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Modelling of rain interception by trees in outdoor urban climate

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Abstract. Studies in building and urban physics can benefit from detailed modelling of outdoor climate conditions. Up to two-thirds of the rain, which a tree is exposed to, can be intercepted by tree foliage, branches and stem and evaporate without reaching the ground. However, the interception of rainwater by trees has not yet been considered in wind-driven rain studies of local urban climate. The aim of our work is to model rain interception by trees and implement it into a microclimate modelling suite (urbanMicroclimateFoam) based on OpenFOAM, in order to consider the outdoor environmental conditions more accurately. Field measurements are performed on a red oak for validation. Numerical results performed with the modelling tool which does not consider rain interception shows an overestimation of rain deposition on the ground, compared to measurements for two rain events of 2022 summer. Ongoing work leads to the addition of sink and source terms to account for interception and to close the presented gaps.

1. Introduction

Building and urban physics studies can benefit from detailed modelling of outdoor climate conditions. Trees in urban environment provide shading, extract sensible heat from the air to transpire water vapor, and reduce wind velocity. As such they provide avenues for heat mitigation, especially during heat wave events. Certain CFD-based (computational fluid dynamics) numerical tools can support such studies of thermal comfort assessment in urban settings, which can help evaluate mitigation measures for heat waves [1]. The modelling suite, urbanMicroclimateFoam, can take into account the influence of vegetation [2]. WindDrivenRainFoam, a related solver can simulate rain deposition on solid surfaces.

Rain interception is a physical phenomenon that has been studied mostly in the field of hydrology and can be also relevant in urban microclimate. Up to two-thirds of the rain can be intercepted by tree foliage, branches and stem and evaporate without reaching the ground. Intercepted rain refers thus to the amount of rain that is caught by tree leaves and that is returned to the atmosphere by evaporation before it can fall onto the ground. Only few analytical models [3] exist to assess rain interception by trees, and some are specialized specifically for trees in cities [4]. It would be of interest to simulate wind-driven rain in urban environments that contain trees and to consider rain interception. The impact of moisture redistribution due to rain interception by foliage on local microclimate and on rain redeposition onto facades of buildings adjacent to trees could then be studied.

In this study, we present the numerical and experimental work done towards the implementation of rain interception by trees into urbanMicroclimateFoam, a suite of numerical models that involves CFD, heat, air and moisture (HAM) transport processes radiation exchanges and wind-driven rain.

Experimental work consists in field measurements of rain interception on an isolated tree in an open field on the Université de Sherbrooke campus during the 2022 summer. Experiments are performed to measure characteristics of the tree and to provide a dataset for validation. Measurement campaign results are presented and compared with simulation performed with OpenFOAM v6 [5]. This simulation is, for now, only performed with windDrivenRainFoam.

2. Methods

2.1. Experimental method

Measurements occurred through the summer of 2022. Five rain events are measured. A meteorological station at Université de Sherbrooke, 350 m from the studied trees, provides wind direction, velocity, air temperature and relative humidity.

Water reaching the soil under the tree is measured during multiple rain events, using a combination of an array of 2 L containers (0,021 m^2 receiving area per container) and an array of rain gauges (0.019 m^2 receiving area per gauge) (Onset RG3-M, USA) of 0.2 mm resolution, positioned under a red oak, on Université de Sherbrooke campus. For this campaign, we have a maximum of 9 rain gauges and 20 containers. The tree is around 20 years old, and isolated from neighboring trees and thus, could be representative of most urban street trees, which are planted at a distance from each other. In contrast with urban environments, no building is in the immediate vicinity of the tree and the ground is mostly covered with grass. Figure 1 shows the site of the measurement campaign on Université de Sherbrooke campus.

