General Response to Reviewer 2

We would like to sincerely thank Reviewer 2 for their thoughtful and constructive feedback on our paper. In response to their general comments, we have made several revisions to improve clarity and conciseness. Specifically, we have shortened the text in the introduction and methodology sections and have relocated or condensed parts of the results section to reduce excessive qualifying language. In cases where we felt the original text provided important context, we have retained it within the results section rather than moving it to the discussion.

We agree with the reviewer that the ENSO and PDO are related but operate on different timescales. The manuscript provides a general summary of how these phenomena may affect ground temperatures, citing recent research on climate change and the Central Chile Megadrought. We also acknowledge the importance of the Southern Annular Mode (SAM) on precipitation and snow cover. Its exclusion was unintentional, and we have now added a brief description of SAM's influence in both the introduction and discussion.

We appreciate the reviewer's perspective on readability and suggestion to reorganize the results in Section 4 by choosing either site number or surface morphology, rather than both. However, we have chosen to retain both approaches, as we believe this structure is important for conveying the relationships (or lack thereof) among the data both in the context of latitude (i.e. site number) and geology/morphology. Additionally, this approach supports later discussions on the relationships with ground temperature and highlights the uniqueness of rock glaciers in the dataset. Our responses to Reviewer 2's detailed comments are provided individually, as summarized in the text below.

Reviewer 2 Detailed Reviewer Comments & Author Responses

Line 16: change to "(i.e., 3600 m to 5250 m)"…following the methodology section

Author Response: Thank you for the comment. The boundaries of some project areas include areas up to 5,500 m in elevation; but as you correctly point out, the boreholes are installed only as high as ~5,250 m. Text revised accordingly.

Line 17-18: I didn't see any borehole at 34° S. I suggest adjusting the latitude range to 27° - 33° S

Author Response: Thank you for the comment. The property boundaries of some of the projects extend to 34° S. However, the location of projects shown on Figure 1 represent the approximate centres of project boundaries, and not necessarily positions of the boreholes. While we are unable to share the exact coordinates of the boreholes, some of them are indeed located closer to 34° S, so it is most accurate to keep the boundaries as presented.

Line 69-72: could be just "Despite…. monitoring boreholes". In a different paragraph, you may detail why the "challenges remain"

Author Response: Thank you for the comment. We revised this paragraph in response to Reviewer 1's comments on L60-74 to make it more concise. However, we believe it's still important to first mention the common challenges faced in the northern hemisphere before transitioning to the specific issues in the Andes. Therefore, we have retained the mention of challenges at northern hemisphere sites in the current paragraph. The revised text now reads:

> *"However, assessing long-term changes in response to climate warming remains challenging at many locations due to sparse borehole distribution and short of discontinuous monitoring records. These challenges are often the result of site access difficulties, high installation and maintenance costs and the narrow focus of monitoring programs, particularly in mountain permafrost regions."*

Line 79: delete "Which make data extremely challenging to obtain"

Author Response: Please see our response to Reviewer #1's comment on this line. We have kept this part of the sentence, but revised to increase clarity. The text now reads:

"Despite a long-standing awareness of the existence of permafrost in the Andes (e.g. Catalano, 1926; Corte 1953), ground-based studies are scarce due to the region's high elevations, harsh climate and rugged terrain. Challenges such as limited funding and inadequate infrastructure for accessing remote locations further complicate data acquisition"

Line 84-86: you state two ideas in one paragraph "Consequently…below DZAA" and "limiting…is evident". Rephrase

Author Response: Thank you for the comment. We have revised the sentence to increase clarity. The sentence now reads as

> *"Consequently, monitoring records often lack the duration and depth required to discern average ground temperatures or trends in warming/cooling below the DZAA, limiting comparisons of the ground thermal state in the Andes with regions where permafrost degradation is evident."*

Line 103-104: could be just "The preliminary…5 m and 13 m depth at one location". The second part of your paragraph does not contribute at all

Author Response: Text revised accordingly.

Line 112-113: unnecessary details. The focus isn't on mining. You could be more general

Author Response: Thank you for the comment. We believe it is important to highlight what is currently driving data collection in the region and how research advancements may be facilitated through collaboration with parties already engaged in monitoring efforts. In many cases, this

involves mining, presenting an opportunity for productive industry partnerships. It is our opinion that it is appropriate to retain the original text, as it does not specifically mention mining, but rather the broader context of precious metals and natural resource development.

