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Assessing the impact of climate change on building heating and cooling energy demand in Canada

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ABSTRACT

In recent years, the building sector has received increasing attention with attempts to limit its energy consumptions and GHG emissions. In fact, buildings account for more than 30% of the overall energy demand worldwide, with projections for increases in this quota due to climate changes, urbanization, and higher living comfort standards. This study investigates the effects of climate changes on the heating and cooling energy demand of buildings in the most populated urban region in Canada, i.e. the city of Toronto in Ontario. Statistical and dynamical downscaling methods are utilized to generate several future weather files, starting from different baseline climates including the old Canadian Weather Year for Energy Calculation CWEC (representing the 1959–1989 period) and the new CWEC 2016 (representing the 1998–2014 period). In dynamical downscaling, a regional climate model is used to obtain a finer resolution than traditional general circulation models. The generated future weather data sets are then used for simulating the energy demand of 16 building prototypes. The simulation results show an average decrease of 18%–33% for the heating energy use intensity, and an average increase of 15%–126% for the cooling energy use intensity by 2070, depending on the baseline climatic file of use and building typology. The forecasted GHG emissions of each building prototype are then discussed. The results demonstrate the need to perform building modelling with sensitivity analysis of future climate scenarios in order to design more resilient buildings.

1. Introduction

As the world continues to urbanize, the urban population forces cities to become larger and more complex than before, leading to increasing demand in housing, transportation, energy systems, and other infrastructure. While the rapid urbanization, due to population growth as well as improvements in the quality of life, has prompted economic and social development, it has also led to significantly increased energy demands and greenhouse gas (GHG) emissions. GHG emissions are one of the leading causes of climate change, producing adverse environmental effects such as global warming, changing weather patterns and extreme weather events. Within this context, it is widely acknowledged that over 32% of total global energy expenditure and 19% of the total GHG emissions are due to building energy processes [1]. Moreover, from 1970 to 2010, the global energy-related CO_2 emissions increased by more than twofold in the building sector and is forecasted to double by 2050 [2]. In Canada, the residential building was responsible for 17.1% of all energy used in 2015, whereas the commercial and institutional buildings accounted for 11.2% [3]. The GHG emissions for residential, commercial and institutional buildings accounted for 22.6% of all secondary energy use related GHGs emitted in Canada [3]. In cities, these values are much higher. For example, the 2017 GHG inventory report of the City of Toronto states that buildings are responsible for 52% of the total GHG emissions in Toronto, primarily because of space and water heating [4].

At the same time, the long-term changes in the outdoor climate conditions have substantial influences on the building energy demand. According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the global mean surface temperature is expected to increase by a range of 2.6 °C–4.8 °C by the end of the 21st century, in relation to the 1986–2005 period [1]. This increase in temperature affects the indoor environment, leading to an increase in energy demand for HVAC-systems.

Significant signs of progress have been made in Ontario with the phase-out of coal for electricity generation as well as the implementation of building appliance standards, but improvements to the building shape, envelope, and operating systems still represent the largest

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List of abbreviation

AOGCM	Atmosphere-Ocean General Circulation Model
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CBECS	Commercial Buildings Energy Consumption Survey
CWEC	Canadian Weather Year for Energy Calculation
CWEEDS	Canadian Weather Energy and Engineering Datasets
DOE	Department of Energy
DSY	Design Summer Year
EPW	EnergyPlus Weather
EUI	Energy Use Intensity
GCM	General Circulation Model/Global Climate Model
GEBA	Global Energy Balance Archive
GHG	Greenhouse Gas
GTA	Greater Toronto Area
HadCM3	Hadley Climate Model 3
HDD	Heating Degree Days
HRM3	Hadley Regional Model 3
HVAC	Heating, ventilation, and air conditioning
IPCC	Intergovernmental Panel on Climate Change
NARCCAP	North American Regional Climate Change Assessment Program
OBC	Ontario Building Code
RCM	Regional Climate Model
RMSE	Root-Mean-Square Error
SHGC	Solar Heat Gain Coefficient
SRES	Special Report on Emission Scenarios
TGS	Toronto Green Standard
TMY	Typical Meteorological Year
TRY	Test Reference Year

unexplored opportunity to reduce the building energy consumption in the future. Kheiri [5] provides an extensive review of the optimization methods and their application in energy-efficient building design. Among the steps for increasing awareness regarding the building energy demand, building performance simulations have gained increasing attention. Models can assess different scenarios with various design and operation systems to determine the overall performance for energy and emission mitigation. However, while often under-considered, the weather parameters are among the most important factors that influence the energy demand in buildings [6]. As a result, it is critical to select the appropriate weather data for building simulations, although little agreements exist regarding the most suitable weather file to use. In fact, current building energy simulation practices utilize weather files that have been established by historical records. However, due to the magnitude of climate change and its impact on building energy demand, simulations utilizing historical weather files lack the ability to project the future trends of heating and cooling in buildings. In Canada, it is common practice to use the Canadian Weather Year for Energy Calculation (CWEC) weather file, which is derived from historical weather data sets representing the 1959–1989 climate. The Toronto Green Standard (TGS) modelling guidelines explicitly state that "projects shall use a Toronto CWEC weather file" [7]. However, as evident in Fig. 1, the weather patterns recorded a few decades ago reflect neither present nor future climate scenarios.

This paper focuses on the creation of future weather files and on the assessment of the impact of these weather files on the building energy demand. In order to generate future weather files, this paper will use both statistical and dynamical downscaling methods. In statistical downscaling, two weather generator tools, CCWorldWeatherGen and WeatherShift™ will be used; moreover, in the dynamical downscaling approach, the HRM3-the Hadley Regional Model 3 will be coupled with the HadCM3-the Hadley Climate Model 3 to improve the resolution of the climate simulation outputs. Ultimately, the future weather files are used to perform building performance simulation of 16 reference building models developed by the United States Department of Energy (DOE) in support of the ASHRAE standard 90.1.

Section 2 reports a short overview of typical weather data sets and meteorological parameters used for building energy simulation, as well as existing literature on future weather file generation. Section 3 outlines the methodology, followed by Section 4 which describes and discusses the results of this study. Finally, concluding remarks are presented in Section 5.

