Reply to referee 1

We appreciate the time and effort spent on the revision of the manuscript "Modelling the evolution of permafrost temperatures and active layer thickness in King George Island, Antarctica, since 1950". 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

Reply to the major comments:

Line 130: The paper states that a "snow factor" of 0.3 is used, but this term is neither defined nor explained in the context of the CryoGrid Model. Clarifying its meaning would enhance reader comprehension.

Reply: The snow depth computed by the model class is based on variables from ERA5, which, due to its spatial resolution, may overestimate accumulation. A sentence was added to clarify the meaning of the snow factor.

"*The snow model represents transient snow density changes due to compaction and wind drift, as well as meltwater infiltration and refreezing. However, given the complexity of the topography at the represented sites and the spatial resolution of ERA5 variables, the model may overestimate or underestimate snow depth. To address this, the ERA5-derived snow is corrected by snow multiplication factor, which allows to phenomenologically increase of reduce the simulated snow depth to facilitate a better fit with observations (Martin et al., 2019). For the KSS permafrost observatory, a snow multiplication factor of 0.3 was used following the simulations for the validation of the surface energy balance model, where GST allows to define the intensity of the insulating effect and duration of the snow cover.*"

Line 132: The text repeatedly references ground column classes, such as "GROUND_freeW_seb_snow." If these classifications are included, they should be clearly explained for those unfamiliar with CryoGrid. Alternatively, consider removing them if they are not essential.

Reply**:** The class names were used in combination with a reference to Westermann et al. (2023), where the authors discuss the model application. The goal was to provide an exact reference to the class used for readers who may wish to apply this approach, particularly in the context of maritime Antarctica. In the revised version, a more detailed explanation was added in the section *3.3.2 Model parametrization*.

"For the sensitivity analysis to subsurface parameters, a one-dimensional model column, with 100 m depth was used, with temperature boundary condition (class "GROUND_freeW_ubT"). Measured GST was used as the upper boundary input, and a geothermal heat flux was applied as the lower boundary. In this class, water phase change occurs at 0 ºC, with the water an ice content remaining constant (Westermann et al., 2023).

All other simulations were performed using a 1D model column with the surface energy balance as upper boundary condition and again the geothermal heat flux as lower boundary condition (Westermann et al., 2023)."

Lines 179-182: The N-factor is introduced abruptly without explanation of its meaning or relevance. Table 1 also includes "Freezing N-factor" and "Thawing N-factor," but their significance is unclear. The authors should explicitly justify the inclusion of N-factors, possibly in the model description section.

Reply: The N-factors for the KSS observatory were calculated using measured temperatures, following the approach of Lunardini (1978). The objective was to characterize the ground thermal regime at the borehole, where a very low insulating effect was observed. Regarding the modelling approach, the N-factors were not used to simulate the TTOP.

To address the question raised, a new paragraph was added to Section *3.2 Ground Temperature Data from the King Sejong Station Permafrost Observatory*, explaining which parameters were calculated and the approaches followed.

"The Active Layer Thickness (ALT) at KSS was calculated by applying a logarithmic best fit to the maximum monthly temperatures at different depths allowing to identify the maximum depth of the 0 ºC isotherm.

The freezing and thawing periods were determined following the approach of Karunaratne and Burn (2004), in which the beginning of the freezing (thawing) period corresponds to the date when the mean daily air and ground surface temperatures remain consistently below (above) 0 ºC. Freezing Degree Days (FDD) and Thawing Degree Days (TDD) are defined as the absolute sum of mean daily air and ground surface temperatures below (above) 0 ºC during these periods (Klene et al., 2001; Smith and Riseborough, 1996).

Freezing N-factors are calculated as the ratio of the FDD of the ground surface (FDDs) to the FDD of the air (FDDa) (Lunardini, 1978). For the Thawing N-factor, TDD values are used. N-factors represent the insulating effect of snow on the ground. When close to 1, a strong thermal coupling exists between the ground and the atmosphere, whereas values below 0.5 indicate a high insulating effect."

Reply to the minor comments:

Line 20: … shoulder season. Please clarify which time period you really address.

Reply: We have replaced "shoulder season" with "during the thawing seasons".

Line 29: 70,000 km2. Please use superscript for km^2

Reply: We have corrected the error.

Line 33: The increase of the MAAT is 3.4°C. Please mention also the date and the original MAAT since the increase of MAAT has occurred. Please clarify.

Reply: The information regarding the initial MAAT was added with the addition of one more reference.

"In the Antarctic Peninsula this uncertainty is especially relevant considering the atmospheric warming trend since 1950, which led to an increase in the Mean Annual Air Temperature (MAAT) of 3.4 ºC (from -5.3 recorded at Esperanza Station in 1946), making the region a hotspot of climate change (Bockheim et al., 2013; Turner et al., 2020; Vaughan et al., 2003)."

