# Wind-driven rain impact on urban microclimate: wetting and drying processes in urban environment

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## Abstract

Simulation of wind-driven rain in the urban environment is complex. Current approaches often simplify the physics involved. A multiscale whole-physics framework is being developed to provide a complete WDR simulation tools and to assess which simplifications are acceptable. WDR deposition is modeled with CFD with Eulerian multiphase approach. Rain droplets impacting different surfaces is captured by analytical models. On-going work focuses on the required next steps that are droplet fate, film forming and run-off.

## Introduction

Wind-driven rain (WDR) refers to rain droplets, driven by the wind, impacting surfaces in the built environment, leading to wetting and drying processes affecting buildings and the urban microclimate. The proper understanding and management of WDR in the built environment as water source is required since evaporative cooling from urban surfaces wetted by rain is seen as one of the future avenues for mitigating urban heat island effects and heat waves, which are expected to increase due to climate change, as discussed further in paper 1443 of the same conference.

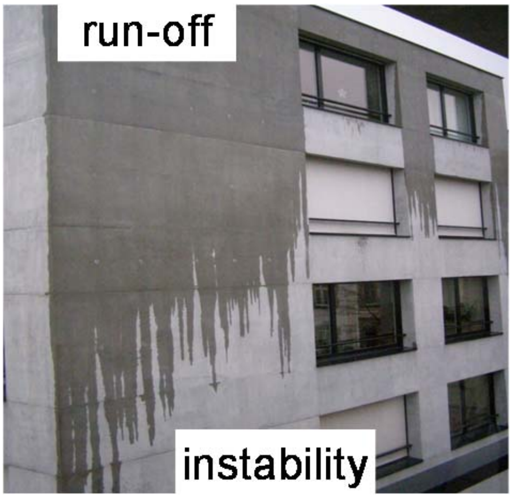



*Figure 1: Rain deposition on building façade displaying also film forming and run-off on concrete façade during rain event.*

A second reason is that WDR is a main agent of deterioration of building materials and, as such with climate change leading to more extreme weather events such as heavy rain, it is expected that building damage risks will increase in the coming decades.

The study of WDR in the urban environment includes the study of a rich pallet of surface and contact phenomena, at short and longer time scale and governed by a wide range of physical processes. These phenomena involve spreading, splashing, rolling or bouncing, coalescence of droplets, hemiwicking on the surface, absorption in a porous medium, evaporation, film forming and runoff under gravity.

## Objectives

This work aims at an accurate understanding and modeling of the impact of wind-driven rain on the urban microclimate, tackling wetting and drying processes at the droplet and the urban environment scales.

## Methods and results

### Rain deposition

To simulate the influence of WDR in the built environment, an urban microclimate model is developed including WDR, which is validated by well-designed experiments and can be used as a tool to analyze the effect of evaporative cooling as mitigation measure to improve the urban microclimate and thermal comfort (Kubilay et al. 2016).

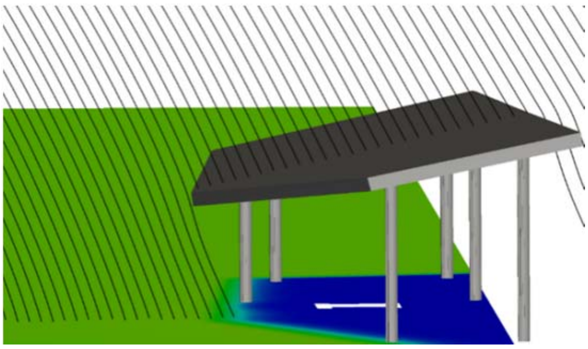
The work builds on a previously developed Eulerian multiphase wind-driven rain modeling approach to predict rain deposition (as described in Kubilay et al. 2013). Simulations require first to resolve the wind flow for a given built geometry. Then rain droplets are considered as separate phases that interact with the air flow. This interaction depends on the droplet sizes and thus we simulate 15 phases to account for the full range of rain droplet size, according to the distribution determined by Best (1950). For each separate rain phase, the following continuity and momentum equations are solved:

$$\frac{\partial \alpha_d}{\partial t} + \frac{\partial \alpha_d \overline{u_{d,j}}}{\partial x_j} = 0 \tag{1}$$

