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#### **Publisher's version / Version de l'éditeur:**

<https://doi.org/10.1088/1742-6596/2069/1/012015>

*Journal of Physics: Conference Series, 2069, 2021-11-01*

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# Development of moisture reference years for assessing long-term mould growth risk of wood-frame building envelopes

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**Abstract.** A moisture reference year (MRY) is generally used to assess the durability, or long-term performance of building envelopes within a long climatological time period, e.g. a 31 year timeframe. The intent of this paper is to develop a set of moisture reference years that can be used to assess risk to the formation of mould growth in wood-frame buildings over the long-term. The set of moisture reference years have been developed based on 15 realizations of 31-year climate data. Replicated Latin Hypercube Sampling is applied to select 15 sub-realizations with 7 representative years having different levels of moisture index (MI) from each realization. Thereafter, hygrothermal simulations are performed for a brick veneer clad wood-frame wall assembly using the 15 sub-realizations; that sub-realization which produces the highest value of maximum mould growth index over 7-year period is selected as the MRY. The selection process is then implemented for all 15 realizations of the 31-years of data sets, from which 15 sets of 7-year long MRYS are selected to represent the original 15 realizations. It is shown that the 15 sets of 7-year long MRYS can produce the same value of maximum mould growth index as well as the uncertainty as compared to the original 15 realizations having a 31-year climate data set.

## 1. Introduction

It has been well recognized that climate change will significantly influence the long-term performance (durability) of building envelopes. It is projected that the annual average temperature across Canada will increase by 6.3 °C for a high emission scenario (RCP 8.5) by the end of 21<sup>st</sup> century compared to a reference period of 1986-2005, and there will be greater amounts of precipitation in all parts of Canada in the future [1]. According to the simulation study completed by Defo and Lacasse [2], the mould growth risk of massive timber walls will increase in most cities in Canada, as were selected for this study, for future projected climates (2062-2092) as compared to historical climates (1986-2016). It was determined that to assess the risk to mould growth in wall assemblies over the long-term is computational expensive, since the hygrothermal simulations have to be implemented for 15 climatic realizations of 31-year climate data, particularly when considering other uncertain variables for stochastic simulation.

To save the computational cost, moisture reference year can be developed to assess the mould growth performance of wood-frame building envelopes in a specific time period, for example, a 30 years' timeframe that is generally recommended for climate change impact assessment [3]. Traditionally, the moisture reference year development was focused on formulating a climate index, which is highly correlated with the building performance index, then the year that is ranked on the top (the worst year or the 90 percentile year) based on the climate index in the investigated time period could be selected as moisture reference year. Cornick et al. developed moisture index, which comprises of a drying index and a wetting index, to reflect the moisture severity level of the years within a specific



time period [4]. Salonvaara et al. proposed severity index, which is calculated based on a regression equation establishing correlation between climatic parameters and RHT-index of the wall [5]. Zhou et al. developed a new climatic index combining wind-driven rain load and potential evaporation, and the new climatic index showed good correlation with RHT-index of the wall [6]. Aggarwal et al. compared the three climate indices aforementioned, it was found the severity index showed better performance in selecting the extreme year for hygrothermal simulation [7]. Although these climatic indices can work properly in selecting a single year with a relatively high severity level, they may not be able to reflect the severity level for long-term weather pattern, specifically the weather pattern of a multiple years' sequence. In addition, the moisture reference year selected based on these climatic indices cannot reflect the year by year variation within a climatological time-period, specifically how the years with different severity levels are distributed through a long-term time period.

This paper aims to develop moisture reference years that can reflect long-term moisture severity level, and can be used for assessing long-term mould growth risk of wood-frame walls. The moisture reference years are developed based on 15 realizations of 31-year climate data extracted from CanRCM4 [8]. For each climate realization, Latin Hypercube Sampling is applied to select 7 representative years with different levels of moisture index, and the sampling is repeated 15 times to generate 15 sub-realizations of 7-year climate data. Then, hygrothermal simulations are performed for a brick veneer clad wood-frame wall using the 15 sub-realizations, the one that produces the highest value of maximum mould growth index of wood sheathing over 7-year period is selected as moisture reference years. The selection procedure is implemented for all the 15 realizations of 31-year data sets, from which a 7-year moisture reference year is generated for each realization, thereby producing, in total, 15 sets of 7-year moisture reference years being considered representative of the original 15 realizations of 31-year climate data. The 15 sets of 7-year moisture reference years can produce the similar maximum mould growth index and uncertainty with the original 15 realizations of 31-year climate data. Following sections present the procedure of the moisture reference years' composition and validation.

