Response to Editor and Reviewer Comments (egusphere-2025-2965)

We would like to thank the editor and two anonymous reviewers for their kind and thorough review of our manuscript. We appreciate the time and effort you have taken to provide feedback which we believe will significantly help improve the quality of the manuscript. Below, please find specific answers to each of the comments provided.

Response to comments from Editor

No.	Comment/Response
#1	**Comment:** Dear authors, Thanks for your responses. The attempts of reviewers for their good comments are also much appreciated. In the revised submission, please ensure that all promised changes are implemented, particularly the following ones: A) the analytical comparison (Stefan/modified Berggren) against measured thaw depth–time, B) an expanded discussion of boundary effects/non-1D thawing and associated limitations, and C) revised figures to remove or explicitly explain any interpolation artifacts and to clearly show sensor locations used for comparisons. **Response:** Thank you very much for taking the time to manage the review process for our manuscript. As outlined below, we have addressed the reviewers' comments in our revised submission. Specific to the particular promised changes: A. We have included a comparison between the measured temperature time histories and the 2-phase Stefan Condition, which we believe substantially improves the discussion related to boundary conditions and heat flux into the sample B. With the addition of the comparison with the 2-phase Stefan Condition, we have expanded the discussion of the boundary effects and how the experiments deviate from the desired one-dimensional thawing condition C. We have removed the contour plots since, as pointed out by Reviewer #2, they give non-physical stepping. In particular, the contouring in time does not make sense as a simple interpolation does not capture the physics of how the temperature changes over time. Instead, the comparison with the Stefan equation provides a more defensible approach to show how and where the 1-D thawing boundary conditions are violated.

Response to comments from Reviewer #1

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#1	**Comment:** The number and elevation of sensors in dense and loose sand samples are inconsistent. For valid comparison, sensors should be placed at the same elevations and in equal numbers across both sample types. Please clarify the rationale for the current setup. **Response:** Thank you very much for this comment. There were different numbers of sensors between the loose and dense samples due to the number of signal conditioners that were available at the time when tests were conducted. We only had 4 signal conditioners available for the loose test, so we decided to place the RTDs in such a way that we could capture the

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	temperature behavior near the boundaries and center of the sample. When the dense tests were conducted, we had procured additional signal conditioners so that we could get a broader spatial resolution of the time-varying temperatures within the sample. However, we did make sure to place sensors in similar locations compared to the loose tests so that we could have direct comparison between the dense and loose tests. The text included in the revised manuscript to describe this is included below: *The difference between the number of RTDs used between the two tests is based purely on the number of signal conditioners that were available at the time when tests were conducted, with more signal conditioners being available for the dense tests. However, care was taken to place RTDs in similar locations compared to the loose tests so that we could have direct comparison between the dense and loose tests.*
#2	**Comment:** In Figure 6, direct comparisons are made between samples with different sensor positions, which can affect the validity of the results. It is recommended to justify this approach clearly, or revise the figure and analysis to focus on results from consistent sensor locations, discussing the potential impacts of any inconsistencies. **Response:** Thank you for this comment. We acknowledge and agree with the reviewer's comment that this comparison should be based on sensors at similar locations to make valid comparisons. We have included an updated Figure 6 that compares sensors at the same locations. In the original comparison in Figure 6, the dense sample sensors at the top and center (RTD 21 and 20, respectively) were deeper compared to RTD 21 and 20 in the loose sample. This showed slower temperature changes in the dense sample compared to the loose sample. In the updated Figure 6, sensors at the same locations are compared (RTD 10 for the dense vs RTD 21 in the loose, and RTD 9 for the dense vs RTD 20 for the loose, location of RTD 18 is the same between tests). As shown in the updated Figure 6, this trend still holds and the discussion of soil density effects remains valid. The updated figure included in the manuscript is shown below:

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	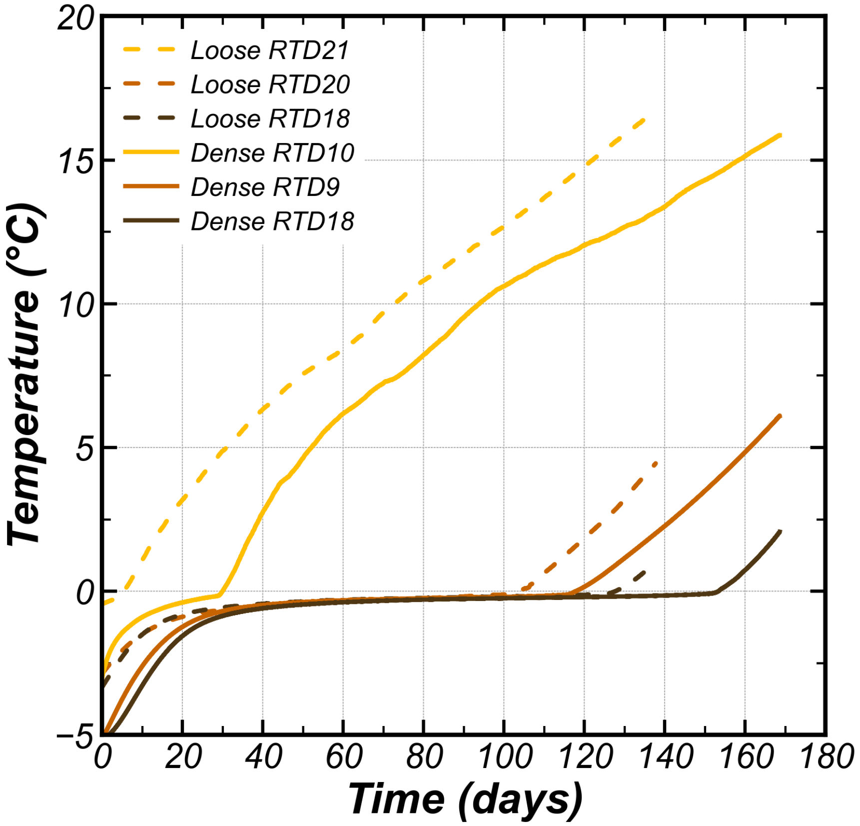 Similarly, Figure 4b was updated to show RTDs 10, 9, and 18 from the dense sample to compare thawing rates with those shown for the loose sample in Figure 4a. In this updated comparison, all sensors are at similar locations to make comparisons valid. The trends observed remain consistent with what was observed previously where the uninsulated samples show faster thawing from both the bottom and top of the sample, while the insulated case shows a 1-D thawing profile from the top downward. However, since the RTDs 10 and 9 are relatively closer to the surface of the dense sample compared to RTDs 20 and 21 (which were plotted in the previous Figure 4b), the timing of thawing in the updated Figure 4b occurs earlier. The updated Figure 4b in the manuscript is included below:

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	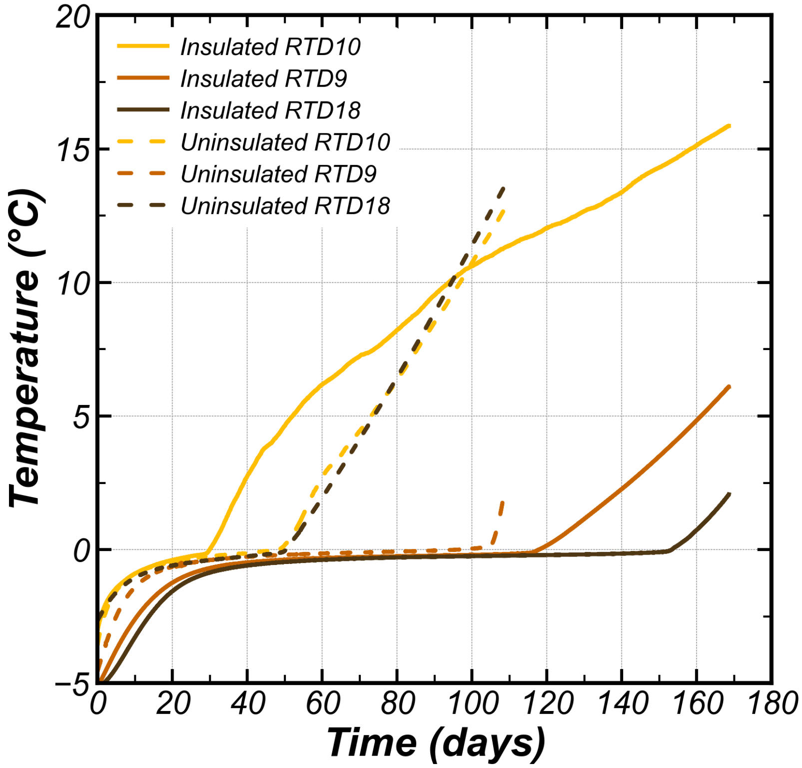

Response to comments from Reviewer #2

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#1	**Comment:** Physical testing in geotechnical and permafrost engineering holds substantial promise for advancing our understanding of complex subsurface processes. Laboratory-based physical modeling, especially under controlled conditions such as hypergravity, enables researchers and engineers to simulate and observe phenomena that are otherwise challenging to capture in the field under controlled conditions. Such testing provides invaluable data for validating analytical and numerical models, refining theoretical frameworks, and informing practical engineering solutions. The manuscript by Gardner et al. leverages these strengths and presents results that are very interesting to the readership of this journal. They really highlight the potential of hypergravity testing in cold regions engineering., However, several aspects of the manuscript could be improved to enhance clarity, rigor, and overall impact. **Response:** Thank you very much for this comment and taking the time to review our manuscript. We have addressed the aspects raised in your review to improve the clarity, rigor and impact of this work. Please see specific responses below.