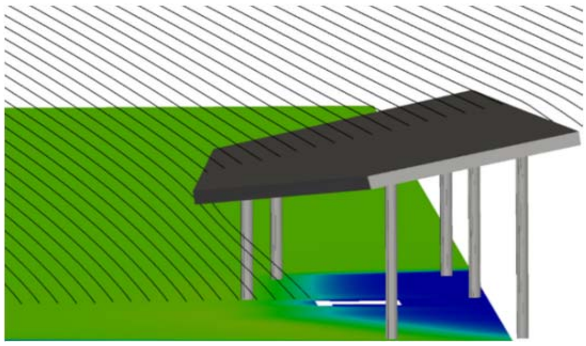
$$\frac{\partial \alpha_d \overline{u_{d,i}}}{\partial t} + \frac{\partial \alpha_d \overline{u_{d,i}}\,\overline{u_{d,j}}}{\partial x_j} + \frac{\partial \alpha_d \overline{u'_{d,i}\,u'_{d,j}}}{\partial x_j} = \alpha_d g_i + \alpha_d \frac{3\mu_a}{\rho_w d^2} \frac{C_d \,\mathrm{Re}_R}{4} \left( \overline{u_i} - \overline{u_{d,i}} \right) \qquad (2)$$

where $\alpha_d$ is the phase fraction of rain phase d, which represents a specific class of raindrop size, $u_{d,j}$ denotes the velocity component of rain phase d, $u_i$ the velocity component of wind in direction i, $\rho_w$ the density of the raindrops, $\mu_a$ the dynamic air viscosity, g the gravitational acceleration, $C_d$ the drag coefficient. $Re_R$ denotes the relative Reynolds number calculated using the relative velocity between the air and rain phases. The third term on the left-hand side in Equation 2 corresponds to the turbulent mass flux, which is the transport of mass due to turbulent motions in the flow. Turbulent dispersion of droplets is due to these turbulent motions. By defining a response coefficient, velocity fluctuations in rain phases are related to the velocity fluctuations in the wind. The model is validated against field measurements on various geometries during rain events with different characteristics.

This model provides the distribution of WDR intensity on all the surfaces of the computational domain, which is influenced by building geometry, position on the surface, wind speed, wind direction and rainfall intensity. Figures 2-7 shows raindrop trajectories and the resulting surface wetting on different geometries.



a)

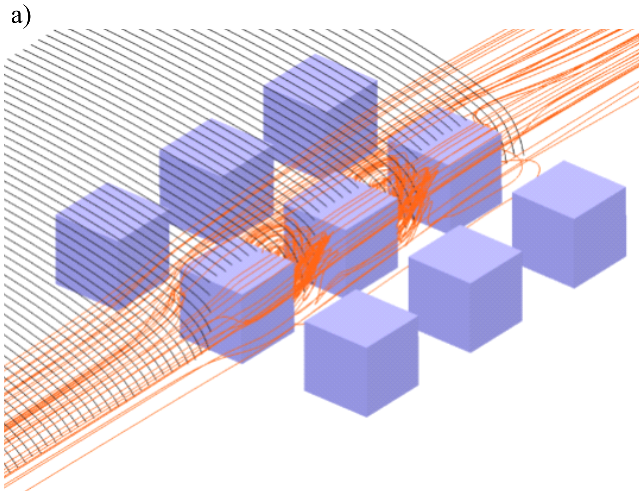


b)

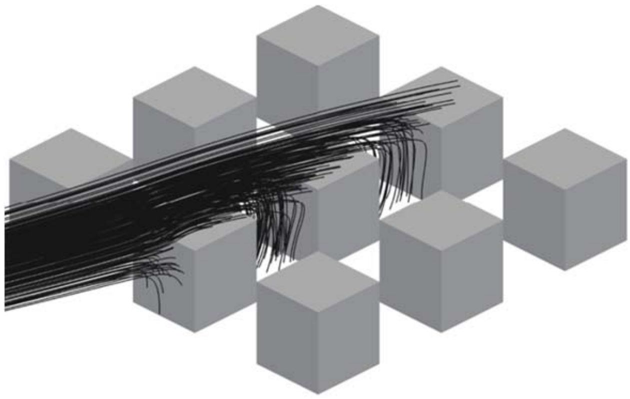
*Figure 2: Simplified rain shelter: trajectories for 0.3 mm raindrops at a) 1 m/s and b) 3 m/s wind speed and delineation of the sheltered area.*

In Figure 2, we show the different outcomes of droplet trajectories for a rain shelter composed of a roof structure in the case of lower and larger wind velocity. We see that such small droplets can undergo significant deviations of their trajectories in the vicinity of the built structure due to their low inertia. Finally, we remark that the sheltered area location varies with wind velocity.

