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Climate Change Effects on Heating and Cooling Demands of Buildings in Canada

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Abstract: Climate change is causing more frequent extreme weather events. The consequences of increasing global temperature on the operating cost of existing buildings, and the associated health, safety, and economic risks were investigated. Eight cities in Ontario, Canada, across climate zones 5 to 8, were selected for this study. Statistical models were employed to forecast daily temperatures for 50 years. The impact of climate change on buildings' heating and cooling demands for energy was measured as changes in heating degree days (*HDD*) and cooling degree days (*CDD*) compared to current design requirements. The results predict an increase in the demand for cooling and a decrease in that for heating within the next 50 years. A drop in the total *HDD* and *CDD* is shown which reflects a more comfortable outdoor thermal condition. Risk to human health attributable to the increase in global temperature is negligible.

Keywords: climate change; energy consumption; existing buildings

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1. Introduction

Climate, which refers to the condition of the atmosphere for a location over a period of many years, is the average condition of the weather as exhibited by temperature, pressure, pollution, humidity, precipitation, wind velocity, and other meteorological elements. Historical records show that over a 100-year period starting in 1900, the planet's temperature has increased steadily reaching a value of +0.7 °C in recent years [1]. In the absence of human influence, the planet's temperature is found to maintain roughly the same pattern over the 100-year cycle. These findings, among others, reveal that the increase in the planet's temperature is mostly influenced by humans [2–4]. Greenhouse gas (GHG) emissions related to energy use, along with urbanization and land use that are changing on a local and regional scale, are the main causes of climate change [3]. Human influence on the climate is reported to have caused an increase of approximately 1.0 °C in global temperature, and global warming is likely to reach 1.5 °C between 2030 and 2052 given the current trends [5]. The global GHG emissions data shows that Canada produced approximately 1.6% of the total in 2014, and the building sector contributed 11.9% of Canada's total GHG emissions [6]. Globally, the building sector consumes 30% of the total energy and produced 28% of the energy-related CO_2 emissions in 2015 [7]. According to a 2016 study by NRCan [8], the energy consumption of residential, commercial, and industrial buildings due to space heating and space cooling is approximately 60% and 5% of the total, respectively. This indicates that the observed changes to the climate will directly impact building energy consumption, specifically space heating and cooling.

Heating degree days (*HDD*) and cooling degree days (*CDD*) are units of measurement adopted by national organizations, such as the National Research Council of Canada (NRC) [9] and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [10], as the industry standard for quantifying the weather. In brief, *HDD* and *CDD* reflect the energy demand for space heating and space cooling of buildings [11–13] as well as the thermal comfort of the outdoor natural environment [14]. Therefore, with the projected climate change a decrease in *HDD* is anticipated while *CDD* is expected to increase by the end of the century [14–18].

Over the last decade, studies have used different methods and models to examine the impact of climate change on energy demand. Studies in the literature were reviewed and categorized by methodology: studies that calculated degree days, studies that used degree day calculations and energy simulations, studies that used only energy simulations, and those that used other simulation programs. The first group of studies obtained future data from CMIP5 models [14], RegCM4 [16], regional climate simulations (REMO) [13], STAR II and CCLM [19], AOGCMs [20], the ESCAPE model [21], and the HadCM3 GCM [22]. These studies then used the ASHRAE method of calculating *HDD* and *CDD* [13,19,23], the UK Meteorological Office (UKMO) equations to calculate degree days [14], the sine method of calculating degree days [21], or other degree day calculation methods [16,20,22]. Studies that utilized degree day calculations and energy simulation included those that used HadCM3 GCM with EnergyPlus, a whole building energy simulation program [24], and MeteoNorm in combination with VISUAL DOE [25,26]. Studies that used only energy simulations utilized HELIOS and EnergyPlus [27,28]. Other simulation programs that have been used include TRNSYS [29], DOE-2.1E [30], and OZClim, a climate change projection software, which was used with the building simulation software AccuRate [31]. The ASHRAE method of calculating *HDD* and *CDD* used in a number of the reviewed studies was selected as the basis for the methodology adopted in this study.

According to ASHRAE's climate zones classification [32], Canada possesses 5 climate zones, ranging from zone 4 which is a mix of warm and cool, to zone 8 which is subarctic. Ontario possesses 4 climate zones, from zone 5 to zone 8. Climate change is expected to impact Canada differently depending on the geographic region and the current climate. It is anticipated that the change in climate will have a direct effect on human health and safety, agriculture and energy sector, transportation, marine life, etc. [4]. According to the Council of Canadian Academies (CCA), 12 main areas will face challenges due to climate change in the next 20 years [33]. Built civil infrastructures, such as buildings, bridges, roads, and other infrastructures, are most at risk to suffer considerable disruption, damage, and total loss in the next 20 years [33]. The risk is increasing due to an increasing number of extreme events such as high wind and tornado, extreme rainfall and flooding, heat wave, wildfire, snowstorm to name a few among other extreme weather events [33]. For reference, the average insured losses have increased from USD 405 million per year between 1983 and 2008 to USD 1.8 billion per year between 2009 and 2017 due to these extreme weather events [34]. Accordingly, studying the effects of climate change on buildings' energy consumption and the buildings' heating and cooling demand is merited. The objective of this study was to quantify the impact of global warming on the heating and cooling energy demands of existing buildings in Ontario, Canada, and to recommend remedial energy retrofit measures for these buildings.

2. Methods

2.1. Climate Zones & Cities

Ontario is the second-largest province in Canada. Its climate spreads over 4 zones, namely zones 5 to 8, according to ASHRAE's climate zone classification [32]. For each climate zone, 2 cities in the province, each having a large population and a weather station, were selected for this study. The cities representing climate zones 5 to 8 were Windsor and St. Catharines, Toronto and Ottawa, North Bay and Sudbury, and Big Trout Lake and Peawanuck, respectively. Furthermore, according to the Köppen climate classification, the northernmost parts of Ontario which include Big Trout Lake and Peawanuck, have a sub-arctic climate, whereas almost all southern Ontario which includes Windsor, St. Catherine, Toronto, Ottawa, North Bay, and Sudbury have a humid continental climate.

Figure 1 shows the location of the cities on a map of Ontario, Canada. Table 1 provides a list of the cities, the location of the weather station, and the city's geographical location, climate zone, and *HDD* and *CDD* [32].

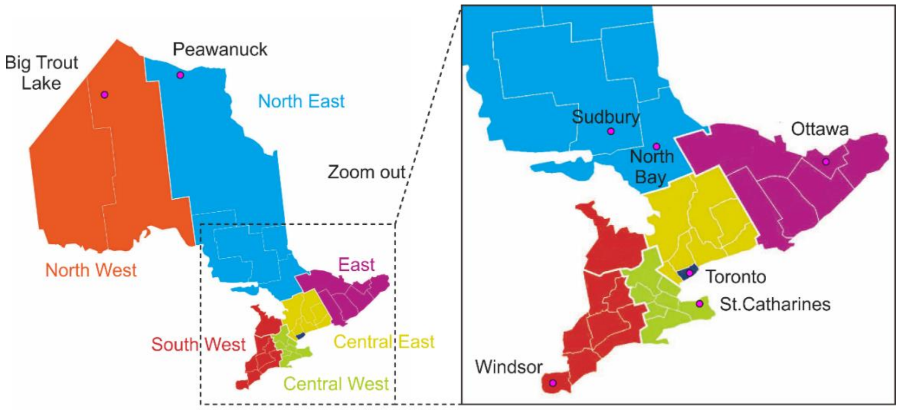

Figure 1. The location of eight selected cities.

Table 1. Climate zone information of eight cities.