## 2. Methods

### 2.1. Sampling method

The 15 realizations of 31-year climate data were generated for 11 Canadian cities, one baseline historical period (1986-2016) and 7 future scenarios with different levels of global warming; the details for the climate data generation can be found in [8]. In this paper, the historical climate data and the climate data with the worst future scenario for global warming (3.5°C global warming) in the city of Ottawa were used for developing the moisture reference years. To select the representative years, the moisture index was calculated year by year based on equation (1):

$$MI = \sqrt{(1 - DI)^2 + WI^2} \quad (1)$$

Where

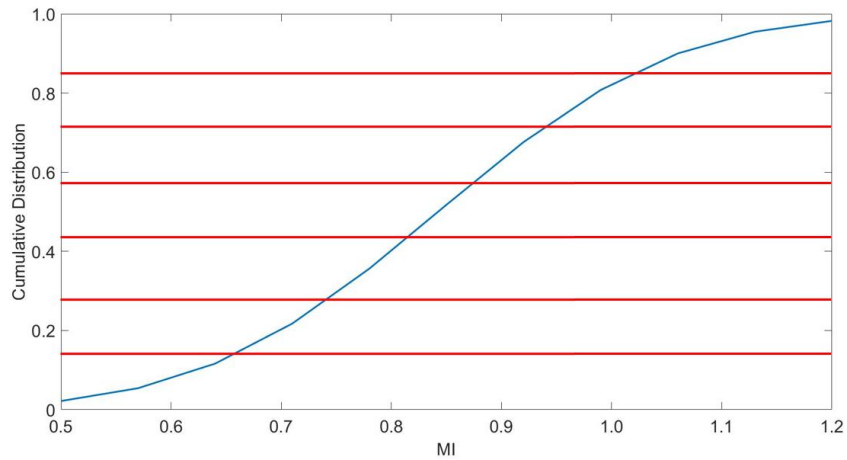
MI - moisture index of a specific year

DI - normalized drying index of a specific year

WI- normalized wetting index of a specific year

The drying index represents the degree of moisture saturation of ambient air, whereas the wetting index considers the wind speed and horizontal rain; details for the calculation of the DI and WI can be found in [4]. What should be noted is that the calculation of MI does not involve any information on the construction of the wall assembly, which implies that the climatic index is construction independent. The yearly values for DI and WI were normalized based on the maximum and minimum values in all the 15 realizations in order to consider the relative difference among different realizations, then the moisture index is calculated for every single year in each 31-year climate realization.

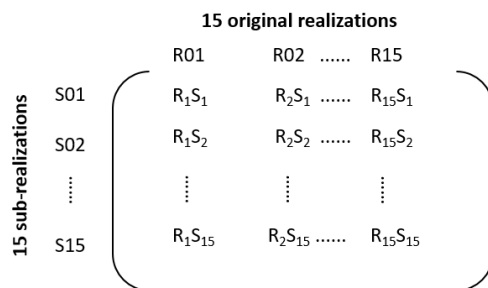
Latin Hypercube Sampling (LHS) was used to select the representative years. For each climatic realization, the cumulative distribution curve of yearly MI over 31 years was divided into 7 equal intervals (Figure 1). From each interval, one year was randomly selected amongst all the years having MI falling within that interval.



