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Climate change effects on the energy performance of a residential ground-source heat pump system

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ABSTRACT

The objective of this paper is to examine the impact of climate change on the energy performance of a typical residential ground-source heat pump (GSHP) system equipped with a horizontal ground heat exchanger (GHE) and located in a heating dominated climate (Montréal, Canada). Simulations results under future weather conditions (Relative Concentration Pathway – RCP8.5) show a drop in heating and a rise in cooling energy loads over 30 years. The outlet temperature from the GHE increases consistently from year to year and shows a high degree of variability in-line with the general trend of future ambient temperature fluctuations. In terms of electricity consumption, the main conclusion is that the use of current TMY weather files is inadequate to predict the yearly electricity consumption fluctuations.

INTRODUCTION

As most future climate predictions suggest, global warming will involve changes in annual weather patterns. Projected ambient temperature increases for 2081-2100 relative to 1986-2005 are between 2.6°C and 4.8°C for the Relative Concentration Pathway RCP8.5 (Collins, et al., 2013). As shown by Robert and Kummert (2012) and Deroubaix et al. (2021), buildings located in cold climates will experience a decrease in annual heating needs and an increase in annual cooling needs. The performance of heating/cooling systems will also be influenced by ambient temperature changes. In the case of ground-source heat pumps (GSHP), the ground heat exchanger (GHE) will be affected by ground temperature variations associated with ambient temperature variations. The changing ratio of the annual heating and cooling needs will also affect the amount of heat being rejected/collected in the ground on an annual basis.

Kharseh et al. (2009) showed that the effect of a 4.5°C linear increase in the ambient temperature over 130 years reduced the required length of a GHE by 50% for a specific case. In another study, Kharseh et al. (2011) measured the impact of global warming on the performance of GSHP systems in buildings for linear increases of 1.5°C and 4.5°C of the ambient temperature over 100 years. It is shown that a linear increase of 4.5°C in the ambient temperature over 100 years reduces the electricity consumption of GSHP systems by 37% in cold climates while it increases by 55% in hot climates compared to the consumption with no ambient temperature increase. These studies were performed with a simple building model based on the degree-day method and a simple linear ambient temperature increase over time.

Shen and Lukes (2015) simulated buildings located in different US climate zones for different climate change scenarios between 2040 and 2069. In regions currently categorised as heating dominated such as Chicago and Philadelphia, global warming will transform these regions into cooling dominated regions and reduce the benefits of a higher COP for the

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heat pump in heating. Pertzborn et al. (2011) investigated the impact of year-to-year weather variability on the optimal design of hybrid GSHP systems for office buildings. In a heating dominated climate (Madison, Wisconsin) it is shown that the yearly variations in weather conditions has a minimal impact on the required size of the GHE but that the auxiliary boiler is larger to accommodate colder years. It is unclear, however, how ground temperature changes resulting from ambient temperature variations are accounted for in their simulations.

Analytical and numerical models have been developed to predict the ground temperature evolution through time. One such model is the numerical model developed by Xing (2014) who used a full surface heat balance coupled with weather files to numerically calculate the ground temperature. Although the numerical model provides ground temperature estimates with good accuracy, it is computationally demanding. The one-harmonic analytical model (Thomson, 1862) can be sufficiently accurate to approximate the ground temperature variation. If high precipitation volumes, snow fall and soil freezing/melting occur, a two-order analytical harmonic model can be used. Results from the numerical model and the two analytical models compared favorably well with soil temperatures measured across the US (Xing & Spitler, 2017).

Luo and Asproudi (2015) aggregated soil temperature measurements at Cockley Park in the UK for over a century spanning from 1907 to 2011. Increases of 0.15°C and 0.17°C per decade were measured at 30 and 100 centimeters, respectively. Seong-Kyun and Youngmin (2020) simulated ground temperature profiles around a GHE in the region of Daejeon in South Korea between 2019 and 2050 while taking into consideration different Representative Concentration Pathway (RCP) scenarios. The temperature difference at 50 meters between the best and worst climate scenario in 2050 was 0.17°C.

