Impact of climate change on the wind-driven rain exposure of a historical building

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Abstract. Due to climate change, considering future rain event patterns and increased average temperatures, wind-driven rain exposure of buildings can increase. In order to assess the future damage risk related to moisture, it is essential to take the future wind-driven rain load into account. Computational fluid dynamics simulations of wind-driven rain are performed on a historical building located in Victoria, BC, Canada using the current and future weather data. The results show an increased wind-driven rain exposure of the building by up to 20%, especially in façade regions which are already exposed to a higher amount of rain.

1. Introduction

Wind-driven rain (WDR) is a significant moisture source on building facades with potentially negative effects on hygrothermal performance and durability. The areas over the building envelope that are exposed to high amounts of rain usually have a higher risk of deterioration due to moisture. Deterioration of building materials due to WDR becomes an important issue when retrofitting old or historical buildings. Therefore, a significant amount of WDR research focuses on the quantification of WDR intensity of building facades [1] and the moisture damage risk related to the rain absorption into porous building materials and leakage into facades [2].

Climate change can have an impact on the WDR exposure of buildings and thus on moisture-induced damage risks. Changing rain event patterns and increased average temperatures can lead to an overall increase in moisture exposure. Moreover, increasing temperatures can lead to an increased risk for freeze/thaw damage in northern countries. Therefore, it is critical to take into account the future WDR load when planning for the preservation and maintenance of buildings.

The present study uses computational fluid dynamics (CFD) simulations of WDR using a validated Eulerian multiphase model to estimate the rain exposure of a historical building located in an urban area in Victoria, BC, Canada. The analyses are performed for the current weather conditions and the predicted future conditions with climate change, with an aim to provide insights into the long-term WDR performance of the historical building.
2. Methodology

2.1. Numerical modeling of wind-driven rain

WDR intensity on building surfaces is commonly calculated based on steady-state simulations of wind and rain. Rain calculations are typically one-way coupled with wind-flow field, ignoring the effect of raindrops on the wind flow. First, the spatial distributions of 'catch ratio' are obtained from the surface wetting due to different raindrop sizes in the air. Catch ratio is the non-dimensional WDR intensity, which is normalized by the horizontal rainfall intensity. This step creates a database of spatial distributions of catch ratio for a range of values of reference wind direction, wind speed and rainfall intensity. Then, the calculated catch ratio values are interpolated for each position on the building surface based on the transient meteorological data in order to obtain temporal variation of wetting [3].

Steady Reynolds-averaged Navier-Stokes (RANS) CFD simulations are used to calculate the incompressible wind-flow field. As for the WDR simulations, a validated Eulerian multiphase model is used [4,5]. Rain is regarded as a continuum and separate governing equations are solved for each rain phase. In this methodology, rain phases correspond to classes of raindrop size for a range of droplet diameters which show similar WDR behavior. WDR simulations provide the distribution of rain fraction and rain velocity everywhere in the computational domain. Then, the catch ratio, $\eta$, on each location on the building can be calculated as follows:

$$\eta = \frac{R_{\text{wdr}}}{R_h} = \int f_h(R_h, d) \eta_d(d) \, dd$$

(1)

where the specific catch ratio, $\eta_d(d)$, is related to rain phase with diameter $d$, and the catch ratio, $\eta$, is related to the entire spectrum of raindrop diameters observed at a rain intensity. In equation (1), $R_{\text{wdr}}$ denotes the WDR intensity, $R_h$ the horizontal rain intensity through the horizontal plane and $f_h(R_h, d)$ the raindrop-size distribution through the horizontal plane at rain intensity $R_h$. The governing equations of rain phases are implemented by the authors into a solver based on OpenFOAM v6 (download available [6]).

2.2. Future climate prediction

Intergovernmental Panel on Climate Change (IPCC) [7] reports an overall increase in global precipitation that will accompany the predicted increase in global temperatures. In the present study, the current weather data is modified using a simplified weather morphing method to reflect the potential changes in rain events. The changes in rainfall amount predicted by the Canadian Earth System Model CanESM2 [8] are used, which are extracted from the Pacific Climate Impacts Consortium (PCIC) Climate Explorer tool [9]. The Capital Regional District (CRD) is selected as the analysis region, which includes Victoria, BC, Canada. An RCP8.5 scenario is considered, as it assumes a worst-case scenario, representing high emission conditions.