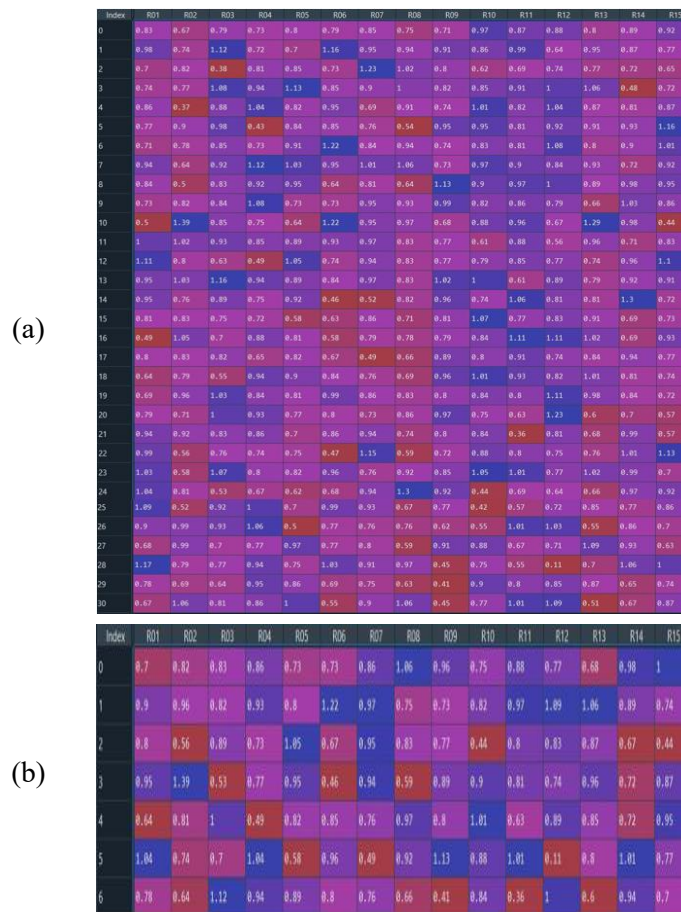
**Figure 1.** Cumulative distribution of yearly MI in a 31-year climate realization.

The sampling was repeated 15 times for each 31-year realization to permit considering the different combinations of representative years. Figure 2 shows the matrix of the sub-realizations of the 7-year climate data set generated from LHS. In total, 225 sub-realizations were generated with each original realization having 15 sub-realizations.

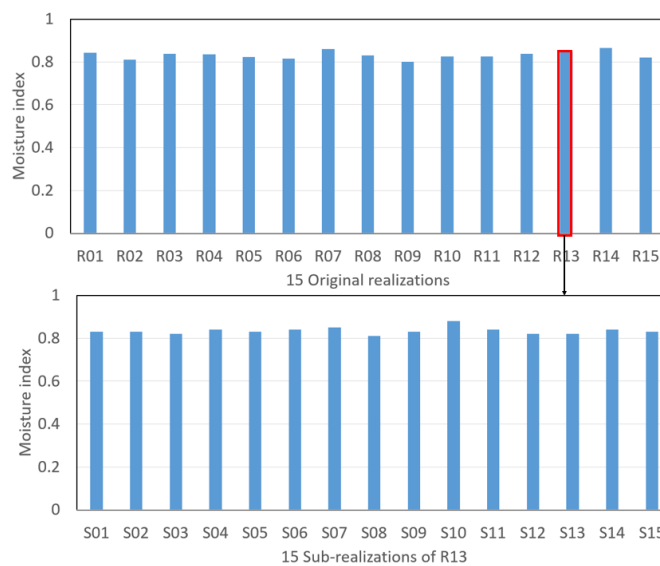
The sequence of the selected years is randomly composed, which means there is no increasing or decreasing trend of MI over time, since the years having different MI values are randomly distributed in the original climatic realization (Figure 3). This reflects the assumption that each historical and future time-period is stationary when performing climate change analysis. As shown by Figure 4, the average values of MI over 31 years of different original climate realizations are very similar (around 0.8), which means the average value of MI may not be suitable as a climatic index to permit differentiating a 31-year climate pattern amongst different realizations although the yearly value of MI varies from 0.5 to 1.2 (Figure 1). This observation was also found for the sub-realizations as generated by the LHS. The sequence of 7-years having different levels of MI is used because 7-years is the shortest sequence that includes two wet years, and which have MI value greater than  $\mu + 1\sigma$  ( $\mu$ , the mean value;  $\sigma$ , the standard deviation). This consideration is to make the sub-realizations sufficiently long to allow incorporating two consecutive wet years, which was found to frequently occur in the original climatic realizations.



