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Aggarwal, Chetan; Defo, Maurice

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Report No.: NRCC-CONST-56516E
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CONSTRUCTION

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Executive Summary

Hygrothermal simulations are necessary to permit analyzing moisture performance when designing wall assemblies. To limit the number of simulations, simulations are performed on a limited number of wall orientations, usually the orientation that potentially leads to the worst moisture response, which is assumed to be the one receiving the highest amount of wind-driven rain (WDR). The objective of this work was to verify this assumption considering different wall assemblies and climate conditions.

Four cardinal orientations (North, East, South and West) and the wall orientation receiving the highest amount of annual WDR, hereafter called default orientation. The study was conducted for four different wood-frame wall systems that differ by their claddings assembly: brick veneer, fiberboard, stucco, and vinyl. Eleven Canadian cities belonging to different climate zones were considered: Calgary (AB), Charlottetown (PE), Halifax (NS), Moncton (NB), Montreal (QC), Ottawa (ON), Saskatoon (SK), St. John’s (NL), Toronto (ON), Vancouver (BC) and Winnipeg (MB).

Three scenarios were investigated. In the first case, it was assumed that there is no rain deposition on the exterior surface of the cladding (no WDR) and as consequence no rain infiltration (no moisture source). The second scenario assumed rain deposition on the exterior surface of the cladding, but no rain infiltration. The final scenario assumes rain deposition on the exterior surface of the cladding and rain infiltration through the deficiencies in the cladding. For this last scenario, the amount of rain that penetrates through openings and reaches the sheathing membrane was assumed to be 1% of the WDR as suggested by the ASHRAE Standard 160. The analyses were performed using the wettest year in each city selected among the 31-year historical climate data based on Moisture Index (MI) ranking.

For the performance analysis, four different performance indicators were evaluated: Maximum Moisture Content (MC) value in the OSB, Average MC in the OSB, Maximum Mould Index (MoI) value in the outer layer of OSB and Average MoI value in the outer layer of OSB. The mould index values were negligible for the cases where there was no WDR and only WDR. Therefore, the mould index analysis was limited only for the third scenarios wherein the water infiltration was assumed. The results obtained with the four performance indicators were similar. Therefore, only the results obtained for the maximum moisture accumulated in the OSB were analyzed.

For the scenario assuming no WDR and no moisture source, it was observed that, irrespective of the orientation, cladding and city, it is the north direction that leads to the worst moisture performance. For the second scenario assuming WDR but no water infiltration and for that assuming WDR and moisture source, it was found that the default orientation leads to highest moisture accumulation in most the cities while in the remaining cities, the maximum moisture accumulation occurred in other orientations than the default one. The critical case was Montreal where the moisture accumulated in OSB using default orientation (North) was significantly different than the maximum values obtained in the East direction.

Overall, the results showed that, for the wall assemblies and cities considered in this study, the North orientation is the one that leads to the worst moisture performance when the wall is well protected against rain deposition. In the scenarios where there is rain deposition on the wall or water infiltration, the orientation receiving the highest amount of annual WDR generally leads to the worst moisture response. However, using only the total amount of WDR may not be sufficient for all the cities and an analysis of hourly distribution of WDR will be required before selecting the orientation for undertaking hygrothermal simulations.

1 Introduction

The moisture performance of a wall depends on the type of climate to which it is subjected and wall characteristics such as type of cladding, level of insulation, thickness of wall, etc. For instance, a wall could lead to satisfactory performance in one type of climate but the same might not be true for another climate. There are many climate variables which could impact the response of the wall. Most of these climate variables are independent of the orientation that a wall is facing but a few are directly dependent on the wall orientation. Among these outdoor climate variables, Wind Driven Rain (WDR) that impinges the surface of the wall depends on the wind direction and speed, and the orientation of wall (Blocken & Carmeliet. 2004). The amount of rain water that infiltrates the wall depends on the amount of WDR and the extent of deficiencies in the wall. Moreover, WDR and solar radiation serve as important orientation dependent boundary conditions for performing any hygrothermal simulation. Therefore, the need to have an appropriate wall orientation becomes critical for climate resilient and durable building envelope design.

The orientation commonly used to perform hygrothermal simulations is the one that receives the highest amount of WDR (Nascimento et al. 2016; M. Nascimento et al. 2019; Cornick et al. 2003; Hansen et al. 2018; De Mets et al. 2017; Wang & Ge. 2018; Abdul Hamid & Wallentén. 2017). It is assumed that the direction receiving the highest WDR is more susceptible to moisture related problems. Zhou et al. (2017) suggested using climatic index to select the wall orientation for performing simulations. Another way of selecting the default orientation is based on the orientation receiving least amount of solar radiation as drying potential will be slow and could result in the highest moisture risk. This has been the rationale of choosing the default orientation for a few studies (Glass. 2013; Kočí & Černý. 2017). The default orientation could also be chosen by simulating each orientation and then selecting the one that leads to the worst moisture performance (Salonvaara et al. 2010).

Nascimento et al. (2016) investigated the impact of wall orientation selection on the moisture performance of walls in Brasilia, Brazil. The results showed that the North, North West and North East orientations lead to worst moisture performance due to higher WDR in those directions. Another study by Nascimento et al. (2019) used hygrothermal simulation to predict the service life of façades. They simulated three buildings with ceramic tile coating on façade in Brasilia, Brazil. It was observed that radiation, wind-driven rain, temperature and difference between daily maximum and minimum temperature ΔT, is a tool for determining the orientation that mostly influences the wall performance. They found that the north orientation receives highest amount of solar radiation and sum of driving rain and thereby results in higher degradation in that direction.

Cornick et al. (2013) tested four different wall systems: stucco, exterior insulated Finish systems (EIFS), Siding-Clad wood-frame walls, and masonry across various cities in North America. They tested four cardinal orientations (North, East, South and West) along with the predominant direction (direction with highest amount of total rain) for the purpose of classifying the years in terms of their severity. In case the difference between total rain amounts between two orientations was similar, the orientation receiving lower direct solar radiation was selected as the predominant direction.

Hansen et al. (2018) performed hygrothermal measurements for four different historical buildings located in Denmark. For analyzing the performance, they tested four wall orientations and used mould index as the performance indicator for hygrothermal simulations. It was found that the orientation with the maximum value sum of WDR leads the highest value of mould index. De Mets et al. (2017) studied the influence of different interior insulation materials on the hygrothermal performance of masonry walls in Belgium. Maximum moisture content was chosen as the performance indicator and it was found that the orientation receiving the lowest WDR amount had the lowest value of accumulated moisture content for all tested insulation materials.

In the study of Wang & Ge (2018) for a highly insulated wood frame wall located in Waterloo and Vancouver in Canada, three different orientations (North, South and East) were chosen for performing the hygrothermal simulations. Moisture content and mould index were used as performance indicators. It was found that the worst performance occurred in the direction receiving the highest amount of WDR. Abdul Hamid & Wallentén (2017) studied the hygrothermal performance of internally added thermal insulation in different cities across Sweden. Mould growth was used as the performance indicator and the simulations were performed for the orientation receiving highest amount of WDR. Zhou et al. (2017) studied the freeze-thaw damage risk of masonry walls retrofitted with insulation on the interior side for two cities situated in Switzerland. RHT index was used as a performance indicator and they suggested the orientation with the maximum value of climatic index to have the highest RHT and hence most prone to moisture risk.

Glass (2013) performed hygrothermal analysis of ten residential buildings in the mixed humid climate location of Baltimore, Maryland, USA, with wall assemblies having OSB sheathing and vinyl siding. The walls differed in stud cavity thickness, level of cavity insulation, presence and type of exterior insulation, and class of interior vapour retarder. Moisture content in the OSB layer was evaluated and the seasonal trend, drying and effect of WDR and air leakage on the moisture content (MC) of OSB was observed. The results showed that MC of OSB was extremely sensitive to wall orientation. The north-facing wall accumulated the highest amount of moisture and the south-facing wall accumulated the least moisture because of solar exposure. The north-facing orientation was hence selected as the default orientation. A study by Kočí et al. (2017) focused on various damage functions for analyzing the results from hygrothermal simulations. Contemporary and historical buildings with nine different building envelope types were simulated in the city of Prague, Czech Republic. Eight different orientations were tested at interval of 45° for all the simulations and the results showed that North, North East, North West orientations give the worst performance based on frost-induced damage.

Salonvaara et al. (2010) studied the effect of selected weather year on hygrothermal responses of the wall. They simulated stucco-clad wood-frame & heavy-weight wall in eight different cities across the US. To identify the orientation giving the worst moisture response based on damage functions considered (Time of Wetness (TOW), RHT-Index, Mould Growth Index, and Maximum Moisture Content), they evaluated eight different wall orientations separated by 45°. It was found that for all the cities and damage functions, the results for the North facing wall showed the worst performance.

All the above-mentioned studies incorporate the effect of wall orientation in some way or another to serve the principal purpose of their research. For most of the studies, it has been said that the orientation receiving the highest amount of WDR or least solar radiation is used as the default orientation for the simulation without considering the type of cladding, structure, moisture source etc. The objective of this study is to assess the effects of wall orientation on the moisture performance based on moisture accumulation in OSB and mould growth for different wall assemblies under different climates for the scenarios where: (i) WDR and moisture source are not considered, (ii) only WDR is considered, and (iii) WDR and moisture source are both considered. Furthermore, effect of varying the type of cladding and weather year will be also considered.

2 Methods

Hygrothermal simulations were performed to assess the effects of wall orientation on the moisture performance of wood-frame wall assemblies. Four cladding types and eleven Canadian cities were selected for analysis. Three scenarios were simulated: (i) no WDR and no Water source, (ii) only WDR, and (iii) both WDR & water source. When the water source was considered, it was calculated as 1% wind driven rain and applied on the exterior side of the sheathing membrane as per ASHRAE 160 (2016). The approach followed in this report is the one provided in Lacasse et al. (2018). In the following sections further details and considerations are provided for the various parameters used in the simulations. It includes the detailed description of the geographical data of simulated cities, wall assemblies, material properties, climate data and the boundary and initial conditions.

2.1 Simulation tool

In this study, simulations were performed using a state-of-the-art hygrothermal modelling software, Delphin 5.9. Material properties were defined as function of volumetric moisture content and climate data was entered as individual files for each climate variable. An initial time step of 0.01s, a maximum time step of 30 min, a relative tolerance of 10-7 and an absolute tolerance for moisture mass balance equation of 10-8 were selected for all the simulations. For simulations, each year selected for analysis was repeated twice.

2.2 Geographic location

For the analysis, eleven cities were chosen from different provinces of Canada. Location and characteristics of the cities considered are shown in the **Error! Reference source not found.**. Among the eleven cities, Vancouver s the wettest city with moisture index (MI) of 1.93 and Calgary is the driest city with MI of 0.37. Other cities lie between these two values.

