Extending thermal response test assessments with inverse numerical modeling of temperature profiles measured in ground heat exchangers

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Abstract

Thermal response tests conducted to assess the subsurface thermal conductivity for the design of geothermal heat pumps are most commonly limited to a single test per borefield, although the subsurface properties can spatially vary. The test radius of influence is additionally restricted to 1~2 m, even though the thermal conductivity assessment is used to design the complete borefield of a system covering at least tens of squared meters. This work objective was therefore to develop a method to extend the subsurface thermal conductivity assessment obtained from a thermal response test to another ground heat exchanger located on the same site by analyzing temperature profiles in equilibrium with the subsurface. The measured temperature profiles are reproduced with inverse numerical simulations of conductive heat transfer to assess the site basal heat flow, at the location of the thermal response test, and evaluate the subsurface thermal conductivity, beyond the thermal response test. Paleoclimatic temperature changes and topography at surface were considered in the model that was validated by comparing the thermal conductivity estimate obtained from the optimization process to that of a conventional thermal response test.

***Keywords*:** geothermal, heat pump, heat exchanger, thermal response test, temperature profile, thermal conductivity.

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1. Introduction

Thermal response tests (TRTs), envisioned in the early 80's [1] and fully developed with mobile apparatus in the 90's [2,3], are now commonly performed to evaluate the subsurface thermal conductivity to design ground source heat pump systems. The test consists of disturbing the subsurface temperature with the circulation of heated water in a pilot ground heat exchanger (GHE) installed before the complete borefield of a given building is fully constructed [4]. Water flow rate circulating in the GHE and temperature at its inlet and outlet are analyzed to infer the bulk subsurface thermal conductivity [5,6]. This parameter is a key to determine the length of ground heat exchanger required to fulfill the energy needs of a building. TRTs are consequently performed for prefeasibility studies to design ground source heat pump systems and evaluate their economic viabilities.

The conventional TRT experiment conducted in the field aims at reproducing heat transfer that can occur during the operation of a ground source heat pump system. A heat injection rate of 50 to 80 W m^{-1} of borehole to create a temperature difference of 3 to 7 °C between the inlet and outlet of the GHE is recommend in North American industry's guidelines [7]. A source of high power varying from 8 to 12 kW is needed to operate the heating element and the pump of the mobile apparatus. The testing unit and its fuel fired generator commonly used to supply power are cumbersome. Mobilizing the equipment in the field and performing the test is a significant expense, which have found limited applications due to its cost. TRTs are mostly carried out for large ground source heat pump systems were the uncertainty in GHE length can offset the cost of a test. One test is typically conducted for the whole borefield and this single thermal conductivity assessment is considered for design although the test radius of influence is limited to less than 1~2 m [8] and the subsurface properties can vary with position at a given field due to heterogeneities.

Recent efforts to develop competitive field tests carried out with GHEs in the scope of geothermal system design resulted in the use of heating cables to inject heat underground [9–11]. The pump is avoided for thermal response tests with heating cables and heat is injected in the standing water column of the GHE, which can facilitate installation of the equipment in the field. The use of a heating cable assembly enclosing sections of heating and non-heating wires was further proposed to perform TRTs with a low power source in GHEs that are commonly more than a hundred meter in length [12,13]. Although TRTs with heating cables provide advantages that can help reducing the test cost, the duration of a test enclosing 40 to 60 hours of heat injection followed by an equivalent duration of thermal recovery remain its main limitation. Gamma ray log have been alternatively used to infer the subsurface thermal conductivity at different depths [14]. Such wireline geophysical log can potentially provide an instantaneous assessment method for the subsurface thermal conductivity but borehole logging have to be performed in an open hole without GHE piping. This limitation is important as pipe can be rapidly installed after drilling to avoid collapsing of the borehole wall. The interpretation of a temperature profile recorded in GHE at equilibrium with the subsurface was additionally proposed to evaluate the subsurface thermal conductivity [15]. A wireless probe was developed for that purpose to measure temperature as the probe sink along the pipe of a GHE [16]. The analysis of equilibrium temperature profiles to determine the subsurface properties was, in fact, achieved in the 70's to determine the thermostratigraphy of sedimentary rocks

[17]. Although measurements are fairly simple to perform in the field, the interpretation of a temperature profile can be limited by inaccurate information about the Earth heat flow, which is essential to analyze the temperature data. The measured temperature gradient can further be affected by topography or by paleoclimatic temperature variations at surface [18,19]. Thermal conductivity assessments with temperature profiling using thermostratigraphic principles are consequently spatially limited, but deserve a broader attention to diversify tools available for subsurface characterization in the scope of geothermal system design. Previous studies described the use of temperature profiling before and after a TRT in the same GHE to improve test analysis with the identification of groundwater flow or vertical variations in subsurface thermal conductivity [20,21]. Temperature profiles can offer further advantages to extend the evaluation of subsurface properties beyond the location of a single TRT, a topic that has not been fully addressed. Evaluation of the subsurface thermal conductivity at more than one location on the same site can be useful when designing large ground source heat pump systems including tens to hundreds of boreholes drilled in a heterogeneous geological medium. Temperature profiles that can be measured at a low cost with a submersible probe in GHEs provide easily accessible data to infer the subsurface thermal conductivity without repeating TRTs on the same site.

The analysis of temperature profiles measured in GHEs undisturbed by heat injection of a TRT and in the absence of accurate information about the Earth heat flow was investigated in this study. The objective of the work presented was to develop and verify a methodology to evaluate the subsurface thermal conductivity from the temperature profile of GHEs recorded with a wired probe and taking into account limitations arising from the unknown site heat flow. Temperature measurements undisturbed by heat injection were achieved in two GHEs located at the same site and that are approximately 140 m deep, a relatively shallow medium where the temperature gradient is affected by topography and the recent climate warming. An inverse numerical analysis method was developed to infer the Earth heat flow at the study site from the temperature profile and a conventional TRT assessment conducted in a first GHE. The numerical simulations took into account the site topography and the historical changes in ground surface temperature that occurred over the past centuries. The same inverse modeling approach was then used to analyze the temperature profile of the second GHE to evaluate the subsurface thermal conductivity beyond the location of the TRT, considering the heat flow value inferred in the first GHE. If the Earth heat flow was known at every surface location where temperature had remained constant, Fourier's Law of heat conduction would be sufficient to infer the subsurface thermal conductivity with an equilibrium temperature profile. Such conditions are seldom if not never meet and the proposed method was developed to overcome those constrains. The field and numerical analysis method relying on wired temperature profiling is fully described in this manuscript, providing an original contribution showing how to extend TRT assessments when more than one test has to be conducted at the same site or within a region of similar heat flow.