**Figure 2.** Matrix of sub-realizations of 7-year climate data.



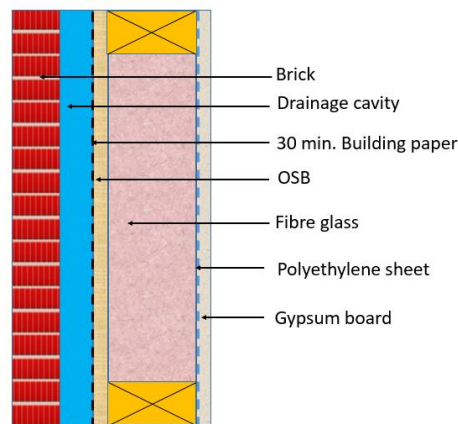
**Figure 3.** Randomness of MI distribution by year: (a) MI distribution of original 31 years’ realizations; (b) MI distribution of 7 years’ sub-realizations generated from one specific original realization; Note: each column represents one realization or sub-realization; red- lowest value, blue-highest value).



**Figure 4.** Average MI for original realizations and sub-realizations.

## 2.2. Hygrothermal model

The wall assembly used for developing the 7-year long MRYs was brick-veneer clad wood-frame wall having a 25 mm drainage cavity and cladding ventilation of 10 ACH. The 1-D hygrothermal model of the wall was created using DELPHIN 5.9, a widely used hygrothermal simulation software. The details of the wall components are presented in Figure 5, and the material properties used in the model were taken from the NRC material database [9].



**Figure 5.** A typical wood-frame wall assembly.

The exterior heat /vapour transfer coefficients were set as dependent on wind speed; the interior transfer coefficients were set as the default values in the software. The short wave absorptivity was set to a value of 0.6 and the long wave emissivity to 0.9. The wind-driven rain was calculated based on ASHRAE 160 having a rain exposure factor of 1 and a deposition factor of 0.5 [10]. The wall was assumed to face the southwest, this orientation receiving the highest amount of wind-driven rain. Indoor conditions were kept constant during the entire simulation period, i.e., 20°C and 50%RH. The wall was assumed as perfectly airtight, which meant that there was no air leakage from the interior, thus minimizing the disruption of indoor conditions given the primary purpose of this study was to investigate the effect of exterior climate patterns. The material properties were assumed as constant values as well as the boundary conditions except for that are dependent on wind speed. The moisture source used was equivalent to 1% of the wind-driven rain, and it was deposited on the exterior surface of the building paper to simulate the rain leakage according to ASHRAE 160 [10]. The mould growth index at the exterior surface of the OSB sheathing was used as a performance indicator to permit investigating the wall response to climatic conditions. The VTT model was used for calculating the mould index with a decline factor of 0.1 [11].

The only uncertainty considered in this study was the outdoor climate pattern, specifically, how the years having different values of MI are distributed. As described in section 2.1, there are 15 sub-realizations for the 7-years climate data generated for each 31-year climatic realization. Simulations were performed for all the 15 realizations of 31-year data, and the results from 31-year simulations were used as reference results. Simulations were also performed for the 15 sub-realizations generated from each original climatic realization. The sub-realization that produced the highest value of maximum mould growth index over 7-year period was selected as a 7-year moisture reference year, and the selection was implemented for all the original climatic realizations to generate 15 sets of 7-year MRYs. Figure 6 illustrates the procedure for the selection of MRYs. To allow validation of this approach, the value for mould growth index that resulted from the 15 sets of 7-year MRYs were compared with those obtained from the original 15 realization of 31-year climate data.