City	Station	Latitude (N)	Longitude (E)	Climate Zone	Thermal Criteria	Cities' Climate Design Condition [10]	
						HDD18 °C	CDD18 °C
Windsor	Windsor International Airport	42.28	277.04	5	3000 < HDD18 °C ≤ 4000	3421	438
St. Catharines	Niagara Falls Airport	43.11	281.05			3664	323
Toronto	Toronto Downsview Airport	43.68	280.37	6	4000 < HDD18 °C ≤ 5000	3837	304
Ottawa	Ottawa International Airport	45.32	284.33			4483	241
North Bay	North Bay Airport	46.36	280.58	7	5000 < HDD18 °C ≤ 7000	5151	126
Sudbury	Greater Sudbury Airport	46.62	279.20			5214	124
Big Trout Lake	Big Trout Lake	53.83	270.13	8	7000 < HDD18 °C	7349	52
Peawanuck	Peawanuck (AUT)	54.98	274.57			8002	36

2.2. Climate Models

In this study, the temperature data were extracted from the NA-CORDEX. The CORDEX is a diagnostic model intercomparison project (MIP) belonging to 23 CMIP6-Endorsed MIPs [35], established on the common downscaling framework provided by previous downscaling intercomparison projects all over the world, and covers the period 1950 to 2100. The CORDEX focuses on downscaling research, it potentially provides the climate change information for impacts, vulnerability, and adaptation investigations [36]. The Regional Climate Models (RCMs) involved in NA-CORDEX include CRCM5, RCA4, RegCM4, WRF, CanRCM4, and HIRHAM5. Driving Global Climate Models (GCMs) include HadGEM2-ES, CanESM2, MPI-ESM-LR, MPI-ESM-MR. EC-EARTH, GFDL-ESM2M.

The model can simulate thousands of years' worth of data based on a few decades of data, all when a supercomputing system is used [37]. Global Climate Models (GCMs) are fundamental and essential for studying trends in the global climate and provide a reliable simulated long-period climate for a zone. Regional Climate Models (RCMs), which are developed by downscaling GCMs, provide high-resolution data for regional areas (approximately 25–50 km) [38].

In this study, five GCM-RCM combined models were used to analyze temperature change trends. The detailed information for the five models is provided in Table 2. In general, RCMs satisfactorily reproduce 2 m surface temperature and other characteristics in most parts of North America at both seasonal and daily timescales under different radiation forcing scenarios. Current RCMs have been significantly improved compared with previous versions. Additional information on these models is available, specifically for CRCM5 [39–41], RCA4 [42,43], and HIRHAM5 [20]. The five selected GCM-RCM models are included in the model-performance study by Al-Samouly et al., in which the performance of multi-model ensembles based on mean value was better than each individual model [44]. The greenhouse gas concentration curve, named Representative Concentration Pathway (RCP), varies between 2.6 and 8.5. These pathways, provide different possibilities while forecasting the climate, depending on the emitted greenhouse gases (GHG) in the coming years. RCP 4.5 scenario is adopted in this study as it is accepted as a common pattern [45].

Table 2. Global climate model (GCM) and regional climate model (RCM) combinations.

No.	GCM	RCM	Simulation	Scenario	Data Resource	Data Time Period
1	CanESM2	CRCM5	0.44°/50 km	RCP 4.5	NA-CORDEX	1 January 2020–31 December 2069
2	CanESM2	RCA4	0.44°/50 km	RCP 4.5		
3	EC-EARTH	HIRHAM5	0.44°/50 km	RCP 4.5		
4	EC-EARTH	RCA4	0.44°/50 km	RCP 4.5		
5	MPI-ESM-LR	CRCM5	0.44°/50 km	RCP 4.5		

2.3. Degree Days

According to ASHRAE Handbook Fundamentals Chapter 14: Climatic Design Information [10], the sum of the difference between the daily average temperature and the base temperature is calculated to represent the heating and cooling degree days. The heating degree days (*HDD*) in a month were calculated as follows

$$HDD = \sum_{i=1}^{N} \left(\mathrm{T_{base}} - \overline{T}_i\right)^+ \tag{1}$$

in which N is the number of days in the month, $\mathrm{T_{base}}$ equals 18.3 °C which is commonly adopted in North America, and $\overline{T}_i$ represents the average daily temperature. The positive sign "+" indicates that only the positive value of the month is taken into consideration. Likewise, the equation for the monthly cooling degree days (*CDD*), where $\mathrm{T_{base}}$ equals 18.3 °C was

$$CDD = \sum_{i=1}^{N} \left(\overline{T}_i - \mathrm{T_{base}}\right)^+ \tag{2}$$

For this study, forecasted mean daily temperatures were extracted from eight different models, thereby calculating the yearly *HDD* and *CDD* corresponding to five models individually. In addition, the mean yearly *HDD* and *CDD* were estimated according to five climate models from NA-CORDEX. Based on the daily temperature extracted from these five models, the 25-year mean monthly temperatures, *HDD* and *CDD*, mean yearly temperature, *HDD* and *CDD*, and standard deviation (SD) were computed and analyzed. Furthermore, we analyze combined *HDD* + *CDD* values for the eight selected cities for historical (1995–2019) and future (2020–2069) periods. *HDD* + *CDD* value is a reasonable indicator to show the outdoor thermal comfort condition. Typically, a lower value of *HDD* + *CDD* means less heating and cooling demands in buildings and better outdoor thermal comfort, lower energy assumption in total, and more suitable environments for people to live in temperature-wise [14]. In this study, 25-year monthly *HDD* + *CDD* and 50-year annual *HDD* + *CDD* were measured.

2.4. ASHRAE Climate Design Condition

The ASHRAE Handbook Fundamentals: Climatic Design Information [10] provides detailed climatic information for many climate zones using thousands of weather stations. It has the standards for building design in relation to *HDD* and *CDD*, helping to set the expected power demands for buildings in the various climate zones. We used data from the Handbook as current design requirements to compare with predicted future data. By comparing the ASHRAE Handbook Fundamentals, 2009 edition, 2013 edition, and 2017 edition, a few variations could be observed: (a) The latitude and longitude of each station became more accurate with higher resolution from 2009 to 2017 edition; (b) Canadian stations increased from 480 (2009 edition) to 765 (2017 edition), 59% increase; (c) The design condition for *HDD* and *CDD* at the selected locations changed over the years [10,46,47]. Table 3 shows the climate design information for each city in the 2009, 2013, and 2017 editions of the Handbook. Figure 2 illustrates the changes in designed degree day between the 2009 edition and the 2013 and 2017 editions separately. It can be observed that the designed *HDD* is decreased from 2009 to 2013 for all eight selected cities, and the designed *CDD* is increased in climate zone 5–7. However, the two cities in climate zone 8, Big Trout Lake and Peawanuck have reduced designed *CDD*, declined about 4% and 3%, respectively. In the 2017 edition, the designed *HDD* for most of the selected cities declined or remained about the same. For designed *CDD*, five cities increased while the other three cities had the opposite trend.

Table 3. Climate design conditions for the selected cities.

City Name	2009 Edition		2013 Edition		2017 Edition	
	HDD18.3	CDD18.3	HDD18.3	CDD18.3	HDD18.3	CDD18.3
Windsor	3482	418	3444	434	3421	438
St. Catharines	3661	327	3658	328	3664	323
Toronto	3956	276	3892	292	3837	304
Ottawa	4563	236	4523	238	4483	241
North Bay	5243	118	5192	123	5151	126
Sudbury	5297	130	5241	132	5214	124
Big Trout Lake	7572	51	7329	49	7349	52
Peawanuck	7912	39	7898	38	8002	36

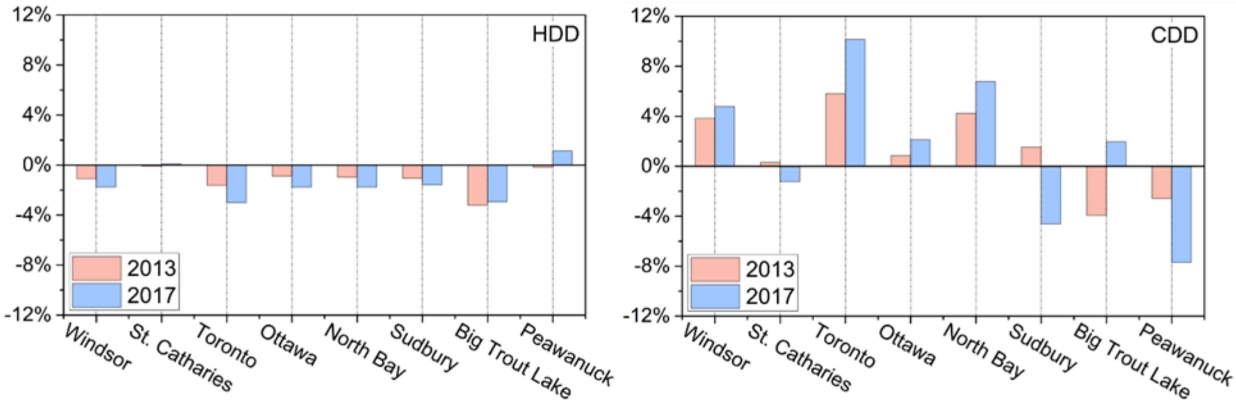

Figure 2. Changes in designed degree day for the selected cities for 2009–2013 and 2009–2017.

