Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3
© The authors and IGS: All rights reserved, 2019
doi: 10.32075/17ECSMGE-2019-0773

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Challenges stabilizing a ground-temperature model at a permafrost site

Défis concernant la stabilisation d'un modèle de température du sol d'un site de pergélisol

C. Ross
GeoEngineering Centre at Queen's-RMC, Royal Military College of Canada, Kingston, Canada

G.A. Siemens, R.A. Beddoe
GeoEngineering Centre at Queen's-RMC, Royal Military College of Canada, Kingston, Canada

ABSTRACT: Thermal modelling of permafrost sites requires careful and time-consuming spin-up analyses to obtain a stable thermal regime consistent with site conditions. In this study, we investigated the initialization temperature and minimum number of spin-up cycles required to stabilize a 50 m deep permafrost profile representing a site in the western Canadian Arctic. Historical climate data applied using a ground-surface energy balance equation was used to drive the model. A metric commonly used to define a stable regime in a nominal number of cycles (inter-cycle variation in cumulative energy flux at the surface being less than 5%) was found to prematurely indicate stability in each case. In some cases, more than 900 spin-up cycles were required to stabilize the thermal regime. Initializing the model at an estimate of mean annual ground temperature can significantly reduce the number of cycles required.

RÉSUMÉ: La modélisation thermique de sites avec pergélisol nécessite des analyses de 'spin-up' d'obtenir un régime thermique stable et compatible avec les conditions d'un site. Dans cette étude, nous avons étudié la température d'initialisation et le nombre minimum de cycles d'analyses 'spin-up' nécessaires pour stabiliser un profil de pergélisol avec une profondeur de 50 m qui représente un site dans l'ouest de l'Arctique canadien. Les données climatiques historiques appliquées à l'aide d'une équation de bilan énergétique sol-surface ont été utilisées pour diriger le modèle. Une métrique communément utilisée pour définir un régime stable dans un nombre nominal de cycles (la variation inter-cycle du flux d'énergie cumulée à la surface étant moins à 5%) indique prématurément la stabilité dans chaque cas. Dans certains cas, plus de 900 cycles d'analyses 'spin-up' étaient nécessaires pour stabiliser le régime thermique. L'initialisation du modèle à une estimation de la température moyenne annuelle du sol peut réduire considérablement le nombre de cycles requis.

Keywords: Ground temperature modelling; permafrost; spin-up analysis; calibration; climate change

1 INTRODUCTION

Geothermal numerical models have become the standard for evaluating the thermal response of permafrost ground to climatic and anthropogenic forcing.

Spin-up analysis is a technique commonly used as part of a geothermal numerical modelling exercise to set the initial thermal regime within the model domain upon which subsequent analyses are based (e.g. Jafarov et al., 2012; Nishimura et al., 2009; O'Neill & Burn, 2017; Riseborough et al., 2008). The objective of spin-up is to establish a stable thermal regime that is both representative of observed or anticipated baseline thermal conditions at a select period in time; and independent of the initialization temperature(s).

Prior to spin-up, the model domain is initialized with a geothermal gradient or at some constant temperature, such as 0ºC or an estimate of the mean annual ground temperature (MAGT). These scenarios are conceptualized in Figure 1.

Typically, one to several years of historical climate data and/or measured ground-surface temperature data is then applied as a surface boundary condition to drive the model for a specified number of repeating cycles. The basal boundary condition may be set as a constant temperature or as a constant geothermal flux.

Spin-up allows the model domain to approach equilibrium with climate conditions such that the temperature profile or cumulative surficial energy transfer at a specific time step in the cycle remains constant or varies minimally over subsequent cycles. It is common to define a stable thermal regime when the inter-cycle variation in the cumulative energy flux at the ground surface is less than 5%.

The spin-up duration (number of cycles) required to establish an acceptable equilibrium depends on the modeled depth, the initialization temperature, ground surface conditions (e.g. vegetation, snow cover, etc.) and the thermal properties of soil and rock. Due to the latent heat effects of phase change, ground temperatures in relatively warm permafrost (loosely defined between 0ºC and -4ºC) may take significantly longer to respond to climatic forcing than colder permafrost.

