Dear Editor,

We would like to sincerely thank you for your thoughtful feedback, which has greatly improved the quality of our paper. We appreciate the time taken to review our responses to the reviewers' comments, as well as your additional suggestions and guidance. In response, we have further revised the manuscript to address the points raised and made editorial changes to improve both clarity and flow.

In response to your specific request regarding other studies, we have followed your guidance to further clarify which information was from previous studies in order to retain Figure 6 in place. Specifically, the main text now reads:

> *" Figure 6 includes representative long-term warming trends from other permafrost regions as documented in Smith et al. (2022). This includes continuous or "cold" Arctic permafrost (temperatures below -2°C, warming rates from ~0.04 to 0.11 °C/yr, monitored since the 1980s), discontinuous or "warm" Arctic permafrost (temperatures between -2° and 0°C, warming rates from~0.01 to 0.05°C /yr, monitored since the late 1970s to early 1980s) and mountain permafrost within the Swiss Alps (average: ~0.02 °C/yr, monitored since in the late 1980s to early 1990s)."*

We have also modified the figure caption to provide this added clarity, which now reads:

> *"Figure 1: Short-term ground temperature changes with time at 20 m depth in the Andes (this study), shown alongside long-term ground temperature trends compiled by Smith et al., (2022) in permafrost regions of the northern hemisphere (i.e., Cold Arctic, Warm / Sub-Arctic and Swiss Alps). The Andean estimates (n permafrost sites = 19; n non-permafrost sites = 9) are based on 2-9 years' worth of measurement and reflect short-term fluctuations in climate. Warming rates for other studies (n Cold Arctic Sites = 9; n Warm / Sub-Arctic Sites = 11; n Swiss Alps sites = 5) were derived from decadal / multi-decadal datasets and represent the effects of climate change. The terms "Cold Arctic permafrost" and "Warm/Sub-Arctic permafrost," from Smith et al. (2022), distinguish cold permafrost as below -2°C and warm permafrost as closer to 0°C. Estimates for the Andes sites are summarized in Table S1 with corresponding r^2 values."*

In response to your request for more specificity regarding changes made in response to Reviewer #1, we have included an updated point-by-point reply at the end of this document, with additions tracked in red text. Furthermore, we have provided an updated version of the manuscript with all reviewer suggestions and changes implemented.

Once again, we thank you and both reviewers for your invaluable feedback, which has significantly enhanced the quality of our manuscript. We appreciate your input and hope that these revisions meet your expectations.

Point-by-point Responses to Reviewer #1 with Detailed Text Adaptations

L10-11 – Suggested revision "…under climate change with International collaborative efforts to collate standardized permafrost monitoring data." (the rest of the second sentence is not necessary).

Author Response: Thank you for the comment. We have adapted the text in the abstract to limit background information, as per the reviewer's general comments. Discussion of standardized data is now only in the introduction.

L11-15 – Suggested revision "Compared to the Northern Hemisphere, there is a scarcity of ground temperature monitoring data in South America (Chile and Argentina). This has limited the understanding of thermal state and possible degradation of mountain permafrost.

Author Response: Thank you for the comment. This sentence has been revised as part of the general text reduction in the abstract. It now reads:

> *"A paucity of ground temperature data in South America has historically limited the characterization of the thermal state of permafrost in the Andes compared to other mountain regions."*

L15-19 – Suggested revision "…..to compile and examine ground temperature trends for mountain (3,500 m to 5,500 m elev.) permafrost regions of the Central Andes. Ground temperature measurements from 53 boreholes along a north-south transect at the Chilean-Argentine border (27°S-34°S) reveals similarities in ground temperature characteristics with other mountain regions. This includes…."