In summary, this review of the literature indicates that there are apparently no studies which isolate the impact of climate change on the performance of GHEs from the impact climate change has on the building heating and cooling loads. The present analysis attempts to alleviate this deficiency for the case of a residential building located in a cold climate with the aim of presenting a general methodology that could be used for other building types and locations. It also examines the potential inaccuracies in the evaluation of future GSHP electricity consumption that would occur if GSHP were designed with current weather conditions. The paper is divided into four major parts. First, the weather files used in this study are presented. Then, the impact of climate change on the evolution of ground temperature is examined. This is followed by a presentation of the simulation methodology including the incorporation of past and future weather files. Finally, results are presented followed by a conclusion.

WEATHER FILES

In this article, four weather data sets for Montréal (Canada) are used: Two Typical Meteorological Years (TMY) and two series of weather files for successive years. The first set is a Typical Meteorological Year based on actual meteorological weather files from 1998-2017. It was obtained from Environment Canada (2022) and it will be referred to as Current TMY, i.e. the one that would currently be used to design and simulate GSHP systems. The second data set contains future weather files from the years 2020 to 2049 under a RCP 8.5 climate scenario. These files were developed by Hosseini et al. (2021) using a machine learning approach. The dataset will be referred to as the RCP85-20-49 dataset. The third data set is a TMY created using these 30 future years. This dataset will be referred to as the Future TMY. The fourth set, called AMY1998-2017, are actual CWEEDS (Canadian Weather Energy and Engineering Datasets) weather files for this 20-year period and are available from Environment Canada (2022).

GROUND TEMPERATURE MODEL

In this study, a simple one-dimensional finite volume ground model is developed to predict the time evolution of the undisturbed ground temperature. The model assumes that ground properties remain constant through time and that they are not affected by snow cover, freezing/thawing or ground water movement. Heat is transferred from the air to the ground and is diffused solely by conduction. The governing one-dimensional transient heat conduction equation is:

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} \tag{1}$$

where T is the ground temperature in °C and x is the depth in meters. Other parameters have their usual meaning and are defined in the nomenclature. Equation (1) is solved numerically using Patankar's finite volume method (Patankar, 1980). The result is a series of algebraic equations to determine the node temperatures at each axial grid location. The initial ground temperature profile is evaluated using the analytical approach presented by Lunardini (1981):

$$T(x) = T_m + gx - (T_{max} - T_m)e^{-x\sqrt{\frac{\omega}{2\alpha}}} \cos\left(\omega\Phi + x\sqrt{\frac{\omega}{2\alpha}}\right) \tag{2}$$

The values used for the various parameters in Equation 2 are specified in Table 1. They correspond to data specific to Montréal (Canada). The ground is meshed exponentially with finer grids near the surface. A grid independence check was performed where the number of nodes was varied from 10 to 100 and the time step from 0.1 to 120 hours. The different configurations yielded results within 0.02 °C of each other. Furthermore, the ground temperatures from the numerical model and the ones predicted by Kharseh et al. (2011) were within 0.01 °C of each other over a depth of 300 meters for a period of 100 years with a 1-hour time step.

The ground temperature model was used to examine the impact of climate change on the ground temperature with the RCP85-20-49 dataset and the ground properties specified in Table 1. Results are shown in Figure 1 where annual average temperatures on the surface and over two depths are plotted. It can be seen in Figure 1 that the average ground temperature over the first 3 meters can experience large variations from year to year. For example, there is a 2°C difference in the yearly average ground temperature between the years 2029 and 2030. The temperature swings are less severe if the average temperature over the first 30 meters is considered. Looking at the trends (dotted lines in Figure 1), the average yearly surface temperature is increasing at a rate of 0.52°C/decade and the average ground temperature of the first 3 meters follows this trend closely with an increase of 0.51°C/decade. The average ground temperature of the first 30 meters is less affected by the surface temperature increase with an increase of 0.24°C/decade. This implies that horizontal GHE located near the surface will be affected more by climate change than vertical GHE.

