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Numerical simulation of ground thermal response in Canadian seasonal frost regions to climate warming

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Abstract

To ensure that public infrastructure can safely provide essential services and support economic activities in seasonal frost regions, the design of their foundation systems must be updated and/or adapted to the impacts of climate change. This objective can only be achieved, if the impact of global warming on the soil thermal behaviour in Canadian seasonal frost regions is well-known and can be predicted. In the present paper, the results of a modeling study to assess and predict the effect of global warming on the thermal regimes of grounds in three Canadian seasonal frost regions (Ottawa, Sudbury, Toronto) are presented and discussed. The results show that future climate changes will significantly affect the soil thermal regimes in seasonal frost Canadian areas. The simulation results indicated a gradual loss in the frost penetration depth due to the climate change, in the three representative sites. The frost period duration will be shorter due to climate change in the three selected regions and will completely disappear in Ottawa and Toronto. However, the impact of climate change would not appear clearly in the first 40 years "up to 2060". The response of the ground to the effect of climate change is a function of the geotechnical characteristics of the ground and the climate conditions. The numerical tool developed and results obtained will be useful for the geotechnical design of climate-adaptive transportation structures in Canadian seasonal frost areas.

Keywords: Climate change, Seasonal frost, Freeze–thaw cycles, Soils, Geotechnical, Foundation

Introduction

Seasonal frost soils constitute a complex topic in frozen ground engineering. Unlike in the permafrost region, where soil remains frozen at a temperature below 0 °C continuously for more than 2 consecutive years, soils in the seasonal frost region are seasonally frozen only during the winter season [19]. The complex thermo-mechanic behavior of seasonal frost grounds raises several issues related to the design of foundations and civil engineering facilities on these soils. The freezing–thawing cycle is a thermal sequence that affects the geotechnical properties and induces ground's heave or settlement movements [19]. Consequently, the impact of temperature on seasonal frost soils becomes significant. However, with a rapidly changing climate, the inadequacy of earlier seasonal frost ground theories and estimated seasonal frost depths has become apparent.

The prediction of climate change remains very challenging in the absence of precise estimation of how humans will behave in the future and how greenhouse gas emission will change [3]. Many studies were conducted on this topic [10], and all have raised serious warnings of rapid global warming. Canada has not been immune from this fast climate warming, and, in fact, the most recent climate change report issued by the Government of Canada points out that Canada's climate is warming at twice the rate of the global average, with the highest level of warming happening in winter [2, 4, 10]. The annual average temperature in Canada raised by 1.7 °C between 1948 and 2016 [26], approximately twice the rise observed for the Earth as a whole (0.8 °C for 1948–2016 according to Osborn and Jones [20]). Moreover, country-wide annual average temperature projections for the late century (2081–2100) range from an increase of 1.8 °C for a low emission scenario (RCP2.6; RCP = Representative Concentration Pathway) to 6.3 °C for a high emission scenario (RCP8.5), compared to the reference period 1986–2005 [10, 21, 26]. These representative concentration pathways (RCPs) (climate scenarios) include consideration of future greenhouse gas emissions, deforestation, population growth and many other factors in estimating future climate changes [10]. RCP2.6 denotes a low emission pathway with a change in radiative forcing of approximately 2.6 W/m^2, whereas RCP8.5 represents a pathway with continuous growth in GHG emissions, leading to a radiative forcing of roughly 8.5 W/m^2 at the end of the century [2].

However, there is a paucity of technical information/data about the impact of climate change on the thermal behaviour of seasonal frost soils. Previous studies were mainly conducted on permafrost soils. For example, Rasmussen et al. [22] established a numerical model to understand the present and future permafrost thermal regimes in Northeast Greenland [22]. The study concluded that permafrost temperatures down to 18 m will likely increase by + 1.5° to + 3.5 °C due to global warming. Correspondingly, Zhou et al. [27] provided a spatio-temporal simulation of permafrost geothermal response to climate change scenarios in a building environment [27]. They concluded that around the middle of this century, the active layer's thickness will likely increase at different rates underneath and around buildings due to climate warming.

While seasonal frost or no permafrost soil spreads over a large portion of the Canadian territory [23], understanding its complex thermal regime is still not addressed in the literature. Therefore, it is a relatively new topic that requires a serious focus due to the significant amount of infrastructure and facilities existing on these soils. The change of the ground temperature and the freezing–thawing frequencies in the Canadian seasonal frost region can induce exhaustive differential settlement movements and bearing capacity variations of the soil [19]. Therefore, many engineering structures, such as roads, bridges, transmission towers, solar panels, houses, built on seasonal frost soils, will face serious serviceability and safety issues related to the impact of climate change. Consequently, these structures will require higher maintenance cost, while their useful life span will significantly decrease, thus, jeopardizing the population safety and economic activities in those regions. All in all, understanding the impact of climate change on the Canadian seasonal frost region will help geotechnical engineers optimize the design and develop safe and cost-effective alternatives to construct resilient foundation systems and infrastructure to meet the climate change requirements.

Due to the lack of research on this topic, this modeling study has been undertaken to understand and assess the effect of climate change on the temperature distribution and variation in grounds located in the Canadian seasonal frost region. Thus, the main objectives of the present paper are: (i) to present the developed approach/tool for modeling and assessing the impact of climate change on the ground thermal regime; (ii) to present and discuss the main results of the simulation of the effect of climate warning on the thermal regime of grounds located in the Canadian seasonal frost region. Three seasonal frost areas (Ottawa, Toronto, Sudbury), located in East-central Canada (Ontario, Canada), are selected in study.

The study area

Geographical description of the study area

The region of interest in this study is the seasonal frost area in Canada. This region extends from the Atlantic coast in the east to the pacific west coast, running mainly through the whole south of Canada [18] (Fig. 1). Due to the large geographical extent, three sites were selected in the seasonal frost region of Ontario (east-central Canada). These sites include Sudbury and Toronto to represent the center, the north, and the south of the Canadian seasonal frost region in Ontario, Canada.

Climate conditions of the study area

The climate of Ontario varies depending on the seasons and the locations [9]. For example, Ottawa has a humid continental climate with an average July maximum temperature of 26.6 °C and an average January minimum temperature of − 14 °C [17]. Summers in Ottawa are warm and humid. Ottawa annual precipitation averages around 940 mm;

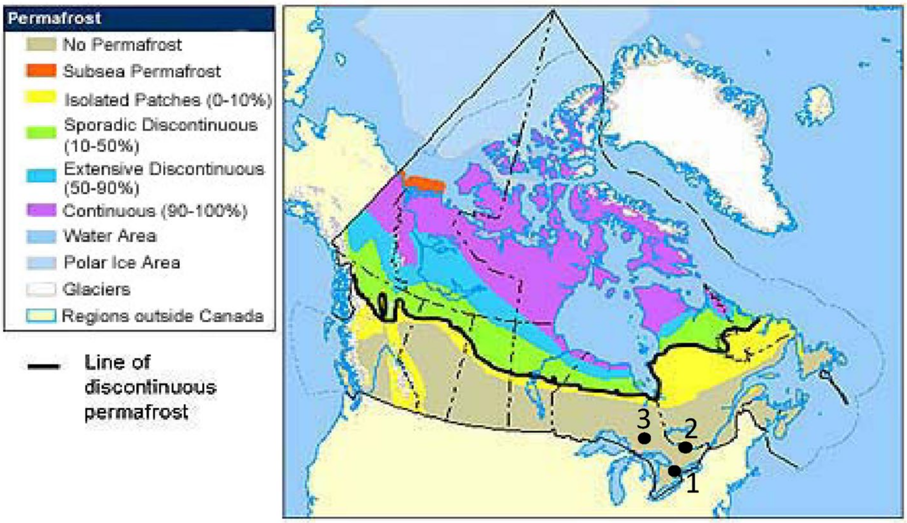


Fig. 1 The geographical limits of the Canadian seasonal frost (or no permafrost) region (modified from [1], 1: Toronto site; 2: Ottawa site; 3: Sudbury site)

snowfall occurs in early November and last for 5 months. Snow and ice are dominant during the winter season, with an average of 224 cm of snowfall annually [17]. Rainfall occurs mostly in summertime. The frost season in the Ottawa region starts early November and lasts until early May [17].

Toronto lies farther south than Ottawa, resulting in significantly warmer winters. The winter in Toronto is cold and temperatures are usually below 0° [16]. The average January maximum and minimum temperatures are −2 °C and −9 °C, respectively. The summer months are characterized by high temperatures with an average July maximum temperature of 27 °C. Toronto receives around 800 mm of precipitations per year, mostly in summertime. Precipitation is evenly distributed throughout the year, but summer is usually the wettest season. The frost season in the Toronto region starts early December and lasts until mid-April [16].

Sudbury is located farther north at the edge of the Canadian seasonal frost region. Therefore, the winter season is long, snowy, and very cold [15]. Sudbury has a humid continental climate, with an average January minimum temperature of −18 °C. The snow cover is expected 6 months of the year. The frost period's duration is approximately 180 days starting from early October to the end of April. The average yearly precipitation is about 540 mm in Sudbury [15].

Climate change models in the study area in the next 100 years

Temperature data gained by Climate Canada have indicated that annual and seasonal mean temperatures across Canada have increased, with the greatest warming occurring in winter. Between 1948 and 2016, the mean annual temperature increase is 1.7 °C for Canada as a whole [2, 10]. To project future temperature or climate changes across Canada, Climate Canada has adopted three different future climate scenarios (RCPs) [13], RCP8.5 (high global emission scenario), RCP4.5 (medium global emission scenario) and RCP2.6 (low global emission scenario). Tables 1, 2, and 3 show the projected average

Table 1 Climate change data—Ottawa [11]

Ottawa	RCPs	Annual minimum temperature change	Annual mean temperature change	Annual maximum temperature change	Annual precipitations change (%)	Annual snow depth change (%)	Annual surface wind velocity change (%)
2021–2040	8.5	+1.6	+1.5	+1.5	+3.6	−32.3	−1.1
	4.5	+1.2	+1.3	+1.6	+3.0	−33.0	−5.1
	2.5	+1.2	+1.3	+1.4	+3.5	−26.5	−0.2
2041–2060	8.5	+3.0	+2.9	+2.8	5.9	−55.1	−1.7
	4.5	+2.2	+2.3	+2.3	4.7	−46.4	−5.7
	2.5	+1.7	+1.7	+1.8	+2.5	−44.6	0.2
2061–2080	8.5	+4.6	+4.4	+4.3	+8.6	−67.9	−2.4
	4.5	+2.9	+2.8	+2.7	+4.5	−52.3	−6
	2.5	+1.7	+1.7	+1.7	+3.6	−49.5	0.5
2081–2100	8.5	+6.1	+6.0	+5.7	+10.3	−80.2	−2.6
	4.5	+3.2	+3.2	+3.1	+6.3	−56.0	−6.5
	2.5	+1.6	+1.7	+1.8	+3.5	−42.7	+0.3

Table 2 Climate change data—Toronto [11]

Toronto	RCPs	Annual minimum temperature change	Annual mean temperature change	Annual maximum temperature change	Annual precipitations change (%)	Annual snow depth change (%)	Annual surface wind velocity change (%)
2021–2040	8.5	+1.5	+1.5	+1.5	+3.0	−43.7	−0.9
	4.5	+1.4	+1.5	+1.5	+2.2	−44.7	−5.8
	2.5	+1.3	+1.3	+1.3	+2.1	−39.3	−0.7
2041–2060	8.5	+2.8	+2.9	+2.9	7.8	−66.2	−1.4
	4.5	+2.2	+2.2	+2.4	+3.9	−58.4	−6.5
	2.5	+1.8	+1.7	+1.8	+2.9	−50.6	−0.3
2061–2080	8.5	+4.4	+4.3	+4.3	+8.0	−78.9	−1.8
	4.5	+2.8	+2.7	+2.6	+5.8	−66.2	−7.7
	2.5	+1.7	+1.8	+1.8	+4.0	−59.2	+0.0
2081–2100	8.5	+5.6	+5.6	+5.5	+14.6	−85.3	−3.0
	4.5	+3.1	+3.1	+3.0	+6.2	−65.9	−8.2
	2.5	+1.8	+1.8	+1.8	3.30	−54.60	−0.20

Table 3 Climate change data—Sudbury [11]

Sudbury	RCPs	Annual minimum temperature change	Annual mean temperature change	Annual maximum temperature change	Annual precipitations change (%)	Annual snow depth change (%)	Annual surface wind velocity change (%)
2021–2040	8.5	+1.6	+1.5	+1.5	+3.9	−36.7	−0.7
	4.5	+1.3	+1.4	+1.5	+2.9	−34.4	−6.0
	2.5	+1.2	+1.3	+1.4	+2.4	−31.6	0.3
2041–2060	8.5	+3	+2.9	+2.8	+8.9	−57.7	−1.6
	4.5	+2.2	+2.2	+2.3	+5	−49.2	−6.8
	2.5	+1.6	+1.7	+1.8	+4.5	−47.5	−0.1
2061–2080	8.5	+4.6	+4.5	+4.4	+0.5	−69.5	−2.3
	4.5	+2.9	+2.8	+2.7	+5.3	−53.2	−7.0
	2.5	+1.7	+1.7	+1.8	+2.8	−51.2	+0.1
2081–2100	8.5	+6.1	+6.0	+5.7	+9.6	−80.1	−2.9
	4.5	+3.2	+3.2	+3.1	+7.4	−58.0	−7.7
	2.5	+1.7	+1.7	+1.7	+3.4	−45.6	−0.1

change in temperature and precipitations in Ottawa, Toronto and Sudbury and under three emissions scenarios (RCPs) for four future time periods: 2021–2040; 2041–2060; 2061–2080; 2081–2100 [11].