Author Response: Thank you for the comment. This text has been revised to be more concise and now reads:

> *"This study represents the first coordinated effort to compile and examine regional baseline conditions using ground temperature data from mountain permafrost of the Central Andes (3,500 m to 5,250 m, 27°S-34°S). Measurements from 53 boreholes along a north-south transect at the Chilean-Argentine border reveal ground temperature characteristics similar to other mountain permafrost regions, including high spatial and temporal variability, correlations with altitude and slope aspect, and distinct thermal attributes of rock glaciers".*

L21-22 – Suggested revision "…observations support the hypothesis that the thermal regime of the Central…….other permafrost regions." (end of sentence is no longer required)

Author Response: Thank you for the comment. The sentence was revised to be more concise and reads:

"Observations support the hypothesis that the thermal regime of the Central Andes is shaped by similar processes, a perspective that was previously lacking data support."

L22-24 – Delete sentence starting with "With the longest record.." and revise the next sentence "The high temporal variability observed in the short records (<9 years) likely reflects short-term...."

Author Response: Thank you for the comment. The sentence now reads:

"The high temporal variability observed in the short records (<9 years) reflects short-term microclimatic fluctuations and topo-climatic attributes unique to the Andean cryosphere."

L29-31 – The last two sentences may not be necessary or at least could be combined and shorter.

Author Response: Thank you for the comment. The text was condensed and now reads:*"This study highlights the need for ongoing ground temperature monitoring, and the critical importance of collaboration between industry, governments, and scientists to advance understanding of a key climate change indicator in a data-scarce region."*

L33-123 – The paper is not a review of global permafrost monitoring but focuses on filling a key regional gap in South America. The information on global monitoring efforts including GCOS, GTN-P etc. should be reduced. All you need to really say is that permafrost thermal state is a key indicator of permafrost change. Highlight that compared to the Northern Hemisphere where there is considerable monitoring there is a gap in South America and explain reasons why it should be addressed. Towards the end of the introduction L110-115 you describe the need for baseline permafrost information. This should come earlier as it gets lost in the lengthy discussion about global monitoring etc. You define a few acronyms in this section (e.g. GCOS, EIA) which are not used again in the paper or defined again when the terms are used. These acronyms can be deleted.

Author Response: Thank you for the comment. We have removed the discussion about global monitoring efforts and refocused the paragraph on the regional gap in South America and importance of addressing it. We also removed GCOS, GTN-P and EIA acronyms. The need for baseline monitoring data was mentioned earlier in the paragraph as suggested.

L34- warming and thawing of permafrost has been documented

Author Response: Thank you for the comment. The sentence now reads:

"Several studies have documented large-scale warming and thawing of permafrost in recent decades"

L45-50 – Be clear here that the active layer thickness refers to the thickness of the layer that freezes and thaws annually. This is not necessarily the same as the depth to the permafrost table particularly where permafrost is degrading and a talik has formed. The statement that the active

layer is the distance from the ground surface to DZAA is incorrect as the DZAA is largely found well below the permafrost table. It is probably better to reduce this paragraph and just give the standard definition of active layer and indicate that the permafrost temperature at DZAA (and why – filter out high frequency variation etc) is commonly used for tracking long-term change. Mentioning that the ground thermal regime and ALT are influenced by climate is fine as is mentioning that the active layer responds more to short-term variations in climate compared to deeper ground temperatures. Other information in paragraph is probably not necessary.

Author Response: We have removed the discussion of the 'thermally defined active layer' and streamlined the paragraph accordingly. The revised version now focuses on the standard definition of the active layer and highlights that permafrost temperature is measured at DZAA because it lies below the influence of seasonal variations, making it ideal for monitoring long-term changes. Additionally, we clarified the distinction between the active layer thickness and the depth to the permafrost table.

L60-74 – See comments above. This section could be reduced substantially. Make the key point that there are many sites in North America, Russia/Siberia and Europe with less monitoring in central Asia, Antarctic and South America. You may want to highlight monitoring in mountain regions here (European Alps) as conditions are likely more comparable to your study.

Author Response: Thank you for the comment. We have reduced and adapted the text. The paragraph now only briefly mentions the many sites in the northern hemisphere with less in Central Asia and the South.

