# Examining Moisture Reference Years and Future Weather for Hygrothermal Analysis

Daniel Chung
University of Toronto, Toronto, Canada

## Abstract

This paper will present research exploring simulated hygrothermal outcomes for building envelopes using historic, future, and reference year weather. Four common wood framed cavity walls are examined in Philadelphia and Chicago using weather from 1998 through 2013 as well as projected weather for 2050 and 2080. Varying air infiltration rates and starting months are stochastically employed to better characterize the distribution of possible outcomes for the studied wall assemblies. Results show that starting month has a high impact on predicted moisture related outcomes and that trends from hygrothermal results from historic weather years may not repeat themselves when transformed to future weather years.

## Introduction

Buildings, their construction and operation, represent significant economic commitments, and their design can impact occupant productivity. In addition to capital costs, buildings have substantial impact on energy consumption and global warming. Building operation and the building construction sector are attributed to annually consuming 38% of global energy and also producing 40% of all green house gas emissions (González-Torres, Pérez-Lombard et al. 2022). Building energy and operation are strongly influenced by weather and climate. As the majority of buildings provide shelter and thermal separation between the outdoor and indoor environment, climate change has been predicted to impact how buildings perform. As a thermal separator, building envelopes are strongly connected to the energy performance of buildings and are often a leading cost category for overall building costs (DOE 2015). Building envelopes and construction materials are known to influence indoor air quality. Off gassing of materials and bacterial growth in buildings due to high levels of moisture are known to create negative health impacts (Xiong, Zhang et al. 2011). Mould and decay of wooden materials is known to occur in envelope assemblies when temperature and moisture conditions favourable to mould growth occur. Hygrothermal simulations can be performed to predict the moisture content, temperature, relative humidity, and possible mould growth in building envelopes (Sadovsky, Koronthalyova et al. 2013).

However, variations in envelope construction and weather profiles can make it difficult to generalize whether a given envelope assembly is at risk for moisture related damage. Given the concurrent issues of mould growth, climate change, and uncertainty this paper reports on a study that examines the relative impact of past, future, and moisture reference year weather on moisture related outcomes of four common wood framed cavity walls using stochastic and parametric methods to include variability of air infiltration, weather years, and starting months. The remainder of this paper is divided into four sections. 1) Background: this section will provide key contextual information for the paper. 2) Methodology: provides details on how the project was performed, 3) Results and discussion, and 4) Conclusion.

## Background

Hygrothermal analysis is the physics-based prediction of heat, air, and moisture (H.A.M.) transport in building envelopes. Numerical analysis of H.A.M. transport has been standardized under the European Standard EN15026: *Hygrothermal performance of building components and building elements – Assessment of moisture transfer by numerical simulation* (15026 2007). EN15026 provides the fundamental interacting equations that are generally used in modern hygrothermal software (15026 2007). HAM-Tools is an open source hygrothermal analysis tool developed by Angela K. at Chalmers University and has been used by researchers to study envelope H.A.M. behaviour (Sasic Kalagasidis 2004). HAM-Tools is built within the MATLAB and Simulink (Mathworks 2015) computing environments and as such can be modified and coupled with other analyses and tools.

While EN15026 provides the numerical requirements for hygrothermal analysis, ASHRAE standard 160: *Criteria for Moisture-Control Design Analysis in Buildings* (ASHRAE 2021) provides the criteria for modelling envelopes and is widely referenced by building envelope professionals in North America. ASHRAE 160 provides the detailed methods of how to define the boundary conditions for hygrothermal analysis including wind-driven rain, weather

data, and indoor temperature and relative humidity. ASHRAE 160 also provides criteria to evaluate mould growth and corrosion risks from hygrothermal analysis results.