The average daily precipitation values for each month are selected for the current conditions, along with the predictions for 2070-2099. Subsequently, for each month, the modified rainfall intensity is obtained from the current rainfall intensity and the percentage change:

$$r_{h,\text{mod}} = r_h \frac{\Delta r_h}{100} + 1$$

(2)

The effects of climate change on wind patterns and velocity are assumed to be relatively modest [10], so no additional modifications are made for the wind flow conditions. However, it should be noted that there is a potential increase predicted in terms of the number of high-intensity gust events, which are currently infrequent [10]. At the same time, the available data on future wind-flow patterns have a high uncertainty, especially at urban level.
3. Description of case study

The case study focuses on The Empress Hotel, a heritage building located on the Inner Harbour of Victoria, where there is significant exposure to WDR. The building is listed as a national historic site and has just undergone significant restoration efforts in the recent years. The Inner Harbour faces west, while the path to the ocean from the harbor is south (figure 1). The topology of the surroundings is relatively flat with some small hills located approximately 15 km to the west.

![Figure 1](image)

**Figure 1.** a) Location of Inner Harbour, Victoria, BC, Canada Location. b) Locations of weather stations (Yellow = Rain, Blue = Wind) and of the historical building (Red) © Google Maps

3.1. Current (measured) and future (predicted) meteorological conditions

The available meteorological data from the nearby weather station at the Inner Harbour (at a distance of 1.5 km) is hourly data, which can introduce errors in WDR analyses based on the guidelines provided in Blocken and Carmeliet [11], which require data acquired at a time resolution of 10 min or hourly data obtained by weighted-averaging of 10-min data. A compromise is made by using the rainfall intensity measurements at 15-min intervals provided by the University of Victoria, located approximately 6 km to the northeast (figure 1b), with hourly wind data from the Inner Harbour, as this weather station provides local wind-flow conditions and also is located to the west, where the building is the most exposed.

An analysis of the measured weather data is performed to determine the meteorological conditions during rain over the course of three years (2016-2018). Figure 2 shows a wind rose from the measured data including only the periods of rainfall. During rainfall, three primary wind directions are observed. WDR events coming from west-southwest have the highest wind speed. West is chosen as the wind direction for analysis, as the main façade of the building is the most exposed in this direction and the weather station with the wind data is located upstream.

For the three-year duration (2016-2018), the average annual precipitation is 680 mm, while the average rain intensity is 1.70 mm/h, representing light rain. For each month in a year, daily average precipitation values for the current period 1980-2010 and the predicted future period 2070-2099 are provided in figure 3a. The wetter periods in fall, winter and spring are anticipated to become even wetter, and the drier season of summer is anticipated to become even drier. Based on the future predicted values, the total quantity of annual rain will increase. Meteorological conditions are summarized in figure 3b based on the data obtained from the weather stations for rainy hours with wind directions between northwest-southwest. Here, average wind speed represents the weighted average values with rainfall intensity. While rainfall intensity does not change significantly throughout the year, wind speed is much larger during the wetter months, which indicates a larger WDR exposure of the western facade during these periods.
3.2. Computational domain and numerical settings

The computational domain includes the nearby buildings as well as the historical hotel building as shown in figure 4a. There are a number of relatively large residential towers located to the east, while the urban area to the north consists of primarily low-to-mid-rise commercial buildings. The model of the hotel building includes the detailed shape of the roof, façade details and overhangs. Past research show a significant influence of roof overhangs, façade detailing such as window sills [12] and recessed façade [13] on WDR intensity. The applied Eulerian multiphase model is convenient especially for such geometries with fine details, as it quantifies the WDR intensity on all surfaces in the computational domain. The surrounding buildings are modeled with simplifications with only their general shapes taken into account. Buildings even further away are not explicitly modeled, but their effects are imposed as ground roughness.

For the ground surface, wall functions with appropriate surface roughness modifications have been used. The atmospheric boundary layer profile at the inlet is based on the log-law relation considering neutral conditions during rainfall. The aerodynamic roughness length at the inlet reflects the roughness conditions of a fetch of 5 km upstream of the inlet. The distances of buildings from domain boundaries satisfy the guidelines stated in Franke et al. [14]. The computational grid shown in figure 4b is composed of approximately 6 million mainly hexahedral cells.
Steady wind-flow field around the buildings is calculated for the reference wind speed \( U_{\text{ref}} \) of 10 m/s at 10 m height. The wind-flow fields for other reference wind speeds of 1, 4, 8 and 18 m/s are obtained by scaling the wind velocity field from the calculated case \([4,5]\) in order to cover the complete range of measured values. For each wind speed, the rain phase calculations are performed for 17 raindrop sizes ranging from 0.3 to 6 mm. From these, the catch ratio distributions are calculated for a range of reference rainfall intensities between 0.1 and 30 mm/h.

**Figure 4.** a) Computational domain with the explicitly-modeled buildings and b) close-up of the computational grid on the surfaces of the ground and the historical building.