2. Site settings

The work was conducted at a site where conventional TRTs has been performed before to validate with experimental results the methodology developed for numerical inversion of the temperature profiles. The site is located in Saint-Lazare-de-Bellechasse, in the Appalachian geological province of Canada (Figure 1), and hosts two GHEs that have a depth of 139 m. The GHEs are located 9 m from each other and were previously installed to evaluate the performance of thermally enhance pipes [6]. The boreholes were drilled until 150 m depth in a sequence constituted of a sandy overburden having a thickness of 10 m followed by mudslates layers of the Armagh Formation [22]. The diameter of the boreholes that were backfilled with silica sand was 0.15 m and a single U-pipe having a nominal diameter equal to 32 mm was installed until 139 m depth since the lower part of the boreholes collapsed. Conventional TRT conducted on each borehole during 168 h of heat injection flowed by 44 to 66 h of thermal recovery indicated a bulk subsurface thermal conductivity equal to 3.0 and 3.5 W m^{-1} K^{-1}at the location of borehole PG-08-01 and PG-08-02, respectively [6].

The groundwater level was measured in the boreholes before installation of the GHEs at 0.72 m depth below the ground surface that is at an elevation of 301 m above sea level (asl) near the GHEs. The site is on the flank of a northwest-southeast trending hill that has an average slope of 3.3 % going downhill toward the northwest. A survey of the groundwater well record for the area revealed a hydraulic gradient on the order of 0.03, following the site topography.

Equilibrium heat flow map are unavailable for the area. The best information about heat flow is from a map drawn at the country scale of Canada that suggest a heat flow in the range of 20 to 50 mW m^{-2} [23]. The nearest equilibrium heat flow measurement was made at a distance of approximately 70 km, which evidences the difficulties in assessing the site heat flow from regional maps. The ground surface temperature in the area has increased over the past two-hundred years [24]. Joint inversion of temperature profiles from 28 boreholes that are 600 m deep and located in Eastern Canada revealed a ground surface temperature that slightly decreased before 1800 and then increased until now [25]. Although this temperature trend was determined for a very large region of Western Ontario and Eastern Québec in the vicinity of the studied site, it was assumed to be representative of the site surface temperature fluctuations as climate trends are similar for the area. Such a temperature evolution was essential to constrain the analysis of the temperature profiles in the GHEs that are typically shorter than the boreholes used for paleoclimatic reconstructions having at least 300 m depth.

3. Methodology

The thermal conductivity assessment from the TRT conducted in a first GHE was used to find the site heat flow with inverse numerical simulations of conductive heat transfer to reproduce the temperature profile measured in the GHE. The heat flow evaluation from the first GHE simulations was then used as an input parameter to find the thermal conductivity at the location of the second GHE with a similar modeling approach to reproduce its temperature profile. The thermal conductivity obtained for the second GHE with inverse modeling was finally compared to that obtain from the TRT conducted in this second GHE to verify the accuracy of the methodology. The field and numerical simulation methods are described below, providing guidelines to reproduce the method at other sites (Figure 3).

3.1 Field measurements

Temperature profiles undisturbed by heat injection and at equilibrium with the subsurface were measured with a submersible pressure and temperature data logger hooked to a wire and lowered inside a pipe of each GHE. The temperature measurements for this study were recorded after TRTs have been conducted since the purpose of the work was to validate the method at a site with existing subsurface information obtained from previous field testing. In a case where the method is actually used to extend thermal conductivity assessment in the context of geothermal system design, it is suggested to measure temperature profiles before the TRT. The submersible data logger used was a RBRduet with a fast temperature response, where the thermistor accuracy, resolution and time constant are ± 2×10^{-3} ºC, 5×10^{-5} ºC and 1×10^{-1} s, respectively. The pressure sensor can go to a depth of 500 m and its accuracy and resolution for depth measurements are 2.5×10^{-1} m and 5×10^{-3} m, respectively. The logger was set to record temperature and pressure every second and was gradually lower in the GHE at a constant pace. Upon lowering the logger in the GHE, the water level inside the U-pipe slightly rise as the volume of the data logger and the wireline displaced the GHE water. This small water movement can affect the geothermal gradient measured in the GHE. The depth measurements were consequently corrected by subtracting the volume introduced in the U-pipe expressed in equivalent length with:

$$D^*(L) = D - \left(\frac{V_{\text{logger}} + V_{\text{wire}}(L)}{2\pi r_{\text{pipe,in}}^2}\right) \quad \text{eq. 1}$$

where D^* and D (m) are the corrected and measured depth and V (m^3) is for the volume of the data logger and wireline that is expressed in equivalent length by dividing by two times the area inside a pipe considering its internal radius r (m). Note that the logger volume is constant and the wire volume increases with its length L (m) unwind in the GHE, which can be determined with the measured depth knowing the water and surface pipe elevations before lowering the probe. This depth correction assumes that the water level rise in the GHE is faster than the time for the temperature of the water that rise in the U-pipe to reach equilibrium with the subsurface temperature. The temperature profile taking into account the corrected depth is tough to provide a measurement of the geothermal gradient which can be repeated in each GHE of a given site. Those observations offer the information needed to find the site heat flow and the subsurface thermal conductivity at different GHEs with inverse numerical modeling if the subsurface thermal conductivity from at least one borehole is known.

3.2 Numerical simulations

The temperature profile measured in a GHE was reproduced with a numerical simulation of transient heat transfer in the subsurface using the finite element program COMSOL Multiphysics [26]. Heat transfer in the GHE was not simulated since the models aimed at reproducing temperature measurements that are in equilibrium with the subsurface temperature. The transient conductive heat transfer equation was solved numerically in two dimensions:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)=\rho c\frac{\partial T}{\partial t} \qquad \text{eq. 2}$$

where λ (W m^{-1} K^{-1}) is the thermal conductivity assumed to be isotropic, ρ (kg m^{-3}) is the density and c (J kg^{-1} K^{-1}) is the heat capacity. Simulations were conducted over a domain representing a cross-section of the subsurface at the studied site oriented in the direction of the topographical slope (Figure 4). The thermal properties of the subsurface were assumed to be uniform, constant with time, and heat generation due to decay of radioactive elements inside the subsurface was neglected. The upper boundary of the simulation domain was drawn according to the site topography and the borehole was located at the center of the horizontal direction. The horizontal and vertical widths of the model were selected to be 1000 m in length to minimize the influence of the vertical and the bottom boundaries. The model mesh formed with triangles refined near the surface for a better resolution at the borehole contained 3046 elements.

