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How to predict wind driven rain in a changing climate?

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Abstract. We are nowadays confronted with changes in moisture-related durability problems arising from climate change. As one example, building facades of historical buildings that before were hardly exposed to frost damage, may in future be exposed to an increase in frost-thaw cycling leading to a higher risk for moisture-related damage. An essential step in hygrothermal and durability analysis is the prediction of wind-driven rain (WDR). A computational fluid dynamics (CFD) Eulerian multiphase model provides WDR catch ratio charts. Building further on this work, methods are developed to predict WDR loads and moisture damage risks.

1. Introduction

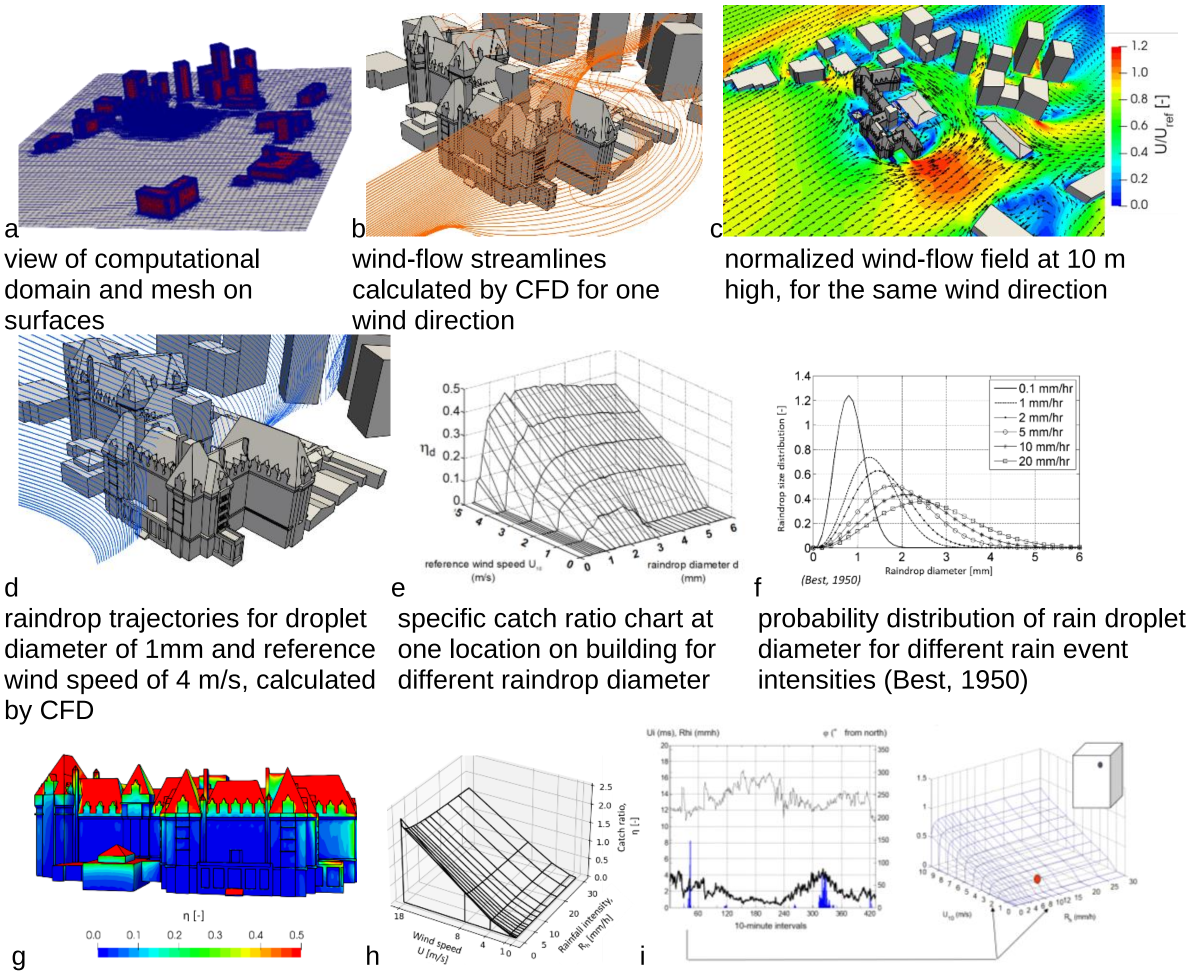
Wind driven rain (WDR) is one of the most important loads determining the risk for moisture damage of building envelopes. We are most likely confronted with significant changes in moisture-related durability problems due to climate change. Examples are building facades of historical buildings that before were hardly exposed to frost damage and that may in the future be exposed to an increase in freeze-thaw cycling leading to a high risk for moisture related damage, or displacement of ecosystems making termites and rotting fungi accessing so far winter-protected territories.

