Effects of climate change on the moisture performance and durability of brick veneer walls of wood frame construction in Canada

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Abstract. The objective of this study was to assess the potential effects of climate change on the moisture performance and durability of red matt clay brick veneer walls of wood frame construction on the basis of results derived from hygrothermal simulations. One-dimensional simulations were run using DELPHIN 5.9 for selected moisture reference years of the 15 realizations of modelled historical (H: 1986-2016) and future (F: 2062-2092) climate data of 12 Canadian cities. The mold growth index at the outer layer of the OSB sheathing panel was used to compare the moisture performance under H and F periods. Results for the base design that meet the minimum requirements of the National Building Code of Canada showed that cities within the interior of the country, characterized by a low annual rainfall, are less likely to develop significant mold growth under H and F periods, whereas cities in coastal areas, characterized by high annual rainfall, present a heightened risk to mold growth under both H and F periods. For cities located on the west coast, a possible solution could be to use a 38-mm ventilated drainage cavity as this measure would help dissipate moisture from within the cavity. On the east coast, apart from using a 38-mm ventilated drainage cavity, other measures aiming at reducing the wind-driven rain deposition (i.e., increasing overhang ratio or the height of the roof) could be introduced. However, the feasibility of such measures needs to be considered in respect to whether these are to be implemented as part of a new building or retrofit of an existing one.

1. Introduction
Climate has been warming globally, causing more frequent, intense and extreme climate events such as heat waves, droughts, wild fires, snow and ice storms, flooding, as well as wind and hail storms [1]. These changes to the climate will have significant effects on building infrastructures and communities, particularly the durability of building materials, as well as the comfort and health of building occupants [2]. These effects should be studied in order to find appropriate solutions.

Some studies have investigated the impacts of climate change on the moisture durability of wall assemblies [3-6]. Grossi et al. [3] found that much of temperate Europe will see a significantly reduced incidence of freezing in the future, which means that porous stone typically used in the monuments of temperate areas may be less vulnerable to frost damage in the future. Nijland et al. [4] evaluated possible trends and tendencies arising from changes of climate parameters in the future on the durability of building materials in the Netherlands. They concluded that damage processes affecting building materials, such as salt damage, rising dampness and biodeterioration, will intensify in the future. Nick et al. [5] investigated hygrothermal performance of ventilated attics in respect to possible climate change in Sweden. The future performance of attics studied showed that the safe solution is to ventilate the attic mechanically. Sehizadeh and Ge [6] assessed the impact of future climates in the Montréal region on...
the durability of typical Canadian residential wall assemblies retrofitted to the PassivHaus (German standard) level. While the decay risk of the plywood sheathing would decrease, the mold growth risk defined by RHT criterion defined in [7] would increase over future climates. Under future climates, mold growth risks of the plywood defined by the mold growth index exist only when rain leakage is introduced and would likely decrease for a double-stud wall assembly.

For brick veneer cladding on wood frame wall, the National Building Code of Canada (NBCC) [8] recommends minimally a 25-mm drained and vented air space (capillary break) in all cities. The capillary break is meant to minimize the water ingress into the wall assembly. It would also permit some removal of excess moisture in the drainage cavity. The objective of this study is to assess the durability and climate resiliency of wood frame wall with red matt clay brick veneer cladding meeting the minimal requirements prescribed in Part 9 of the NBCC [8].

2. Methods

2.1. Cities selected for the study
Twelve (12) Canadian cities were selected for this study. Their location and current climate design data as found in [8] are shown in Table 1. The selected cities are located in the far north of Canada (Whitehorse, YT), as well as from the west to the east coast, and cover a range of moisture index (MI) and Heating Degree-Days. The definition of moisture index can be found in [9].

2.2. Climate data
The ensemble climate data comprised of modelled hourly time-series of climate variables necessary to undertake hygrothermal simulations for a baseline period spanning 1986–2016 and 31-year long future periods when global warming levels of 2 °C and 3.5 °C (with reference to the baseline period) are expected in the future. The climate datasets were generated to capture the effects of the internal variability of the climate for future climate projections in fifteen hourly realizations (this study also referred to as “runs”) that are part of the 50-member datasets derived from the large ensemble of climates simulated by the Canadian Regional Climate Model (CanRCM4) - version 4. Each of the fifteen hourly realizations was initialized under a different set of initial conditions in the Canadian Earth System Model (CanESM2). A detailed description of the procedure used to generate modelled historical (H) and projected future (F) climate data can be found in [10].