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#2	**Comment:** The study presents an approach to investigating thawing rates in frozen sand using hypergravity. The uniform conditions established in the experiments offer an ideal setting for comparison with established analytical solutions, such as the Stephen equation and the modified Berggren equation. Incorporating a more detailed discussion on a comparison between model and analytical results would significantly strengthen the manuscript and add value for readers. Additionally, further elaboration on the impact of insulation—particularly at the bottom of the samples—would provide deeper insights into how to avoid boundary effects in future physical models. **Response:** Thank you for this comment. In terms of comparison with established analytical solutions, we agree that including this comparison would substantially strengthen the manuscript. We have included a comparison between the measured temperature time histories at different depths with the analytical solution to the 2-phase Stefan Condition. Additionally, this comparison has been paired with further elaboration on the impact of insulation as how this contributes to deviation between the analytical solution and the experimental results. As noted in the manuscript, we observed the introduction of heat into the soil container through small exposed portions near the surface of the container that introduced some heating throughout the entire container. We include relevant portions of the updated text and figures below: *Figure 5 shows a comparison between the two-phase Stefan Condition (as described by Equation 7) and the measured temperature time histories for the dense tests (both insulated and uninsulated). For this comparison, we calibrated the analytical solution to the measured values at RTD 21 for the insulated case as this sensor location best matches assumptions in the solution of Equation 7. The properties used for this sensor location are then applied to all other locations to evaluate the efficacy of the insulation and potential introduction of undesirable heat into the soil sample. In this preliminary testing, the impact of simply placing insulation around the sides and bottom of the aluminum container can be clearly seen when comparing the insulated (Figure 5a) with the uninsulated (Figure 5b) case. In Figure 5a, the temperature time histories for RTDs 20 and 21 match the Stefan equation quite well. However, RTD 18 and the later times for RTD 20 show faster thawing compared to the analytical prediction. This indicates the initial efficacy of the insulation in maintaining a 1-D thawing front, but how heat introduced into the system through the top of the aluminum container causes the deepest sensor (RTD 18) to thaw before the sensor in the middle of the sample (RTD 20). A small portion along the top of the container (Figure 3b) was still exposed to the surrounding air in the insulated tests. This small exposure of the top of the aluminum container, which has higher heat conductivity, provided a pathway for heat to flow into the container and introduce undesirable heat to the bottom and sides of the frozen sample, partially compromising the one-dimensional thawing profile of the test. While this did not compromise our tests entirely, it did reduce the feasible run times for which a top-down thawing profile could be maintained. Comparatively, as illustrated in Figure 5b, when no insulation is placed around the container, both the timing and slope of the analytical and measured temperature time histories diverge substantially. The soil near the bottom of the container thaws much more rapidly than any of the other locations and a 1-D thawing profile is never achieved. Further, due to the essentially infinite capacity of the warm air surrounding the aluminum container, large amounts of heat can be introduced into the sample in such a way that violates the assumed boundary conditions for Equation 7. Future testing specifically addresses this issue by ensuring the aluminum centrifuge container is completely wrapped in*