L75 "– Revise to "The lack of ground temperature data…"

Author Response: Thank you for the comment. The sentence now reads:

> *"The lack of ground temperature data, especially at depths greater than a few metres, is particularly pronounced in South America, where permafrost regions are largely understudied compared to other regions of the world"*

L79 – revise to "…make data collection challenging (Areson…)"

Author Response: Text has been updated to increase clarity and flow. 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"*

L80 – suggested revision "While limited ground temperatures have been collected and analysed in the Andes (e.g. Trombotto.....), most instruments.... "

Author Response: Thank you for the comment. We have kept the text as-is because we believe it more effectively highlights the importance of the few studies that have been conducted, rather than focusing on the limited number of studies.

L89 – suggested revision "This lack of measurements in deep boreholes...:

Author Response: Thank you for the suggestion. We have revised the text as follows:

> *"This lack of deeper measurements has been acknowledged in a proposed permafrost national monitoring plan for Chile..."*

L91 – suggested revision "....of permafrost using boreholes..."

Author Response: Thank you for the comment: The text now reads:

> *"....which recommends long-term monitoring using boreholes extending to the base of permafrost."*

L93 – suggested revision "Some permafrost studies in..."

Author Response: Thank you for the comment: The text now reads:

> *"Some permafrost studies in....."*

L96 – revise to "..with annual increases in ALT by up to 25 cm" Note that layers have thickness rather than depth so you can refer to thickening of the active layer or deepening of the permafrost table.

Author Response: Thank you for the comment. The text now reads:

> *"....with annual increases in ALT by up to 25 cm."*

We have also revised text in other areas of the document to refer to thickening of the active layer or deepening of the permafrost table.

L95-98 – Combine sentences and reduce text "Monnier and Kinnard (2013) installed two boreholes with thermistor strings reaching 18-25 m depth in the upper Choapa valley of northern Chile."

Author Response: Thank you for the comment. The sentences were combined and the text now reads:

"Monnier and Kinnard (2013) reported findings from two boreholes with thermistor strings reaching 18-25 m in the upper Choapa valley of northern Chile."

L100 – replace "deep" with "thick"

Author Response:Replaced "deep" with "thick".

L100-101 – Revision suggested to combine sentences and reduce text "Preliminary data from three boreholes (20-40 m deep) installed at the Goldfields Salres Norte mining project Chile, indicated favorable conditions for permafrost between 15 and 13 m depth at one borehole (Atacama Ambiente, 2017).

Author Response: Thank you for the suggestion. The text now reads:

"Preliminary data from three boreholes (20-40 m deep) installed at the Goldfields Salares Norte mining project in Chile, indicated favorable conditions for the presence of permafrost between approximately 5 m and 13 m depth at one borehole (Atacama Ambiente, 2017)."

L104-105 – revision suggested "Although these other studies provide valuable…."

Author Response: Thank you for the suggestion, The text now reads:

"Although these studies provide valuable insights into the thermal state and changes to permafrost….."

L110-115 – The importance of adequate baseline permafrost information for informed engineering design and environmental assessment of resource development projects should be mentioned earlier in the introduction as this is a key reason for addressing the regional permafrost knowledge gap.

Author Response: Thank for the comment. We have adapted the text to introduce this idea at the beginning of the second paragraph in Section 1.

L115 – suggested revision "Valuable data are generated that can…"

Author Response: Thank you for the comment. We have revised the sentence for clarity and flow. The sentence now reads as:"*These investigations generate valuable data that can help assess the ground thermal regime in regions that have not yet been characterized and shared with the broader research community.*"

L119-120 – suggested revision "Temperature measurements were made available…"

Author Response: Thank you for the comment. The text now reads:

"Temperature measurements were made available to the authors by BGC Engineering Inc., with permission of the individual project owners."

L121 – revision suggested "…. site conditions to support…"

Author Response: Thank you for the comment. The text now reads:

"The data were accompanied by confidential field notes and reports detailing instrumentation and site conditions to support the interpretations presented."

L121-122 – suggested revision "All instrumentation was installed …" (EIA) can also be deleted as it is not used elsewhere in paper (where it is used you define acronym again so better to delete)

Author Response: Deleted EIA as suggested.

