Impact of temperature and moisture dependent conductivity of building insulation materials on estimating heating and cooling load using typical and historical weather data

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Abstract. This paper investigates the impact on heating and cooling load estimation when effective thermal conductivity of materials is incorporated into building energy simulation in conjunction with historical weather data. Under current practice, thermal performance of building envelope systems is usually represented by a lumped nominal conductivity value. In reality, effective conductivity is influenced by many factors such as temperature and moisture content. To minimize computing time, building energy simulation is also conducted with typical meteorological weather data, which is sufficient in estimating average energy use of buildings, but lacks the ability to truly reflect building performance under long term weather conditions. Preliminary research has been conducted by simulating a typical residential house in Toronto using WUFI plus - a comprehensive hygrothermal building simulation program. Historical CWEED - 1998 to 2014 weather data and typical weather files CWEC-1990s and 2016 have been used for this work. The results shows: 1) a reduced representativeness of typical weather data in building energy simulation as climate changes over time; 2) estimation using typical weather data is not representative of any individual historical year and 3) performance of insulation materials changes when temperature and moisture dependent conductivity is considered and affects the results of building energy simulation.

1. Introduction
Current energy simulation practice uses constant material properties[1] and typical year weather data [2][3][4][5][6]. The creation and use of typical year weather data was necessary from a time when computational power and simulation time are limited [6]. The frequent occurrence of malfunction in weather instruments and communication equipment is also a factor, since months with missing weather data can be eliminated from the statistical based selection method for typical weather year when data gap filling is not performed[7]. While the use of typical weather data is usually sufficient for comparative analysis between different building designs, it lacks the ability to represent weather extremities and the expanded set of weather conditions contained in historical weather datasets[4][5][6], which may be important for net zero energy building designs[5]. Prior studies[2][3][4] have compared results from energy simulation of various building types using typical (1 year) and historical (multi-year) weather datasets, and have generally concluded with similar findings: 1) average total energy usage estimations are similar when both typical and historical weather data is derived from the same dataset and 2) peak energy load estimations have greater deviation. Studies [2] and [4] also found that buildings in colder climate observe greater discrepancies in simulation results.

The use of nominal thermal conductivity also stems from a need for model simplification when computing power was limited. Under current practice, measurements of thermal conductivity are generally completed in a lab environment where insulation material is preconditioned to its dry state, conductivity values are then measured at a set mean temperature and temperature differential at steady
state[8]. In North America, thermal conductivity is typically measured only at a mean temperature of 24 °C, which originates from the standardized reporting practice by the FTC R-value Rule developed in the 1970s[9]. Whereas in Europe, conductivity is typically measured at a mean temperature of 10 °C[10]. Beyond being a conventional practice, the scientific rationale supporting the selection of the determined set mean temperature is unclear in the reviewed literatures. Nevertheless, the use of reported conductivity values should be appropriate if the performance of material measured under the prescribed environment is representative of the range of operating conditions, and the insulation layer remains dry throughout its service life. However, from industry experience and research in the academia, it is evident that neither could be true under real application. Research on temperature and moisture dependency of thermal conductivity in building insulation materials has been conducted by prior studies [10][11][12][13], with its significance recognized in standards ISO 8301[14] and ASTM C1058[15]. Prior research also investigated the impact of temperature dependent thermal conductivity of insulation materials in external wall and flat roof application under Canadian climate, which showed conductivity of building envelope systems may fluctuate with changes in outdoor temperature[1]. However, comprehensive temperature and moisture dependent conductivity values are typically not included in common building material properties references used in North America, such as the ASHRAE handbook of fundamentals [16]. Moisture management is also a recurring issue in the North American building stock, in which best practices typically assume moisture may enter through various mechanisms such as bulk water penetration, vapor diffusion, and capillary suction, indicating the presence of moisture in a building envelope system is generally expected under current building design and craftsmanship [17].

Accurate estimation of heating and cooling demand is important for equipment sizing, especially for net zero energy buildings, where performance of renewable energy systems may be impacted[5]. Prediction of building condition through simulation also relies on accurate weather and material property inputs. The goal of this study is 1) to investigate whether typical weather data is representative of historical weather data in the context of building energy simulation when both heat and mass transfer is considered and 2) the impact of disregarding temperature and moisture dependent conductivity on heating and cooling demand estimation when historical weather data is used.