Line 52-56: This is your validation strategy. Please make this clearer. The first hypothesis is a direct validation of your local borehole conditions, and the second hypothesis is an indirect comparison between MAAT values and your permafrost borehole observations. Therefore, the second hypothesis can only be fulfilled if the first hypothesis delivers acceptable results. Please clarify the explanation of the hypothesis.

Reply: The sentences were rewritten for clarity.

"Two hypotheses were tested: 1) The CCM stratigraphy can accurately represent the surface and sub-surface conditions at the King Sejong Station observatory, thereby incorporating detailed information that is missing from other models; 2) ERA5 data can reliably reproduce meteorological conditions at Barton Peninsula when used to force model simulations. For the validation of the first hypotheses, a sensitivity analysis to subsurface parameters was performed comparing measured and

simulated ground temperatures produced by simulations using different configurations. To validate the second hypotheses, a comparison between ERA5 air temperature and in situ observations was conducted."

Line 69: The MAAT mentioned here is -2.2°C for 1969 to 2022. If we calculate the warming rate of 0.09°C per year for the given time period then a warming of 4.77°C will result, which does not correspond to the value increase of MAAT of 3.4°C which is given in the introduction section? Please clarify.

Reply: The sentence was rewritten for clarity. The 3.4 ºC MAAT increase reported by Vaughan et al. (2003) was observed at Esperanza Station since 1946 in the context of the "regional climate warming" study in the Antarctic Peninsula. The value presented in the manuscript (0.02 ºC) was obtained for Bellingshausen Station, as it is the closest station to Barton Peninsula with available records in the Met READER database (Colwell, 2013).

"The Bellingshausen Station at nearby Fildes Peninsula recorded a Mean Annual Air Temperature of -3.8 ºC in 1969 and -0.8 ºC in 2022, with a warming rate of 0.02 ºC per year."

Line 75-78: In the first sentence you present different values for sea level (-0.9°C) and unglaciated peaks (-3.2°C) but in the next sentence you give values of -3.6 to-0.8°C not explaining on which altitudes these values for MAGST are measured. Please clarify. Please also mention in the paper at which altitude the borehole was drilled.

Reply: The sentence was rewritten for clarity. Concerning the study of Lim et al. (2022) the exact altitude of each site is not given. It is possible to understand the altitudinal range from a map that the authors presented with coloured contour lines. Regarding the borehole's altitude, on the section *3.2 Ground temperature data from the King Sejong Station Permafrost Observatory*, we detailed the site.

"Lim et al. (2022) recorded Mean Annual Ground Surface Temperatures (MAGST) from -3.6 (> 200 m asl) to -0.8 ºC (< 50 m asl) while evaluating the snow cover effect on near-surface ground temperature between December 2011 and January 2013."

Line 81-81: do you have a reference for this statement?

Reply: These were the main conclusions from the article mentioned on the previous sentences. However, to reinforce the origin of the statement, the reference was added to the end of the sentence.

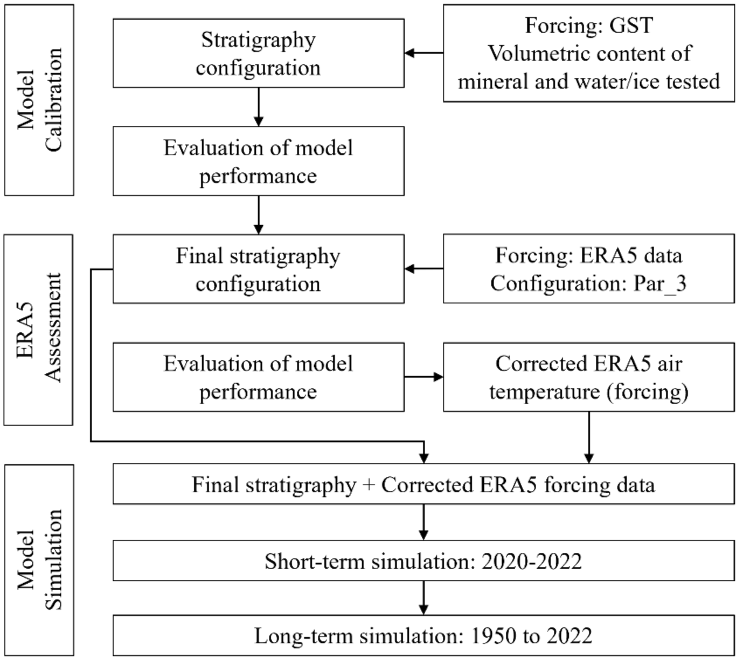
"The main controls on ground temperature regimes were elevation, snow cover duration, and potential solar radiation (Baptista et al., 2024)."