Line 113: "Site investigation" or "Minning sites". What is the focus of this paragraph?

Author Response: Thank you for the comment. The paragraph refers to general environmental assessments needed for natural resource development, not specifically mining. To clarify, we've revised the text to:

> *"Scientific investigations, often including the collection of ground temperature data in permafrost zones, are necessary to support environmental permitting and engineering designs."*

Line 117: "Semi-arid Central Andes"? to be consistent with the concepts. Is Central Andes or Semi-arid Central the central term?

Author Response: Thank you for the comment. While it is correct to use the qualifying term "semi-arid" it is not necessary in the context of this paragraph. Text has been updated accordingly.

In Fig 1: I wonder if A and D are necessary for the legend

Author Response: We agree that A and D are not necessary in the legend as neither equatorial or polar climates appear on Figure 1. Legend was updated accordingly.

In Fig 1: It would be great to know the year and authors who updated the Koppen-Geiger climate classification

Author Response: Koppen-Geiger zones are based om Kottek et al., (2006) for Argentina and Sarricolea et al., (2017) for Chile. We have updated the figure caption and added the citations to the list of references, which are:

> Kottek, M., J. Grieser, C. Beck, B. Rudolf, and F. Rubel, 2006: World Map of the Köppen-Geiger climate classification updated. Meteorol. Z., 15, 259-263. DOI: 10.1127/0941-2948/2006/0130.
>
> Sarricolea, P., Herrera-Ossandon, M. & Meseguer-Ruiz, Ó. (2017). Climatic regionalisation of continental Chile. *Journal of Maps, 13*(2), 66–73. https://doi.org/10.1080/17445647.2016.1259592.

Line 136-137: 2,000 mm as average annual precipitation is extremely high for the latitudes of your study site. Please check

Author Response: Thank you for the comment. The stated value of 2,000 m was incorrect and citation was incomplete. We have corrected the value to 500 mm and added the source Viale and Garreaud (2015)

> Viale, M. and Garreaud, R. (2015) Orographic effects of the subtropical and extratropical Andes on upwind precipitating clouds. Journal of Geophysical Research: Atmospheres, 120, 4962–4974.

Line 205: Then, how was the frequency of data collection expressed in the results? monthly average? Seasonal average?

Author Response: The data are generally expressed as monthly averages (e.g., Figure 5) and, in some cases, as annual averages or most recent measurements when sufficient data for averages were not available (e.g., Figures 9, 11, 12, 13). The supplementary information package includes raw data in time series, reflecting the frequency at which it was collected (e.g., hourly, daily).

Line 148-152: could be simpler. For instance: "Seasonal average temperatures at 4000 m range from XXX XXx in July (reference). Nevertheless, some rock extend at 3500 m (reference)"

Author Response: Thank you for the comment. We have simplified the text, which now reads as:

> *"With seasonal average temperatures ranging from ~18°C in January to ~8°C in July, permafrost will not form and is unlikely to exist in this zone; where it does exist, it is naturally degrading."*

Line 153-154: is contradictory with the previous sentence

Author Response: Thank you for the comment. We aim to convey that summer temperatures are above 0°C, while annual temperatures are not. To improve clarity, we have revised the text as follows:

> *"In contrast, the climate of the ET belt (elevations generally >4,000 m) is associated with low temperatures year-round and mean annual air temperatures (MAATs) below 0°C (Vuille et al., 2003; Garreaud, 2009), creating favourable conditions for permafrost formation. During the summer months (December to February), temperatures within the ET belt remain above 0°C, with daily highs exceeding 15°C and averages below 10°C. "*

Line 162-164: It sounds as discussion. Why talk about other mountain regions in your study area section?

Author Response: Thank you for the comment. We have adjusted the text and cited literature to be specific to the Andes. The text now reads as:

"Slight variations in altitude (usually spanning a few hundred metres) can generate marked differences in air temperature, precipitation, vegetation, snowpack, solar radiation, and glacial cover over short lateral distances (Arenson et al., 2022)."