Table 1 – enlarge text

Author Response: text enlarged

L130 – Refer to Fig. 1 for location.

Author Response: Thank you for the comment. Reference to Figure 1 was added.

L137 – delete "also"

Author Response: "also" deleted.

L141 – revision suggested "The eight project sites are situated at high…."

Author Response: Thank you for the comment. The text now reads:

"The eight project sites in this study are situated at high altitudes,"

L142 – delete "also"

Author Response: "also" deleted.

L156 – "remotely sensed imagery"

Author Response: Thank you for the comment. The text now reads:

"Surface geomorphic indicators of permafrost in this belt, identified in the field and through remotely sensed imagery, include rock glaciers, gelifluction slopes, and patterned ground"

L157-158 – suggested revision "…and remains until spring…"

Author Response: Thank you for the comment. The text now reads:

"In both climatic belts, snow accumulates at high altitudes during winter and remains until spring."

L176-195 – This section is probably too long and you could consider reducing. Given the relatively short records and the period covered by the records, you should consider what is necessary here and what might be more useful in your discussion and interpretation of results. This would reduce some of the repetition. Provide a short description of long-term change and indicate influence PDO and ENSO have in the region.

Author Response: Thank you for the comment. As suggested, we have shortened the section to describe long-term changes and reduce repetition in the discussion. We have described the influence of PDO and ENSO as reported by climate change researchers, and introduced ENSO and PDO in a more general sense earlier in the paragraph. The repeated sentence in the discussion was deleted.

L197 – Change subheading to "3.1 Ground Temperature Data and Permafrost Presence" as this is a more correct description.

Author Response: Subheading changed to "3.1 Ground Temperature Data and Permafrost Presence".

L203 – Accuracy and precision of measurement system should be provided. Were data loggers used to for data collection or were manual readings made?

Author Response: We have provided the range of accuracy and precision of instruments. Most measurements were obtained with dataloggers, although occasionally manual measurements were collected. Text has been adapted to provide this detail.

L222-225 – If deep measurements below DZAA are available and temperature is below 0°C for most of the year, can you assume permafrost is present? Temperature changes are limited at these depths.

Author Response: Thank you for the comment. Yes, it is reasonable to assume permafrost is present based on these deeper measurements. Text was simplified at L222-225 and adjustments

throughout the manuscript were made to refer to the sites as either "permafrost" or "non-permafrost" (i.e., "possible permafrost" was changed to "permafrost").

L256-263 – I don't think you ever described the drilling methods used. Were fluids used which would cause significant disturbance compared to methods that don't require drilling fluids.

Author response: A combination of dry sonic and diamond drilling methods were used. The latter used fluids, which could further affect early temperature measurements. A description of drilling methods was added to the text, noting the locations that could be further influenced by fluids.

L264-268 – Was the gully related to drilling disturbance or natural processes? If natural processes, the measurements were not necessarily compromised because they reflect the changes that occur at the surface, both changes in climate change and disturbance (natural or related to human activities). Knowledge of changes in surface conditions however are critical to interpretation of the ground temperature data. Assuming the casing hasn't been affected yet, the temperature data would indicate that permafrost conditions are changing in the area.

Author Response: The gully formed due to two factors: 1) A platform was constructed to install the thermistor string at a site of a previous exploration drill hole, and loose fill was used for the platform. 2) The platform altered snowmelt runoff, concentrating it at the borehole location and forming the gully. Thus, the gully resulted from both the loose fill used for the platform and the redirected runoff. This explanation has been added to the text.

L283-285 – Are these data spikes or noisy data for short periods? We have observed spikes in our data which could be electrical influences (lightning etc.). (no revision expected, just a question)

Author Response: Thank you for your question. Spikes in the data can occasionally occur for brief periods, such as those caused by electrical storms or nearby construction activities affecting ground movement. While it is not always possible to correlate these spikes with specific events to filter out noisy data, field staff were occasionally able to identify disturbances and remove the affected data when the timing of such events was clear. In cases where the cause could not be reliably determined, the noisy data were retained in the record to ensure transparency.