Tolerance for inter-cycle temperature variation is an important consideration in determining the duration of a spin-up analysis. Equilibrium may not always be reached within a reasonable computing time, and may not always be important as in the case where only near-surface soils that respond quickly under the influence of strong thermal forcing are considered (e.g. Lawrence & Slater, 2005). In other cases, the response of deep pile foundations to incremental warming over a 50 year design life or estimations of subsurface heat storage in General Circulation Models (e.g. Stevens et al., 2007) require accurately developed thermal conditions at depth.

In this study, we compare various scenarios for initializing the thermal profile prior to spin-up, and investigate the number of cycles required to stabilize a 50 m deep thermal profile at a relatively warm permafrost site in the western Canadian Arctic.

In the process, we evaluate the 5% cumulative energy flux criteria for determining whether a spin-up analysis has obtained sufficient inter-cycle thermal stability for application to transient analyses of a deep permafrost site.

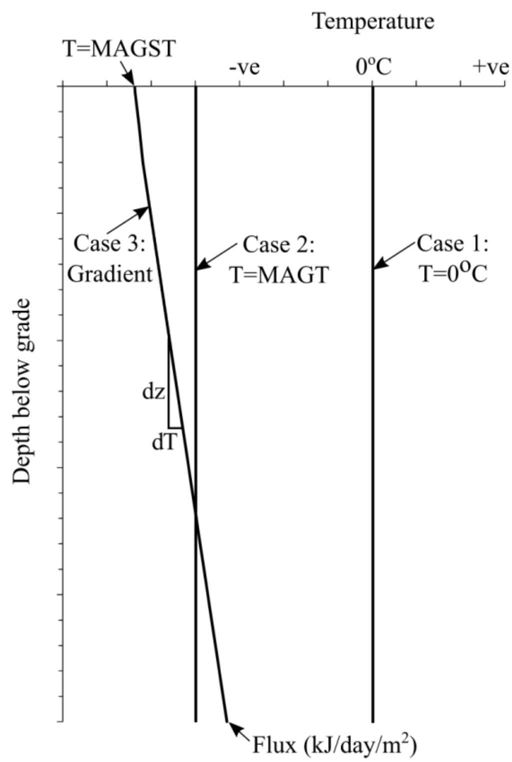

Figure 1. Initialization temperatures for spin-up analysis considered in this study included a default of 0ºC; an estimation of mean annual ground temperature (MAGT) at depth-of-zero-annual-amplitude; and a steady-state thermal gradient between measured mean annual ground-surface temperature (MAGST) and a constant geothermal flux applied at the base.

2 NUMERICAL MODEL

Numerical modelling for this study was conducted in the TEMP/W module of the GeoStudio 2018-R2 commercial software suite developed by GeoSlope International Ltd. The module solves finite-element equations for conductive heat transfer including phase change, and has a fully developed Land-Climate-Interaction (LCI) boundary condition that employs a ground-surface energy balance equation for thermal flux at the ground surface (GEOSLOPE International Ltd., 2017).

2.1 Model site and data

A site on the Beaufort Sea northwest of Inuvik, Northwest Territories was considered representative of the continuous permafrost zone of the western Canadian Arctic and provided the context for a geothermal model for this study.

Historical weather data available for the site provided a Mean Annual Air Temperature (MAAT) of - 9.1 ^{0}C for the decade of 2001 to 2010. A single year (2001) of historical weather data was compiled for use in the spin-up analyses. 2001 had the same MAAT of -9.1 ^{o}C as the decadal mean.

Ground temperature measurements at 0.5 m intervals in the upper 5.5 m below grade were also available for 2001 from a thermistor cable installation at the site. The ground temperature data was used to estimate the Mean Annual Ground Temperature (MAGT) and Mean Annual Ground Surface Temperature (MAGST) for initializing the model temperature prior to spin-up (Figure 1).

2.2 Model domain

A one-dimensional model domain was developed to represent geothermal conditions to a depth of 50 m. The model domain was discretized into 0.01 m elements in the upper 8 m, followed by 0.1 m elements between 8 m and 20 m, and 1 m elements below 20 m.