a)



b)



c)

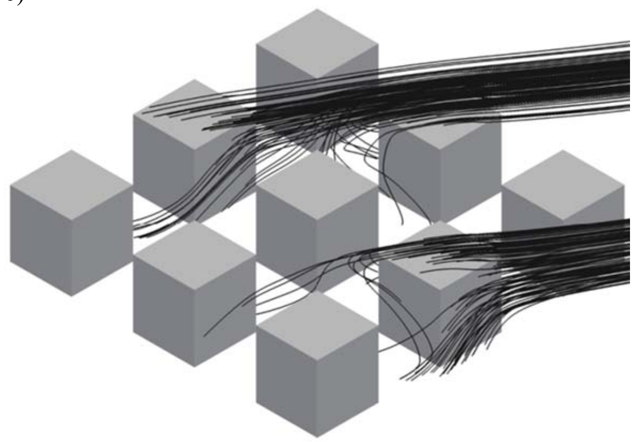


*Figure 3: Examples of rain droplet trajectories in the built environment consisting of an array of 9 cubes, a) joint visualisation of streamlines of wind in orange and of trajectories of rain in black, b) trajectories of 0.3 mm droplets at 5 m/s, with perpendicular wind, c) and with 45 degree oblique wind.*

In Figure 3, the built environment is more complex, consisting of nine cubic buildings. Both the wind flow and the rain trajectories are thus more complex, and less intuitive. In between the buildings, the recirculation of wind flows leads to highly affected rain trajectories. The trajectories of raindrops between two downstream cubes in Figure 3b move vertically due to the recirculation regions in the wind flow in Figure 3a. We also remark that a variation in wind direction can significantly influence the raindrop trajectories, and eventually the wetting patterns, as shown with an angle of attack of 45º in Figure 3c.

Once the wind flow and the rain phases are simulated, we agglomerate the rain deposition from the 15 different phases and compare this total amount of deposited water to the water deposited horizontally away from the building, namely the horizontal rainfall intensity. This normalized value is called catch ratio. We illustrate catch ratio distribution with two examples. In Figure 4, the rain catch ratios on the surfaces of the building and on the ground are determined. There is a clear increase of rain deposition on the ground along an arched region in front of the building. The top edge of the windward façade receives more rain than the rest of the façade and the roof close to this edge receives less rain than the rest of the roof. In Figure 5, the impact of a neighbour building is studied in terms of rain trajectories and rain catch ratios.

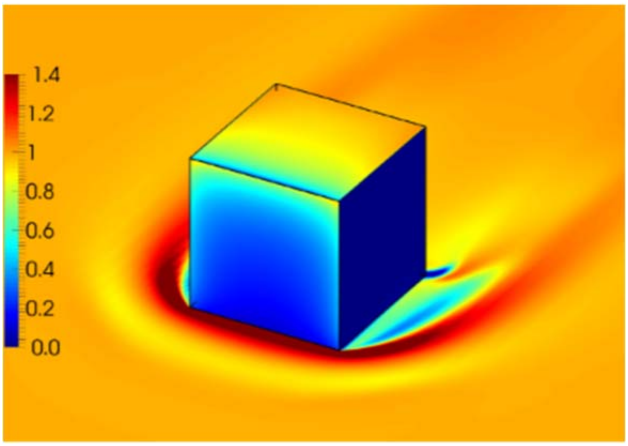



*Figure 4: Effects of geometry on WDR catch ratios using Eulerian-Lagrangian CFD modelling demonstrated with a 10m high cubic building (facades and ground) for a rain intensity of 1 mm/h and a wind speed of 10 m/s.*

The efficiency of the Eulerian Multiphase model is especially significant as the distribution of impinging WDR intensity is necessary for more comprehensive studies of WDR. For example, in order to model the complete moisture redistribution in the urban environment, a multiscale approach is necessary. At the neighborhood scale, absorption in the built environment and the wetting and drying cycles of building materials are modeled. For this, heat and moisture transport in the built environment, i.e. building facades, ground, vegetation, are coupled with WDR intensity using building-envelope heat-air-moisture (BE-HAM) models (e.g. Janssen et al. 2007, Abuku et al. 2009). This is presented below. But first, we must consider the fate of single droplets on the different surfaces found in the built environment.

