

Parameter Variation Analyses of Thermal Properties Used in Ground Temperature Simulations



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ABSTRACT

Currently, 50% of the Canadian landmass is overlying either continuous or discontinuous permafrost. Many structures in these areas rely on the permafrost to provide stability to their foundations, including buildings, roads, railways, and soil embankments. If large swaths of permafrost begin to thaw, then roads and railways may become unusable, thereby isolating communities, increasing resource extraction costs, and hindering military operations. A previously calibrated thermal numerical model allows researchers to accurately model a permafrost profile over an extended period. However, numerical models are dependent upon, and thereby limited by, the reliability of their inputs. In the previously created model, a one-dimensional finite element model was developed and calibrated using a large dataset of in-situ temperature recordings; however, the soil properties, including thermal conductivity, thermal heat capacity, water content, and the unfrozen water content curves, were almost entirely unmeasured and were assumed. In this paper, the calibrated model inputs are varied over a wide range to assess the impact of the soil property inputs and determine the magnitude of change on the model's outputs. The results show that, except for widely varied properties, the simulated trumpet curves and active layer depths were minimally impacted to both modifications in the thermal properties as well as the depth in the soil column at which the change was made.

RESUME

À l'heure actuelle, 50% de la masse continentale canadienne recouvre un pergélisol continu ou discontinu. De nombreuses structures dans ces zones dépendent du pergélisol pour assurer la stabilité de leurs fondations, notamment des bâtiments, des routes, des voies ferrées et des remblais en terre. Si de larges bandes de pergélisol commencent à dégeler, les routes et les chemins de fer risquent de devenir inutilisables, isolant ainsi les communautés, augmentant les coûts d'extraction des ressources et entravant les opérations militaires. Un modèle numérique créé précédemment permet aux chercheurs de modéliser avec précision le comportement thermique du sol sur un pergélisol sur une longue période; Cependant, les modèles numériques dépendent de la fiabilité de leurs entrées et sont donc limités par celle-ci. Dans le modèle créé précédemment, un modèle unidimensionnel à éléments finis a été développé et calibré à l'aide d'un vaste ensemble de données d'enregistrements de température in situ; cependant, les propriétés thermiques du sol n'ont presque pas été mesurées. Les recherches effectuées dans le présent document ont été utilisées pour vérifier la sensibilité des entrées de propriétés du sol, afin de déterminer quelles propriétés ont un impact sur les résultats du modèle et l'importance de ces impacts. Les résultats indiquent que les résultats du modèle sont sensibles aux modifications de la propriété du sol, à l'ampleur de la modification de la propriété et à la profondeur de la colonne de sol à laquelle la modification a été apportée.

1 INTRODUCTION

Currently, 50% of the Canadian landmass is overlying either continuous or discontinuous permafrost (see Figure 1). Many structures in these areas rely on permafrost to provide stability to their foundations, including buildings, roads, railways, and soil embankments. For example, buildings use slabs, or piles driven into permafrost, roads and railways rest on permafrost soils, and soil embankments use the ice for strength or to retain hazardous chemicals. If large swaths of permafrost begin to thaw, then roads and railways may become unusable, thereby isolating communities, increasing resource extraction costs, and hindering military operations.

Smith and Burgess (1999) show that 70% of the Canadian permafrost has a moderate to high sensitivity to a warming climate. Permafrost sensitivity is dictated by the following attributes: it exists at temperatures between 0°C and -2°C, has high ice contents, and is made of thermally conductive soils. Since 1984, there has been a 6000% increase in occurrences of landslides due to permafrost losses on Bank's Island in the Canadian arctic, with similar

increases recorded on nearby islands (Lewkowicz and Way, 2019). These landslides release sediments into the water, which are anticipated to have a significant detrimental effect on water quality and water-based ecosystems on those islands.

Figure 1: Permafrost zones in in Canada (After Atlas of Canada, 2010).