2.3 Geothermal material properties

The model domain was divided into four stratigraphic soil layers considered representative of typical permafrost ground conditions in the western contiguous Canadian Arctic. The idealized stratigraphy consisted of a thin gravel cover overlying partially saturated sands and silts to the full model depth.

To define each soil layer, the density, porosity and degree of saturation was estimated, from which volumetric water content and the geothermal parameters of frozen and unfrozen heat capacity and thermal conductivity were calculated (e.g Andersland & Ladanyi, 2004). Built-in approximations of soil-freezing characteristic curves were applied to each layer based on simplified soil classifications.

2.4 Boundary conditions

A single year of climate data was used to drive the spin-up analyses using the numerical modelling software's Land-Climate Interaction (LCI) boundary condition. The climate variables used in the surface energy balance equation included recorded daily air temperature and wind speed, snow cover and conductivity, estimated albedo, ground cover (vegetation thickness), and an estimated sinusoidal function of solar radiation based on latitude. All climate functions were set to repeat after a 365-day cycle.

The boundary condition at the base of the model was assigned as a constant geothermal flux of 4.32 kJ/day/m^2 (e.g. Burn & Zhang, 2009).

Material properties and boundary conditions were consistent between analyses.

3 SPIN-UP ANALYSES

3.1 Initialization Temperatures

Three different initialization temperature profiles were investigated in separate spin-up analyses. The three profiles, shown on Figure 1, were as follows:

- **Case 1:** initialized at 0 °C (default)
- **Case 2:** initialized at -4 °C (~MAGT)
- **Case 3:** initialized with a steady-state thermal gradient developed between -5.6 °C (MAGST) at the ground surface and a geothermal flux of 4.32 kJ/day/m^2 at the base.

A rough estimate of MAGT at depth-of-zero-annual-amplitude was obtained from trumpet curve plots of measured ground temperature data from thermistors that were deep enough (5.5 m) to capture the approach toward the depth of zero annual amplitude. The value of (+/-) -4 °C was estimated by visually extrapolating the narrowing trumpet curve envelope to the apparent depth of zero annual amplitude.

For the gradient profile, MAGST was determined to be -5.6 °C by averaging the 2001 daily temperatures recorded at the ground surface at the reference site. The steady-state analysis generated an equilibrated thermal profile between -5.6 °C at the surface and -3.5 °C at 50 m depth.

3.2 Spin-up duration

Each spin-up analysis was evaluated at three specified durations of 70 cycles, 200 cycles and 500 cycles. In the first analysis (initialized at 0 °C), the spin-up analysis was also evaluated at 1000 cycles.

Since a single year of climate data was used for the spin-up analyses a cycle constitutes a single year. All spin-up analyses were simulated with 12-hour time steps with results saved annually on January 1.

4 RESULTS

Results of the three spin-up analyses are shown in Figures 2 through 4. Ground temperature progression with time is plotted at four depths (5, 10, 25 and 50 m) in each figure. The results are repeated in each figure for three progressively longer spin-up durations of a) 70 years, b) 200 years, and c) 500 or 1000 years. Temperature data corresponds to the modelled ground temperatures on January 1 of each year.

4.1 Case 1: Initialized at 0 °C

In the case where the model domain was initialized at 0 °C, temperatures throughout the domain appeared to be stabilizing after approximately 70 spin-up cycles (Figure 2a). Furthermore, the prescribed <5% threshold for percentage difference in cumulative energy transfer at the surface between cycles was satisfied after only 12 cycles (Figures 2a and 5). However, extending the spin-up duration beyond 70 cycles revealed that the thermal regime had not stabilized and in fact only did so after nearly 1000 years (Figures 2b and c). The near-surface (-5 m) temperature stabilizes first, followed in progression by -10 m, -25 m and -50 m depths.