An essential step in hygrothermal and durability analysis is the prediction of WDR. WDR may be predicted using semi-empirical or computational methods. The latter approach is based on computational fluid dynamics (CFD), i.e. determination of the wind flow field using RANS (Reynolds-averaged Navier Stokes) for different wind orientations and determination of WDR field using Eulerian multiphase model for different droplet diameter classes and wind directions. The WDR solver developed by the authors using OpenFOAM is open source and available for download [1]. The outputs of solver include WDR distribution on surfaces, wind streamlines and droplet trajectories for different wind speed, wind orientation and droplet diameter.

WDR deposition is modeled using local wind flows, thus care is needed in selecting a computational domain large enough to capture all relevant air movement. We distinguish a WRD study from a local urban climate study, which requires to take into account radiative exchanges and heat and mass transport in porous media in addition to wind flows, and with adequate boundary conditions, as done in e.g. [12, 13]. So WDR studies usually rely on wind flow and direction and rain intensity available from weather files. Future climate scenarios provide guidelines on ranges of probable impacts given different scenarios of greenhouse gas emissions. We acknowledge that climate change predictions may exhibit uncertainties, especially regarding precipitation predictions. Nevertheless, exploring the impact of future scenarios, using our current level of knowledge, may provide stakeholders with points of attention for building design and maintenance.

2. Overview of methodology

In Figure 1, we present a case study discussed in this paper to illustrate the CFD-based prediction of WDR. The building of interest is a complex historical building located in Victoria, BC, Canada: the Empress Hotel, a Canadian Pacific heritage building on the inner harbor of Victoria located on the southeast tip of Vancouver island. First, data must be assembled on the configuration of the building and its neighborhood and on the topography, and wind directions are selected in terms of co-occurrence with rain, based on weather data. Second, a computational domain is built, using more refined computational cells closer to the building, and following guidelines for wind flow development between the domain boundaries and the buildings and for height of the domain respective to blockage ratio (Figure 1a). Third, wind-flow fields are obtained by CFD for different wind directions (Figure 1b, c). Scaling provides the wind velocities for different reference wind velocity.



a view of computational domain and mesh on surfaces

b wind-flow streamlines calculated by CFD for one wind direction

c normalized wind-flow field at 10 m high, for the same wind direction

d raindrop trajectories for droplet diameter of 1mm and reference wind speed of 4 m/s, calculated by CFD

e specific catch ratio chart at one location on building for different raindrop diameter

f probability distribution of rain droplet diameter for different rain event intensities (Best, 1950)

g distribution of global catch ratio for rain intensity of 2mm/h and reference wind speed of 4 m/s

h global catch ratio chart

i illustration of the use of catch ratio chart using, along a rain event, the recorded wind velocity and direction, and the rain intensity

Figure 1. Illustration of the steps of CFD-based WDR method: (a-c) determination of normalized wind flow field; (d-e) determination of specific catch ratio; (f-i) global catch ratio and its use (b,c,d,g from [10] with permission).

Fourth, WDR streamlines are obtained using a Eulerian approach that allows to track the “concentration” of rain at all locations for droplets of a specific diameter (Figure 1d). Intersection of streamlines with solid surface indicates rain deposition, from which specific catch ratios (ratio of rain deposited at any location compared to rain deposited on the ground far from building interaction) are determined. This calculation is done for 17 sizes of droplets. A specific catch ratio chart can be built showing the catch ratio per droplet size (Figure 1e). Thus, for every location on the building, charts of the specific catch ratio, giving the ratio between WDR as a function of droplet diameter and wind speed is obtained. Sixth, as rain events of different intensities present different probability distributions for droplet sizes (Figure 1f, as measured e.g. Best [2]), the determination of global catch ratio requires aggregating specific catch ratio along rain intensity distribution. Combining specific charts with information of the droplet size distribution for different rain intensities, global catch ratio can be represented for every location of the building façade for a reference rain intensity and reference wind speed for different wind directions (Figure 1g, h). Using this information, the WDR load on facades can be predicted for the period of interest (Figure 1i). An overview of this method, as developed and extensively validated by the authors can be found in [9], and full description in [3-8].