Mould growth on building materials have been studied by researchers (Salonvaara, Zhang et al. 2011, Chung and Wen 2019, Brambilla and Sangiorgio 2020). Studies have shown that mould growth is highly dependent on the substrate, temperature, and relative humidity. Researchers have developed predictive models for mould growth that are used in building envelope risk analysis. ASHRAE 160 includes the use of a mould growth model known as the VTT model (Viitanen, Krus et al. 2015). This model determines a mould growth index value between zero and six. A mould index value of zero predicts that no mould growth will occur. A mould index value of three predicts that mould growth will occur and can be visible when in close proximity without magnification (Viitanen, Vinha et al. 2011). A mould growth index value of six predicts a growth that is easily visible and tightly covers the substrate. ASHRAE 160 list a criterion of keeping envelopes to a mould index value of less than three to limit the negative impact of mould growth on building envelopes.

Weather data is used in H.A.M. analysis to provide the outdoor boundary conditions and typically include, dry-bulb air temperature, relative humidity (or dew point temperature), solar radiation, windspeed, wind direction, and precipitation. ASHRAE 160 prescribes the use of hourly weather data for either a moisture reference year or ten consecutive years of weather data. There have been multiple methods for selecting moisture reference years. Wetting Index, Drying Index, and Moisture Index methods, developed by European researchers have tried to use annual weather data to select appropriate weather years for hygrothermal analyses (Cornick, Djebbar et al. 2003).

ASHRAE Research Project Report RP-1325 Environmental Weather Loads for Hygrothermal Analysis and Design of Buildings (Salonvaara, Zhang et al. 2011) studied these methods in the context of North American cities and found that they were not well suited for the envelope assemblies and weather in North America. The researchers developed a new methodology for ranking historic weather years for a given location to determine an appropriate moisture reference year. The method examines thirty years of recent weather data for a given location and scores them using a damage function referenced in the literature as RHT(70). The damage function is the result of a multi-step regression analysis when performing hydrothermal simulations on the historic weather years on two typical wall assemblies. The three historic weather years with the highest RHT(70) scores are then selected as Year 1, Year 2, and Year 3 and used as reference years for hygrothermal simulations. These weather years are included as ASHRAE Years 1, 2, and 3 in the popular WUFI Pro (Zirkelbach, Schmidt et al. 2007) software for 100 North American cities.

Previous studies have shown that in addition to selecting an appropriate weather year, the starting month of the hygrothermal simulation can have a significant impact on moisture outcomes (Chung, Wen et al. 2023). This is due to the practice of setting the starting moisture content of the materials to be aligned with the equilibrium moisture content that would occur at 80% relative humidity. This is done to account for built-in moisture that would occur during construction when envelope assembly materials are exposed to the outdoor weather including rain. When the assembly has a high built-in moisture content, condensation and/or mould growth can be accelerated in the starting months.

The International Panel on Climate Change (IPCC) has studied predicted changes in weather in future years based on expected greenhouse gas emissions. Researchers have adapted these large regional climate circulation models to develop future weather files for building simulation uses to estimate building performance in future years. The process of generating future weather files typically utilizes existing historic weather or typical meteorological years and transforms them to a future scenario. This transformation often involves stretching and/or shifting historic weather data based on future climate models. In this way the patterns of weather remain intact while the amplitude and magnitude are modified.

Moisture movement in hygrothermal analysis can be greatly influenced by air infiltration and air movement through the envelope. As a potential source of moisture and drying, air movement through the envelope is an important parameter. As most hygrothermal software tools are designed as one-dimensional tools there has been some difficulty incorporating air flows through envelopes, as the actual air movement is two or three dimensional. Researchers have studied methods of numerically approximating convective air movement through envelopes within one-dimensional hygrothermal analysis based on experimental observations and have determined that using thin air layers located strategically inside the assembly which exchange air with both the indoor and the outdoor air is appropriate. The US Department of Energy's Building Technology Office (USDOEBTO) has published a guideline (Lstiburek, Ueno et al. 2016) which includes procedures on how to model this air movement through envelopes when using WUFI Pro software.