The boundary conditions were adiabatic at the vertical side walls, a constant heat flow at the bottom and a uniform temperature at surface varying with time to reproduce paleoclimatic changes in ground surface temperature over the past six centuries (Figure 4). The constant heat flow boundary at the bottom represents the Earth natural heat flow directed toward the surface. The upper surface temperature varying with time was determined according to paleoclimatic reconstructions of the past six centuries that have affected the temperature profile measured at the depth of the borehole. The initial temperature condition was calculated according to the basal heat flow and the subsurface thermal conductivity to represent the equilibrium geothermal gradient at steady state before the recent surface warming disturbed the thermal state of the subsurface. The temperature measured at the base of the GHEs, which is less influenced by the ground surface temperature variations than the temperature in the upper section of the GHEs, was extrapolated upward and downward according to the equilibrium geothermal gradient to set the initial temperature distribution. This initial temperature condition was therefore recalculated for every simulation where the basal heat flow or the subsurface thermal conductivity was changed in the optimization process to reproduce the temperature profile of the GHEs.

The simulations were conducted for a period of 615 y, with constant time steps of 5 y to reproduce the surface warming and the propagation of the thermal disturbance in the subsurface until the present moment, when the temperature profiles were measured in the GHEs. In other words, the end of the simulations corresponded to the time when the temperature measurements were taken and the simulations were for the historic 615 y preceding the measurements. The time to complete a single simulation of the subsurface temperature evolution was on the order of 20 s on a desk top computer with an Intel i5 3.33 GHz processor and 8 Go of random access memory. This fast simulation time obtained with a light cross-section model allowed to conduct multiple simulations to find the unknown basal heat flow and subsurface thermal conductivity with optimization of the temperature profiles.

The basal heat flow was considered as unknown for simulations of the temperature profile in the first GHE, whereas the thermal conductivity is assumed to be known and taken from the TRT results. Identification of the proper basal heat flow is essential since the simulations aim at reproducing the temperature of the subsurface for a heat tracing experiment lasting centuries where the source of perturbations are paleoclimates. The sum of squared residuals between the observed and simulated temperature profiles was minimized with the coordinate search method [27] to find the basal heat flow that best reproduced the observed temperatures. In this case, the optimization solver searches for the minimum sum of squared residuals by constructing an estimate of the gradient and performs a line search along this direction before attempting a new evaluation along the coordinate direction. The optimality tolerance of the solver was set to 1×10^{-3} to 1×10^{-4}

and the maximum number of objective evaluations was determined to be 40, although the solver always converged before the 40 iterations.

Once the basal heat flow was determined with the optimization of the temperature profile in the first GHE with a known subsurface thermal conductivity, it was used as an input for simulations of the temperature profile in the second GHE to find the subsurface thermal conductivity at this location. The optimization process was similar, with the minimization of the sum of squared residuals between the observed and simulated temperatures using the coordinate search method to find, in this case, the thermal conductivity. This inverse numerical simulation process allowed extrapolating the thermal conductivity assessment obtained with a TRT at the location of the first GHE to the location of the second GHE without doing a TRT and simply relying on temperature profiling.

The assumptions involved in the simulation process can be synthetized as the following:

- Heat is transferred by conduction in 2D space and there is no internal heat generation,
- Land use affecting the temperature at surface and the basal heat flow is similar among the boreholes,
- The basal heat flow remains constant through time,
- The thermal properties of the subsurface at the location of each borehole are uniform and constant through time.

In the case of a flat topography, heat transfer could be assumed vertically and the model becomes unidimensional. A change of land use is defined here as a modification of the natural environment at surface, which can affect the shallow subsurface temperature. The temperature variations at surface due to paleoclimates induce a thermal perturbation slowly penetrating the subsurface. This perturbation is used to evaluate the site basal heat flow and subsurface thermal conductivity among boreholes having a similar surface evolution.

4. Results

The temperature profiles undisturbed by heat injection and measured in the GHEs located at the study site in Saint-Lazare-de-Bellechasse are described below with their interpretation, providing a field example to verify the inverse numerical simulation method. Temperature measurements corrected for the depth with equation 1 to take into account the wired probe volume are similar in PG-08-01 and PG-08-2 (Figure 5), except for the depth interval ranging from about 255 to 290 m asl. The observed departure from the expected temperature profile in PG-08-02 is believed to be caused by groundwater flow, which can vary among the two boreholes due to fractured rock heterogeneties. Other than this feature, both temperature profiles show a reversed geothermal gradient with increasing temperature upward from 210 to 280 m asl due to warming at surface. The upper 20 m of the temperature profiles, from 280 to 300 m asl, are further affected by the seasonal temperature variations. Those two temperature profiles that were collected within a few minutes of field work offer the required observations to infer the site heat flow and extent the TRT assessment beyond PG-08-1.

4.1 Evaluation of the site heat flow

Properties of the subsurface model used for inverse numerical simulations to find the heat flow was a thermal conductivity equal to 3.0 W m^{-1} K^{-1}, which was evaluated with a conventional TRT in PG-08-01, and a volumetric heat capacity equal to 2.5 MJ m^{3} K, which was estimated according to a description of the geological materials sampled while drilling [6]. Optimization of the basal heat flow to reproduce the temperature profile in PG-08-01 with the numerical solution considered the observed temperature from 160 to 280 m asl. It was not attempted to match the temperature measured in the upper 20 m of the boreholes since this interval is affected by seasonal temperature variations, which are not taken into account by the model upper boundary representing the historic ground surface temperatures. Changes in temperature specified for this boundary are the yearly average temperatures of Figure 2 changed every 5 y or more and extended until year 2015, when the temperature profile was measured in PG-08-01. The seasonal temperature variations could have been considered according to the meteorological record but would have increased the simulation time. Matching the upper temperatures affected by the seasonal temperature variations was instead avoided. The absolute temperature value at the upper boundary for the starting point of the simulation was calculated from the initial geothermal gradient condition inferred with the basal heat flow changed every simulation for optimization.