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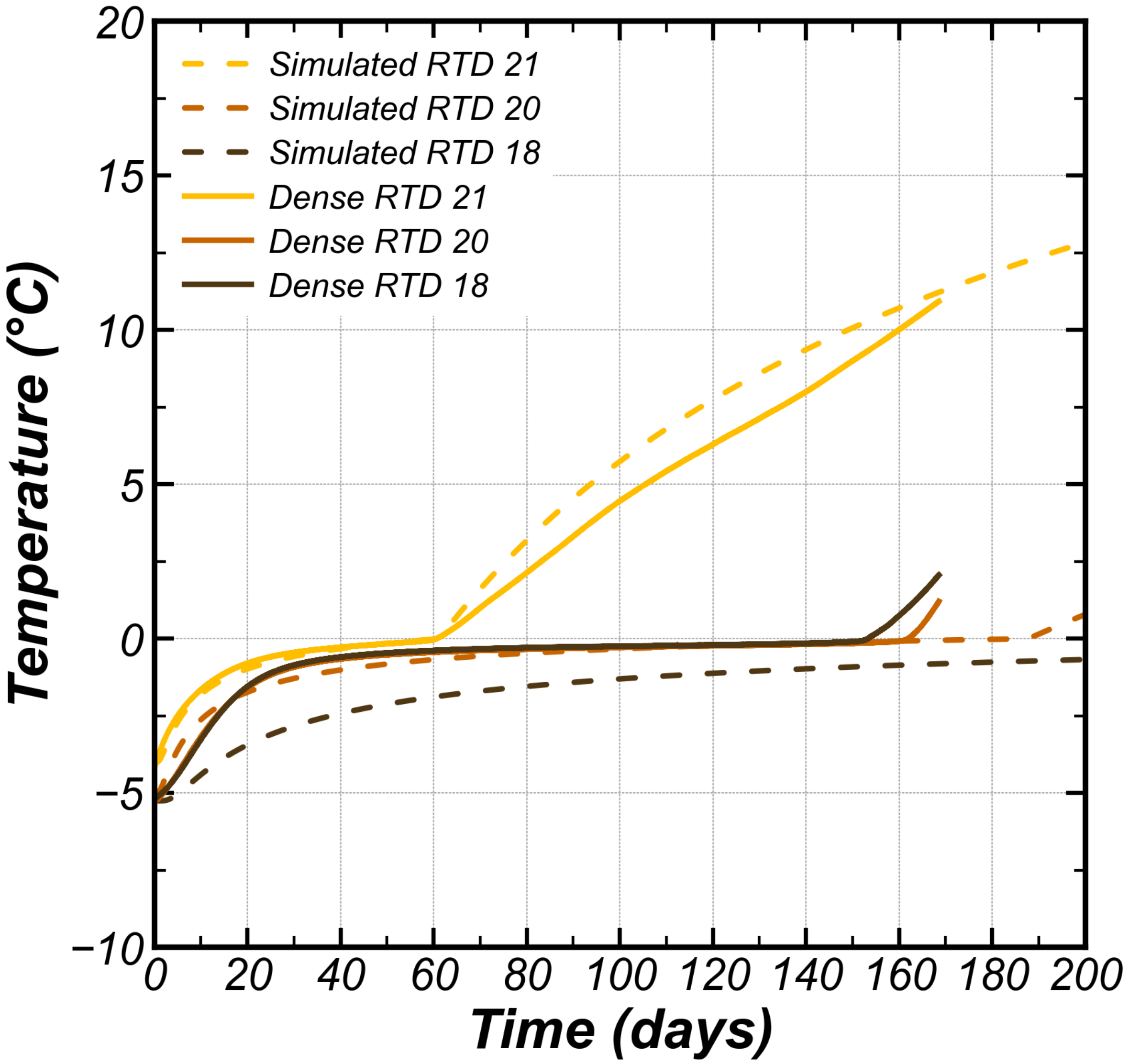
	insulation on both the inside and outside, with exposure only where instrumentation must be secured for testing. 