Stochastic methods, probability, and uncertainty have been increasingly explored by researchers in the building science community (Hagentoft, Ramos et al. 2015) as they can help provide a more robust understanding of predicted outcomes. Researchers have shown that weather years, starting month, and air infiltration are significant contributors to envelope moisture outcomes (Chung, Wen et al. 2023). Varying these input parameters allows for a more robust understanding of the potential risks of moisture outcomes.

## Methodology

This section provides the methodology used to study the relative impact of past, future, and moisture reference year weather on predicted building envelope moisture outcomes of four common wood framed cavity walls. This includes the steps the project uses to vary air infiltration, weather years, and starting months in hygrothermal simulations.

As wood framed cavity walls are amongst the most frequently constructed envelope systems for contemporary residential construction in North America they are used as the wall assemblies in this study. Four different wood framed wall configurations are examined and are listed in the Table 1 below. Table 2 shows the material thickness and properties of the assemblies used in the simulations. Figures 1 and 2 present wall sections of two of the assemblies used in the study. Two insulation types (fiberglass and closed cell spray polyurethane foam - ccSPF) and two cladding types (brick and wood siding) are included. All four assemblies use plywood sheathing, spun bonded polyolefin, a class I vapour retarder (0.1 perm), and painted gypsum wall board. The hygrothermal modelling follows the same methods as listed in USDOEBTO guidelines which have been previously incorporated into models created in HAM-Tools (Chung, Wen et al. 2020) and when compared to WUFI Pro models has produced nearly matching results. HAM-Tools is used as the modelling platform in this project as HAM-Tools allows for customization within MATLAB and Simulink that facilitates large numbers of simulation trials used in stochastic and parametric methods. This study uses the variation of air infiltration rates, weather years, and starting months to examine the potential risks of high envelope moisture content.

Weather data for this study was collected for Philadelphia, Pennsylvania and Chicago, Illinois in the United States. Both locations experience cold winters, hot and humid summers, significant annual precipitation, and have substantial wood framed building stock that are representative of the wall assemblies used in this study. Weather for 1998-2013 was downloaded from the National Oceanic and Atmospheric Administration (NOAA) website. While additional weather years were available, they lacked rain data that is needed for hygrothermal assessments for the two locations in this study. Often weather files that have been created for building energy modelling or other uses do not contain rainfall data and instead have precipitable water, which is the amount of water in the atmosphere that could become precipitation. As wind-driven rain is one of the most important input parameters when assessing envelope moisture risks this study only used weather files that had appropriate hourly rain data. The moisture reference years created by ASHRAE RP-1325 are used within this study for both Philadelphia and Chicago. ASHRAE RP-1325 reportedly selected these years from 1960-1990 weather years. As such the 1998-2013 weather years do not overlap with the ASHRAE moisture reference years and instead

Table 1. List of modelling assembly scenarios and materials

| Scenario # | Exterior Cladding | Water + Air barrier | Sheathing | Insulation | vapor retarder | Interior Material |
|---|---|---|---|---|---|---|
| 1 | Brick + 25mm air gap | Spun Bonded Polyolefin Membrane | Plywood | Fiberglass | Class I Vapour Retarder, Polyethylene sheet (5.72 $ng \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}$) | Gypsum Wall Board |
| 2 | | | | ccSPF | | |
| 3 | Composite Wood siding + 5mm air gap | | | Fiberglass | | |
| 4 | | | | ccSPF | | |