2.5. Data Analysis

2.5.1. Probability of Exceedance

The probability of forecasted *HDD* and *CDD* exceeding the current design requirement is derived from the *Z*-score method. The equation for *Z*-score is given by

$$Z_i = \frac{x_i - \overline{x}}{S} \tag{3}$$

In which $\overline{x}$ is the sample mean value, x_i is the forecasted value, and S the standard deviation. Briefly, the *Z*-score provides the number of standard deviations the forecasted value is above or below the mean value. The probability is obtained from the *Z*-score tables.

2.5.2. Weather Data Analysis

The future weather data were generated using RCMs. The weather data corresponding to estimates of past weather were first analyzed to establish relevance and confidence in the RCMs. Subsequently, the forecasted future weather was analyzed to derive trends and probabilities of occurrences. Data on daily temperature was derived from the weather files and formed the basis of the database.

3. Results and Discussion

3.1. Past and Future Temperature

3.1.1. Monthly

Historical daily temperature data for the selected 8 cities in the province of Ontario representing the 4 climate zones from 1 January 1995 to 30 November 2019 were extracted from the Government of Canada website [48]. Examination of the data sets revealed missing daily temperature data for certain cities. Of significance was the dataset for Peawanuck, where the daily temperature from 2010 to 2013 was missing. Given that the temporal step for this analysis is 25 years, it was deduced that the dataset still possesses enough data points to provide the trends and forecast of the whole.

The forecasted daily mean temperatures were obtained from the NA-CORDEX resources [49]. Five independent climate models were used to forecast the daily temperature from 2020 to 2069, a 50-year period. Thus, the temporal domain ranged from 1995 to 2069 representing a total period of 75 years. By dividing the total period into three distinct periods, the corresponding average monthly temperature and standard deviation for all 8 cities were calculated (Figure 3). The average monthly temperature was calculated over a period of 25 years. For the forecasted values, the average was further averaged using the results from the 5 models. The error bars represent ±1 standard deviation.

The results revealed a similar trend for all the cities. Moreover, the average temperature was found to increase when comparing the results for the three periods, and the increase was not uniform across the periods or the climate zones. The average temperature for August, September, and October for Windsor, Ottawa, North Bay, and Sudbury decreased contrary to what was observed for the other months. The differences in the monthly temperature between 1995 and 2019 and 2020 and 2044 and between 2020 and 2044 and 2045 and 2069 are given in Tables 4 and 5, respectively. These results confirm that the trend was not uniform and was affected by the seasons. For the coming 50 years, the results showed that the monthly temperature will increase during the winter season and that it will either not change or decrease during the summer season. The results also revealed that the increase in the average monthly temperature in the first 25 years ranged between 0.63 °C and 2.29 °C across the 8 cities, which was significant when compared to the second 25 years with a range of 0.67 °C to 1.52 °C. Closer examination shows that climate zone 5 had the lowest increase in the average temperature followed by climate zone 6, climate zone 7, and climate zone 8 which had the highest increase.

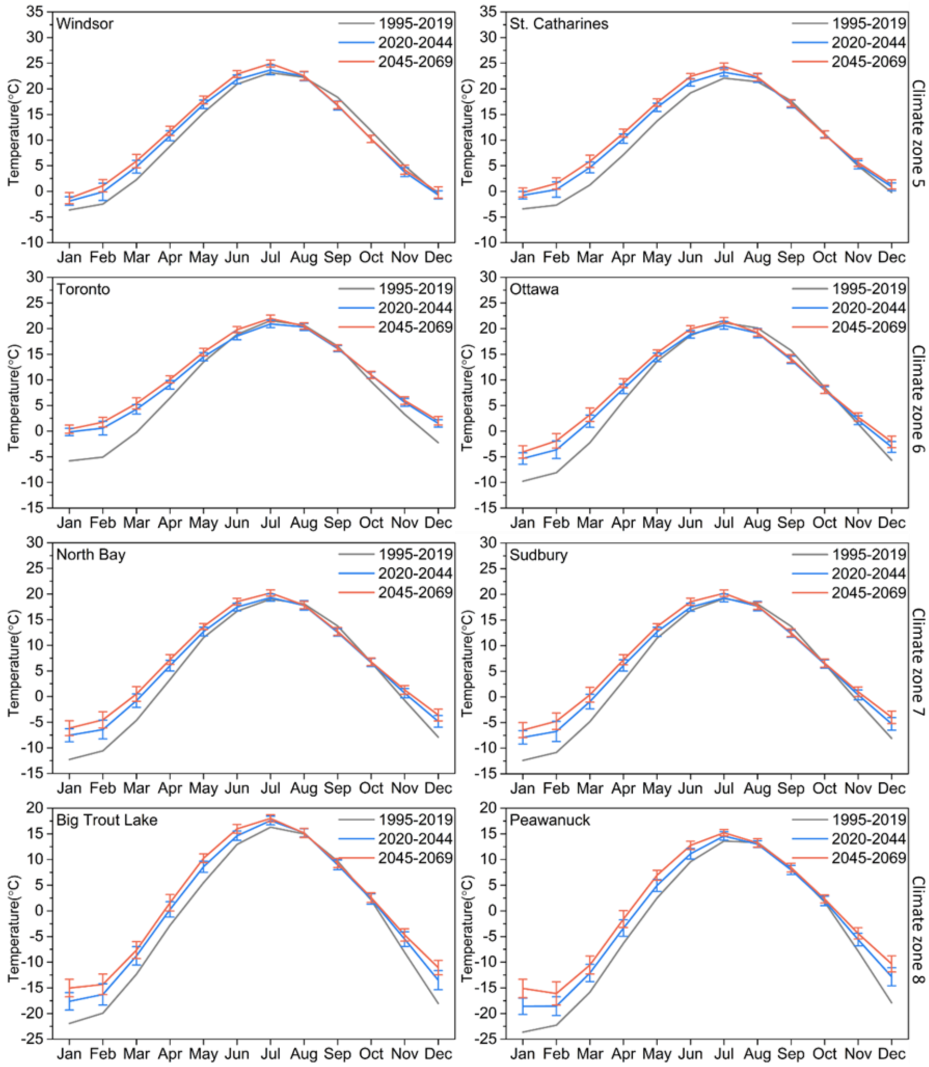

Figure 3. Historical (1995–2019) and future (2020–2069) monthly average temperature for the selected cities.

Table 4. Monthly temperature difference between 1995 and 2019 and 2020 and 2044 for the 8 cities.