The minimum and maximum bound for the basal heat flow optimization was 20 and 50 mW m^{2} and the optimization started at the lower bound. This range of heat flow was determined from the available heat flow map [23], although data coverage for the studied site is poor. A total of 25 iterations were necessary for the optimization solver to converge toward the solution that provided the best fit with the observed temperatures

(Figure 6). The sum of the squared residuals decreased from ~13 to 9.3×10^{-2} for the best fit scenario that revealed a basal heat flow converging toward 25 mW m^2. The initial temperature condition for the best fit scenario was a surface temperature and gradient equal to 6.3 ºC and 8.3×10^{-4} ºC m^{-1}, respectively (Figure 7).

4.2 Extension of the subsurface thermal conductivity assessment

Inverse numerical simulations to find the thermal conductivity at the location of PG-08-02 were conducted similarly, except that the basal heat flow and the initial surface temperature inferred previously were now treated as input parameters. The model subsurface thermal conductivity was the unknown to find with the optimization process. Observed temperature below the groundwater perturbation (Figure 5) was matched to simulated temperature since conductive heat transfer only was simulated. The minimum and maximum bound for the optimization process was a subsurface thermal conductivity equal to 2.8 and 4.2 W m^{-1} K^{-1} and the optimization started at the lower bound. This range of possible thermal conductivity was determined from geological information about the site bedrock [22], assuming a thermal conductivity range can be assigned to the identified rock type. A total of 24 iterations were needed for the coordinate search solver to converge toward a subsurface thermal conductivity near 3.2 W m^{-1} K^{-1} (Figure 8), decreasing the sum of squared residuals from 2.5×10^{-1} to 2.5×10^{-2}. The initial temperature condition for the best fit scenario was a temperature gradient equal to 7.8×10^{-4} ºC m^{-1} (Figure 9).

The subsurface thermal conductivity estimate obtained at the location of PG-08-02 is within 9 % of that previously measured with a TRT (3.5 W m^{-1} K^{-1}; [6]). The inability to reproduce the observed temperature in the 35 m long section perturbed by groundwater flow may explain the differences in thermal conductivity estimates from the two methods. In order words, the conventional TRT provides an evaluation of the equivalent subsurface thermal conductivity that takes into account groundwater flow, while the estimate obtained with inverse numerical modeling of the temperature profile in PG-08-02 neglected advective heat transfer due to groundwater flow. However, both methods yielded thermal conductivity estimates that are sufficiently close to validate the inverse modeling approach, showing its capacity for extrapolation of TRT assessments within boreholes of a given site using temperature profiling undisturbed by heat injection.

5. Discussion and conclusions

A method to make use of temperature profiles in equilibrium with the subsurface and measured in ground heat exchangers (GHEs) was presented in this manuscript to extend a thermal response test (TRT) assessment to other GHEs of the same site. The temperature profiles are measured with a wired probe and corrected for the probe and cable volumes inserted in the GHE piping. The field measurements can be completed within a few minutes, offering accessible data to diversify the methods used for TRT assessments.

The observed temperature profiles undisturbed by heat injection of a TRT are reproduced with inverse numerical modeling of conductive heat transfer to infer the site basal heat flow and the subsurface thermal conductivity. The historic ground surface temperature changes and the site topography define the model upper boundary. A first in situ thermal conductivity assessment from a TRT is needed to find the site heat flow with the temperature profile of one GHE. The obtained basal heat flow is subsequently used as an input to find the subsurface thermal conductivity at the location of other GHEs by reproducing the temperature profiles. The optimization of the unknown basal heat flow, in the first case, and the thermal conductivity, in the second case, is achieved with a derivative free solver.

The developed methodology was verified at a site located in Saint-Lazare-de-Bellechasse, Canada, where two GHEs had previously been the subject of conventional TRTs. The temperature profiles and the thermal conductivity assessment in the first GHE provided the observations to find the basal heat flow and the thermal conductivity at the location of the second GHE. The subsurface thermal conductivity found by optimization was sufficiently close to that evaluated with the TRT to validate the inverse modeling method. Although uncertainties about the historic ground temperature imposed at the model upper boundary can persist [25], the assessment of the subsurface thermal conductivity can be accurate enough to verify if there are important changes in subsurface properties among different boreholes, as similarly done with pioneer work on thermostratigraphy [17].

While this procedure is not expected to replace conventional TRTs, it can find most applications to extent a TRT assessment in large borefields were the performance of several GHEs can be influenced by the heterogeneous subsurface conditions. In cases where there is sufficient information to reduce uncertainty about the site heat flow, the optimization of this parameter may be skipped and the method can potentially replace the conventional TRT to evaluate the subsurface thermal conductivity as done by Rohner et al. [15] on a 300 m deep GHE, but taking into account paleoclimates and surface topography as proposed in this manuscript for shallower boreholes of 139 m depth. However, information about the Earth heat flow can be difficult to find in regions where equilibrium temperature measurements of deep boreholes are sparse, like North East America [28]. In this context, the proposed inverse numerical modeling methodology can be used to extent TRT assessment of any large GHE fields, where more than one evaluation of the subsurface thermal conductivity can be needed. One TRT could be performed in a first GHE and temperature profiles could be measured in all the other GHEs as the borefield is installed to verify if there are significant changes in subsurface thermal conductivity among the borehole locations. The design of the GHE field could be adapted as the analysis of temperature profiles in boreholes reveals the subsurface thermal conductivity distribution. The method could also be used to map the subsurface thermal conductivity in an urban district where the installation of serval ground source heat pump systems is planned. A few TRTs would have to be performed to define the basal heat flow at the district scale and the temperature profiles measured in GHEs could be used to extrapolate the thermal conductivity assessment at the location of each system. The maximum distance between two GHEs for the method to be applicable has not been determined. Giving an exact distance is difficult since it is expected to be affected by the evolution of surface land use that is not directly represented in the model and can affect the subsurface temperature. As long as two GHEs are in an area with a similar basal heat flow and surface land use history, although land use may evolve, the inverse numerical modeling method may offer a descend estimate of the subsurface thermal conductivity.

The work presented is a first step to make broader use of temperature profiles in GHEs. The inverse numerical simulation method could be improved to consider groundwater flow, and infer the subsurface hydraulic conductivity when temperature disturbances due to groundwater flow are observed as previously suggested [20]. The simulations could further take into account varying thermal conductivity layers to identify potential subsurface heterogeneities like done for TRT combined with temperature profiling [21]. Additional work has to be done to address those issues that can be positively anticipated with the contributions offered by this study. The assessment of the subsurface thermal conductivity in the scope of geothermal heat pump system design can benefit from alternative methodologies that will be further improved.