L325-338 – See earlier comment regarding discussion of trends. It is good you added this explanation given you are making comparison of trends determined over short periods to those in Swiss Alps where some records greater than 2 decades (same for Arctic and sub Arctic). However, is it even valid to determine trends when record is only 2-3 years long? It is important to note that for some Arctic/sub Arctic boreholes the surficial conditions are quite different from your sites. In Canada especially, there can be thick glacial sediments (including those that are fine-grained silts/clays) with high moisture/ice contents where latent heat effects are important. Also, in circumpolar region there are frozen peatlands so thermal response will also be different from your

study sites. Comparisons to mountain permafrost regions is probably better to focus on or Arctic areas where finer grained material or peatlands are less likely. Here and in Fig. 6 reference is made to cold and warm permafrost. It might be useful to indicate how you are distinguishing between these.

Author response: Thank you for the comment. We agree that it is not valid to infer long-term trends from our datasets or any record shorter than a decade. We understand that the conditions of the sites and the quality of the data are different and a direct comparison should not be done. However, we still see value in reporting estimates from other sites for reference.

The main purpose of our discussion was to highlight the significant variability within the dataset (warming vs. cooling), reflecting local topoclimatic complexity and short-term climate fluctuations. Presenting our data alongside warming rates for other regions was intended to emphasize that any long-term trends might be overshadowed by these short-term effects, including periods of cooling in the short-term in the Andes.

We also aimed to show that short-term fluctuations at non-permafrost sites are more variable than permafrost sites, likely due to factors like latent heat effects or greater thermal insulation of the ground at permafrost sites.

Additionally, we intended to convey that northern hemisphere sites show unidirectional temperature changes as climate change indicators, whereas our sites cannot yet make this claim.

We also acknowledge that thermal response in circumpolar regions will differ, as peatlands and fine-grained materials behave differently than mountain permafrost. Our goal was not to provide an in-depth comparison of thermal responses across regions, but instead to note that well-established permafrost monitoring sites in the Arctic and Alps show consistent warming based on their multidecadal datasets.

The terms "cold permafrost" and "warm/sub-arctic permafrost" are directly based on Smith et al. (2022). In their study, the authors define cold permafrost as permafrost with temperatures below -2°C. To provide additional clarity, we have included further explanations of this terminology in Section 4.1 and the caption of Figure 6.

L350 – Fig. 6 – It would be useful to give the number of sites considered in each region.

Author Response: The number of sites considered in the Andes was added to Figure 6 and Figure 10. The number of sites documenting long-term warming rates from other permafrost regions (Arctic, Sub-Arctic and Swiss Alps, aster Smith et al., 2022) were also added to Figure 6.

L354 – ALT was defined earlier so the sentence can be revised to “ALT in cryotic…”. You might want to consult Riseborough (2008, ICOP) regarding using interpolation/extrapolation to determine ALT and the best approach to use.

Author Response: Thank you for the comment. We understand Riseborough's (2008, ICOP) points on extrapolating the zero-degree isotherm to estimate the active layer thickness (ALT) and agree

that this may be a more optimal approach. However, we lack sufficient measurements in the active layer to confidently extrapolate temperature data from above. Additionally, snow cover varies greatly at our sites. In areas with little snow, the active layer is not thermally insulated, and atmospheric gradients affect its temperature. In contrast, where snow is present, the permafrost table is influenced by the snow cover (e.g., BTS method by Haeberli, 1978).

Our main goal is to track potential changes and compare sites, which is best achieved using a consistent approach. Thus, we focus on relative comparisons rather than absolute ALT values.

We also acknowledge linear interpolation of the zero-degree isotherm may overestimate the active layer thickness, and, due to limited shallow data and variable snow cover, it should be considered a proxy, not the exact permafrost table depth.

We have adjusted the text to convey these ideas.

L369-370 – revision suggested "…overall increase in ALT over time…"

Author Response: Thank you for the comment. This section was edited for conciseness and to limit reference to long-term trends. The text now reads:

> *"There is no consistent increase in ALT over time across the dataset, and in some locations, the active layer may be shallowing."*

L369-372 – These results reflect short-term fluctuations in climate.