	Climate Zone 5		Climate Zone 6		Climate Zone 7		Climate Zone 8	
	Windsor (°C)	**St. Catharines (°C)**	**Toronto (°C)**	**Ottawa (°C)**	**North Bay (°C)**	**Sudbury (°C)**	**Big Trout Lake (°C)**	**Peawanuck (°C)**
January	1.75	2.65	5.63	4.42	4.72	4.50	4.31	5.02
February	2.38	3.03	5.65	4.46	4.16	4.10	3.65	3.72
March	2.54	3.41	4.51	4.17	3.84	3.90	3.57	3.74
April	2.04	3.14	2.56	2.34	2.71	2.99	3.08	2.98
May	1.63	2.67	1.02	0.80	1.17	1.24	3.12	2.46
June	0.92	2.06	−0.33	0.23	0.81	0.64	1.69	1.57
July	0.52	1.16	−0.64	−0.53	0.30	0.12	1.29	0.99
August	0.21	0.72	−0.35	−1.01	−0.30	−0.42	0.20	−0.34
September	−1.63	−0.64	−0.50	−1.83	−1.25	−1.43	−0.73	−0.40
October	−1.57	−0.10	1.29	−0.50	−0.06	−0.06	0.21	0.23
November	−1.21	0.22	2.35	0.72	1.42	1.34	2.59	2.24
December	−0.07	1.07	3.77	2.61	3.09	2.83	4.54	5.08

Table 5. Monthly temperature difference between 2020–2044 & 2024–2069 for the 8 cities.

	Climate Zone 5		Climate Zone 6		Climate Zone 7		Climate Zone 8	
	Windsor (°C)	St. Catharines (°C)	Toronto (°C)	Ottawa (°C)	North Bay (°C)	Sudbury (°C)	Big Trout Lake (°C)	Peawanuck (°C)
January	0.56	0.53	0.54	1.27	1.38	1.41	2.59	3.48
February	1.18	1.19	1.16	1.73	1.89	1.99	1.95	2.45
March	1.09	1.19	1.14	1.27	1.29	1.33	1.12	1.55
April	0.96	1.08	1.06	1.09	1.20	1.11	1.30	1.76
May	0.83	0.93	0.89	0.85	0.99	1.02	1.64	2.00
June	1.04	1.15	1.24	1.05	1.05	1.08	1.35	1.62
July	1.25	1.13	1.06	0.94	0.89	0.89	0.42	0.63
August	0.09	0.18	0.19	0.10	0.07	0.06	−0.05	0.24
September	0.08	0.15	0.17	0.24	0.18	0.16	0.35	0.44
October	0.01	−0.06	−0.01	0.13	0.15	0.16	0.27	0.36
November	0.46	0.43	0.36	0.63	0.62	0.59	0.83	1.21
December	0.49	0.47	0.51	0.99	1.23	1.28	2.46	2.50

3.1.2. Annual

The annual average temperature was calculated based on daily temperature data from the past 25 years to the future 50 years. For the forecasted values, the average was further averaged using the results from the 5 models. The calculation results were plotted in Figure 4 to analyze the variation tendency of annual temperature for the 8 cities for individual climate zones. As shown, the gray and black curves on the graph represent the annual temperature of two cities in one climate zone for the past 25 years, whereas the colored curves stand for the prospective annual temperature values. Moreover, the dash lines in the diagram are the rates of change concerning each fluctuant curve, which is forecasted within each independent period. The values of the slopes are indicated beside the corresponding curve.

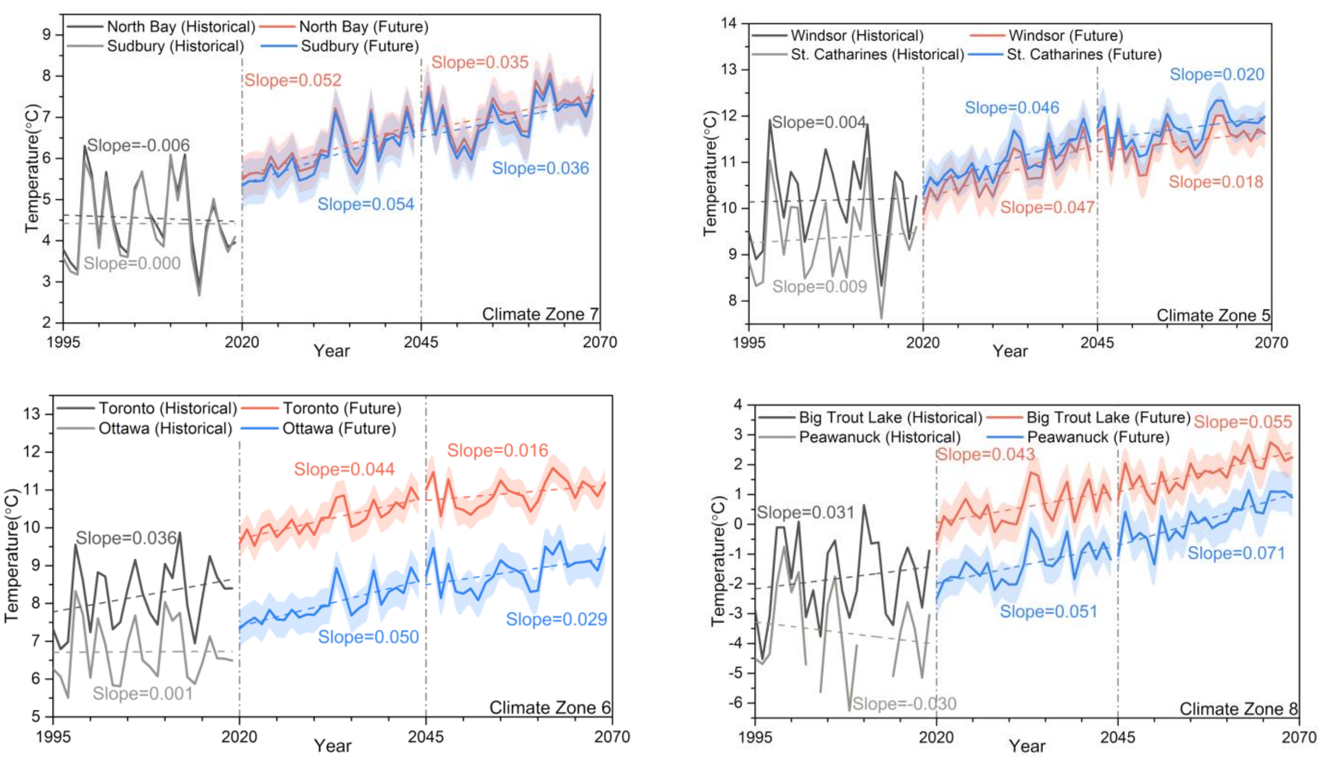

Figure 4. Historical (1995–2019) and future (2020–2069) annual average temperature for climate zones.

The result reveals that the annual temperature for all cities has the same increasing trend. The average temperature was found to increase when comparing the results for the three periods, and the increase was not consistent across the periods or the climate zones. The annual average temperature difference for each city is provided in Table 6. There was a larger growth in the first 25 years compared with the second 25 years, except in climate zone 8, which corresponds with the trend line in the figures before. Ontario will experience approximately 1 °C to 2 °C annual temperature increase during the next 50 years. Moreover, the greater increase will happen in the higher latitude than lower latitude. At the end of next 50 years, the annual average temperature for climate zone 5 will reach around 11–12 °C, climate zone 6 will reach about 9–11 °C, climate zone 7 will reach almost 6–7 °C, and climate zone 8 will reach nearly −1–2 °C.

Table 6. Annual temperature difference between 2020 and 2044 and 2024 and 2069 for the 8 cities.

	Climate Zone 5		**Climate Zone 6**		**Climate Zone 7**		**Climate Zone 8**	
	Windsor (°C)	**St. Catharines (°C)**	**Toronto (°C)**	**Ottawa (°C)**	**North Bay (°C)**	**Sudbury (°C)**	**Big Trout Lake (°C)**	**Peawanuck (°C)**
2020–2044	1.14	1.10	1.05	1.19	1.25	1.31	1.04	1.23
2045–2069	0.42	0.48	0.39	0.70	0.84	0.86	1.32	1.71

3.2. Past and Future Degree Day

3.2.1. Monthly

In this study, monthly *HDD* and *CDD* were estimated separately by utilizing the daily mean temperature data based on the calculation method for degree day described above. The results are plotted in Figure 5 for monthly *HDD*, Figure 6 for monthly *CDD*, and Figure 7 for monthly *HDD* + *CDD*. In each graph, three 25-year periods are divided as the diagram demonstrates, the gray solid curve represents the monthly average DD for the past 25 years (1995–2019), and the colored solid curves stand for the prospective DD values with error bars to express SD.