Line 89: This means that you have not a measured stratigraphy at the borehole site? When you did the drilling, you have not established a stratigraphy? Please clarify?

Reply: When the borehole was drilled, rock cores were collected for characterization. Moreover, a thermophysical analysis was performed, from which a conductivity value was obtained. However, in line 89, when we use the word *stratigraphy*, we are referring to the setup of the ground column for the model simulations. In this column, besides the main configuration derived from the rock core analysis, other smaller configurations are possible. However, their impact must be evaluated through a "model sensitive analysis to subsurface parameters".

Figure 3: I would like that you integrate the expressions like validation and calibration within your model workflow to make the overall understanding clearer.

Reply: We have changed the figure in the revised version of the manuscript.



Line 118, 127, 132: please explain these classes such as "GROUND_freeW_seb_snow" or remove it from the text because they do not explain the reader anything if youare not working with CryoGrid.

Reply: The sentences were rewritten for clarification.

Line 118 – *"For the sensitivity analysis to subsurface parameters, a one-dimensional model column, with 100 m depth was used, with temperature boundary condition (class "GROUND_freeW_ubT"). Measured GST was used as the upper boundary input, and a geothermal heat flux was applied as the lower boundary. In this class, water phase change occurs at 0 ºC, with the water an ice content remaining constant (Westermann et al., 2023)."*

Line 127 – *"The seasonal snow cover was represented by a snow microphysics scheme following the Crocus model (Vionnet et al., 2012; Zweigel et al., 2021), again with surface energy balance as upper boundary condition (class "SNOW_crocus_bucketW_seb" in the CCM). The snow model represents transient snow density changes due to compaction and wind drift, as well as meltwater infiltration and refreezing. However, given the complexity of the topography at the represented sites and the spatial resolution of ERA5 variables, the model may overestimate or underestimate snow depth. To address this, the ERA5-derived snow is corrected by snow multiplication factor, which allows to phenomenologically increase of reduce the simulated snow depth to facilitate a better fit with observations (Martin et al., 2019). For the KSS permafrost observatory, a snow multiplication factor of 0.3 was used following the simulations for the validation of the surface energy balance model, where GST allows to define the intensity of the insulating effect and duration of the snow cover. Additionally, snowpack properties such as grain size are computed which affect the snowpack parameters like the albedo."*

Line 132 – *"The ground column was represented by the class "GROUND_freeW_seb_snow" in the CCM (Westermann et al., 2023), using a vertical grid resolution ranging from 0.05 to 0.5 cm and an albedo of 0.3 following Kim et al. (2006). In this class, the phase change of water again occurs at 0 ºC and the water and ice contents remain constant, but the surface energy balance is applied to simulate energy exchange processes between the atmosphere and the model's first grid cell (Westermann et al., 2023). The heat conduction is the main mode of heat transport in subsurface."*

Line 130: what means a 'snow factor of 0.3'. Please clarify.

Reply: The snow factor represents the percentage of the total snow given. It is used to adjust the snow depth in the simulation and to correct overestimation or underestimation. See also the detailed explanation in major comments section, line 130.

Line 134: jhc please use subscript j_{hc}.

Reply: Corrected.

Line 179-182: Here the authors suddenly introduce the N-factor. It was nowhere before presented in the paper. Please read my content about the N-factors mentioned above.

Reply: To address the comment, a new paragraph was added to Section *3.2 Ground Temperature Data from the King Sejong Station Permafrost Observatory*. See also the detailed explanation in major comments section, line 179-182.

"Freezing N-factors are calculated as the ratio of the FDD of the ground surface (FDDs) to the FDD of the air (FDDa) (Lunardini, 1978). For the Thawing N-factor, TDD values are used. N-factors represent the insulating effect of snow on the ground. When close to 1, a strong thermal coupling exists between the ground and the atmosphere, whereas values below 0.5 indicate a high insulating effect."

Line 180: FS and TS are not officially introduced in the text, please define it at the first place in the text and then afterwards only use the introduced abbreviation.

Reply: The abbreviations are now introduced on the section *4.1 Air and ground temperatures at the King Sejong Station Observatory*. However, are used only on the figure 13 to improve readability.

"During the freezing season (FS) of 2020, intense ground surface cooling was observed due to lower air temperatures, that averaged -3.3 ºC, with daily lows reaching -20 ºC. This, combined with strong thermal coupling due to a thin snow cover (N-factor = 1), resulted in 970 FDDs (Table 1). In the freezing season of 2022, air temperatures did not fall below -15 ºC, leading to a lower number of FDD (589) and an N-factor of 0.9, indicating weaker thermal coupling between the surface and atmosphere. For the thawing season (TS) of 2020/2021, the average air temperature of 1.2 ºC was slightly higher compared to the thawing season of 2021/2022 with 1.0 ºC. This was also reflected in the TDDs, which decreased from 251 in 2020 to 207 in 2021. Despite this, the N-factor increased from 1.7 to 1.9 over the period, suggesting improved thermal coupling."