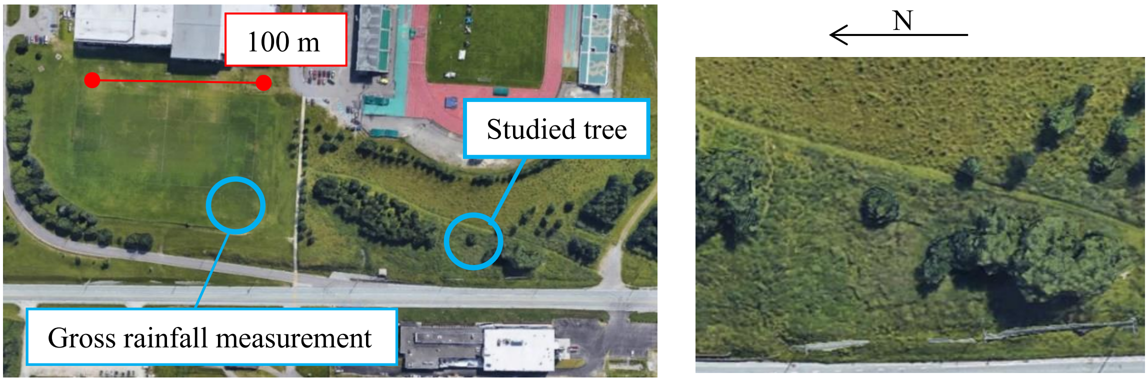

Figure 1 – Measuring campaign site (images from google.earth)

The area of interest under the tree canopy (100 m^2) is delimited with twine to form a 4×4 matrix, forming 16 sections as shown in figure 2. Measurement equipment is positioned arbitrarily within these sections. Each section has one container in it (total of 0.332 m^2 measurement area). However, the positions of the 9 rain gauges (0.167 m^2 measurement area) are selected considering wind direction. We conducted a few measurements using both systems concurrently for comparison purposes.

In addition, one gauge and one container are positioned in an open area, approximately 150 m from the studied tree, and provide the gross rainfall in the open environment as reference (see figure 1).

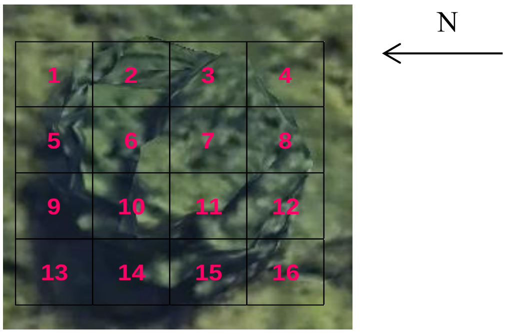

Figure 2. Division of measurement area into 16 sections under tree canopy

As rain is intercepted by the foliage, part of rainwater runs down the systems of branches to reach the trunk. To measure the amount of this water, a PVC hose, cut in half longitudinally to form a gutter, is fixed around the trunk, just below the crown of the tree. Water that flows from the stems to the trunk ends in this pipe, which is then connected to a rain gauge or to a water container on the ground [6].

As we measured the rain that fell through the foliage or down the stem, rain interception is measured indirectly. The water measured with the rain gauges or containers on the ground is called throughfall, which is the sum of rain that drips from the leaves to the ground after being caught by the leaves and the rain that manages to go through the leaves without hitting them (free throughfall). Rain interception, which is defined as the part of water that is caught by the leaves of a tree, and that will be evaporated from there, is the difference between the reference gross rainfall and the sum of the measured throughfall and stemflow quantities.

2.2. Simulation method

Rain is simulated with windDrivenRainFoam. Numerical model solves an isothermal wind flow with Reynolds-averaged Navier Stokes (RANS) equations and turbulence model k-ε. It also performs wind-driven rain calculations with an Eulerian multiphase approach [7].

In CFD, trees are considered as porous zones with momentum source for drag [8], linked to the leaf area density (LAD). The momentum source is considered in momentum equation in the following way:

$$s_u = -\rho c_d a|\bar{u}|\bar{u} \tag{1}$$

Where c_d is the leaf drag coefficient of 0.2, a is LAD, ρ is air density (1.225 kg m^{-3}) and $\bar{u}$ is the main velocity vector, in m s^{-1}.

To compare simulation results with experimental data, a domain of 180×300 m^2 is created with a mesh close to 1.7 million cells. A patch of trees, similar to a small urban forest with several trees, and the studied red oak are included in the domain. The geometry used for the patch of trees is a 15 m high trapezoidal prism, with a foliage that starts approximately at a height of 1.5 m above the ground. The red oak is represented with a pyramid shape that has a 7×7 m^2 base and a 5.8 m height. The foliage starts at a height of 1.5 m above the ground. An LAD value of 1.5 m^2 of leaves per m^3 is used for foliage density, based on a measured value for the same tree species [9]. The same LAD value is used also for the patch of trees. Figure 3 shows geometrical features of trees, the domain and the mesh.