Table 1. Ground and weather parameters

Parameter	Value	Units
ρC_p	2.2×10^6	J/m³ K
k	2.5	W/m K
T_m	7.77	°C
T_{max}	22.97	°C
g	0.02	°C/m
ω	1.99×10^{-7}	rad/s
α	1.14×10^{-6}	m²/s
Φ	1794240	s

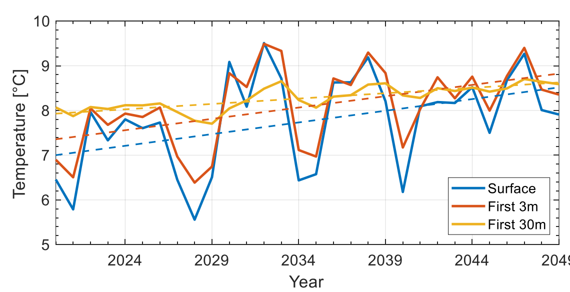

Figure 1 Average yearly ground temperature at the surface, for the first 3 meters and the first 30 meters from 2020 to 2049 using the RCP85-20-49 future weather dataset. The doted lines represent the result of linear regressions.

SYSTEM SIMULATION

The impact of climate change on the performance of a residential GSHP system equipped with a horizontal GHE is examined here using multi-year TRNSYS simulations. The important components of the system are shown in Figure 2. Standard TRNSYS components are used except for the horizontal GHE model which required modifications as presented below. The residential building is a modified version of the example building contained in the TEES Library of TRNSYS 18 (Klein, et al., 2017). It consists of a two-story building with a basement and an attached garage as well as a sunroom. Each story has a 139 m² area. It is modeled in TRNSYS using Type 56. The building is subdivided into six thermal zones: basement, ground floor, first floor, garage, sunroom and attic. Only the first three are heated and cooled. The original insulation levels have been upgraded to meet the National Energy Code of Canada for Buildings or NCEB (2022). Internal heat gains from people and appliances at a 15-minute time interval were read from an external file. These data are based on studies performed at the Canadian Center for Housing Technologies (Swinton et al., 2001). Exposed to the Current TMY weather conditions, the peak heating and cooling loads are 13.1 and 6.3 kW, respectively.

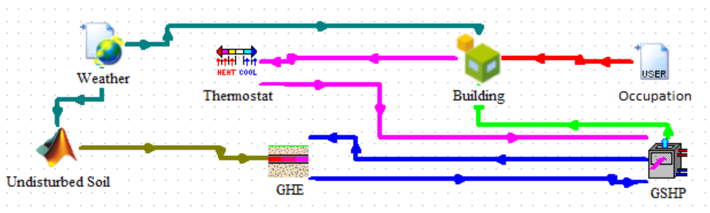

Figure 2 Main TRNSYS components and connections.

The energy performance of the water-to-air GSHP is based on a commercially available 3-ton (10.5 kW) single-speed machine (Water Furnace, 2022). Manufacturer data were processed to obtain normalized heating and cooling performance maps to be used in TRNSYS with Type 919. Figure 3 shows the resulting normalised heating and cooling capacities as well as the COP in heating and cooling as a function of the entering water temperature. The heating and cooling capacities are 9.38 and 10.73 kW at 10 and 21.1 ℃, respectively (marked as a red cross in Figure 3). Using a normalised performance map is useful as the nominal heating or cooling capacity can be adjusted for values other than 3-ton but keeping the same performance trends. A GSHP with a nominal heating capacity of 11.6 kW for an EWT of 10°C was selected. With this capacity, the GSHP is able to meet 70% of the peak heating load with an entering water temperature of 0°C in accordance with canadian practice (CSA Group, 2021). A 10 kW electric auxiliairy heater provides backup heating in peak periods.