Figure 5: Please show air temperature, and borehole temperature in 0.02, 0.4, 1.2, 2.0 m depth in one figure and 3 to 13 m depth in another figure with different axis to better show the variabilities.

Reply: We have changed the figure in the revised version of the manuscript.

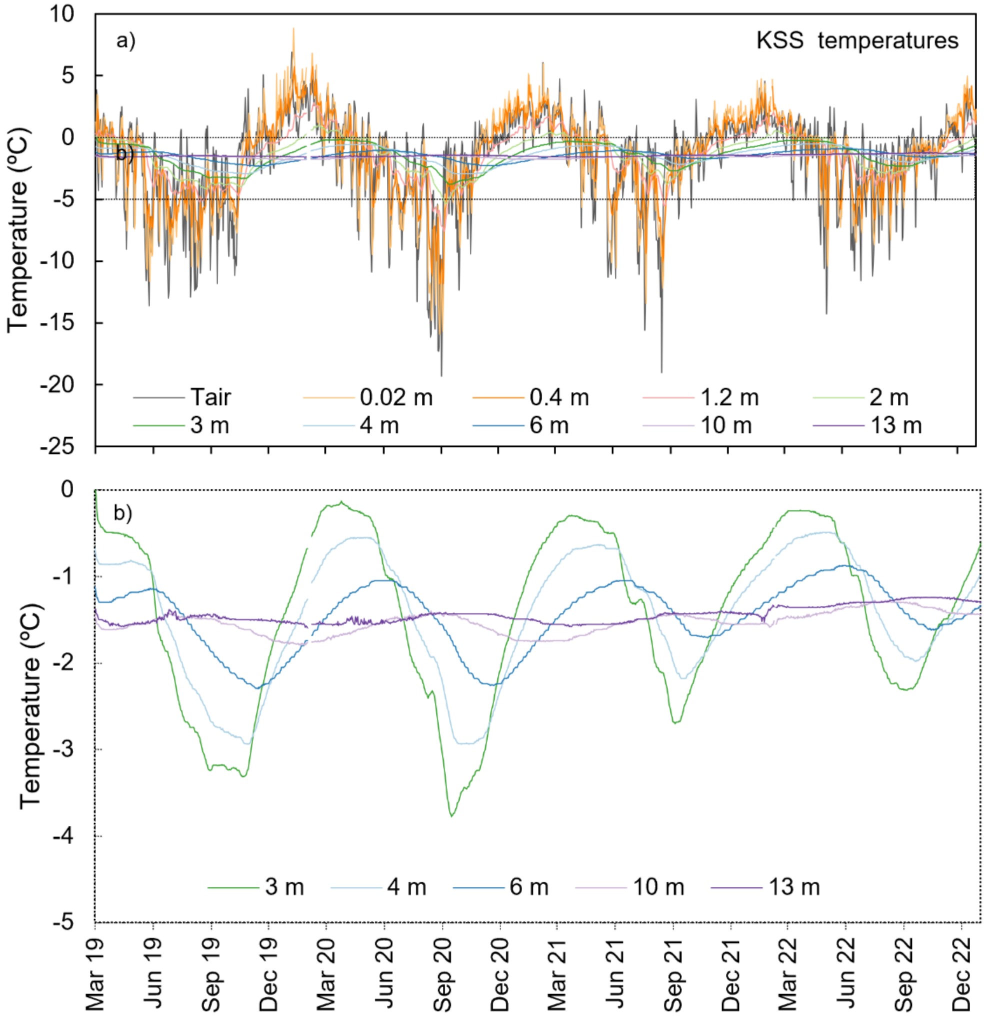
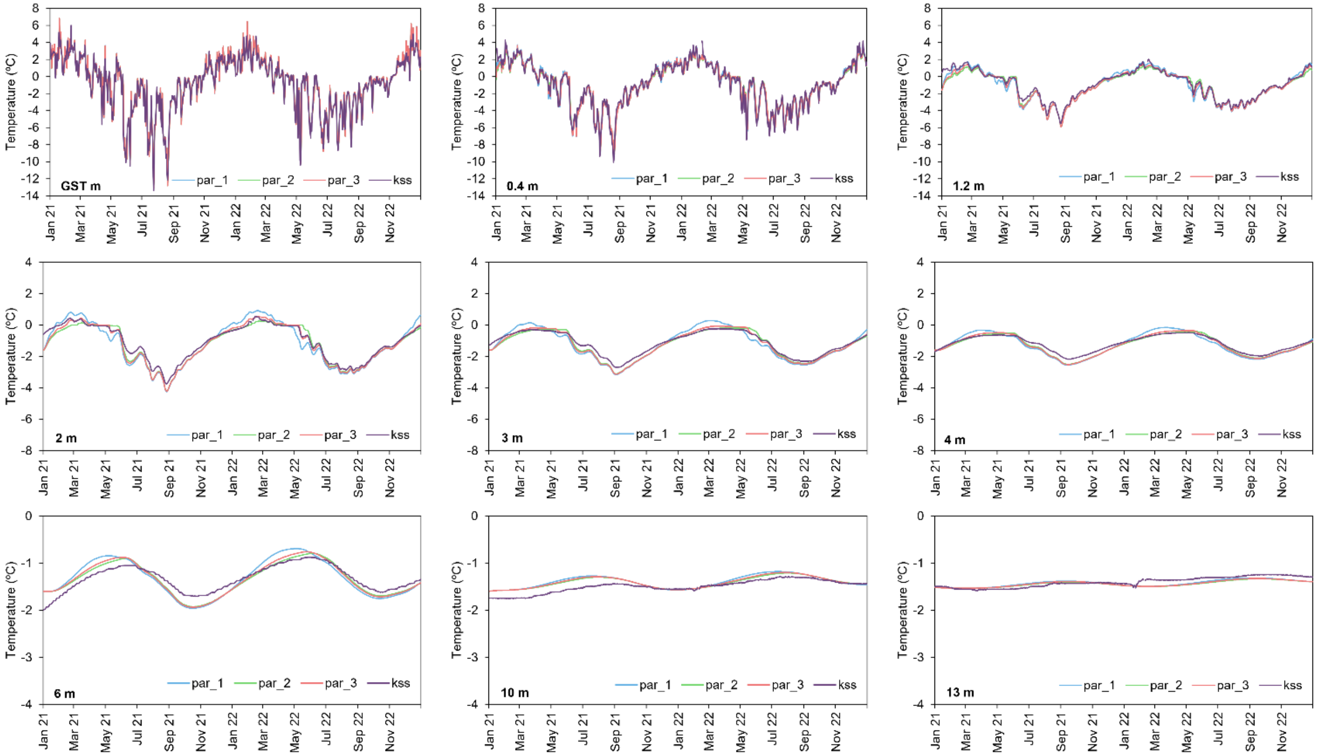