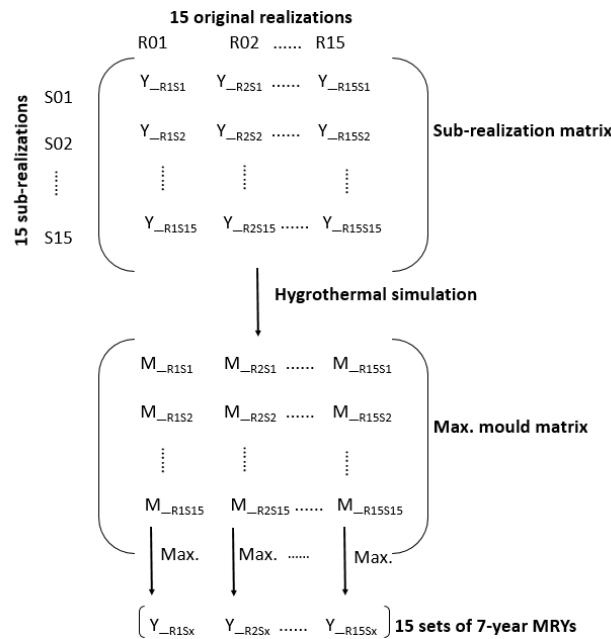


Figure 6. Selection procedure of 7-year MRVs.

### 3. Results and discussion

Figure 7 shows that the maximum values for mould growth index over 31 years produced by 15 original climate realizations vary from 1.3 to 3.5, although there is no significant difference in 31 years' averaged MI amongst the different climatic realizations (Figure 4). The difference in maximum mould growth index amongst different sub-realizations is more significant, which can vary from 0 to 3.9. Since there is a large variability in distribution of the years with different MI among different realizations, it can be said that the long-term mould growth performance is primarily influenced by how the years with different MI are distributed instead of the average MI over a period of several years.

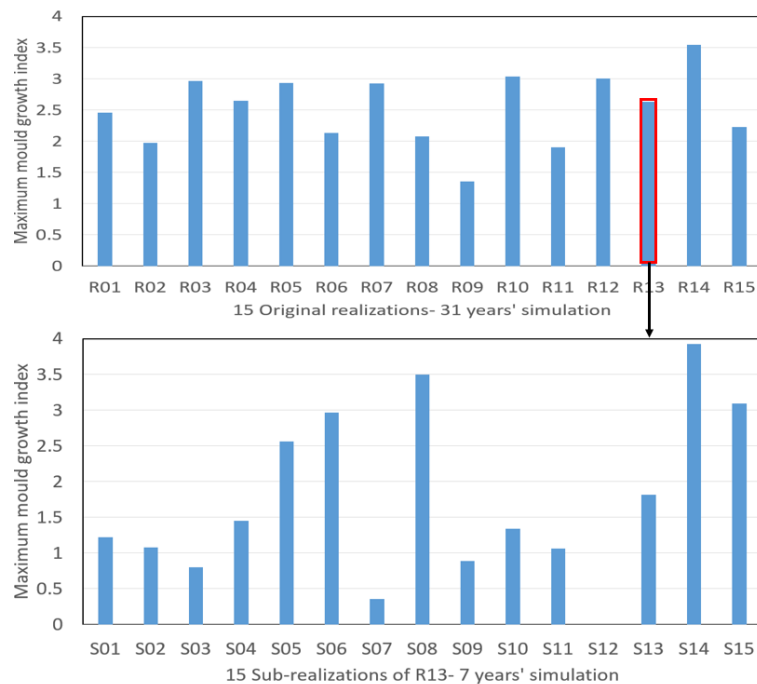
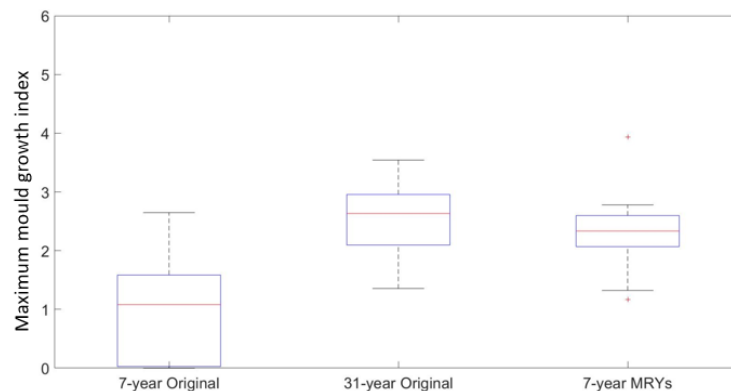
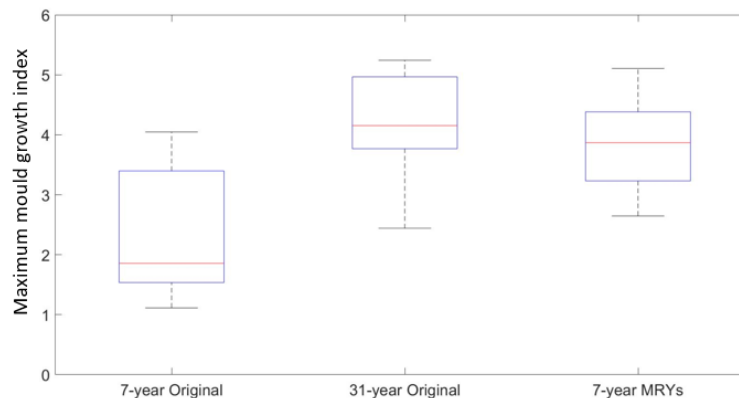