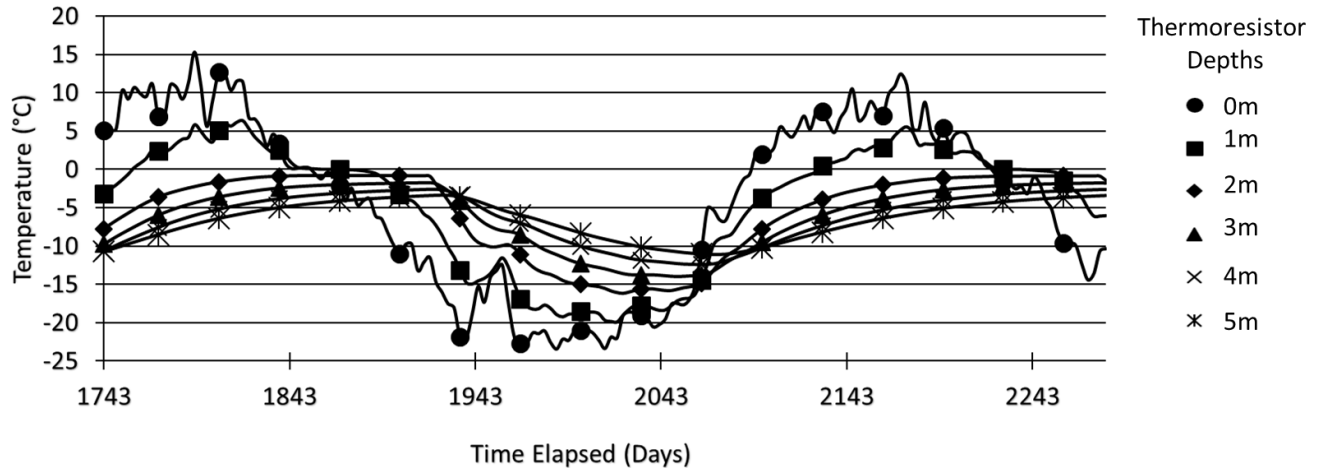
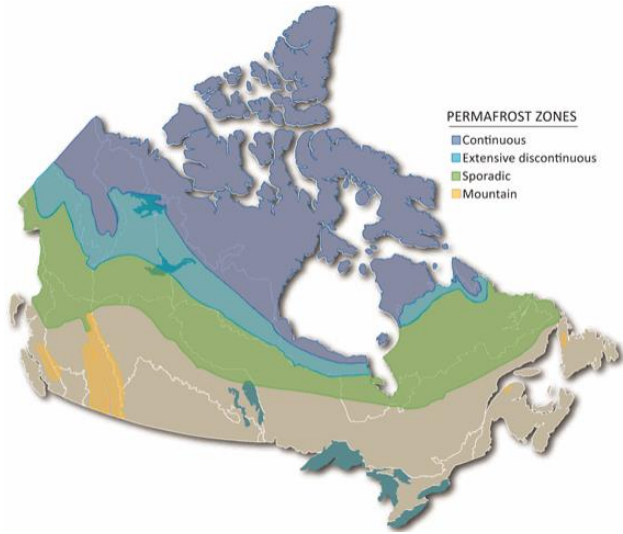


Figure 2: Typical time dependent thermal model data.

Widespread in-ground temperature measurements were previously limited in scope by high costs and risks associated with arctic research. Recently, these limitations were overcome by obtaining access to a ground temperature database that encompasses dozens of sites across the Canadian arctic from Yukon to Baffin Island (Fournier, 2017). This database was created following environmental monitoring and remediation work at Distant Early Warning (DEW) Line sites in the Canadian arctic, which are indicated on Figure 1.

A previously calibrated numerical model, (typical data plotted in Figure 2), accurately modeled a permafrost profile over an extended period; however, numerical models are dependent upon, and thereby potentially limited by, reliability of their inputs. The data in Figure 2 is the one-dimensional finite element model developed and calibrated using a large dataset of in-situ temperature recordings; however, the soil's thermal properties were entirely unmeasured. Model development incorporated a simplified thermal boundary condition at the surface, which reduced the calculation intensity for the computer and eased the calibration process. The temperature of this boundary was

created using recorded temperatures at 0m, which are shown in

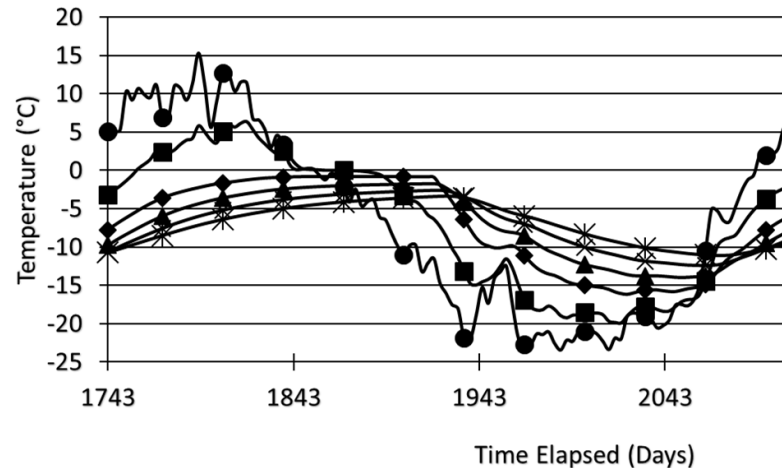


Figure 2. The thermal boundary condition at a depth of 50m used a constant temperature of approximately -5 °C. In the numerical model, energy

transfer in the soils was via conduction only. Figure 3 shows the developed soil profile and the mesh sizes for each layer.