Figure 6: Please use other scale of the y-axis to see the variabilities of the borehole temperatures within 6, 10 and 13 m better.

Reply: We have changed the figure in the revised version of the manuscript.

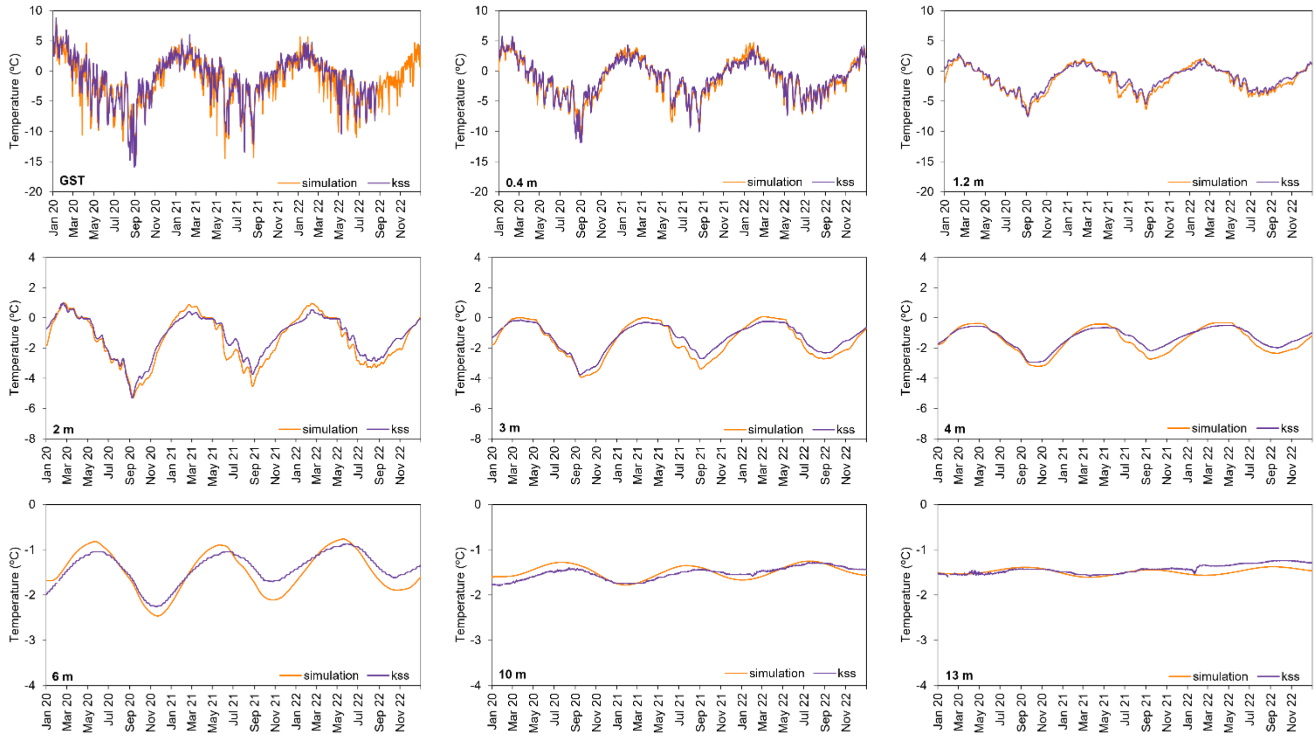


Line 247: Only ground temperatures measurements are validated in this chapter, which is ok. However, there is no validation of any surface energy balance variables as you have not measured them. Therefore, please change the title here to Validation of ground temperatures based on the model results.