This case demonstrates the significant amount of time required for the deep 50 m profile to respond to climatic forcing due to substantial latent heat effects of phase change when ground temperatures are initialized close to 0 °C. It appears that the plotted ground temperatures at 25 m and 50 m below grade are initially responding (warming) to the positive geothermal flux at the base, before peaking between 50 and 70 cycles and cooling back towards 0 °C as the deeper profile begins its lagged response to the cold climate influence at the surface (MAAT = -9.1 °C). It takes nearly 700 cycles before the base of the model domain re-freezes and another 200+ cycles to stabilize to its final (January 1) temperatures.

4.2 Case 2: Initialized at -4 °C (MAGT)

In Case 2 (Figure 3) temperatures throughout the model domain stabilize much faster than in Case 1, reaching equilibrium by approximately 200 cycles. The ground temperature at all depths remained below 0 °C throughout the spin-up duration. Similar to Case 1, the energy transfer criterion at the surface (Figure 5) is satisfied after only 8 cycles; much earlier than it takes for the deeper profile to reach a stable equilibrium.

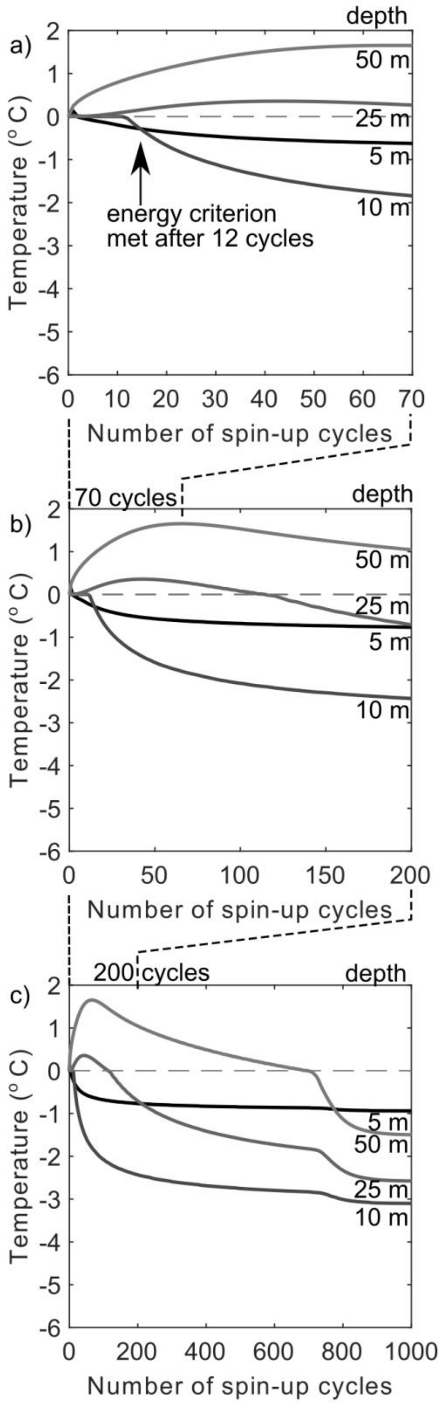

Figure 2. Ground-temperature evolution for different spin-up durations of 70, 200 and 1000 cycles; each initialized at a default temperature of 0 ºC (Case 1).