The differences in some of the climate variables between all the runs of H and F datasets for all the twelve cities considered are illustrated Figure 1. It can be observed that in all cities of this study, the: (i) Annual average temperature (T) will increase significantly between the two timelines; (ii) Values for relative humidity (RH) will generally increase; (iii) Total annual rainfall will generally increase; and (iv) Average annual wind speed will decrease with the one exception for Whitehorse, where in the future it will almost remain at the same level as in H period. Figure 1 also shows that for both H and F periods, Vancouver (west coast) is the warmest city; cities on the east coast (Moncton, Charlottetown, Halifax and St. John’s) exhibit the highest RH values whereas Vancouver is amongst the cities having the lowest average annual RH values. The average total annual rainfall is relatively greater for cities in coastal areas as compared to those located in the interior of the country. Vancouver has the lowest annual average wind speed whereas cities located on the east coast have the highest wind speed. Given the differences in climate variables among cities and between H and F periods, one should expect differences in moisture responses among cities and between H and F periods. Variability in the different realizations of the modeled F climate data, as shown by the variations in boxplots, should also lead to multiple possible moisture responses.

2.3. Building and wall configuration for the base design
A 3.5-storey (10-m height) wood frame building of typical residential construction and having a low-slope roof was considered for this study; it was assumed that that the building was located in a suburban area.
Table 1. Location and climate design data of the selected cities.

| City (Province)   | Latitude (°) | Longitude (°) | Time Zone | Climate Zone | HDDb | Moisture Index | Rain (mm) |
|------------------|--------------|---------------|-----------|--------------|------|----------------|-----------|
| Whitehorse (YT)  | 60.7         | -135.1        | -8        | 7B           | 6580 | 0.5            | 170       |
| Vancouver (BC)   | 49.3         | -123.1        | -8        | 4            | 2825 | 1.4            | 1325      |
| Calgary (AB)     | 51.1         | -114.1        | -7        | 7A           | 5000 | 0.4            | 325       |
| Saskatoon (SK)   | 52.1         | -106.7        | -6        | 7A           | 5700 | 0.4            | 265       |
| Winnipeg (MB)    | 49.9         | -97.1         | -6        | 7A           | 5670 | 0.6            | 415       |
| Toronto (ON)     | 43.7         | -79.4         | -5        | 5            | 3800 | 0.9            | 730       |
| Ottawa (ON)      | 45.3         | -75.4         | -5        | 6            | 4500 | 0.8            | 750       |
| Montreal (QC)    | 45.5         | -73.6         | -5        | 6            | 4200 | 0.9            | 830       |
| Moncton (NB)     | 46.1         | -64.8         | -4        | 6            | 4680 | 1.0            | 850       |
| Charlottetown (PE)| 46.2       | -63.1         | -4        | 6            | 4460 | 1.1            | 900       |
| Halifax (NS)     | 44.7         | -63.6         | -4        | 6            | 4000 | 1.5            | 1350      |
| St-John's (NL)   | 47.6         | -52.7         | -4        | 6            | 4800 | 1.4            | 1200      |

Climate zones 4, 5, 6, 7A and 7B correspond to zone with HDD ranging from 2000 to 2999, 3000 to 3999, 4000 to 4999, 5000 to 5999, and 6000 to 6999, respectively.

HDD: Heating Degree-Days below 18 °C

Figure 1. Boxplots of the run averaged annual average temperature, relative humidity and wind speed, and annual sum of horizontal rainfall for the historical (H) and future (F) time periods in the 12 cities considered.