Table 1. Characteristics of the selected cities

City (Province)	Latitude	Longitude	HDD18	MI	TZ	CZ	Annual rain (mm)
Calgary (AB)	51.05°	-114.07°	5000	0.37	-7	7A	325
Charlottetown (PE)	46.24°	-63.13°	4460	1.09	-4	6	900
Halifax (NS)	44.65°	-63.57°	4000	1.49	-4	6	1350
Moncton (NB)	46.09°	-64.77°	4680	1.02	-4	6	850
Montreal (QC)	45.5°	-73.56°	4200	0.93	-5	6	830
Ottawa (ON)	45.25°	-75.42°	4440	0.84	-5	6	750
Saskatoon (SK)	52.13°	-106.65°	5700	0.41	-6	7A	265
St. John's (NL)	47.55°	-52.71°	4800	1.41	-4	6	1200
Toronto (ON)	43.65°	-79.38°	3800	0.87	-5	5	730
Vancouver (BC)	49.28°	-123.12°	3100	1.93	-8	4	1850
Winnipeg (MB)	49.9°	-97.14°	5670	0.58	-6	7A	415

HDD18 – heating degree days below 18°C
MI – moisture index
TZ – time zone
CZ – climate zone

2.3 Wall configuration

The modeled building was assumed to be 3.5-storey tall (10-m height) and located in a suburban setting. The wall construction type simulated consisted of a lightweight wood frame wall assembly with four different claddings. The wall was assumed to be perfectly airtight. Each cladding material has a different dimension: brick (90 mm), fibreboard (10.5 mm), stucco (19 mm), and vinyl (1.1 mm). Details of wall elements are shown below:

- Sheathing membrane (30 Minute asphalt impregnated kraft paper, 0.22 mm)
- Exterior grade wood-based sheathing panel (OSB, 11 mm)
- Insulation within vertical stud cavities (glass fibre batt insulation, 140 mm)
- Vapour barrier (polyethylene sheet, 0.15 mm)
- Interior finish (gypsum panel with latex primer and 1 coat of latex paint, 12.7 mm)

A drainage cavity was incorporated in brick and vinyl walls with a depth of 25 mm and 2 mm (average thickness of hollow space behind vinyl), respectively, for all the cities. For fibreboard, there was no drainage cavity and for stucco, a cavity of 10 mm was assumed only for the cities of Vancouver and St. John's.

2.4 Climate data and default orientation

The climate data used for the present study includes hourly values of climate variables necessary to undertake hygrothermal simulations. They were sourced from the hourly and daily climate databases of Environment and Climate Change Canada (ECCC). Missing values were filled-in using bias-corrected Climate Forecast System Reanalysis (CFSR: Saha et al. 2010). Fifteen different runs are available for each city based on different set of initial conditions used for generating the modeled climate data. Among those fifteen runs, the median run based on moisture index (MI) value was selected for each city. Each run consists of a series of 31 years of data. The wettest year based on the MI ranking was chosen from the median run for each city. Table 2 shows the median run, the wettest year and the corresponding default orientation (for the wettest year) for the cities considered.

Table 2. Median run, wettest year and Default orientation for each city

City	Median run	Wettest year	Default orientation
Calgary	10	2016	292.5° (WNW)
Charlottetown	9	1993	157.5° (SSE)
Halifax	2	1991	180° (South)
Moncton	1	1999	22.5° (NNE)
Montreal	6	1992	0° (North)
Ottawa	10	1991	22.5° (NNE)
Saskatoon	11	1994	22.5° (NNE)
St. John's	6	1994	202.5° (SSW)
Toronto	15	1994	202.5° (SSW)
Vancouver	4	1994	157.5° (SSE)
Winnipeg	9	2002	67.5° (ENE)

Figure 1 shows the distribution of airfield wind driven rain for all eleven cities. The default orientation for each city was selected based on the orientation with the maximum value of annual sum of WDR. This amount is calculated by adding the amount of rain received in a sector of 22.5° with the central angle being the direction where the value is being calculated. For instance, amount of rain received at an orientation of 45° involves the sum of all the rain intensities falling in a range of 33.75° to 56.25°.

Figure 1. Airfield wind driving rain distribution ($m^2/(s.yr)$) for a wall facing different directions.

To understand the general trend of the climate in the eleven cities, temperature, relative humidity (RH), rain, and wind speed were plotted. As shown in Figure 2 through Figure 4, the median temperature, median wind speed and median wind speed are quite different amongst the eleven cities. As shown in Figure 3, Calgary and Vancouver have the least RH among the 11 cities. Moreover, Figure 4 illustrate that St. John's has the highest wind speed and hence could further results in higher WDR. The total annual rainfall also varies significantly among these cities (Figure 5). Vancouver receives the highest annual rainfall while Saskatoon has the lowest annual rainfall.

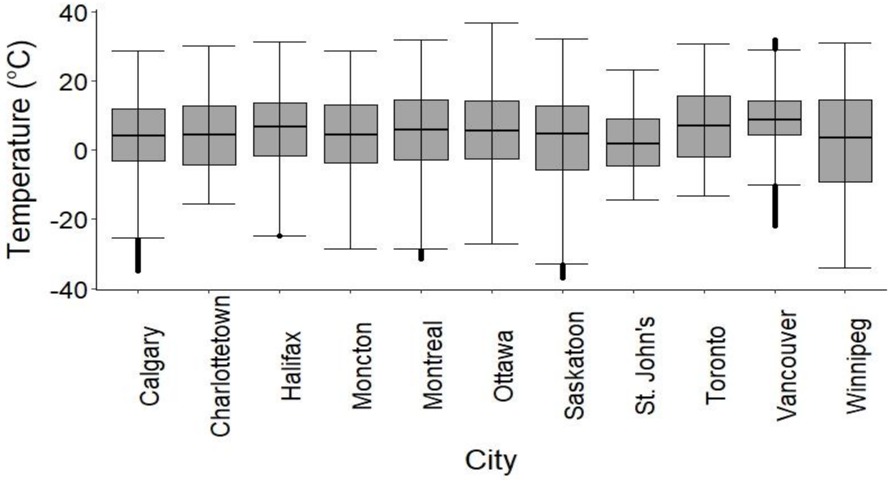

Figure 2. Boxplot of temperature for the wettest year for each city considered

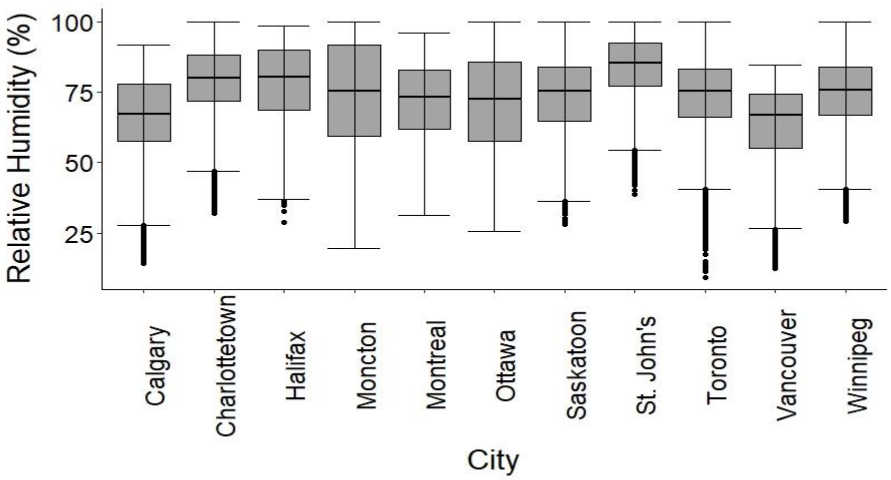

Figure 3. Boxplot of relative humidity for the wettest year for each city considered

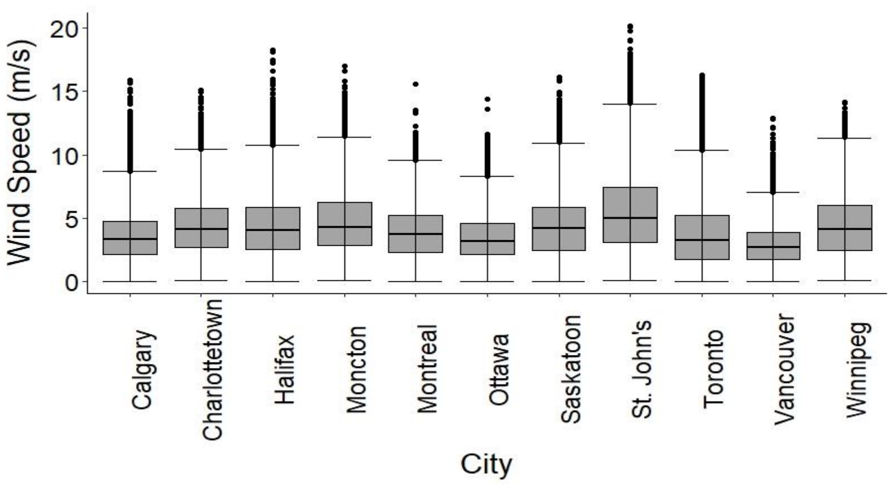

Figure 4: Boxplot of wind speed for the wettest year for each city considered

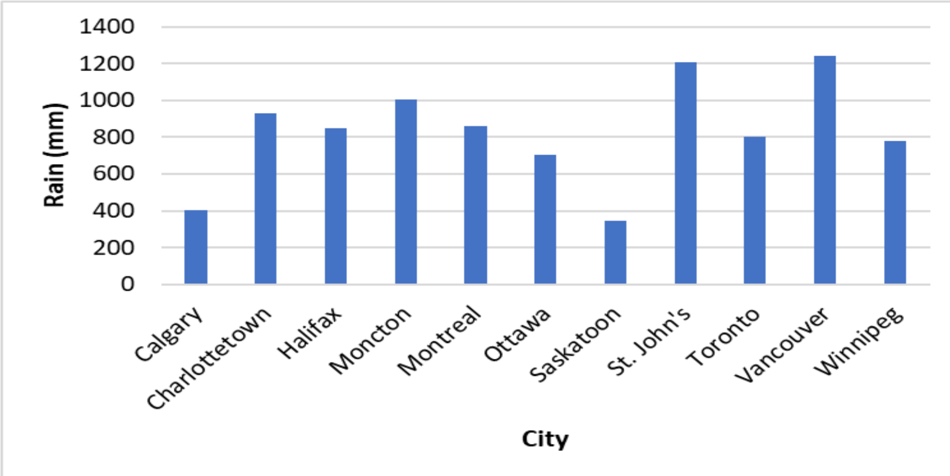

Figure 5: Comparison of total annual rain for the wettest year for each considered city

2.5 Boundary conditions

2.5.1 Initial conditions

The initial conditions for relative humidity and temperature were set, respectively, to 60% and 21°C for all components.

2.5.2 Indoor conditions

For all the simulations, temperature and RH were set constant with values of 21°C and 50%, respectively. The indoor exchange coefficient for heat conduction, α, was set to 8 W/m^2K and the indoor vapour diffusion coefficient, β, was set to $3*10^{-8}$ s/m.

2.5.3 Outdoor boundary conditions

In this study, WDR was calculated using the ASHRAE method (ANSI/ASHRAE, 2016) considering a 3.5-storey building located in the suburban area. The model proposed by the ASHRAE standard is given by equation 1:

$$R_{wdr} = F_E . F_D . F_L . U_{10} . \cos\theta . R_h \quad (1)$$

Where: F_E is the rain exposure factor, depending on the building height, the terrain topography and the surroundings; F_D is the rain deposition factor accounting for the spatial distribution of the WDR on the façade; F_L is an empirical constant (= 0.2 kg·s/(m^3.mm)); U_{10} is the hourly mean wind velocity at 10 m; θ is the angle between normal to the wall and the wind direction; and R_h is the rain intensity on the horizontal surface (mm/h). For this study, values of F_E and F_D were set to 1.0 and 0.5, respectively to assume medium exposure and the walls below a slope roof (ANSI/ASHRAE, 2016).

Other outdoor boundary conditions include, heat conduction, vapour diffusion, short wave radiation and long wave radiation and were applied on the exterior surface of cladding. The parameters used for defining various outdoor boundary conditions are listed below in Table 3.

Table 3: Outdoor boundary conditions and radiation coefficients

Type	Value
Outdoor heat transfer coefficient	$5 + 7.2v^{0.78}$
Outdoor vapor transfer coefficient	$3 * 10^{-8} + 4.392 * 10^{-8}. v^{0.78}$
Ground shortwave reflection	0.1
Shortwave surface absorption	0.6
Ground longwave emission coefficient	0.9
Surface longwave emission coefficient	0.9

v: wind speed (m/s)

2.6 Discretization of the wall components

For discretizing the wall assembly components, an automated variable discretization was used for all layers of the configuration. The number of elements for each layer is shown in Table 4.