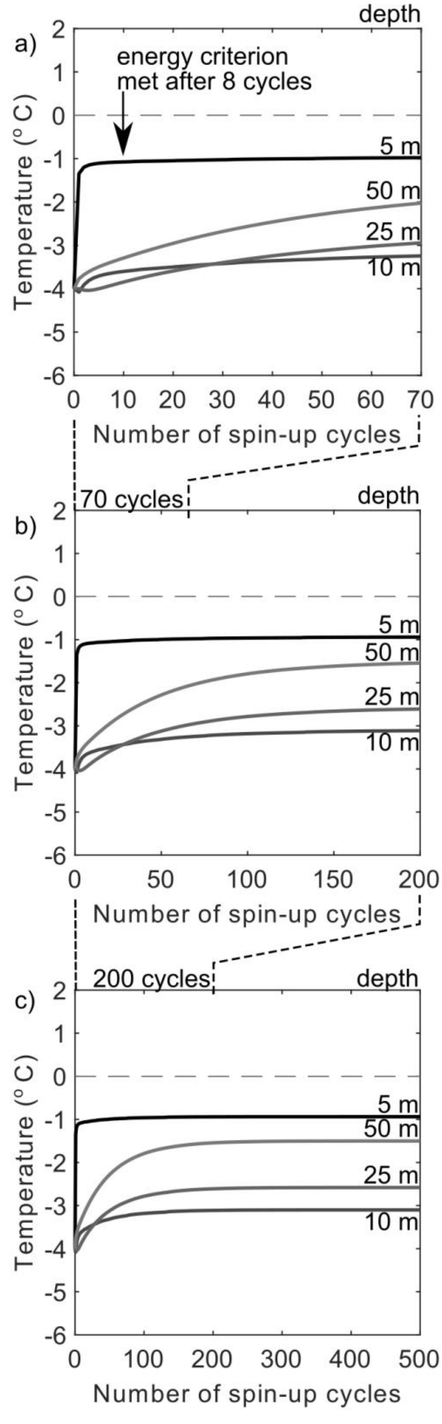

Figure 3. Ground-temperature evolution for different spin-up durations of 70, 200 and 500 cycles; each initialized at an estimated MAGT of -4 ºC (Case 2).

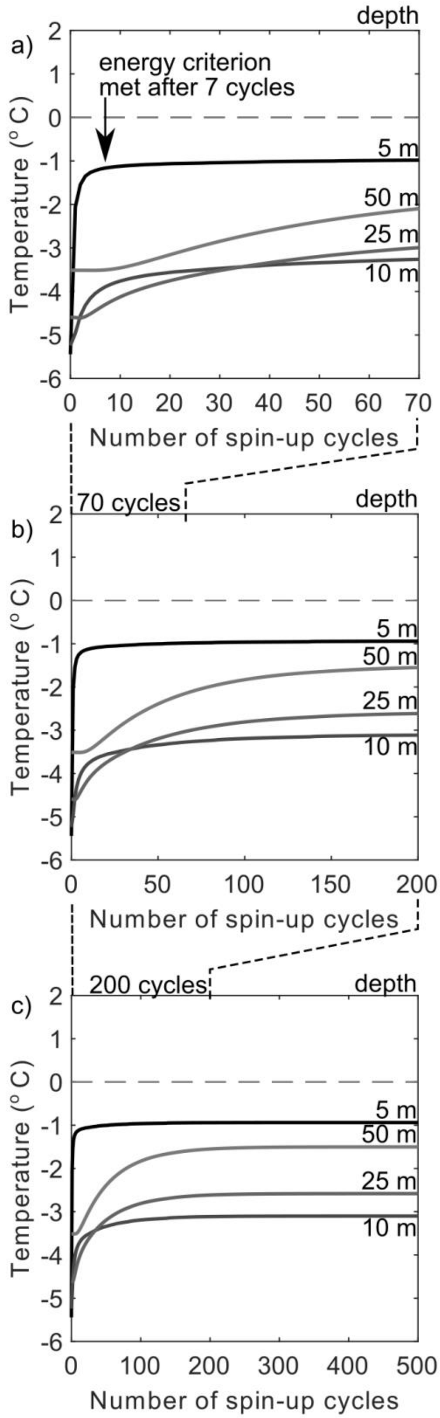

Figure 4. Ground-temperature evolution for different spin-up durations initialized with a steady-state geothermal gradient developed between MAGST and constant geothermal flux at the base (Case 3).

It appears that the energy criterion is met around the same time that the near-surface (-5 m) plotted depth stabilizes, perhaps an indication that this criterion is better suited to evaluating spin-up for shallow ground models only.

4.3 Case 3: Initialized Gradient

Case 3 (Figure 4) results in a similar temperature evolution as observed in Case 2. This can be attributed to the similar initialization temperatures between the two cases, particularly in the deep profile (refer to Figure 1); and their significant thermal offset from 0°C. A colder initialization temperature at the ground surface does not significantly increase the required the spin-up duration since the near-surface temperatures respond quickly to climatic forcing.