Line 164-169: this could be just one phrase. Once you have presented all the topographic and climate background, you may state "topo-climate conditions in Central Andes favors a highly heterogeneous occurrence of permafrost in the region (Hilbich et al., 2022)"

Author Response: Thank you for the comment. These second sentence discusses the specific subsurface processes (i.e., infiltration, freeze/thaw and movement of air and water) influencing the heterogeneity of permafrost, which are induced by topo-climatic conditions. We have decided to retain the original text as it accurately reflects this distinction.

Line 173-176: Repeated. You already state that permafrost has heterogeneous occurrence

Author Response: Thank you for the comment. These lines discuss the distribution of permafrost in relation to slope orientation, not just the heterogenous occurrence of permafrost. We have decided to retain the original text as it accurately reflects this distinction.

Line 173: I suggest "the southern margin of our study area (32-33°S)…"

Author Response: Please see our response to comments on Line 17-18. It is most accurate to keep the southern boundary at 34° S.

Line 177-178: which several studies? Please, cite them

Author Response: Thank you for the comment. We have listed the studies at the end of the sentence.

Line 194-195: it is not necessary. I suggest deleting

Author Response: Thank you for the comment. Since Section 2 aims to describe the regional setting in relation to the permafrost thermal regime, we have decided to retain the reference. This text is relevant as it discusses climate and infiltration processes that directly influence the ground's thermal regime. However, in response to Reviewer 1's comment on Lines 176-195, the section has been shortened and made more concise.

Line 198-200: Re-phrase to something like "Ground temperature was monitored between the years 2006 and 2017 at eight sites located distributed near the Chile and Argentinean border (Fig.1)"

Author Response: Thank you for your comment. We aimed to clarify that the monitoring start dates varied within the given timeframe and did not all begin in 2006. The data for some locations extend to 2022 and continue to the present, with some locations still actively collecting data. We have revised the text as follows:

" Between 2006 and 2017, ground temperature monitoring was systematically initiated at eight industrial project sites located between 27°S and 34°S and within approximately 25 km of the Chile-Argentine border (Figure 1)."

Line 211-214: Re-phrase to something like "The duration of monitoring varies from less than a month to nine years. Several monitories had interruptions that were attributed to climate/terrain factors (i.e., slope instability) and lack manutention". After this phrase, you must explain how to solve the gaps

Author Response: Thank you for the comment. We have updated the text as follows to improve clarity:

> *"The duration of monitoring varied by borehole, ranging from less than one month to nine years (Figure 2). Several locations experienced interruptions to data collection due to factors such as electrical storms, instrument malfunctions, inaccessibility for download or maintenance due to remoteness, adverse weather, slope instability and/or changing regulatory requirements."*

We discuss how the gaps were solved in Section 3.2.

Line 214-216: It is not necessary. Perhaps keep "A comprehensive discussion of data collection is included in section 3.2"

Author Response: We appreciate the comment, but think it is important to introduce the challenges of data collection in a general sense, before going into detail in Section 3.2. We have therefore decided to keep the text as-is.

Line 218-220: It is not necessary. I suggest deleting

Author Response: Thank you for the comment, which we addressed in combination with a similar comment by reviewer 1 (RC1 Comment L222-L225). As a result, we have significantly reduced the discussion of permafrost presence in this part.

Line 227-228: Needs to be relocated after you describe the existence of "gaps" (i.e., line 211-214)

Author Response: Thank you for the comment. This is addressed as part of our response to comments on Lines 211-214.

Line 235: It is not necessary. I suggest deleting

Author Response: Adapted text accordingly.

Line 238-241: must be shortened

Author Response: Thank you for the comment, text was simplified and now reads as

> *"Challenging terrain, remoteness, and lack of financial support can limit site access, leading to poor instrument maintenance and data loss. Other factors affecting ground temperature monitoring unrelated to mountainous regions may include instrument damage by wildlife, vandalism, construction, or damage during instrument installation."*

Line 242-251: must be shortened

Author Response: Thank you for the comment. The text was simplified and now reads as:

> *"Many of these challenges were encountered across the study area, with most interferences or malfunctions identified by field staff before analysis. The most common causes of data interruptions were battery power loss, faulty connections, or sensor failures between maintenance visits. Irregular funding for ground temperature monitoring based on specific project needs, led to inconsistent and unpredictable field work and maintenance schedules, making it challenging to perform routine upkeep (e.g., battery replacement of sensor repairs) proactively or in a timely manner."*

Line 255-259: It sounds like results. Relocate

Author Response: Thank you for the comment. We believe this information is appropriate for its current placement, as it describes the preparation of datasets and the rationale for discarding anomalous data before interpretation. We therefore propose to keep the text as-is.