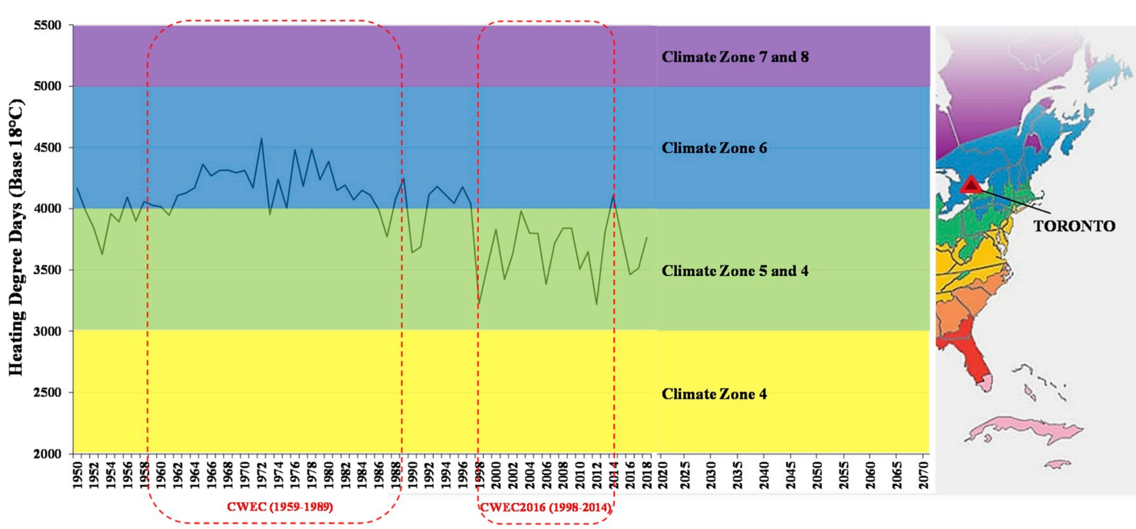

Fig. 1. DOE climate zone classification and warming trends seen in Toronto in terms of heating degree days (base 18 °C).

2. Building simulation weather file

2.1. Typical weather file

Typical data files for weather conditions used in dynamic building simulations consist of 8760 hourly values of some selected meteorological parameters such as ambient temperature, solar radiation, relative humidity, and wind velocity. Several methods for averaging or creating weather data have been used in the past, in order to determine typical environmental conditions. As an output of those methods, different types of weather years were defined, such as Test Reference Year (TRY), Typical Meteorological Year (TMY), and Design Summer Year (DSY). Many studies have been presented extensively about the creation of weather files and the differences among previous reference years. For example, Bilbao et al. used several different methods for the generation of TRY from long-term hourly meteorological data and evaluated them by comparing the performance of different solar systems [8]. According to their findings, Bilbao et al. suggested a methodology for the TRY generation in the Mediterranean area. Chan et al. reviewed different approaches for deriving a TMY and generated TMY for Hong Kong using 25 years of recorded weather data [9]. In Estonian, Kalamees and Kurnitsky created TRY for heating and cooling energy calculations [10]. In South Korea, Lee et al. generated TRY from 20 years of meteorological data according to ISO15927 standards for seven major cities [11]. Zang et al. proposed a modified method for the generation of TMY for 35 cities in China from recorded weather data [12]. Liu and Coley created and analyzed the application of DSY for UK dwellings to assess indoor thermal comfort [13].

The most common sets of weather data used for assessing building energy use and carbon emission for buildings is the TMY. A TMY consist of typical months of meteorological data selected from various years over long-term weather data [14]. In the literature, TMY has been developed using various statistical techniques and meteorological prioritization for the selection of the most "typical" single months from long-term weather data. One of the most commonly used methodologies for generating a TMY was developed by Hall et al. using the Finkelstein-Schafer (FS) statistics [15]. The generated TMY was based on a meteorological measure including, dry bulb temperature, dew point temperature, wind velocity, and solar radiations. Pissimanis et al. employed the same method to generate TMY for the city of Athens by employing global solar radiation data and six other meteorological parameters [16]. Petrakis et al. generated a TMY for Nicosia, Cyprus, using FS statistical method for a period of seven years (1986–1992) [17]. For Hong Kong, Lam et al. showed that the Finkelstein- Schafer (FS) used for generating TMY offers a good indication of the long-term weather data [18]. The first TMY data set for the United States was produced by Sandia National Laboratories [19]. The Sandia method generates TMY by selecting a set of meteorological and solar radiation data for one year. The TMY data, however, do not relate to any actual year of recorded weather data, but rather represent a multi-year comparison of month-by-month, selecting the twelve most typical months to generate a "composite" year. Later updates introduced a newer TMY, the TMY2, and TMY3 data, that had more complex solar models as well as adjustment in weighting criteria [19].

In a Canadian context, two sets of typical weather files are available for use. The first is the CWEC which is developed using statistical criteria from the Canadian Weather Energy and Engineering Datasets (CWEEDS) [20]. The CWEC files include data from 1959 through 1989 and are available for 75 locations in Canada. The CWEC files are created by selecting the twelve most typical months from CWEEDS similarly to the method of the Sandia method for the development of TMY [20]. According to the Meteorological Service of Canada [21], the 'typical' months are selected by comparing statistically individual months with long-term monthly means for daily total global radiation, dry bulb temperature, dew point temperature, and wind speed. Daily mean dry bulb temperature and daily total radiation are given higher prioritization in the selection process for typical months compared to other meteorological parameters. Siurna et al. provide a complete description of the procedure and weighting criteria used for the creation of CWEC files [22]. In 2016, an updated version of CWEEDS including 492 Canadian locations for the period between 1998 and 2014 (CWEC2016) was released by the Government of Canada.

2.2. Literature review

General Circulation Models (GCMs), also known as Global Climate Models, have been increasingly used in projecting future climate conditions, but they provide monthly data that are valid and reliable at a large spatial scale only. This means that such models are not suitable for building performance simulation tools, which require hourly weather data. As a result, the GCMs need to be temporally and spatially downscaled to generate hourly data compatible with building simulation tools.

Several methods have been widely used for integrating the impacts of climate change into weather files. Guan [23] provides a complete literature review of these methods. The creation of a future weather file for building performance simulation can be classified into two categories. The first category relies on historical weather data and includes the extrapolating statistical method, imposed offset method, and the stochastic weather model. *The extrapolating statistical method* generates future weather conditions based on the projection of the historical weather data trends into the future. This simple and fast method predicts building energy consumption based on the degree-day method. Christenson et al. [24], Rosenthal et al. [25], and Cox et al. [26] applied this method to assess the impact of climate change on building energy demand for different locations. However, since solar radiation or humidity are not considered, degree-day analysis can lead to large deviations in building energy simulation, making its application limited [27].

The imposed offset method predicts future climate information from complex climate models in addition to the recorded typical weather data sets. This method has been the most widely used in literature for preparing future weather files to study future building energy demand. The imposed offset method includes the morphing technique, as described by Belcher et al. [28], and it requires one of three following operations: "shifting" (addition), "stretching" (multiplication), or a combination of the two (shifting and stretching). The morphing method is applied to the climate parameters acquired from local weather stations in order to generate future weather data. Crawley used the morphing method to generate weather files, describing various scenarios of climate change and urban heat islands for 25 locations worldwide [29]. In the United States, Wang and Chen used the morphing technique to downscale HadCM3 [30]. They predicted a net increase in source energy use by 2080 for warm and hot climate zones and a net decrease in cold climate zones based on 9 building types. Moreover, Shen used the "morphed" weather data to predict the impacts of future energy use patterns for residential buildings in the United States, illustrating the substantial impacts of climate change on residential and office building energy use during the year 2040–2069 in four U.S. cities [31]. In Australia, using the morphing method, Wang et al. reported that the total energy would change by a range of 48%–350% by 2100 with significant large carbon emissions in the future [32]. Chan illustrated an increase in air conditioning energy use ranging from 2.6 to 14.3% for office buildings and 3.7–24% for residential buildings as a result of future change in Hong Kong [33]. In Canada, Robert and Kummert used the morphing method to developed hourly future climate data to evaluate the performance of a zero-energy building in the future [34]. It was concluded that climate-sensitive buildings such as net zero energy buildings should always be designed utilizing weather data that take into account climate change. In the UK, Jentsch et al. used the morphing technique to illustrate the practicality of generating future weather files [35]. They developed a software tool that enables for generating future weather files for any location in the world using HadCM3 and A2 emission scenarios.

