# Numerical simulations of coupled groundwater flow and heat transport incorporating freeze/thaw cycles and phase change in a continuous permafrost environment



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## ABSTRACT

This study presents a series of numerical simulations to investigate the factors that control permafrost freezing and thawing in the shallow soil zone of the continuous permafrost environment at the Iqaluit Airport in Nunavut, Canada. A simplified conceptual model is first developed to represent the groundwater flow and thermal regime of the soil column and future climate scenarios are prepared based on those proposed by the IPCC (Intergovernmental Panel on Climate Change). A numerical model is then calibrated against ground temperatures. The calibrated model produced an excellent match with observed data and the mean absolute error is estimated to be 0.64 °C, which is 1.6% of the maximum temperature range. Numerical simulations reveal that under climate warming, conductive heat transport is the main driver for permafrost degradation at this site and that advective heat transport plays a minor role. This result can be attributed to the thaw front not migrating deeply enough into the ground to allow significant flow to develop and to the significant extent of low-permeability soil close to surface, which decreases the rate of flow and reduces the possible effects of thaw driven by advection.

## RÉSUMÉ

Cette étude présente les résultats de simulations numériques utilisées pour identifier les facteurs qui contrôlent les cycles de gel et de dégel du pergélisol de l'aéroport d'Iqualuit au Nunavut (Canada) sous l'effet des changements climatiques. Dans un premier temps, le modèle numérique fut calé pour représenter les conditions actuelles du climat puis les projections climatiques produites par le GIEC. En plus d'évaluer l'impact des changements climatiques sur le pergélisol, cette étude évalue également le rôle des processus de transport advectif de la chaleur sur le régime thermique du site d'étude. Les résultats obtenus avec le modèle couplant le transport advectif et conductif sont sensiblement les mêmes que ceux obtenus avec le modèle uniquement conductif. L'effet limité du transport advectif peut s'expliquer par la présence d'une couche de matériaux fins en surface limitant les écoulements horizontaux et la recharge et de ce fait limite le transport advectif de la chaleur.

## 1 INTRODUCTION

Climate variations at high northern latitudes induce frequent freeze and thaw cycles, which can have profound impacts on hydrogeological processes in cold regions and can adversely affect infrastructure. Permafrost thawing at the Iqaluit Airport, Nunavut, for example, has become a major threat to the stability and vulnerability of the existing roads and embankment structures. Subsidence resulting from permafrost thaw, as well as frost heave, frost cracks, ice wedges, and surface movements have increased maintenance costs for roads and have decreased their life expectancy.

Numerical simulations of groundwater flow and heat transport in some permafrost areas have been the subject of recent studies, including among others, Rowland (2011), Wellman et al. (2013), and McKenzie and Voss (2013). Kurylyk et al. (2014) states that more reliable predictions of permafrost behaviour in response to climate warming will require further research that considers advection in large-scale studies of cold regions, compares results obtained from numerical simulations against measured field data, and which includes climate warming models coupled with surface and subsurface coupled flow and heat transport models.

The purpose of the present study is to identify hydrogeological factors and environmental drivers that have the greatest influence on permafrost degradation at the Iqaluit Airport, based on future climate scenarios proposed by the Intergovernmental Panel on Climate Change (IPCC). Numerical simulations of coupled groundwater flow and heat transport have been designed to test the impact of plausible combinations of hydrogeological parameters and surface conditions on the temporal and spatial evolution of permafrost degradation on a typical cold region terrain.

An idealized conceptual model was first developed, based on the subsurface and surface flow characteristics and on climate conditions at the Iqaluit Airport. The conceptual model assumes that current conditions are representative of a typical cold-region paved terrain. Based on the conceptual model, a numerical model was developed and calibrated to reproduce measured ground temperatures. The calibrated model was then used as the reference model for subsequent simulations that test a series of scenarios aimed at investigating various climate change hypotheses.

The numerical model used here is HEATFLOW/SMOKER (Molson and Frind, 2015), which simulates density-dependent groundwater flow coupled with heat transport. It incorporates freeze/thaw cycles and liquid-ice phase change and accounts for latent heat. The results presented in this study include: 1) calibration, 2) simulation of ground temperature distributions for climate scenarios over the time periods 2013-2040, 2041-2070, and 2071-2100, and 3) analysis of the relative effect of advective versus conductive heat transport (Scenario 1).