2. Methodology
To illustrate the impact of temperature and moisture dependent conductivity, WUFI plus V.3.1.1.0 - a building energy simulation package with a comprehensive heat and mass transfer engine and material database with hygrothermal properties is used [18]. A typical two-story house with 2” by 4” wood frame construction, commonly found in the Greater Toronto Area is simulated. The total floor area is 198m². There are two input variable changes in this study - insulation material and weather files. Other input variables such as ventilation and infiltration rates are maintained at the default values defined in WUFI plus; internal loads and schedules are selected from the default database; and HVAC system is assumed to supply ideal load. Due to the scope of this paper, exact values are not included in the current discussion. Please also note that vapor control layers (such as vapor retarders) are not included in this analysis, which means vapor can migrate in or out of the building envelope more freely.

Two cellulose fiber insulation materials are selected for comparison, they are selected from the built-in WUFI material database which contains properties from multiple sources. Properties of Cellulose A are from the Fraunhofer IBP database [18], whereas properties of Cellulose B are from the ASHRAE 1080-RP[8]. They are selected for this study because even though both materials are labelled as cellulose fiber, their properties have obvious differences. Notably, the thermal conductivity of Cellulose A is both temperature and moisture dependent, whereas Cellulose B is only dependent on temperature. It is worth noting that Cellulose B has greater moisture sorption capacity, as indicated in the relatively less drastic rate of change towards the end of the moisture sorption curve. Cellulose B also has a relative humidity dependent diffusion resistance factor, in which diffusion resistance decreases with relative humidity, whereas Cellulose A’s remains constant. Since Cellulose A and B have different characteristics in their properties, a direct comparison on the resulted heating energy and peak load estimations would not yield meaningful results. To illustrate the impact of disregarding
the temperature and/or moisture dependent thermal conductivity, two materials (Cellulose A-c10/A-c24 and Cellulose B-c10/B-c24) are derived from Cellulose A and B where thermal conductivity is set to remain constant at the value measured at 10°C and 24°C.

Two types of weather files are compared in this study - Typical Year (TY) and Historical Year (HY). The Canadian Weather Energy Engineering Dataset (CWEED - HY) is released by Environment and Climate Canada, and there were 3 major releases in the past – in 1993, 2005 and 2016[7]. Unlike raw daily weather data, CWEED datasets fills in missing data fields through interpolation, solar radiation estimations are also added by methods described in [7]. The Canadian Weather Year for Energy Calculation (CWEC - TY) is created from CWEED datasets based on the TMY selection method developed by the Sandia National Laboratory [7]. For this study, simulations are completed with the CWEED data for the period between 1998 and 2014 from the Toronto Pearson Airport weather station (43.67N, 79.63W). The original dataset was in WYEC3 format [7], which is not compatible with most simulation packages, conversion to the more popular EPW format [19] is completed prior to simulation. Simulation results using HY weather data are compared with results using 2 versions of CWEC TY weather files – CWEC 1990s and CWEC 2016. CWEC 1990s is currently available on the EnergyPlus website [20], it is assembled with weather data from 1953 to 1995[21]. CWEC 2016 is currently available through Environment and Climate Change Canada[22] and is assembled with weather data from 1998 to 2014[7]. The comparison with two generations of TY weather files is to show how simulation results can be affected with changes in climate.

The metrics compared in this study are: 1) total heating and cooling energy, which is defined as the heating and cooling energy needed to maintain the conditioned spaces at the design condition temperature range, which is between 20°C and 27 °C; and 2) the peak heating and cooling, which is defined as the maximum hourly heating and cooling power required to maintain the conditioned spaces at the design condition temperature range.

3. Results and Discussion

3.1. Comparison of results between simulation using historical weather data and typical weather data

| Table 1. Total Heating and Cooling Differences |
|-----------------------------------------------|
| HY(1998 to 2014) Vs TY(2016 Version) - Cellulose A | 0.99% | -1.35% |
| HY(1998 to 2014) Vs TY(2016 Version) - Cellulose B | 1.04% | -1.12% |
| HY(1998 to 2014) Vs TY(1990s Version) - Cellulose A | -14.63% | 36.26% |
| HY(1998 to 2014) Vs TY(1990s Version) - Cellulose B | -14.78% | 33.53% |

The total heating and cooling energy estimation (see Table 1) using CWEC 2016 is close to the estimation using historical year simulation, in which difference is between 0.99% to 1.04% overestimation in total heating energy, and between 1.12% to 1.35% underestimation in total cooling energy. The results from simulation using CWEC1990s is significantly different from the historical year simulation, where estimation in total heating energy is between 14.63% and 14.78% underestimation and estimation in total cooling energy is 33.53% to 36.26% overestimation. The large difference observed in comparing results from two different generations of Typical Year weather files indicates that climate at the location is changing and the representativeness of Typical Year weather reduces over time.