The drawback of this method is its computational cost. Therefore, methods have to be developed that allow predicting accurately WDR load and moisture damage risk at low computational cost. In this paper we present two methods. The first is simplifying analysis by reducing the sampling sets. The second is simplifying determination of moisture risk by using a climatic index accounting for wetting versus drying potential.

3. Determination of impact of climate change on wind driven rain load during long time periods

In a first method, we use a statistical method, i.e. Latin Hypercube Sampling (LHS) that allows to select a small set of correlated WDR data. Using statistical sampling from cumulative distribution functions (CDFs) of correlated 10-year data for wind direction, wind speed and rainfall intensity, samples are generated based on the frequency of occurrence which represent long term WDR conditions. It is found that 200 samples generated by LHS show the same WDR load as compared to wetting over a period of 3 years. For more details on the method, we refer to [10]. Advantage of the method is that the WDR load on complex buildings for long periods can be determined with much less computational effort, which allows to study the influence of climate change on WDR. The method is applied to the Empress hotel, Victoria, BC, Canada and the difference in global catch ratio obtained with full meteorological conditions versus LHS is shown in Figure 2.

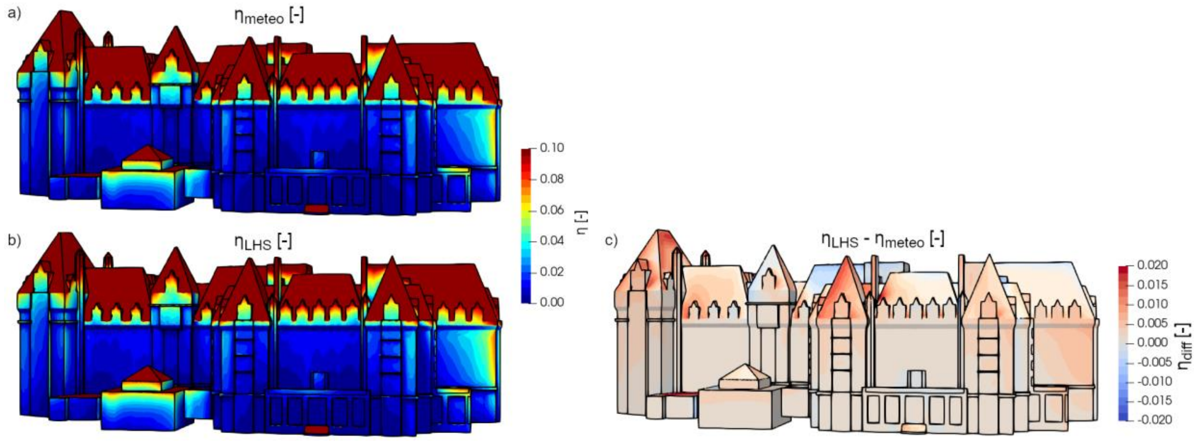


Figure 2. Global catch ratio distribution over the western façade of the building using a) 3 years of measured meteorological conditions and (b) LHS with a sampling size of 200. (c) Difference between a) and b). (From [10] with permission).

Climate change will have an impact on the Victoria Region: winter, fall, and spring will become more wet and summers will become more dry. We found that parts of facade that are currently exposed to a higher amount of WDR show also the highest increase in future WDR load. Further, keeping wind conditions constant, the change in future WDR load is mostly due to increase in rainfall (up to 25%) and the change in wetting distribution is minimal, while the largest impact is expected in future when wind velocity changes. We show the applicability of this method to quickly and accurately predict the WDR load and identify locations that show high risk for various wind-rain scenarios with respect to the climate change.

4. Durability assessment of complex historical building using dynamic climate index

In a second method, a WDR study on the Canadian parliament serves as basis for an assessment of long-term time-varying wetting load due to WDR and potential evaporation, using several years of meteorological data (Figures 3 and 4). A cumulative assessment can provide a fast method to identify critical locations and periods for moisture damage. More information is available in [11].

