Building energy demand within a climate change perspective: The need for future weather file

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Abstract. The building sector is accountable for about one-third of the global energy consumption and contributes to 19% of greenhouse gas (GHG) emissions relating to energy processes. Given the changing climate and its impact on building heating and cooling demands, energy models based on historical weather data cannot accurately simulate the performance of a building in the future. Accordingly, this paper generated several future weather data sets and applied them to the energy simulation of 16 ASHRAE reference building models for Toronto, Canada. Both statistical and dynamical downscaling techniques were used for generating these future weather files. The results indicate an average decrease of 17.8-27.2% in heating loads and an average increase of 13.5-55.4% in cooling loads, depending on the building type, leading to an overall decrease in energy use intensity (EUI) for the majority of the 16 reference building models. It is concluded that the application of future weather files for building performance simulation leads to a more realistic quantification of building energy demand in the future. Furthermore, depending on the availability and accuracy of regional climate models (RCM), the weather files generated using dynamical downscaling provide a more reliable forecast of the local boundary conditions for building performance simulation.

1. Introduction

In recent years, the building sector, a large energy-consuming system, has received increasing attention for sustainable development and decarbonization policies [1]. According to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, the global mean surface temperature will increase, in relation to the 1986-2005 period, by a range of 2.6°C to 4.6°C by the end of the 21st century [2]. Therefore, development of effective long-term strategies and policies in response to climate change must appropriately quantify future trends of building energy demand influenced by climate change.

Building performance simulation provides a useful tool in measuring building energy demands. Energy models can assess various design and operation systems to determine the most appropriate design with the most suitable overall energy performance. In this regard, calculation of annual building energy demand in building simulations incorporate hourly Typical Meteorological Year (TMY) weather file. Commonly, used weather files are based on historical environmental records, representing the average climate conditions. However, given the scale of climate change and its impact on building heating and cooling demands, simulations using hourly TMY weather files fail to forecast the trends of building energy demand in the future. As a result, several methods have been developed to generate future weather file for building performance simulations. Herrera et al. [3] provide a comprehensive review of the methods used to create future weather data for use in building simulation.

Forecasting future climate conditions is the basic principle for all climate change impact studies. General circulation models (GCMs) were presented to provide quantitative estimates of future changes in the climate based on different emission scenario possibilities as put forward by IPCC. However, the outputs of GCMs have a relatively low level of spatial (100-500 km) and temporal resolution (daily or monthly) for direct use in building simulation. In fact, most building-related research is undertaken by
means of building simulation tools that require local weather data with hourly resolution. GCM adjustments are made possible by a process of “downscaling”, which refers to the generation of climate change information at finer spatial and temporal resolutions.

As of now, two main forms of downscaling technique exist. First is statistical downscaling which establishes an empirical relationship between large-scale circulation variables and local climate variables. Once a relationship has been determined, future atmospheric variables that GCMs project are used to predict future local climate variables [4]. This approach relies on the critical assumption that the present relationship between large-scale circulation and local climate remains valid under different forcing conditions of possible future climates. Research had been conducted on the use of a morphing technique described by Belcher et al. that requires “shifting” and “stretching” of the climatic variables in the present-day recorded weather data, producing new weather data that illustrate the average projected climate change in the future [5]. Crawley applied this technique to create weather files that represent the future climate for about 25 locations worldwide, illustrating a range of predicted climate change and heat island scenarios for building simulation [6]. Moreover, Chan examined the application of morphing for Hong Kong’s subtropical climate [7]. In Canada, Robert and Kummert reported on the use of morphing methodology on the creation of weather files for the city of Montréal, assessing energy performance of a zero-energy building [8]. In the UK, Jentsch et al. described a method of morphing output from the Hadley Center global climate model (HadCM3) and created a tool by which future weather data for use in building simulation can be generated for any location worldwide [9].

The second downscaling technique is dynamical downscaling, where the output from a GCM is used to drive a regional model in higher spatial resolution. This method relies on the use of a regional climate model (RCM) which is fundamentally similar to a GCM but provides a finer resolution. This method generates realistic climate information at a spatial resolution of approximately 2.5–50 kilometers. It is worth mentioning that since the RCM is integrated in a GCM, the overall quality of dynamically downscaled RCM output is tied to the accuracy of the large scale forcing of the GCM and its biases.