The stochastic weather model was developed by Van Paassen et al. [36] and Adelard et al. [37] to generate future weather data, based on generating an artificial meteorological database. In addition, some weather generators use mathematical algorithms that create weather parameters comparable to local weather station data [27]. In this context, Herrera et al. offer a complete description of methods for the creation of weather variables for building simulation [14]. For instance, the Meteonorm software can extrapolate hourly data from statistical weather data for any site worldwide. Meteonorm utilizes physical processes and stochastic models for radiation parameters [38]. This tool combines its climate database, spatial interpolation tool, and stochastic weather generator, with global radiation data obtained from the Global Energy Balance Archive (GEBA). Thus, the application of stochastic weather models in generating future weather data is significant, particularly in areas where historical data are not available. As reported by Ebrahimpour and Maerefat [39], the TMY generated using Meteonorm software has good agreement with the long-term average recorded data during the year. An advantage of this method is that all the relationships between different weather variables are accounted for in the same way as for baseline data [34]. Despite that, Guan [23] argued that the stochastic weather model is too complex and computationally intensive. Overall, the imposed offset method is the most practical method for developing future weather, as the extrapolating statistical method only considers degree-day measure while the stochastic weather model requires high computing power.

The second category relies on the use of numerical climate models as an alternative to the historical weather data approach. For instance, GCMs are used to generate local future weather files utilizing the dynamical downscaling or Regional Climate Model (RCM). This has become a commonly used approach to enhance the resolution of the climate model outputs [40]. Nik et al. [41] and Moazami et al. [42] showed that the RCMs, when compared to GCMs, have the advantage of generating physically consistent data sets for different variables and are capable of enhancing the landscape and mesoscale processes. This provides a more reliable forecast of the boundary conditions of the future climate at the local level.

Studies have been carried out on the design of net-zero energy building [34], the durability of building envelopes [43], and a variety of roof designs [44] under future climate conditions in Canada. In spite of that, there is a lack of comprehensive assessment of the climate change impact on the building heating and cooling energy demand under various global and regional climate models. This study aims to provide not only future weather files based on a more reliable projection of the local boundary conditions than previously seen in other studies in Canada, but also to offer an insight on the impacts of climate change on building energy demand for all the 16 ASHRAE prototype building models.

3. Methodology

3.1. Generating future weather files

The availability of historical weather data is limited for all locations across the City of Toronto due to the availability of weather stations for every location in the past. As of now, two historical weather files are available for Toronto, Ontario (Fig. 1). These CWEC files were selected as a baseline climate for overlaying the changes projected by high-resolution weather data obtained from GCMs, as previously done by Jafarpur and Berardi [45]. Initially, the CWEC file representing weather data from 1959 to 1989, 30 years of recorded historical weather, was selected, providing long-term duration for the selection of a statistically typical month. Then, the more recent CWEC2016 file representing the typical climate from 1998 to 2014 was selected, to consider the most recent trends. These CWEC files represent the twelve most typical months selected from a 30 and 15-year timeframe (Table 1).

In this study, the CCWorldWeatherGen and WeatherShift™ tools, which adhere to the imposed offset method, are utilized to statistically downscale GCMs for future weather file generation. The statistical downscaling method is used to create future weather files by establishing a correlation between GCMs and historical weather data. Once this connection has been made, the climate model projection was used to forecast the local climate parameters for the future. In addition, the Hadley Regional Model 3 (HRM3) coupled with Hadley Climate Model 3 (HadCM3) was used to create future weather files using dynamical downscaling, providing a better spatial resolution. Thus, the use of HRM3 intends to offer better-quality projections and include greater local geological characteristics (Fig. 2).

3.1.1. CCWorldWeatherGen tool

The Climate Change World Weather Generator (CCWorldWeatherGen) tool allows for the fast projection of future climate change to an existing weather file [46]. With the application of the statistical downscaling method as well as a time series adjustment technique (morphing), the CCWorldWeatherGen tool can develop a future weather file for each inputted TMY file. Jentsch et al. created this tool by utilizing the morphing method [35]. According to Moazami et al. [47], after six GCMs under AR3 and 23 GCMs under AR4 were reviewed, it was concluded that the most suitable GCM for applying the morphing technique was the HadCM3 for A2 emission scenario. The A2 emissions scenario put forward by the IPCC AR3 represents a ‘business as usual’ case with continuously increasing global population and regionally oriented economic growth [48].

In order to create future weather files, first, CWEC files were uploaded to the CCWorldWeatherGen. The HadCM3, A2 scenario and a future projection timeframe were then selected, respectively. Then, the morphing procedure was initiated to generate the future weather files by superimposing the forecasted future climate conditions on meteorological parameters existing in the original CWEC weather file. Therefore, applying the CCWorldWeatherGen tool to each of the CWEC files will project the changes in 1961–1990 baseline on to the data from 1959 to 1989 and 1998–2014. For this research, it was assumed that the useful life of a building is approximately 50 years, as they go through different stages of their life cycles. Therefore, the future weather files created using the CCWorldWeatherGen tool were selected for the years 2041 through 2070.

3.1.2. WeatherShift™

The second tool used for the projection of changes in the future climate to an existing weather file is WeatherShift™. This tool was acquired from Arup and Argos Analytics for the purpose of this research and utilizes 14 GCMs made available under IPCC’s AR5 for its future climate projection [49]. With the application of the statistical downscaling method as well as a time series adjustment technique, the WeatherShift™ tool can develop a future weather file for each inputted TMY.

Table 1
Selected years of each month in the Canadian Weather Year for Energy Calculation for the period of 1959–1989 (CWEC file) and 1998–2014 (CWEC2016 file).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CWEC	1969	1965	1964	1964	1963	1970	1981	1989	1978	1969	1983	1961
CWEC2016	1999	2004	2006	2009	2006	2001	2013	2011	2003	2010	2000	2003

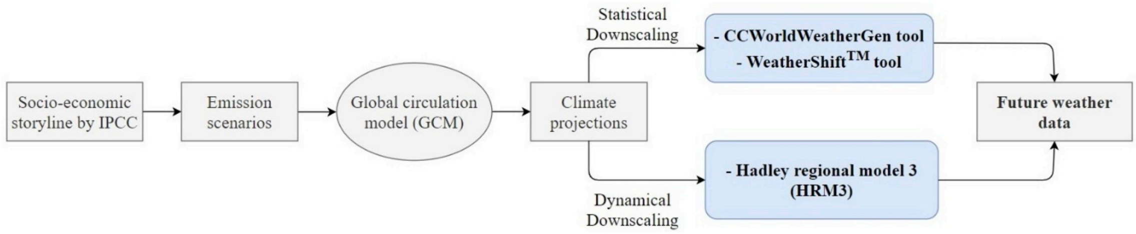

Fig. 2. Flowchart of various methods used for preparing high-resolution weather data suitable for generating future weather file for building performance simulation.