The results plotted in Figure 5 indicate the maximum *HDD* for the 2045–2069 period will be lower than 2020–2044, which is lower than the maximum *HDD* for the past 25 years, a continuously decreasing trend. However, the decreasing trends are not consistent. For regions of lower latitude, the trend for the warmer months, May–September, is a slightly increasing *HDD* for the future compared to the past. Windsor shows an exception of the future as the months from October to December show a slight increase in the *HDD* trend for the future rather than the decreasing trend observed for the rest of the locations.

The results plotted in Figure 6 show the maximum monthly *CDD* in July, while the winter season shows a *CDD* of 0. The maximum *CDD* for the 2045–2069 period will be higher than for 2020–2044, which is higher than the maximum *HDD* for the past 25 years, a continuously increasing trend. Windsor and Ottawa show a slight exception, with a slightly decreasing trend for the future in *CDD* for the months August–October. From 2020 to 2044, the highest *CDD* for climate zone 5 is around 170 *CDD*, about 110 *CDD* for climate zone 6, around 60 *CDD* for climate zone 7, and about 30 *CDD* for climate zone 8. From 2044 to 2069, the largest monthly mean *CDD* is around 200 *CDD* for climate zone 5, about 140 *CDD* for climate zone 6, around 80 *CDD* for climate zone 7, and about 40 *CDD* for climate zone 8. Overall, monthly *CDD* showed a continuously increasing tendency in the next 50 years.

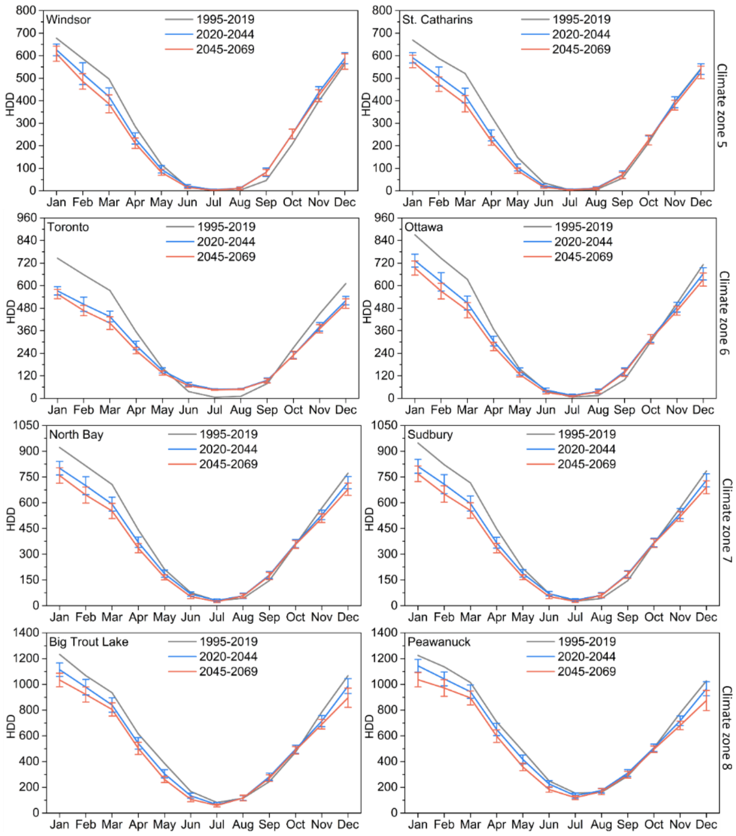

Figure 5. Historical (1995–2019) and future (2020–2069) monthly *HDD* for selected cities.

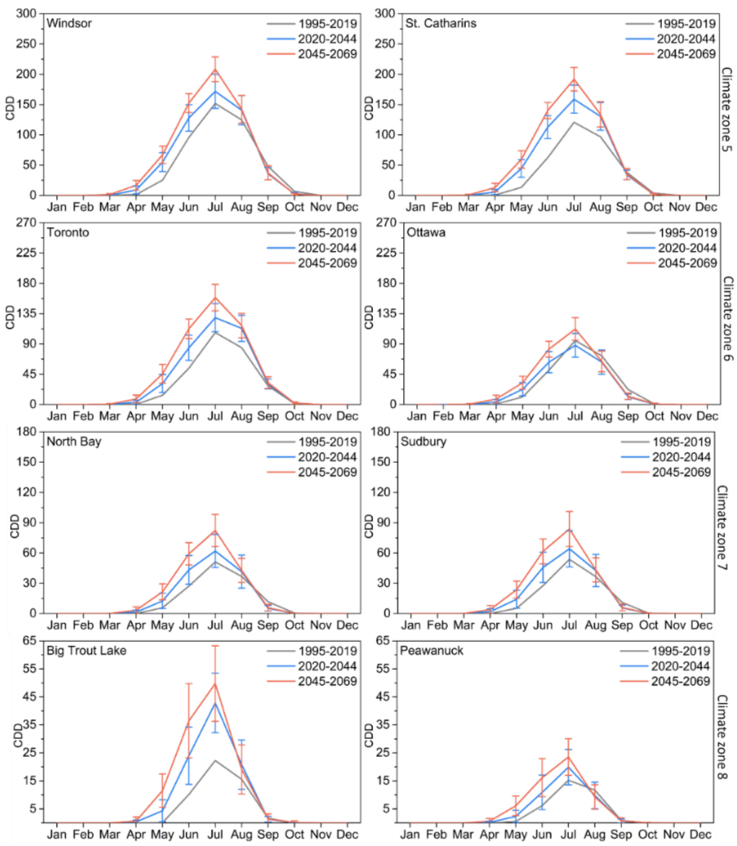

Figure 6. Historical (1995–2019) and future (2020–2069) monthly *CDD* for selected cities.

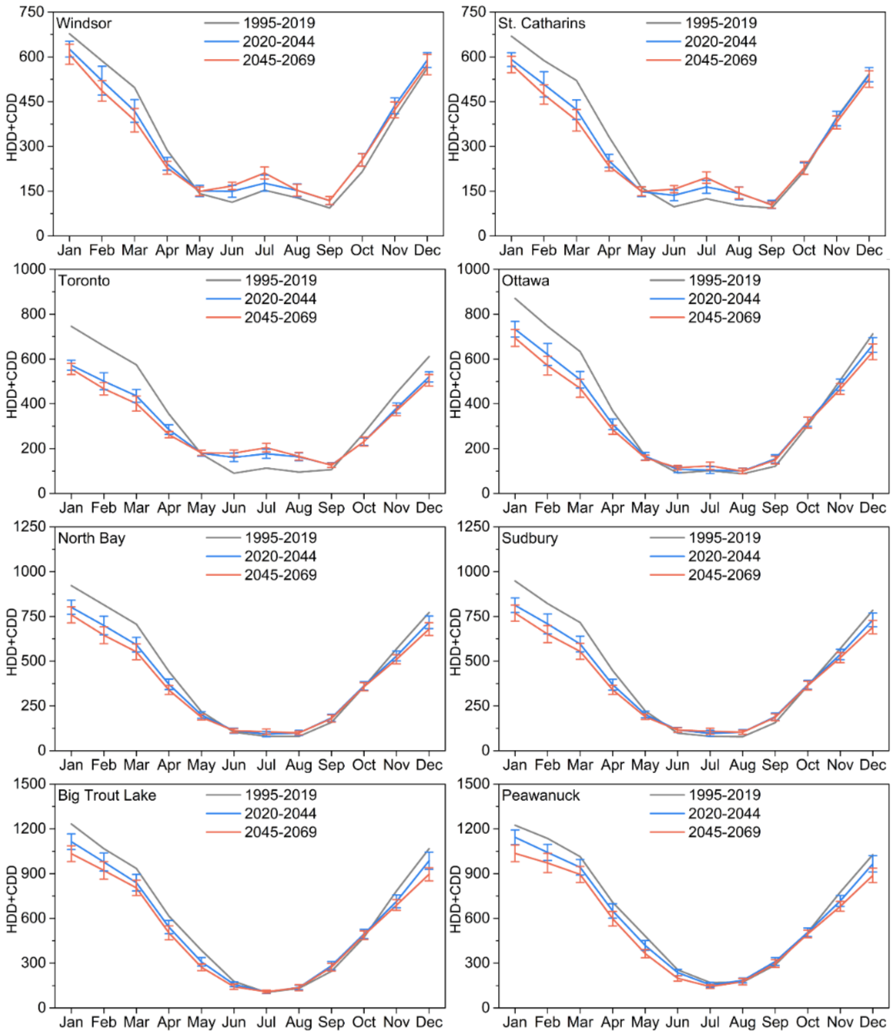

Figure 7. Historical (1995–2019) and future (2020–2069) monthly *HDD* + *CDD* for selected cities.