Line 259-262: re-write to something like "Boreholes affected by drilling disturbances had less weight in the analyses". What do you mean with "weight"? clarify

Author Response: Thank you for the comment. We meant that these measurements were considered with caution, without applying a formal weighting scheme. The text now reads:

> *"Early measurements from Site 1 and other locations with approximately one year of data (i.e., boreholes 6 8 and 6-11, 7-4, 7-5 and 7-6) were treated with caution in the analyses, particularly those collected during the initial two to three months , as they are unlikely to represent average ground temperature conditions."*

Line 265-266: It is not necessary. I suggest deleting

Author Response: Thank you for the comment. We believe that discussing the changing landscape is integral to understanding monitoring conditions in mountain permafrost, as well as the communicating the unique challenges posed by industrial sites. These topics are of interest to the permafrost community, and therefore, we propose to retain these lines in the paper.

Line 266-270: It is part of the discussion

Author Response: Thank you for the comment. While we understand the reviewer's perspective, we believe that this section is more appropriately placed in the results, as it explains the rationale for discarding anomalous data prior to interpretation. Therefore, we propose to retain the text in place.

Line 275-286: It is part of results and/or discussion. You could erase these lines

Author Response: Similar to our response to feedback on Line 266-270, we propose to keep the text in its current placement as it describes site conditions and rationale around data processing.

Line 301: replace "goodness" by another term or re-write

Author Response: Replaced "goodness" with "quality".

Line 323-324: why does this reference to northern permafrost appear here? Move to discussion

Author Response: Thank you for the comment. The reference to the northern hemisphere is included to highlight the extensive research on permafrost warming and to provide a reference for our results. This reference helps contextualize our dataset within the broader body of permafrost research, which has clearly demonstrated the link between permafrost degradation and global climate change.

Our data from the Andes, on the other hand, do not (yet) show similar warming patterns, and a detailed analysis of warming trends or comparisons with northern hemisphere regions is not feasible in the discussion section of the paper due to the limited duration of our dataset.

Therefore, we propose to retain the text as-is in its current location, as it serves only to contextualize our findings without further discussion in the paper.

Line 330-342: Again, why do you refer to other permafrost regions in your results? Move to the discussion in a subsection called something like "thermal state of permafrost regions"

Author Response: Thank you for your comment. As mentioned in our response to the comment on Lines 323-324, we reference other permafrost regions to help contextualize our results within the broader body of permafrost research, without intending to discuss them in detail. Therefore, we suggest keeping the text in its current location.

In Fig 5 and 7: What do you mean with “Glacial Deposit”? moraines? are glacial deposits cryotic or non-cryotic features? Besides, please check the “@” in the label

Author Response: By Glacial Deposits we mean sediments left behind by a moving glacier in general, and this isn’t just limited to moraines. While glacial deposits can sometimes be cryotic features, in this dataset they are non-cryotic. We believe the "@" symbol in the label is a display error caused by the download process, and as such, we have not made any changes to the figures.

Fig 6: Move to discussion. It is valuable data. But not in your results

Author Response. Please refer to our response to the comment on Lines 323-324. Figure 6 is intended to serve as a point of reference of other studies for context only. Since we are not yet able to evaluate long term trends in the Andes data, we feel it is best to retain Figure 6 here alongside the results rather than being moved to the discussion section.

Line 354-355: why is this line not in the section methodology?

Author Response: As with Sections 4.1, 4.3, and 4.4, section 4.2 includes a brief description on how the plotted parameter was calculated. To streamline the text and avoid repetition, we opted not to include these details in the methodology. We therefore propose keeping the text as-is.

Line 367-369: It is not necessary. I suggest deleting

Author Response: Thank you for your comment. The high depth and variability observed in our boreholes within rock glaciers is not typical of rock glaciers in general—many rock glaciers in the Alps, for example, show relatively shallow permafrost depths. Additionally, this characteristic may not apply to all rock glaciers in the Andes, and our observation may be influenced by sampling location bias.