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Figure Captions

Figure 1. Localisation of the studied site hosting two GHEs numbered PG-08-01 and PG-08-02.

Figure 2. Ground surface temperature variations inferred by Chouinard and Mareschal[25] from 28 boreholes in the vicinity of the study area.

Figure 3. Flow chart of the described methodology to extent subsurface thermal conductivity assessments with inverse modeling of temperature profiles.

Figure 4. Simulation domain, boundary conditions and mesh showing the location of the borehole to reproduce its temperature profile.

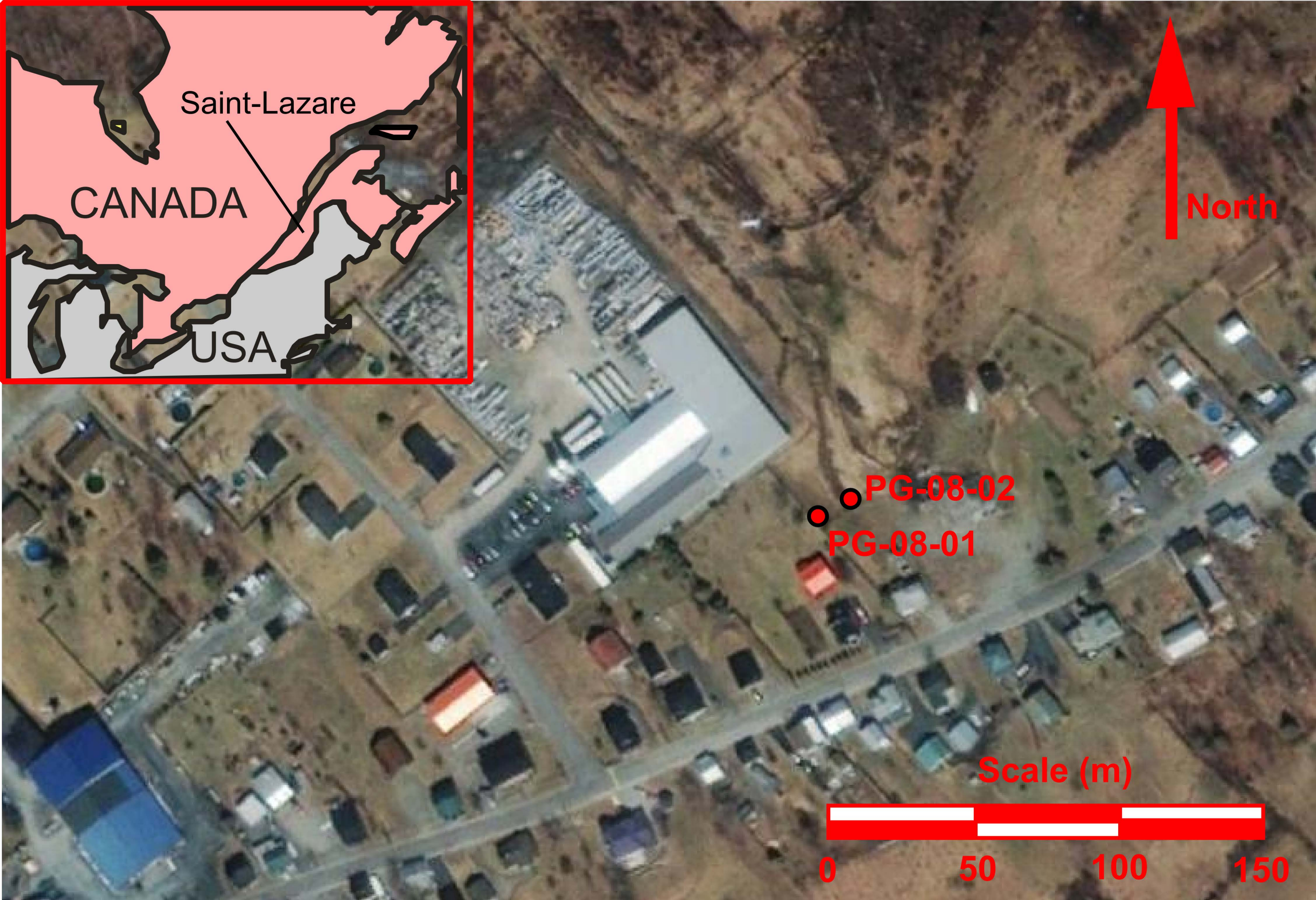
Figure 5. Temperature profiles in equilibrium with the subsurface corrected for the wired probe volume and recorded in PG-08-01 and PG-08-02.

Figure 6. Histogram of basal heat flow values tried by the coordinate search solver to find the solution that best reproduces temperature measurements in PG-08-01.

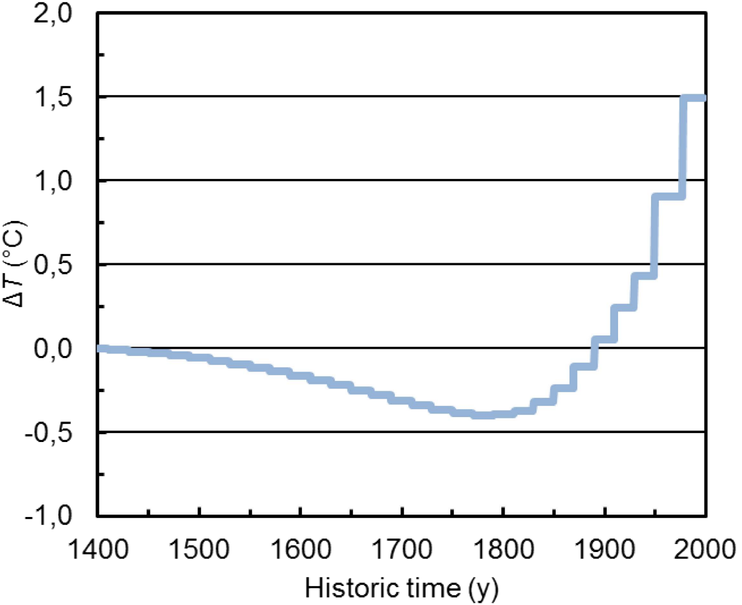
Figure 7. Simulated temperature for the initial condition in 1400 and after the historic ground surface temperature changes in 2015, which are matched to the observed temperature in PG-08-01.