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	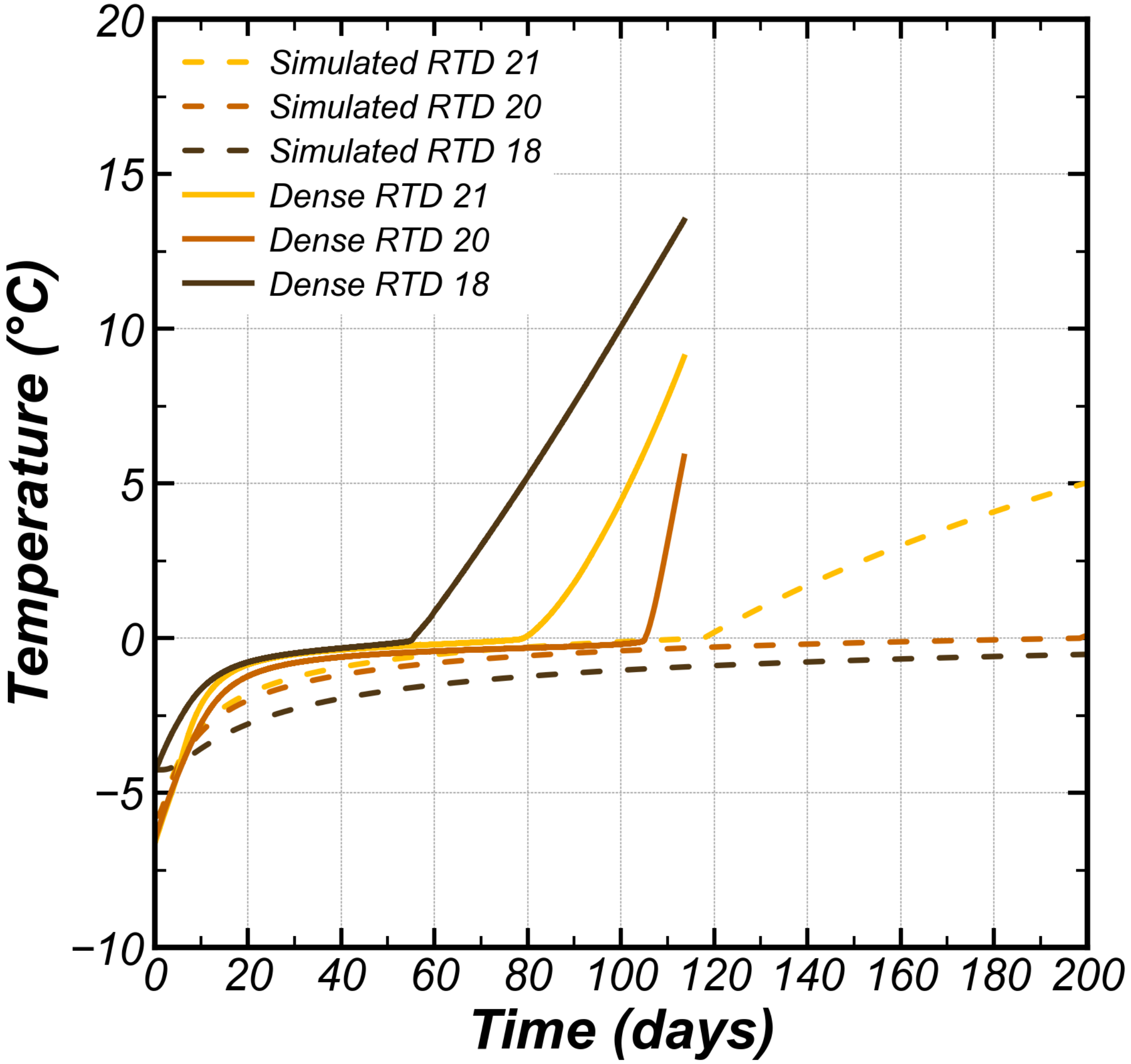
#3	**Comment:** Abstract: The manuscript refers to active layer thicknesses of “10s of meters.” This is not realistic; while 10 – 15 m may be possible in bedrock, the development observed is typically that of a supra-permafrost talik where the frost depth no longer reaches the permafrost table. **Response:** Thank you for this comment. We agree that stating the thickness of the active layer is 10s of meters thick is perhaps not entirely realistic. The point of giving a large range that encompasses even the most extreme cases is to highlight the difficulty in capturing all possible ranges in laboratory testing. We have updated the text to provide a more realistic range of active layer thickness, while also including discussion of all potential ranges that includes extreme cases. Relevant changes shown below: *The active layer typically ranges from a few centimeters to several meters, but can be more*

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	than 10 meters thick…
#4	**Comment:** Line 9: When introducing permafrost, it is recommended to use the latest definition published by the CPA (Lewkowicz et al., 2025). While the current definition is not incorrect, adopting the most recent terminology is encouraged. **Response:** Thank you for this comment. We have updated the revised manuscript to use the latest published definition of permafrost and include the relevant citation. The updated text is included below: *Permafrost–earth materials (soil or rock and included moisture, gases and organic material) that remain at or below 0° for at least two consecutive years (Lenkowicz et al, 2025)...*
#5	**Comment:** Line 15: The use of the term "diseases" in reference to permafrost thawing is discouraged. Although this terminology is sometimes used by colleagues in Chinese literature, permafrost degradation should be described as a hazard, danger, or risk, rather than a disease. **Response:** Thank you for this comment. The term "disease" is used here not to refer to thawing of permafrost as a disease, but instead refers to potential pathogens contained in the permafrost that may be released during thawing (based on work from Wu et al., 2022). We have updated the wording in the revised manuscript to make this aspect more clear: *This has substantial implications in terms of infrastructure performance (Hjort et al., 2022) and ground stability (Niu et al., 2016), as well as global carbon release (Schuur et al., 2015), forced migration (Ramage et al., 2021), and release of potential pathogens during thawing (Wu et al., 2022).*
#6	**Comment:** Line 38: The manuscript alternates between "field scale" and "prototype scale." It is recommended to unify this terminology throughout the text for consistency. **Response:** Thank you for this comment. Prototype scale and field (full) scale may not necessarily be the same and will depend on experimental design. For example, for the length scaling discussed in the manuscript, depending on the g-level in testing and the size of the specimen, the prototype scale could vary from a few meters up to tens of meters. In either case, the prototype would still not necessarily be field scale. However, we do see how our discussion in the manuscript did not make this distinction clear, so we have revised wording in the manuscript to make the difference between prototype and field scale, and how they are related, clear: *Here, hypergravity testing in a geotechnical centrifuge is a promising approach that enables testing of a permafrost layer at prototype scale that captures the full thickness of the active layer–testing can be designed such that the centrifuge model scales to an equivalent prototype that describes the scale of interest in the field.*
#7	**Comment:** Line 41: In discussing the experimental configuration, the authors should emphasize the importance of heat fluxes rather than absolute temperature values. Ensuring consistent and uniform heat flow direction that are representative for porotype conditions is