Author Response: Thank you for the comment. We have added text at the end of the sentence to indicate that these results reflect snort-term fluctuations in climate.

L373 – What is meant by deepening of permafrost? Referring to permafrost table or base? Be clear here.

Author Response: We are referring to the permafrost table, or top of permafrost. We have adapted the text to clarify, which now reads:

> *"In contrast, the top of permafrost is deepening in rock glaciers, at rates of approximately 0.4 m/yr at borehole 6-1, 0.8 m/yr at borehole 6-2 and 1.5 m/yr at borehole 6-4."*

L385 – Fig. 8. Is it possible to clearly delineate talik where it occurs so that it is clear to reader?

Author Response: Added labels to Figure 8 to indicate location of taliks.

L421 – Delete ""in this dataset"

Author Response: This text was adapted as part of editorial revisions to this paragraph. The sentence now reads:

> *"Potential exceptions to this are noted in rock glaciers at Site 6 (i.e., boreholes 6-2, 6-5, 6-8 and 6-11), which, as noted above, are characterized by shallow isothermal conditions near ~ 0°C then increasing temperatures with depth."*

L436 Fig. 9 – some symbols are difficult to see

Author Response: Thank you for the comment. We have increased the size of symbols on the figure.

L439 – I think this section is good and makes use of the deeper temperatures that are available to give an indication of changes over several decades depending on depth.

Author Response: Thank you for the comment. No adjustments made.

L482 – suggested revision "..decrease as elevation increases (Figure…."

Author Response: Thank you for the comment. The text now reads:

> *"Consistent with cooler temperatures at higher altitudes, both depth to permafrost and permafrost thickness decrease as elevation increases."*

L487 – Be clear if permafrost depth refers to permafrost table rather than base.

Author Response: We have adapted the text to clarify this point. The sentence now reads:

> *"Excluding rock glaciers, the depth to top of permafrost decreases by approximately 1.9 m/km elevation gain"*

L488 – suggested revision "..increase as altitude increases at…"

Author Response: Thank you for the suggestion. We have revised this sentence to shorten, and the text now reads:

> *"Excluding rock glaciers, the depth to top of permafrost decreases by approximately 1.9m/km elevation gain (r2 = 0.30), while permafrost thickness increases at approximately 300 m/km (r2 = 0.45)."*

L510-519 – This repeats information provided in the introduction and isn't necessary. You could start the section with line 520 and be clear that your study addresses a critical knowledge gap and then describe insights revealed etc.

Author response: Thank you for the comment. The first paragraph of S 5.1. was removed since the information was stated earlier. The following text was augmented to state that the study closes a critical knowledge gap in permafrost research in the region.

L525-526 – revision suggested "..allows for characterization of average ground temperature below seasonal influences and thermal gradients...."

Author Response: Thank you for the suggestion. We have adapted the text, which now reads:

> *"Adequate depth of monitoring throughout the dataset enables characterization of average temperatures below the DZAA"*

L534 – revision suggested "...without adequate ground temperature data..."

Author Response: Thank you for the suggestion, the text now reads:

> *"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"*

L562 – revision suggested "...of our sites in the Andes...."

Author Response: Thank you for the suggestion. The text now reads:

> *"At several of our boreholes in the Andes"*

L572-573 – Lewkowicz et al (2012) is also relevant here – uses ground surface temperature and ground temperature in the analysis to show the colder ground conditions in valley bottoms.

Author Response: Included Lewkowicz et al (2012) as a reference to the concept of temperature inversions.

L628 – You can make a stronger statement here by replacing "illustrated" with "confirmed"

Author Response: Replaced "Illustrated" with "confirmed"

L632 – "from other boreholes" can be deleted (or replace with "from other sites")

Author Response: Deleted "from other boreholes"

L687 – (EIA) can be deleted since you give the term

Author Response: Thank you for the comment. We have deleted "(EIA)"

L693 – Delete “(GCOS)” since you give the term

Author response: Thank you for the comment. We have deleted “(GCOS)”