Similar to the CCWorldWeatherGen tool, CWEC files were uploaded to the WeatherShift™ tool to create future weather files. Then, in WeatherShift™, the RCP8.5 emission scenarios and the period of 2056–2075 projection timeframe were selected to simulate and superimpose the changing climate of the future on different weather parameters. It is also worth noting that the WeatherShift™ offers a cumulative distribution function (CDF) for each of the variables, allowing the users to assign a likelihood to the projections [49]. CDF has been previously applied to the UKCP09 probabilistic projections [50]. For the purpose of this study, the 50th (median) percentile was chosen for generating future weather files according to the two CWEC files for the City of Toronto.

3.1.3. Weather file generation from Hadley Regional Model 3

To create a future weather file using RCM, this study used HRM3 that was dynamically downscaled through the North American Regional Climate Change Assessment Program [51]. The NARCCAP is an international program dedicated to using RCMs driven by GCMs to generate high-resolution climate projections. The program includes two main phases. In phase 1, six RCMs use boundary conditions from the National Center of Environmental Prediction-Department of Energy (NCEP-DOE) Reanalysis II (R2) for a 25-year period (1980–2004); then in Phase 2, boundary conditions from 4 atm-ocean general circulation models (AOGCMs) are used for 30 years of current climate (1971–2000) and future climate (2041–2070) [52]. The output data obtained from the AOGCMs simulated using the Special Report on Emission Scenarios (SRES) A2 were utilized for driving the RCMs.

To generate a future weather file, this research used the output data from the combination of HadCM3 downscaled by HRM3 and forced by the SRES A2 emission scenario. The reason for selecting this GCM-RCM combination was due to the fact the CCWorldWeatherGen tool uses the same GCM (HadCM3) for generating a statistically downscaled future weather file. This allows for a direct comparison of the two downscaling methods, as the climate models used are the same.

Initially, five meteorological parameters were extracted from NetCDF format corresponding to the grid point closest to the latitude and longitude of the weather station located at Toronto Pearson International Airport. These parameters included surface air temperature, pressure, specific humidity, zonal wind speed, and meridional wind speed. They were selected for their significant role in building energy consumption and represent the climate conditions used in building performance simulation. This research study chose not to include cloud cover and solar radiation data, leaving the EnergyPlus Weather (EPW) file at their initial values. The limitations to include cloud cover and solar radiation in developing a future weather file arise from the output data from the NARCCAP for these parameters in the future. Besides, surface solar radiation is often believed to stay constant for the future when no significant amount of aerosol and air pollutants are emitted to the atmosphere. Secondly, HRM3 data for periods of 1970–2000 and 2041–2070 were corrected and organized to generate 8760 values, corresponding to the EPW format. Next, linear interpolation was used to estimate the hourly values for each meteorological parameter from the 3-hourly temporal resolution data. Finally, the units for meteorological values of relative humidity, dew-point temperature, wind speed, and wind direction that are not directly compatible with building simulation were converted to correspond to the EPW format.

The present work used the back-casting technique to assess the ability of HRM3 to reproduce accurate climate data for the City of Toronto. To that end, the dry bulb variables from HRM3 output for the period of 1971–2000 at 3-h resolution were compared with the actual observed weather data from the weather station for the same period. The results show that the model performance evaluation for the HRM3 data for Toronto was in compliance with the NARCCAP assessment of HRM3 climate model [52]. According to Mearns et al. [52], the root-mean-square error (RMSEs) for the seasonal temperature of the HRM3 was in the range of 3–6, which was similar to RMSEs calculated for the extracted temperature values for the city of Toronto. It is worth noting that the biases and RMSEs present in HRM3 are within the range found in many other regional climate models.

To measure the magnitude of climate change for each weather parameter from the coupled HadCM3-HRM3 model, two main approaches were used. First, the 1971–2000 values for all parameters were subtracted from 2041 to 2070 values, averaged for the 30-year period, and added to each of the original CWEC files to produce a future weather file. This “shifts” weather parameters in the historical weather file similar to the morphing method developed by Belcher et al. [28]. In the second approach, the parameters acquired from HRM3 were directly used to generate typical months. In this case, the natural variability of the climate projections is saved.

3.2. Building energy simulation

Building energy modelling using OpenStudio 2.8.0 was carried out to simulate the impacts of climate change on building heating and cooling energy demand for the City of Toronto. The OpenStudio software allows the user to work with prototype building models developed by the United States Department of Energy (DOE) [53]. These models follow the 2013 version of ASHRAE standard 90.1 and are made of 16 buildings with different dimensions and operations. Fig. 3 displays the rendering of the building models used in the OpenStudio software.

The technical descriptions for each of the building envelope components for the selected prototype building models are presented in Table 2. The objective of this research was to assess the impact of climate change on future building energy demand under the assumption that no technological advancement takes place in buildings. Excluding technological advancement provides the opportunity to better understand how existing buildings will react to climate change, eliminating the uncertainties regarding improvements in the building characteristics. The results could then provide the opportunity to study what types of improvement would be feasible in the future.