The lower the *HDD* + *CDD* value, the more comfortable the outdoor thermal condition is for humans [14]. The results in Figure 7 show the highest *HDD* + *CDD* values are in the winter months, explained by the heating demand due to the colder climate in Canada. It also shows the *HDD* + *CDD* values decreasing in the future during the cooler months of the year and increasing in the future during the warmer months of the year. This means less heating is required by the population for the winter, but more cooling during the summer months. In the next 25 years, the largest monthly *HDD* + *CDD* is around 600 *HDD* + *CDD* for climate zone 5, about 650 *HDD* + *CDD* for climate zone 6, around 800 *HDD* + *CDD* for climate zone 7 and about 1150 *HDD* + *CDD* for climate zone 8. From 2044 to 2069, the largest monthly *HDD* + *CDD* is around 590 *HDD* + *CDD* for climate zone 5, about 630 *HDD* + *CDD* for climate zone 6, around 760 *HDD* + *CDD* for climate zone 7 and about 1040 *HDD* + *CDD* for climate zone 8. Overall, the value of *HDD* + *CDD* showed a decrease with time.

3.2.2. Annual

Annual *HDD* and *CDD* calculation results for climate zones 5–8 are shown below, with Figure 8 showing annual *HDD*, Figure 9 showing annual *CDD*, and Figure 10 showing annual *HDD* + *CDD*. The dashed lines in the diagrams represent the trend for the fluctuant curves in each 25 year period, and the shadows for the forecasted years represent the standard deviation associated with the city within the zone. In the *HDD* graphs, the thermal criteria for climate zones according to ASHRAE are represented by the gray striped band. For example, the thermal criteria for climate zone 5 are from 3000 *HDD* to 4000 *HDD*.

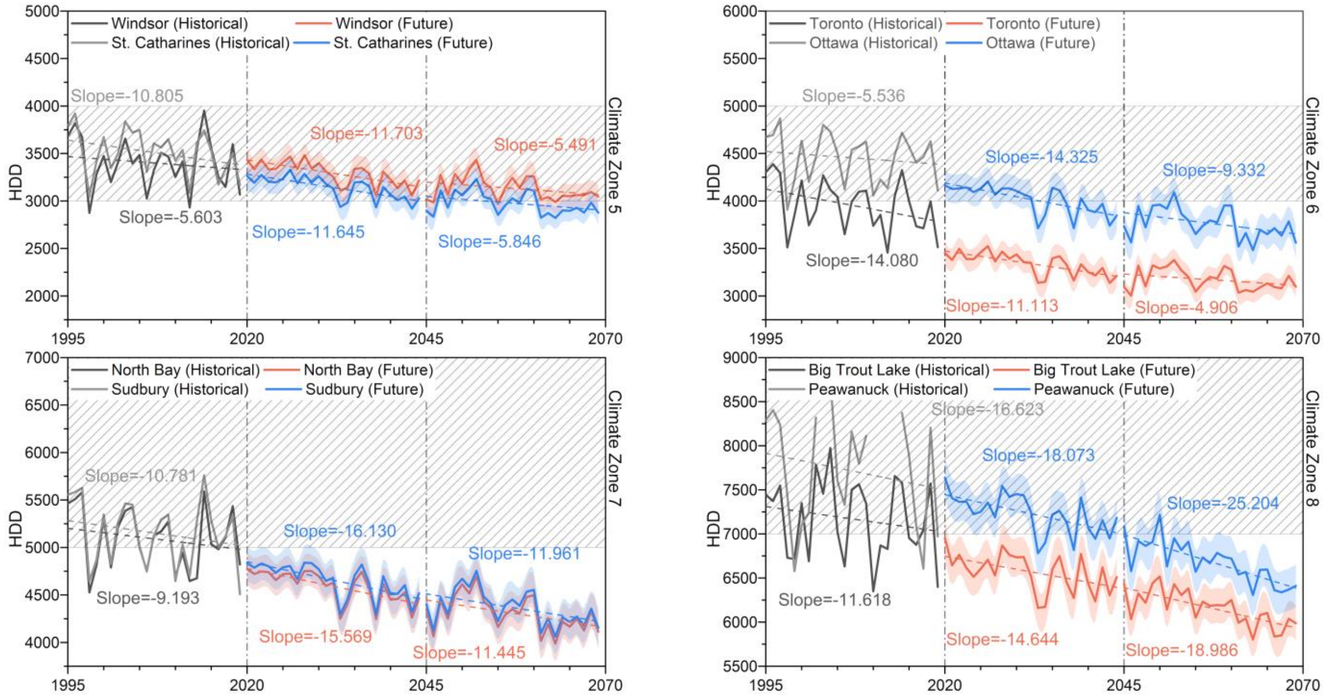

Figure 8. Historical (1995–2019) and future (2020–2069) annual *HDD* for climate zones.

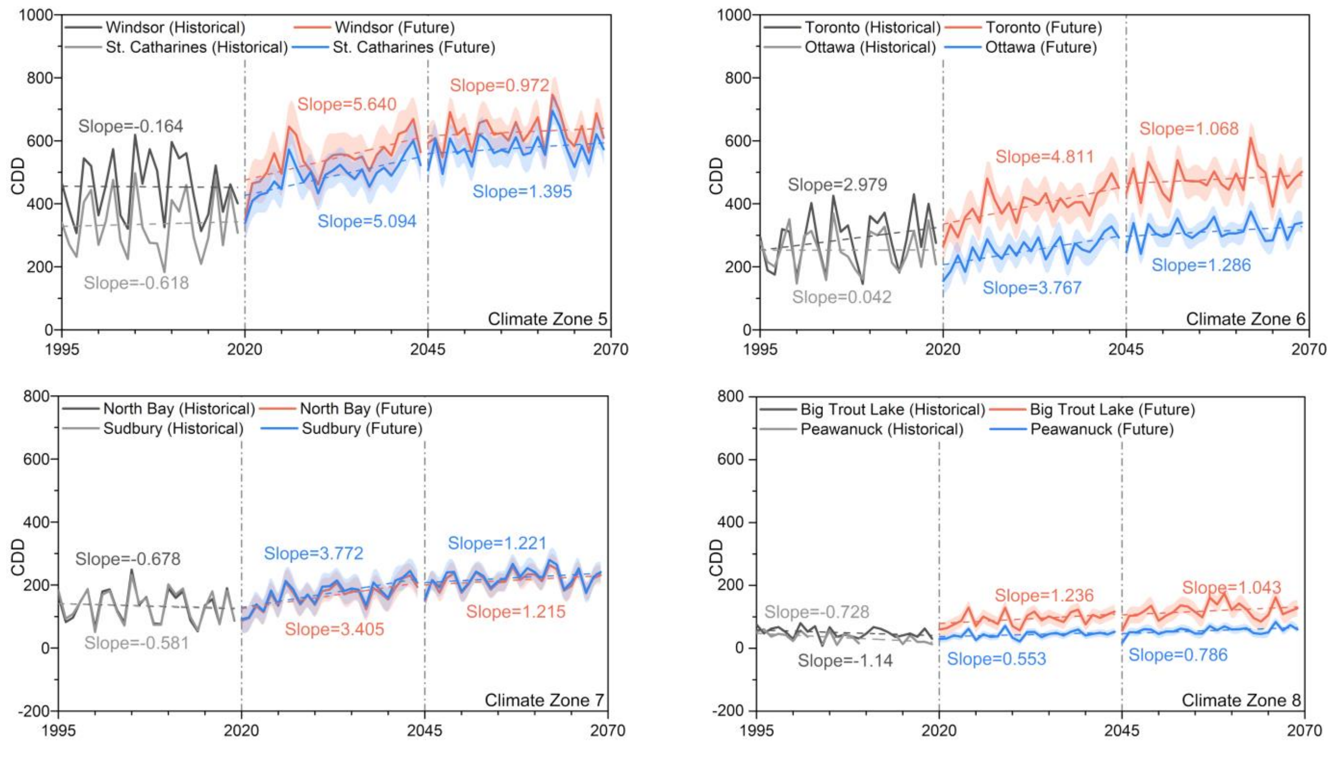

Figure 9. Historical (1995–2019) and future (2020–2069) annual *CDD* from climate zones.