Representative soil profiles of the study area

The Canadian seasonal frost region embraces several geological patterns; therefore, soils have dissimilar geotechnical and physical properties within this region [18]. Canada's national geological survey provides borehole logs of several sites among Canadian territory, including Ottawa, Toronto, and Sudbury. Accordingly, the geotechnical profiles of the three cities were developed based on the information included in the borehole logs of the national survey. Essentially, for the first 10 m into the ground, the soil composition comprises layers of clay, silt, sand and gravel. The bedrock layer was not detected in the representative boreholes [18]. Beside the soil profile, the borehole logs include recordings of the relative density, temperature of the soil with depth, and the P waves' velocity in the sublayers of the soil stratum [18]. The geotechnical composition and the geometry of the three selected sites for the thermal simulation are presented in "Modeling of the thermal responses of the selected sites to climate changes" section.

Methodology

Approach

Figure 2 displays the developed approach or method for assessment of the impact of future climate on the thermal regimes of grounds in the selected Canadian seasonal frost regions and the link between the different work stages of the studies performed. The method adopted comprises four main stages. The first stage (see "Description and validation of the thermal model" section) deals with the establishment of the simulation tool, which includes the determination of the suitable thermal model and its validation against field measurement data. The second stage (see "Climate data collection" section) involves the acquisition of the actual climate conditions and climate change predictions for the study area. The actual climate data was obtained from Environment Canada, whereas climate change predictions were gained from the climate change interactive maps published on the Climate Change Canada website [11]. Three climate change scenarios, RCP 2.5, RCP 4.5, and RCP 8.5, were considered in the present study, as mentioned earlier. The third

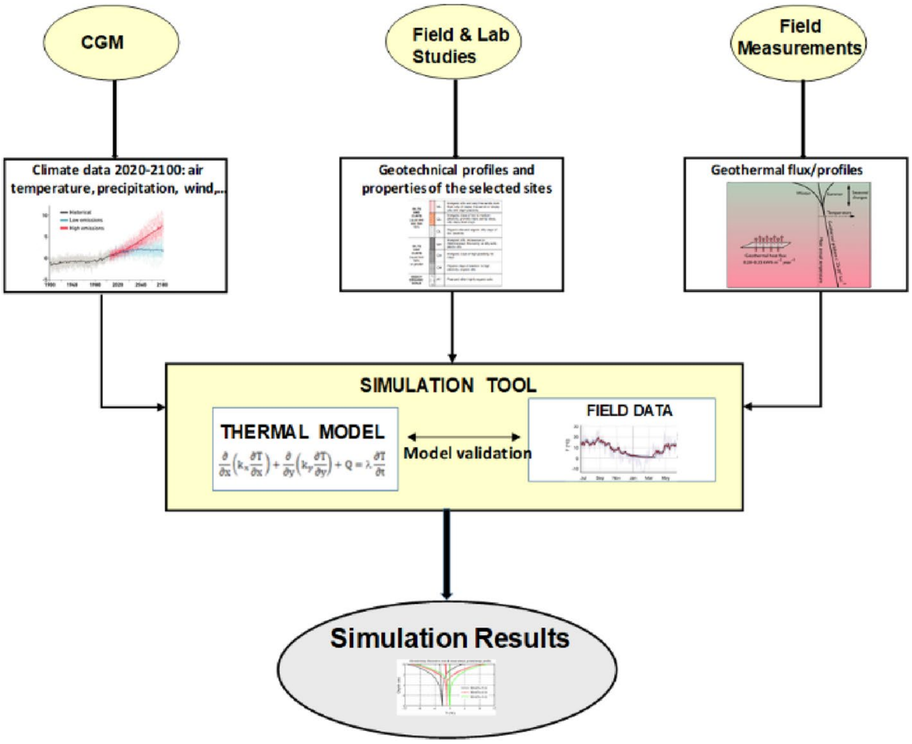


Fig. 2 Flow chart of the analysis

stage consists ("Geometry and material properties of the thermal models" section) of the acquisition of the required geotechnical, physical and thermal data of the grounds in the studied sites, which were used as input data in the modeling work to be conducted. In the fourth stage of this investigation ("Modeling of the thermal responses of the selected sites to climate changes" section), numerical modeling and simulations of the effect of future climates on the thermal responses of the grounds in the studied sites were conducted. Subsequently, the simulation results were integrated and analysed. The approach or method developed in this study can also be adopted or adapted to simulate the ground thermal regime under changing climate conditions in other seasonal frost regions in Canada or worldwide. The aforementioned stages are described in detail below.

Description and validation of the thermal model

TEMP/W software package from Geo-Slope International Ltd. [7] was used to develop a model of the ground thermal regime. TEMP/W provides a platform to simulate heat transfer through fully or partially saturated and fully or partially thawed material. TEMP/W includes five thermal different material models: no-thermal, interface, coupled convective thermal, simplified, and full thermal model. The simplified thermal option was used in this study for all the simulations. This model is used for problems in which the latent heat of phase change is not considered in the freezing process, and the phase change is assumed to occur at the phase change temperature instead of occurring over a range of temperatures [7].

General formulations

Temperature changes in the soil are driven by four modes of heat transfer: radiation, conduction, convection, and phase changes. The radiative heat transfer is dominant at the soil–air interface where the soil receives direct solar shortwave radiation [6]. The radiative heat flow is often negligible in the formulation of heat transfer in the soil for the following reasons. The effect of radiations decreases with depth. The influence of radiation on soil temperature is more prominent at the soil surface, where solar radiation can directly heat the top layer. However, when considering the impact of global warming on soil temperatures, the focus is typically on deeper soil layers, where radiation plays a minor role compared to conduction and convection. Moreover, in seasonal frost regions, the primary heat transport mechanisms are conduction and convection. These mechanisms are more significant compared to radiation in terms of heat transfer within the soil. In addition, soil has relatively low thermal conductivity, meaning it is a poor conductor of heat. This characteristic limits the effectiveness of radiation as a heat transfer mechanism in the soil. Soil contains various particles such as minerals, organic matter, and water, which can absorb and scatter radiation. This absorption and scattering process reduces the penetration depth of radiation into the soil, making it less effective in transferring heat. Likewise, the convective heat transfer due to gas flow at the soil surface is neglected because the volumetric heat capacity of gas is three orders of magnitude smaller than the volumetric heat capacity of the solid or liquid [19]. For the reasons described above, radiative and convective heat transfers were neglected in the present modeling study.

In most instances, conduction is the principal mode of energy transport in soils, although radiation and convection in very shallow layers also may transfer energy. Heat flow in soil can be considered analogous to heat flow in a solid to which Fourier's Law is applied:

Conduction equation:

$$q = -k * \left(\frac{dT}{dx}\right) \tag{1}$$

The heat flux, q (J/s), directly depends on the thermal conductivity, k (J/(s × m × °C)), and temperature change, T (°C), over a distance, x (m).

The differential equation that governs the formulation of 2D numerical solutions can be expressed as follows:

General 2D heat flow formulation [7]:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + Q = \lambda \frac{\partial T}{\partial t} \tag{2}$$

where T = temperature, kx = thermal conductivity in the x-direction, ky = thermal conductivity in the y-direction, Q = applied boundary flux, λ (J/(m^3 × °C) = capacity for heat storage, and t = time.

Steady-state formulation At steady state, the heat flux entering and leaving an elemental volume of soil are equal; therefore, the equation for 2D heat flow becomes:

2D heat flow formulation at steady state [7]:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + Q = 0 \tag{3}$$

Transient analysis formulation In the transient analysis, the heat flux entering and leaving an elemental volume of soil at a point in time are not equal; therefore, heat energy is stored in the soil matrix. The amount of heat energy stored depends on the thermal properties of the soil. The capacity to store heat "λ" is expressed as follows:

The capacity to store heat [7]:

$$\lambda = c + L\,\frac{\partial w_u}{\partial T} \tag{4}$$

where c = volumetric heat capacity (material property), L (J/m^3) = latent heat of water, wu = total unfrozen volumetric water content and T = temperature,

Substituting for λ in the main thermal equation leads to the complete 2D heat flow differential equation:

2D heat flow formulation at transient analysis [7]:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + Q = \lambda \frac{\partial T}{\partial t} = \left(c + L_w \theta \frac{\partial \theta_u}{\partial T}\right) \frac{\partial T}{\partial t} \tag{5}$$

where Q is the heat flux, kx and ky are the thermal conductivities in the x and y directions, λ the capacity for heat storage, t time. The capacity to store heat in the soil λ is composed of two parts: the volumetric heat capacity, c, that depends on whether the material is frozen or unfrozen, and L, the latent heat of fusion of the material. The latent heat calculation requires the volumetric water content, θ, the unfrozen volumetric water content, θu (m^3/m^3) and L_w the latent heat of water [7].

Validation of the thermal model/simulation tool

The model validation aims to verify the accuracy of the selected thermal models from TEMP/W software to simulate the ground thermal regime. For this purpose, field measurement data from previous geotechnical investigations conducted in the region of the national capital, Ottawa [5] were used in the validation.

Model geometry and material properties The geometry of the validation model is retrieved from a past geotechnical report of National Research Council Canada, which included temperature measurements of soil temperature from May 1954 to April 1955 under snow cleared surface [5]. The model geometry extended 15 m laterally from the centre line and 5 m below the natural ground surface. Different geometries that increased the lateral extent to 40 m were tested; however, the isotherms (temperature contours) beyond 30 m were the same and did not affect the results. The temperature measurements provided in the geotechnical report were given to a depth of 5 m; therefore, the depth of the model was selected as 5 m [5]. Mesh properties can be modified so that certain geometric objects can have a finer mesh or a different pattern of mesh elements such as triangles or quadriparas [6]. A square mesh of 0.2 m diameter was selected. Finer dimensions were tested; however, the software could not establish the analysis due to storage limitations.

All materials were modelled using a simplified thermal model, which requires the volumetric heat capacities (cu and cf), thermal conductivities (ku and kf), the in-situ volumetric water content (VWC), and the unfrozen volumetric water content [7]. The Thermal properties used in the validation model were selected from previous studies on the Ottawa clay soil. The soil is assumed to be fully saturated. The soil properties are summarized in Table 4 [19].

Boundary conditions The validation model featured two analyses; a steady-state and transient analysis. The steady state analysis aims to establish the thermal equilibrium in the soil during the first day of the transient analysis. At a steady state, the top boundary condition is set to the average annual temperature in 1954. A constant unit heat flux representing the geothermal gradient was applied to the model's bottom extent as shown in Fig. 3. Geothermal gradients vary by location but generally range between 0.9 and 3.3 °C per 100 m [12]. A constant unit flux of 3.87 kJ/m^2·day was used for Ottawa based on the Geothermal Map of Canada published in 2009 [12].

Table 4 Thermal properties of the validation model [19]

Soil type	ϴ, m^3/m^3	Unfrozen thermal conductivity, kj/d/m·°C	Frozen thermal conductivity, kj/d/m·°C	Unfrozen volumetric heat capacity, kj/m^3/°C	Frozen volumetric heat capacity, kj/m^3/°C
Ottawa clay	0.4	191 (2.21 W/m·K)	562 (6.51 W/m·K)	6556 (6556 kj/m^3/K)	4683 (4683 kj/m^3/K)

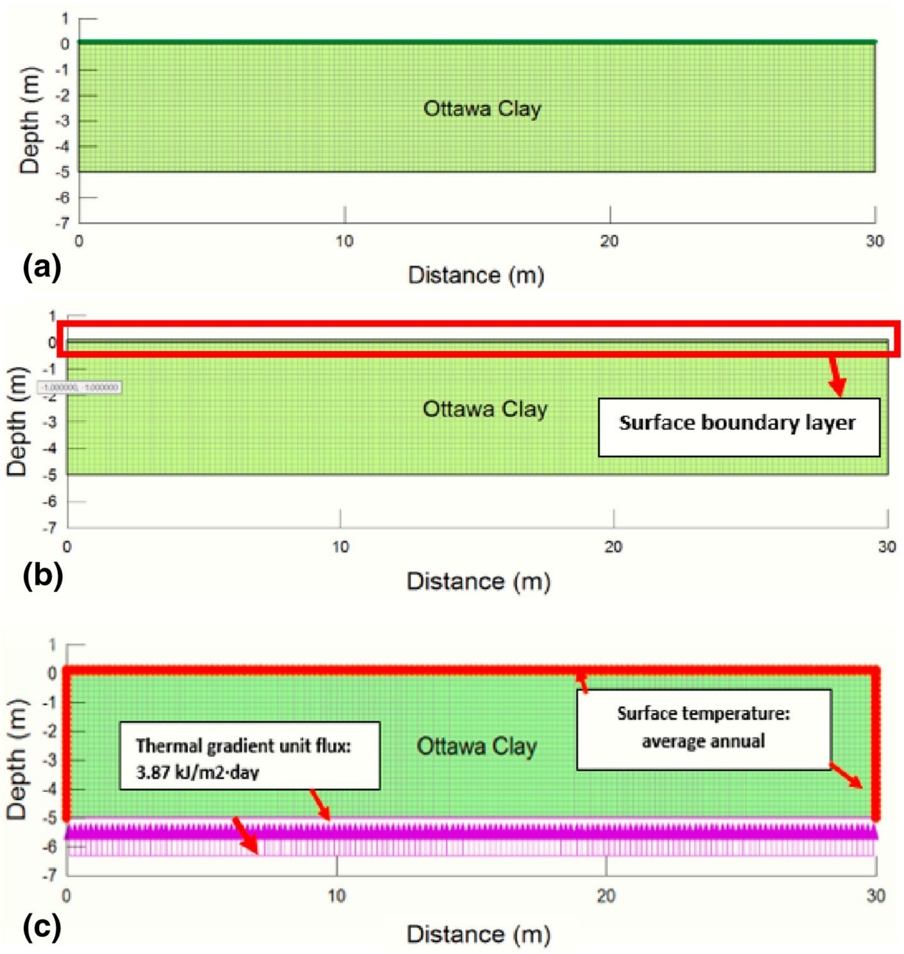


Fig. 3 **a** Cross section of the validation model, **b** Model surface boundary layer, **c** steady state boundary condition

The transient analysis comprises a whole year of climate data. The climate data was obtained from the Environment Canada website. Climate data was downloaded for every day from the first day of May 1954 to the last day of April 1955 [9].