Table 1 displays the calibrated soil properties for the model (Figure 3). The soil in layer 1 was a compacted sand and gravel fill and layer 2 was a silty peat. Both layers are located in the active layer and thaw annually. Layers 3 and 4 remain frozen from year to year and are ice rich with small amounts of silt present. The time period used in the model was 3,667 days (2000-2010) and initial soil temperatures were provided by in-situ temperature measurements.

Rather than a traditional sensitivity analysis to fine-tune the parameters, the intent of this exercise was to determine what impact changing thermal properties over an extremely wide range would have on the final output including annual trumpet curves and active layer depth. The impact of changing these properties at various depths was also investigated.

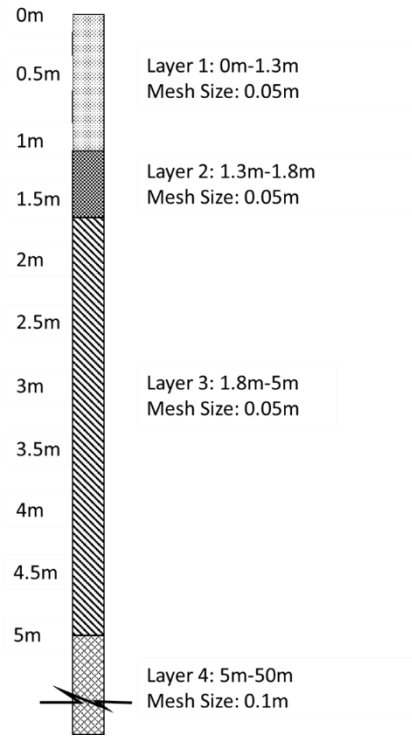


Figure 3: Soil profile and mesh sizes for the 1D model.

Table 1: Calibrated soil properties prior to parameter variation analyses.

Layer	Unfrozen thermal conductivity (kJ/sec m °C)	Frozen thermal conductivity (kJ/sec m °C)	Unfrozen volumetric heat capacity (kJ/m ³ °C)	Frozen heat capacity (kJ/m ³ °C)	Water Content (%)
1	0.0029	0.0029	1600	1400	11%
2	0.001	0.0015	2000	1600	35%
3	0.00065	0.0024	4187	1500	90%
4	0.001	0.0022	2000	2000	20%

Table 2: Thermal conductivities used in parameter variation analyses.

Layer	Deg C	Thermal Conductivities (kJ/sec/m ² /°C)								
		1%	25%	50%	75%	100 % (Original)	125%	150%	175%	199%
1	-1	0.000029	0.000725	0.00145	0.002175	0.0029	0.003625	0.00435	0.005075	0.005771
	0	0.000029	0.000725	0.00145	0.002175	0.0029	0.003625	0.00435	0.005075	0.005771
2	-1	0.000015	0.000375	0.00075	0.001125	0.0015	0.001875	0.00225	0.002625	0.002985
	0	0.00001	0.00025	0.0005	0.00075	0.001	0.00125	0.0015	0.00175	0.00199
3	-1	0.000024	0.0006	0.0012	0.0018	0.0024	0.003	0.0036	0.0042	0.004776
	0	0.0000065	0.0001625	0.000325	0.0004875	0.00065	0.0008125	0.000975	0.0011375	0.0012935
4	-1	0.00002	0.0005	0.001	0.0015	0.002	0.0025	0.003	0.0035	0.00398
	0	0.00001	0.00025	0.0005	0.00075	0.001	0.00125	0.0015	0.00175	0.00199

Table 3: Water contents used in parameter variation analyses.