3.3. Summary of assumptions and inputs

The shape, total area, floor height, the number of zones, and HVAC

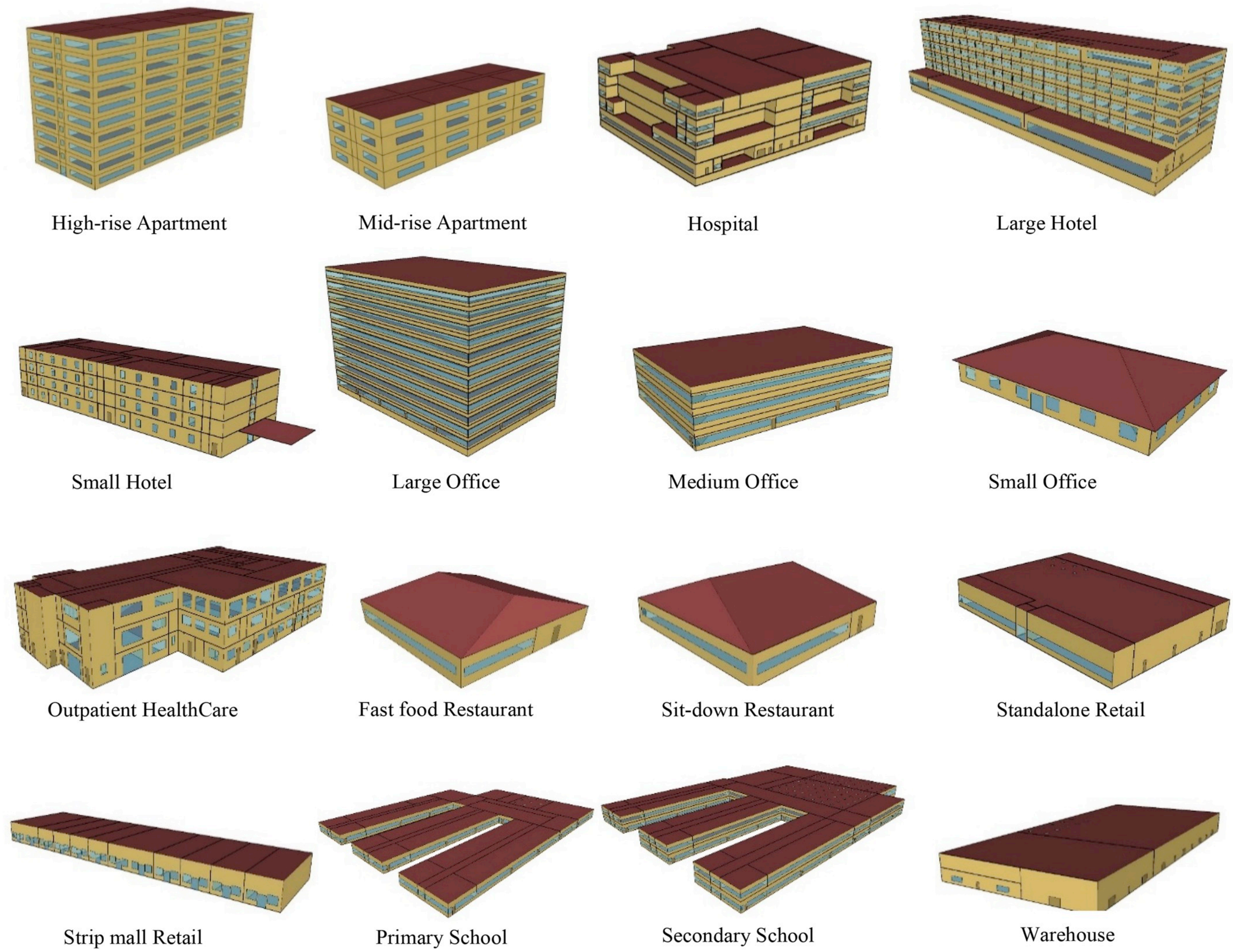

Fig. 3. Reference building models from the ASHRAE 90.1 standard [54].

Table 2
Building envelope components of pre-designed reference building models.

Building Type		U-factor (W/(m² K))				Solar Heat Gain Coefficient (SHGC)	
		Roof	External Wall	Glazing		Glazing	
				Window	Skylight	Window	Skylight
Apartment	High-rise	0.18	0.31	2.65		0.43	
	Mid-rise	0.18	0.31	2.65		0.43	
Hotel	Large	0.18	0.45	2.65		0.43	
			0.51				
	Small	0.18	0.31	2.65		0.43	
				2.85		0.29	
Office	Large	0.18	0.51	2.65		0.43	
	Medium	0.18	0.31	2.65		0.43	
	Small	0.15	0.29	2.65		0.43	
Health	Hospital	0.18	0.45	2.65		0.43	
			0.51				
	Outpatient	0.18	0.31	2.65		0.43	
Restaurant	Fast food	0.15	0.29	2.65		0.43	
	Sit-down	0.15	0.31	2.65		0.43	
Retail	Stand-alone	0.18	0.51	2.65	2.96	0.43	0.34
	Strip-mall	0.18	0.31	2.65		0.43	
School	Primary	0.18	0.31	2.65		0.43	
	Secondary	0.18	0.31	2.65	2.96	0.43	0.34
Warehouse		0.21	0.28	2.65	2.96	0.43	0.34
		0.53	0.47				

Table 3
The building composition of the 16 ASHRAE building prototype models.

Building Types	Number of Floors	Gross Floor Area (m^2)	Floor-to-Ceiling Height (m)	Window-to-Wall Ratio	Number of Zones
High-rise Apartment	10	7836.48	3	30%	80
Mid-rise Apartment	4	3134.59	3	20%	32
Hospital	5	22,436.08	2.4 (basement) 4.3	16%	162
Large Hotel	6	11,345.29	4 (ground floor) 2.4 (basement) 3 (2nd −6 floors)	30.2%	195
Small Hotel	4	4013.58	2.7 (ground floor) 3.4 (upper floor)	10.9%	54
Large Office	12	46,320.38	2.7	37.5%	74
Medium Office	3	4982.19	2.7	33%	18
Small Office	1	511.16	3	22.2%	6
Outpatient HealthCare	3	3804.01	3	20%	118
Fast Food Restaurant	1	232.34	3	17.5%	2
Sit-down Restaurant	1	511.15	3	21.4%	2
Standalone Retail	1	2293.99	6.1	7.1%	5
Strip Mall Retail	1	2090.32	5.2	10.5%	10
Primary School	1	6871.00	4	35%	25
Secondary School	2	19,592.00	4	33%	46
Warehouse	1	4835.13	4.3 (office)	0.71%	3

system type for each of the prototype building models were determined from 1999 to 2003 Commercial Buildings Energy Consumption Survey (CBECS) dataset as well as previous studies of the existing building stock [51] (Table 3). Like the weather files, the prototype building models change across various locations. As a result, the design and construction of the buildings are modified according to the location as well as applicable codes and practices. The 16 prototype building models used in this study were selected to follow ASHRAE standard 90.1 (2013), and climate zone 5A that is defined as Cool – Humid, as the City of Toronto. Moreover, the HVAC sizing calculations to meet peak cooling and heating loads are based on the "Design Days" weather data. As a result, to allow for climate change impact assessment, the design day used for sizing the HVAC equipment was kept the same for all building types.

Both historical CWEC files and the future weather files created for this research were used to run building energy simulations. A total of eight weather files (two historical and six future) were used. To investigate the impacts of climate change on building energy demand, each of the building models was simulated using the eight weather files, which resulted in a total of 128 simulations. The structure of the simulation runs is illustrated in Fig. 4.

Table 4
Heating degree day (HDD), base 18 °C, for Toronto Pearson International Airport.

Weather Files	HDD
CWEC (1959-1989)	4,179
CCWorldWeatherGen tool	3,427
WeatherShift tool	3,157
HRM3	3,509
CWEC2016 (1998-2014)	3,695
CCWorldWeatherGen tool	3,033
WeatherShift tool	2,769
HRM3	3,122

4. Results and discussion

4.1. Future weather file features

Comparing the two historical CWEC weather files suggests higher dry-bulb temperatures for the most recent 15-year weather file (1998–2014). Table 4 reports the annual degree days for heating and cooling of the historically recorded CWEC files and their future projections. In this study, Heating Degree Days (HDDs) indicate the number of degrees that a day's mean temperature is less than 18.3 °C for which the building requires heating. Whereas the Cooling Degree Days (CDDs) indicate a threshold of 18.3 °C for which air conditioning is required every time the mean temperature exceeds that value. As per the results, higher temperatures reduce the number of HDDs and increase the number of CDDs. It is expected that the City of Toronto will experience a shift from the existing climate zone 5 (Fig. 1) to a possible climate zone 4 by 2070.