3.2. Comparison of yearly total heating/cooling demand and peak heating/cooling load.

Unlike comparison in the aggregated total of heating and cooling energy, the year to year estimations show large discrepancies even when the most updated typical year weather file is used. For Cellulose A (see Table 2), difference in yearly total heating energy estimation is between underestimation of 17.24% and over estimation of 15.65%, whereas differences in yearly total cooling energy estimation is between underestimation of 23.57% and overestimation of 30.96%. Simulation using Cellulose B exhibit similar differences, hence results is not shown in this paper. This indicates that simulation using typical year weather data may not represent actual usage of any individual year, which resonates with findings in prior studies[2][4][5]. The estimation of yearly peak heating and cooling load also
shows large discrepancies, except for the year where the heating or cooling dominating month is selected to be in the TY weather file.

### Table 2. Cellulose A - Yearly total heating/cooling demand and peak heating/cooling load.

| Weather File | Year | Total Heating Energy [kW] | % Difference with Typical | Total Cooling Energy [kW] | % Difference with Typical | Peak Heating [kW] | % Difference with Typical | Peak Cooling [kW] | % Difference with Typical |
|--------------|------|---------------------------|---------------------------|---------------------------|---------------------------|------------------|---------------------------|------------------|---------------------------|
| HY-CWED 1998| 15155| -15.65%                   | 5243.2                    | 8.23%                     | 10.73                     | -19.50%          | 9.07                      | -9.66%           |                          |
| HY-CWED 1999| 16895.9| -5.96%                    | 5836.9                    | 10.72%                    | 13.45                     | 0.75%            | 10.05                     | 0.10%            |                          |
| HY-CWED 2000| 18342.6| 3.23%                     | 3665.3                    | -24.34%                   | 12.39                     | -7.05%           | 8.52                      | 0.37%            | -15.14%                   |
| HY-CWED 2001| 16306.9| -9.34%                    | 4958.8                    | 2.36%                     | 11.0                      | -10.73%          | 10.27                     | 2.29%            |                          |
| HY-CWED 2002| 17699.7| -1.99%                    | 5845.2                    | 20.66%                    | 10.9                      | -18.23%          | 10.15                     | 1.10%            |                          |
| HY-CWED 2003| 19997.6| 11.30%                    | 4183.2                    | -13.65%                   | 12.61                     | -5.40%           | 9.59                      | -4.48%           |                          |
| HY-CWED 2004| 19304.2| 7.44%                     | 3534.6                    | -27.25%                   | 13.37                     | 0.50%            | 9.32                      | -7.17%           |                          |
| HY-CWED 2005| 19694.7| 9.62%                     | 5986.3                    | 23.57%                    | 12.93                     | -3.00%           | 9.64                      | -3.98%           |                          |
| HY-CWED 2006| 16194.6| -9.86%                    | 4654.3                    | -3.93%                    | 10.15                     | -23.86%          | 10.54                     | 4.98%            |                          |
| HY-CWED 2007| 19430.3| 8.20%                     | 5486.2                    | 13.25%                    | 12.07                     | -9.45%           | 9.89                      | -1.49%           |                          |
| HY-CWED 2008| 19202.4| 6.88%                     | 3952.3                    | -18.42%                   | 11.49                     | -13.80%          | 8.98                      | -10.50%          |                          |
| HY-CWED 2009| 18752.8| 4.37%                     | 3446.6                    | -30.96%                   | 12.27                     | -7.95%           | 8.50                      | -15.34%          |                          |
| HY-CWED 2010| 17536.4| -2.40%                    | 5276.1                    | 8.91%                     | 11.65                     | -12.60%          | 9.60                      | -4.33%           |                          |
| HY-CWED 2011| 18161.7| 1.08%                     | 5115                      | 5.58%                     | 12.37                     | -7.20%           | 10.44                     | 3.98%            |                          |
| HY-CWED 2012| 15532.1| -13.59%                   | 5904.7                    | 21.88%                    | 11.06                     | -17.03%          | 10.05                     | 0.10%            |                          |
| HY-CWED 2013| 19064.1| 6.11%                     | 4581.6                    | -5.43%                    | 12.14                     | -8.93%           | 10.04                     | 0.00%            |                          |
| HY-CWED 2014| 21064.5| 17.24%                    | 4160.7                    | -14.11%                   | 13.57                     | 1.80%            | 8.82                      | -12.15%          |                          |