As in the previous cases, the energy transfer criterion is satisfied in a nominal number of cycles, around the time the near-surface temperatures stabilize but much sooner than the lower depths of the model domain have stabilized.

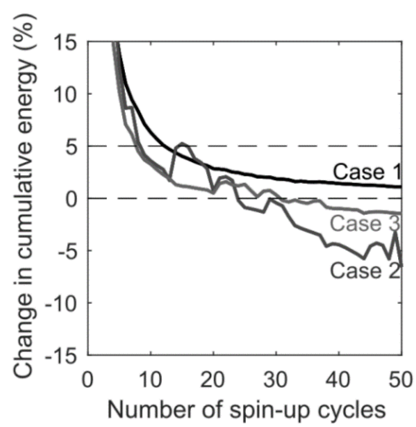

Figure 5. Percent change in cumulative energy transfer at the ground surface between cycles for each spin-up case.

The final stabilized temperatures at the four tracked depths are summarized in Table 1 and are equal for all three spin-up cases. The duration required to obtain a stable temperature to within three decimal places at the base of the model is also tabulated.

Table 1. End-of-spin-up ground temperatures (°C) at select depths, with spin-up duration for obtaining a stabilized thermal regime in each case.

Spin-up:	**Case 1 (0°C)**	**Case 2 (-4°C)**	**Case 3 (Grad)**
-5 m	-0.94	-0.94	-0.94
-10 m	-3.10	-3.10	-3.10
-25 m	-2.58	-2.58	-2.58
-50 m	-1.50	-1.50	-1.50
Duration (cycles):	906	192	198

5 DISCUSSION

The results illustrate the importance of careful spin-up planning when initializing a geothermal model. The results of Case 1 demonstrate the potential for prematurely assuming stabilization after a nominal number of cycles when temperatures approach a temporary maximum or minimum as they did around 70 cycles (Figure 2a).

In addition, established criteria for determining thermal stability, such as the percent change in cumulative energy transfer at the surface, may not apply to deep, relatively warm permafrost ground conditions. This criterion is more likely suited to modelling exercises evaluating shallow soil profiles undergoing seasonal freeze-thaw cycles such as the active layer in permafrost zones or the frost penetration depth in temperate zones.

Alternative criteria to define thermal stability in deep permafrost profiles are needed. Jafarov and others (2012) used a spin-up criterion that defined a stable thermal regime when maximum inter-cycle temperature differences at all levels in the domain dropped below 0.01°C. However, this criterion was also satisfied after only 70 to 80 cycles in all three cases evaluated in this study.

A more refined alternative may be when inter-cycle temperature change at all depths is less than 1/1000th of a degree for 10 or more consecutive cycles. This approach was used to establish the minimum spin-up duration presented in Table 1.

An approximate but reasonably accurate estimation of the MAGT at depth-of-zero-annual-amplitude can also greatly reduce the number of spin-up cycles required to obtain a stable thermal regime, particularly compared to a default initialization temperature of 0 °C.

In this study, an estimate of MAGT at depth-of-zero-annual-amplitude was obtained from trumpet curve plots of ground temperature data that were deep enough to capture the approach to the depth of zero annual amplitude. Alternatively, an initial estimate of MAGT may be taken from the Permafrost Map of Canada (Heginbottom, 1995) or from published relationships with MAAT (e.g. Smith & Burgess, 2000); however the latter are now generally considered too unreliable for practical use (Canadian Standards Association, 2010).

The actual MAGT at depth-of-zero-annual-amplitude associated with the 2001 climate forcing appears to be in the range of -2 to -3 °C (Table 1) based on the expectation that the depth of zero-annual amplitude occurs somewhere between 10 to 20 m below grade (Andersland & Ladanyi, 2004). This is warmer than the utilized value of -4 °C estimated from trumpet curve plots of ground temperature measurements in the top 5.5 m at site. There are a few reasons for this. First is that the annual temperature spread recorded in the deepest thermistor encompasses the actual and estimated values and a visual extrapolation within this range is inherently prone to some error. Secondly, the 2001 measured data may carry a lingering thermal ‘hangover’ from previously colder years, especially in the deeper thermistor beads.