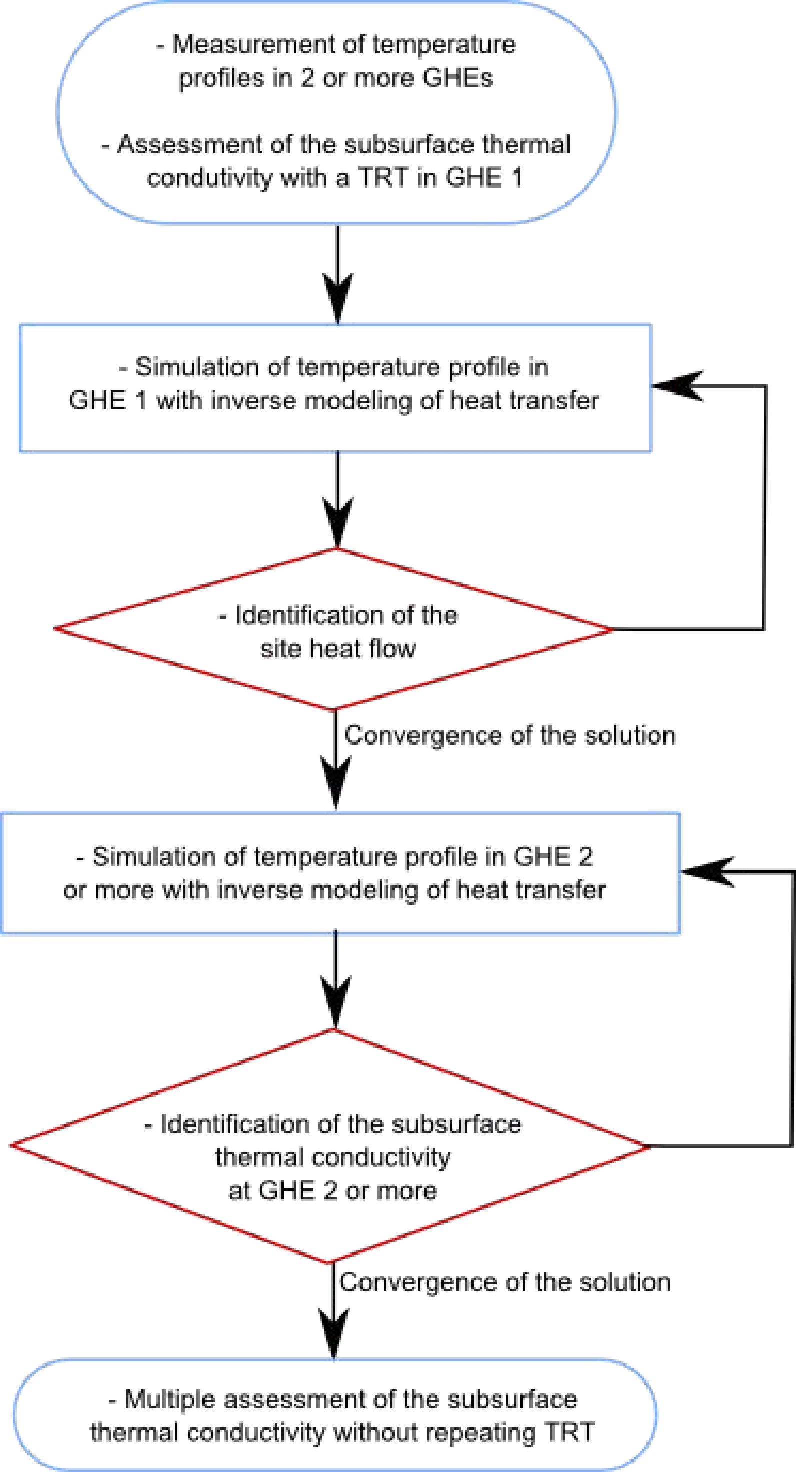
Figure 8. Histogram of subsurface thermal conductivity values tried by the coordinate search solver to find the solution that best reproduces temperature measurements in PG-08-02.

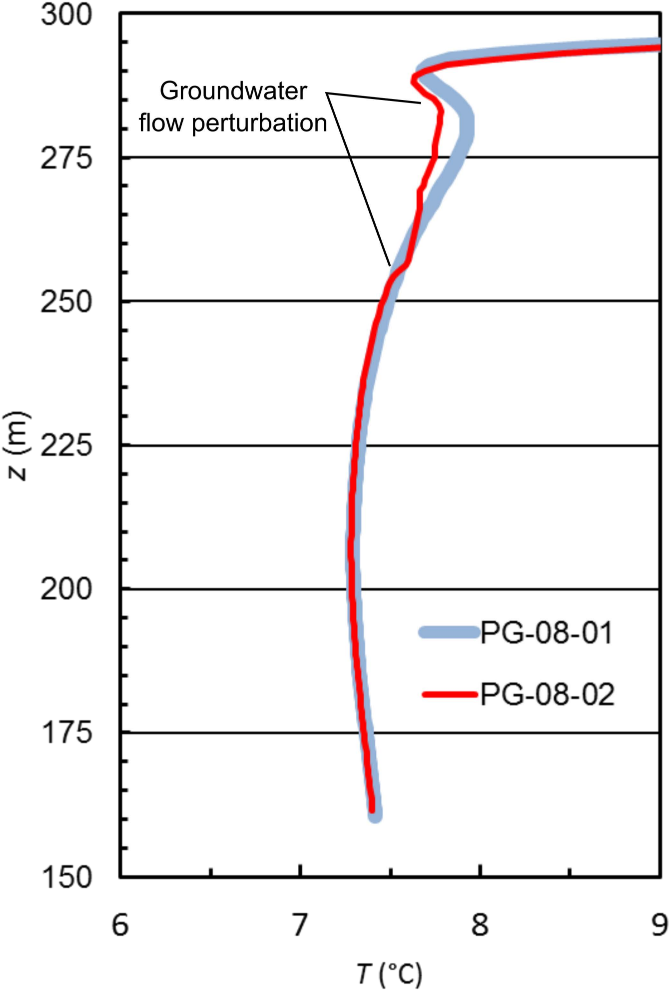
Figure 9. Simulated temperature for the initial condition in 1400 and after the historic ground surface temperature changes in 2015, which are matched to the observed temperature in PG-08-02.