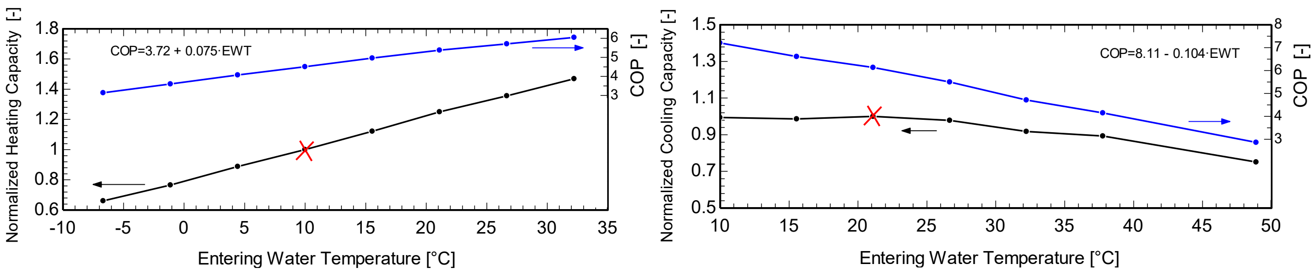

Figure 3 Normalized capacity and COP in heating and cooling as a function of the entering water temperature (EWT). The red cross indicates the rated heating and cooling conditions.

The result of a linear curve fit on the COP is indicated on both figures. It shows that the COP variation as a function of the entering water temperature is relatively small. In fact, the COP in heating increases by 1.66% for a 1 °C change of the EWT at 10 °C and in cooling it decreases by 1.7 % for a 1 °C change of the EWT at 21.1 °C.

The horizontal GHE was modeled using a modified version of Type 952 to take into account the changing ground temperature profile due to the changing climate conditions. The original version uses an analytical equation, internal to Type 952, analogous to equation 2 to calculate the far-field ground temperature at the different depths around the GHE to perform the required heat transfer calculations. It can be seen that equation 2 is solely dependant on the initial parameters and can not account for ambient temperature changes. In the modified version of Type 952 the far-field ground temperatures are calculated externally for the different required depth (using a Matlab subroutine of a unidimentionnal finite volume model of the ground as described earlier) using the ambient temperature as the ground surface temperature and inputed into Type 952 at each simulation timestep as indicated in Figure 2. All the far-field temperatures calculated as well as the soil temperatures are updated at each timestep. The horizontal GHE was designed based on a 30 year simulation of the complete system performed with the Current TMY weather file. Based on these simulations, a GHE with a length of 300 m at a depth of 3 m was selected. With these conditions, the minimum inlet fluid temperatures to the heat pump was -3.7°C.

RESULTS

To establish a baseline energy consumption for the residence, a one-year simulation is undertaken using both Current and Future TMY files. Figure 4 shows the resulting monthly cooling and heating loads. The heating and cooling load variations are not uniformely distributed throughout the months of the year. In fact, Figure 4 shows that future weather conditions induce increased heating loads in certain months when compared to the current weather conditions. As for the cooling loads, future weather conditions lead to increases in monthly cooling loads for almost every month.