Layer	Water Content (%)								
	1%	25%	50%	75%	100 % (Original)	125%	150%	175%	199%
1	0.11	2.75	5.5	8.25	11	13.75	16.5	19.25	21.89
2	0.35	8.75	17.5	26.25	35	43.75	52.5	61.25	69.65
3	0.9	22.5	45	67.5	90	100	100	100	100
4	0.2	5	10	15	20	25	30	35	39.8

Table 4: Volumetric heat capacities used in analysis

Layer	Soil State	Volumetric Heat Capacity (kJ/m ³ /°C)								
		1%	25%	50%	75%	100 % (Original)	125%	150%	175%	199%
1	Unfrozen	16	400	800	1200	1600	2000	2400	2800	3184
	Frozen	14	350	700	1050	1400	1750	2100	2450	2786
2	Unfrozen	20	500	1000	1500	2000	2500	3000	3500	3980
	Frozen	16	400	800	1200	1600	2000	2400	2800	3184
3	Unfrozen	41	1046	2093	3140	4187	5233	6280	7327	8332
	Frozen	15	375	750	1125	1500	1875	2250	2625	2985
4	Unfrozen	20	500	1000	1500	2000	2500	3000	3500	3980
	Frozen	20	500	1000	1500	2000	2500	3000	3500	3980

2 PARAMETER VARIATION DESCRIPTION

The previously developed numerical model is quite complex, with a significant number of interdependent input variables in multiple soil layers. To conduct the parameter variation analysis a one-at-a-time (OAT) approach was taken. The numerical model used TEMP/W module (version 9.0.0.11777) of the GeoStudio program developed by GEOSLOPE INC. The OAT method allowed the authors to determine the influence of each input variable upon the model's output, thereby isolating the magnitude and depth of change. The following process was used:

1. Starting with the uppermost soil layer, perform multiple model runs applying an increase or decrease to each variable by a predetermined percentage. The altered input is returned to the baseline for subsequent analyses.
2. Continue this process through each soil layer in the soil column.

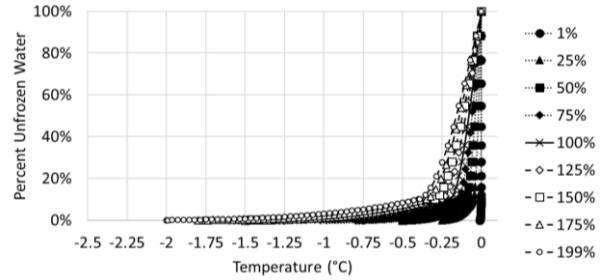
The OAT approach is time and computationally intensive, requiring many hours to run each series of models. As a result, determining interdependencies or magnification

effects between the soil properties is outside the scope of this paper.

2.1 The analysis results from days 1,869 to 2,282 were compared to the original model's results during the same period. These days were selected for comparison as all analyses had ceased significant year-to-year fluctuations. Soil Property Variation

The soil properties used in the numerical model were thermal conductivity, volumetric heat capacity, water content, and unfrozen water content. The initial value of these properties was previously determined during model calibration and are shown in Table 1. The values used in the analysis were percentages of the initial value (1%, 25%, 50%, 75%, 100%, 125%, 150%, 175%, and 199%.) and are listed in Table 2, Table 3, Table 4, and Figure 4. In these tables/figures, the 100% value represents the initial value for that soil property.

The large range of modifications used in the parameter variation analyses ensures that any potential behavior changes at the extremes would be captured. Additionally, the impacts of the changes minor at percentages less than 25%, which is demonstrated below. Volumetric water content was limited to a maximum value of 100% (equivalent to simulating water). Some soil property values may be outside the possible theoretical ranges for that soil. While not realistic, it was allowed as future modellers may be working with unique soils or synthetic materials (insulations, etc) different from what was present at the station in this study.



c)

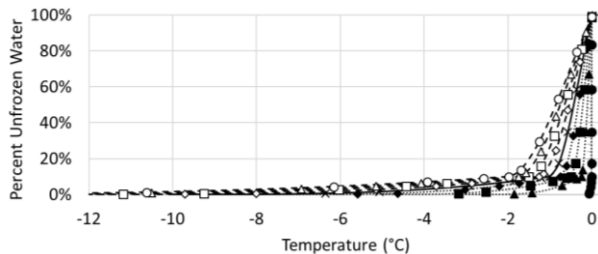
Figure 4: Unfrozen water content curves used in parameter variation analyses for a) Layer 1, b) Layer 2, and c) Layer 3.

3 RESULTS

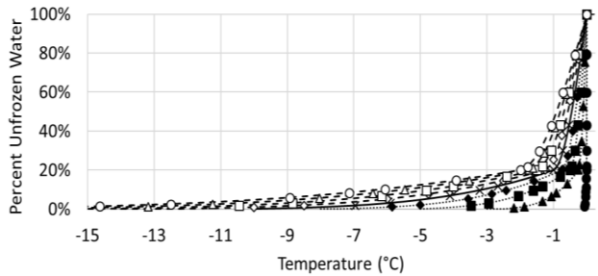
The results produced by each modification in soil property are first compared by plotting the maximum and minimum temperatures over a period of one typical year. The years selected for this comparison were 2006-2007 as a thermal equilibrium was achieved in all analyses and there was no noticeable change in behavior after that year.