#### 2 STUDY AREA AND CONCEPTUAL MODEL

A simplified conceptual model was developed based on the climate, hydrogeological and surface conditions at the lqaluit Airport, Nunavut, Canada, which is located in the south-eastern part of Baffin Island at the head of Frobisher Bay, at latitude 63°75' N (Figure 1a). The airport is built on a flat terrain located above a succession of glacial deposits and surrounded by hills and rocky plateaus of the Precambrian Shield, in a region of continuous permafrost.

The availability of data on hydrogeological units and ground temperature recorded along section A-A' across Taxiway Alpha was the primary reason for choosing the location of the conceptual model (Figure 1b).

At location (A-A') shown in Figure 1b, a basic twodimensional conceptual model was developed, which is representative of a typical cold-region paved terrain (Figure 2). The model extends 100 m horizontally and 50 m vertically, and represents the basic soil lithology obtained from a borehole analysis at Taxiway Alpha.

The distinct zones specified in the cross-section represent four different geological units, which vary from coarser (higher permeability) to finer (lower permeability). Zone 1 represents the bedrock which underlies Zones 2 and 3, which are relatively coarse to medium glaciomarine sediments and categorized as sand. A thin layer of lacustrine deposits composed mostly of silt (Zone 4) overlies the medium soil and extends from the left side of the domain to the sub-embankment material (Zone 5). The road embankment material is considered to be gravel and sand, which is covered with a thin 10 cm layer of paved asphalt material. The hydraulic and thermal properties considered for the different geological units are presented in Table 1.

#### 2.1 Boundary and initial conditions

The bottom and left boundaries of the domain are assumed to be impermeable for groundwater flow. A specified head is assigned to the vertical right boundary of the domain to allow groundwater to leave the system. For the sake of simplicity, recharge is accounted for by assigning a fixed sloping groundwater elevation at the top of the domain.

The head variation associated with the water table starts from the far left top node with a head of 49 m, then decreases linearly across the top of the domain with a fixed hydraulic gradient of 0.001 (resulting in a recharge rate that is representative of that expected in the region).

For heat transport, a time-varying air temperature is assigned to the upper surface heat-exchange boundary, both for the current conditions for the calibration step and



Figure 1. a) Location of the Iqaluit Airport, Nunavut, Canada, at the south-eastern part of Baffin Island at the head of Frobisher Bay. The coordinates for the airport are 63.75° N and 68.54° W. b) Taxiway Alpha and the location of the 2-D cross-section transverse to the taxiway, which is the focus of the present study.

for scenarios that investigate climate warming. A zero conductive heat-flux condition is assigned along the vertical sides of the system. A geothermal heat flux of  $0.03 \ (W/m^2)$  is applied along the lower model boundary based on the thermal conductivity and geothermal gradient of a typical shallow granite-gneiss bedrock (Leblanc et al. 2015).

The initial temperature considered throughout the domain is -5 °C which is the current mean annual ground temperature.

To simulate the current permafrost distribution under Taxiway Alpha at the airport, the idealized conceptual model was first run by applying the monthly air temperature variations observed during the 1971-2012 period under quasi-steady conditions, until equilibrium was reached.



Figure 2. Outline of the two-dimensional vertical conceptual model developed in this study for the location indicated in Figure 1b. The surface condition includes a snow cover over a length of 22 m at the left and right extremities and a nosnow surface in the central portion, over a length of 56 m. A 1 m unsaturated zone is considered for the heat transport system. The hydraulic and thermal properties assumed for the different geological units are presented in Table 1.

Table1.	Properties of	of the hyd	rogeological	units (z	zones)	shown in	Figure 2	(measured	or estimated	from li	terature)
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	Layer	Porosity (-)	Density of solid grains (kg/m <sup>3</sup> )	Thermal conductivity of solid grains (J/ s m °C)	Specific heat of solid grains (J/kg °C)	Hydraulic conductivity (m/s)
Zone 1	Bedrock *	-	2600	3.0	800	-
Zone 2	Coarse sand	0.25	2650	2.9	732.7	10 <sup>-04</sup>
Zone 3	Fine sand	0.47	2650	2.9	732.7	10 <sup>-05</sup>
Zone 4	Silt	0.50	2650	2.9	732.7	10 <sup>-07</sup>
Zone 5	Embankment	0.11	2650	2.9	732.7	10 <sup>-06</sup>
-	Asphalt	-	2100	1.5	976	-

#### 2.2 Observed climate data and warming scenarios

Iqaluit's observed annual air temperature and total annual precipitation for 1971-2012 were obtained from the online database available from the Environment Canada website for an adjacent station. The mean annual air temperature during the period 1971-2012 is estimated at -9.08 °C, with a minimum and maximum annual temperature of -27.1 °C and 8.0 °C, respectively. The total annual precipitation is 420.16 mm.