Table 2. List of Material, their properties and thickness for modeling scenarios

| Material | density [$kg/m^3$] | thermal conductivity [W/mK] | vapor resistance factor [-] | Capillary Saturation [$kg/m^3$] | max. liquid transport coefficient [$m^2/s$] | Thickness [mm] |
|---|---|---|---|---|---|---|
| Brick | 1935 | 0.495 | 137.8 | 56.115 | 1.53E-9 | 92.08 |
| Composite wood siding | 740 | 0.094 | 53.1 | 347 | 1.64E-11 | 9.53 |
| Plywood (USA) | 470 | 0.084 | 1078.2 | 550 | 2.22E-10 | 15.88 |
| Spun Bonded Polyolefin Membrane | 65 | 2.3 | 49.3 | 0.0471 | 0 | 139.7 |
| Fiberglass | 30 | 0.035 | 1.3 | 46.7 | 0 | 139.7 |
| ccSPF | 39 | 0.025 | 88.93 | 28 | 0 | 139.7 |
| vapor retarder | 130 | 2.3 | 33025.6 | 0.0471 | 0 | 0.15 |
| Gypsum Wall Board | 625 | 0.706 | 7.03 | 430.6243 | 8.46E-07 | 12.7 |

Note that thicknesses listed are derived from standard building materials available in North America that use fractional inches.

provide a more recent historical set of years for assessment. In practice in North America it is difficult for most users to obtain 30 years of consecutive weather data for one location ready for use in hygrothermal software without purchasing a service to aggregate and format them, even then complete sets of data may not exist. As such many simply rely on using the moisture reference years built into software tools.

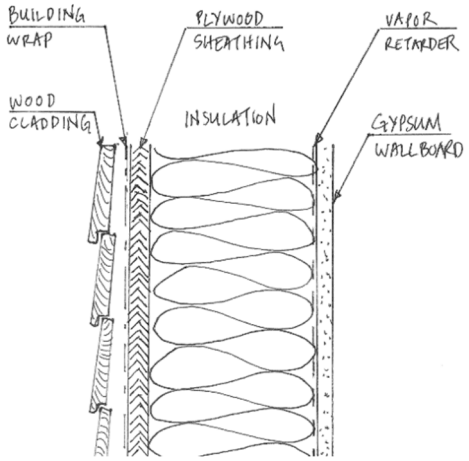


*Figure 1. Wall Assembly Scenario 3 (SC3)*

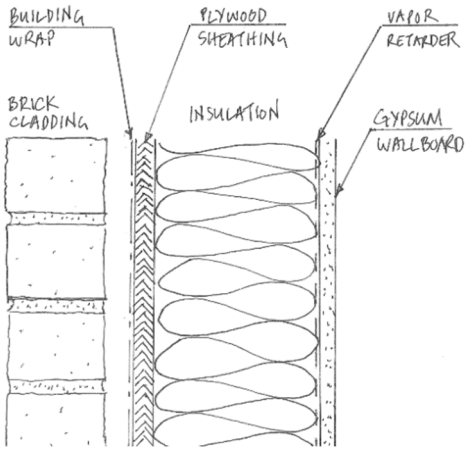


*Figure 2. Wall Assembly Scenario 1 (SC1)*

Previous studies have shown that when using stochastic methods two-year simulation periods provide a comparably effective duration to evaluate moisture risks when compared to ten-year simulation periods for hygrothermal modelling. As such this study uses two-year simulation periods by selecting 24-consecutive months starting with January 1998 and ending with December 2013. This provides 169 historic two-year simulation periods for each location. When using the ASHRAE RP-1325 moisture reference years these are also simulated for two-years by repeating the year. For each moisture reference year there are twelve starting months and thus twelve two-year simulation periods for each location.

Future moisture reference years are not readily available in most hygrothermal software tools. CCWorldWeatherGen is a software tool based on the HadCM coupled climate model and can be used to create 2050 and 2080 weather files (Jentsch 2012). As such the methodology used in CCWorldWeatherGen is used in this study to transform historic and reference year weather to future 2050 and 2080 weather scenarios.