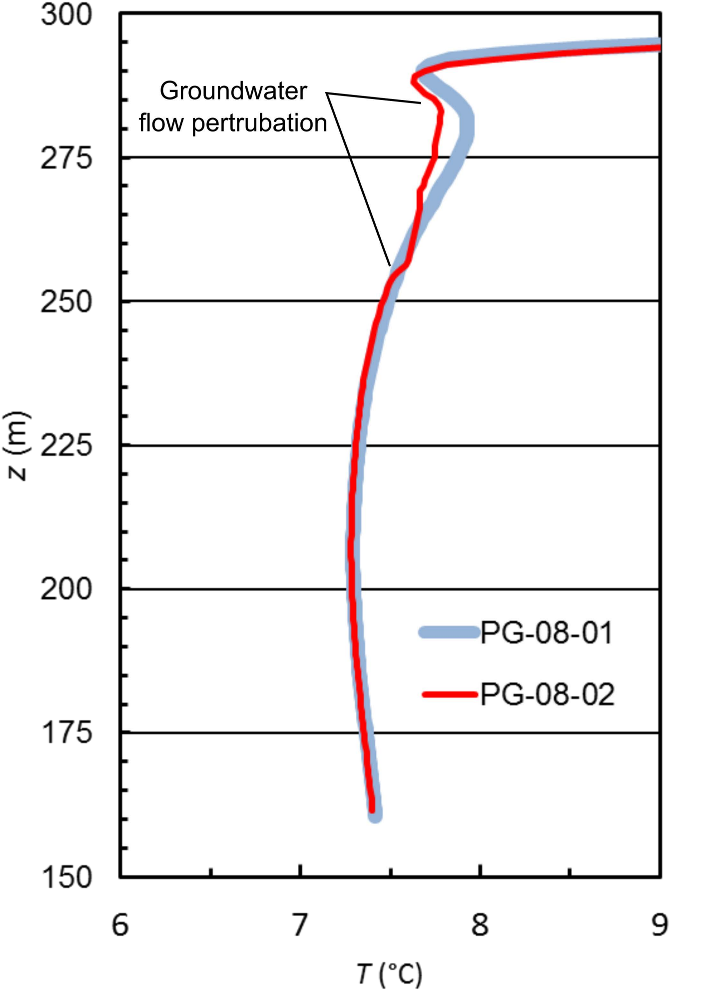
Saint-Lazare
CANADA
USA
North
PG-08-02
PG-08-01
Scale (m)
0
50
100
150


2,0
1,5
1,0
0,5
0,0
-0,5
-1,0
ΔT (°C)
1400
1500
1600
1700
1800
1900
2000
Historic time (y)

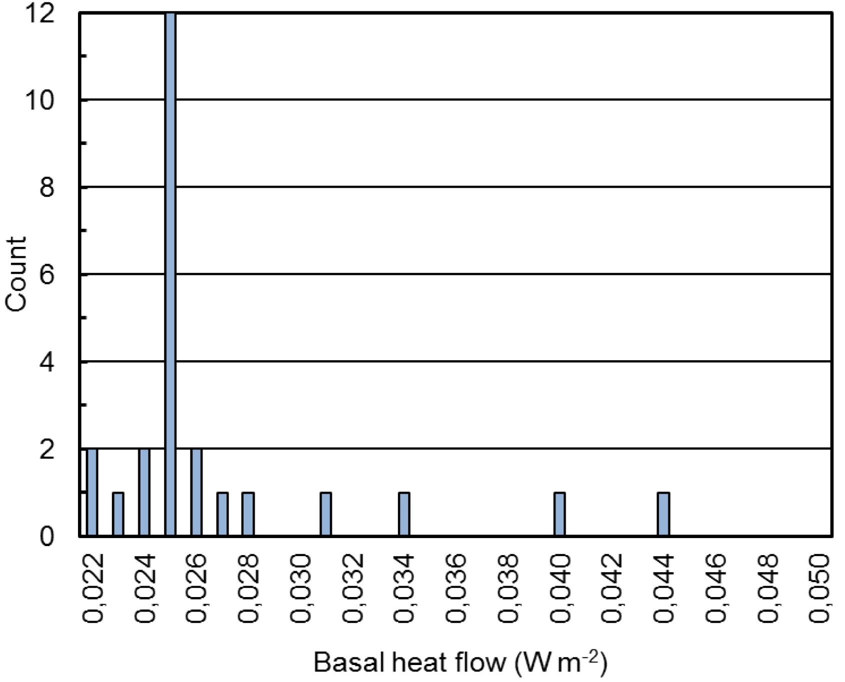

- Measurement of temperature profiles in 2 or more GHEs
- Assessment of the subsurface thermal condutivity with a TRT in GHE 1
- Simulation of temperature profile in GHE 1 with inverse modeling of heat transfer
- Identification of the site heat flow
Convergence of the solution
- Simulation of temperature profile in GHE 2 or more with inverse modeling of heat transfer
- Identification of the subsurface thermal conductivity at GHE 2 or more
Convergence of the solution
- Multiple assessment of the subsurface thermal conductivity without repeating TRT



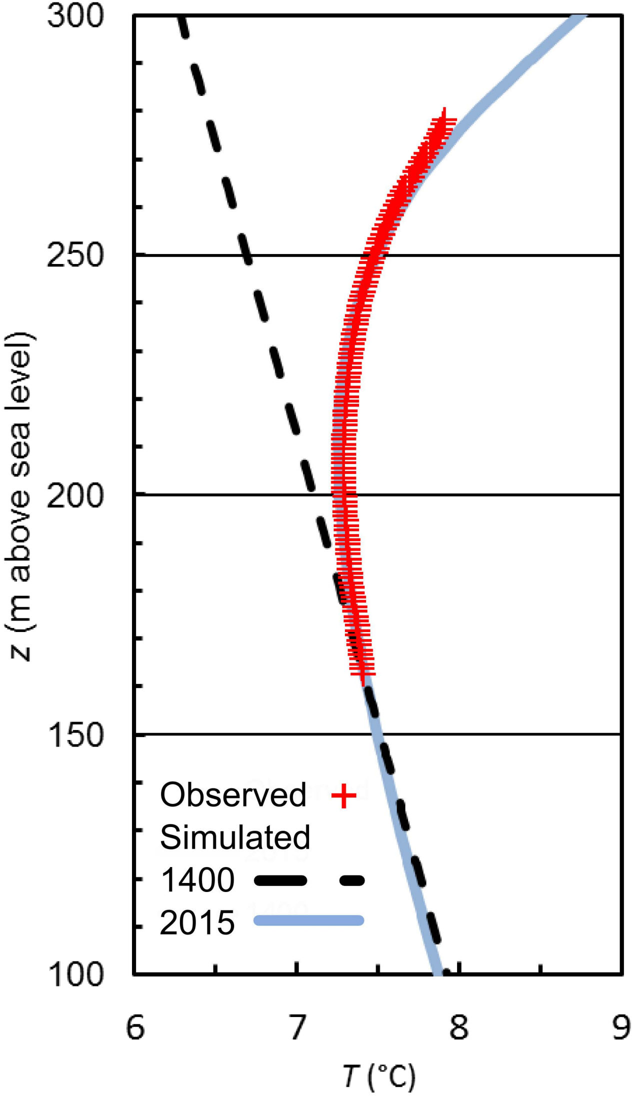
Groundwater
flow perturbation
PG-08-01
PG-08-02
300
275
250
225
200
175
150
z (m)
6
7
8
9
T (°C)