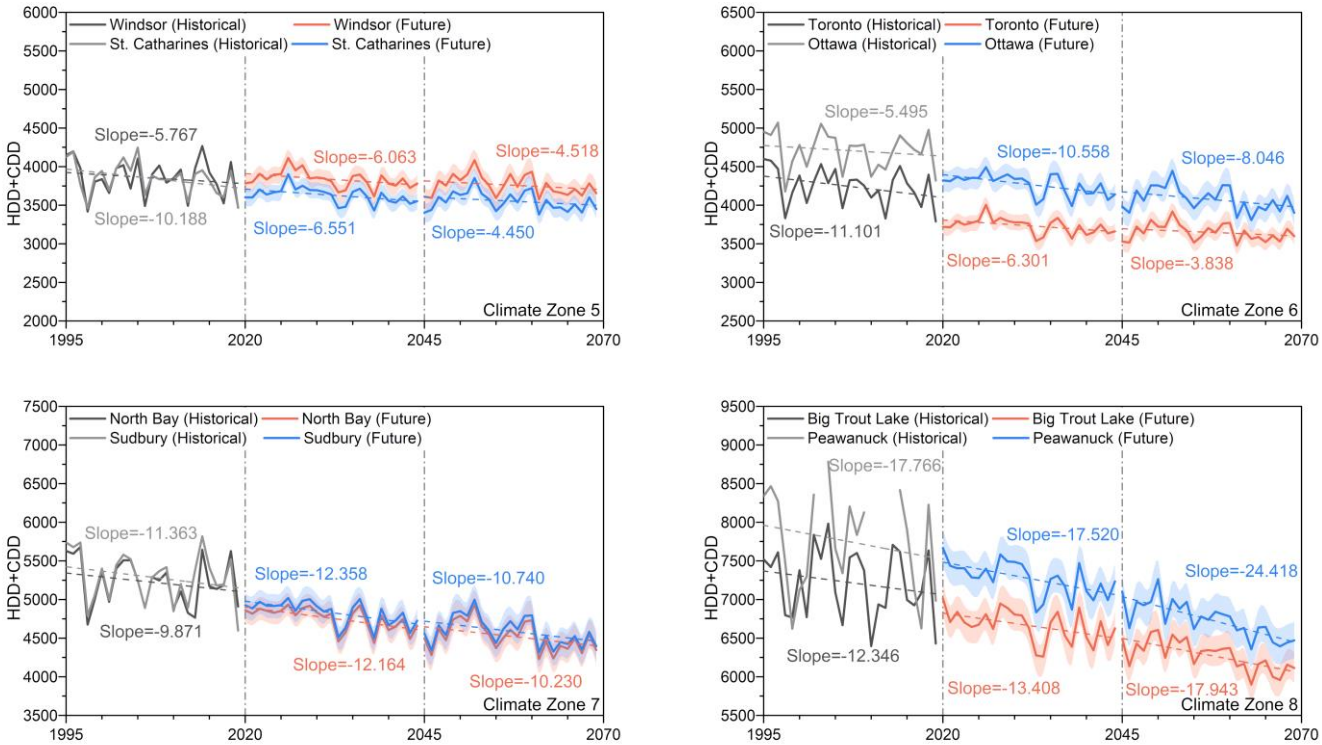

Figure 10. Historical (1995–2019) and future (2020–2069) annual *HDD* + *CDD* for climate zones.

For annual mean *HDD*, all 8 cities displayed a significant decreasing trend over the next 50 years. Climate zones 5–7 display a slowing trend in the *HDD* decrease over time, while climate zone 8 displays a speeding up in the *HDD* decrease over time. The further north the climate zones are located, the sharper the predicted drop of the *HDD* over the next 50 years, as indicated by climate zone 5 having a drop of 400 in *HDD*, and climate zone 8 having a drop of 900. Climate zones 6–8 are projected to need to lower their thermal criteria or modify the climate zone that a city belongs to. For example, cities in climate zone 5 may belong to climate zone 4 in the future because their *HDD* will be around 1800 to 2000 *HDD* in future decades (climate zone 4 thermal criteria are 2000 < HDD18 °C $\leq$ 3000 and CDD10 °C $\leq$ 3500).

The annual mean *CDD* results are displayed below in Figure 9. The annual mean *CDD* is projected to increase over the next 50 years, whereas it shows a slight decrease over the past 25 years. The further north the climate zones, the lower the projected increase in annual mean *CDD*, as indicated by climate zone 5 having an increase of 190 *CDD* but climate zone 8 having an increase of 40 *CDD*. All climate zones display a slowing trend in the *CDD* increase over time.

The purpose of analyzing the projected change of *HDD* + *CDD* is to provide information about outdoor thermal comfort, and overall heating and cooling demands. Figure 10 demonstrates that in all climate zones, there is a clear decreasing trend in the *HDD* + *CDD* values. The further north the climate zones, the larger the projected decrease in the *HDD* + *CDD* value, as can be seen with climate zone 8 showing a 900 *HDD* + *CDD* decrease and climate zone 5 showing a 200 *HDD* + *CDD* decrease. The noticeably higher rate of decrease in climate zone 8 can be attributed to climate change, with *HDD* being the dominant parameter.

3.3. Probability of Degree Days Exceeding ASHRAE Design Requirement

In this study, we measured the probability of degree days exceeding the ASHRAE design condition for each climate zone. For *HDD*, all the selected cities have a 0% chance of exceeding the *HDD* design conditions according to the ASHRAE, except Windsor and

St. Catharine's where the probabilities of exceeding are 15% and 1%, respectively. The heating demands for current buildings will not be a problem in the future due to a decreasing trend in *HDD*. The implications are that current equipment, either boilers or furnaces, will satisfy the building heating demands for the next 50 years.

In terms of *CDD*, the probability of *CDD* exceeding the ASHRAE design condition was calculated and presented in Table 7. The results also include the *CDD* for a 50%, 25%, and 10% probability of occurrence and the corresponding percentage difference when compared to the current design requirement. For example, the analysis for Windsor (climate zone 5) revealed that there is a 94% chance the ASHRAE design condition of a *CDD* value of 438 between 2020 and 2044 will be exceeded. Moreover, there is a 50% and 10% chance it will exceed a *CDD* value of 543 and 631, respectively. *CDD* values of 543 and 631 are 24% and 44% increases, respectively, when compared with the ASHRAE design condition (438 *CDD*). In summary, it is noticeable that the forecasted *CDD* is more likely to exceed the standard requirements between 2045 and 2069 than from 2020 to 2044, due to the growing trends of annual mean *CDD* predicted by five climate models.

Table 7. The probability of future *CDD* exceeding the ASHRAE *CDD* design conditions (2020–2044 average and 2045–2069 average).