Figure 5 shows the maximum change in the trumpet curves caused by modifying each property in the top two soil layers by 1% to 199% of their initial value. At the extremes, changes to the thermal conductivity have the largest effect on soil temperatures irrespective of the depth at which the change occurs. For all other properties as depth increases, the ground temperatures for the calibrated model and parameter variation analyses converge.

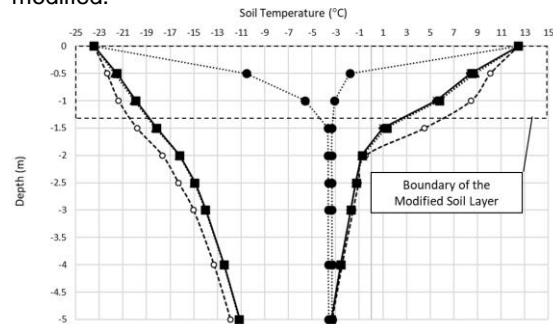
Figure 6 through Figure 13 show the effects of modifying each property in greater detail. Figures marked by (a) and (b) show the temperature vs time at the center of the first and second soil layers respectively (depths 0.65m and 1.55m). Figures marked with (c) show the trumpet curves of the maximum and minimum temperatures during the specified period. The dashed boxes on the trumpet curves indicate the depth and thickness of the soil layer in which the property was modified.



a)



b)



a)

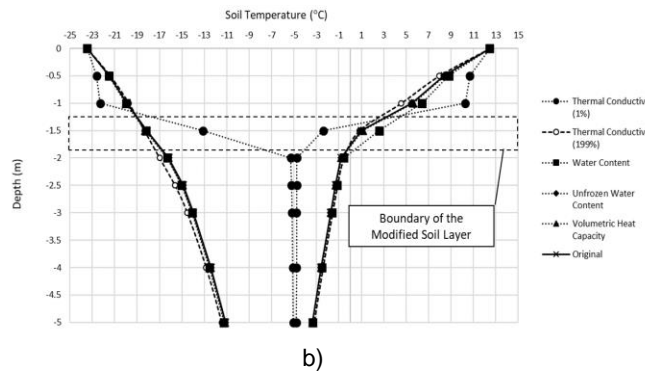


Figure 5: Trumpet curve profiles of the maximum changes created by modifying the soil's properties in the a) Layer 1 (0-1.3m depth) and b) Layer 2 (1.25-1.8m depth).

Changes to Thermal Conductivity. In Figure 6, modifications to the top layer affect both the top and second layer substantially. The effect of varying thermal conductivity in the upper layer from 50% to 199% of the original value, increases the temperatures by approximately 1°C at 0.65m and 3°C at 1.65m, with the trumpet curves in Figure(c) showing a corresponding effect with the active layer of the soil varying by over 0.5m. In the second layer, varying the thermal conductivity from 50%-199% changes the temperatures by approximately 0.5°C at 0.65m and 1°C at 1.65m.

The output variation due to thermal conductivity appears to be relatively linear with no large deviations. The one exception is the 1% modification analysis, which had a significant insulating effect on both soil layers. This insulating effect nearly isolates the second layer (b) from any surface temperature fluctuations. It should be noted that the 199% modification did not cause such significant change to the results.

Changes to Water Content. In Figure 8, changes to the water content of the top layer had little effect on the results in both the first and second layers. The only potential impact would to alter the latent energy required to change phase, however the analyses show this had little effect. Figure 9 shows that modifications to the second layer had increasing impacts on the results of that layer with the first layer remaining relatively unchanged.

Changes to Unfrozen Water Content Curves. For both the first and second layers (Figure 10 and Figure 11), the majority of the differences resulting from modifications to the curve were confined to temperatures near 0°C. For changes to both layers, the minimum temperature in the second layer was increased slightly (subsection b in Figure 10 and Figure 11)

Changes to Volumetric Heat Capacity. In both Figure 12 and Figure 13, any change in the outputs due to modifications to the volumetric heat capacity were minimal and did not increase with increasing modifications.

4 DISCUSSION

The parameter variation analyses examined the effect of varying each parameter individually. In this section, further discussion on these effects will be presented as well as limitations.

Changes in Soil Properties. The research demonstrates that, among the parameters varied, thermal conductivity has the greatest impact on the time series temperatures and trumpet curves. While expected, these effects were most apparent when thermal conductivity was reduced. The consequence of increasing the thermal conductivity was much less of an impact. The limited temperature differences that occurred from increasing thermal conductivity are due to the limit on the available energy. The thermal boundary condition used in the numerical model limited the amount of energy available to the soil and, when the amount of energy available was increased, the ground temperatures rose. The use of a different, less restrictive, boundary condition, such as a land climate interaction, could allow temperatures to rise further.