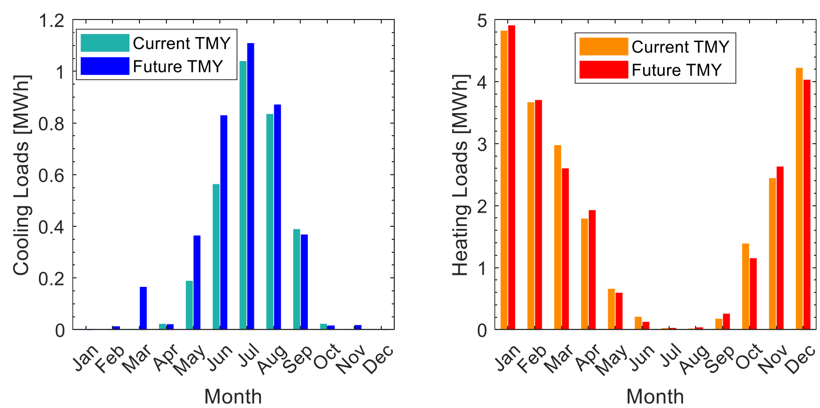

Figure 4 Monthly cooling (left) and heating (right) loads of the residence under Current and Future TMY.

Figure 5 illustrates the yearly building load variations for three weather data sets. As shown in Table 2, loads increase from 3.1 to 3.8 MWh in cooling and decrease from 22.3 to 21.9 MWh in heating when results obtained with Current and Future TMY files are compared. When the RCP85-20-49 weather conditions are used, the heating loads decrease by 3.5% (761 kWh) per decade (tendency line on Figure 5) while the cooling loads increase by 7% (268 kWh) per decade. Table 2 shows the highest (H), lowest (L), and average (A) annual loads of the residence under both the RCP85-20-49 and AMY1998-2017 conditions. Notable details include a higher maximum heating load under the RCP85-20-49 conditions compared to the AMY1998-2017 conditions (25.60 vs 24.43 MWh). However, the annual heating loads calculated with the Current and Future TMYs, and the average heating loads calculated using the AMY1998-2017 and RCP85-20-49 data sets are very similar (22.30, 21.90, 22.31, 21.84 MWh). As for the cooling loads, RCP85-20-49 conditions lead to a high yearly cooling load reaching a value 55% above predictions with the Current TMY (4.81 vs 3.1 MWh). This is much greater than the highest value experienced with the AMY1998-2017 weather file (3.80 MWh).

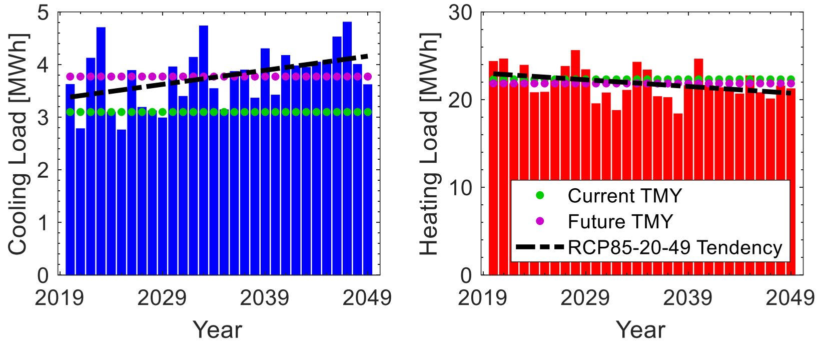

Figure 5 Yearly cooling and heating loads of the residence under the RCP85-20-49 and the Current and Future TMY weather conditions.

Table 2. Annual loads and electricity consumption under four weather datasets (H, A, and L stand for Highest, Average, and Lowest) as well as the heating SPF and the average cooling COP.

Annual Building Heating and Cooling Loads [MWh]						Annual GSHP System Electricity Consumption [MWh]							
		Heating	Relative	Cooling	Relative			Heating	Relative	SPF	Cooling	Relative	COP
C TMY		22.30	100%	3.10	100%	C TMY		7.27	100%	3.07	0.76	100%	4.08
F TMY		21.90	98%	3.80	123%	F TMY		7.51	103%	2.92	0.92	120%	4.13
AMY 98-17	H	24.43	110%	3.81	123%	AMY 98-17	H	8.93	123%	2.74	0.93	122%	4.10
	A	22.31	100%	3.10	100%		A	7.36	101%	3.03	0.75	99%	4.13
	L	19.77	89%	2.03	66%		L	5.85	81%	3.38	0.49	64%	4.14
RCP8.5 20-49	H	25.60	115%	4.81	155%	RCP8.5 20-49	H	10.18	140%	2.51	1.24	162%	3.88
	A	21.84	98%	3.77	122%		A	7.51	103%	2.91	0.93	123%	4.05
	L	18.37	82%	2.76	89%		L	5.22	72%	3.52	0.65	85%	4.25