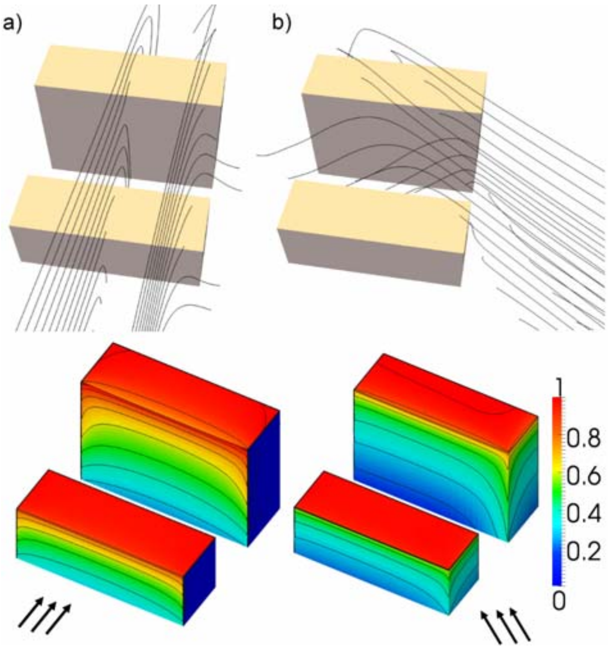



*Figure 5: WDR deposition for two buildings with perpendicular and 45º oblique wind directions, a) and b) trajectories of 0.3 mm droplets and c) catch ratio for rain intensity of 1 mm/h at 3 m/s wind speed.*

**Droplet-impact phenomena**

At the droplet scale, the fate of rain droplets after impingement is studied at the scale of a droplet based on the input coming from the WDR model. Droplet physics can be numerically modeled using methods such as the volume of fluid (Lee et al. 2016b) as shown in Figure 6a.

Figure 6a illustrates the different outcomes of a water droplet impacting an impervious flat surface at 90° for different impact speeds in the 0.1 to 3 m/s range. At low impact speed, the droplet spreads and recedes until equilibrium on the surface. At higher velocity, the droplet may split with a daughter droplet during the receding phase. At even higher velocity, the spreading is no longer along a circular shape and fingering may occur, also possibly leading to break-up of these fingers and the formation of several droplets at equilibrium. Starting from around 3 m/s, splashing may occur.

We developed a scaling law that allows to predict the maximal spreading when the impact speed and impact angle are known (Lee et al. 2016a,b) and presented below. The maximum spreading ratio is defined as

$$\beta_{max} = D_{max} / D_0 \quad (3)$$

where $D_{max}$ is the maximum spreading diameter and $D_0$ the initial drop diameter prior to impact. Spreading is governed by the balance between kinetic, capillary, and viscous energy. Using the dimensionless parameters, Weber number ($We = \rho V_i^2 D_0/\gamma$) and Reynolds number ($Re = \rho V_i D_0/\mu$), we derive a universal scaling to predict maximum spreading between two asymptotic behaviors takes into account low impact speeds by correcting with a spreading ratio of the droplet at very low impact speed, $\beta_{Vi=0}^2$:

$$(\beta_{max}^2 - \beta_{Vi=0}^2)^{1/2} \cdot Re^{-1/5} = We^{1/2}/(A + We^{1/2}) \quad (4)$$

a)

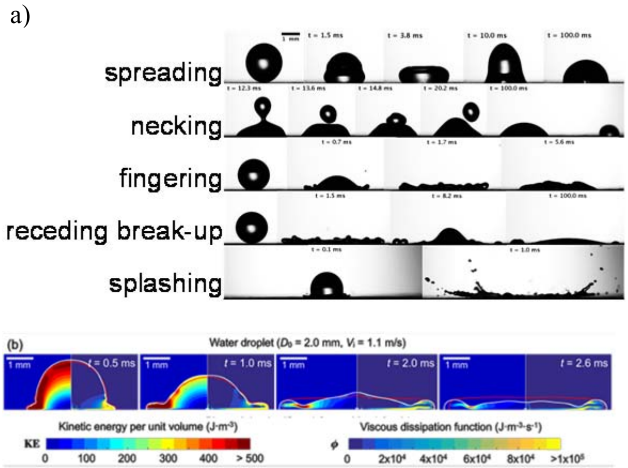



*Figure 6: a) Own measurements of droplet impact on impervious surface for impact velocity of 0.1 to 3.0 m/s (Derome et al. 2017), b) CFD VOF simulation of water droplet during spreading (Lee et al 2016c).*