Table 4. Description of meshing for different layers of wall assembly

Layer	Dimension of layer (mm)	Total elements	Minimum element thickness (mm)	Maximum element thickness (mm)
Brick	90	24	1	7.5
Stucco	19	22	0.09	1.87
Fibreboard	10.5	18	0.09	1
Vinyl	1.1	3	0.36	0.36
Sheathing membrane	0.22	3	0.07	0.07
OSB	11	18	0.09	1.12
Insulation	140	41	0.06	11.8
Vapour barrier	0.15	3	0.05	0.05
Gypsum	12.7	20	0.06	1.23
Air cavity (Brick)	25	24	0.09	2,1
Air cavity (Stucco)	10	17	0.09	1.14
Air cavity (Vinyl)	2	10	0.09	0.25

2.7 Air changes across the drainage cavity

A drainage cavity was added for the brick and vinyl claddings with a dimension of 25 mm and 2 mm respectively for all the cities. For fibreboard, there was no drainage cavity and for stucco, a cavity of 10 mm was assumed only for the cities of Vancouver and St. John's. For all the cases where a drainage cavity was present, an air change per hour (ACH) of 2 was assumed. For vinyl, Lstiburek et al. (2016) suggest 200 ACH for vinyl siding. The purpose of this study was not to evaluate the actual performance of the wall systems considered, but to evaluate their relative performance as function of wall orientation. The ACH values used do not reflect what may happen in real conditions.

2.8 Material properties

The material properties were obtained from the NRC hygrothermal material property database (Kumaran. 2006). Basic material properties of various layers and different cladding are shown in Table 5.

Table 5. Material properties of the various layers of the wall assembly

Material	Thickness (mm)	Dry density (kg/m³)	Specific heat capacity (J/kg.K)	Thermal conductivity (W/m.K)	Porosity (m³/m³)
Brick	90	1900	800	0.5	0.21
Fibreboard	10.5	730	1880	0.09	0.57
Stucco	19	1960	840	0.40	0.23
Vinyl	1.1	1500	1260	0.16	0.03
OSB	11	600	1880	0.09	0.96
Glass fiber batt insulation	140	11.5	840	0.04	0.99
Vapor barrier	0.15	1256	840	0.15	1.34
Sheathing membrane	0.22	909	1256	0.15	0.97

A comparison of the moisture storage capacity, moisture diffusivity and vapour permeability of the different cladding materials used in the wall assemblies are shown in Figure 6. At lower level of RH, brick has the least moisture storage capacity followed by vinyl, stucco, and fibreboard. However, at higher RH levels (RH>95%), brick has more storage capacity than vinyl with fibreboard being the cladding material with highest capacity. For the liquid diffusivity and vapour permeability, vinyl is practically impermeable to water vapour and liquid water. At lower level of RH (RH<95%), brick has the lowest liquid diffusivity but above 95% RH, the liquid diffusivity increases sharply. For vapor permeability, vinyl has the lowest value and among the other three claddings, above 50% RH, fibreboard and brick have the highest and lowest vapor permeability, respectively.

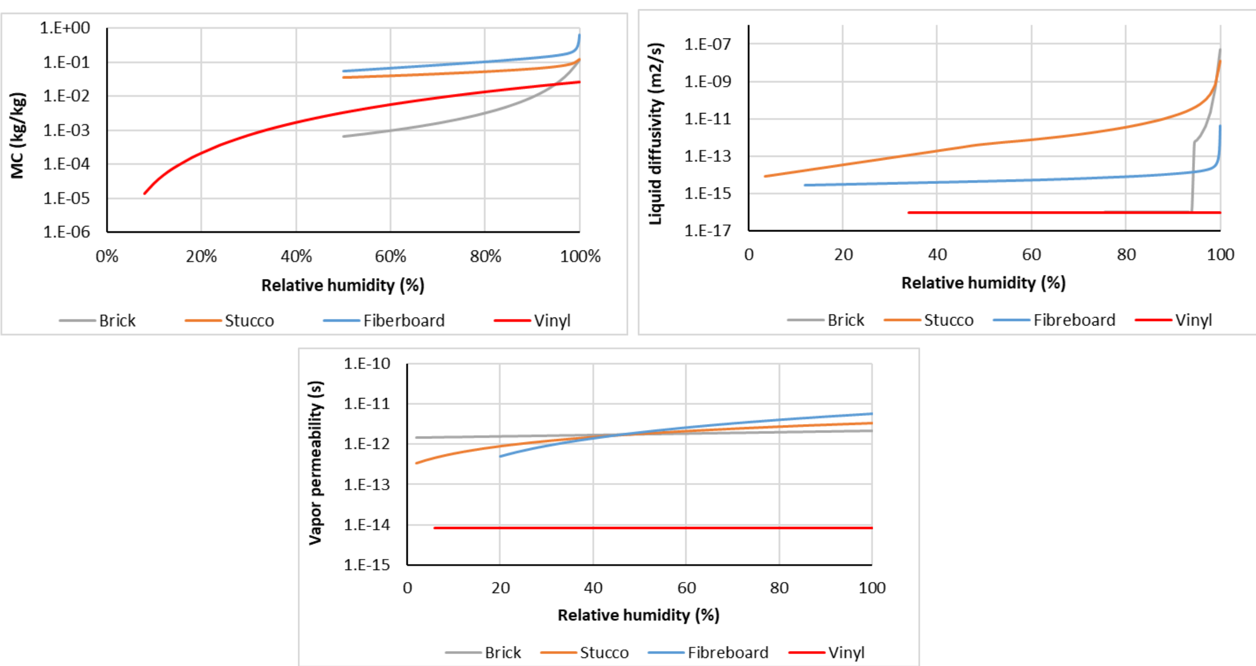

Figure 6: Moisture Content, liquid diffusivity and Vapour permeability of the cladding materials

2.9 Performance assessment

There are several performance attributes, criteria and evaluation processes that can be used to analyze the results obtained from hygrothermal simulations (Lacasse et al. 2018). In this study, two damage functions were selected, *i.e.*, Moisture content (MC) and Mould Index (MoI). Absolute moisture content was considered. The mould index was computed at the exterior of the OSB layer (0.1mm thick element size) using the method proposed by Ojanen et al. (2010).The calculations were made assuming the sensitive class for material and surface and a decline factor of 0.5 (assuming significant decline) when the conditions become unfavourable for mould growth. Maximum MC, average MC, maximum MoI and average MoI were used to compare the performance of wall assembly facing different orientations.

3 Results and discussion

The results are presented firstly for the cases without WDR and water penetration, secondly for the case with WDR only, and finally for the case with WDR and water source. It was found that the results obtained with the four performance indicators were generally in good agreement. Therefore, only the results obtained using maximum moisture content as performance indicator are discussed. Results obtained with other performance indicators can be found in the Appendix.

3.1 Scenario with no WDR and moisture source

The first analysis is based on the case where there was no WDR or rain infiltration. Figure 7 shows the maximum MC in the OSB layer obtained at different wall orientations for all the cities and claddings. Table 6 shows, for brick cladding, the maximum MC for the default orientation and the maximum MC for the orientation which has the highest value of maximum MC among the orientations compared. For all the cities, irrespective of the cladding type, the highest value of maximum MC was observed when the wall is facing the north orientation. This is due to the significantly lower amount of solar radiation in the North direction. The results are consistent with the one found by Lepage et al. (2017).

Table 6: Maximum moisture content (MC) values in the OSB layer for brick cladding with no WDR and moisture source for the wettest year

City	Default orientation		Orientation with Max. MC	
	Orientation	Max. MC (kg)	Orientation	Max. MC (kg)
Calgary	292.5° (WNW)	0.50	0° (North)	0.51
Charlottetown	157.5° (SSE)	0.56	0° (North)	0.62
Halifax	180° (South)	0.60	0° (North)	0.65
Moncton	22.5° (NNE)	0.61	0° (North)	0.61
Montreal	0° (North)	0.58	0° (North)	0.58
Ottawa	22.5° (NNE)	0.56	0° (North)	0.57
Saskatoon	22.5° (NNE)	0.54	0° (North)	0.55
St. John’s	202.5° (SSW)	0.60	0° (North)	0.64
Toronto	202.5° (SSW)	0.55	0° (North)	0.59
Vancouver	157.5° (SSE)	0.51	0° (North)	0.51
Winnipeg	67.5° (ENE)	0.57	0° (North)	0.59

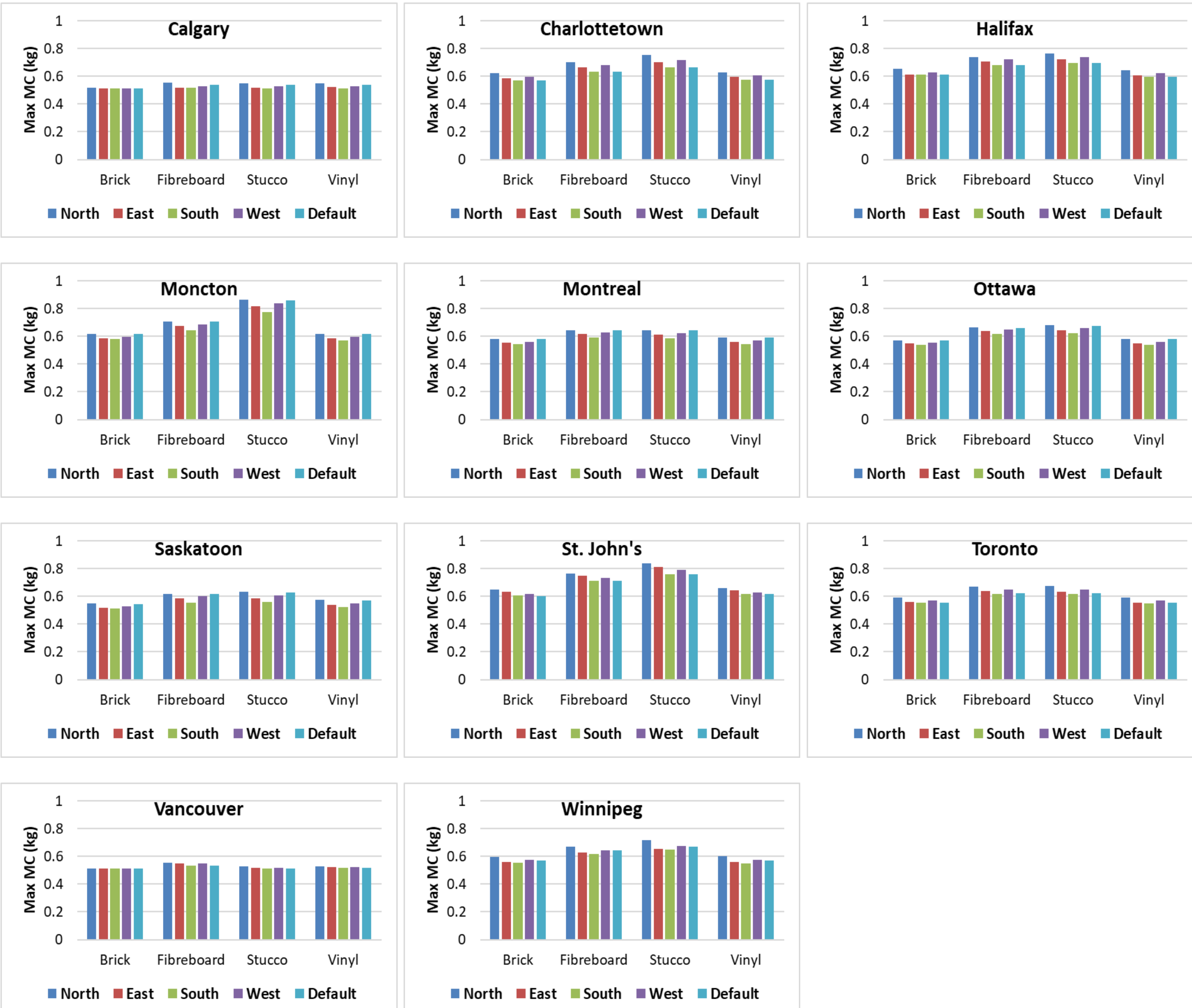

Figure 7. Maximum moisture content of OSB layer for all selected cities with no WDR and no moisture source

For Calgary and Vancouver, it was observed that the maximum MC is relatively lower than other cities. As there is no rain, the only factor which results in moisture accumulation is vapour diffusion. Moreover, as shown in Figure 3, outdoor RH in Calgary and Vancouver is lower than other cities and hence results in lower moisture content in the OSB layer.