Figure 7. Maximum mould growth index over simulation periods.

Figure 8 shows the maximum mould growth index of the 7-year MRYs and the comparison with the 31-year original realizations as well as the first 7-years of original realizations. In general, the mould growth index produced by the 7-year MRYs has close level and uncertainty with that produced by 31-year original realizations for both historical and future periods. And the MRYs' mould growth index level is higher than that of the first 7-year of original climatic realizations, while the uncertainty is lower. Therefore, the 7-year MRYs have similar moisture severity level with original 31-year climatic realizations in terms of impacting mould growth performance of the wood-frame wall. In the future climatic condition, the maximum mould growth index of the 15 sets of 7-year moisture reference year have higher uncertainty (the difference between max. and min. is 2.5) than that in the historical climatic condition (the difference between max. and min. is 1.4), which indicates the uncertainty in climatic pattern is higher in the future than in the historical period.



a) Historical climatic realizations



b) Future climatic realizations

**Figure 8.** Comparison of mould index between original climatic realizations and MRYs. Note: 7-year original means the first 7 years in 31-year original climatic realization.

#### 4. Conclusions and future work

The possibility of selecting a 7-year long set of MRYs to represent 31-years of climatic data was explored in this paper to permit assessing the long-term moisture performance of wood-frame wall in respect to the risk to mould growth. It was found that the randomness of distribution of the years having different values of moisture index significantly influences the moisture performance in respect to mould growth over the long-term. Using the Latin Hypercube Sampling method, it is possible to select 15 sets of 7-year long MRYs that have a similar moisture severity level as 15 realizations of a 31-year climatic data set so that they can produce similar maximum mould growth index with 31-year's simulation. The

original simulations of 15 realizations for 31-years of data require around 24 hours, whereas, the simulations of 15 sets of moisture reference year of 7-years duration take around 8 hours. The selected 7-year long MRYs produced a higher level of severity as compared to the first 7-years of the original climatic realizations, which indicates the maximum mould growth index over a 31-year period could occur in a 7-year period due to the randomness of yearly distribution of heavy rainfall events and high outdoor vapour pressure events. The premature degradation may be more likely to occur when the frequency of the co-occurrence of heavy rainfall events and high outdoor vapour pressure events in 7-year period is similar with that in 31-year period. The selected 7-year long MRYs based on a brick-veneer clad wall might be able to produce similar maximum values of mould index using the 31-year climatic realizations for the wall having other types of cladding, however, this needs to be validated in future work. In addition, the length of the moisture reference years may vary depending on different regions. For some regions that have higher moisture indices, i.e. the coastal cities like Vancouver and Halifax, it may take only 3 to 5 years to get a maximum mould growth index that is equal to the maximum mould growth index achieved over 31 years. Last but not least, the weather pattern of the selected 7-year long MRYs could be characterized in order to reduce the computational cost when selecting the long-term MRYs for other climate zones.

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