Coupled numerical simulations of cooling potential due to evaporation in a street canyon and an urban public square

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Abstract. The extent and duration of evaporative cooling, as a countermeasure to the urban heat island effect, depend on factors such as moisture availability and material liquid capacity and permeability. The present study investigates the evaporative-cooling potential of conventional urban materials and green surfaces using two case studies: an isolated street canyon and a historical public square in the city of Zurich with a particular focus on pedestrian thermal comfort. The numerical model couples computational fluid dynamics (CFD) simulations of wind flow with the heat and moisture transport (HAM) in urban materials in order to resolve storage and transport in urban settings. This way, we aim to provide a framework for the development of sustainable and resilient solutions for local heat islands.

1. Introduction

The built environment directly influences the urban climate, modulated by characteristics such as building configuration, vegetation coverage, choice of urban materials, etc. Mitigation measures for the urban heat island (UHI) effect, e.g. promoting evapotranspiration and shading through the use of vegetation, can improve outdoor thermal comfort, building energy use and public health. Past research in simplified geometries show that the cooling potential due to evaporation at porous material urban surfaces depends on the properties such as liquid permeability of materials and is also affected by moisture distribution and liquid water availability [1]. Similarly, transpiration from vegetation depends on the water availability in the soil [2]. For determining outdoor thermal comfort, accurate estimations of local surface temperatures and wind-flow field are necessary, which are directly influenced by the interactions between different physical processes. Therefore, resolving moisture storage and transport at local level is required for the estimation of amount and duration of evaporative cooling.

The present study investigates the impact of evaporative cooling in two case studies: an isolated street canyon and a historical public square in the city of Zurich with a particular focus on the pedestrian thermal comfort. The numerical model couples computational fluid dynamics (CFD) simulations of wind flow with the heat and moisture transport (HAM) in urban materials. Thermal comfort is modeled based on the Universal Thermal Comfort Index (UTCI), which provides locally the perceived temperature based on the mean radiant temperature, air temperature, relative humidity and wind speed [3]. The outcome is valuable when comparing different strategies that aim at improving the urban microclimate at local scale.
2. Numerical model and methodology

The coupled model consists of three separate submodels to solve: 1. the transport in the air subdomain, 2. the long-wave (thermal) and short-wave (solar) radiative exchanges and 3. the absorption, transport and storage of heat and moisture in the subdomains representing porous urban materials and for vegetation. The model is implemented into OpenFOAM v6. The general framework and the detailed methodology of the model are given in Kubilay et al. [1,4].

In the air subdomain, wind flow is solved using Reynolds-averaged Navier-Stokes (RANS) with the realizable k-ε model. Additionally, transport equations for the turbulent and convective transport of heat and moisture are solved. Heat is considered as an active scalar with buoyancy and moisture is modeled as a passive scalar, where the transported quantity is the humidity ratio. Surface wetting due to wind-driven rain is calculated based on an Eulerian multiphase model [5].

In the solid subdomains, which model porous urban materials, the transport of heat and moisture (HAM) is solved. The present study uses the continuum modeling approach, where the different phases are not distinguished separately at a certain point in the material but, instead, the macroscopic behavior of the porous material is modeled. The coupled heat and moisture transport equations are given in equations (1) and (2), respectively [6]:

\[
(c_0 \rho_0 + c_l \omega) \frac{\partial T}{\partial t} = -\nabla (q_e + q_a)
\]

\[
\frac{\partial \omega}{\partial p_c} \frac{\partial p_c}{\partial \tau} = -\nabla (g_l + g_v)
\]

where \(c_0\) denotes the specific heat of dry material, \(\rho_0\) the density of dry material, \(c_l\) the specific heat of liquid water, \(\omega\) the moisture content, \(T\) absolute temperature and \(p_c\) capillary pressure. The derivative \(\partial \omega / \partial p_c\) represents the moisture capacity of the porous material. On the right hand side, \(q_e\) and \(q_a\) denote the conductive and advective heat fluxes, whereas \(g_l\) and \(g_v\) denote liquid and vapor moisture fluxes. The advective heat transfer represents the heat flow due to vapor and liquid flow including latent heat transport. Vapor flux includes transport due to capillary pressure gradient and due to temperature gradient. The implemented HAM model is verified by comparing with the HAMSTAD (Heat Air and Moisture STAndards Development) benchmark study [7] which is specifically developed for moisture transport in building materials.