To generate the future climate data for the Iqaluit Airport, 24 different GCM models (global circulation models) are used from AR4 (IPCC, 2007) over 30-year periods for the time series from 2011 to 2100. The reference period is 1971-2000 and the three emission levels used are B1 (optimistic), A1B (moderate) and A2 (pessimistic). The GCM output was downscaled with the delta change method (Roosmalen et al. 2007) to project the future climate input for all scenarios. The climate data used here is from Scenario A2, which projects the maximum rate of temperature increase over the 21<sup>st</sup> century.

Scenario A2 for the periods of 2011-2040, 2041-2070 and 2071-2100 predicts annual temperature increases of 1.46 °C, 3.02 °C, and 5.22 °C, and increases of 12.8%, 18.6%, and 29.4%, respectively, in total annual precipitation, with respect to the reference data for the period 1971-2000 in which the mean annual air temperature is -9.65 °C with a total annual precipitation of 412.5 mm.

## 3 NUMERICAL MODEL

HEATFLOW-SMOKER is a finite element code that simulates three-dimensional density-dependent groundwater flow coupled with heat transport, incorporating freeze-thaw cycles and liquid-ice phase change (Molson & Frind 2015). The model accounts for effects of freezing involving temperature-dependent variations of density, viscosity, thermal conductivity, heat capacity, relative permeability, latent heat released or absorbed during the freezing of water and thawing of ice, respectively, and unfrozen water content changes. The model can be applied to solve fully-saturated flow and includes an option to account for a partially-saturated zone for thermal transport. To evaluate the numerical stability of the HEATFLOW/SMOKER model, the code was verified against a number of benchmark problems including analytical solutions presented by Lunardini (1985) and using benchmarks from the INTERFROST consortium (Grenier et al. 2015).

An exponential unfrozen moisture content function is used for all simulations. This function relates the fraction of unfrozen water content to temperature changes over freezing and thawing cycles. The residual unfrozen water content is assumed to be 0.2 which applies at a temperature of about -5 °C. The temperature changes affect the permeability of the frozen soil, which increases as the permafrost melts and the unfrozen water content increases.

## 4 RESULTS

#### 4.1 Model Calibration

The objective of this calibration is to define a reference model that is representative of the possible permafrost dynamics and subsurface hydrogeological conditions under a cold-region paved surface. The coupled heat transport and groundwater flow model is calibrated against ground temperatures measured in 2012 with a thermistor cable installed approximately 3 m from the paved road, on the south side (Figure 3). The thermistor cable was inserted into a borehole that was drilled to a depth of 15 m and that intersects 2 m of the embankment material and 13 m of the underlying sediments. The best match obtained between the observed and simulated data for 2012 is presented in Figure 3. The grid size is uniform in the horizontal direction (1m) but varies vertically with a layer discretization of 1, 0.5, and 0.05 m from bottom to top. The time step in all simulations is  $\leq$  1 day. To reproduce the observed temperatures, the following parameters were adjusted: heat flux across the surface thermal exchange layer, surface snow thickness, freezing functions, thermal properties of the shallow soil layers, and characteristics of the unsaturated zone.

As shown in Figure 3, for both simulated and measured temperature profiles, the maximum thickness of the active layer is 2 m (at 48 m elevation), where the zero-

temperature line intersects the maximum monthly mean temperature curve. The mean absolute error (MAE) averaged over 1 year at all depths is 0.64  $^{\circ}$ C, which is only 1.6% of the maximum temperature range at ground surface.



Figure 3. One-dimensional simulated and observed ground temperature profiles, showing minimum, maximum and mean annual values for 2012. The observed data is obtained from a thermistor cable inserted in an embankment 3 m away from the south side of the road and extending to a depth of 15 m below surface.

#### 4.2 The role of groundwater flow

Scenario 1 (SE-1; Cases 1-2) assesses the impact of groundwater flow on permafrost thaw at the Iqaluit site. A simulation with only conductive heat transport (Case 1) is compared to a conduction-advection controlled system (Case 2). The calibrated conceptual model shown in Figure 3 is used as the reference model for the cases considered here. The difference between the two cases results from the surface flow boundary, wherein for coupled groundwater flow and heat transport, a fixedgradient water table is applied at the top surface, thus introducing a component of advective heat transport. This water table gradient, with the associated soil hydraulic conductivity, produced a realistic groundwater recharge rate for the Igaluit study site. Flow velocities were simply deactivated (assumed negligible) in the conduction-only case.