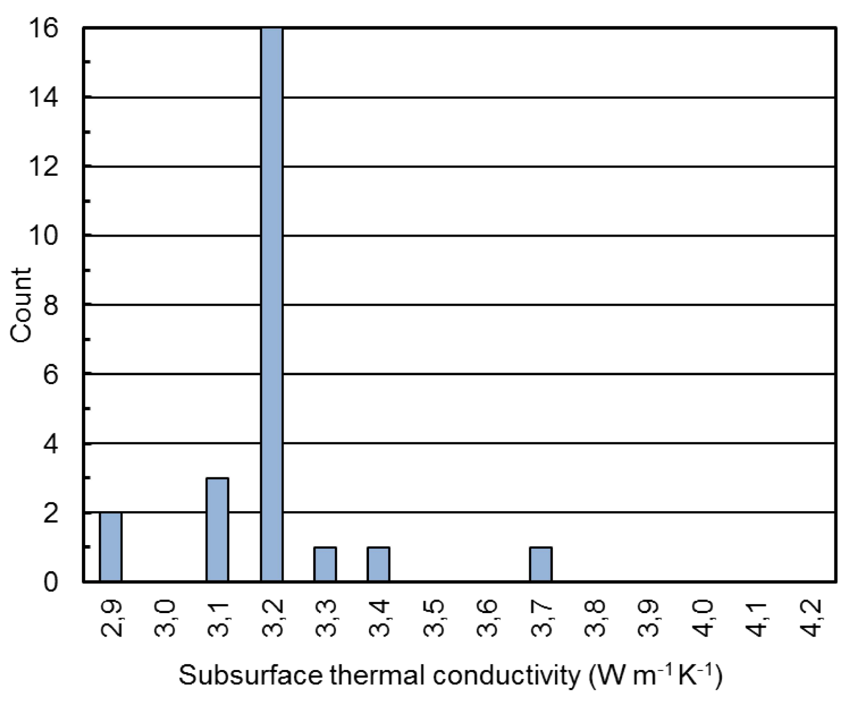


Groundwater
flow pertrubation
PG-08-01
PG-08-02
z (m)
T (°C)
300
275
250
225
200
175
150
6
7
8
9

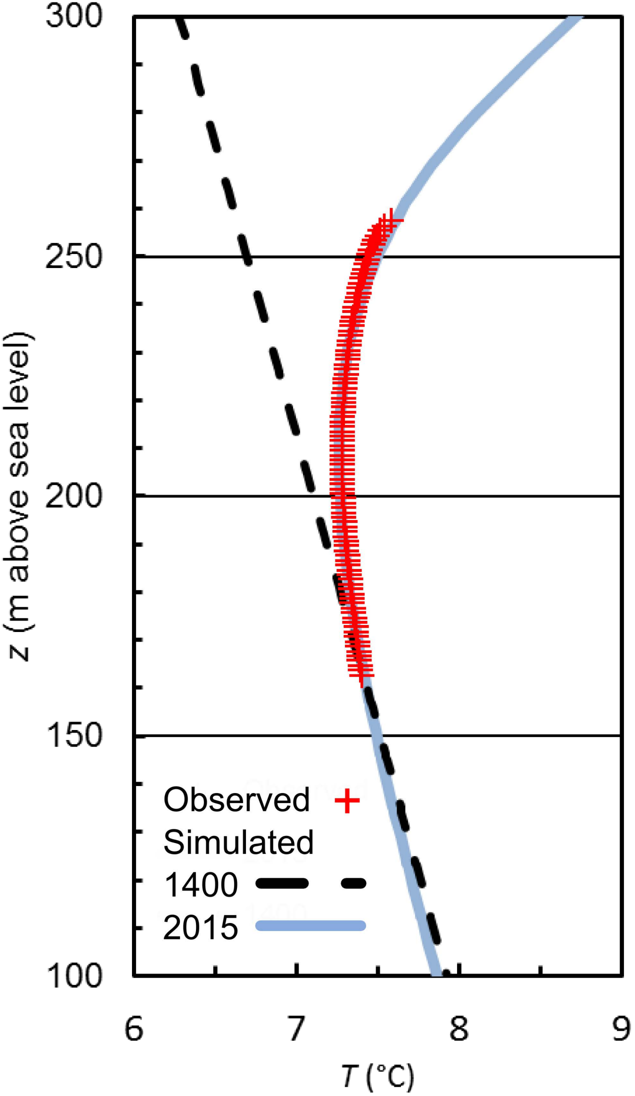


Count
0
2
4
6
8
10
12
0,022
0,024
0,026
0,028
0,030
0,032
0,034
0,036
0,038
0,040
0,042
0,044
0,046
0,048
0,050
Basal heat flow (W m-2)


300
250
200
150
100
z (m above sea level)
6
7
8
9
T (°C)
Observed
Simulated
1400
2015



Count
16
14
12
10
8
6
4
2
0
2,9
3,0
3,1
3,2
3,3
3,4
3,5
3,6
3,7
3,8
3,9
4,0
4,1
4,2
Subsurface thermal conductivity (W m-1 K-1)


300
250
200
150
100
z (m above sea level)
6
7
8
9
T (°C)
Observed
Simulated
1400
2015