Short-wave (solar) and long-wave (thermal) radiative fluxes between the domain surfaces and with the sky are calculated with separate systems of linear equations based on a radiosity approach. The incoming solar radiation is composed of direct and diffuse components. The direct component of incoming solar radiation is calculated with ray tracing. Multiple reflections of both solar and thermal radiation are calculated using view factors. Air is considered as a non-participating medium, i.e. absorption, scattering and emission of radiation by air are neglected. All building surfaces are assumed opaque to both longwave and shortwave radiation. The model further assumes that surfaces are grey and reflections are diffuse, i.e. properties are independent of wavelength and direction.

Grass is modeled using a leaf energy model, assuming a stationary leaf energy balance and neglecting the dynamic thermal storage of heat in leaves [3]. Grass leaf temperature is calculated with an iterative energy balance calculation based on latent and sensible heat fluxes. Transpiration from grass blades is calculated based on the leaf stomata resistance. The absorbed (and transmitted) solar radiation at the leaf is modeled based on the Beer-Lambert law. Once the leaf temperature is calculated, the grass model provides the source/sink terms for heat, moisture and momentum to the air. The implemented grass model is verified by comparing the grass leaf temperature and the soil surface temperature underneath with a numerical study [8], which provides a detailed parametric study on green roofs, validated with laboratory experiments within an environmental chamber.

3. Coupling algorithm

The coupling between the air and porous solid subdomains is performed by sequentially solving the steady RANS equations in the air and the unsteady heat and moisture transfer in porous building materials. Information exchange between subdomains is performed each 10 min, i.e. exchange time step.
Transient heat and mass transport in porous solid subdomains are simulated using adaptive time steps [6], during which the solution of the air domain remains constant. At each time step, internal iterations between heat and moisture equations are performed until temperature and moisture content values converge. Finally, the new values for temperature and moisture are used to solve the steady air flow for the next exchange time step. At the coupled boundaries of the air subdomain, Dirichlet boundary conditions are used, where the values for temperature and humidity ratio calculated for the urban materials are imposed. Neumann boundary conditions are used at the coupled exterior surfaces of urban materials, where the heat and moisture fluxes are defined.

4. Case study 1: isolated street canyon

The first case study is performed on an isolated three-dimensional street canyon, composed of two identical buildings with the dimensions height × length × width of 10×10×50 m³. The computational domains and grids for the air and porous subdomains are shown in figure 1. For the outer layer of the street-canyon ground, which has a thickness of 0.10 m, different materials are considered: concrete, soil and two types of brick pavement. Moisture retention and transport properties are given in figure 2. Beneath this layer, an additional soil layer with a depth of 1.90 m is present for each case. The leeward and windward facades of the street canyon are finished with an exterior layer of brick masonry with a thickness of 0.09 m.

The study considers a typical early summer day with moderate ambient temperatures in Zurich, Switzerland. The daily ambient temperature varies between 11°C and 19°C, while the relative humidity varies between 62% and 86% RH. For simplicity, a constant wind direction from west and a constant wind speed of 5 m/s at the building height are considered. At the inlet, uniform values for ambient temperature and humidity ratio are set. For wind speed and turbulence parameters, atmospheric boundary layer log-law profiles have been used assuming a neutral stratification.

The reference ‘dry’ simulations are performed over a duration of three days for each material for the street-canyon ground. For ‘wet’ conditions, rain events of constant intensity are considered for a duration of 10 hours at nighttime with three different rainfall intensities: 1.0, 2.5 and 5.0 mm/h, where 1 mm/h is around the yearly average for Zurich, Switzerland.

Figure 3a compares the surface temperature at the center of the street-canyon ground. Before the rain event, the differences in surface temperatures reflect the thermal diffusivity and specific heat of the materials. After the rain event, due to evaporation, the maximum surface temperature decreases by as
much as 20-22°C for the two bricks and 15°C for soil. The decrease in surface temperatures can be seen more clearly in Figure 3b. A larger reduction of temperature is observed for bricks than for soil as the bricks have a larger liquid permeability at partial saturation than soil. The rate of evaporation from porous urban surfaces is high as long as there is liquid water present at the top pores and material surface is at almost 100% RH. At these conditions, i.e. first drying phase, the drying rate depends mainly on external conditions. The high rate of evaporation can be sustained as long as capillary transport within the material can replace the water loss at the top surface. In this case, at similar level of partial wetting conditions, bricks show a relatively longer first drying phase than soil. For concrete, the decrease in maximum temperature is negligible as a much smaller amount of water is absorbed.

Figure 3. Temporal variation of a) surface temperature and b) decrease in surface temperature on the street-canyon ground for different pavement materials at a rainfall intensity of 1 mm/h.

Figure 4. Decrease in a) surface temperature and b) UTCI due to rain at different rainfall intensities for brick as the pavement material.