Climate Zone 5					
Windsor					
Prob. of Occurrence (%)	**2020–2044 Avg *CDD***	**Difference (%)**	**Prob. of Occurrence (%)**	**2045–2069 Avg *CDD***	**Difference (%)**
94	438 (ASHRAE)	0	100	438 (ASHARE)	0
50	543	24	50	628	43
25	589	34	25	661	51
10	631	44	10	690	58
St. Catharines					
Prob. of Occurrence (%)	**2020–2044 Avg *CDD***	**Difference (%)**	**Prob. of Occurrence (%)**	**2045–2069 Avg *CDD***	**Difference (%)**
100	323 (ASHRAE)	0	100	323 (ASHRAE)	0
50	488	51	50	576	79
25	525	63	25	607	88
10	559	73	10	635	97
Climate Zone 6					
Toronto					
Prob. of Occurrence (%)	**2020–2044 Avg *CDD***	**Difference (%)**	**Prob. of Occurrence (%)**	**2045–2069 Avg *CDD***	**Difference (%)**
95	304 (ASHARE)	0	100	304 (ASHARE)	0
50	393	29	50	477	57
25	430	41	25	510	68
10	462	52	10	539	77
Ottawa					
Prob. of Occurrence (%)	**2020–2044 Avg *CDD***	**Difference (%)**	**Prob. of Occurrence (%)**	**2045–2069 Avg *CDD***	**Difference (%)**
60	241 (ASHRAE)	0	100	241 (ASHRAE)	0
50	252	5	50	312	30
25	280	16	25	335	39
10	305	27	10	354	47

Table 7. *Cont.*

Climate Zone 7					
North Bay					
Prob. of Occurrence (%)	**2020–2044 Avg *CDD***	**Difference (%)**	**Prob. of Occurrence (%)**	**2045–2069 Avg *CDD***	**Difference (%)**
86	126 (ASHARE)	0	100	126 (ASHARE)	0
50	166	32	50	215	71
25	191	52	25	235	86
10	214	70	10	252	100
Sudbury					
Prob. of Occurrence (%)	**2020–2044 Avg *CDD***	**Difference (%)**	**Prob. of Occurrence (%)**	**2045–2069 Avg *CDD***	**Difference (%)**
90	124 (ASHRAE)	0	100	124 (ASHRAE)	0
50	174	40	50	223	80
25	201	62	25	244	96
10	226	82	10	263	112
Climate Zone 8					
Big Trout Lake					
Prob. of Occurrence (%)	**2020–2044 Avg *CDD***	**Difference (%)**	**Prob. of Occurrence (%)**	**2045–2069 Avg *CDD***	**Difference (%)**
97	52 (ASHARE)	0	100	52 (ASHARE)	0
50	94	80	50	119	129
25	108	108	25	137	163
10	121	133	10	153	193
Peawanuck					
Prob. of Occurrence (%)	**2020–2044 Avg *CDD***	**Difference (%)**	**Prob. of Occurrence (%)**	**2045–2069 Avg *CDD***	**Difference (%)**
75	36 (ASHRAE)	0	100	36 (ASHRAE)	0
50	44	21	50	56	57
25	51	43	25	65	80
10	58	62	10	72	101

There is a likelihood scale that was adopted by IPCC to explain risk and probability using specific terms [49]. The detailed scale is provided in Table 8. According to the likelihood scale, *HDD* is extremely unlikely to exceed the ASHRAE design condition in the next 50 years given that the probability of exceeding is less than 1%, and that *CDD* is likely/very likely to exceed the design value in the next 25 years and very likely/virtually certain to exceed the design afterward. It is worth noting that the trend of the possibility to exceed the standard design requirements for *CDD* is inverse to that of *HDD* where it is very unlikely. The observed trends and corresponding probabilities of exceedance support the notion with certainty that heating demands of buildings will decrease, and cooling demands will increase in the future.

Table 8. IPCC qualitative descriptors [50].

Probability Range	Descriptive Term
<1%	Extremely unlikely
1–10%	Very unlikely
10–33%	Unlikely
33–66%	Medium likelihood
66–90%	Likely
90–99%	Very likely
>99%	Virtually certain

3.4. Risk Assessment

Risk is defined as the product of the probability of occurrence and the consequences. Consequences pertain to health, safety, and economy. The probability of occurrence refers to the probability that the *CDD* will be higher than the design values.

3.4.1. Health

The health of living beings, especially humans, is evaluated using the sum of *HDD* and *CDD*. The results show that the range of *HDD* + *CDD* is decreasing, indicating less severe weather and therefore consequences for the health of people, especially for colder climate zones. The decrease in *HDD* + *CDD* implies that a forecast of more comfortable temperatures for Ontario. Accordingly, the risk of climate change to cause health issues to the people living in Ontario appears to be negligible when only considering the temperature. However, it should be noted that temperature is only one of many environmental parameters to consider.

3.4.2. Safety

Human safety is evaluated by examining extremely high temperatures. The results show that the increase in extreme temperature is moderate which singularly does not increase the probability of fires or other extreme events occurring. The risk to human safety is therefore negligible when only considering average daily temperature changes. It should be noted that the average daily temperatures are suited for calculating the *HDD* and *CDD* but not for extreme climate conditions. A safety risk needs to analyze for extreme temperatures and must account for other environmental factors such as rain, lightning, humidity, wind, etc.

3.4.3. Economy

The economic effects of climate change can be assessed through the increase or decrease of the heating and cooling loads of the buildings. The probabilities of *CDD* being larger than the design values were calculated and are presented in Table 7. The estimate of the annual energy consumption for heating and cooling can be obtained using the following relationship

$$E_{heating} \cong Q_{heating} \times HDD \tag{4}$$

$$E_{cooling} \cong Q_{cooling} \times CDD \tag{5}$$

in which $Q_{heating}$ and $Q_{cooling}$ are the building heating and cooling loads, respectively. Therefore, the increase and decrease in the cost of heating and cooling are proportional to the changes in the *HDD* and *CDD*. Alternatively, building heating and cooling loads can be improved by implementing energy retrofit measures. The results show that the cooling load will have a negative impact on the building's energy consumption. There are two paths to estimating economic risk. The first scenario assumes the building cooling capacity is sufficient to meet the increased cooling demand and therefore the cooling energy consumption will increase proportionally to the increase in *CDD*. The corresponding risk is therefore equal to the probability that *CDD* will be greater than the design value times the increased cooling energy cost. This approach is not environmentally friendly as it will lead not only to higher operating costs but also to an increase in GHG and depletion of non-renewable material. The second scenario considers the upgrade of the building. Given that most buildings are aging and require ongoing maintenance and upgrade, implementing energy retrofit measures to reduce the energy consumption of the building will lead to a decrease in demand, much lower operating cost, and reduced generation of GHG. Possible energy retrofit measures include upgrading the HVAC system, building envelope system, and lighting system, improving the building airtightness, and adding renewable energy generation systems such as solar, geothermal and/or wind. By adopting the second scenario, the economic risk due to climate change is therefore mitigated.

4. Conclusions & Recommendations

Based on this study results, the followings are concluded:

(1) The annual average temperature is projected to increase by 1–2 °C in Canada, and climate zones further north are expected to see larger increases.

(2) The values of annual *HDD* will experience a significant decrease, ranging from 400 *HDD* to 900 *HDD*, over the next 50 years. The further north a climate zone is, the larger the expected decrease.

(3) The values of annual *CDD* will experience a noticeable increase, ranging from 40 *CDD* to 190 *CDD*, over the next 50 years. The further north a climate zone is, the smaller the expected increase.

(4) The values of *HDD* + *CDD* will experience a significant decline, ranging from 200 *HDD* + *CDD* to 900 *HDD* + *CDD*, over the next 50 years. The further north a climate zone is, the larger the expected decrease.

(5) The probability of *HDD* exceeding ASHRAE requirements is extremely unlikely to happen (<1%) in the next 50 years, and *CDD* is likely/very likely/virtually certain (60–100%) to happen in the next 50 years.

(6) The risks to human health caused by temperature changes are likely to be negligible. However, the economic risk can be mitigated through remedial energy retrofit measures to reduce the energy consumption of buildings, operating costs, and generation of GHG.

(7) The findings from this study are applicable to every city and town whose ASHRAE climate zone is classified 5 to 8.

For future research, a larger database can be used to improve the accuracy and confidence intervals of the results. The inclusion of more environmental parameters, such as wind, rain, and climate zones will help diversify the data in zones with different extreme natural events such as floods, droughts, and forest fires. Lastly, these results are beneficial to the building industry and building code committees as they provide insights for future planning and development.

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