The wall assembly of the base design was composed of (from exterior to interior): 90-mm red matt clay brick cladding; 25-mm drainage cavity; 0.24-mm sheathing membrane (30 minute asphalt impregnated building paper); 11-mm Oriented Strand Board (OSB); 140-mm or 184-mm mineral fibre insulation located in the stud cavity for buildings in cities falling within climate zone 4 to 7A, and that in 7B, respectively (Table 1); 0.15-mm polyethylene vapor barrier; 12.7-mm interior grade gypsum panel with latex primer and one coat of latex paint. This wall assembly configuration, associated with weep holes spaced not more than 800 mm apart at the bottom of the wall, meets the minimum energy requirements and prescription for minimizing damage due to water ingress. It was also assumed no air leakage through the wall so as to only assess the risk related to water ingress.
2.4. Hygrothermal simulations
Hygrothermal simulations were performed using DELPHIN v5.9 on a vertical section of the wall passing through the middle of the stud cavity, far from and not including spruce wood studs. In this position in the wall, the flow is almost unidirectional and can be represented by a one-dimensional configuration. Material properties of wall components were obtained from [11].

2.4.1. Moisture reference years. For each climate run, the moisture reference years (MRYs) were composed of two representative years selected based on their MI as defined in [9]. The first and second years were those within the 31-year series with, respectively, the median and the 90 percentile value for MI.

2.4.2. Indoor and initial conditions. Indoor ambient T and RH were set constant to 21 °C and 50%, respectively. The initial T and RH for all components were set to 21 °C and 80%, respectively. As air leakage was not considered and with the presence of vapor barrier, the impact of indoor RH on the performance of OSB is limited.

2.4.3. Wall orientation and wind-driven rain calculation. Wind-driven rain (WDR) impinging on the building façades was determined based on ASHRAE Standard 160 [12], assuming an exposure factor of 1.0 (building less than 10-m height with medium exposure) and a deposition factor of 0.5 (low-slope roof). The wall orientation in each realization was selected as the direction in which the rain deposition rate was the highest for MRYs of that realization. Figure 2 shows the distribution of the 15 runs’ sums of WDR in the selected wall orientation over the two selected MRYs for historical and future periods in the 12 cities considered. In all the cities, there is a trend of increasing WDR in the future for the two selected MRYs.

2.4.4. Boundary conditions. The indoor convective heat transfer coefficient was set to 2.5 W/m²K, and the outdoor convective heat transfer coefficient was calculated using Equation (1) [13]:

\[ \alpha_{ce} = 4 + 4V \] (1)

were \( \alpha_{ce} \) is the outdoor convective heat transfer coefficient in W/m²K and \( V \) is the wind speed (m/s). The outdoor and indoor convective vapour transfer coefficients were calculated using the corresponding convective heat transfer and the Lewis number. The indoor radiative heat transfer coefficient was set to 5.5 W/m²K [13], whereas the longwave exchange between the cladding surface and the environment was explicitly calculated assuming a longwave emissivity of 0.9 for the surface and the surrounding ground, and 1.0 for the sky. The ground surface temperature and albedo were set to the air temperature and 0.2, respectively. The shortwave absorption coefficient of the cladding was set to 0.6, assuming a red-coloured surface.

2.4.5. Moisture source and air change rate. The moisture source was assumed to be 0.3% of WDR and was applied on the exterior surface of the sheathing membrane. This value is rather low in comparison with the value of 1% recommended in ASHRAE STANDARD 160 [12]. However, this value was selected based on observations from water penetration tests (results to be published), that determined that the value of 1% is largely overestimated for brick veneer walls having a drainage cavity of 25 mm. An air change per hour (ACH) of 3 was used in all cities. In fact, for a vented wall, as was used for the base design and having open head joints at every 800 mm, the ACH is in the range 0 to 10, with the distribution of values for ACH largely skewed to the left [14-15].

2.4.6. Performance evaluation. The outer layer (0.5 mm) of the OSB wood panel was used as the critical location from which to extract results (i.e. RH and T) from hygrothermal simulations. These two variables were then used for calculating the mold growth index (MoI) profiles with the use of the empirical formula given in [16]. The acceptable solution was the one for which 100% of the climate realizations had a mean value of MoI less than 1 (initial stage of mold growth).
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Figure 2. Boxplots of the 15 runs’ sums of wind driving rain over the two MRYs for historical (H) and future (F) time-periods in the 12 cities studied.