Figure 4a compares the resulting difference in surface temperature between the 'wet' and 'dry' conditions for different rainfall intensities. As an example, when the rainfall intensity increases from 1 mm/h to 2.5 mm/h, soil remains in the first drying phase for a longer duration. The reduction in temperature increases from 15°C to 20°C on the day following the rain event. As the rainfall intensity further increases to 5 mm/h, the surface temperature of soil does not decrease further at t = 38h. This is due to the fact that the environmental conditions, such as radiation and convection, are identical at each wetting.

The resulting thermal comfort at pedestrian height is given in terms of UTCI in Figure 4b. The factors influencing the difference in UTCI the most are the decreases in mean radiant temperature and air temperature in this case. The general trend is similar to what is seen in surface temperatures. The improvement in UTCI after wetting is up to 2.5°C, while UTCI is less affected on the last day with a
decrease between 0.5-1.5°C at lower rainfall intensities. For more detailed analysis with different wetting scenarios, refer to Kubilay et al. [4].

5. Case study 2: urban public square
The second case study focuses on a historical public square in the city of Zurich, Switzerland, namely "Münsterhof". The computational domain representing part of the Zurich city center and a close-up view of Münsterhof are given in figure 5. The shapes of the buildings in the immediate surroundings of Münsterhof are captured more accurately, while the buildings in the outermost layer are modeled simpler. Buildings further away are not modeled explicitly, but only as a surface roughness on the ground. The smallest cell height is about 0.3 m on the building surfaces.

![Figure 5](image_url)

The variations of ambient temperature and total solar radiation intensity are based on June 29th 2015, during a heat wave in Zurich. Wind velocity and air temperature above the canopy are obtained in 1-hour intervals from previous COSMO simulations with Double Canyon Effect Parameterization (DCEP) urban canopy model [9]. The daily ambient temperature varies between 17.6°C and 27.1°C, while the ambient relative humidity between 40%-70%.

The ground surface of the Münsterhof, indicated with red and green in Figure 5b, is modeled as a coupled boundary, where heat and moisture exchange occur between the air and the porous solid subdomains. A top layer of concrete with 30-cm thickness is considered as reference case. Beneath this layer, a soil layer with a depth of 1.70 m is present. Then, two additional cases are considered within the rectangular zone of 25×25 m², indicated with green in Figure 5b: the top layer with 30-cm thickness is replaced with A) brick and B) grass-covered soil, both with moisture content at capillary saturation. The remaining surfaces, such as ground, building facades and roofs, are assumed impermeable and their surface temperatures are obtained from the above-mentioned COSMO simulations [9].

![Figure 6](image_url)

Figure 6a compares the variation of average surface temperature for different configurations. For the case grass-covered soil, temperature of the grass blades and the soil underneath are given separately. The highest temperature is observed at the concrete surface which heats up until about 57°C. For wetted brick, a significantly lower surface temperature is observed. The temperature difference is also
maintained at the times where the rate of evaporation is dominated by solar radiation, which indicates that there is still liquid water present within the brick layer. In contrast to the street-canyon case, soil has a lower temperature than brick due to the fact that part of the solar radiation is intercepted by grass. The resulting UTCI values and thermal stress levels are given in Figure 6b. For the calculation of UTCI in case B, soil is assumed to be fully covered with grass and only the grass leaf temperature is considered. In general, a similar level of improvement is obtained as in the case for the street canyon.

6. Discussion and conclusions
The impact of evaporative cooling on the thermal comfort is analysed using various urban surface covers. The isolated street canyon is more suitable for parametric studies given that it is computationally less complex and that its boundary conditions are more controlled. On purpose, it is simplified compared to a real urban geometry, allowing careful considerations of the impact of different parameters. Nevertheless, the improvement in thermal comfort due to evaporative cooling is found to be in a similar range for both case studies.

The cooling potential due to evaporation depends on parameters such as liquid transport properties, initial conditions of surface layer and moisture availability. The applied numerical model allows for the detailed analysis of the coupled heat and moisture transport in urban materials at local scale.

The results provide insights on the comparison and optimization of different strategies that aim to improve urban microclimate. Solutions such as “smart wetting” of materials, e.g. varying the wetting period and wetting amount and the use of permeable materials, e.g. varying the porosity and pore size distribution, towards optimizing the cooling and providing thermal comfort can be investigated in detail. Such solutions can provide additional ways to improve thermal comfort during a heat wave, e.g. as a mitigation measure. The coupled model can estimate the impact of extreme weather conditions such as drought, during which vegetation would be unable to provide cooling through transpiration.

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