Since the observed depth variability is likely specific to the sites visited and not a general characteristic of rock glaciers, we prefer to retain the statement because it reflects the advanced degradation noted by the field team.

Line 369-371: Move to discussion (“Similar…atmospheric warming”)

Author Response: Thank you for the comment. We have shortened the sentence to avoid referencing long-term trends, but have not expanded on the idea in the discussion section. As noted in our response to the comment on Lines 323-324, we acknowledge it is not feasible to analyze long-term trends due to the limited duration of our dataset. We have also made clarifications throughout the paper to address this more clearly, which is why the idea has not been moved to the discussion.

Line 395-400: Move to discussion

Author Response: Thank you for the comment. We believe that the introductory sentences describing factors influencing profile shape provide helpful context for the results and are more appropriately placed in this section rather than in the discussion. We have edited the text to make it more concise. The text now reads:

> *"The temperature profile within a borehole is shaped by factors such as regional geothermal heat flux, lithology variations, local topo-climatic variations, and historical fluctuations in ground surface temperatures. These factors result in a wide range in ground temperatures (from approximately -7 to 7°C) and varied profile curvatures (Figure 9), reflecting the complex thermal landscape of the Andes."*

Line 402: I think section 4.3. starts here

Thank you for the comment. Please see our response to comments on Lines 395-400. The text has been edited for conciseness, but the introductory ideas have been retained for context.

Line 412-419: Move to discussion

Thank you for the comment. The text in this section has been edited and reduced for clarity, focusing on results and minimal interpretation.

Line 421-430: Move to discussion or present just as results

Thank you for the comment. The text has been edited in this section to present results only, with minimal interpretation.

Line 441: delete "may" and "some"

Author Response: Thank you for the suggestions, We have adapted the text accordingly.

Line 443-447: It sounds like methods. Move or delete

Author Response: Please see our response to comment on Line 354-355. A brief description of how the plotted parameter was calculated has been included here. To streamline the text and avoid repetition, we chose not to include these details in the methodology. We propose keeping the text as-is.

Line 468-472: Move to discussion or conclusion

Thank you for your comment. These lines are intended to describe the results presented in the figures, and we feel that this is best conveyed in this section rather than the discussion. Since the text focuses solely on the presentation of the results, without elaborating on their implications, we suggest leaving the text as is.

Line 476-478: Move to discussion

Thank you for your comment. In these lines, we are summarizing the results of the compilation and providing a brief remark on the uniqueness of rock glaciers. As mentioned in our previous response, we believe this is best presented in this section rather than the discussion, and we suggest leaving the text as is.

Line 495: move to the discussion

Thank you for the comment. The text has been shortened in this section to present results only, with minimal interpretation.

Line 532-534: re-write. I suggest something like this "This work provides temperature and depth permafrost data recovered from in situ measurements, evidencing XXX. Our findings contrast (or are coherent) with statistical methods…"

Author Response: Thank you for the comment. We have simplified the text; however, we have not discussed specific implications for permafrost distribution models developed by others. Our primary aim with this idea was to emphasize that in-situ data are now available to update or develop new models, whereas previously models were based solely on field observations and statistical methods used by other researchers. Our text now reads as:

> *"Another important implication of this work is that the data can be used to validate existing permafrost distribution models in the region, which were previously developed without any borehole temperature data (e.g., Arenson and Jakob, 2010; Ruiz and Trombotto, 2012). Additionally, having ground temperature data within permafrost and non-permafrost zones helps reduce the risk of site-selection bias towards permafrost presence, which can complicate evaluations of spatially distributed models predicting permafrost."*

Line 553: “medium”? Do you mean ground properties?

Author Response: Yes; we have adapted the text accordingly.

Line 579: Please check the reference of Schultz et al., 2012. That paper refers to the Arid Coastal of Chile (18-30° S)

Author Response: Thank you for the comment. This sentence has been removed in response to a comment from Reviewer #1 on L176-195 to reduce repetition. It is correct however that this paper refers to coastal Chile. We have indicated this in the text within Section 2, where the reference to the paper is made.

Line 593: would be great to recall the latitude when you cite Site 3

Author Response: Thank you for the suggestion. We have adjusted the text accordingly.