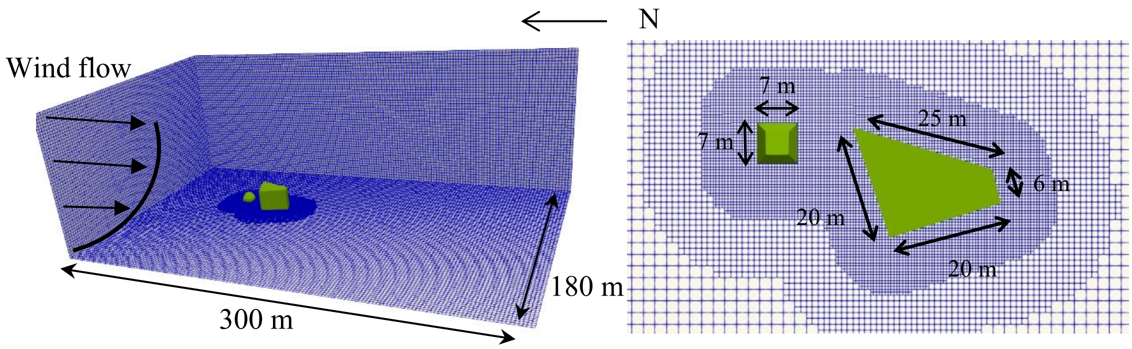

Figure 3. Computational domain in OpenFoam v6

3. Results

3.1. Measurement campaign results

We present the rain event of June 9th and August 8th. During the event of June 9th, both rain gauges and containers are used. Wind is from north with a velocity that reaches approximately 2 m s^{-1} at 2.5 m. Air temperature is around 15 °C and relative humidity is close to 95 %.

For the event of August 8th, only rain gauges are used. Wind is from north and with very low mean speed, showing some gusts of 0.5 m s^{-1} at 2.5 m. Air temperature is 19 °C and relative humidity 96 %.

Comparison of results from rain gauges and containers is done in sections 6, 13, 16, and in the open area. Throughfall quantities measured over time for those sections show some important differences between the two measuring techniques (close to 35 % of rain amount at the end of the event). Figure 7b in a following section of the paper support this affirmation.

Throughfall measurements of June 9th (in mm h^{-1}) at the 16 sections after two time frames during the rain event are presented in figure 4, at approximately 2:45 pm and 3:50 pm. These are measured from containers and measurements are done every 20 minutes. Spatial differences are due to combined effects of wind on rain deposition but are also strongly linked to the tree variability. Wind seems to yield a rain intensity that is higher on the two sections at the western corners under the tree canopy. The throughfall quantities also decrease towards the southeast corner.

a) Reference 6.1

wind →

3.2	4.5	3.0	2.5
3.7	4.3	4.6	3.5
5.5	4.4	4.3	5.4
6.8	3.8	4.9	7.2

← N

b) Reference 1.4

wind →

0.8	1.2	0.8	0.6
0.9	0.7	1.1	0.7
1.1	0.9	0.8	0.9
1.5	0.7	1.6	1.5

Figure 4. Rain intensity (mm h^{-1}) in the 16 slots and at reference location at a) 2:45 pm and b) 3:50 pm

3.2. Simulation results

In a first step, we simulate rain deposition on the ground, without rain interception and, thus, using the wind-driven rain solver as it is now. Therefore, only the disturbance of wind caused by tree leaves is considered. Figure 5 shows wind flow field, at 2.5 m. The approaching wind speed is 2 m s^{-1} at 2.5 m height for the event of June 9th (a) and 0.5 m s^{-1} at same height for the event of August 8th. For both simulation a constant wind flow from north is assumed.