Initializing the model with a thermal profile that varied with depth added unnecessarily complexity without reducing the required spin-up duration. As an alternative to the gradient developed in this study, the actual MAGT gradient for a given year or years may reduce the necessary spin-up duration, but recorded ground temperature data of sufficient depth is rarely available to generate the MAGT gradient.

Since near-surface temperatures will respond quickly to climate-forcing at the surface, it is recommended to initiate the thermal model at a reasonable estimate of MAGT at greater depth, such as depth-of-zero-annual-amplitude, prior to spin-up.

Once a representative, stable thermal regime has been established, further transient analyses may be conducted that apply additional thermal boundary conditions such as heat input or extraction from proposed infrastructure, or long-term climate warming. These subsequent analyses can be conducted with certainty that observed changes to the thermal profile are independent of the initial conditions.

6 CONCLUSIONS

A series of spin-up analyses were developed to test the influence of initialization temperature on the number of cycles required to obtain a stable thermal regime within a model domain representing a typical permafrost profile in the western Canadian Arctic.

Results indicated that initializing the model domain with a reasonable estimate of the mean annual ground temperature (MAGT) provided the greatest reduction in required spin-up duration to obtain thermal stability. Furthermore, a surface energy transfer criterion commonly used to determine when a spin-up model is sufficiently stable appeared not to apply when deep ground profiles at relatively warm permafrost sites are modelled.

The results of this study illustrate the importance of a well-developed spin-up model, particularly when the thermal evolution of deep permafrost is of interest in further transient analyses.

7 ACKNOWLEDGEMENTS

This work was supported by the Department of National Defense and the RMC Foundation at the Royal Military College of Canada.

8 REFERENCES

Andersland, O.B., Ladanyi, B. 2004. *Frozen Ground Engineering, Second Edition*. Hoboken, New Jersey: John Wiley & Sons, Inc.

Burn, C.R., Zhang, Y. 2009. Permafrost and climate change at Herschel Island (Qikiqtaruq), Yukon Territory, Canada. *Journal of Geophysical Research: Earth Surface*, *114*(2), 1–16.

Canadian Standards Association. 2010. *PLUS 4011-10 Technical Guide - Infrastructure in permafrost: A guideline for climate change adaptation* (1st Ed.). Mississauga, Canada

GEOSLOPE International Ltd. 2017. *Heat and mass transfer modeling with GeoStudio 2018 (Second Edition)*. Calgary, Canada

Heginbottom, J.A. 1995. *Permafrost Map of Canada 5th Ed.* Natural Resources Canada.

Jafarov, E.E., Marchenko, S.S., Romanovsky, V.E. 2012. Numerical modeling of permafrost dynamics in Alaska using a high spatial resolution dataset. *Cryosphere*, *6*(3), 613–624.

Lawrence, D.M., Slater, A.G. 2005. A projection of severe near-surface permafrost degradation during the 21st century. *Geophysical Research Letters*, *32*(L24401), 1–5.

Nishimura, S., Martin, C.J., Jardine, R.J., Fenton, C.H. 2009. A new approach for assessing geothermal response to climate change in permafrost regions. *Géotechnique*, *59*(3), 213–227.

O'Neill, H.B., Burn, C.R. 2017. Impacts of variations in snow cover on permafrost stability, including simulated snow management, Dempster Highway, Peel Plateau, Northwest Territories. *Arctic Science*, *3*(2), 150–178.

Riseborough, D., Shiklomanov, N., Etzelmuller, B., Gruber, S., Marchenko, S. 2008. Recent Advances in Permafrost Modelling. *Permafrost and Periglacial Processes*, *19*, 137–156.

Smith, S.L., Burgess, M.M. 2000. Ground Temperature Database for Northern Canada. *Geological Survey of Canada*, *Open File*, 28.

Stevens, M.B., Smerdon, J.E., Gonza, J.F., Stieglitz, M., Beltrami, H. 2007. Effects of bottom boundary placement on subsurface heat storage : Implications for climate model simulations. *Geophysical Research Letters*, *34*(L02702) 1–5.