Furthermore, for brick cladding, it was seen that the values are similar irrespective of the orientation in these two cities. This is due to the low vapour permeability of brick cladding for the outdoor RH range. Considering the brick cladding is 90 mm thick brick, the transport of vapour via diffusion is further limited. Therefore, irrespective of the orientation, the moisture accumulated in the OSB for brick cladding is almost the same.

3.2 Scenario with WDR but no moisture source

In this section, the results are discussed where wind driven rain (WDR) is taken into consideration while assuming no deficiency in the cladding and hence no water penetration. In general, it was observed that unlike the previous case where the north orientation always leads to the worst performance irrespective of city or cladding, in this case, the results are not as consistent. Table 7 shows the result for maximum moisture content in the OSB layer for brick cladding wall in all the eleven cities. It was observed that in 7 out of 11 cities the default orientation resulted in worst performance. Four cities, Moncton, Montreal, Saskatoon, and Winnipeg performed worst in an orientation other than the default. With the exception of Montreal, the difference in maximum MC between the default orientation and the one given the maximum MC is not significant for these cities.

Table 7. Maximum moisture content (MC) values in the OSB layer for brick cladding with WDR but no moisture source for the wettest year

City	Default orientation		Orientation with Max.MC	
	Orientation	Max. MC (kg)	Orientation	Max. MC (kg)
Calgary	292.5° (WNW)	0.68	292.5° (Default)	0.68
Charlottetown	157.5° (SSE)	1.61	157.5° (Default)	1.61
Halifax	180° (South)	1.69	180° (Default)	1.69
Moncton	22.5° (NNE)	1.52	90° (East)	1.62
Montreal	0° (North)	0.86	90° (East)	1.67
Ottawa	22.5° (NNE)	0.96	22.5° (Default)	0.96
Saskatoon	22.5° (NNE)	0.80	90° (East)	0.84
St. John’s	202.5° (SSW)	1.48	202.5° (Default)	1.48
Toronto	202.5° (SSW)	0.71	202.5° (Default)	0.71
Vancouver	157.5° (SSE)	1.71	157.5° (Default)	1.71
Winnipeg	67.5° (ENE)	1.08	90° (East)	1.18

For Montreal, it was observed that there was a significant difference in the max. MC for default (0°) and the direction with highest max. MC i.e. east (90°). The WDR rose for Montreal (Figure 1) shows that the north direction has the highest amount of WDR and hence was chosen as the default orientation. Figure 8 shows the WDR and cumulative WDR distribution for north and east direction for Montreal. It can be seen that highest sum of WDR in north is because of few singular high intensity rain events in this direction. North orientation has a few spikes in the graph which means that there were a few hours in the year when there was high WDR intensity in this direction. A further analysis showed that the spikes make around 70% of the total WDR that had occurred throughout the year in that direction. These high rain events leads to a greater sum of WDR in the year but is less of a concern in terms of durability of the wall as water absorption capacity of the cladding is limited and most of the water is going to be drained off. On the other hand, for east direction although the overall sum remains low, but the WDR was better distributed throughout the year.

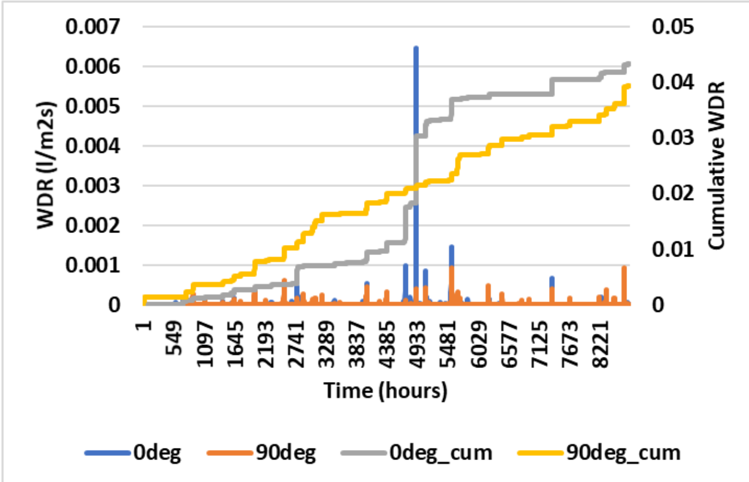

Figure 8. WDR distribution in north and east orientation in Montreal

Figure 9 shows, for each city and cladding, the maximum moisture content obtained in each orientation. In general, the maximum MC was highest for the stucco cladding. This is due to the fact that stucco has the highest liquid diffusivity up to certain range (approximately 95%) of RH (Figure 6) and later superseded by brick for higher RH level. However, as the thickness of brick is approximately five times more than stucco, it takes longer for the moisture to transport through brick. This results in the highest maximum MC in the stucco cladding for all the orientations and cities.

For fibreboard and vinyl claddings, the results were similar irrespective of the orientation. The MC values for these two claddings were lower than brick and stucco claddings. Vinyl being impermeable to water did not allow any vapour transport and hence behave as if there was no rain and the results were similar to those presented in previous section. On the other hand, for the given thicknesses of cladding materials, fibreboard has the highest vapour permeance and hence the drying capacity. Having said that, although the rain received in the default orientation is the highest, but the high drying capacity of fibreboard nullifies the higher rain and resulted in similar value of MC for all the orientations

The results can be further divided into two groups. The first group comprises 7 cities (Vancouver, Calgary, Toronto, Ottawa, St. John's, Halifax, and Charlottetown). For these cities, when only WDR is assumed, the brick and stucco cladding gives worst performance in the default orientation. The second group comprises the remaining 4 cities (Moncton, Montreal, Saskatoon, and Winnipeg) where the maximum MC occurred in other orientation than the default. However, with the exception of Montreal, the difference is not significant, and it can be said that the default orientation either yields the worst response or is among the orientations performing the worse.

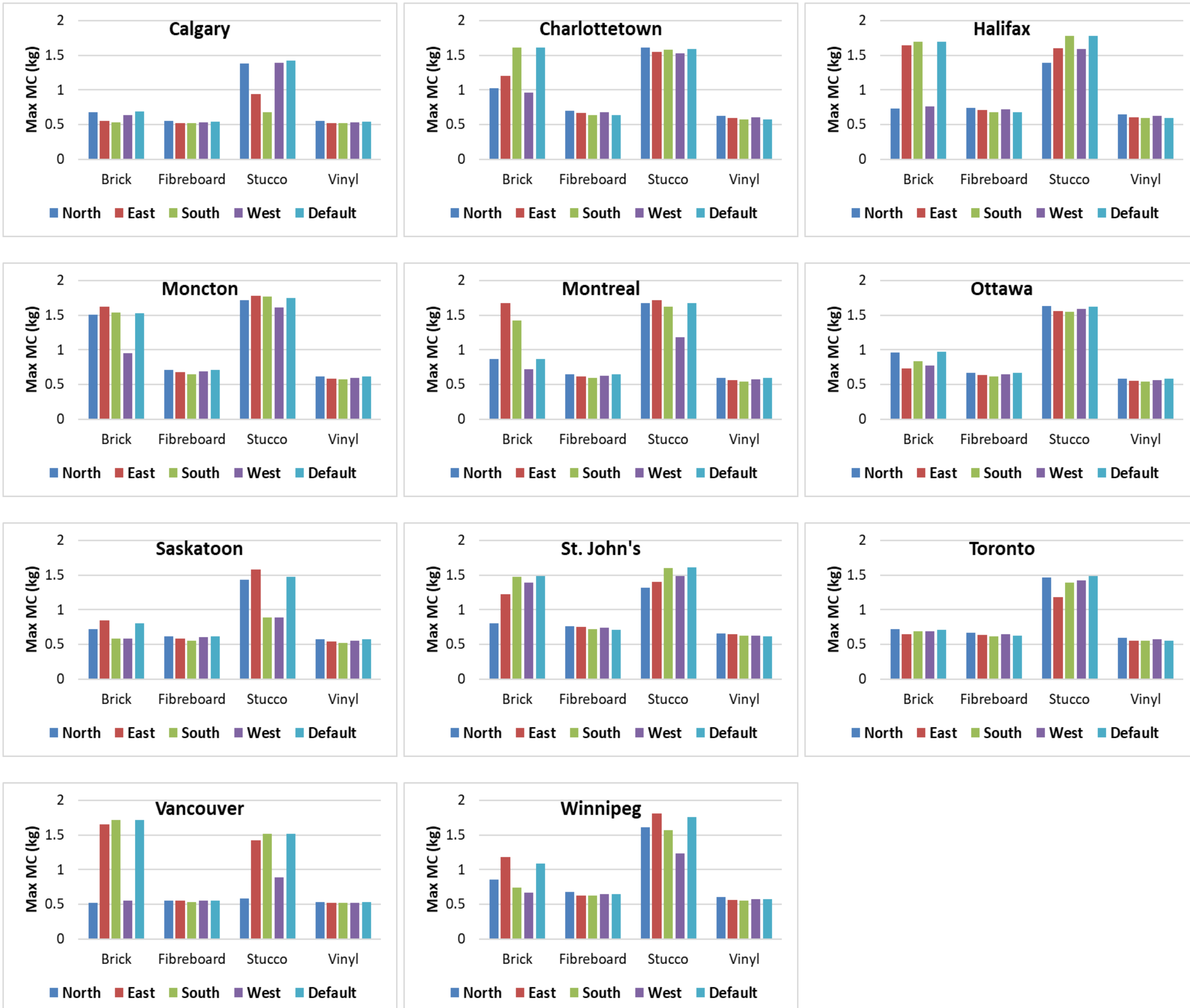

Figure 9. Maximum moisture content of OSB layer for all selected cities with WDR but no moisture source

3.3 Scenario with WDR and moisture source

In this scenario, WDR was assumed and the walls were also assumed to have some deficiencies that allows water to penetrate in the structure. Water source was calculated as 1% of WDR and deposited at the exterior layer of the sheathing membrane. Results for all cities and claddings are summarized in Figure 10. Table 8 shows, for the brick cladding, the max. MC in the OSB layer obtained with the default orientation and with the orientation having maximum MC in different cities.

Among all claddings, vinyl showed the highest value of accumulated moisture content. This is because vinyl is impermeable and the air change rate is low. These does not allow the water deposited on the sheathing membrane to dry to the exterior and hence, with the occurrence of more rain events, the moisture grows continuously.

In terms of orientation leading to worst performance, the default orientation led to the highest maximum MC in all cities but Moncton, Montreal and Winnipeg for brick veneer cladding. However, the difference in maximum MC between the default orientation and that giving the highest maximum MC is negligible in Moncton (0.02 kg) and in Winnipeg (0.12). In Montreal, this difference is significant (0.61 kg) and, as for the scenario with WDR only, can be explained by the presence of few singular high intensity rain events in this default orientation (North), compared to a relatively better distribution in orientation having the highest maximum MC (South in this case).