The designed simulation cases were run under climate scenario data obtained from 24 different GCM models of AR4 (IPCC, 2007) over 28-yr and 30-yr periods for the time series from 2013-2040, 2041-2070, and 2071-2100. These simulations included seasonal air temperature variations with an average increase of 3.2 °C over 90 years (2011-2100) compared to the reference period of 1971-2000 with a mean annual temperature of -9.65 °C. The temporal and spatial location of the active layer was selected as an indicator by which the difference between the contributions of the two cases to permafrost thaw will be distinguished.

Temperature distributions over a period of 88 years as

a result of conduction and advection are presented in Figure 4a and 4b, showing the temperatures for September of the last year of each simulation period, which represent the 28<sup>th</sup>, 58<sup>th</sup> and 88<sup>th</sup> year, respectively.

In a conduction-controlled system, the temperature propagation in the ground, where the effects of warm surface temperatures become less at a greater depth, is not uniform, with higher thermal gradients at the sides compared to the central section of the domain (Fig. 4a). This result can be attributed to the presence of snow at the sides of the taxiway, which prevents heat loss in previous months. The shoulder snow covers keep the underlying ground warmer than the central portion of the taxiway where no-snow conditions are assumed and where the ground surface is in direct contact with the air.

For the conduction-only cases (Fig. 4a), in the last year of 2013-2040, after 28 years of simulation, the initial thaw rate from surface occurs faster at the center. However, due to increasing air temperatures from 2071-2100, after 88 years, the thaw front migrates deeper at the right side of the domain, as the conductive thermal transport from the surface is higher in the coarse sand with lower porosity, allowing a greater penetration of heat into the ground via conductive heat transfer.

In the coupled conduction-advection controlled system (Fig. 4b), the simulated ground thermal regime is similar to the conduction-only case. For the 2013-2100 periods, accounting for groundwater flow did not produce significant differences, and the simulated soil temperature variations are similar to those for the conductive-controlled model.

The depth of the seasonally active layer as a function of distance along the transect, for both cases considered, is depicted in Figure 4c. The initial location of the active laver in the calibrated model in 2012 is also shown. For all simulations, the location of the thaw front (active layer depth) is considered to be the depth from surface to the freezing zone where the temperature reaches 0 °C. After 28 years of simulation for an average air temperature increase of 1.46 °C, the predicted depth of the thaw front shows almost no difference with respect to the initial location of the active layer simulated in 2012. The differences between the thicknesses of the active layer become considerable when the increase in air temperature reaches an average value of 3.02°C under the warming scenario period of 2041-2070. The maximum difference between the active layer depth after 58 years (2041-2070) and its initial depth in 2012 is 1.22 m, which is within the coarse sand (Zone 2). After 88 years (2071-2100), the active layer will grow considerably within all the different soil layers in the domain, wherein the maximum difference between the developed active layer and its initial location in 2012 is 6.6 m within the coarser soil zone.

For all scenarios, in the coupled conductive-advective heat transport case, the depth of the simulated thaw front is quite similar to the conduction-only case, with a maximum increase in thaw depth of about 0.89 m near the right (downgradient) boundary after 88 years (in 2100) when advection is included (Fig. 4c). Thus, the temperature distribution over the entire domain is primarily controlled by surface conductive heat transport. The active layer is deeper on the sides of the domain compared to the central section. At the far right side of the domain, within the coarse soil zone where the active layer thickness is greatest, the maximum increase of the active layer depth, with respect to its initial depth of 2.1 m in 2012, is 3.3 m and 8.7 m after 58 years and 88 years, respectively. At a distance of 73 m, where the model is calibrated against the data obtained from the thermistor cable, the maximum depth of the active layer ranges from 2 m (in 2012) to 3.9 m, within the coarse zone, after 88 years.

In general, as permafrost thaws seasonally as a result of conductive heat transport from the surface, groundwater flow should increase in the system, which can in turn induce further permafrost thaw driven by advection.

Figure 5 presents the simulated temporal and spatial formation of groundwater flow for the coupled groundwater flow and heat transport system. As the air temperature seasonally increases, the amount of unfrozen water content increases to a maximum value of 1. The relative permeability increases gradually as well, and based on the hydraulic conductivity of the soil (Fig. 6), and on the hydraulic gradient and porosity, the flow system evolves accordingly over time.

According to the specified freezing and relative permeability functions chosen for the models, some flow still occurs even below the freezing temperature and during the phase change.