Reply: The surface energy balance model is the designation used for the model version applied.

Figure 8: Please use other scale of the y-axis to see the variabilities of the temperatures within 6, 10 and 13 m better.

Reply: We have changed the figure in the revised version of the manuscript.



Line 325: Please remove the word ‘thin’ as it is always a relative statement here and just focus on the real value of 1.6 m.

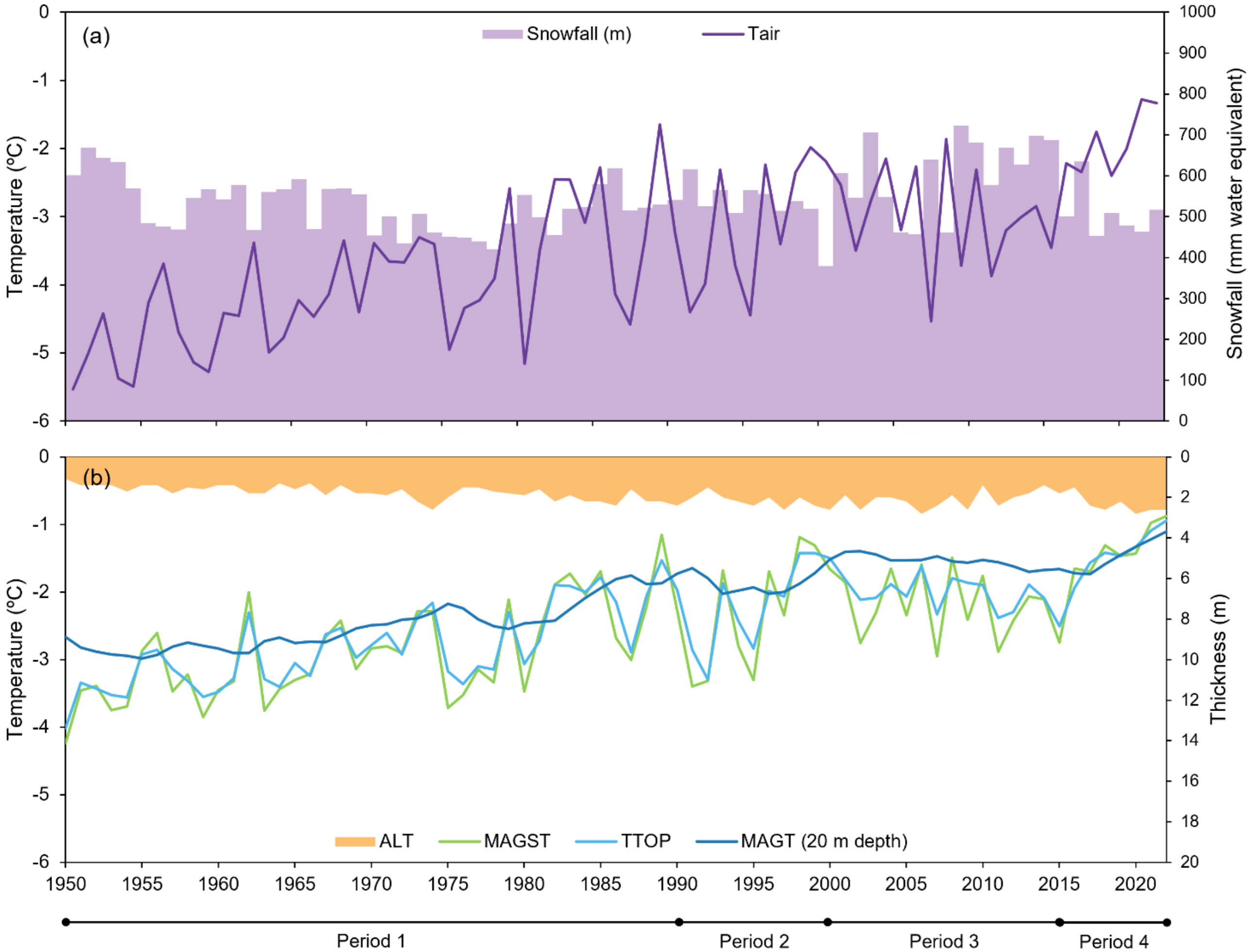
Reply: Corrected.