Fig. 5 displays the annual outdoor dry-bulb temperatures for the future weather files generated using both downscaling methods according to the two historical baseline climates. The future weather files forecast a mean temperature increase of 3.7–4.5 °C for the City of Toronto. This increase is almost 2.0 °C greater than the IPCC forecast of global mean surface temperature for the same period [1] and is aligned to predictions for the Canadian context. Boxplots for the outdoor dry-bulb air temperature shows a continuous increase in the average temperatures for the future and the impacts of climate change are clearly seen in the generated future weather files. However, the projections for the future are significantly higher in the weather files developed by the WeatherShift™ tool. Besides, for all future weather file projections, increases in maximum and minimum temperatures based on the 1998–2014 baseline is higher compared to the 1959–1989 period. This is due to the fact that in statistical downscaling the baseline period is used to superimpose the changing climate of the future to create the future weather file. Thus, higher temperature values observed for 1998–2014 baseline years directly influence future weather file generation, resulting in higher temperature values. The general trend for a decrease in relative humidity values are expected in the future. However, the changes in wind speed and direction for the future is rather complex and simple trends cannot be obtained from the results for these variables. Overall, the changes in average solar radiation at surface, as well as average wind speed and wind direction for the future climate are insignificant when compared with the historical recordings.

4.2. Building energy simulation results

Heating and cooling energy use intensity (EUI) for all 16 building prototype models are illustrated in Fig. 6. As per the building simulation results, rises in cooling EUI and decreases in heating EUI are projected

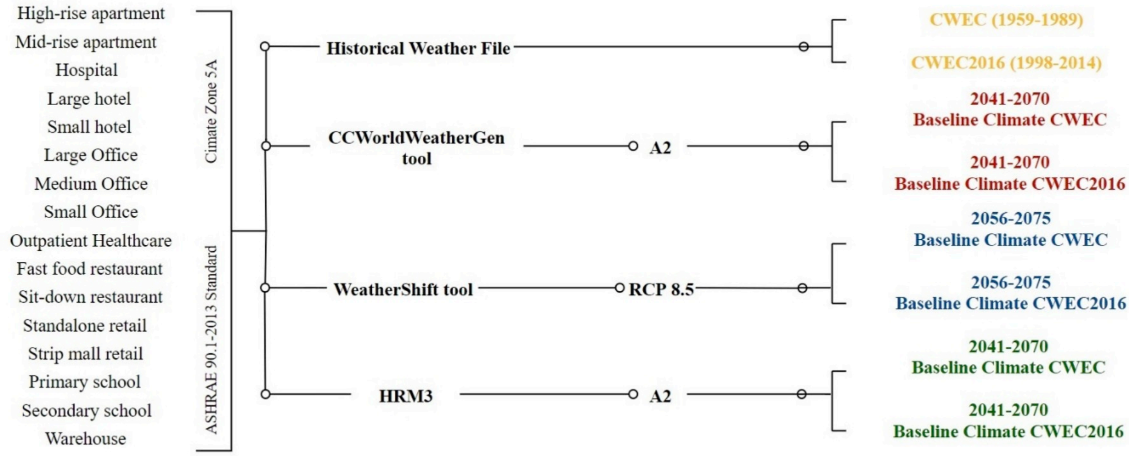

Fig. 4. Configuration of simulation runs of 16 building prototype models used in this study under the historical and future weather files.

for the future. However, the findings suggest that the magnitude of the building's heating and cooling EUI is highly influenced by the baseline climate employed and the building typology itself. For instance, for the 1959–1989 baseline period, an average decrease of 18–33% for heating EUI, and an average increase in the range of 15–126% for cooling EUI is observed. Furthermore, a comparison between the two baseline climates indicates higher heating and lower cooling energy use for the CWEC's future weather files, mainly due to lower temperature values seen for the 1959–1989 period.

Not only the changes in heating and cooling EUI of the 16 prototype buildings are affected by climate change, but they are also associated with the building typology. As Table 5 indicates, for the 1959–1989 baseline period, the large hotel and outpatient healthcare building models experienced an average reduction of 18% in heating EUI for the future, the lowest among all building types. On the other hand, the largest reduction in heating EUI was for the small office building model, with an average reduction of 33% in the future. These results are similar to Xu et al. [55] findings that due to envelope heat loss/gain making up a higher fraction of small buildings heating and cooling load than that of large buildings, the heating EUI of a large building is not as susceptible to variations of climate conditions as a small building. The results are also consistent with Verbeke and Audenaert [56] review on the impacts of building thermal inertia on thermal comfort and energy use for space heating and cooling.

Regarding cooling EUI, the hospital building model had the smallest increase in cooling EUI with 15%, whereas the fast-food restaurant building model had the largest increase by 126%. For the hospital building model, the change in heating and cooling EUI is relatively smaller due to larger internal loads of interior equipment and lighting that remains constant regardless of outdoor climate conditions. Moreover, the hospital model has a large ratio of zones to floor area and a small window-to-wall ratio (16%) compared to other building models. As previously discussed, the hospital building model experiences smaller changes in heating and cooling EUI in the future.

In the case of fast food and sit-down restaurants, the large heating and cooling EUI values are due to high ventilation rates in these buildings compared to others. Furthermore, the model for restaurant buildings has uninsulated attics and all the zones are exposed to the outdoor conditions (Fig. 2). Similarly, in the retail building models, all zones are directly exposed to the outdoors and a high rate of air exchange is present. A comparison of high-rise and mid-rise apartment buildings also shows that the decrease in heating and increase in cooling EUI are

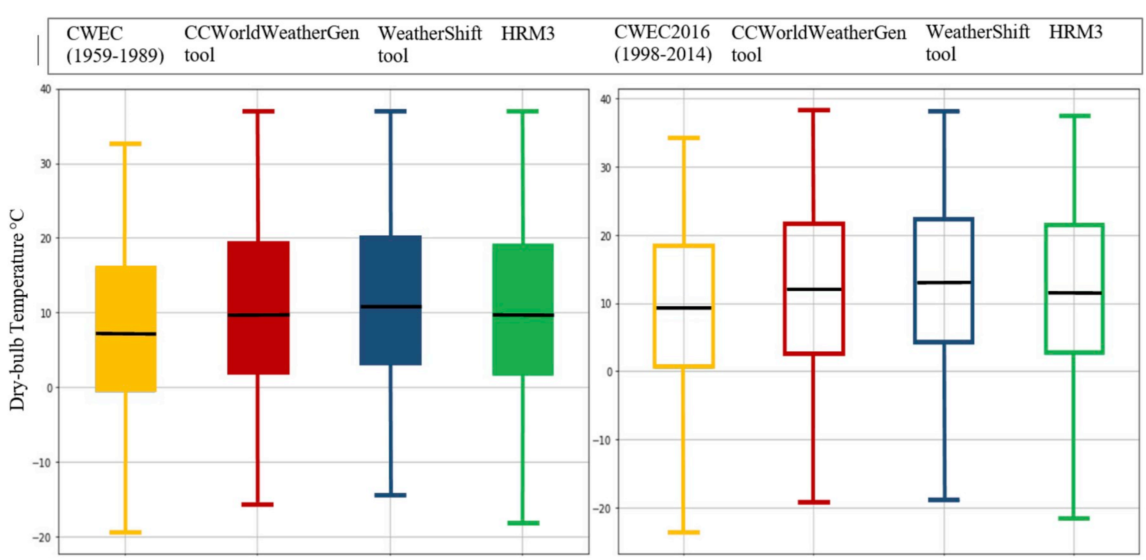

Fig. 5. Outdoor dry-bulb temperature values for the historical weather file of CWEC (solid color) and CWEC2016 (hollow color), together with the three future weather files generated. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