Water content was the property which had the next greatest impact on the maximum and minimum yearly temperatures with changes to the second soil layer creating the larger differences.

Changes to the unfrozen water content did not impact the maximum or minimum yearly temperatures but impacted the time at which the soil temperature passed through 0°C as can be seen most noticeably in Figure 9 (a) and (b).

Changes to the volumetric heat capacity, even large ones, did not create any significant deviations from the original values.

With the exception of large changes to the thermal conductivity of the soil in Layer 1, the depth of the active layer remained relatively unchanged for all modifications.

Depth Effects For all soil properties, the depth at which the soil property was modified impacted the results, with the noted exception of volumetric heat capacity. Varying the surface layer impacted the output of all the soil layers below by either becoming a greater conduit for energy flow or an insulating layer. Whereas modifying the second layer's properties had an outsized impact on the soil temperatures in the top layer while causing minimal impact to the temperatures below.

Limitations of this Research In order to limit the calculation complexity, and isolate the effect of changing the soil properties, the research used a surface boundary condition consisting of a thermal condition using recorded ground surface temperatures. As this condition established a specified temperature at each point in time, it influenced the results of this analysis by forcing all models to converge on a given surface temperature. A land climate interaction boundary condition is expected to give more freedom to the ground surface temperature, allowing for potentially greater changes to occur.

In this analyses, only one property changed at a time, meaning that potential magnification, or buffering effects, created by changing multiple soil properties at the same time is outside the scope of the paper. Changes to multiple properties should be investigated in the future as certain

combinations may produce larger magnitudes of change or counteract each other.

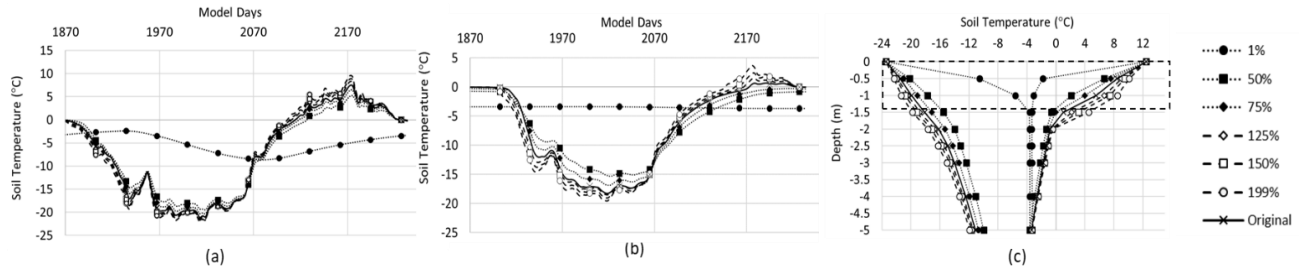


Figure 6: Effect of varying thermal conductivity in the Layer 1 (0-1.3m depth) on (a) ground temperatures at 0.65m, (b) ground temperatures at 1.55m, and (c) trumpet curves. See Table 2 for values used

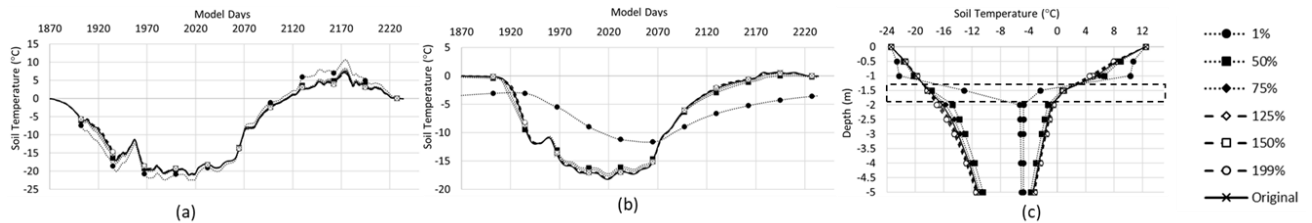


Figure 7: Effect of varying thermal conductivity in the Layer 2 (1.3-1.8m depth) on (a) ground temperatures at 0.65m, (b) ground temperatures at 1.55m, and (c) trumpet curves. See Table 2 for values used