“Period 1 (1950 – 1990): This period begins with the lowest MAGST and TTOP values of the series, around -4 ºC, and an ALT of 1.6 m.”

Line 326-327: I do not understand this sentence: what means snowfall with a decrease from 15 m to 13 m? Please clarify.

Reply: The sentence was rewritten following the correction of the values presented on figure 12.

“The snowfall shows the opposite trend, with a slight decrease of precipitation from 602 mm water equivalent in 1950 to 541 mm water equivalent in 1990.”



Line 341: Maybe the word 'intensity' is better than the word 'severity'.

Reply: The word "severity" was replaced by "intensity".

"Concerning the freezing and thawing seasons, which contribute to the characterization of the four periods, a general trend of intensity decrease is observed for the freezing season, while the opposite trend is evident for the thawing season (Figure 13).

In the initial period (1950–1990), the interquartile range (IQR) for ground surface intensity was between 1090 to 1407 FDD. By contrast, in the most recent period (2016–2022), the intensity decreased, with an IQR ranging from 638 to 836 FDD, *alongside with a narrowing of the range between minimum and maximum values. The freezing season duration showed no clear trend in the first three periods, with an IQR of 230–290 days, but decreased to 207–232 days in 2016–2022 (Fig. 13b). In contrast, the thawing season demonstrates an increase in intensity. During the initial period (1950–1990), the IQR was between 137 to 222 TDD. In the final period (2016–2022), this range increased, with an IQR between 262 to 346 TDD (Fig. 13c). While thawing season duration showed no trend initially, with IQR spanning from 68 to 150 days, it extended to 138–154 days during the 2016–2022 period (Fig. 13d).”*

Line 364-365: I do not fully understand this sentence. If you had more snow in spring and early summer it would actually protect permafrost thawing as at the time during the year when you have the highest shortwave incoming radiation and there is still snow on the surface, the energy is used to melt the snow and not to heat up the surface ground cover. Therefore, it is not clear what you want to express with this sentence? Please clarify.

Reply: The impact of atmospheric rivers on the Antarctic Peninsula has been recently studied, and the latest publications refer to both snowfall and rainfall events. The impact of snowfall becomes problematic when it occurs later in the thawing season or summer, as the ground surface temperature is rising and the ground has already begun to thaw, since causes sudden insulation. If this snow persists longer during the freezing season, the surface is not exposed to cooling, as it remains insulated by the snow.

“These warm episodes are linked to the formation of atmospheric rivers, which transport heat and moisture from the Southern Ocean at lower latitudes (Gorodetskaya et al., 2023; Zou et al., 2023). In the coastal areas of the Antarctic Peninsula, such events can cause intense snowfall (later in the thawing season) or rainfall, and combined with warm temperatures, they have a direct impact on snow cover melting and ground temperature (Bozkurt et al., 2022; Gorodetskaya et al., 2023). Consequently, in ice-free areas, these events can affect the extent and duration of snow patches with insulating effect and intensify surface warming, particularly due to excessive summertime shortwave radiation associated with warm anomalies (Bevan et al., 2020; Bozkurt et al., 2022), while the effect of warm rainfall water advection has not been yet accounted for.”

Line 423: change: for permafrost since inhibit to distinguish

Reply: Corrected.

References:

Baptista, J. P.: Regime térmico do solo e do permafrost na Península de Barton (Ilha de Rei Jorge, Antártida): características e fatores condicionantes, 1–197, 2021.

Bevan, S., Luckman, A., Hendon, H., and Wang, G.: The 2020 Larsen C Ice Shelf surface melt is a 40-year record high, Cryosphere, 14, 3551–3564, https://doi.org/10.5194/tc-14-3551-2020, 2020.

Bozkurt, D., Marín, J. C., and Barrett, B. S.: Temperature and moisture transport during atmospheric blocking patterns around the Antarctic Peninsula, Weather Clim Extrem, 38, 100506, https://doi.org/10.1016/j.wace.2022.100506, 2022.

Colwell, S.: Surface meteorology at British Antarctic Survey Stations, 1947-2013 (Version “1.0”) [Data set], 2013.