**TY-CWEC 2014 version**

### Table 3. Comparison between Cellulose A/B and Cellulose A-c24/B-c24.

| Weather File | Year | Total Heating energy % Difference | Total Cooling-energy % Difference | Total Heating energy % Difference | Total Cooling-energy % Difference |
|--------------|------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| HY-CWED      | 15155| -15.65%                           | -1.88%                           | -1.88%                           | 0.00%                            |
| HY-CWED      | 16895.9| -5.96%                           | -1.92%                           | -1.92%                           | 0.21%                            |
| HY-CWED      | 18342.6| 3.23%                           | -1.95%                           | -1.95%                           | 0.20%                            |
| HY-CWED      | 16306.9| -9.34%                           | -1.87%                           | -1.87%                           | 0.20%                            |
| HY-CWED      | 17699.7| -1.99%                           | -1.85%                           | -1.85%                           | 0.12%                            |
| HY-CWED      | 19997.6| 11.30%                           | -1.95%                           | -1.95%                           | 0.20%                            |
| HY-CWED      | 19304.2| 7.44%                           | -1.92%                           | -1.92%                           | 0.24%                            |
| HY-CWED      | 19694.7| 9.62%                           | -1.90%                           | -1.90%                           | 0.15%                            |
| HY-CWED      | 16194.6| -9.86%                           | -1.79%                           | -1.79%                           | 0.18%                            |
| HY-CWED      | 19430.3| 8.20%                           | -1.88%                           | -1.88%                           | 0.15%                            |
| HY-CWED      | 19202.4| 6.88%                           | -1.87%                           | -1.87%                           | 0.21%                            |
| HY-CWED      | 18752.8| 4.37%                           | -1.90%                           | -1.90%                           | 0.15%                            |
| HY-CWED      | 17536.4| -2.40%                           | -1.75%                           | -1.75%                           | 0.15%                            |
| HY-CWED      | 18161.7| 1.08%                           | -1.89%                           | -1.89%                           | 0.20%                            |
| HY-CWED      | 15532.1| -13.59%                          | -1.90%                           | -1.90%                           | 0.18%                            |
| HY-CWED      | 19064.1| 6.11%                           | -1.87%                           | -1.87%                           | 0.21%                            |
| HY-CWED      | 21064.5| 17.24%                          | -1.90%                           | -1.90%                           | 0.18%                            |

### As mentioned in the methodology, thermal conductivity of Cellulose A varies with both temperature and moisture content, whereas Cellulose B only varies with temperature. The comparison between simulation results (see Table 3) using Cellulose A and Cellulose B with their derived form with constant thermal conductivity - Cellulose A-c24 and Cellulose B-c24 shows the impact of disregarding these effects. The most apparent difference between the two sets of results is the yearly heating energy estimation of Cellulose A being consistently greater than Cellulose A-c24 which has constant thermal conductivity, whereas the estimation with Cellulose B is consistently lower than Cellulose B-c24. This indicates that moisture contained in the insulation layer does affect the heating energy estimation and could be the result of moisture migration into the building envelope without any vapor barrier. To further examine the effects of moisture dependent thermal conductivity, hourly heating requirement between hour 24 and hour 36 of the simulation year using CWEC 2016 weather file (see Figure 1) is analyzed. The results show the heating estimation using Cellulose A could be greater than the heating estimation using both Cellulose A-c10 and Cellulose A-c24. This is contrary to the common belief that conductivity of insulation material in cold climates would be closer to the conductivity measured at a mean temperature of 10°C, which is exhibited in the results of Cellulose B (see Figure 2) when conductivity only varies with temperature and heating estimation is closer to the estimation using Cellulose B-c10.
4. Conclusions
The results of this study showed the representativeness of typical weather files can reduce as climate changes over time. This may be an issue with increasing rate of climate change, as typical year weather files are generally not updated frequently, and they are always created from historical weather data from previous decades. Energy modelers should be cautious about the time range of the weather data selected to create typical weather datasets and determine whether the weather data is appropriate for the intended building simulation. Typical weather data may also not represent any individual year as indicated in the large discrepancies between the results from typical and individual historical year simulation. Energy modelers should determine whether the weather condition included in the representative months contain sufficient weather variations for the intended analysis as this is also suggested by prior research. Thermal conductivity can exhibit different characteristics when it varies with both temperature and moisture content, the conventional practice of using constant conductivity measured at its dry state may not be sufficient in representing the performance of insulation materials in real application where moisture is present. Further investigation will be conducted on the following: 1) evaluate the yearly reduction in the representativeness of typical year weather data, and determine whether simulation using the most updated historical weather years may generate more insight for some application; 2) evaluate the impact of temperature and moisture dependent thermal conductivity in more building types and envelope designs to expand representativeness.

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