Climate boundary condition-validation model The OTTAWA CDA weather monitoring station is a part of the cooperative climate network and it is located at the Horizontal coordinates "Lat: 45.38, Long: −75.72". It provides a complete set of climate data for the national capital region [9].

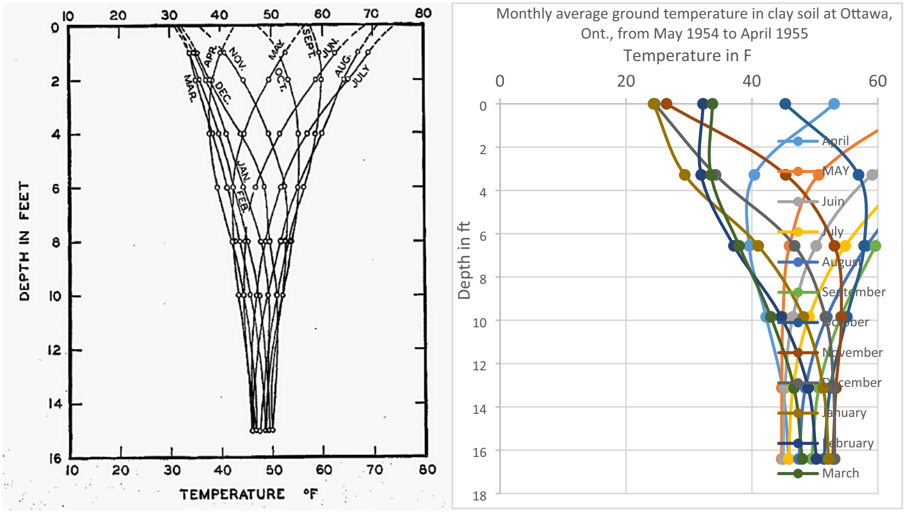
The climate boundary condition developed by TEMP/W required several input parameters which included: maximum and minimum daily temperatures, maximum and minimum daily relative humidity, daily average wind speed, and daily total precipitation. The latitude was set at 45.38° north to incorporate solar radiation's effects [9]. A thin layer of finite elements called a surface layer was required at the top surface to apply the climate boundary condition in a TEMP/W model [7].

To account for the fact that the air temperature at the surface differs from the ground temperature, even at shallow depths, "n" modifying factors were required. "n" factors are empirically based coefficients used to estimate ground surface temperatures based on air temperatures [19]. The n-factor is the ratio between thawing and freezing indices of the ground surface and the air [19]. They vary depending on the geographic location and surface cover. Both the freezing and thawing n factors are required in the TEMP/W analysis.

Recommended n-factors were used based on values provided in TEMP/W manual. For a bare soil, the recommended thawing and freezing factors are respectively: $n_{th} = 1.4$ and $n_f = 0.7$ [7].

Discussion of the validation results The data provided in the National Research Canada report includes the monthly average temperature of an Ottawa clay soil between May 1954 and April 1955 [5]. The measured field temperature graphs are represented in Fig. 4a. Ground temperature is provided for each month along the whole year. The validation model provides daily ground temperature measurement for an Ottawa clay ground; were processed to develop average monthly temperature graphs of the Ottawa clay ground similar to the National Research Council Canada graphs. The results of the validation simulation are presented in Fig. 4b [5].

The simulation results obtained are approximately similar to the original (measured) ground temperature data. First, the validation model established similar thermal regimes in both the cold and the warm seasons. The graphs of the monthly average temperature in both seasons have approximately the same trend and shape as in the National Research Council Canada's original report. Some divergence was observed from the original temperature ground data at shallow depths (from 0 to 4 ft). Nevertheless, at a depth of 6 ft, the thermal model succeeded in simulating the original temperature data to a large extent. For instance, at 6 ft, the temperature spectrum ranges between 38 and 58 F in the original and the simulation data. Likewise, the temperature spectrum at the bottom of the model ranges between 45 and 52 F for the original ground temperature



(a) (b)

Fig. 4 Monthly ground temperature in clay soil at Ottawa from May 1954 to April 1955, **a** measured data, **b** modeling results data and between 43 and 55 F for the simulation results. Thus, the divergence at the bottom of the model is very minor.

The divergence at shallow depths could be due to several reasons; first, the validation model used material properties retrieved from a different source for the Ottawa clay due to the absence of any information about the material properties in the original report. Second, TEMP/W 2012 considers the conduction as the main heat transfer mechanism even at shallow depths [7]; nevertheless, on the actual site, other processes affect the thermal regime of the ground including convection and radiation. Finally, climate data for the year 1954–1955 were retrieved from the Environment Canada website, separately from the original report. Therefore, the climate data used to build the model could be slightly different from the actual climate data used in the original report. All these factors might influence the validation model and might lead to the observed slight divergences. All in all, the adopted thermal model and the simulation tool provided a good understanding of thermal regime of the ground and could be used to simulate the impact of climate warming on the thermal regime of the ground.

Climate data collection

It is commonly assumed that climate is relatively stable with no major climate changes within 20 years period [11]. So, for the aim of this study, climate conditions are defined in four-time segments of 20 years.

Climate data were collected from the Climate Canada website using projections map with temporal resolution available at a seasonal and annual scale and spatial resolution approximately 10 km [11]. The projection map provides information on the projected 20-year average changes in minimum, mean, and maximum temperature. It also provides information on the average change in precipitation, snow depth, and surface wind velocity.

These interactive maps (Fig. 5) simulate climate change under the main three emission scenarios; RCP2.6, RCP4.5, RCP8.5 for Four-time frames starting from 2019 until 2100 [10].

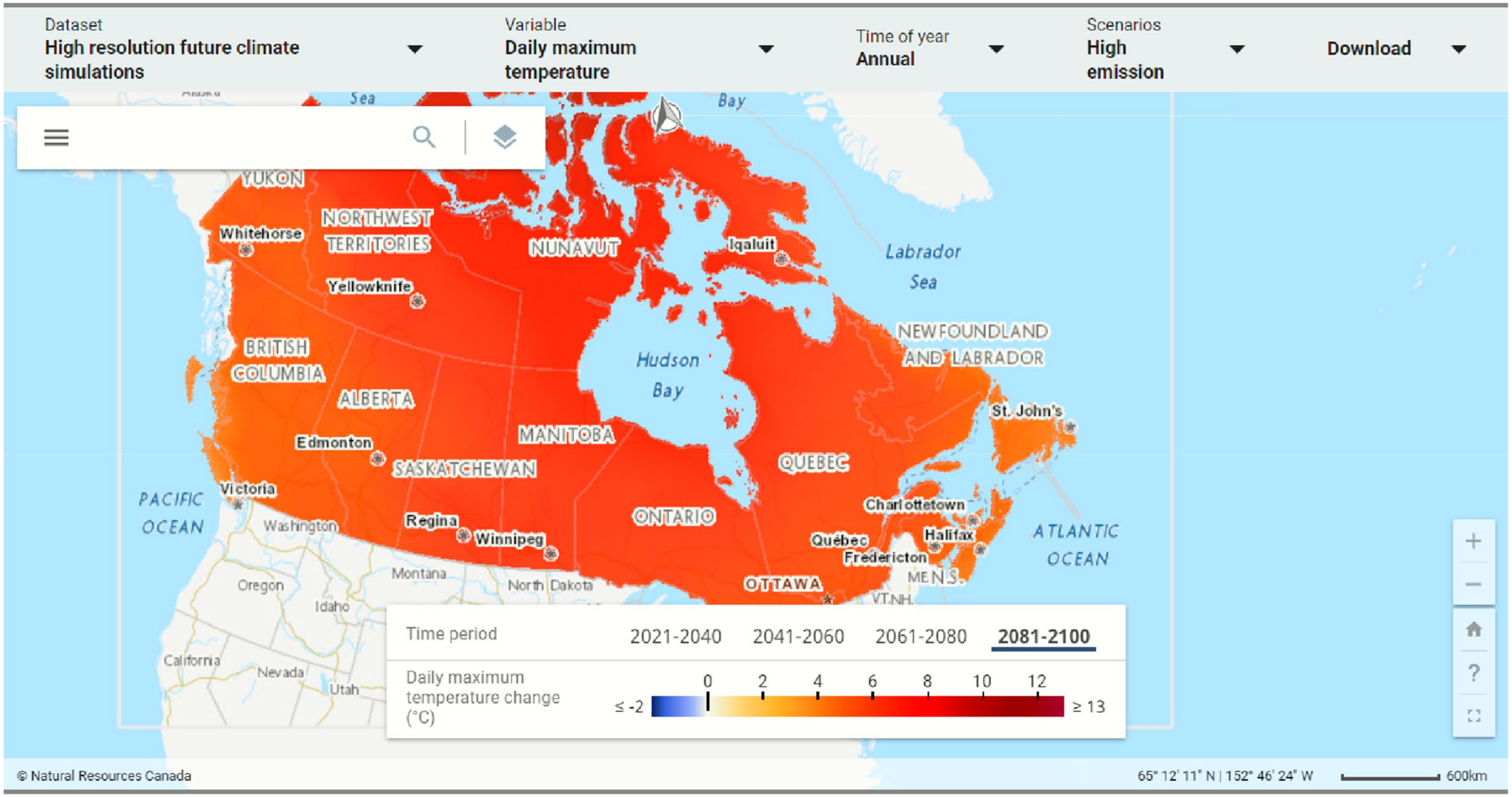
Climate change is evaluated relatively to the reference period from 1900 to 2005. Climate conditions in 2019 are assumed to be similar to these climate conditions of 2005 (within 20 years). Therefore, climate change is assumed to occur relative to the climate condition in 2019.

The actual climate data were collected from the climate Canada official website. The selected climate monitoring stations are summarized in Table 5 [11]:

Geometry and material properties of the thermal models

Geometry

The simulation models' geometry was retrieved from Canada geological survey records for Ottawa, Toronto, and Sudbury. Each model was developed based on two adjacent boreholes logs located at each city. All boreholes provide continuous information on the sub-surface geotechnical profile to a depth of 20 m [18]. The geometry of the three models extended 15 m laterally from the centreline, and 20 m below the natural ground surface. A thin layer of finite elements called a surface layer was required at the top surface to apply the climate boundary condition in a TEMP/W model [7]. The mesh properties



Dataset
High resolution future climate simulations

Variable
Daily maximum temperature

Time of year
Annual

Scenarios
High emission

Time period: 2021-2040 2041-2060 2061-2080 **2081-2100**

Daily maximum temperature change (°C): ≤ -2 0 2 4 6 8 10 12 ≥ 13

Fig. 5 Climate change interactive map [11]

Table 5 Climate stations at Ottawa, Toronto and Sudbury [11]

City	Name	Latitude	Longitude
Ottawa	OTTAWA CDA	45.38	− 75.72
Toronto	Toronto	43.67	− 79.4
Sudbury	SUDBURY A	46.63	− 80.8

are set to a finite square of 0.2 m diameter for the three simulation models. The selected mesh dimensions provided accurate simulation results compared to a larger mesh. The software did not allow to use of thinner mesh due to limited storage of the computer. Furthermore, thinner mesh require a longer computation time [6].