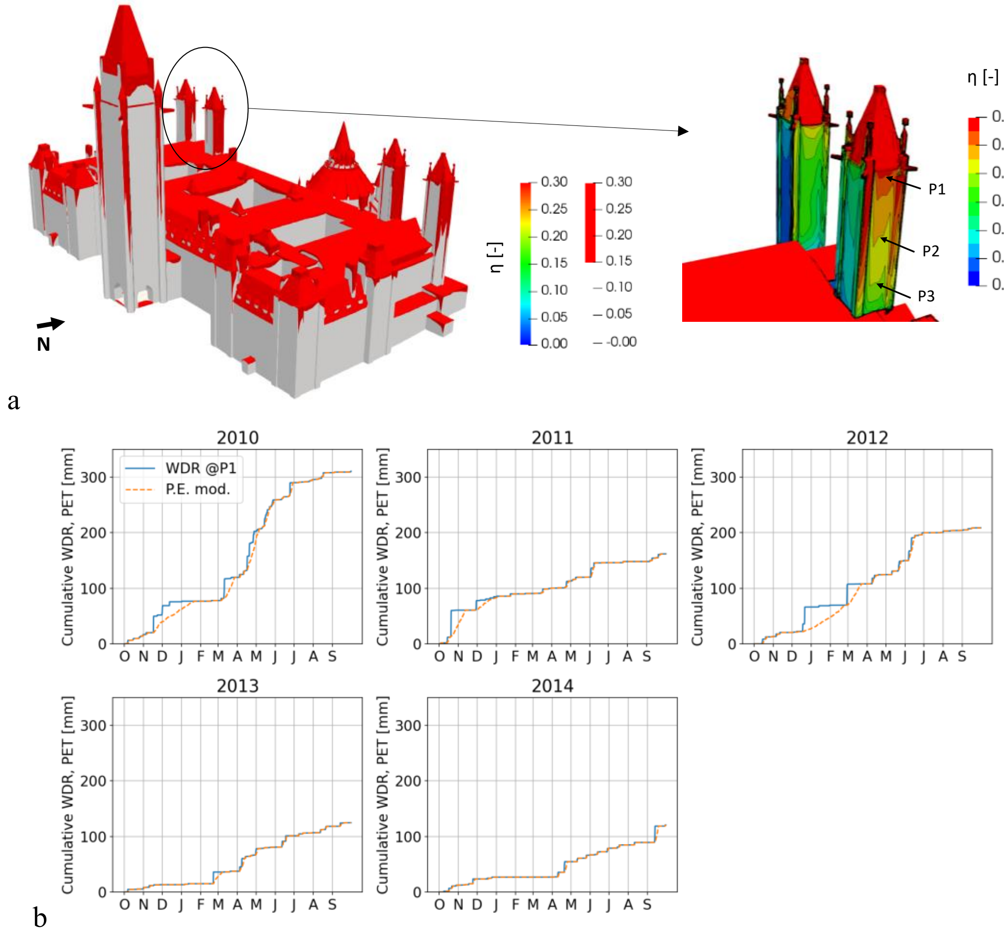
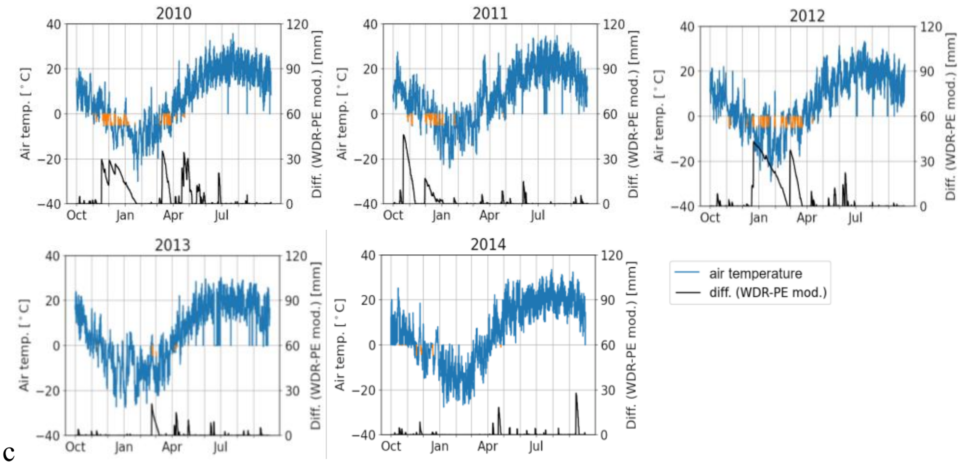


Figure 3. Wind-driven rain deposition on the Parliament Building, Ottawa: a) distribution of long term (10 years) catch ratio larger than 0.15, shown in red, and close-up of redistribution on two western small towers, showing a catch ratio is 0.3 for part of masonry; b) cumulative WDR deposited and evaporation potential at the said location, compared over 5 years. Critical periods show WDR above PET (from [11] with permission).