Rain penetration and air flow through the envelope due to ventilated cladding and air infiltration are incorporated in the HAM-Tools models using the methodology prescribed in the USDOEBTO guidelines and have been previously described in detail when integrated with HAM-Tools (Chung, Wen et al. 2020). Air infiltration rates are varied using a log normal distribution published by researcher who examined the composition of previous air infiltration survey studies and extrapolated the infiltration to the general US building stock at large. The air infiltration rate is estimated to have a geometric mean of 0.44 air changes per hour and and geometric standard deviation of 2.14 air changes per hour (El Orch, Stephens et al. 2014). Historic weather and starting month are sampled uniformly. Given the variation of weather and air infiltration, the air infiltration rate has been sampled at the 5$^{th}$, 50$^{th}$, and 95$^{th}$ percentile values and applied to the weather years.

For each location, four assemblies, three time periods (historic, 2050, 2080), three air infiltration rates, and the historic and reference weather data were used to perform HAM-Tools simulations. A total of 6,516 2-year simulation trials were performed for each location.

## Results

Figure 3 presents the results for the Philadelphia simulations in box and whisker plots starting with maximum moisture content in the top portion (blue), maximum mould index value in the middle portion (green), and highest annual hours exceeding corrosion criterion at the bottom (orange). Results are grouped by wall assembly with scenario 1 (SC1) on the left, and scenario 4 (SC4). Figure 4 presents the results for the Chicago simulations in box and whisker plots and is arrange in the same manner as in Figure 3.

Maximum moisture content, mould growth, and corrosion analysis results are focused on the plywood sheathing layer of the assemblies. For cold climate buildings, the sheathing layer is the location most likely to have moisture damage in a cavity wall wood framed assembly that uses insulation in the cavity. This is because when it is cold outside and warmer inside, the sheathing layer is on the cold side of the insulation and a likely surface for condensation to occur when air from the inside leaks towards the outside. The mould and corrosion results presented in this paper are determined at the inside facing surface of the sheathing layer.

Looking at both Figures 3 and 4, it is clear that using a variable starting month and air infiltration rate, results in a much larger range of outcomes than using a deterministic simulation with an average infiltration rate and a simulation period starting in January. When comparing the range of

moisture content outcomes from simulations using variable starting months, the reference year results show similar ranges as the historic (1998-2013) results for Philadelphia.