2.5. Alternative wall designs
Different design options were further investigated, including: 1) replacing the type of water resistive barrier (30 min. building paper / BP30, vapour permeance = 440 ng/m²sPa) with either 60 min. building paper (BP60, vapour permeance = 1510 ng/m²sPa), spun bonded polyolefin (SBPO, vapour permeance = 4080 ng/m²sPa), bituminous felt #15 (FB15, vapour permeance = 28 ng/m²sPa) or by doubling (2X) the layers of these membranes; 2) replacing the OSB sheathing with plywood (PLW), exterior grade gypsum board (GYP) or asphalt coated fibreboard (FBD); 3) increasing the slope of the roof from low- (LSlope) to steep-slope (SSlope), corresponding to changing the WDR deposition rate from 0.5 to 0.35 [12]); 4) increasing the depth of the drainage cavity from 25 mm to 38 mm; 5) increasing the ventilation in the 25-mm drainage cavity from 3 to 5 ACH by implementing openings at the top of the cladding (ventilated as opposed to vented) or to 11 ACH by increasing the number of openings at top and bottom from 2 to 4 per 1.2 m of wall; and 6) increasing the ventilation in the 38-mm drainage cavity from 2 to 4 ACH by implementing openings at the top of the cladding or to 7.5 ACH by increasing the number of openings at top and bottom from 2 to 4 per 1.2 m of wall. These ACH values were estimated from theoretical calculations based on the work of [14] and a pressure differential of 1.5 Pa. The option of changing the roof slope may not be applicable for retrofitting existing buildings but only for new ones.

3. Results and discussion

3.1. Base wall design
Figure 3 shows the distribution of run mean values of MoI obtained for the base design of the brick veneer wall assembly having red matt clay brick as cladding under H and F periods in all the cities considered, and for the scenario with and without moisture source.

There seems to be not much difference between the scenarios with and without moisture source. For example, for future period, the maximum mean mold index in Vancouver is about 3.6 for the scenario without moisture and 3.9 for the scenario with moisture source. The moisture source was set to 0.3%WDR and applied on the exterior surface of the sheathing membrane. This is less than 1%WDR recommended in ASHRAE 160 [12] but justifiable for brick veneer wall having 25-mm drainage cavity. These results would certainly have been different if the moisture source had been applied on the exterior or interior surface of the sheathing panel as opposed to the exterior of the sheathing membrane.

There is general trend of increasing risk of mold growth in all the cities studied but Whitehorse where the risk of mold growth under both H and F periods is nil. This observation is in agreement with the increase in T and total annual rainfall (Figure 1) or WDR (Figure 2) in the future. It is also in agreement with other studies in which it has been suggested that the increase in T and WDR in certain regions will likely increase the risk of mold growth [4].
There is a significant risk of mold growth under both historical and future periods in the cities of Vancouver, Halifax and St. John’s and for just the future period in Moncton and Charlottetown. Unlike in the cities located in the coastal areas with heightened risk to mold growth, the wall assembly having red matt clay brick as cladding seems to be climate resilient in the cities located in the interior of Canada as the mean MoI obtained for the 15 runs of the future climate data set are all less than 1.0.

The results obtained for H period in the cities of Vancouver, Halifax and St. John’s may not reflect what happens in reality. In fact, the climate data used for the H period was modelled (to permit comparison with F period) and may not reflect the actual climate conditions. As well, similar ACH of 3 was used in all the cities or it is known the air flow rate in the drainage cavity is driven by outdoor temperature (stack effect) and wind speed [14].

Given the heightened risk of mold growth in the coastal areas and the potential increase in the future for wood frame walls having red matt clay brick as cladding, there is a need to explore alternative solutions to reduce this risk. Two cities were selected: Vancouver on the west coast and Halifax on the east coast. As well, only the realization of the future climate data having yielded the maximum mean mold index in each city was used with the scenario with moisture source. This is based on the fact that in most of the cases, the risk is higher in future than in historical time period and higher for the case with moisture source than for the case with no moisture. Lowering the mean mold index for the worse climate realizations of future time period will necessary lower that of all other realizations.