Our approach combines the WDR model for the calculation of wind-driven rain distribution over the façade with a model describing the individual raindrops behavior. First a probability based Monte Carlo approach is used to simulate rain droplet impact yielding the number of raindrops of different droplet diameters, which arrive on the different zones of the surface during a 10-minute rain interval. Based on the droplet diameter and wind conditions, the impact speed and impact angle can be determined from EM-WDR. Then a semi-empirical runoff model is used to simulate spreading, coalescence and runoff of different droplets. Finally, a simplified droplet evaporation model is used assuming a constant contact angle mode of evaporation on glass. The model will be validated by experiments. However, the model is semi-empirical, meaning the model is based on physics, but a lot of parameters are obtained from experiment. This probabilistic approach is presently being extended to droplet rain impact on porous-substrates aiming to include complete rain droplet physics.

Another feature of the presented model is that it incorporates film forming and runoff (as seen on Figure 1a and described in Martin et al. 2015), accounts for all relevant droplet physics of multiple impacting droplets (as shown in Figure 6a) as well as the influence of heat and mass exchange at the liquid-air interphase, as presented next.

**Moisture transport in porous media**

Part of the rainwater reaching the porous surfaces in urban area is absorbed in the material. The extent of such wetting and drying processes are dependent on the moisture properties of the material, which have direct relation to the evaporative-cooling potential in urban areas. This subsection presents the coupled heat and moisture transport equations in porous building materials. WDR is an important boundary condition for moisture influx in such models, which can be used in urban thermal comfort models.

The governing equations for moisture transport within the porous domains are defined as:

$$\frac{\partial w}{\partial p_c}\frac{\partial p_c}{\partial t} = -\nabla(g_l + g_v) \quad (5a)$$

$$g_l = -K_l \nabla p_c \quad (5b)$$

$$g_v = -\frac{\delta_v p_v}{\rho_l RT}\nabla p_c - \frac{\delta_v p_v}{\rho_l RT^2}(\rho_l L_v - p_c)\nabla T \quad (5c)$$

where $g_l$ and $g_v$ denote liquid and vapour moisture transfer. In Equations 5a-5c, w denotes moisture content, $p_c$ capillary pressure, T absolute temperature, $K_l$ the liquid permeability, $\delta_v$ the vapour permeability, $p_v$ the vapour pressure, $\rho_l$ the liquid density, R the gas constant and $L_v$ the heat of vaporization. The derivative $\partial w/\partial p_c$ represents the moisture capacity, i.e. the derivative of the moisture retention curve which gives the moisture content w as a function of the capillary pressure $p_c$. $K_l$ and $\delta_v$ are dependent on moisture content and are typically obtained by using experimental techniques.

The governing equations for heat transport within the porous domains are defined as:

$$(c_0\rho_0 + c_l w)\frac{\partial T}{\partial t} + \left(c_l T\frac{\partial w}{\partial p_c}\right)\frac{\partial p_c}{\partial t} = -\nabla(q_c + q_a) \quad (6a)$$

$$q_c = -\lambda \nabla T \quad (6b)$$

$$q_a = (c_l T)g_l + (c_v T + L_v)g_v \quad (6c)$$

where $q_c$ and $q_a$ denote conductive and advective heat transfer. In Equations 6a-6c, $c_0$ denotes the specific heat of the dry material, $c_v$ the specific heat of water vapour, $c_l$ the specific heat of liquid water, $\rho_0$ density of the dry material, and $\lambda$ the thermal conductivity. The advective heat transfer, $q_a$, represents advective heat flow due to vapour and liquid flow including latent heat transport. A detailed description of the derivation of Equations 5 and 6 as well as the underlying assumptions can be found in Janssen et al. (2007).

## Conclusion

The method developed brings about an important step towards quantitative predictions of wind-driven rain and its physical processes at droplet and urban scales. This model includes WDR deposition on all surfaces of the built environment and accounts for the full physics of droplets deposition and coalescence, urban surface moisture phenomena such as film forming and runoff as well as heat and mass exchange at the liquid-air interphase, and absorption by the porous medium.

The combination of advanced modeling at droplet and urban environment scales of wetting/drying processes of porous material surfaces and the time-resolved measuring of these processes provides insights in understanding rain deposition and water redistribution in the built environment. The approach relies on modeling at different scales of the problem and transferring the required information between scales.

## Acknowledgments

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