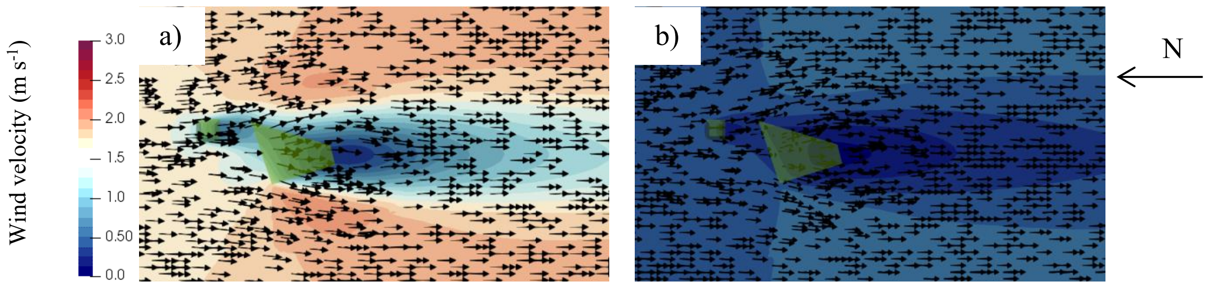

Figure 5. Wind velocity in a horizontal plane at a height of 2.5 m in a pure WDR simulation (i.e. no interception) for rain event of a) June 9th and b) August 8th 2022

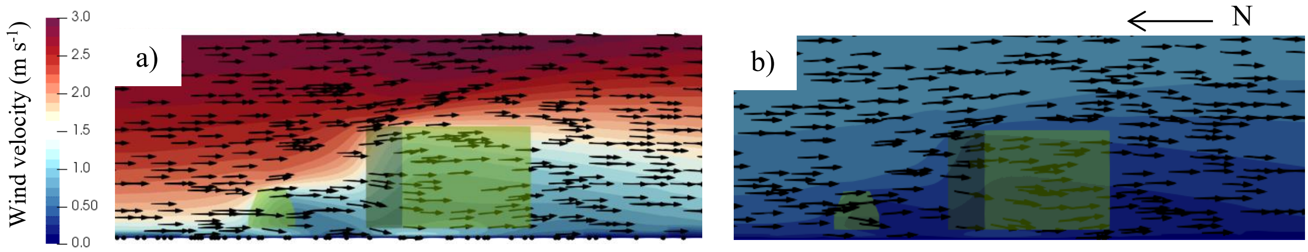

Figure 6. Wind velocity in a vertical plane going through the trees in a pure WDR simulation for rain event of a) June 9th and b) August 8th 2022

Figure 5 shows that for the event of June 9th (a), the wind speed falls below 1 m s^{-1} in the wake of the isolated tree. The following patch of trees is subjected to a slower wind flow, as a zone below 0.5 m s^{-1} is created. For a wind coming from the north, the patch of trees does not create a blockage effect windward that affects the flow around the single tree.

For the event of August 8th (b), the area where the flow velocity is slowed by the trees follows a similar pattern, but the zone with low wind speed is larger. For both events, the wind flow deviates from its main trajectory due to the presence of trees, but no recirculation zone is seen.

For its part, figure 6 presents a vertical 2D slice through the trees during the event of June 9th (a) and August 8th (b). In both cases, the reference velocity (i.e. 2 m s^{-1} and 0.5 m s^{-1}) is observed at the trees top. The extent of the blockage on the windward side of trees is also limited. The trajectory of flow is slightly affected by the trees, but without any important vertical motion and recirculation zone.

The wind flow disturbance in the region of interest yields a particular catch ratio distribution on the ground. Catch ratio is the rainfall intensity at locations on the ground surface divided by the reference rainfall intensity, away from the trees. Figure 7a and 7c shows such a pattern for a rain intensity of 2 mm h^{-1} for the two presented rain events. From the catch ratio values, accumulated amount of water over time can be calculated. Catch ratio time gross rainfall gives water amount, which can be compared with field measurements. Figure 7b and 7d compare preliminary numerical results with measurements.

In figure 7a below, the distribution of catch ratio is distinctly separated under the single tree canopy. Higher values of catch ratio (~1.02) are obtained windward, and lower values are obtained leeward (~0.97). The higher catch ratio zone, in red, is concentrated while the lower catch ratio zone, in blue, spreads in the direction of the wind. Results under the patch of trees present a similar pattern (figure 7c), but values get higher windward (~1.04) and lower leeward (~0.96). The difference in the spatial extent of the catch ratio values zone is also magnified.