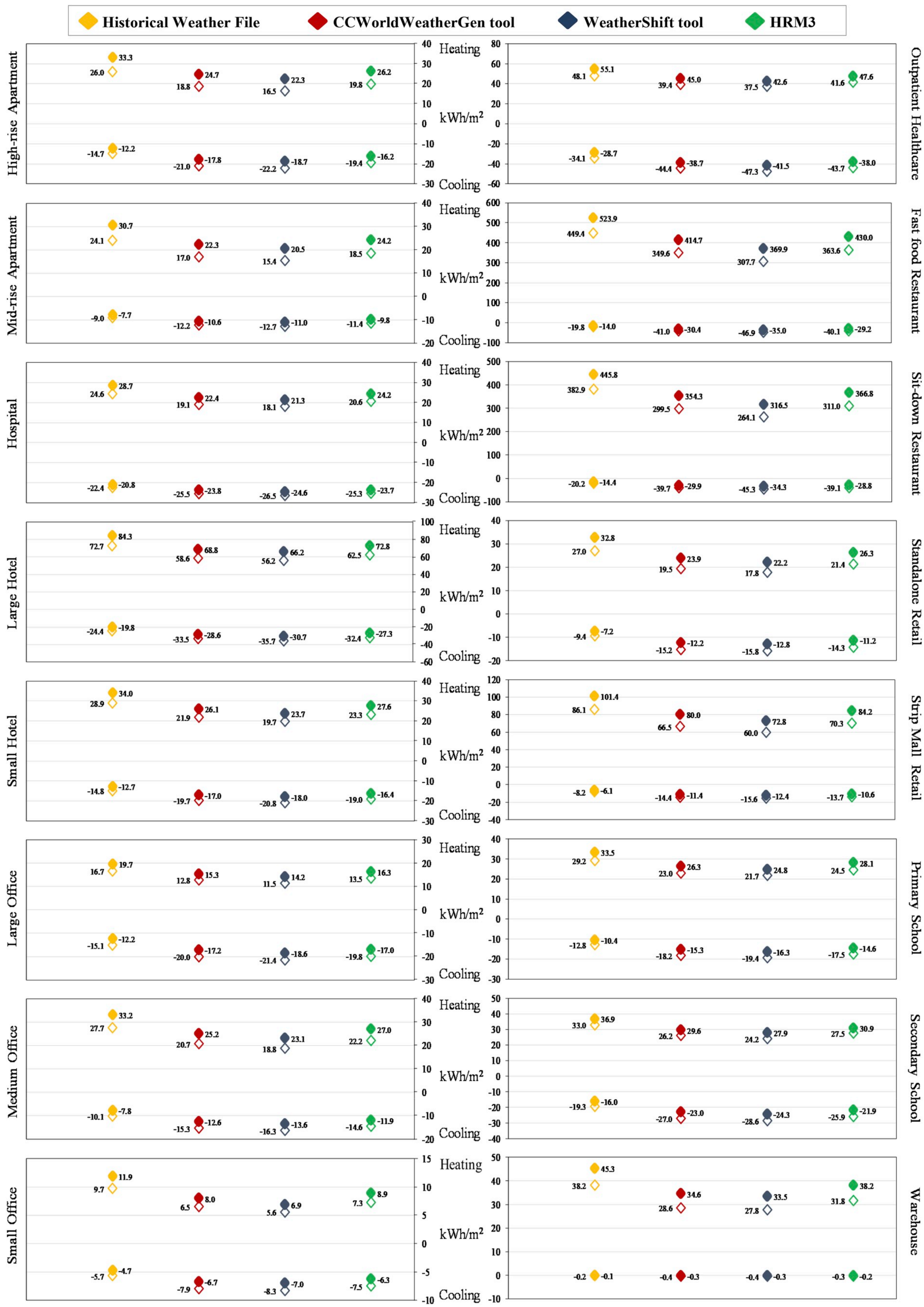

Fig. 6. Scatterplots showing the annual heating energy (positive values) and cooling energy (negative values) under historical and future weather data sets for all 16 prototype buildings. Values for the 1959–1989 baseline period are presented in solid color markers, those for and the 1998–2014 baseline period in hollow color markers. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 5
The average decrease and increase in heating and cooling EUI due to climate change in different building types in the future.

Building Type	Baseline Climate CWEC (1959–1989)		CWEC2016 (1998–2014)	
	Heating	Cooling	Heating	Cooling
High-rise Apartment	−29%	42%	−27%	44%
Mid-rise Apartment	−30%	34%	−27%	36%
Hospital	−22%	15%	−21%	16%
Large Hotel	−19%	39%	−18%	46%
Small Hotel	−25%	34%	−24%	35%
Large Office	−24%	36%	−23%	44%
Medium Office	−26%	52%	−24%	64%
Small Office	−33%	39%	−33%	41%
Outpatient HealthCare	−18%	32%	−18%	37%
Fast Food Restaurant	−24%	115%	−23%	126%
Sit-down Restaurant	−24%	105%	−22%	116%
Standalone Retail	−28%	61%	−26%	68%
Strip Mall Retail	−24%	78%	−22%	87%
Primary School	−21%	44%	−21%	48%
Secondary School	−21%	41%	−20%	44%
Warehouse	−23%	109%	−22%	110%

comparable, and the difference is associated with the higher internal load of the high-rise apartment compared to the mid-rise building. In fact, this is true in the case of large and small hotel building models, as well as primary and secondary school buildings. Finally, according to Fig. 6, the cooling EUI of the warehouse building model is significantly low when compared to other building types, illustrating the fact that the climate conditions might not be the dominant force driving the energy use of this building model. All in all, the findings suggest that buildings with higher insulation levels, higher zone ratios, lower window-to-wall ratios, and smaller outdoor air supply are less disturbed by outdoor conditions.

The shift in heating and cooling EUI is present for all buildings but significantly varies in magnitude for each future weather file and building type. Furthermore, the temperature rise brought by climate change substantially influences the cooling demand for the hot months of July and August, adding to the summer peak load electricity demand. From the results of the analysis, it is determined that the sizing and selection of HVAC systems must be done according to the future climate. Besides, apart from HVAC systems, other methods including the addition of thermal mass, improvements in windows, glazing and envelope insulation are important in helping tackle some of the climate change challenges.

4.3. *Climate change implications on greenhouse gas emissions*

The energy use breakdown for the 16 prototype building models illustrates that heating is generated primarily from natural gas while cooling is provided solely by electricity. The challenge in the transition to a low-carbon development for the building sector is mostly economic. The cost disparity between natural gas and electricity has made it impracticable to use electricity for meeting the heating energy demands in buildings. Using energy use data and the local emission factors[1] for natural gas (179.95 g CO_2 eq. per kWh) and electricity (36 g CO_2 eq. per kWh), the total GHG emissions associated with heating and cooling energy demand for each building type was calculated. Fig. 7 details the GHG emissions for the 16 prototype building models. In reading this chart, it is worth noting that the emission factors for electricity could vary substantially between provinces or cities, and even historically for the same location, so the results would need to be considered carefully within the context and the assumptions used for their generation.