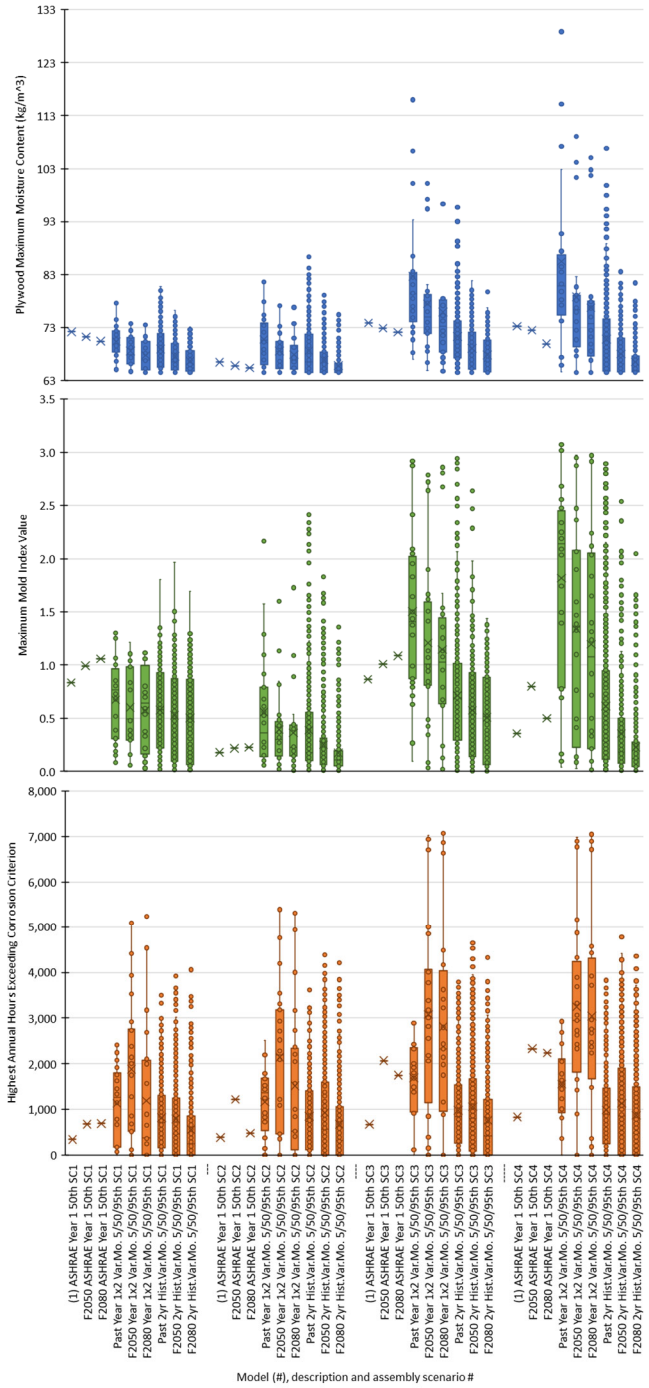


*Figure 3. Philadelphia hygrothermal results, 4 assemblies, historic and future weather years. SC1 denotes brick cladding with fiberglass, SC2 denotes brick cladding with ccSPF, SC3 denotes wood siding with fiberglass, SC4 denotes wood siding with ccSPF, Year 1 denotes ASHRAE RP-1325 weather year, Var.Mo. denotes variable starting month.*

