cover tends to warm the ground. Likewise, cooling simulated for 2000–2015 is difficult to explain by reduced snowfall.

Reply: Thicker and longer snow cover are well-known to be key controls in warmer ground conditions in the Arctic, as you point out. However, in very moist and cloudy environments, with low annual thermal amplitude (not very cold winters – mean monthly air temperature ~-5ºC and cool summers air temperatures ~+1ºC), such as the Maritime Antarctic, where permafrost is close to 0 ºC, the effect of snow insulation becomes key in the shoulder seasons and summer. It has been shown by various authors that the ground cooling period between 2000 and 2015 was associated with a progressive development and longer persistence of the snow cover, including during the thawing season (De Pablo et al., 2016; Ramos et al., 2017, 2020). As reported by De Pablo et al. (2016) for Livingston Island, persistent snow cover during summer can limit surface warming by increasing albedo and reducing the heat loss. In contrast, snow accumulation occurring early in the freezing season may favour warmer ground conditions because the snowpack acts as an insulating layer, reducing heat loss from the ground after the thawing season. Therefore, the thermal effect of snow cover depends not only on its thickness, but also on its timing, duration, and seasonal persistence.

We have revised the manuscript to emphasize that the observed ground temperature response is associated with the persistence and seasonal timing of snow cover.

"The cooling recorded between 2000 and 2015, together with increased snowfall that led to persistent snow cover during the thawing season that limited surface warming by increasing albedo and reducing the heat loss, produced a slight reduction in MAGT (<1 ºC) and temperature trends at 20 m depth ranging from -0.05 ± 0.02 ºC dec^{-1} to -0.01 ± 0.02 ºC dec^{-1}."

P24L513–514: Remove the first sentence in the section 5.2; it is redundant.

Reply: Corrected.

P24L516: Why are the periods 2000–2015 and 2016–2022 discussed in the section entitled "Future evolution of permafrost temperature (2022 - 2100)"?

Reply: They were there to better frame the results. However, we agree and removed the first period and kept the period 2016 to 2022.

"In the three CMIP6 scenarios, the evolution of the MAAT, MAGST and MAGT exhibit one similar period prior to the divergence into distinct warming trends. This period, from 2016 to 2040, is characterized by a rapid increase in temperature.

The initial years of this period (2016-2022) correspond to a phase of intensified warming marked by several warm weather episodes documented by (González-Herrero et al., 2022; Gorodetskaya et al., 2023).*"*

P25L532: Change "Under the more optimistic SSP1-2.6 scenario, …" to "Under the SSP1-2.6 scenario, …"

Reply: Corrected.

P25L539: Add "with values ranging from 1 to 2 °C in 2100."

Reply: Corrected.

P26L557: Specify to what depth the bias refers to.

Reply: Corrected.

"The bias calculated from measured and simulated ground temperatures at 4 depths (0.4, 1.2, 3.0, and maximum depth of borehole) was below 1 ºC"

P26L574: Change "In the worst-case scenario (SSP5-8.5), …" to "Under the SSP5-8.5 scenario, …"

Reply: Corrected.

P27L582: Change "thermokarst and landslide activity should increase" to "thermokarst and landslide activity will likely increase"

Reply: Corrected.

P31L666: Change "An historical period …" to "A historical period …"

Reply: Corrected.

P31L674: Change "improved coupled between" to "improved coupling between"

Reply: Corrected.

P31L679: Change “a RMSE of 1.33 °C. and a standard deviation” to “a RMSE of 1.33 °C and a standard deviation”

Reply: Corrected.

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