The flow systems that are plotted in Figure 5, in addition to flow that occurs where the unfrozen water content is equal to 1, also include the relatively high flow rate zones that still exist below the freezing temperature (between temperatures of 0 °C to -2 °C), when ice-water coexist in the soil's pore space. During climate warming, there is downward flow into the system through the fixed water table boundary.

Flow is mostly horizontal throughout the system and water exits across the right boundary imposed as specified heads. In the highest hydraulic conductivity areas (green to red areas in Figure 6), which are due to a higher temperature-dependent unfrozen moisture content and a relatively higher intrinsic hydraulic conductivity of the soil, total flow increases in the system.

Most of the flow develops in the highly permeable coarse soil (Zone 2) at the right side of the domain, where the depth of the active layer was at its maximum in reference to the result depicted in Figure 4c.

## 5 DISCUSSION AND CONCLUSIONS

The role played by advective heat transport on permafrost thaw has been investigated numerically by, among others, Rowland (2011), Wellman et al. (2013), and McKenzie and Voss (2013). However, the findings regarding the interaction between groundwater flow and permafrost dynamics are limited and still need to be understood through numerical models for a range of different hydrogeological systems (Kurylyk et al. 2014).

One objective of the work presented here was to assess the impact of advection in a coupled heat transport



Figure 4. Conduction and advection-driven permafrost thaw under climate warming scenarios for the periods 2013-2040, 2041-2070, and 2071-2100. (a), (b) Temperature distribution for conduction and advection-controlled systems, respectively, and (c) the spatial and temporal depth of the active layer as a function of distance along the transect.





Head (m)

Figure 5. Simulated evolution of the groundwater flow system combined with equipotential lines in an advection-conduction controlled system, under climate scenario periods of 2013-2040, 2041-2070, 2071-2100.

system representative of the Iqaluit Airport, which represents a typical cold-region paved terrain.

For this objective, a simplified 2D conceptual model based on the subsurface hydrogeological, surface and climate conditions at the Iqaluit Airport was developed, a numerical groundwater flow and heat transport model was calibrated, and thermal behavior was predicted under different climate change scenarios. The contribution of advective heat transport in this case was relatively limited, with thermal conduction playing a more important role.

Numerical simulations with the HEATFLOW/SMOKER code for a period of 88 years under the highest climate warming rate, including seasonal air temperature fluctuations, show that conductive heat transport is the main driver for degradation of continuous permafrost. There are two possible explanations for these results. Figure 6. Effective hydraulic conductivity variations during the warming scenarios in the different soil layers, as permafrost thaws within a conduction-advection controlled system.

First, for the rate of temperature increase considered here, the thickness of the developing active layer that formed conductively was not deep enough due to the presence of less conductive finer material near the surface.

Thus the thaw front did not penetrate deeply enough into the ground to allow significant flow to develop in the system. Second, the soil characteristics, including the significant extent of finer soil (least permeable) from the left side of the domain under the embankment, decreases the rate of flow and reduces the possible effects of thaw driven by advection.

In contrast to conduction, the role of advection on permafrost thaw strongly depends on the distribution and configuration of the hydraulic conductivity of the subsurface deposits. Predicted increases in air temperature will increase the rate of permafrost thaw, which will increase the effective hydraulic conductivity of the soil, thus increasing the depth of the active layer and promoting greater groundwater inflow. Thus, a positivefeedback process develops which accelerates thaw. In addition to climate impacts, permafrost thaw controlled by advection is also controlled by the configuration of different near-surface soil layers which affects surface recharge rates. Well-sorted permeable surface layers can allow significant groundwater recharge to penetrate deeply into the ground, in contrast to less permeable soil layers which reduce advection-controlled thaw by decreasing the rate of flow into the active layer.

The simulation of coupled groundwater flow and heat transport presented in this study shows that, as a result of conductive heat transport, the maximum active layer thickness in the coarse soil (Zone 2) will reach 3.3 m and 8.7 m for the periods 2041-2070 and 2071-2100, under the highest climate warming-rate scenario.

Future work will consider the calibrated model presented here for the Iqaluit Airport to assess the influence of plausible combinations of hydrogeological parameters and surface conditions on the temporal and spatial evolution of permafrost degradation. The scenarios that will be considered include the presence of an unsaturated zone, the influence of snow cover, calculation of thaw settlements, impact of heterogeneity of subsurface glacial deposits and the influence of the unfrozen water content function.

The results obtained from the various simulations have provided insight into the interaction between the physical/thermal processes and the response between permafrost and the hydrogeological and climate conditions, which are issues of concern to hydrogeological studies in cold regions.

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