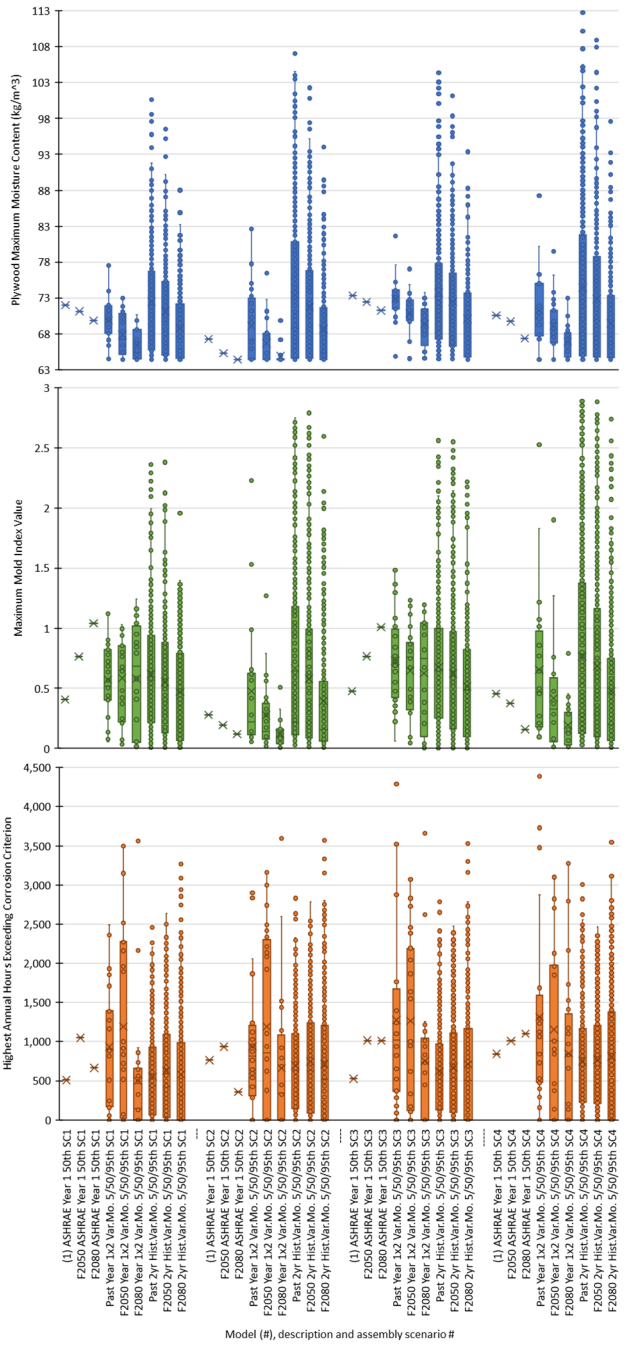


*Figure 4. Chicago hygrothermal results, 4 assemblies, historic and future weather years. SC1 denotes brick cladding with fiberglass, SC2 denotes brick cladding with ccSPF, SC3 denotes wood siding with fiberglass, SC4 denotes wood siding with ccSPF, Year 1 denotes ASHRAE RP-1325 weather year, Var.Mo. denotes variable starting month*

For Chicago, the moisture content and mould results from reference year simulations are generally much lower than the historic (1998-2013) simulations. From these results it appears that deterministic and reference year analysis may underpredict moisture risks.

When viewing the results, the overall performance of the brick clad ventilate walls (SC1 and SC2) in comparison to the wood clad ventilate walls (SC3 and SC4), the brick clad assemblies generally have lower moisture content for the two cities. Philadelphia's brick clad assemblies have a much tighter range of outcomes for moisture content. This is interesting as Philadelphia has a higher amount of average annual rainfall than Chicago.

Examining the overall performance of the walls with fiberglass insulation (SC1 and SC3) in comparison to the walls with ccSPF (SC2 and SC4), it appears that the ccSPF walls have lower predicted moisture content when using the ASHRAE RP-1325 reference year. However, the opposite appears to be the case when assessing the simulations using the 1998-2013 weather years.

When comparing the location, the results appear to show that Chicago has overall lower maximum moisture content, mould index values, and risk of corrosion than Philadelphia for the walls studied. While Chicago has colder temperatures than Philadelphia, Philadelphia typically has a larger amount of annual rainfall, which may explain the location differences.

When examining the results between historic and future weather scenarios, the figures show that for the reference years, the 2050 and 2080 moisture content results are progressively lower. This trend appears in the variable starting month studies whether using reference year or historic years. Surprisingly though, the predicted maximum mould index value for more than half of the wall assembly scenarios shows an increase in value for 2050 and 2080 simulations when using the reference year. When using the historic years, the range of maximum mould index values appears to decrease. This could be due to the fact that the reference year analyses use a repeating year, whereas the historic year analyses use two consecutive years of actual weather data (not repeated).

Previous research has shown that for some wood framed wall assemblies, increased air infiltration can lead to higher ranges of maximum moisture content within the sheathing layer (Chung, Wen et al. 2023). The results in Figure 5 appear to reinforce that statement. Figure 5 plots the maximum moisture content ranges for wall assembly SC3 in Chicago and groups the results according to time period (past, 2050, 2080) and air infiltration rates (5th, 50th, and 95th percentiles). One can see again that for the same air infiltration rate the future moisture content results are lower than the past results. Likewise, for the same time period, the higher the air infiltration rate the higher the range of moisture content.

Figure 6 shows an interesting result when looking at the same wall assembly and location, but this time for mould index value. This time the relationship between air infiltration and mould growth does not appear always positively correlated.