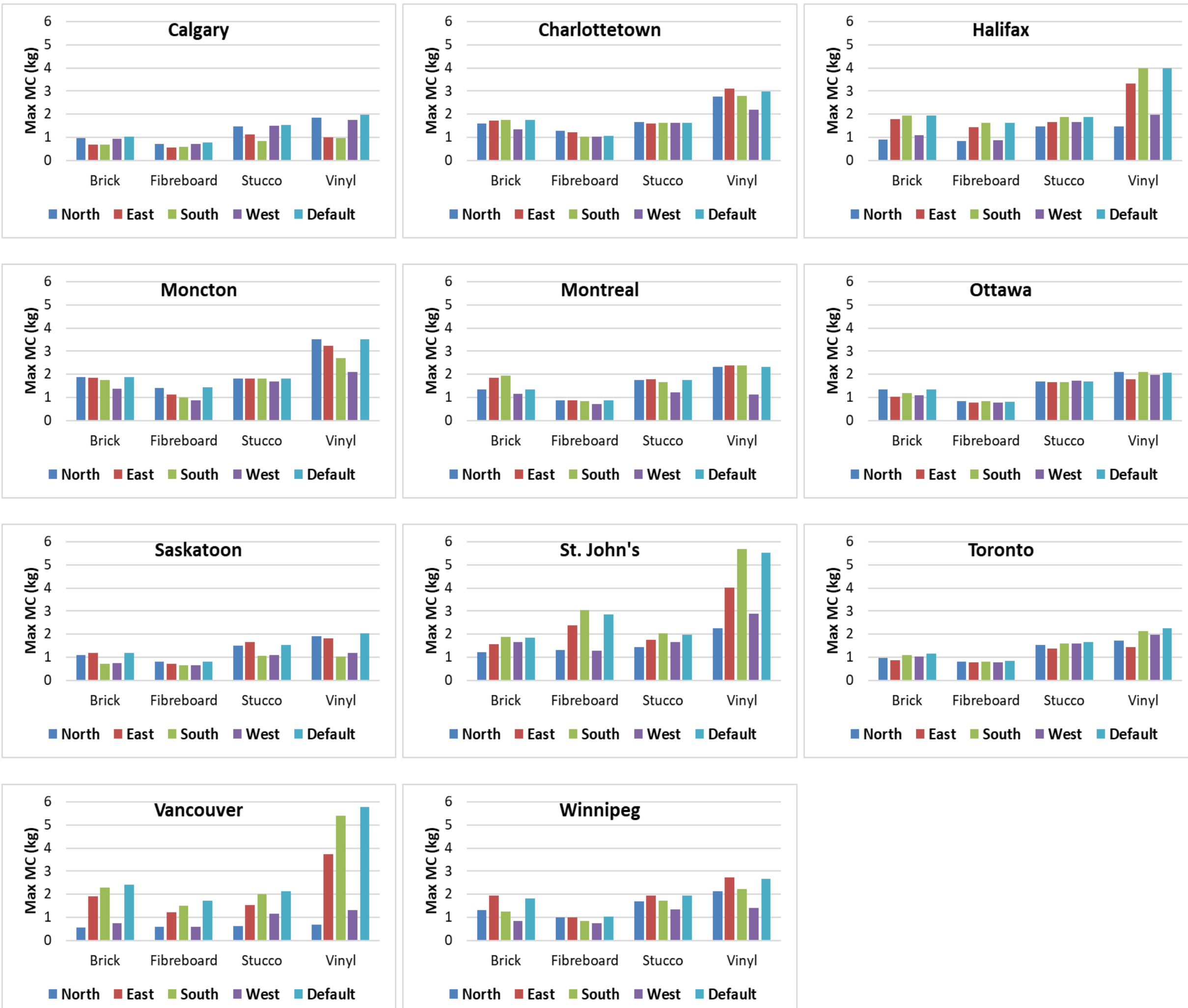

Figure 10. Maximum moisture content of OSB layer for all selected cities with WDR and moisture source

Table 8. Maximum moisture content (MC) values in the OSB layer for brick cladding with WDR and moisture source for the wettest year

City	Default orientation		Orientation with Max. MC	
	Orientation	Max. MC (kg)	Orientation	Max. MC (kg)
Calgary	292.5° (WNW)	1.02	292.5° (Default)	1.02
Charlottetown	157.5° (SSE)	1.74	157.5° (Default)	1.74
Halifax	180° (South)	1.92	180° (Default)	1.92
Moncton	22.5° (NNE)	1.85	0° (North)	1.87
Montreal	0° (North)	1.33	180° (South)	1.94
Ottawa	22.5° (NNE)	1.35	22.5°(Default)	1.35
Saskatoon	22.5° (NNE)	1.16	22.5° (Default)	1.16
St. John’s	202.5° (SSW)	1.86	202.5° (Default)	1.86
Toronto	202.5° (SSW)	1.16	202.5° (Default)	1.16
Vancouver	157.5° (SSE)	2.39	157.5° (Default)	2.39
Winnipeg	67.5° (ENE)	1.80	90° (East)	1.92

4 Summary and Conclusions

For hygrothermal simulations, the wall orientation receiving the highest sum of WDR as depicted from WDR rose is commonly used, with the assumption that it will lead to the most conservative results in terms of the moisture performance of the wall. The purpose of this study was to verify that assumption. Simulations were performed for four different wall claddings of residential wood frame wall in eleven Canadian cities. Four principal orientations and the default orientation, i.e., the orientation receiving the highest amount of wind-driven rain, were evaluated. Furthermore, three different scenarios were considered: a scenario with no WDR and moisture source, a scenario with WDR but no moisture source, and a scenario with WDR and moisture source.

When the wall is protected against WDR, for all the cities studied, the north orientation is the one leading to the worst performance with respect to maximum accumulated moisture in the OSB, irrespective of the cladding material. This is because of the least amount of incident solar radiation on the north-facing wall in northern hemisphere.

When there is rain deposition on the wall or rain infiltration, the orientation receiving the highest amount of annual WDR led to the worst moisture performance for 10 cities out of 11. The exception was Montreal in which the default orientation underestimated significantly the moisture performance of the wall.

Analysis of hourly WDR distribution in the default orientation in Montreal showed that there are some intense rain events that occur throughout the year. These high rain events leads to a greater sum of WDR in the year but are less of a concern in terms of durability of the wall as water absorption capacity of the material is limited and most of the water is going to be drained off. It is recommended to equally consider both the total sum of WDR and the hourly distribution when selecting the orientation to perform hygrothermal simulations.

The present study only accounts for results obtained using the historical climate data without considering the effect of climate change. Under projected future climate, with higher expected precipitation, the response of the wall might change, and this will be included in a future study.

5 Acknowledgments

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Appendix

A1 WDR Distribution

A1.1 North Orientation

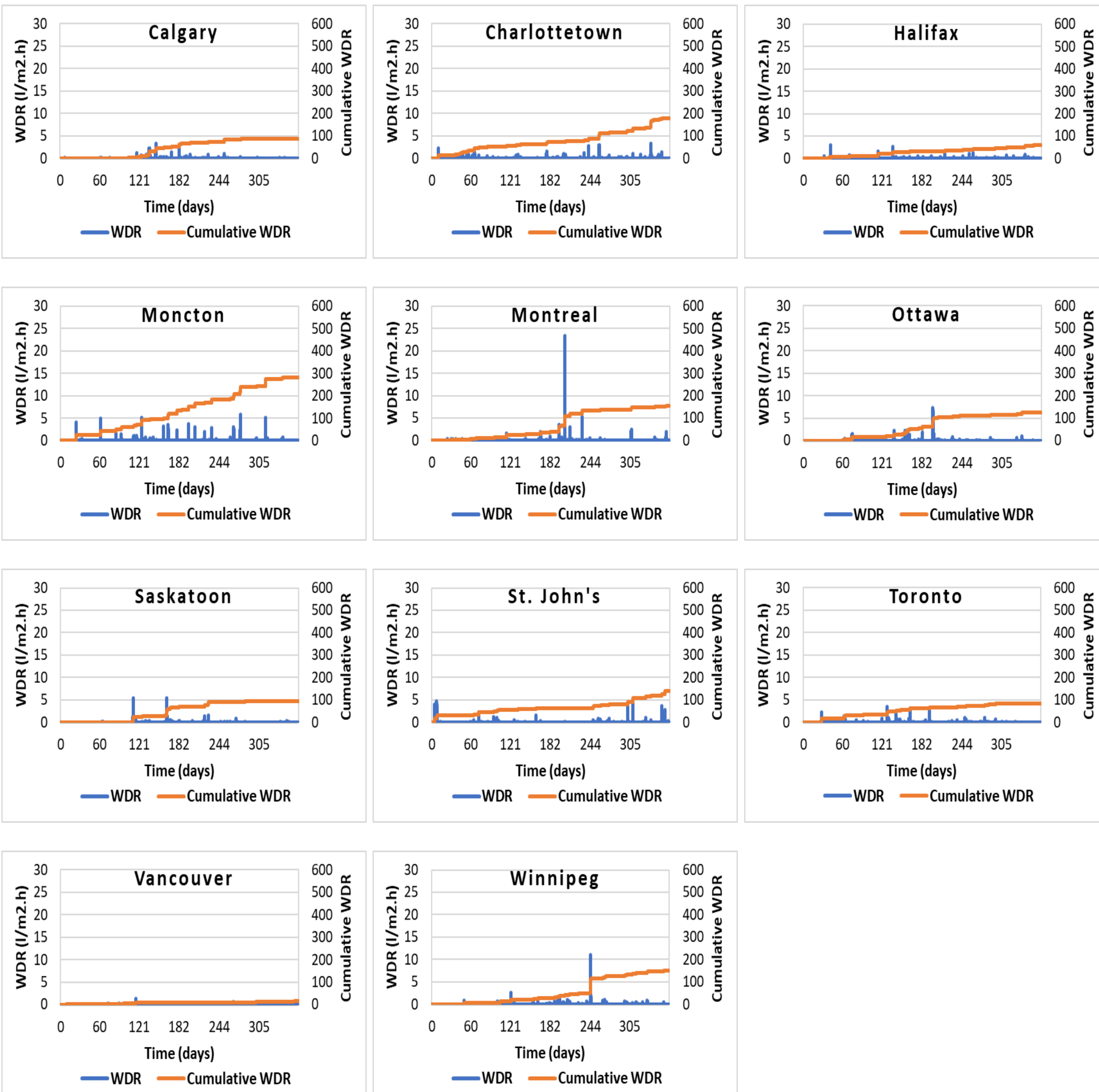

Figure A1. Hourly and cumulative values of WDR for all cities for the North orientation