Before moving to the analysis of the annual electricity consumption, the evolution of the inlet temperatures to the GSHP (i.e. the outlet temperature from the horizontal GHE) will be examined in Figure 6 for the Current TMY and RCP85-20-49 weather conditions. In the case of the Current TMY, the same file is used over the 30 year period much like what would be done if such a system were designed today.

As expected, the minimum and maximum GSHP inlet temperatures decrease over time (0.09°C/decade) when the Current TMY is used in the 30 year simulation. This reduction is due to the heating dominated nature of the loads and therefore an overall energy extraction from the ground occurs which in turn reduces the average ground temperature arround the GHE. The minimum and maximum yearly GSHP inlet temperatures experience several important fluctuations caused by climate variability and the inlet temperatures to the GSHP dips well under the -3.7 °C minimum attained under the Current TMY weather conditions even reaching a value of -5.2 °C for harsh winters occuring in the first half of the 30 year period. It can be shown that this minimum temperature can be reached under the Current TMY weather conditions with a 240 m GHE (20% shorter). The minimum inlet temperature increases at an average rate of 0.38°C/decade under the RCP85-20-49 weather conditions while, as shown earlier, the ground temperature increase over the first 3 m is of the order 0.51°C/decade with no GHE. This difference is partly accounted for, as the building loads are still heating dominated, by the natural decrease of the ground temperature arround the GHE (in the order of 0.09°C/decade as shown earlier) due to the overall energy extraction during a full heating/cooling season cycle as mentioned above.

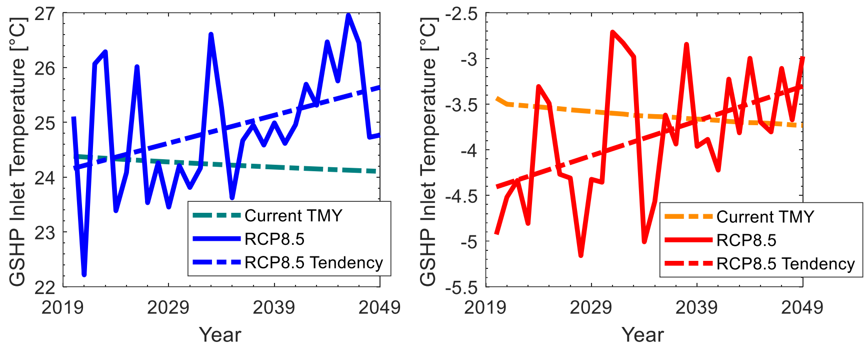

Figure 6 GSHP maximum (left) and minimum (right) yearly inlet temperature.

A similar picture is painted by the maximum yearly inlet temperature in Figure 6 with an average yearly increase of 0.51°C/decade under the RCP85-20-49 weather conditions. One would have expected an average increase similar to the minimum yearly inlet temperature but this difference is due to a secondary effect (shown in Figure 7) related to the fact that the electricity consumption of the GSHP system in cooling mode increases by 8% per decade (+7.4 kWh/year), implying an overall increase in the GSHP operation time from year to year in cooling mode and therefore, a higher heat injection in the GHE during the summer.