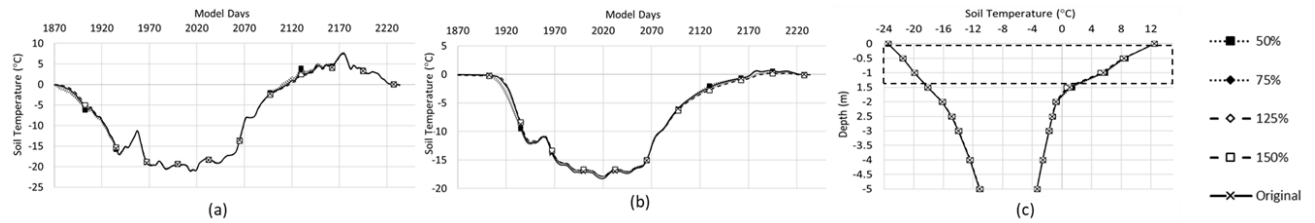


Figure 8: Effect of varying water content in the Layer 1 (0-1.3m depth) on (a) ground temperatures at 0.65m, (b) ground temperatures at 1.55m, and (c) trumpet curves. See Table 3 for values used

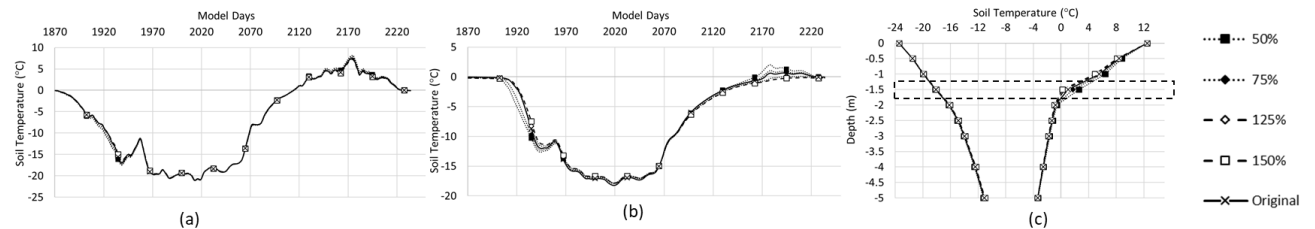


Figure 9: Effect of varying water content in the Layer 2 (1.3-1.8m depth) on (a) ground temperatures at 0.65m, (b) ground temperatures at 1.55m, and (c) trumpet curves. See Table 3 for values used

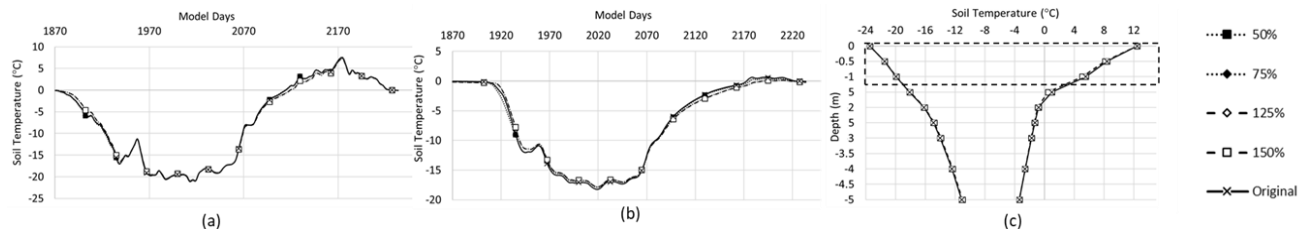


Figure 10: Effect of varying unfrozen water content function in the Layer 1 (0-1.3m depth) on (a) ground temperatures at 0.65m, (b) ground temperatures at 1.55m, and (c) trumpet curves. See Figure 4 for values used

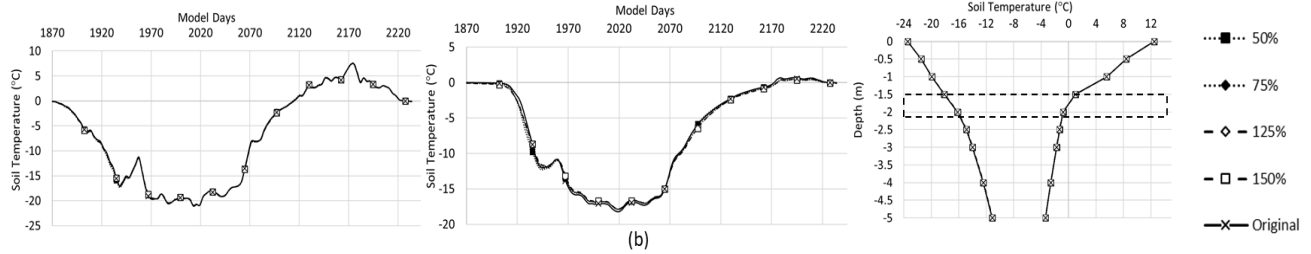


Figure 11: Effect of varying unfrozen water content function in the Layer 2 (1.3-1.8m depth) on (a) ground temperatures at 0.65m, (b) ground temperatures at 1.55m, and (c) trumpet curves. See Figure 4 for values used