Material properties

The thermal properties required to build the thermal model are the volumetric heat capacities (cu and cf), thermal conductivities (ku and kf), the in-situ volumetric water content (VWC), and the unfrozen volumetric water content. The material properties were retrieved from literature for each material [19]. Tables 6, 7, and 8 summarize the thermal properties of simulation models for Ottawa, Toronto, and Sudbury, respectively:

Modeling of the thermal responses of the selected sites to climate changes

Boundary conditions

Steady-state boundary conditions At a steady-state, the boundary condition describes the initial thermal regime of the ground. A constant temperature was applied at the top boundary and the edges of the three models. It was assumed that at a steady-state, the ground surface temperature is equal to the average annual air temperature [7]. At the bottom extent of each model, a constant heat flux was applied to take into consideration the impact of the geothermal gradient. The heat flux value depends on the location but generally range between 0.9 and 3.3 °C per 100 m [12]. The thermal unit heat flux values

Table 6 Material thermal properties—Ottawa model [19]

Soil type	ϴ (m^3/m^3)	Unfrozen thermal conductivity (kj/d/m·C)	Frozen thermal conductivity (kj/d/m·C)	Unfrozen volumetric heat capacity (kj/m^3/K)	Frozen volumetric heat capacity (kj/m^3/K)
Brown silty clay	0.4	191.6	562.2	6556.3	4683.0
Grey soft silty clay	0.713	59.3	234.7	3488.7	2491.9
Grey Firm silty clay	0.7	65.5	235.0	3567.0	2547.9

Table 7 Material thermal properties—Toronto model [19]

Soil type	ϴ, m^3/m^3	Unfrozen thermal conductivity, kj/d/m·C	Frozen thermal conductivity, kj/d/m·C	Unfrozen volumetric heat capacity, kj/m^3/K	Frozen volumetric heat capacity, kj/m^3/K
Silty sand	0.52	84.9 (0.98 W/m·K)	83.1 (0.96 W/m·K)	1755.2	1253.7
Stiff grey silty clay	0.42	159.5 (1.84 W/m·K)	185.5 (2.15 W/m·K)	2519.8	1799.9
Dense silty clay	0.35	275.2 (3.19 W/m·K)	382.0 (4.43 W/m·K)	3438.3	2455.9

Table 8 Material thermal properties—Sudbury model [19]

Soil type	Θ, m^3/m^3	Unfrozen thermal conductivity, kj/d/m·C	Frozen thermal conductivity, kj/d/m·C	Unfrozen volumetric heat capacity, kj/m^3/K	Frozen volumetric heat capacity, kj/m^3/K
Clay	0.52	246.7 (2.85 W/m·K)	412.1 (4.78 W/m·K)	4261.2	3043.7
Silty clay	0.55	224.2 (2.60 W/m·K)	422.1 (4.89 W/m·K)	4635.1	3310.8
Clayey silt + trace of sand	0.52	171.1 (1.98 W/m·K)	240.7 (2.79 W/m·K)	3137.0	2240.7
Red clay	0.52	345.6 (4.00 W/m·K)	587.4 (6.81 W/m·K)	4771.7	3408.3
Sandy gravel	0.32	92 (1.07 W/m·K)	91.2 (1.06 W/m·K)	1831.0	1307.8

applied on the three models were retrieved from the thermal map of Canada. Figure 6a–c represents the steady-state boundary conditions for Ottawa, Toronto and Sudbury.

Transient analysis boundary conditions

The transient analysis comprises a whole year climate data. Climate data was downloaded for every day from the first day of January 2018 to the last day of December 2018. These data represent the actual climate data used to build the actual climate condition analysis. The transient simulation involves several steps; the first part of the analysis establishes the ground's thermal regime for the actual climate conditions. For this purpose, five transient analyses were established using the actual climate data of 2018 (Fig. 7). This is to minimize the effect of the initial temperature through five cycles of the same actual climate conditions. After five transient simulations using the actual climate condition of 2018 the simulation of climate change started. The simulations include four-time periods; 2020–2040, 2041–2060, 2061–2080, and 2081–2100. The climate data used for each simulation are based on the actual climate data, including the climate change modifications listed in Tables 1, 2, and 3, to account for the impact of climate change. The climate values used in the simulations are modified for each time period; for example, following the RCP8.5, the daily maximum temperature of air will increase by 1.6 in Ottawa by 2040, given that the maximum temperature in March 1st was 4 °C in 2019, the maximum daily temperature in Ottawa in March 1st will be 5.6 °C by 2040 following the RCP 8.5. The same logic applies for the rest of the climate patterns used in the analyses [10]. For each city, three models were built; each model simulates a climate change scenario; RCP 2.5, RCP 4.5, and RCP 8.5.

Below (Fig. 7) represents the analyses sequence implemented in the modeling software for all three thermal models.

Simulation results and discussion

A large amount of simulation results have been obtained. The results include ground temperature profiles and ground temperature at different depths along the sub-surface strata for December 31st and March 1st as well as the effect of the snow cover variation on the thermal regime of the studied grounds. These 2 days were selected to provide an understanding of the ground thermal regime at the beginning and the end of the winter

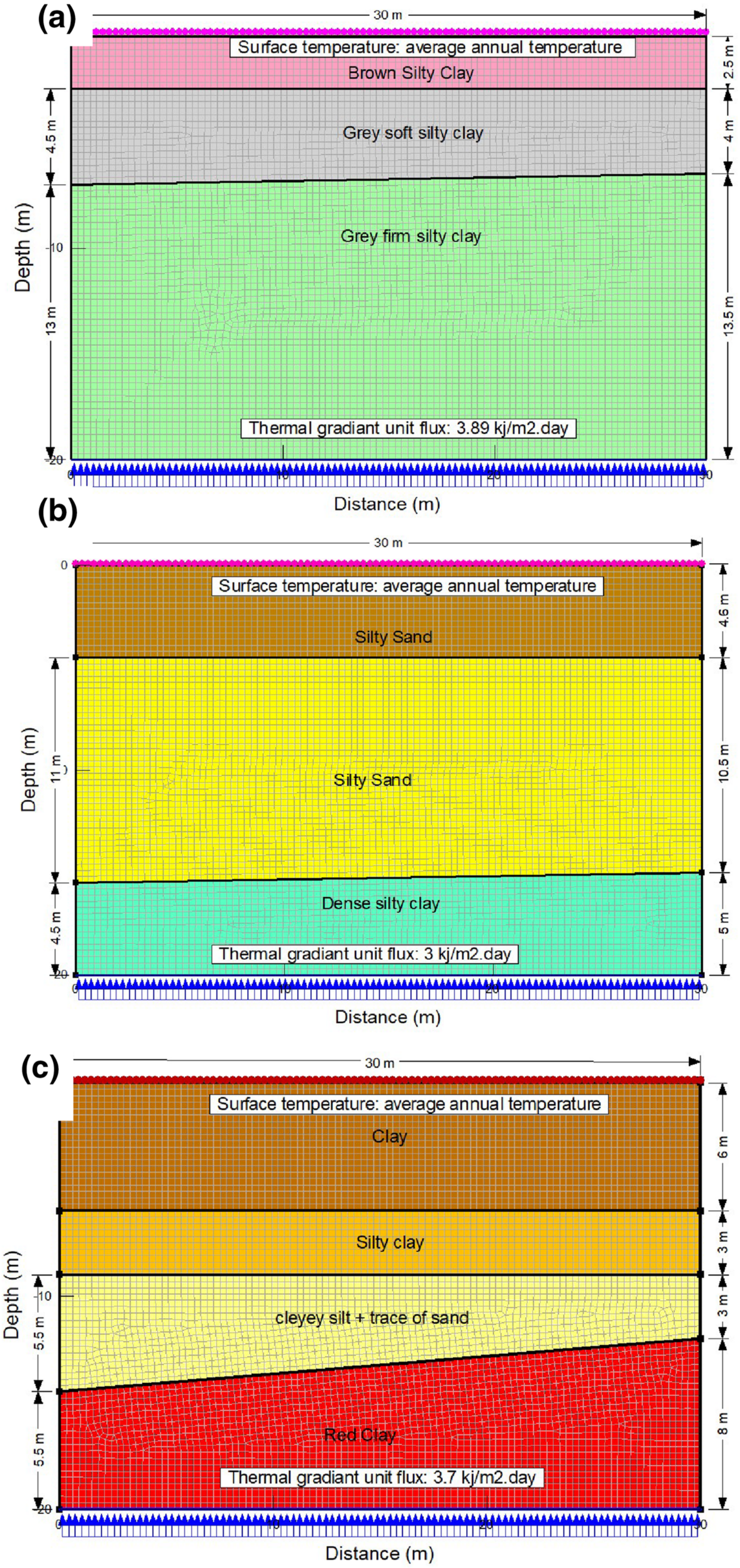


Fig. 6 Simulation model steady state boundary conditions **a** Ottawa **b** Toronto **c** Sudbury

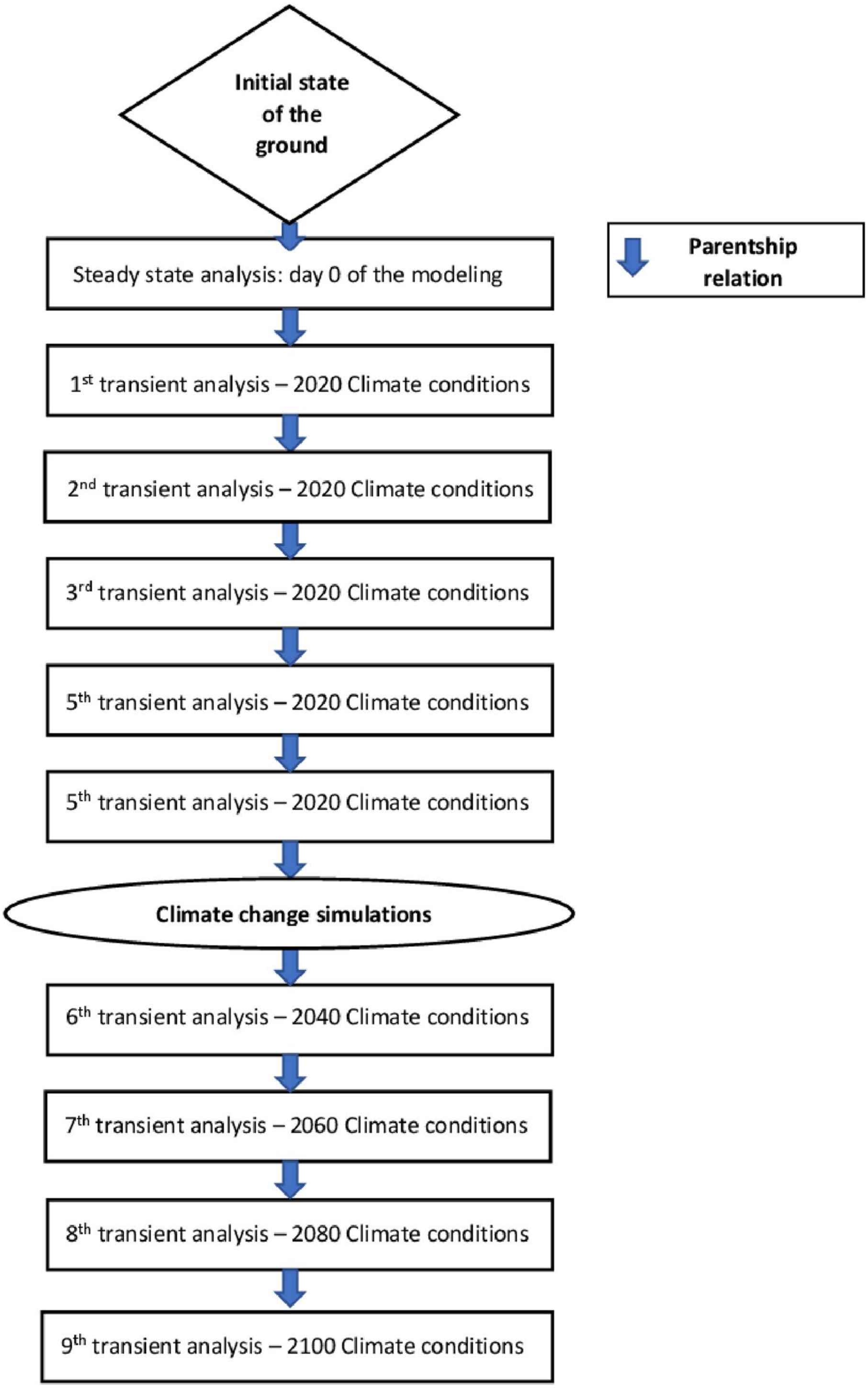


Fig. 7 Analyses sequence established and implemented in the modeling tool

season, respectively. For the sake of keeping the length of the manuscript and the number figures reasonable, only selected typical simulations results will be presented in this chapter. All simulation results obtained are available in Marrah [14].