The main objective of this paper is to generate future weather files, using both statistical and dynamical downscaling techniques, to provide a quantification of the future trends of building energy demand for the city of Toronto. The generated future weather files are used to simulate 16 commercial reference building models developed by the United States Department of Energy (DOE) in support of ASHRAE Standard 90.1 [10]. In the following, the methods used for generating the future weather files as well as the building simulations are presented. The results are discussed in Section 3 and are followed by conclusions in Section 4.

2. Methods

Given the limitations of historically recorded weather data and the availability of long-term hourly time resolution for every location, two Canadian Weather Year for Energy Calculation (CWEC) files generated by Environment and Climate Change Canada were selected for this study [11]. On one hand, a CWEC file that spans a 30-year period of historical weather data (1959-1989) was chosen to provide a better representation of the historical climate. Alternatively, a more recent CWEC file, which spans from 1998-2014 was chosen to characterize the most current warming trends. The future weather data sets developed in this research were generated by statistical downscaling technique using two future weather generator tools, CCWorldWeatherGen and WeatherShift™, as well as a dynamical downscaling technique using one regional climate model, the HRM3-the Hadley Regional Model 3 (Figure 1).

![Flowchart](image-url)

**Figure 1.** Flowchart of various methods used for preparing high-resolution weather data suitable for generating future weather file for building performance simulation.
2.1 Preparing future weather data for building performance simulation

The Climate Change World Weather Generator (CCWorldWeatherGen) tool was developed by Jentsch et al. [9], who applied the morphing method using HadCM3 (Hadley Centre Coupled Model, version 3) forced with IPCC A2 emission scenario to generate EnergyPlus Weather (EPW) file. The HadCM3, A2 scenario, simulates changes in monthly values of climate condition relative to the 1961-1990 baseline years. The CCWorldWeatherGen tool superimposes these changes of the future climate on the meteorological parameters stored in Typical Meteorological Year (TMY). The original TMY files used were the CWEC data for Toronto, derived from the observations for the period of 1959-1989 and 1998-2014. The future weather files generated by this tool are for the 2041-2070 timeframe. In the case of CWEC file for the period of 1998-2014, as higher temperature values are observed compared to the 1961-1990 baseline year, an overestimation of the results in the morphed data set is expected.

The WeatherShift™ tool uses 14 GCMs (out of approximately 40 models) for its climate change projection and allows for the generation of future weather files relative to the 1976-2005 baseline years. The weather file generated for the period of 2056-2075 was chosen for the purpose of this work. This tool simulates and superimposes the changes in the future climate conditions, creating a future weather file by applying the morphing technique to its 14 GCMs. Moreover, the WeatherShift™ tool offers a cumulative distribution function (CDF) for each of the variables, allowing the users to assign a likelihood to the projections. The 50th CDF percentile along with the RCP 8.5 emission scenario were selected for generating future weather data sets based on the two CWEC files for Toronto.

This work used a dynamically downscaled RCM output developed under the North American Regional Climate Change Assessment Program (NARCCAP) to generate a future weather file by projecting climate change information based on the RCM [12]. Initially, modelled data for the coupled GCM-RCM (HadCM3-HRM3) were downloaded for five variables including surface air temperature, surface pressure, surface specific humidity, zonal surface wind speed, and meridional surface wind speed. These variables were selected due to their significance in projecting climate conditions in building energy performance. Cloud cover and solar radiation data were excluded due to limitations for the output data from the NARCCAP for cloud cover and solar radiation of the future climate. As a result, cloud cover and solar radiation of the future weather file were left at their initial TMY values. Extraction, correction and conversion of HRM3 data from NARCCAP to the appropriate input data for building performance simulation was done by Microsoft Excel and coding in Python. The HRM3 output for the five climate variables at a 3-hour resolution require changing the time-step to hourly data for building performance simulation. Linear interpolation was applied to 3-hourly data sets, generating hourly weather data for the periods of 1970-2000 and 2040-2070. Subsequently, the proper parameters used for building performance simulation such as relative humidity, dew-point temperature, wind speed, and wind direction that are not directly available from the HRM3 output data were calculated. To quantify the magnitude of climate change for each weather variable from the HRM3, the differences between the 2041-2070 values and 1971-2000 values were calculated for the interpolated hourly values. The differences between these two hourly data sets for all five variables were then averaged over the 30-year period for each month. Here, the morphing technique similar to that used by Belcher et al. [5] was used to “shift” the climatic variables in the present-day recorded weather data (CWEC files) to produce new weather data that illustrate the average projected climate change in the future.