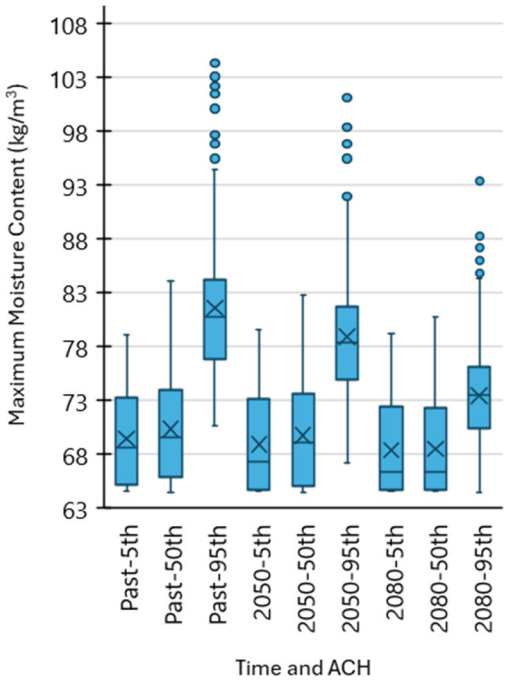


*Figure 5. Chicago, wall assembly #3 (SC3) maximum moisture content in sheathing plotted with varying air infiltration and time period, Past=1998-2013, 2050=Past transformed to 2050, 2080=Past transformed to 2080*

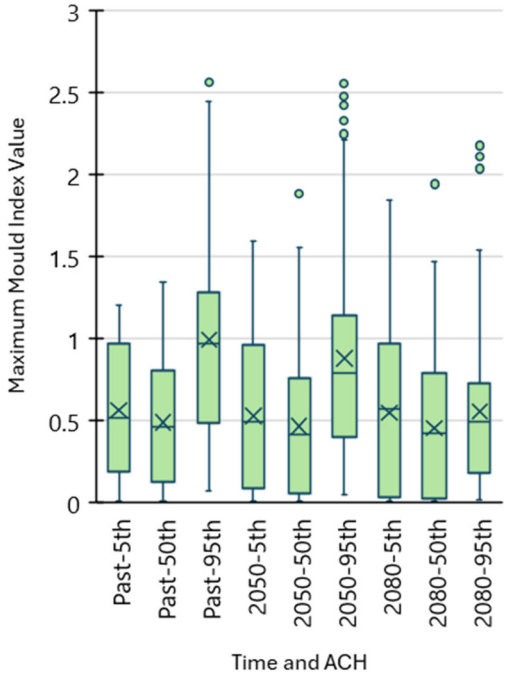


*Figure 6. Chicago, wall assembly #3 (SC3) mould index values plotted with varying air infiltration and time period, Past=1998-2013, 2050=Past transformed to 2050, 2080=Past transformed to 2080*

In each of the time periods, the range and average for maximum mould index value increases when reducing air infiltration from the 50th percentile ACH to the 5th percentile ACH. There still is a large positive correlation with mould index values when increasing air infiltration from the 50th percentile ACH to the 95th percentile ACH.

Figure 6 shows an interesting result when looking at the same wall assembly and location, but this time for mould index value. This time the relationship between air infiltration and mould growth does not appear always positively correlated. In each of the time periods, the range and average for maximum mould index value increases when reducing air infiltration from the 50th percentile ACH to the 5th percentile ACH. There still is a large positive correlation with mould index values when increasing air infiltration from the 50th percentile ACH to the 95th percentile ACH.

Given the outcomes in this project, it would be recommended that practitioners at the very least use variable starting months, variable air infiltration rates and moisture reference years in their analysis to obtain a likely distribution of possible outcomes in their risk analysis.

## Conclusion

This paper aimed to examine the simulated moisture outcomes for four common wood framed wall constructions in North America when varying weather years, starting months, future scenarios, and air infiltration. The study included historic (1998-2013) and reference year weather sets and simulated them using an open source hygrothermal analysis tool. Results in the study showed that in general as climate change progresses and warmer weather occurs, maximum moisture content in the building sheathing will likely decrease. The comparisons between reference year and historic years showed that more recent years can sometimes produce much higher ranges of moisture, mould, and corrosion risks. Thus, it may be prudent to use a collection of more recent historical weather years in addition to existing reference years, as the reference years that are provided in commercial software may be somewhat dated. Varying starting month continues to be an important step in simulated hygrothermal behaviour as the ranges of outcomes are much greater than single deterministic analysis. Further study needs to be done to better understand the results that showed decreasing maximum moisture content in future scenarios that are also coupled with higher maximum mould index values.

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