Gorodetskaya, I. V, Durán-Alarcón, C., González-Herrero, S., Clem, K. R., Zou, X., Rowe, P., Imazio, P. R., Campos, D., Santos, C. L.-D., Dutrievoz, N., Wille, J. D., Chyhareva, A., Favier, V., Blanchet, J., Pohl, B., Cordero, R. R., Park, S.-J., Colwell, S., Lazzara, M. A., Carrasco, J., Gulisano, A. M., Krakovska, S., Ralph, F. M., Dethinne, T., and Picard, G.: Record-high Antarctic Peninsula temperatures and surface melt in February 2022: a compound event with an intense atmospheric river, NPJ Clim Atmos Sci, 6, https://doi.org/10.1038/s41612-023-00529-6, 2023.

Kim, J., Cho, H. K., Jung, Y. J., Lee, Y. G., and Lee, B. Y.: Surface Energy Balance at Sejong Station, King George Island, Antarctica, Atmosphere (Basel), 16, 111–124, 2006.

Klene, A. E., Nelson, F. E., Shiklomanov, N. I., and Hinkel, K. M.: The N-factor in Natural Landscapes: Variability of Air and Soil-Surface Temperatures, Kuparuk River Basin, Alaska, U.S.A., Arct Antarct Alp Res, 33, 140–148, https://doi.org/10.1080/15230430.2001.12003416, 2001.

Lim, H. S., Kim, H. C., Kim, O. S., Jung, H., Lee, J., and Hong, S. G.: Statistical understanding for snow cover effects on near-surface ground temperature at the margin of maritime Antarctica, King George Island, Geoderma, 410, https://doi.org/10.1016/j.geoderma.2021.115661, 2022.

Lunardini, V. J.: Theory of n-factors, in: Third International Conference on Permafrost , 40–46, 1978.

Martin, L. C. P., Nitzbon, J., Aas, K. S., Etzelmüller, B., Kristiansen, H., and Westermann, S.: Stability Conditions of Peat Plateaus and Palsas in Northern Norway, J Geophys Res Earth Surf, 124, 705–719, https://doi.org/10.1029/2018JF004945, 2019.

Smith, M. W. and Riseborough, D. W.: Permafrost monitoring and detection of climate change, Permafr Periglac Process, 7, 301–309, https://doi.org/10.1002/(SICI)1099-1530(199610)7:4<301::AID-PPP231>3.0.CO;2-R, 1996.

Turner, J., Marshall, G. J., Clem, K., Colwell, S., Phillips, T., and Lu, H.: Antarctic temperature variability and change from station data, International Journal of Climatology, 40, 2986–3007, https://doi.org/10.1002/joc.6378, 2020.

Vaughan, D. G., Marshall, G. J., Connolley, W. M., Parkinson, C., Mulvaney, R., Hodgson, D. A., King, J. C., Pudsey, C. J., and Turner, J.: Recent rapid regional climate warming on the Antarctic Peninsula., Clim Change, 60, 243–274, https://doi.org/10.1023/A:1026021217991, 2003.

Vionnet, V., Brun, E., Morin, S., Boone, A., Faroux, S., Moigne, P. Le, Martin, E., and Willemet, J.-M.: The detailed snowpack scheme Crocus and its implementation in SURFEX v7.2, Geosci Model Dev, 5, 773–791, https://doi.org/10.5194/gmd-5-773-2012, 2012.

Westermann, S., Ingeman-Nielsen, T., Scheer, J., Aalstad, K., Aga, J., Chaudhary, N., Etzelmüller, B., Filhol, S., Kääb, A., Renette, C., Schmidt, L. S., Schuler, T. V., Zweigel, R. B., Martin, L., Morard, S., Ben-Asher, M., Angelopoulos, M., Boike, J., Groenke, B., Miesner, F., Nitzbon, J., Overduin, P., Stuenzi, S. M., and Langer, M.: The CryoGrid community model (version 1.0) – a multi-physics toolbox for climate-driven simulations in the terrestrial cryosphere, Geosci Model Dev, 16, 2607–2647, https://doi.org/10.5194/gmd-16-2607-2023, 2023.

Zou, X., Rowe, P. M., Gorodetskaya, I., Bromwich, D. H., Lazzara, M. A., Cordero, R. R., Zhang, Z., Kawzenuk, B., Cordeira, J. M., Wille, J. D., Ralph, F. M., and Bai, L. S.: Strong Warming Over the Antarctic Peninsula During Combined Atmospheric River and Foehn Events: Contribution of Shortwave Radiation and Turbulence, Journal of Geophysical Research: Atmospheres, 128, https://doi.org/10.1029/2022JD038138, 2023.

Zweigel, R. B., Westermann, S., Nitzbon, J., Langer, M., Boike, J., Etzelmüller, B., and Schuler, T. V.: Simulating Snow Redistribution and its Effect on Ground Surface Temperature at a High-Arctic Site on Svalbard, J Geophys Res Earth Surf, 126, https://doi.org/10.1029/2020JF005673, 2021.