2.2 Building energy performance simulation models

In order to assess building energy demand within a climate change perspective, 16 commercial reference building models developed by the United States Department of Energy (DOE) in compliance with ASHRAE 90.1-2013 standards were simulated. These building models are a relatively realistic representation of buildings and typical construction practices. They represent approximately 80% of the commercial building stock in the United States [10].

3. Results and discussion

Both the current and future weather files generated in this study were used as input for the building performance simulation. The impacts of different hourly weather files on total energy use intensity (EUI)
of each of 16 reference commercial building models are illustrated in Figure 2. For the historical 1959-1989 weather file the results indicated a future decrease in total EUI for all reference building models, except for large office (2.3-2.8 kWh/m² increase) and secondary school (0.2-0.8 kWh/m² increase) buildings. Similarly, the historical 1998-2014 weather file display a larger number of buildings experiencing a decrease in EUI in the future. Furthermore, the EUI associated with the quick-service and full-service restaurants show that the climate conditions are not the dominant force driving the energy use of these buildings.

![Figure 2](https://via.placeholder.com/150)

**Figure 2.** Total site energy use intensity (EUI). (a) 1959-1989 baseline years used for the future weather files generation. (b) 1998-2014 baseline years used for the future weather files generation.

The building simulations show that the impact of climate change varies significantly among different types of buildings. The results also suggest an average decrease of 17.8-27.2% in heating load and an average increase of 13.5-55.4% in cooling load percentages, depending on the building type, when compared to typical conditions of 1959-1989 (Figure 3). In fact, the decrease in heating load and increase in cooling load projections for the 1998-2014 baseline years are 17.9-33.4% and 12.9-53.3%, respectively. These projections are in line with the IPCC global mean surface temperature increase for the end of the century. However, due to the use of higher temperature values observed for the 1998-2014 years, the calculated cooling load is greater for the future weather files generated using the 1959-1989 baseline years.
Figure 3. Total heating and cooling loads. (a) 1959-1989 baseline years used for the future weather files generation. (b) 1998-2014 baseline years used for the future weather files generation.

It should be noted that the projections presented by WeatherShift™ tool are for the 2056-2075 period, which is slightly different from the CCWorldWeatherGen and the HRM3 period (2041-2070). Also, the WeatherShift™ tool uses a combination of 14 GCM for generating its future weather files that could explain the variation between their building energy projections. The weather files generated by HRM3 provide a finer spatial resolution and a better representation of the local climate conditions compared to the CCWorldWeatherGen tool which uses HadCM3. Therefore, the results generated by building performance simulation of the 16 reference building models for the HRM3 weather files offer a more reliable projection for the local climate change impact assessments.
4. Conclusions

The research described in this paper establishes the importance of considering future weather file for building performance simulation. According to the results, future weather files can demonstrate long-term impacts of climate change on building energy demand, and thus, a decrease in building heating load and an increase in building cooling load should be expected for the future. Both statistical and dynamical downscaling techniques provide adequate information on the long-term impacts of climate change on building energy performance. However, in statistical downscaling, it is evident that different TMY selected for the baseline period can project diverse future climate conditions. Thus, it is important to consider appropriate historical data periods for generating future weather file. Moreover, in dynamical downscaling, as assessment of building energy performance tends to focus on impacts of climate change at the local level, finer spatial resolution generated by RCM present a more reliable representation of the regional boundary conditions. Overall, the use of future weather file for building performance simulation is the only effective approach for the quantification of future trends of building energy demand influenced by climate change. Only then, applicable long-term strategies and policies in response to climate change can be developed.

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