Ottawa RCP 8.5:

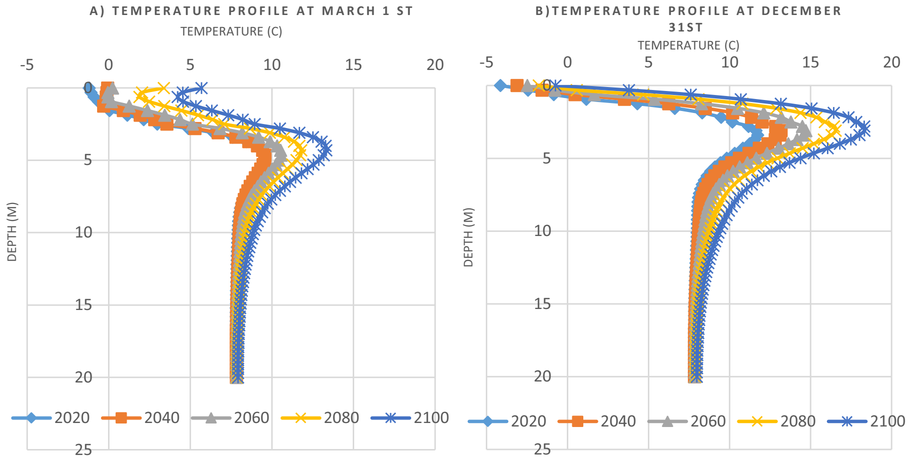


Fig. 8 Ground temperature profiles at **a** March 1st and **b** December 31st for 2020–2040–2060–2080–2100; RCP8.5

Ottawa RCP 4.5:

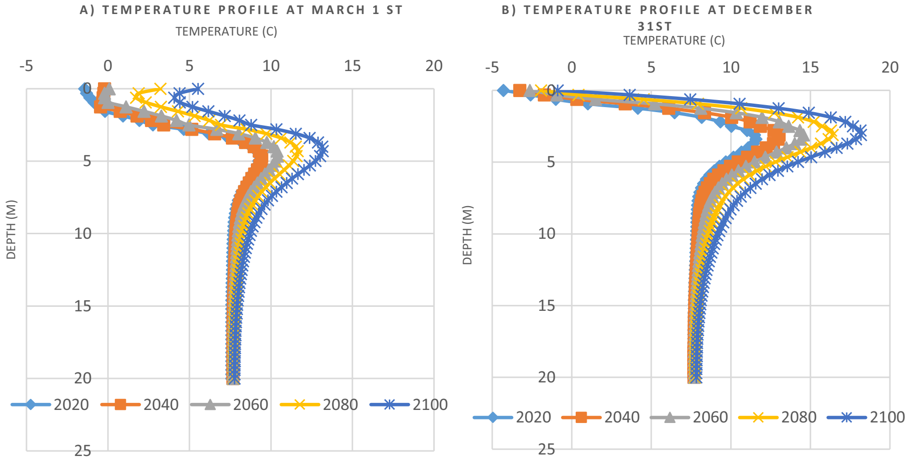


Fig. 9 Ground temperature profiles at **a** March 1st and **b** December 31st for 2020–2040–2060–2080–2100; RCP4.5

Temperature profiles

Typical simulated ground temperature profiles for the climate change scenarios, in Ottawa (Figs. 8, 9, 10), Toronto (Fig. 11) and Sudbury (Fig. 12) at 2020, 2040, 2060, 2080 and 2100, are presented below.

Climate change scenario—sensitivity analysis

For comparison purposes, typical temperature profiles for March 1st and December 31st in 2040, 2060, 2080, 2100 for the three Climate change were combined in the same graph as illustrated in Fig. 13 (Ottawa), Fig. 14 (Toronto), and Fig. 15 (Sudbury) below.

Ottawa RCP 2.5:

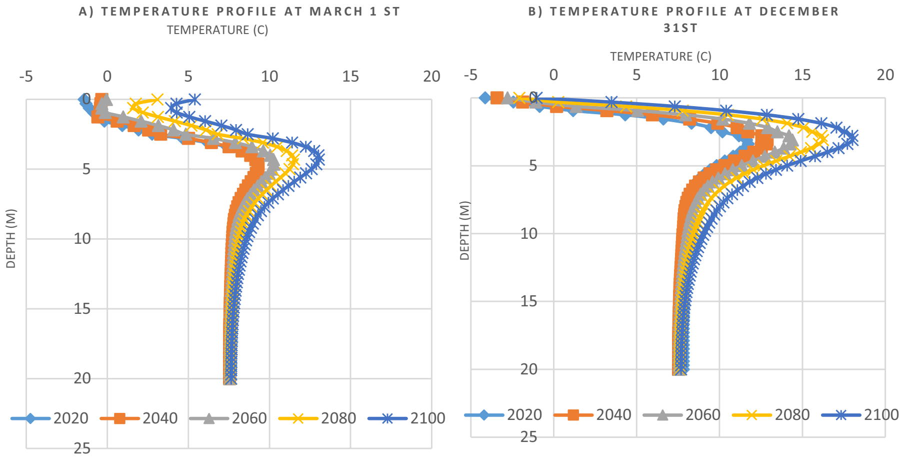


Fig. 10 Ground temperature profiles at **a** March 1st and **b** December 31st for 2020–2040–2060–2080–2100; RCP 2.5

Toronto RCP 8.5:

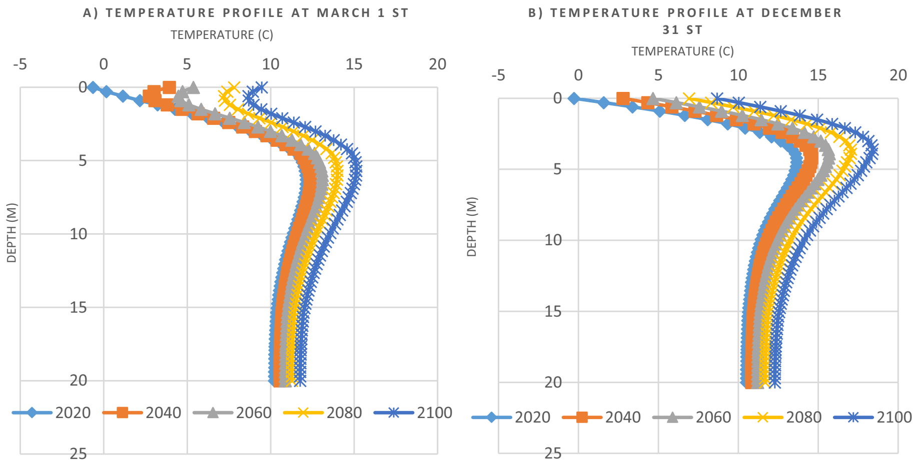


Fig. 11 Ground temperature profiles at **a** March 1st and **b** December 31st for 2020–2040–2060–2080–2100; RCP8.5

Ground temperature at different depths

Ground temperature at 1 m, 2 m, 3 m, 4 m, 15 m, and 20 m below the ground surface was reported along the analysis's full period. These depths were selected to visualize the temperature variation and the impact of climate change at shallow and deep depths. Since the climate conditions at 2020 represent the actual climate conditions, the ground temperature will not be affected by the climate change scenarios; thus, only one graph was reproduced to report the temperature at different depths of the sub-surface strata in the actual climate conditions. Figures 16, 17, 18, and 19 summarize the ground temperature at 1 m, 2 m, 3 m, 4 m, 15 m and 20 m for Ottawa for the RCP8.5, RCP4.5 and RCP2.5, whereas Figs. 20, 21, 22, and 23 show the ground temperature for Toronto and Sudbury for the RCP8.5.

Sudbury RCP 8.5:

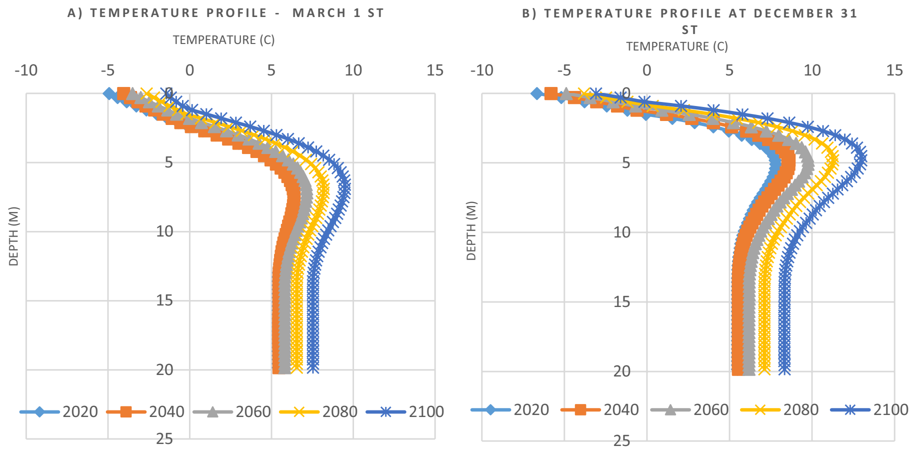


Fig. 12 Ground temperature profiles at **a** March 1st and **b** December 31st for 2020–2040–2060–2080–2100; RCP8

Snow depth—sensitivity analysis

A sensitivity analysis was conducted to assess the effect of the snow cover variation on the thermal regime of the ground in the study areas. The snow cover variation was modeled as a variation in the n_freezing factor in the cold season [24]. In the summer season, the n_thawing factor varies with vegetation and surface cover [7]; nevertheless, the variation of the summer cover conditions is not assessed. Therefore, the n_thawing factor remains constant in all the thermal simulations. Three additional case scenarios were considered in the sensitivity analysis; (i) a realistic higher n-factor that reflects a thinner snow depth, (ii) a realistic mean n-freezing factor reflecting a mean snow depth, and (iii) a realistic lower n-factor that represents thicker snow in the study areas [24]. The sensitivity analysis was conducted only for the worst-case climate change scenario, RCP8.5. Table 9 summarizes the values of the n-freezing and n-thawing factors used in the sensitivity analysis in the study areas.

Figure 24a–c represents the ground temperature profiles in March 1st, 2100 of Ottawa, Toronto and Sudbury for different snow cover conditions as follow:

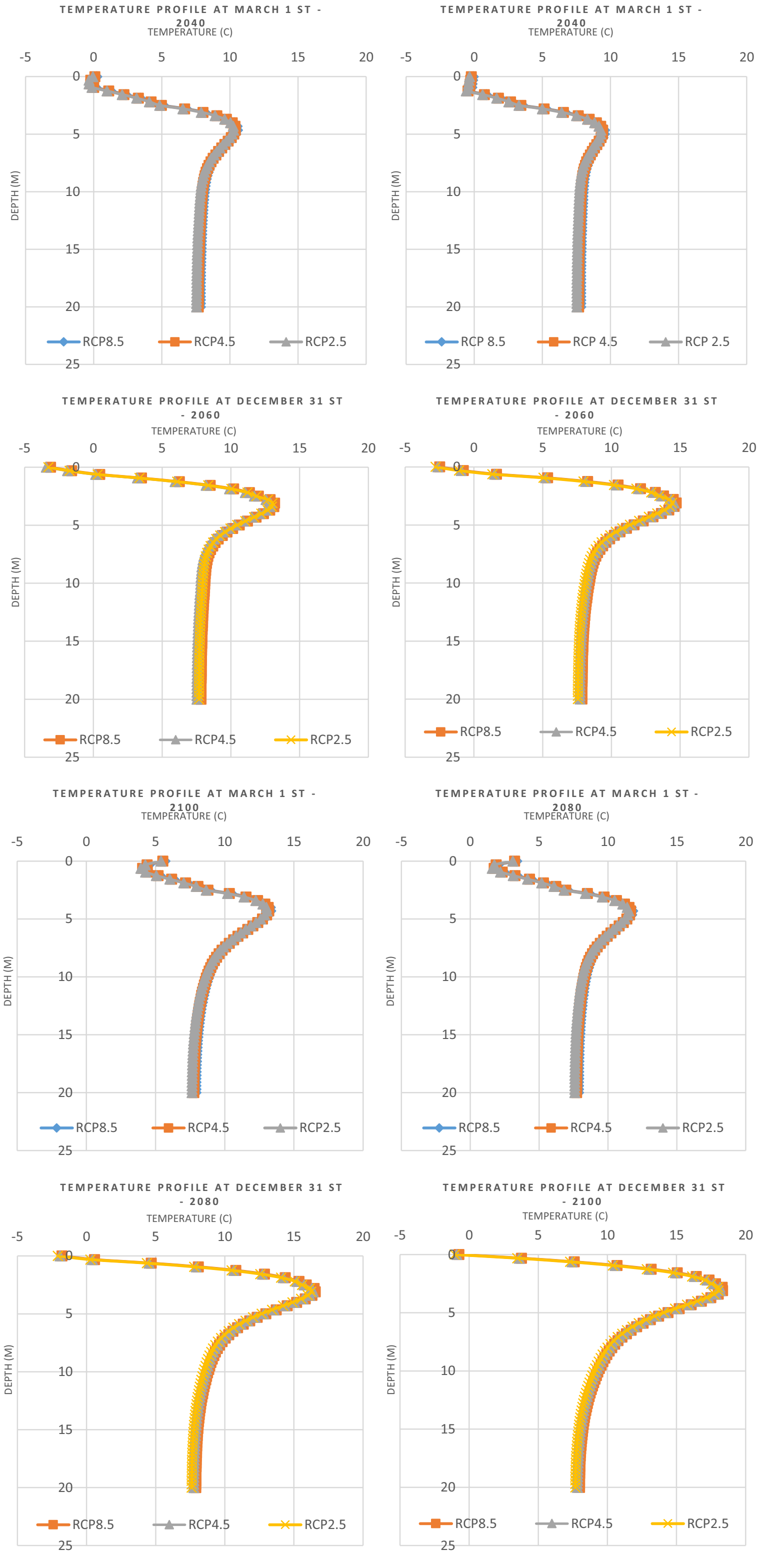
Discussion of results

Impact of climate change on the ground temperature profiles in the study area

Figures 8, 9, 10, 11, and 12 display the ground temperature profiles on March 1st and December 31st, respectively in Ottawa, Toronto, and Sudbury for the climate change scenarios. The thermal regimes in the beginning and the end of the winter season are similar in shape and profile with minor differences. It was observed that the general shape of the temperature profiles in the study areas show a nonlinear distribution of heat through the soil matrix. Temperature tends to become higher towards the bottom of all simulation models.