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	critical in physical modeling. **Response:** Thank you for this comment. We agree with this observation and have updated the manuscript to emphasize heat flux in terms of boundary conditions and pathways into the specimen: *In the case of permafrost testing in the centrifuge, careful consideration must be given to temperature and heat flux boundary conditions, both in terms of what might be representative conditions for the process at hand, and how the experimental configuration may introduce undesirable heat fluxes into the system that cause deviation from the desired model configuration. As such, it is important to measure temperature in the experiments in such a way that the boundary conditions can be verified and confirmed to provide the necessary temperature and heat flux boundary conditions.*
#8	**Comment:** Line 45-46: The manuscript notes that freezing and thawing should occur in a one-dimensional manner to eliminate three-dimensional effects. **Response:** Thank you for this comment. Yes, our point in this statement is that we aimed our experimental design at considering freezing and thawing associated with heat flux only at the soil surface. By creating a uniform soil profile and insulating the sample on all sides except the soil surface, we aim to create a condition that reflects how heat is introduced at the surface of the soil for a uniform soil deposit. This enables us to assess the efficacy of the insulation design. While for this work, we aim to create a 1-D thawing profile, the approach is not necessarily constrained to only do 1-D experiments. We create boundary conditions that allow for heat to ideally enter only through the soil surface; however, variable soil conditions can be created that are non-uniform that would create non-1D thawing conditions.
#9	**Comment:** Please verify and clarify the first sentence on line 61, as it appears incomplete. **Response:** Thank you for this comment. We have updated the wording of this sentence to clarify its meaning. The intended meaning is that if stress-strain response is being investigated, it is important to ensure that stresses in the model scale identically to stresses in the prototype. This ensures that model stress-strain response is representative of the desired prototype. The updated wording is provided below: *When investigating stress-dependent behavior of soil in hypergravity models, it is necessary to ensure that the stresses in the model scale identically to the prototype case to ensure the stress-strain response observed in the scaled model is representative of the desired prototype.*
#10	**Comment:** Line 81: The scaling for heat conduction is provided, but the scaling for phase change (freezing and thawing) is not addressed. Please elaborate on how phase change is reacting to hypergravity. **Response:** Thank you for this comment. In the hypergravity experiments conducted, we scale lengths down by the same factor that gravity is scaled up, so these are the only two quantities that may introduce scaling in other quantities. Whether a quantity will be affected in hypergravity experiments will thus depend on whether it has any dependence on length or

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	gravity. When considering phase change as described by the Stephan condition through energy conservation across the interface there is no gravitational dependence, so only length scaling will have an impact on phase change scaling based on the Stephan condition. Based on this, we find that time rate of scaling for phase change will scale to be $t^* = 1/N^2$. We have updated the text to include this discussion, and the relevant changes are shown below: *When considering phase change as described by the Stephan Condition (Alexiades, 2018) through energy conservation across the interface, we consider the following differential equation:* $\rho L\frac{dx}{dt} = - k_L\frac{du}{dx} + k_S\frac{du}{dx}$ *where the density (ρ), latent heat (L), and thermal conductivities of the liquid and solid (k_L and k_S , respectively) are material properties and thus do not depend on gravity. There is no gravitational term in this equation and thus the enhanced gravity in the centrifuge will not impact thawing/freezing. However, length quantities in the model are scaled down by a factor of N. Considering the left side of the equation, it will have a 1/N factor while the right side of the equation will have a N factor. Solving for time, we find that time rate of scaling for phase change will scale to be* $t^* = 1/N^2$*. Thus, heat conduction and phase change will have the same time rate scaling.*
#11	**Comment:** Line 87 and throughout: The term “thaw” should be used consistently throughout the manuscript, rather than “melting,” as permafrost undergoes thawing, not melting. **Response:** Thank you for this comment. We apologize for this mistake, and we have updated the manuscript throughout to consistently use “thaw”.
#12	**Comment:** Figure 3: It is recommended to add scales, annotate and label thicknesses of insulation and sample heights to improve clarity. **Response:** Thank you for this comment. We agree that adding scales and annotations to Figure 3 will improve clarity, and we have included this in the revised manuscript. Please note that all dimensions shown in the figure are in model scale. The updated figures are included below, which we have been included in the revised manuscript:

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	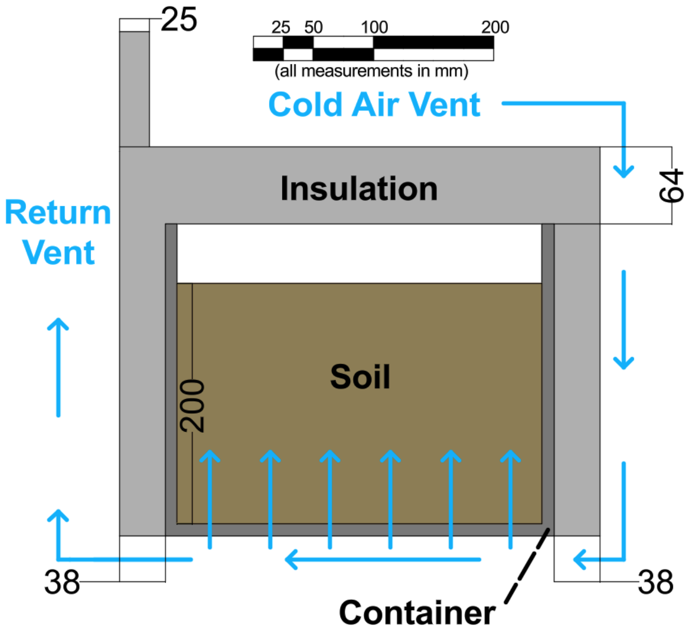 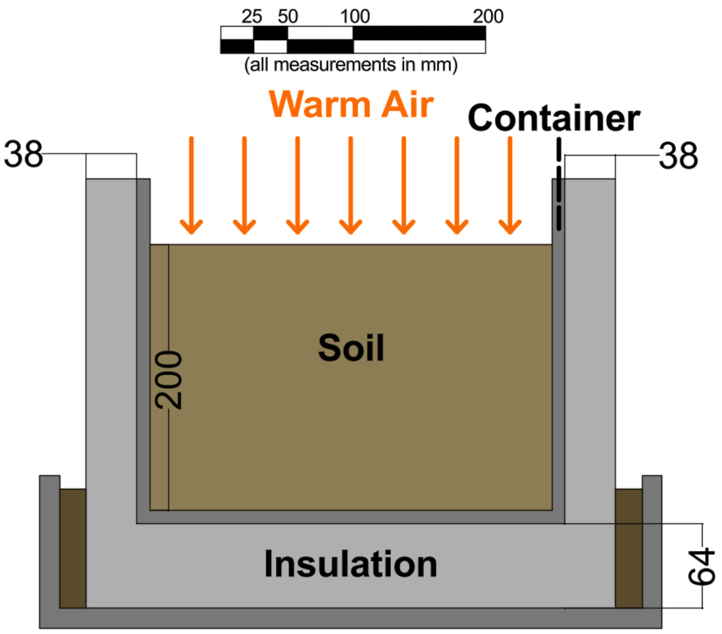
#13	**Comment**: Figure 5: Please provide an explanation for the observed steps in thaw penetration and why the process does not proceed gradually. Additionally, consider adding a figure showing thaw depth versus time for both insulated and un-insulated tests. **Response:** Thank you for this comment. The stepping shown in the plot is a function of the interpolation used when contouring the experimental data and does not represent what the actual temperatures were; the contouring does not capture the actual flow of heat in a