### 4. Results

Figure 5a shows the calculated wind-flow field for wind approaching from the direction of Inner Harbour, which is located to the west of the building. In front of the western main facade of the building, a stagnation zone of lower wind velocity is visible. This is where the raindrop trajectories start to move downwards due to the standing vortex (figure 5b). Wind streamlines approaching along the side plane of the building and the resulting raindrop trajectories are shown in figure 5c. Raindrops are driven towards inside the small courtyard at the southern wing of the building due to the local wind-flow field.

As a next step, the distributions of catch ratio on the building facade for meteorological conditions representing the current weather in 2018 and the predicted future weather in 2099 are compared. Instead of using a complete annual analysis, periods that show both a large rainfall amount and a large predicted increase in rainfall are chosen, considering rain events with a wind direction from west. Among these, January, February and November have similar rainfall intensity and total rainfall amount. May has a lower total rainfall, despite also showing a large predicted increase in rainfall. Figure 6 shows the surface wetting conditions for February and November. Catch ratio based on the current weather data, \( \eta_{2018} \), is defined as the ratio of the total WDR reaching the surface, \( S_{\text{wdr,2018}} \) [mm] and the total horizontal rain, \( S_{\text{rain,2018}} \) [mm]. The results show that, in addition to the roof, parts of the facade and chimneys receive a considerable amount of surface wetting. In February, there is a significant portion of the facade reaching a catch ratio around 0.3, while the southern wing exceeds this value, reaching catch ratio around 0.5. Catch ratio values for November are lower due to a lower average wind speed (see figure 3b).

In order to estimate the impact of future climate on WDR exposure of the facade, equation (3) is defined, where \( S_{\text{wdr,2099}} \) and \( S_{\text{wdr,2018}} \) represent the total WDR [mm] for future and current weather, respectively. Their difference is then divided by the total horizontal rain, \( S_{\text{rain,2018}} \) [mm], in order to obtain the relative difference in terms of WDR exposure.

\[
\theta_s = \frac{S_{\text{wdr,2099}} - S_{\text{wdr,2018}}}{S_{\text{rain,2018}}} \quad (3)
\]
As shown in figure 6, WDR exposure increases during February for almost all locations on the façade, while some façade elements show an increase in surface wetting of up to 20%. The predicted increase in the future is milder during November, which shows an increase almost only at the southern wing. Note that, for both periods, the locations with the highest increase are similar to the ones that already receive more rain. The reason is based on the fact that the catch ratio distributions do not show a significant difference between current and future weather data. Keeping wind velocity patterns constant, the future data modifies only the rainfall intensity. Due to the different inertia of raindrops of different sizes, one can expect the catch ratio to change the most when the current rainfall intensity is relatively low and the predicted change in the future is relatively high. However, in the cases of February and November, the increase of average rainfall intensity from 1.8 to 2.3 mm/h does not change the wetting distribution significantly. In this case, wind speed seems to be a more dominant factor. Larger differences can be expected if rain event durations also change together with the rainfall amount, e.g. shorter rain events with larger rainfall intensity.
Figure 6. Distribution of catch ratio (current data) and relative difference in WDR exposure between future and current data for a) February and b) November, both for rain events from west.

5. Discussion and conclusions
The results for the predicted future conditions show a WDR intensity pattern on the exposed facade of the building that is similar to the current conditions. However, the WDR exposure increases for almost all locations on the façade, in some cases by up to 20%. Moreover, WDR exposure increases the most at locations that are already showing the highest amount of catch ratio. This observation provides important insights into potential areas for worst-case durability problems. WDR intensity is used as a boundary condition in studies of moisture transport in the building envelope and film runoff. Such changes in the WDR exposure as a result of climate change can lead to a higher risk of biodegradation and freeze/thaw damage in the future. CFD simulations allow for high spatial resolution of WDR deposition for the critical time periods in a year. Such input can improve the hygrothermal analyses of the facades when assessing moisture damage risk, which should take into account the change of WDR intensity on the façade, as well as the increasing average temperatures.

RCP8.5 scenario is considered in the present study, which indicates worst case “business as usual” conditions. An intermediate scenario such as RCP4.5 presents differences in predicted changes in the future, e.g. February has a lower increase, while November has a larger increase in rainfall. However, the changes are not large enough to change the main outcome.

One particular limitation of the present study is related to the weather morphing of rainfall intensity data. Rainfall intensity during the measured rain events are scaled according to the change in daily precipitation in the PCIC Climate Explorer tool. However, climate change can also lead to a change in rain event duration, e.g. shorter rain events with higher intensity while remaining at the same daily average rainfall amount. Such changes may lead to 1) a different distribution of WDR intensity due to a difference in raindrop size probability distribution and 2) cases like higher runoff amount and lower absorption in porous materials.

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