A1.2 East Orientation

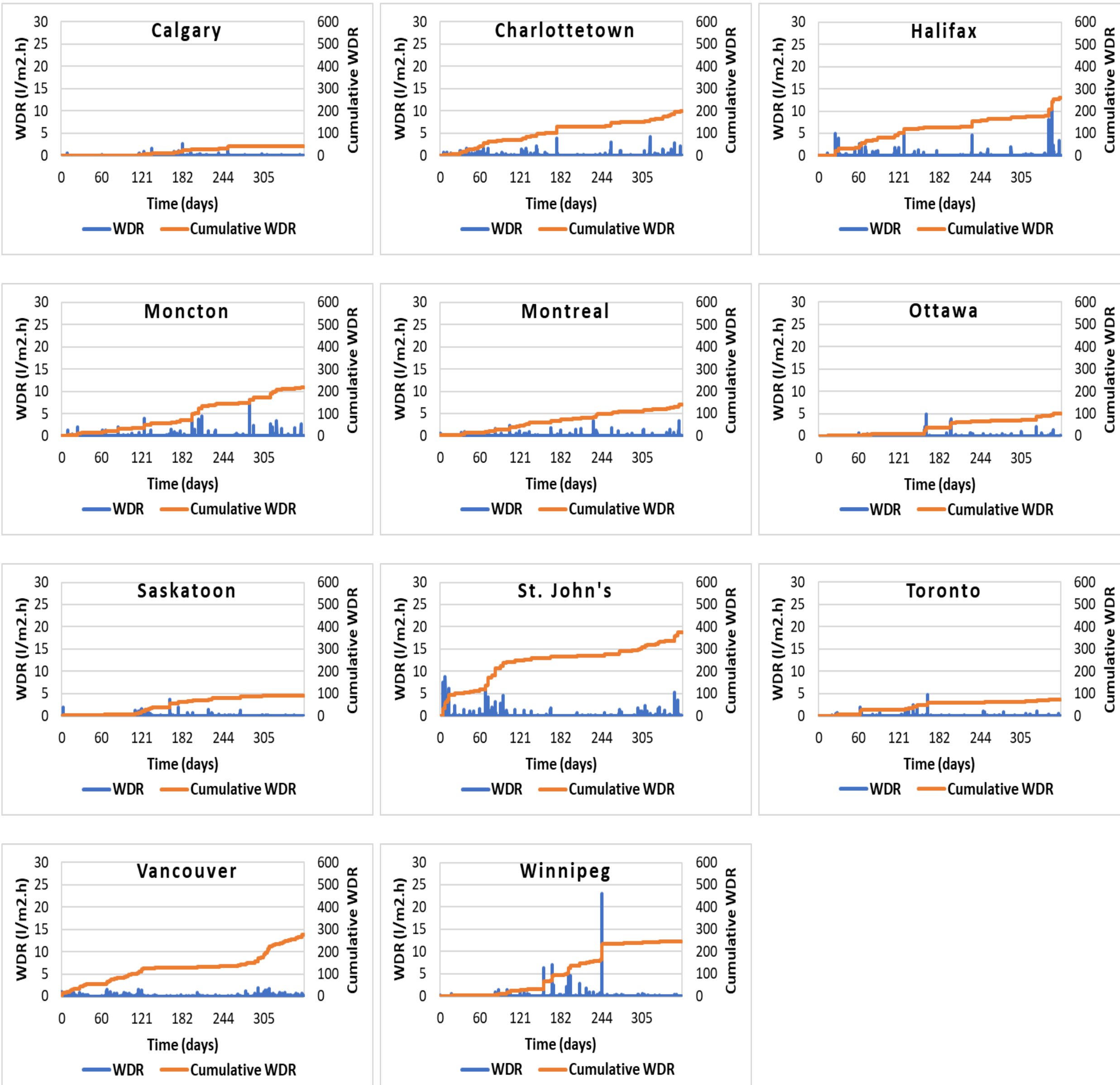

Figure A2. Hourly and cumulative values of WDR for all cities for the East orientation

A1.3 South Orientation

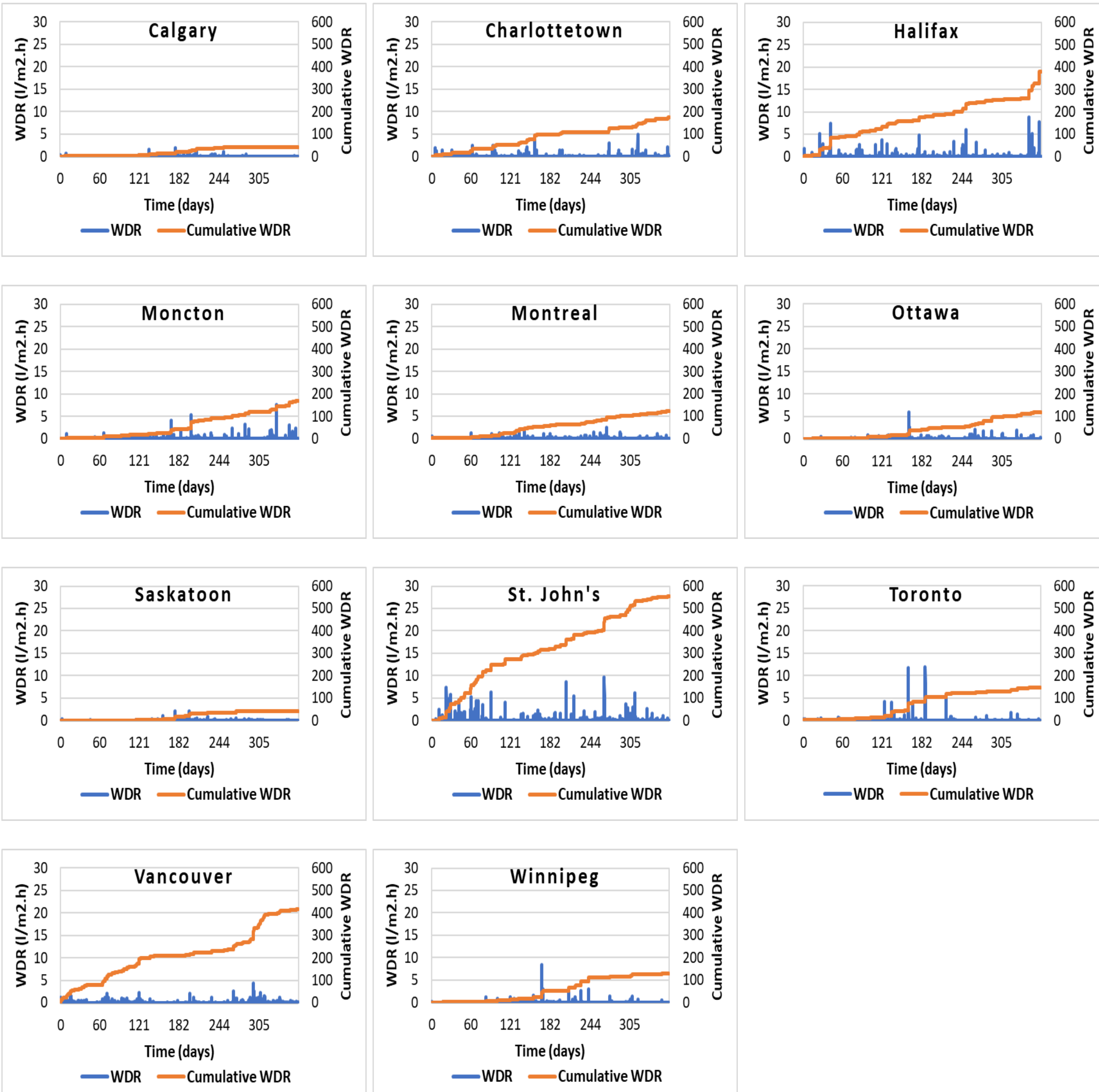

Figure A3. Hourly and cumulative values of WDR for all cities for the South orientation

A1.4 West Orientation

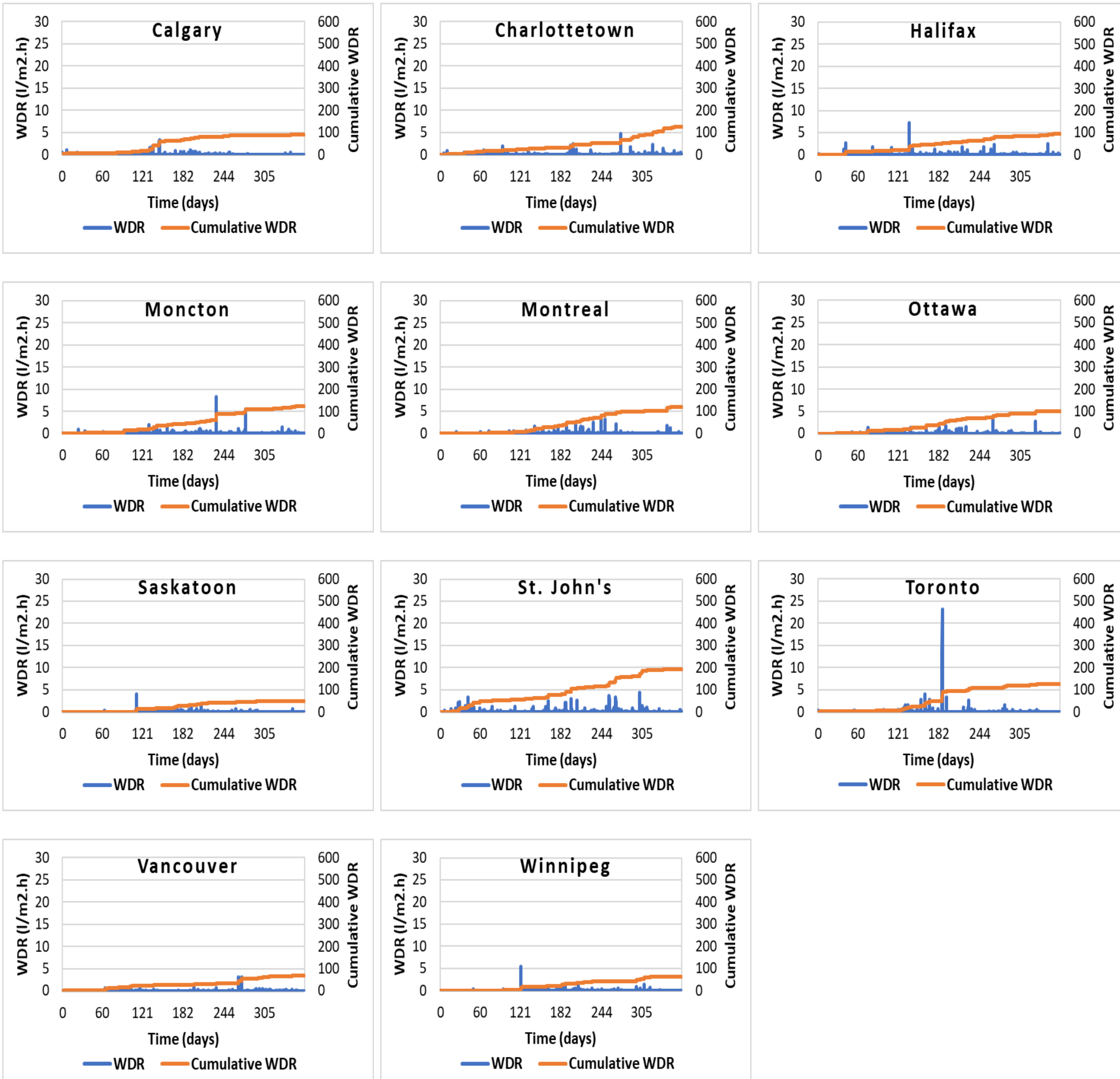

Figure A4. Hourly and cumulative values of WDR for all cities for the West orientation