Figure 7b and 7d shows that without any source and sink terms to account for rain interception, the pure WDR simulation overestimates rain deposition on the ground. In figure 7b, the rise in rainfall amounts in rain gauges is reduced compared to the one of reference rainfall, while numerical results yield a similar curve than the reference one. In figure 7d, the slopes are much different for measurements below the canopy and at the reference location around 11:30 pm and 00:10.

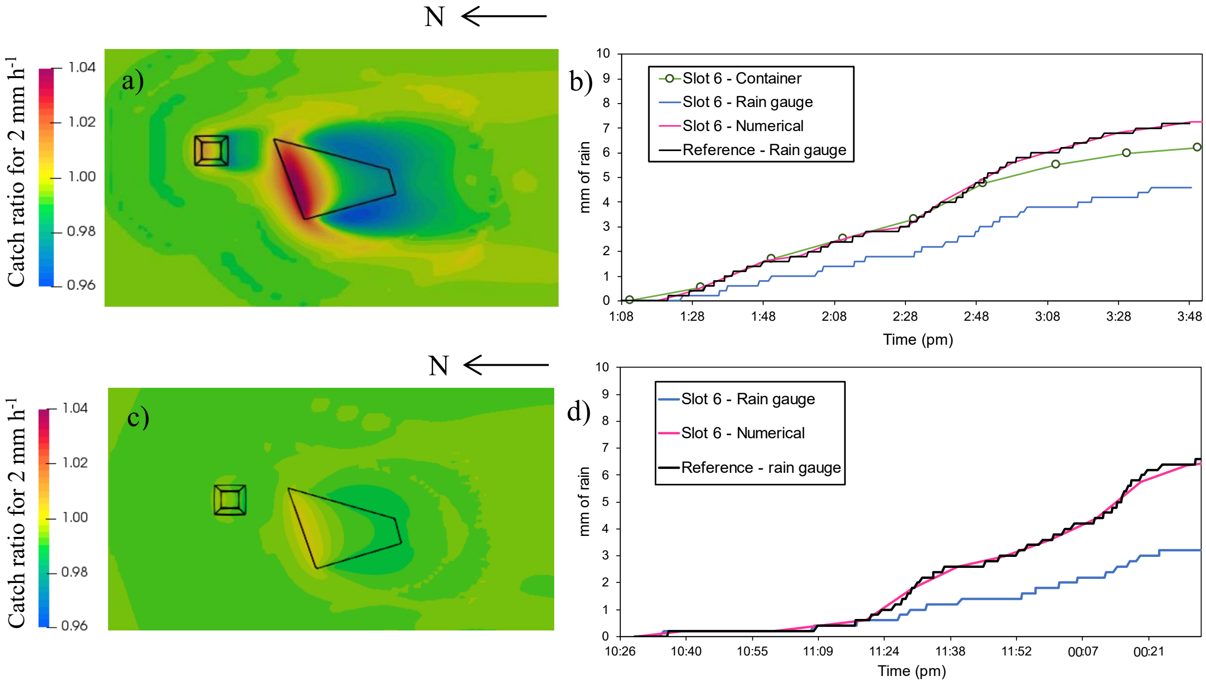

Figure 7. Numerical results of throughfall comprising catch ratio distribution on the ground for rain intensity of 2 mm h^{-1} and amount of rain in mm calculated from simulation for rain event of June 9th (a,b) and August 8th (c,d)

4. Conclusion

In this paper, we show the experimental and numerical methods developed toward implementation of a new capability, rain interception by trees, in the microclimate computational tool urbanMicroclimateFoam. Numerical and experimental results are presented for a red oak on Université de Sherbrooke campus. An initial comparison between experimental and numerical results is shown.

Our next steps consist in adding source and sink terms in wind-driven rain conservation equations to represent both storage of rainwater on leaves and dripping of stored rainwater on the ground and determining their magnitude. Such terms would likely change catch ratio on the ground, and on near facades in urban setups. Because water would be stored and then evaporates in the environment, trees would become a moisture source. The understanding of their impact on post-rain drying conditions is an important potential outcome of this study. The conference presentation will include the latest developments of this project.

In our future work, the modelling of this phenomenon should be applied in the urban environment. A numerical simulation could be performed to understand where the rainwater goes, where surfaces can dry, and how moisture damaged risk evolves on buildings near vegetation. We could then give more insights whether tree sheltering and evaporation can have impacts on a building facade.

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