It can be concluded that for heating dominated climates, where a GHE is sized for the heating load, more extreme winters will induce strains on the GHE and the GSHP as the minimum inlet temperature will dip considerabely below the design temperature predicted with the Current TMY weather file. For example, in the year 2028, the minimal EWT dips down to -5.2°C, 1.5°C below the -3.7°C design temperature. For regions where the cooling load is much larger than the heating load, it is expected that the surplus heat injected during a full heating/cooling season cycle will add to the already rising ground temperature due to global warming and the maximum inlet temperature will increase from year to year, a point to be taken into consideration while dimensioning the GHE.

The trends in yearly electricity consumption of the GSHP system in heating and cooling over the 30-year period for three weather data sets (Current TMY, Future TMY, and RCP85-20-49) are shown in Figure 7. The electricity consumption includes the consumption of the GSHP, the ventilators, the controllers as well as the auxiliary heater in heating. Table 2 summarises these results and shows the highest (H), lowest (L), and average (A) annual electricity consumption as well as the heating SPF and the average cooling COP for the RCP85-20-49 and AMY1998-2017 weather data sets. Figure 7 shows a decrease of 8%/decade (-60 kWh/year) in the total electricity consumption of the GSHP system in heating mode under the RCP85-20-49 weather conditions. This is due to the combined effect of a 23%/decade (-43 kWh/year) decrease in the auxiliary heating electricity consumption and a 3%/decade (-17 kWh/year) decrease in the GSHP system electricity consumption (excluding the auxiliary heating) over the 30 years. Consequently, the GSHP system becomes less reliant on the inefficient (compared to the GSHP) auxiliary heater.

Future cooling electricity consumption is, on average, underestimated by 20% when compared to Current TMY conditions (0.76 vs 0.92 MWh). However, the heating electricity consumption predicted using Future TMY conditions is 3% higher (7.27 vs 7.51 MWh) than what is predicted using Current TMY conditions. Even though the building's heating load is on average lower with Future TMY conditions, harsher winters, affecting the EWT and building loads, reduce the COP of the GSHP and causes a higher usage of the auxiliary heater that is less efficient causing the increase in the overall electricity consumption (7.27+0.76 vs 7.51+0.92) as well as a decrease in the heating SPF (3.07 vs 2.92). Therefore, the heating system will operate less in the future but when operating it will run under harsher conditions reducing its overall efficiency.

Table 2 shows the highest (H), lowest (L), and average (A) loads of the residence under both the RCP85-20-49 and

AMY1998-2017 conditions. It is interesting to note that the highest yearly heating loads under the RCP85-20-49 conditions is higher than the one calculated with the AMY1998-2017 data set (25.60 MWh vs 24.43 MWh). The highest yearly cooling electricity consumption under the RCP85-20-49 conditions is 62% higher the predicted annual cooling electricity consumption using the Current TMY conditions. The heating electricity consumption under the RCP85-20-49 weather conditions ranges (L to H) from 72% to 140 % of the prediction obtained with the Current TMY. The corresponding values are 81% and 123% for the AMY1998-2017 weather conditions. This indicates a higher variability in electricity consumption in the future due to strong variability in the predicted climate. The average cooling COP of the GSHP system exhibits a 0.04 variation (4.14-4.10) during the AMY1998-2017 years in contrast to a 0.37 variation (4.25-3.88) during the RCP85-20-49 years implying higher cooling performance variations from year to year.