A1.5 Default Orientation

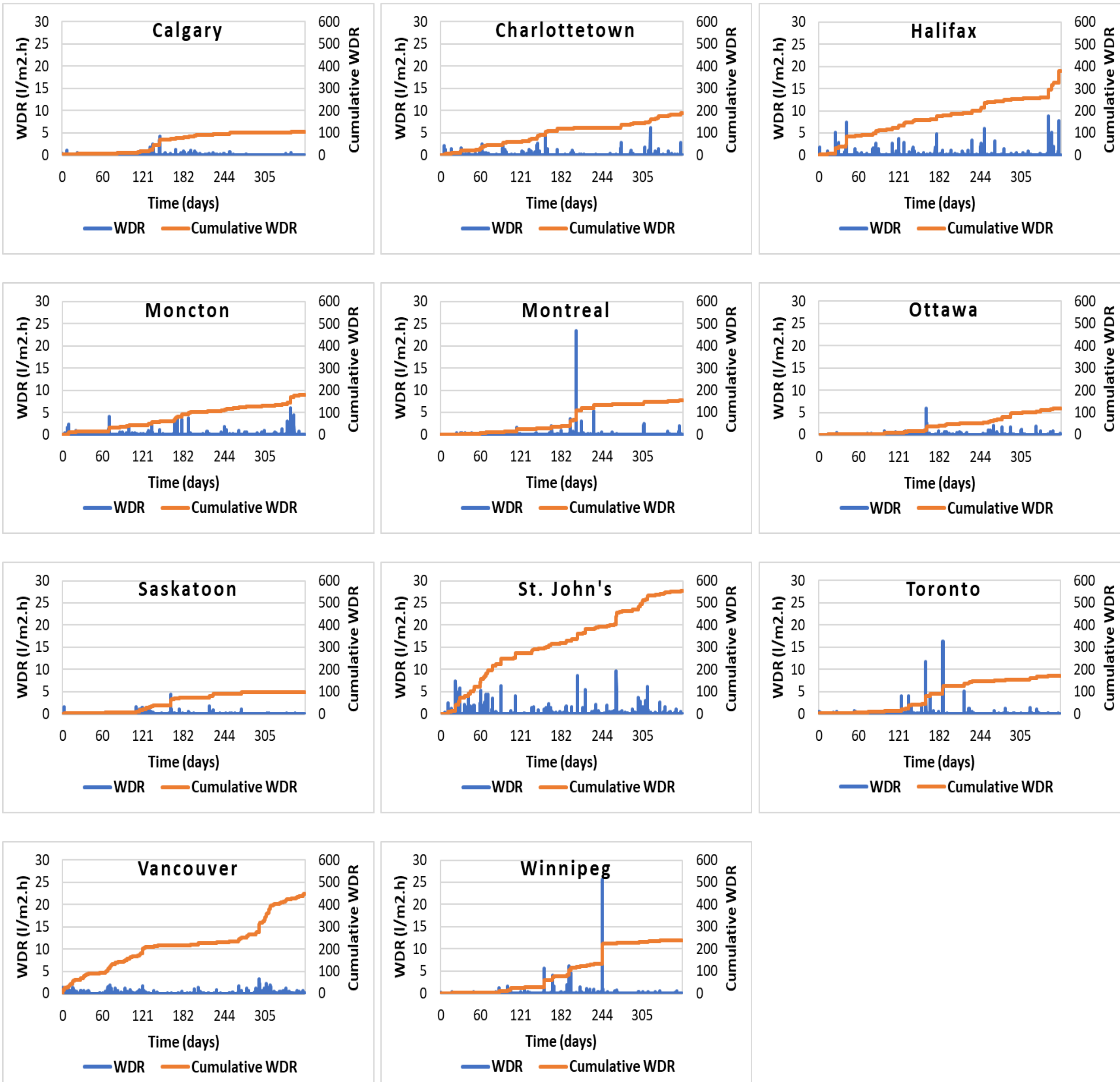

Figure A5. Hourly and cumulative values of WDR for all cities for the Default orientation

A2 Results obtained with the Mean Moisture Content (MC)

A2.1 Scenario with no WDR and no moisture source

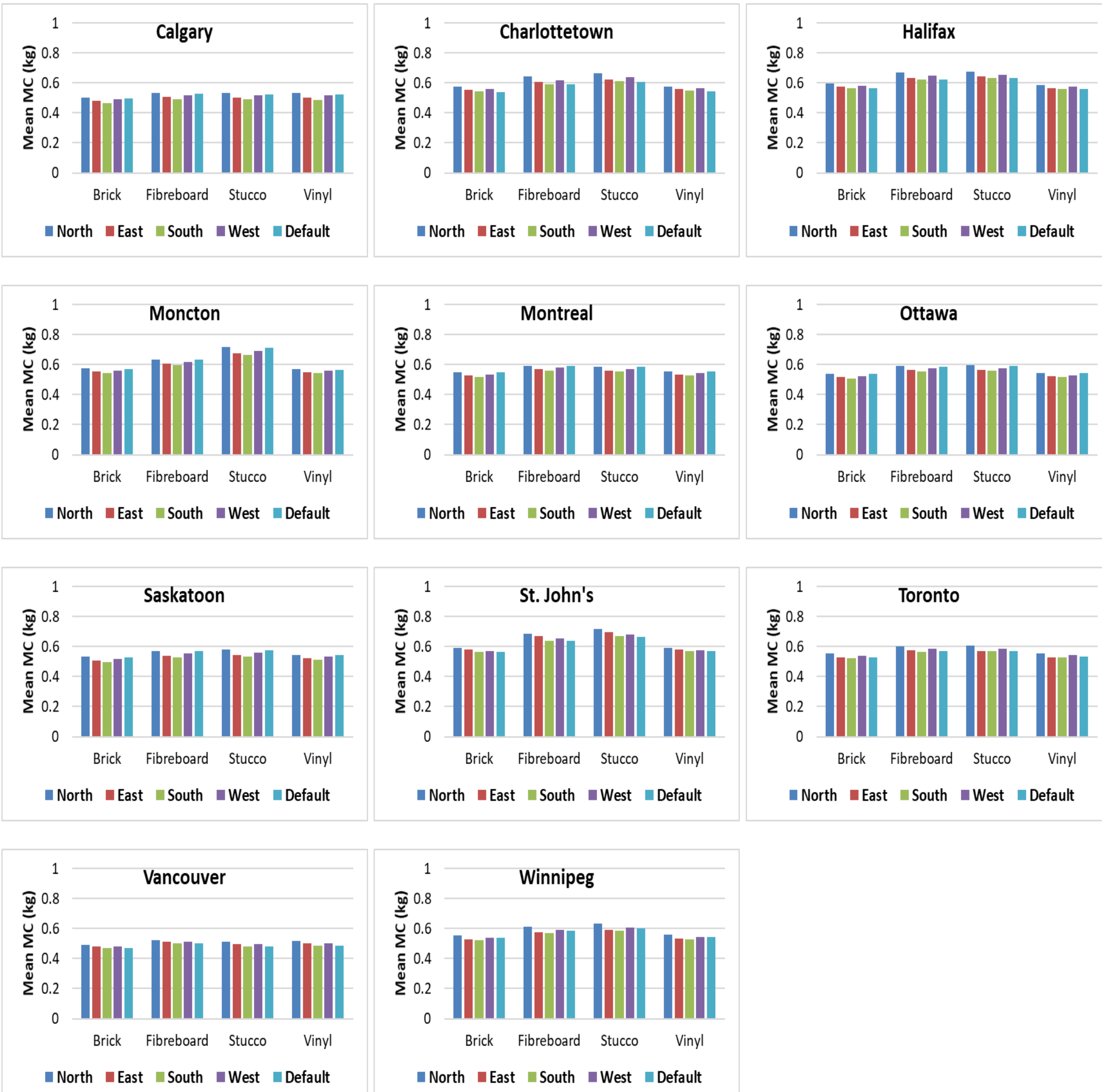

Figure A6. Mean Moisture content of OSB layer for all selected cities with no WDR and no water source

A2.2 Scenario with WDR and no moisture source

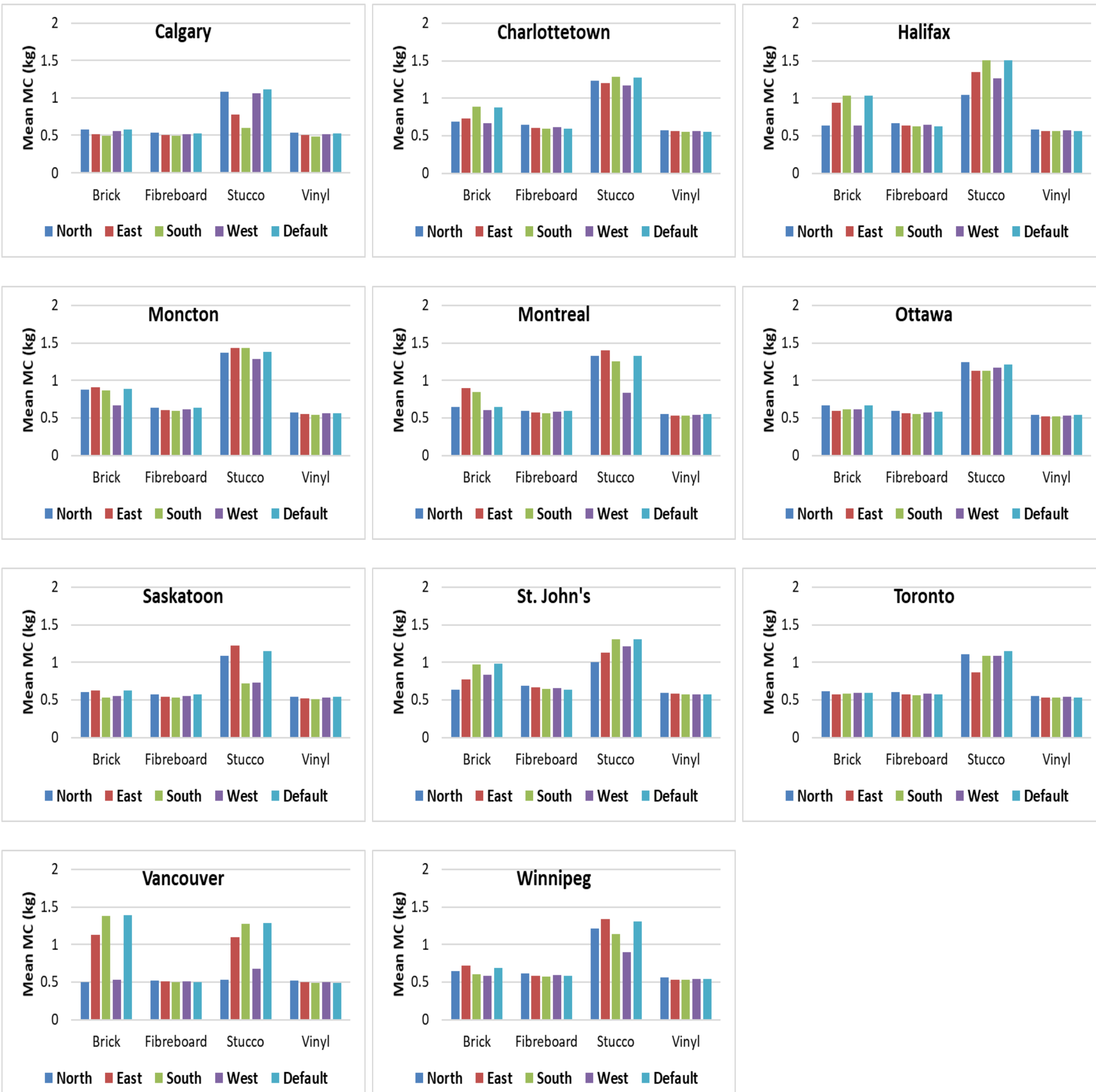

Figure A7. Mean Moisture content of OSB layer for all selected cities with WDR and no water source