3.2. Alternative wall designs

Figure 4 shows the results obtained with some possible modifications on the base design in Vancouver and Halifax, using in each case, the most severe realization of future climate. None of the single intervention shown in Figure 4 is able to reduce the mean value for MoI below the threshold value of 1.0. Amongst the different sheathing membranes tested, only SBPO seems to have substantial effects on the moisture response of the walls in both cities, especially if two layers are used. The use of fibreboard or exterior grade gypsum sheathing permits a substantial reduction in the mean value of MoI for buildings located in either city, in comparison with the use of plywood or OSB sheathing. The effect of reducing the rain deposition rate from 0.5 to 0.35 (variation in type of roof structure) has more impact on the moisture response of the wall assemblies in either city, although a slightly greater effect in Vancouver.

The impacts of depth and ventilation of the drainage cavity are shown in Table 2. Increasing the depth of the drainage cavity alone is not sufficient to control the mold growth risk whereas increasing the ventilation rate, by implementing openings at the top and/or increasing the number of openings, has more significant impact on the moisture response of the wall.

With the recommended 25-mm ventilated drainage cavity, if the number of opening is increased from two to four, the mean MoI will be reduced to 1.43 and 1.38 in Vancouver with BP30 and SBPO,
respectively, and to 2.00 and 1.65 in Halifax using BP30 and SBPO, respectively. Despite this significant reduction, there's still a potential risk of mold growth, even when using SBPO. Therefore, to reduce the mean MoI to below the acceptable level of 1.0, the number of openings or the size of the openings need to be increased more. Alternatively, the number of openings can be kept to four but associated with actions to reduce the amount of WDR loads (wider roof overhangs, steep-slope roof).

Figure 4. Impacts of different alternative solutions on the mean mold growth index in the cities of Vancouver and Halifax. The red line represents the acceptable limit for the mean mold growth index. The red bar refers to the reference case.

With a 38-mm ventilated drainage cavity, if the number of openings is increased from two to four, the mean MoI will be reduced to 1.02 and 0.98 in Vancouver with BP30 and SBPO, respectively, and to 1.90 and 1.58 in Halifax with BP30 and SBPO, respectively. This design with 38-mm cavity and four openings at the top and the bottom would suffice to decrease the risk to an acceptable level in Vancouver, but barely in Halifax. In fact, increasing the ACH in the 38-mm cavity does not impact the moisture response significantly in Halifax because outdoor air is more humid and bring more vapour in the cavity. As such, ventilation alone could not be able to reduce the risk in Halifax. It should be coupled with other actions such as using wide overhangs or increasing the slope of the roof or using exterior gypsum sheathing that is more vapour permeable.

Table 2. Impact of drainage cavity depths and ventilation on the mean mold index in Vancouver and Halifax using either 30 minute building paper (BP30) or spun bonded polyolefin (SBPO).

| City     | Cavity depth (mm) | Number of Openings | Air change (h⁻¹) | Mold dindex BP30 | Mold dindex SBPO |
|----------|-------------------|--------------------|------------------|------------------|------------------|
| Vancouver| 25                | 2                  | 5                | 3.23             | 3.13             |
| Halifax  | 25                | 2                  | 5                | 3.45             | 2.78             |
| Vancouver| 25                | 4                  | 11               | 1.43             | 1.38             |
| Halifax  | 25                | 4                  | 11               | 2.00             | 1.65             |
| Vancouver| 38                | 2                  | 4                | 2.61             | 2.52             |
| Halifax  | 38                | 2                  | 4                | 3.19             | 2.57             |
| Vancouver| 38                | 4                  | 7.5              | 1.02             | 0.98             |
| Halifax  | 38                | 4                  | 7.5              | 1.90             | 1.58             |

4. Conclusions
Results for the base design of brick walls having red matt clay brick as cladding and that meets the minimum requirements of the National Building Code of Canada show that cities having a
comparatively reduced annual rainfall within the interior of the country are less at risk to mold growth under historical and future periods whereas those cities located in coastal areas present a risk to mold growth under both historical and future periods, with an increase in the future. On the west coast, a solution to minimize the mold growth risk could be to increase the drainage cavity to 38 mm while ensuring an adequate air exchange by use of a ventilated cavity wall. On the east coast, a solution could be to consider using a 38-mm ventilated drainage cavity coupled with some measures such as those aiming at reducing the wind-driven rain deposition such as increasing the overhang ratio or the height of the roof. These results could be further enlightened by considering the variability in material properties and other uncertainties in the simulation input parameters, as well as the practicality of the proposed solutions.

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