The new durability assessment method proposed is based on a dynamic climatic index. The Climatic Index is defined as the ratio between the annual wetting load and annual drying potential. The potential evaporation is determined based on the Penman equation, which only depends on climate conditions but depends per orientation. It is independent of the location on the building facade, and the storage and transport of heat and moisture within the building envelope. The advantage of this method is that it is not dependent on material properties, allowing for the evaluation of the building prior to material selections or without knowledge of material hygrothermal properties.



c

Figure 4. Wind-driven rain deposition on the Parliament Building, Ottawa: Plots of critical periods and air temperature, with co-occurrence with freezing temperature (-5 to 0ºC) highlighted in orange. (from [11] with permission).

5. Conclusions

Wind driven rain (WDR) is a major source of moisture on the building envelope. As more and more extreme rain events expected due to climate change, moisture-related damage risks in buildings could increase in the future, reinforcing the need for accurate spatial and temporal distribution of WDR in the built environment. We propose here two methods to further the use of WDR information in interpretation and prediction of such risks.

We also would like to mention that WDR can be considered in solutions to building durability and urban comfort, not necessarily only as a source of problems in building durabilty. Further work including understanding the role of rain as a moisture source in mitigation of urban heat island effects, which are exacerbated during heat waves, should be considered. For example, this WDR approach has been embedded in a suite of models for local urban modelling [12, 13].

References

[1] Website for downloads and tutorials: https://carmeliet.ethz.ch/research/downloads/wind-driven-rain.html

[2] Best AC. (1950). The size distribution of raindrops, Q. J. R. Meteorol. Soc, 76:16-36.

[3] Kubilay A, Derome D, Carmeliet J. (2017). Analysis of time-resolved wind-driven rain on an array of low-rise cubic buildings using large eddy simulation and an Eulerian multiphase model, Building and Environment, 114: 68-81.

[4] Kubilay A, Carmeliet J, Derome D. (2017). Computational fluid dynamics simulations of wind-driven rain on a mid-rise residential building with various types of facade details, J. Building Performance Simulation, 10:125-143.

[5] Kubilay A, Derome D, Blocken B, Carmeliet J. (2015). Numerical modeling of turbulent dispersion for wind-driven rain on building facades, Environmental Fluid Mechanics, 15: 109-133.

[6] Kubilay A, Derome D, Blocken B, Carmeliet J. (2015). Wind-driven rain on two parallel wide buildings: field measurements and CFD simulations, J. Wind Engin. and Industrial Aerodynamics, 146:11-28.

[7] Kubilay A, Derome, Blocken B, Carmeliet J. (2014). High-resolution field measurements of wind-driven rain on an array of low-rise cubic building, Building and Environment, 78: 1–13.

[8] Kubilay A, Derome D, Blocken B, Carmeliet J. (2014). Numerical simulations of wind-driven rain on an array of low-rise cubic buildings and validation by field measurements, Building and Environment, 81:283-295.

[9] Derome D, Kubilay A, Defraeye T, Blocken B, Carmeliet J. (2017). Ten questions concerning modeling of wind-driven rain in the built environment, Building and Environment, 114: 495–506.
[10] J Bourcet, A Kubilay, D Derome, J Carmeliet. (2023). Representative meteorological data for long-term wind-driven rain obtained from Latin Hypercube Sampling–Application to impact analysis of climate change, Building and Environment 228, 109875.
[11] Kubilay A, Bourcet J, Gravel J, Zhou X, Moore TV, Lacasse MA, Carmeliet J, Derome D. (2021). Combined use of wind-driven rain load and potential evaporation to evaluate moisture damage risk: case study on the Parliament Buildings in Ottawa, Canada, Buildings, 11:476.
[12] Kubilay A, Allegrini J, Strebel D, Zhao Y, Derome D, Carmeliet. (2020). Advancement in urban climate modelling at local scale: urban heat island mitigation and building cooling demand, Atmosphere, 11:1313.
[13] Kubilay A, Derome D, Carmeliet J. (2018). Coupling of physical phenomena in urban microclimate: A model integrating air flow, wind-driven rain, radiation and transport in building materials, Urban Climate, 24:398-418.