A2.3 Scenario with WDR and moisture source

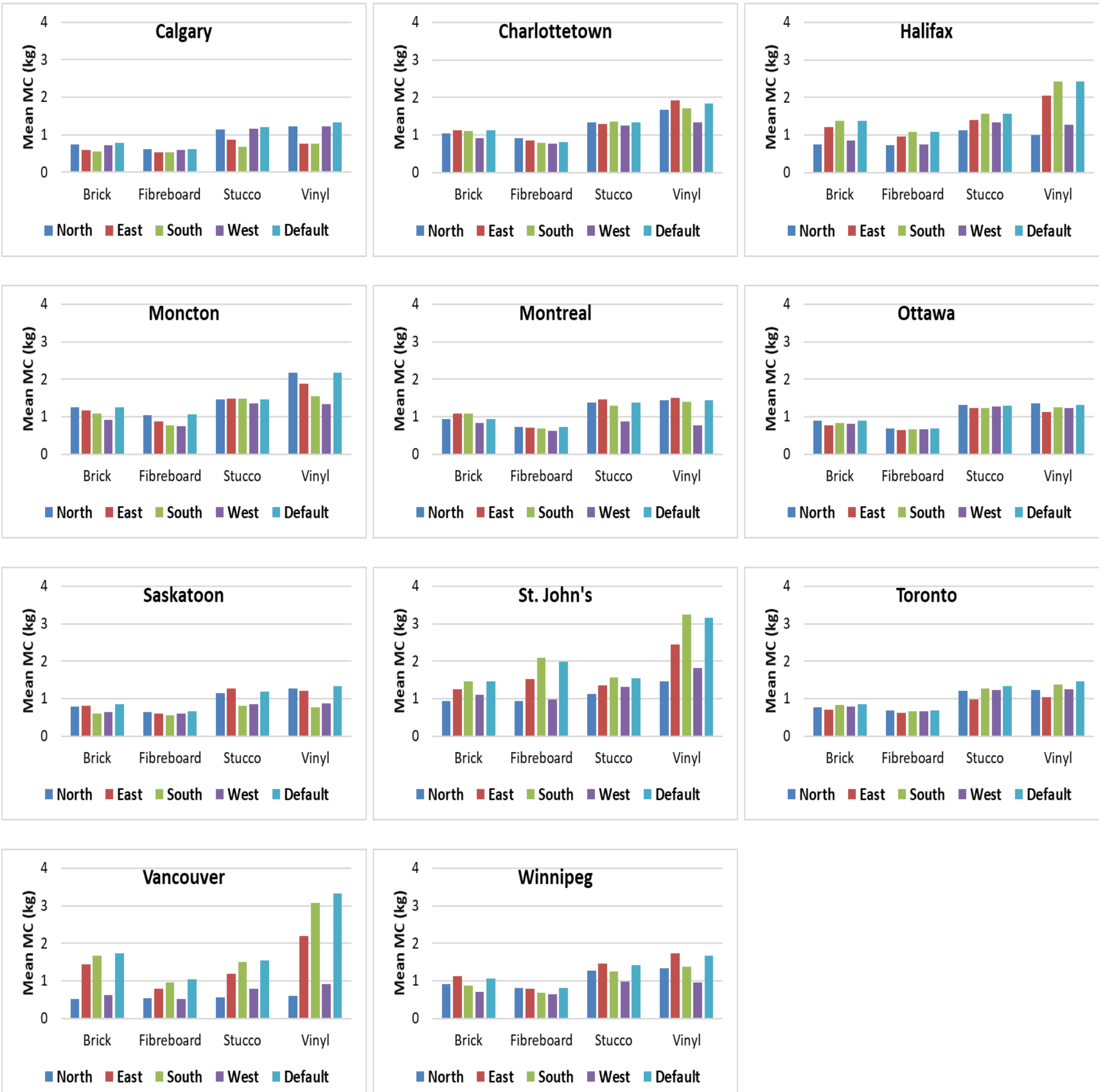

Figure A8. Mean Moisture content of OSB layer for all selected cities with WDR and water source

A3 Results obtained with the Maximum Mould Index (MoI)

The Mould Index values were negligible for the scenarios where there is no moisture present in the wall assembly. Having said that, the results were computed only for the third scenario comprising of WDR along with 1% deposition rate at the exterior layer of OSB.

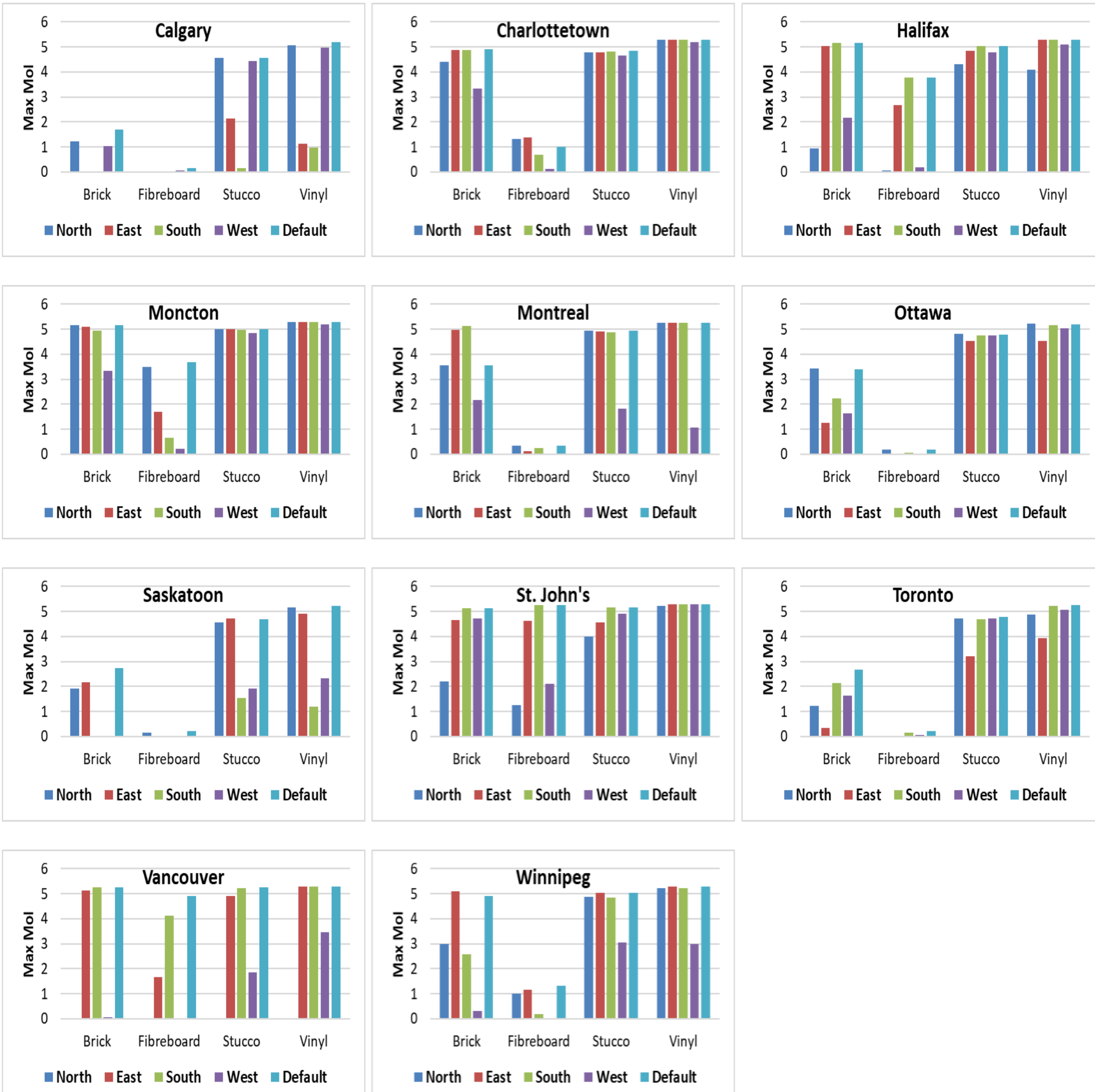

Figure A9. Maximum Mould Index at the exterior layer of OSB for all selected cities with WDR and moisture source

A4 Results obtained with the Mean Mould Index (MoI)

Similar to the analysis for Maximum Mould Index values, the results are shown only for the scenario with WDR and moisture source.

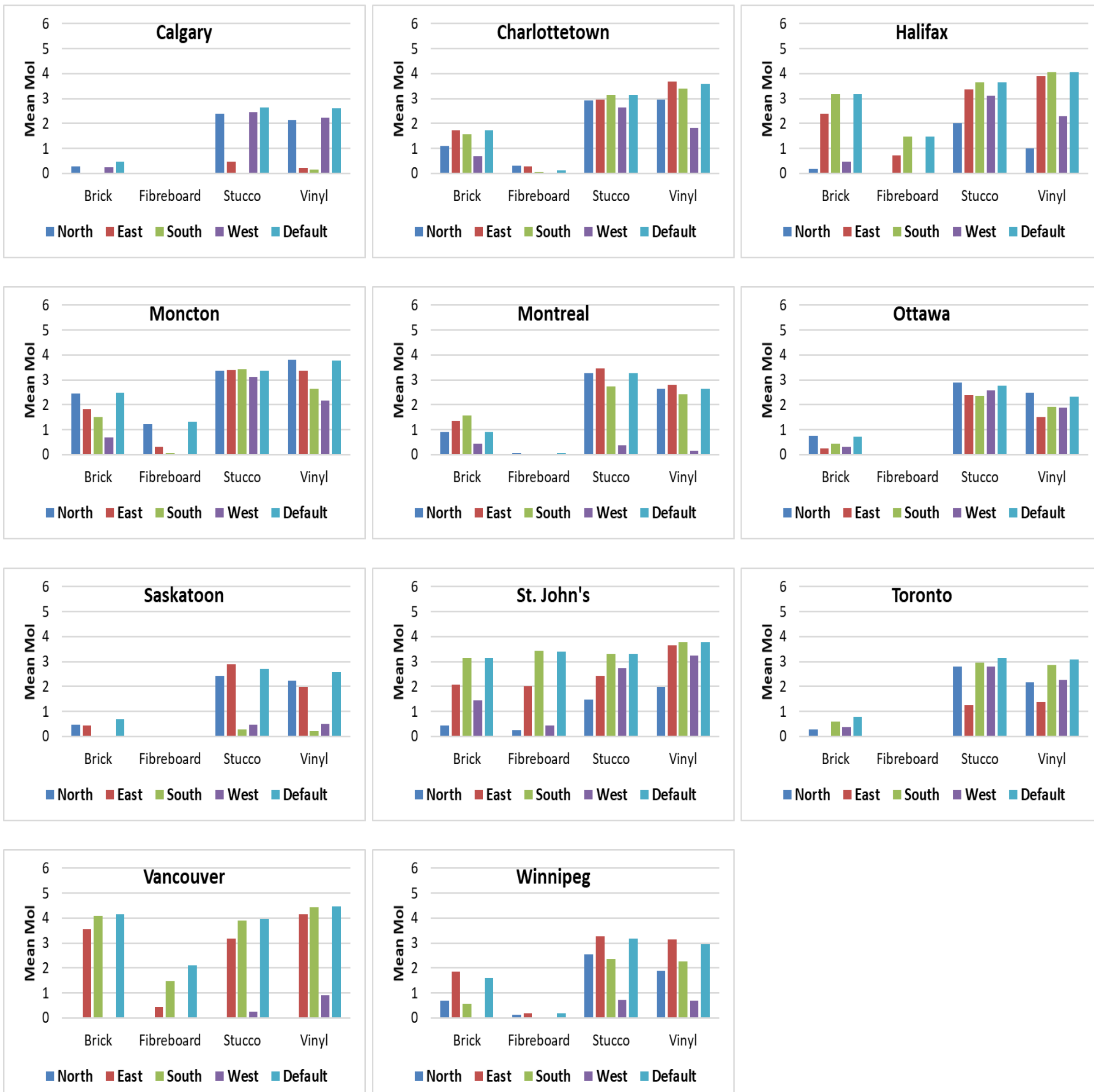

Figure A10. Mean Mould Index at the exterior layer of OSB for all selected cities with WDR and moisture source