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	physical way and the steps are artefacts of interpolation. The simple interpolation used does not capture the physics of how the temperature changes over time and is misleading, so we have removed this plot from the revised manuscript. Instead, based on your suggestion, we include the comparison with the Stefan equation which provides a more defensible approach to show how and where the 1-D thawing boundary conditions are violated. The rapid melting in the uninsulated case illustrates how the most heat is introduced through the bottom and not the top of the specimen due to contact between the container and the centrifuge arm (which is a giant piece of metal that can introduce essentially infinite amounts of heat into the soil container). For the insulated case, the thaw is substantially more gradual and initiates from the top surface. There is still thawing from the bottom, though at a much slower rate and is likely largely due to heat introduction into the top of the aluminium container that can then make its way into the bottom of the sample (addressed in response to Comment #14). The relevant updates to the text and the plots showing the comparison between the measured temperatures and the 2-phase Stephan Condition are shown in the response to Comment #2.
#14	**Comment**: Figure 5 and Related Discussion: The data indicate that thawing occurs from the bottom up, suggesting that the process is more complex than a purely one-dimensional problem. The manuscript should discuss the implications of this finding and the role of heat flow within the samples. **Response:** Thank you for this comment. Yes, we agree that there is thawing of varying degrees within the model depending on the insulation which detracts from a purely one-dimensional melting profile. As discussed in the original submission, this is likely associated with how the insulation was placed and how heat was introduced into the sample due to exposure of portions of the aluminium container exposed at the top of the sample. We have also included an updated Figure 5 (b), which shows the uninsulated case where the rapid introduction of heat through the bottom of the sample is clearly seen–the aluminium container is directly in contact with the metal centrifuge arm and heat can be quickly introduced into the sample leading to rapid thawing. In the updated Figure 5 (a), the sample is shown to thaw much more slowly while also showing faster thawing at the soil surface. The thawing observed at the bottom is due to heat introduction into the aluminium soil container at the exposed top portion of the container. The updated Figure 5 (a) and (b) are shown in the response to Comment #2. The updated text discussing this point is included below: *Figure 5 shows a comparison between the two-phase Stefan Condition (as described by Equation (7)) and the measured temperature time histories for the dense tests (both insulated and uninsulated). For this comparison, we calibrated the analytical solution to the measured values at RTD 21 for the insulated case as this sensor location best matches assumptions in the solution of Equation (7). The properties used for this sensor location are then applied to all other locations to evaluate the efficacy of the insulation and potential introduction of undesirable heat into the soil sample. In this preliminary testing, the impact of simply placing insulation around the sides and bottom of the aluminum container can be clearly seen when comparing the insulated (Figure 5a) with the uninsulated (Figure 5b) case. In Figure 5a, the temperature time histories for RTDs 20 and 21 match the Stefan equation quite well. However, RTD 18 and the later times for RTD 20 show faster thawing*

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	compared to the analytical prediction. This indicates the initial efficacy of the insulation in maintaining a 1-D thawing front, but how heat introduced into the system through the top of the aluminum container causes the deepest sensor (RTD 18) to thaw before the sensor in the middle of the sample (RTD 20). A small portion along the top of the container (Figure 3b) was still exposed to the surrounding air in the insulated tests. This small exposure of the top of the aluminum container, which has higher heat conductivity, provided a pathway for heat to flow into the container and introduce undesirable heat to the bottom and sides of the frozen sample, partially compromising the one-dimensional thawing profile of the test. While this did not compromise our tests entirely, it did reduce the feasible run times for which a top-down thawing profile could be maintained. Comparatively, as illustrated in Figure 5b, when no insulation is placed around the container, both the timing and slope of the analytical and measured temperature time histories diverge substantially. The soil near the bottom of the container thaws much more rapidly than any of the other locations and a 1-D thawing profile is never achieved. Further, due to the essentially infinite capacity of the warm air surrounding the aluminum container, large amounts of heat can be introduced into the sample in such a way that violates the assumed boundary conditions for Equation (7). Future testing specifically addresses this issue by ensuring the aluminum centrifuge container is completely wrapped in insulation on both the inside and outside, with exposure only where instrumentation must be secured for testing.
#15	**Comment**: Section 5: As previously mentioned, a comparison with analytical solutions such as the Stephen or modified Berggren equations would add significant value when discussing thaw penetration. **Response:** Thank you for this comment, we think this point in particular has substantially strengthened the manuscript. We definitely agree that this comparison would add significant value and impact to this work, and would also facilitate discussion on the efficacy of insulation to achieve the desired boundary conditions. We have included a comparison with the 2-phase Stephan Condition in the revised manuscript. The updates to Section 5 based on this point are included below: *This was illustrated through comparison of the measured temperature time histories with predicted temperature time histories based on the analytical solution to the Stefan Condition. The entry of undesirable heat through small exposures of more conductive material allow heat to be quickly transferred to the other portions of the sample, which can lead to deviations from the one-dimensional thawing profile.*