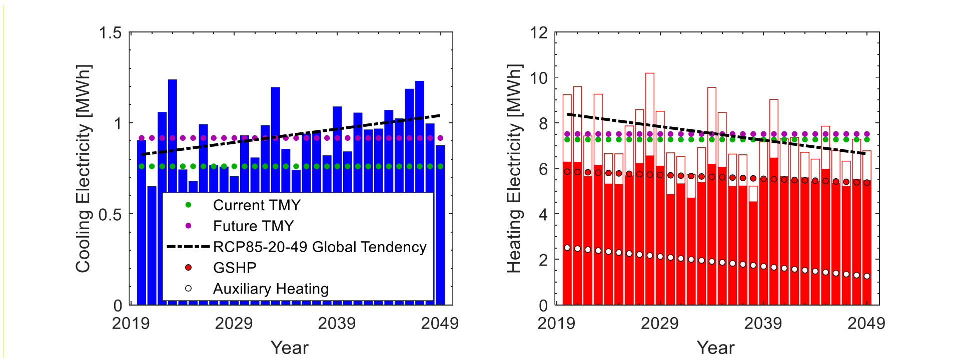

Figure 7 GSHP system electricity consumption in cooling and heating mode with its global variation tendency over the 2020-2049 period as well as the mean consumption under Current and Future TMY.

CONCLUSION

The effect of climate change on a residential building equipped with a GSHP system coupled with a horizontal GHE located in a cold climate (Montréal, Canada) is examined using multi-year TRNSYS simulations. Four different weather data sets are used: 20 years of actual weather (AMY1998-2017); 30 years of future weather (RCP85-20-49) and two TMY (called Current and Future) based on these two sets of data.

In the first part of the paper, a simple one-dimensional numerical ground model is presented. When used with the RCP85-20-49 weather files, it is shown (Figure 1) that the yearly average ground temperature over the first three meters increases by 0.51°C/decade which closely corresponds to the surface temperature change (0.52°C/decade). The ground model is incorporated in a modified version of the horizontal GHE model in TRNSYS to better predict ground temperatures changes as a function of ambient temperature changes.

If the GSHP system is designed with the Current TMY (same weather file used for 30 years), the minimum heat pump inlet temperature is expected to reach -3.7 °C after 30 years. However, when the RCP85-20-49 weather is used, large yearly fluctuations are observed and the minimum inlet temperature to the heat pump reaches -5.2 °C in a harsh winter. This can induce a 20% difference in the GHE design length.

Yearly electricity consumption are compared using the four different weather data sets and the main results are shown in Figure 7 and Table 2. The average yearly electricity consumption for cooling obtained with Current TMY is 20% below the value obtained with the Future TMY. However, the heating electricity consumption predicted using Future TMY conditions is 3% higher than what is predicted using Current TMY conditions. Even though the building's heating load is on average lower with Future TMY conditions, harsher winters, affecting the inlet temperature to the heat pump and the building loads, reduce the COP of the GSHP and causes a higher usage of the auxiliary heater causing the increase in the overall electricity consumption and a reduction of the heating SPF. The maximum cooling electricity consumption under the RCP85-20-49 conditions is 62% above the predicted consumption using the Current TMY conditions. The heating electricity consumption range under the RCP85-20-49 conditions is 68% (140%-72%) compared to 42% (123%-81%) under the AMY1998-2017 conditions indicating a higher future electricity consumption variability.

These results show that designing a GSHP system with Current TMY files as weather conditions for multi-year simulations might be inadequate. It is preferable to use future weather files which show the range of expected electricity consumption and variability in the outlet temperature from the GHE which are essential in its sizing. This study has only looked at climate change effects on a residential building heated and cooled by a GSHP equipped a horizontal GHE and located in a cold climate. More work is needed on different building types, locations, and climate change scenarios. Hopefully, the approach used here could be employed under other conditions to further broaden the understanding of the influence of climate change on the dimensioning and operation of GSHP systems.

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NOMENCLATURE

α = Ground thermal diffusivity [m²/s]
t = Elapsed time [s]
ρ = Density [kg/m³]
C_p = Ground specific heat [J/kg K]
k = Ground thermal conductivity [W/m K]
T = Temperature [°C]
g = Geothermal gradient [°C/m]
m = mean
max = Maximum
Φ = Initial phase shift [s]
ω = Climatic period [rad/s]
H = Highest
A = Average
L = Lowest
C = Current
F = Future
SPF = Seasonal Performance Factor
COP = Coefficient Of Performance
TMY = Typical Meteorological Year
GSHP = Ground Source Heat Pump

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