The temperature profile on December 31st reflects the expected behavior of the ground thermal regime within the three study areas during the winter season. Under

Ottawa:



TEMPERATURE PROFILE AT MARCH 1 ST - 2040

TEMPERATURE PROFILE AT MARCH 1 ST - 2040

TEMPERATURE PROFILE AT DECEMBER 31 ST - 2060

TEMPERATURE PROFILE AT DECEMBER 31 ST - 2060

TEMPERATURE PROFILE AT MARCH 1 ST - 2100

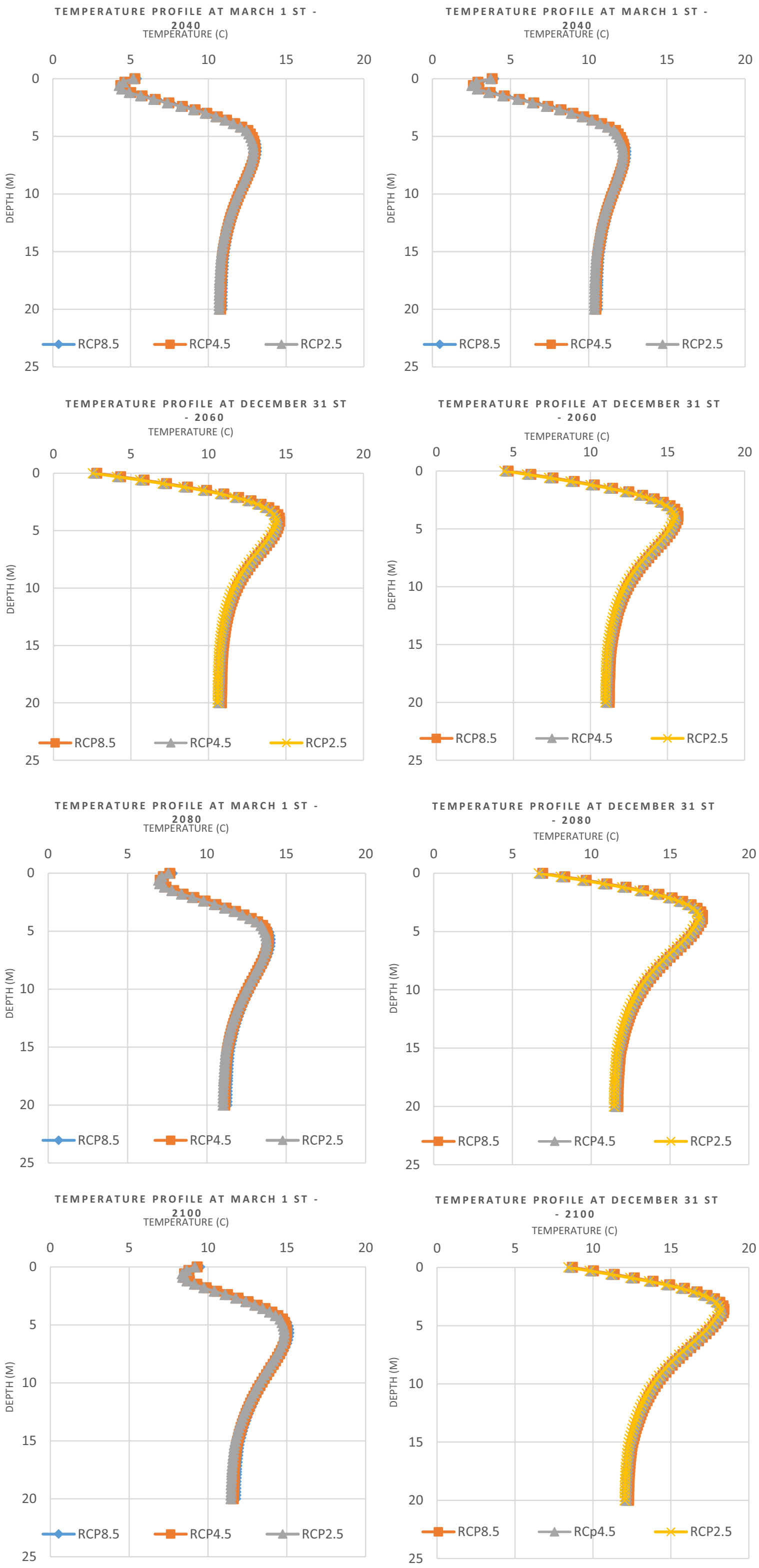
TEMPERATURE PROFILE AT MARCH 1 ST - 2080

TEMPERATURE PROFILE AT DECEMBER 31 ST - 2080

TEMPERATURE PROFILE AT DECEMBER 31 ST - 2100

Fig. 13 Temperature profiles at Mach 1st and December 1st in 2040, 2060, 2080 and 2100 for different RCPs—Ottawa

Toronto:



TEMPERATURE PROFILE AT MARCH 1 ST - 2040

TEMPERATURE PROFILE AT MARCH 1 ST - 2040

TEMPERATURE PROFILE AT DECEMBER 31 ST - 2060

TEMPERATURE PROFILE AT DECEMBER 31 ST - 2060

TEMPERATURE PROFILE AT MARCH 1 ST - 2080

TEMPERATURE PROFILE AT DECEMBER 31 ST - 2080

TEMPERATURE PROFILE AT MARCH 1 ST - 2100

TEMPERATURE PROFILE AT DECEMBER 31 ST - 2100

Fig. 14 Temperature profiles at Mach 1st and December 1st in 2040, 2060, 2080 and 2100 for different RCPs—Toronto

Sudbury:

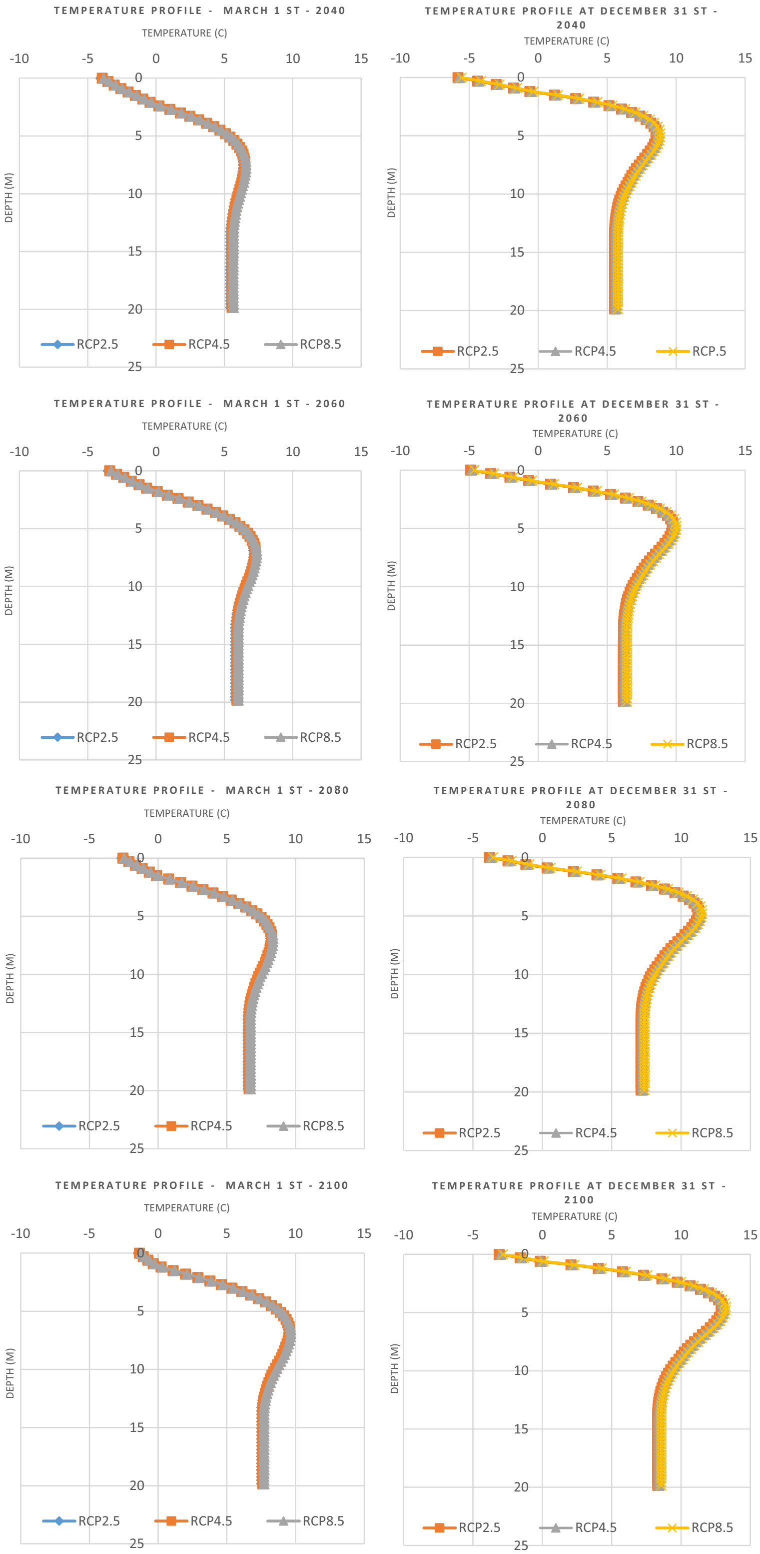


Fig. 15 Temperature profiles at Mach 1st and December 1st in 2040, 2060, 2080 and 2100 for different RCPs—Sudbury

Ottawa:

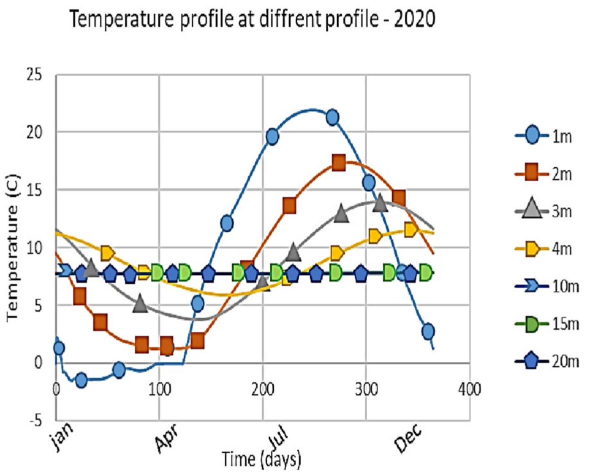


Fig. 16 Temperature profile at different depths—2020—Ottawa

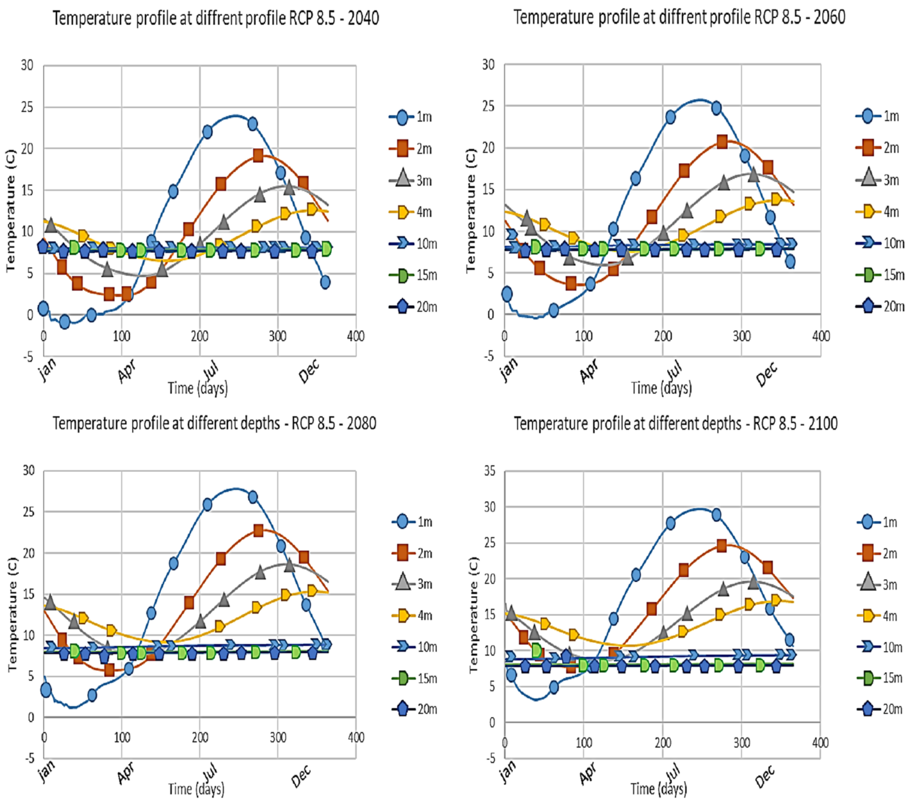


Fig. 17 Temperature profile at different depths—RCP 8.5—at 2040, 2060, 2080, 2100—Ottawa

the actual climate conditions, a frozen layer near the surface starts to form due to the impact of the cold air temperature in winter and continues to crawl down into the ground. On December 31st, 2020, the frozen layer's depth is approximately 0.5 m in Ottawa, 0.1 m in Toronto, and 0.9 m in Sudbury. The difference in the depth of the