The Canadian federal government introduced a carbon pricing system of $20 per tonne of CO_2 in 2019. The carbon pricing systems will increase by $10 per tonne of CO_2 per year until capping off at $50 per tonne in 2022 [57]. It is expected that carbon pricing will provide a cost-effective measure by providing incentives to innovate and find ways to lower GHG emissions, transitioning to low-carbon development. Under the assumption that the emission factors remain the same, the $50 carbon price would translate into substantial costs in the future. Table 6 shows an estimate for the average cost of CO_2 emissions for the total building energy use for each of the 16 building models considered in this study. The carbon pricing system could provide a tool for closing the gap between the cost of natural gas and electricity, making it more feasible to transition to a low-carbon development by using electricity to meet building heating demands.

5. Conclusions

This study described the results of climate change impact assessment on the energy performance of 16 ASHRAE prototype building models for Toronto, Ontario. The results established the significance of considering future weather files for energy simulations. Initially, this work focused on future weather files generation using statistical and dynamical downscaling methods. The use of global and regional climate models allowed for the projection of future climate conditions, providing information on the impact of climate change on building energy demand. Overall, in statistical downscaling, the historical weather files selected as baseline climate projected significantly different future climate conditions. This is an indication that the appropriate selection of baseline climate for superimposing HadCM3 projections is critical. On the other hand, the higher spatial resolution of dynamical downscaling compared to the statistical method presents a better picture of the local climate conditions. Thus, better quantifying the impacts of climate change on building energy demand which tends to focus on the local level. Besides, the HRM3 projected weather parameters in 3-h time-steps, significantly better than the monthly time-steps seen in HadCM3, reducing the significance of the statistics in data interpolation. This study concludes that the use of multiple GCMs rather than just a single model for future weather file generation creates statistically significant results. Therefore, a combination of multiple GCM, as seen in the WeatherShift™ tool, alongside RCM, such as HRM3, provides the most accurate climate prediction for the future.

Based on the developed future weather files, Toronto's cold climate will see a decrease, with various magnitude, in heating needs, and an increase in cooling loads. The resulting future HDDs illustrate a shift in climate zone classification for the City of Toronto, demonstrating the need to modify building code guidelines and building modelling regulations to also consider future scenarios. The impacts of climate change were seen in prolonged cooling seasons while diminishing the duration of the heating season. This means that for a cold Canadian climate, the more heating energy a building consumes, the greater potential it will have to decrease its EUI in the future.

For different building typology, the simulation results showed a drop in annual heating EUI and an increase in cooling EUI. It was concluded that buildings with higher insulation levels, higher zone ratios, lower window-to-wall ratios, and smaller outdoor air supply are less affected by climate change. The simple conclusion is that there is a need to consider the use of future weather files in building design to maximize energy efficiency, reduce GHG emissions, and limit the cost of future changes. Therefore, as buildings tend to exist for decades, it is essential to evaluate how design decisions made today can meet the demands of a more extreme and varying climate in the future.

In future works, it is suggested to use the weather files generated in

[1] Obtained from the 2017 Annual Energy Consumption and Greenhouse Gas (GHG) Emissions report made available by the Environment and Energy Division, City of Toronto, Canada. Available at: https://www.toronto.ca/wp-content/uploads/2019/01/958c-2017-Annual-energy-consumption-and-GHG-emissions-report-compressed.pdf.

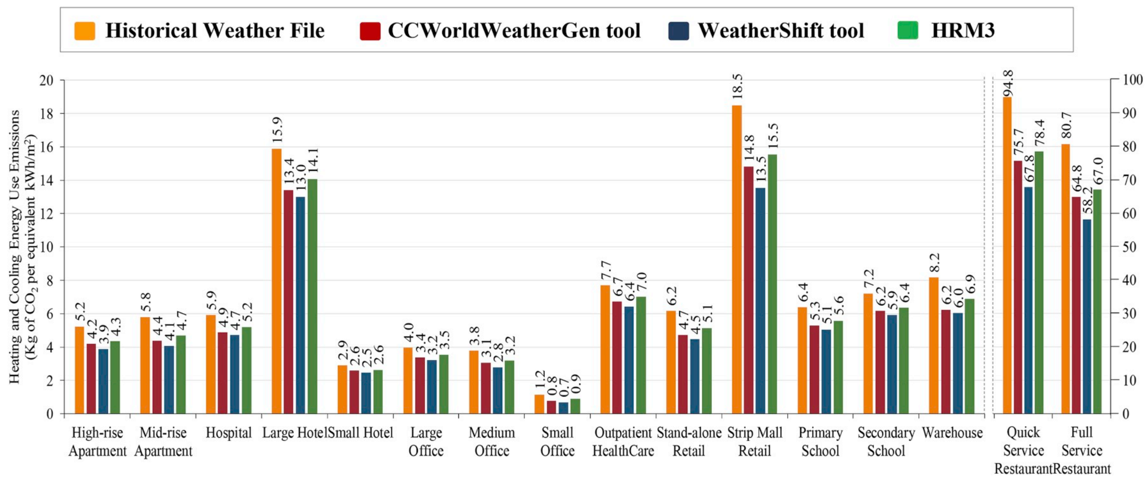

Fig. 7. The total energy use emissions for the 16 prototype building models using the CWEC 1959–1989 file as baseline period for generating three future weather files for 2070.

Table 6
Average cost of CO_2 emissions for the total energy use in various building types under the Canadian carbon pricing system. Data obtained averaging the simulation results for the three future weather files.

Building Type	Average cost at $20 per tonne	Average cost at $50 per tonne
High-rise Apartment	$2578.50	$6446.24
Mid-rise Apartment	$555.06	$1387.64
Hospital	$12,792.22	$31,980.55
Large Hotel	$10,288.06	$25,720.16
Small Hotel	$2134.75	$5336.86
Large Office	$11,536.83	$28,842.08
Medium Office	$705.46	$1763.64
Small Office	$38.15	$95.37
Outpatient HealthCare	$1725.11	$4312.77
Fast Food Restaurant	$1026.91	$2567.27
Sit-down Restaurant	$2148.99	$5372.47
Standalone Retail	$501.34	$1253.36
Strip Mall Retail	$808.24	$2020.60
Primary School	$1882.58	$4706.44
Secondary School	$6738.66	$16,846.66
Warehouse	$742.63	$1856.57

this study to assess mitigation measures to climate change on different building types and to investigate their resiliency by looking at the dynamic hourly evolution of their energy demand. Future studies should also incorporate cities across the region with different climate conditions, as building energy demand and GHG emissions differ across Canada. In addition, it is recommended to consider the effects of urban heat island effect together with extreme conditions, as the current study considered the buildings as entities and neglected inter-building effects. Finally, with the implementation of future weather files in the building's climate change impact study, it is essential to develop climate models with a higher temporal and spatial resolution for Canada. Moreover, high-resolution climate models should deliver values for all climate variables important in projecting climate conditions.

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