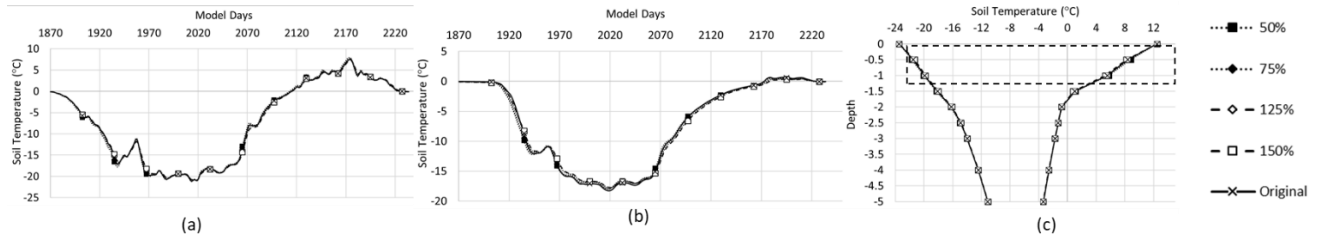


Figure 12: Effect of varying volumetric heat capacity in the Layer 1 (0-1.3m depth) on (a) ground temperatures at 0.65m, (b) ground temperatures at 1.55m, and (c) trumpet curves. See Table 4 for values used

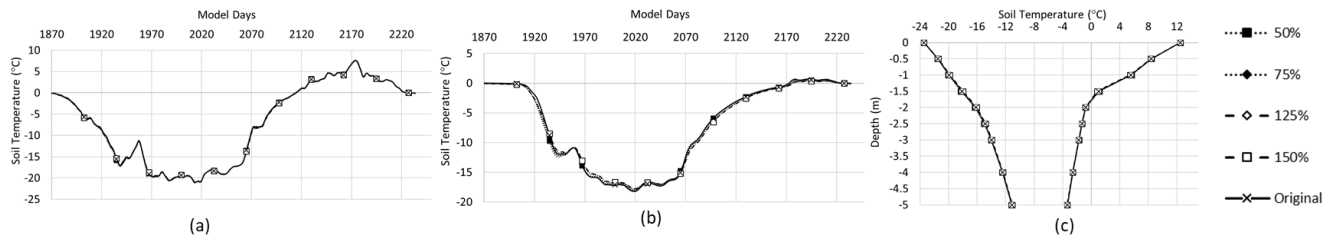


Figure 13: Effect of varying volumetric heat capacity in the Layer 2 (1.3-1.8m depth) on (a) ground temperatures at 0.65m, (b) ground temperatures at 1.55m, and (c) trumpet curves. See Table 4 for values used

5 CONCLUSION

Preparing for the effects of climate change requires reliable predictions on its impact on ground temperatures. Future climate change is anticipated to increase active layer depths and may lead to devastating effects to the extremely sensitive arctic landscape. Computational models are only as reliable as their inputs. Previous research has calibrated long-term computational models for ground heat transfer. Since model inputs in this research were entirely assumed, the relationship between model inputs and model output is not fully understood. This paper presents the results of a sensitivity analysis examining the effect of material parameter variation over a wide range.

Varying the thermal properties over a wide range was deemed important for this study due to the limited ground information available and the fact they were completely derived by inferring them indirectly from available site information and via an iterative process. Although thermal properties were varied over a relatively wide range the impact on the time series, trumpet curves, and active layer was, somewhat surprisingly, relatively minor for the majority of the simulations. Only large changes to the

thermal conductivity produced a significant change in the depth of the active layer. Other variables, regardless of the magnitude of change, did not produce any deviations in the active layer depth.

The parameter variation analyses used an OAT approach to isolate the impact of each property and the depth at which the property was changed. The properties were changed by percentages from 1% to 199%.

The results of the within research demonstrates that thermal conductivity overwhelmingly produced the greatest effect on the results. Water content and unfrozen water content affected temperatures at, and just below, freezing. Changes to volumetric heat capacity had minimal effect. Future modeling efforts can now use this information to more efficiently calibrate ground temperature models. The results show that both modifications to the soil property and the depth at which the modification occurs can have an effect but that any impact that does occur is reduced with depth.

6 REFERENCES

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