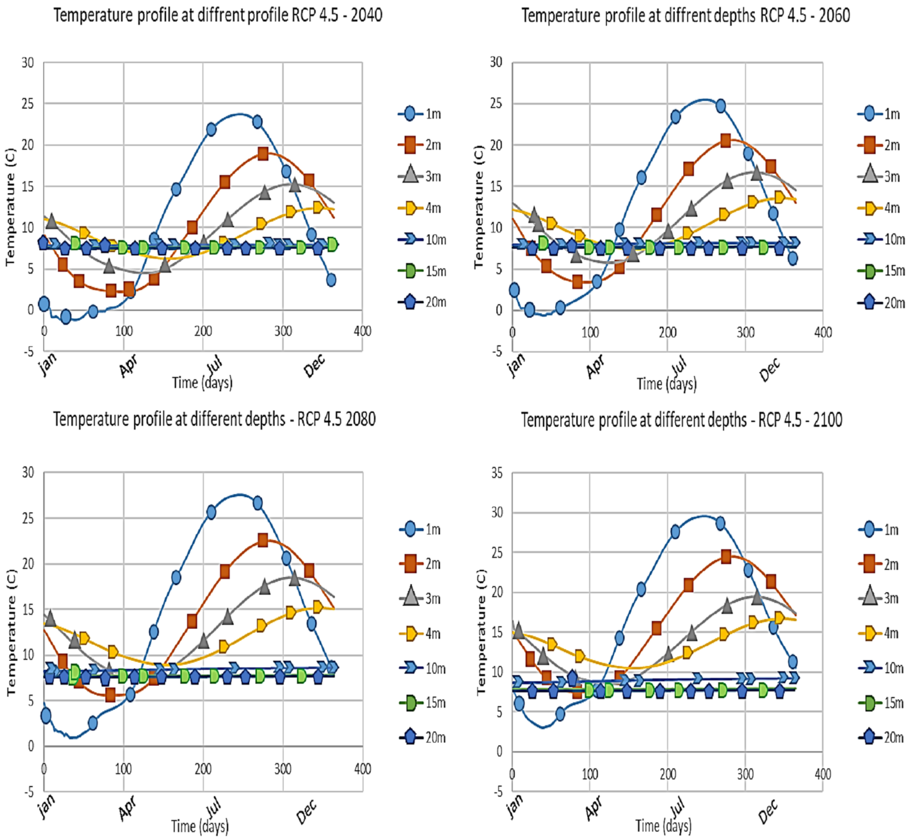


Fig. 18 Temperature profile at different depths—RCP 4.5—at 2040, 2060, 2080, 2100—Ottawa

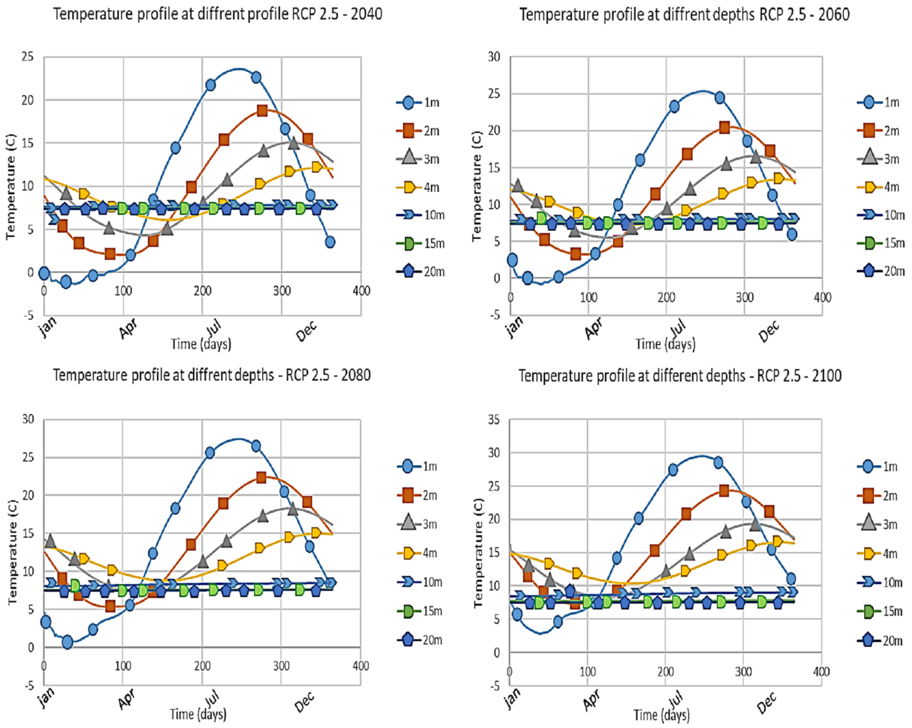


Fig. 19 Temperature profile at different depths—RCP 2.5—at 2040, 2060, 2080, 2100—Ottawa

Toronto:

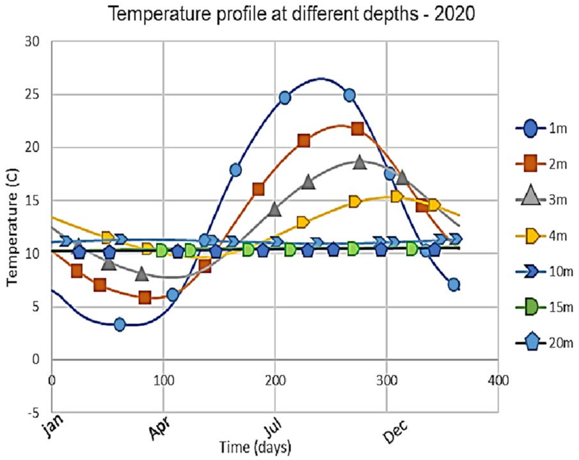


Fig. 20 Temperature profile at different depths—2020—Toronto

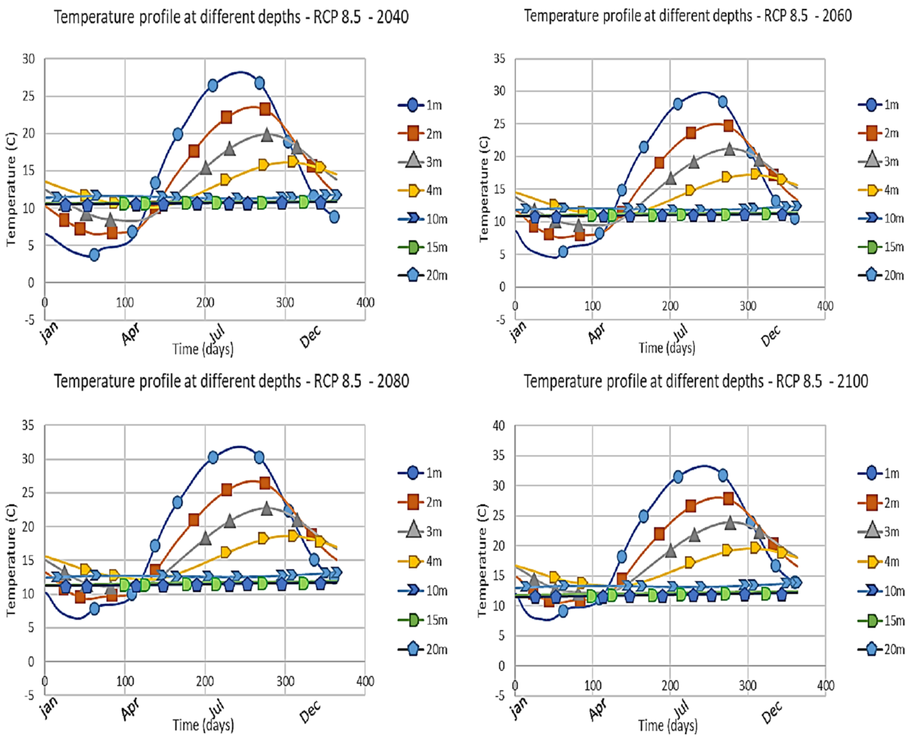


Fig. 21 Temperature profile at different depths—RCP 8.5 at 2040, 2060, 2080, 2100—Toronto

seasonally frozen layers in the study areas is mainly due to the climatic conditions. For instance, the higher frost depth is found in Sudbury where the climate is colder in winter. Accordingly, the lower frost depth is in Toronto were the climate is warmer is the winter season.

The temperature profile of March 1st represents the ground's thermal behaviour after 3 months of being exposed to the cold winter conditions. Although it is expected that

Sudbury:

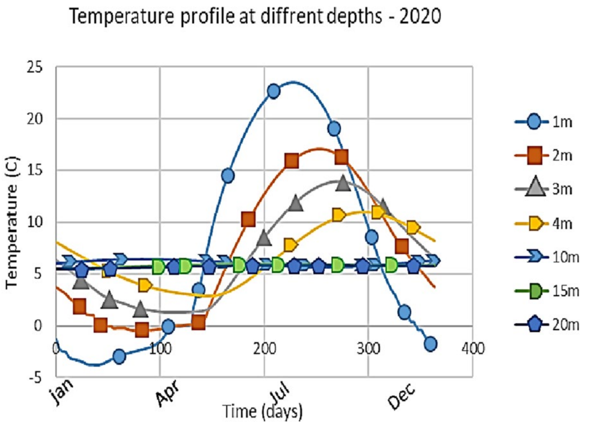


Fig. 22 Temperature profile at different depths—2020—Sudbury

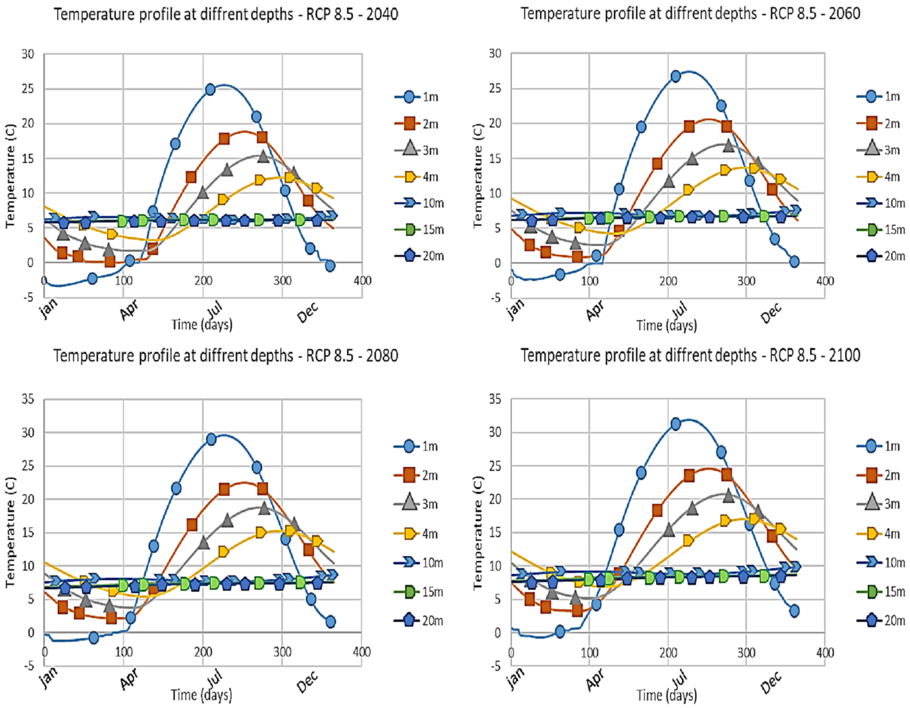


Fig. 23 Temperature profile at different depths—RCP 8.5 at 2040, 2060, 2080, 2100—Sudbury

ground temperature tends to become higher towards the bottom of the models, the results show an early warming stage of the frozen layer near the surface in Ottawa and Toronto. The new thermal condition's development indicates that the freezing process had reached its maximum before March 1st. Accordingly, the thawing process starts to take effect within the seasonally frozen layer in Ottawa and Toronto. The maximum depths of the seasonally frozen layer observed in Ottawa and Toronto are approximately 1.3 m and 0.3 m on March 1st, 2020, respectively. Due to Sudbury's colder weather, the seasonally frozen layer is not yet affected by the early warming process on March 1st,

Table 9 n-freezing and n-thawing factors used in the sensitivity analysis in the study areas [24]

	Snow depth (cm)	n_thawing	n_freezing
Ottawa			
Max snow depth	47	1.4	0.08
Min snow depth	15	1.4	0.35
Mean snow depth	25	1.4	0.15
Toronto			
Max snow depth	34	1.4	0.05
Min snow depth	6	1.4	0.43
Mean snow depth	15	1.4	0.22
Sudbury			
Max snow depth	63	1.4	0.11
Min snow depth	20	1.4	0.28
Mean snow depth	35	1.4	0.19

2020. Therefore, the ground surface temperature is colder than the layers underneath it. The maximum frost depth observed in Sudbury is 2.5 m on March 1st, 2020.

The study areas' ground temperature undergoes a significant escalation from 2020 to 2100 for all the three Climate change scenarios. From 2020 to 2040, the ground temperature increases slightly due to the tiny air temperature increase. In fact, the effect of global warming will be clearly apparent by 2060 and will last for the simulation's whole duration in the three study areas.

The ground's thermal response varies according to the depth; it was noted that air temperature heavily influences the thermal regime of the first 5 m of the sub-surface strata, but that effect gradually fades with depth. On the contrary, at deeper depths, the ground thermal regime is governed by the effect of the Earth's geothermal gradient.

The simulation results reveal a noticeable effect of climate change on the thermal regime of the ground's top layers. From 2020 to 2100, the total increase in the temperature of the ground ranges between 1 and 4 °C at shallow depths in the three study areas. The ground surface and near surface layers temperatures experience a larger rise due to the climate's direct interaction (Figs. 13, 14, 15).

From a depth of 10 m to 20 m, the three sites showed a slightly different thermal behaviour, in Ottawa, the ground temperature profiles at 2020, 2040, 2060, 2080, and 2100 overlap at the bottom of the model starting from a depth of 16 m. This behaviour could be explained by the geo-thermal gradient's impact on the model and the ground's high thermal conductivity involved in the Ottawa model. In the presence of a ground with a high thermal conductivity, the impact of the geothermal gradient crawls up in the model leading to a constant ground temperature at greater depths [7]. However, in Toronto and Sudbury, there is no such convergence due to impact of climate change. The ground temperature will go on increasing with time even at greater depths. The ground thermal equilibrium is not observed at a depth of 20 m in both study areas. In fact, the effect of the geothermal gradient will certainly be encountered at deeper level where ground temperature will become constant.

In the city of Ottawa, the frost depth is shifted up from 1.5 m on March 1st, 2020 to 0 m on March 1st, 2100 for all the RCPs. Likewise, the frost depth completely disappears

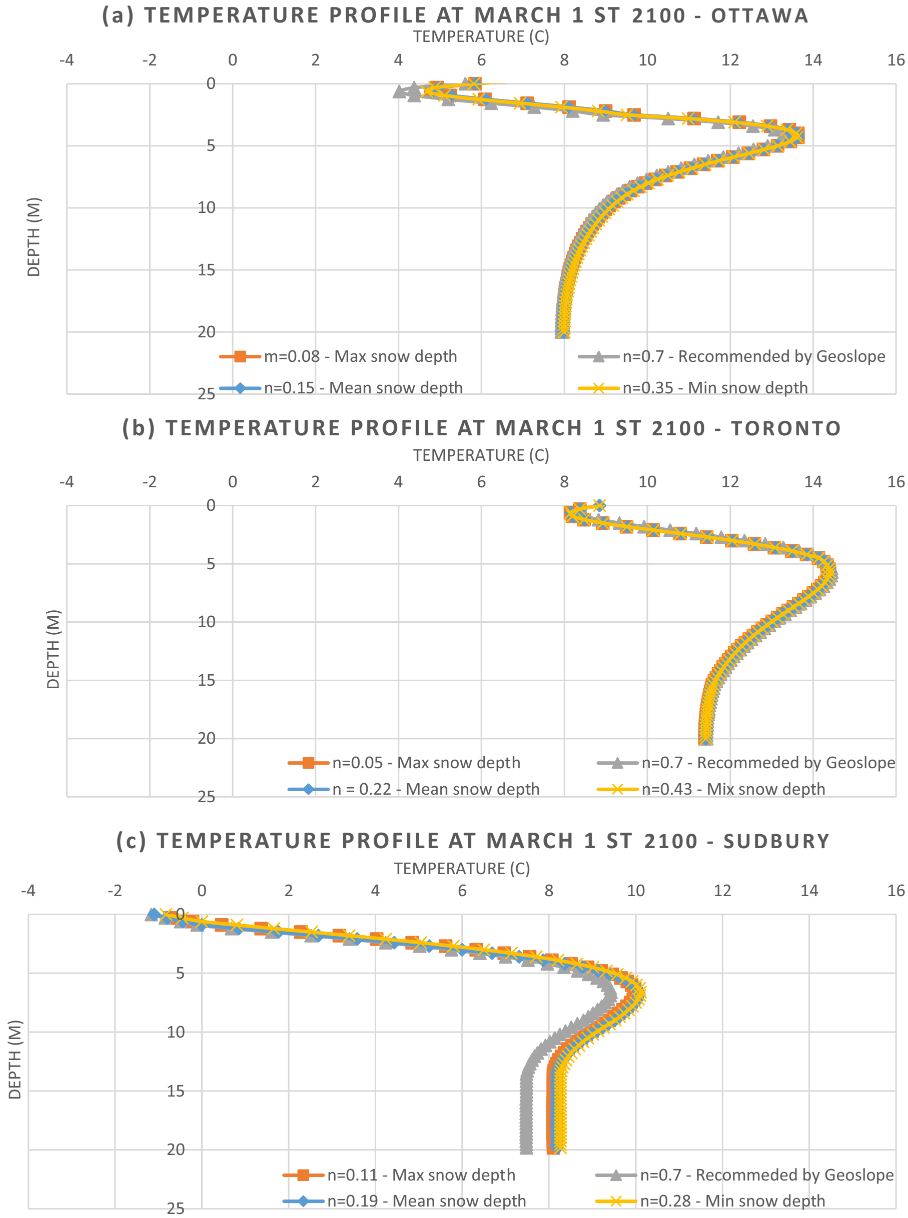


Fig. 24 Ground temperature profile in March 1st 2100 **a** Ottawa, **b** Toronto **c** Sudbury

in Toronto on March 1st, 2100. In Sudbury, the frost depth is shifted up from 2.5 m in March 1st, 2020 to 0.75 m in March 2100 for all the RCPs due to climate change.

A combined analysis was established to compare the results from the three-climate change scenarios. Figures 13, 14, and 15 show the temperature profiles at 2040, 2060, 2080 and 2100 for Ottawa, Toronto and Sudbury for the three RCPs. The ground temperature slightly increases from RCP 2.5 to RCP4.5, and likewise, the temperature graphs slightly vary between RCP4.5 and RCP8.5. For instance, RCP8.5 provides the highest temperature values. The difference between the results provided by RCP 2.5 and 4.5 is in the order of a lees than a half degree on March 1st and December 31st. Likewise, the difference between the RCP 4.5 and RCP8.5 does not exceed 0.2 °C in the three selected sites. All in all, the climate change scenarios do not seem to significantly affect the ground thermal response to global warming greatly.

Effect of climate change on the ground profiles at specific depths

Figures 16, 17, 18, 19, 20, 21, 22, and 23 display the ground temperature at depths of 1 m, 2 m, 3 m, 4 m, 10 m, 15 m and 20 m for Ottawa for the RCP 8.5, RCP4.5 and RCP 2.5, Toronto and Sudbury for the RCP 8.5. These depths were selected to provide an understanding of the thermal behaviour at both shallow and deeper depths. The air temperature at shallow depths heavily impacts the temperature fluctuations of the ground. The ground thermal regime follows yearly periodic temperature cycles at 1 m, 2 m, 3 m and 4 m depth. The ground temperature fluctuates depending on the seasons creating a frost period where the ground freezes. The frost period's length depends mainly on the climate conditions and the ground thermal properties [7]. Therefore, it is different from a city to another. The longest frost period was observed in Sudbury, located in the north of the Canadian seasonal frost region and has the coldest climate in the winter between the three cities. The results showed that Sudbury's frost period lasts for approximately 170 days under the actual climate conditions. Similarly, Ottawa experiences a frost period lasting for approximately 140 days. Toronto has the shortest frost period for approximately 120 days under the actual climate conditions.

Climate change had a significant impact on the length of the frost period in the three cities. It will gradually decrease from 2020 up to 2100. A loss of approximately 25% of the frost period was observed in the three cities by 2040. The frost period undergoes a continuous loss up to 2100 where it completely disappears in Ottawa and Toronto. In Sudbury the frost period becomes 65 days in the year. The three climate change scenarios showed approximately similar results.

Effect of snow cover on the thermal regime of the ground exposed to climate change

The snow cover effect on the thermal regime of the ground was assessed in a second sensitivity analysis in the three selected sites in the Canadian seasonal frost region. Figure 24 displays typical soil temperature profiles on March 1st, 2100 for different snow cover depths in Ottawa, Toronto and Sudbury.

Due to its low thermal conductivity, snow is as an excellent insulator between the atmosphere and the ground surface. The seasonal snow cover protects the ground from heat loss in winter resulting in higher ground temperatures (Goncharova et al. [8]). Essentially, the thicker the snow cover on the soil surface, the lesser is the heat loss from the ground to the atmosphere [25].

The graphs reflect the ground's expected thermal response to snow cover variation in all the study areas. However, results showed a minimal effect of the snow cover variation on the thermal regime of the ground in the three selected sites. The ground temperature difference is hardly noticeable between the realistic maximum, mean and minimum snow covers.

The value recommended by Geoslope for the n_freezing factors reflects an even thinner snow cover than the realistic minimum during the winter season in the three cities. Accordingly, it is interesting to note a slight drop in ground temperature in winter due to the minor insulation effect induced by the reduction of the snow cover in the three cities.

In Sudbury, the excessive reduction of snow cover does not seem to influence the first 6 m of the ground. However, in the order of a degree Celsius, a noticeable temperature drop is observed starting from a depth of 6 m and continues to the bottom of the model. As it is located in the north of the Canadian seasonal frost region, Sudbury experiences the coldest winter weather of the three cities. Therefore, each winter, in the presence of a thick seasonal snow cover, the ground thermal equilibrium at greater depths is not affected by the cold air temperature, which helps the ground maintain its temperature and prevent any heat loss at deeper levels. However, if the winter seasonal snow cover is thin, the insulation effect is reduced. This fact, affects the ground thermal equilibrium at greater depths, leading to an accumulated heat loss through the years. By 2100, the ground temperature at deeper depth will become colder in the presence of a thin snow cover than with a thicker one in Sudbury, which explains the temperature drop starting from a depth of 6 m. In Ottawa and Toronto, the effect of the snow cover variation is not very apparent. The reduction of the snow cover appears not to have a significant effect on the ground thermal regime all along the depth of the models in both cities.

The net effect of snow cover on the ground's thermal regime and its magnitude depend upon the timing and severity of the climate condition in the winter season [25]. For example, in Sudbury, the climate is very severe in winter compared to Ottawa and Toronto [15]; this helps the snow to accumulate and delays its melting process. Accordingly, the soil surface remains isolated from the atmosphere during the whole winter season without any interruption. On the other hand, in Ottawa and Toronto the climate is warmer during winter. On occasions, the air temperature on some winter days becomes higher than the freezing point, which induces a partial melting of the snow cover [11]. These air temperature fluctuations below and above the freezing point weakened the structure and the density of the snow cover leading to discontinuous snow covering. Due to all these reasons, the snow cover variation does not significantly influence the thermal regime in these two cities.

Summary and conclusions

This paper aims to study the impact of climate change on the thermal regimes of the ground in the Canadian seasonal frost region. The study was conducted for three cities (Ottawa, Sudbury and Toronto) located in different regions in the seasonal frost region of Canada. The new research established future simulations of the ground thermal regime.

The first part of the research comprises the development and validation of an approach and simulation tool for the assessment of the impact of future climate on the thermal regimes of grounds in the study area. The second part of the research consists of assessing the impact of climate change on the thermal regimes of grounds in the study area by using the aforementioned simulation tool. Three climate change scenarios were considered in the study; RCP 2.5, RCP4.5 and RCP8.5. The RCP 8.5 represents the worst-case scenario in terms of climate change predictions. The RCP 2.5 is the optimistic climate change scenario. The study established the thermal regime of the ground in 2020, 2040, 2060, 2080 and 2100.

The study has come to the following conclusions:

1. The developed numerical tool provided accurate results in simulating the ground thermal regime under different climate conditions. The validation model delivers good results in simulating the existing thermal conditions of the ground.
2. The simulation results showed a gradual loss in the frost penetration depth due to the climate change, in the three representative sites. In Ottawa and Toronto, the seasonally frozen ground will disappear completely by 2100, in Sudbury, the frost penetration depth will become 0.75 m compared to 2.1 m in 2020.
3. The frost period duration will be shorter due to climate change in the three selected sites and will totally vanish in Ottawa and Toronto. In Sudbury, the ground will likely remain frozen for only 80 days in 2100 compared to 180 days in 2020.
4. The mean average ground temperature and the thickness of the seasonally frozen soil would have significant changes due to climate warming for the study period of 2020–2100. The mean average ground temperature would be much higher, and the frost penetration depth would be significantly reduced.
5. The impact of climate change, would not appear clearly in the first 40 years "up to 2060". The mean average ground temperature and the frost penetration depth would both slightly decrease in the first 40 years period followed by a significant decrease in the subsequent 40 years period in the three selected cities. This nonlinear effect implies that substantial changes could follow in a short timeframe and climate change will need at least 40 years to mobilize a significant change in the ground's thermal behaviour.
6. The response of the ground to the impact of climate change varies with the geotechnical composition of the ground and the climate conditions. Overall, in the center and south of the study area, the changes are more significant than the north of the study area.
7. Climate change scenarios would affect much the ground's thermal behavior, RCP2.5 and RCP4.5 would produce a similar impact, but slightly less severe than that RCP 8.5 could produce.

Author contribution

Mohammed Marrah: Conceptualization, Methodology, Investigation, Writing- Original draft preparation. Mamadou Fall: Conceptualization, Methodology, Resources, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. Husham Almansour: Resources, Writing - Review & Editing, Co-supervision.

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Data availability

Not applicable.

Declarations

Competing interests

The authors declare that they have no competing interests.

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