Mitigation measures for urban heat island and their impact on pedestrian thermal comfort

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Abstract. A multiscale coupled model is presented that allows for the detailed analysis of the local impact of urban heat island mitigation measures. The model uses coupled computational fluid dynamics (CFD) simulations with unsteady heat and moisture transport (HAM) in porous urban materials in order to take into account the dynamic heat and moisture storage in the built environment. A realistic case study is performed for a public urban square in the City of Zurich during heat wave conditions. The impacts of two different mitigation strategies, i.e. adding artificial wetting of pavements and adding vegetation, on pedestrian thermal comfort are evaluated and compared with the existing situation. The results show an improvement in thermal comfort in both conditions. The improvement resulting from the addition of trees is larger and lasts longer due to shadowing effects, even though a reduced ventilation and an increased relative humidity by trees have an adverse effect on the thermal comfort.

1. Introduction

Recorded data show that heat waves are getting more frequent and intense with longer duration while affecting larger regions. The resulting local conditions in urban areas can impose very strong heat stress levels, especially when compounded with situations that lead to local heat islands. Counter-measure strategies should involve careful planning with a combination of effective mitigation strategies, while keeping sustainability in mind. It can be that the same mitigation measures for the urban heat island (UHI) effect can work better in under certain conditions. Furthermore, they can have advantages and disadvantages, e.g. vegetation has the potential to improve thermal comfort by shading and evapotranspiration, but too dense vegetation without careful planning can decrease the ventilation potential due to wind blocking. Numerical simulations can be used to resolve the complex interactions between the physical phenomena involved in the urban environment such as 1) turbulent air, heat and moisture flow due to wind and buoyancy, 2) shortwave and longwave radiation exchange between the built environment and the sky, 3) dynamic heat and moisture storage in the built environment, 4) removal of heat and moisture from surfaces due to convection, 5) vegetation effects and 6) anthropogenic heat.

In the present study, the impacts of two different mitigation strategies, i.e. artificial wetting of pavements and vegetation, on pedestrian thermal comfort are evaluated. A coupled approach is performed for a public square in the city of Zurich. Computational fluid dynamics (CFD) simulations are coupled with a radiation model and a model of unsteady heat and moisture transport (HAM) in porous urban materials. This allows for an accurate tracking of moisture content near surfaces available...
for evaporative cooling and for the calculation of drying rate and cooling potential. Trees are modeled as porous objects within the CFD domain including transpirative cooling based on the plant physiology. Boundary conditions driving the flow during heat wave conditions are obtained from mesoscale meteorological simulations including urban parametrization. The resulting pedestrian thermal comfort with and without mitigation measures is evaluated with the Universal Thermal Climate Index (UTCI) [1].

2. Methodology

2.1. Coupled modeling approach

The present study uses a multiscale coupling approach [2], downscaling from mesoscale using meteorological models at a computational domain size < 200 km to building-resolved neighborhood scale simulations at a computational domain size < 2 km and to material scale which resolves transport and storage at porous urban materials.

At the mesoscale, COSMO simulations with the DCEP double-canyon effect urban parametrization [3] are performed. DCEP represents a multi-layer urban canopy, taking into account the radiation exchange for two parallel street canyons. While urban parametrization incorporates the influence of the urban environment at city scale, even with sub-kilometer resolution (250 m), the model resolution is too coarse to capture local conditions. Furthermore, there is no detailed information on the local velocity field resolved around the buildings due to the statistical representation of the urban morphology, which complicates a detailed comfort analysis. Thus, this detailed information may be captured by the neighborhood-scale CFD simulations based on steady Reynolds-average Navier-Stokes (RANS) model, consecutively run for each timestep in a day [4]. Dynamic storage in the built environment is taken into account with a coupled unsteady heat and moisture transport model (HAM) at material scale. The long-wave and short-wave radiative exchanges are calculated by including multiple diffuse reflections. The temporal coupling between the three scales is summarized in figure 1.

![Figure 1. Temporal coupling between subdomains. Figure adapted from Kubilay et al. [7] with permission. Black filled circles indicate the output timesteps when coupling is performed (n: exchange timesteps between CFD and HAM, m: adaptive timesteps for the unsteady HAM, t: output timesteps for mesoscale subdomain).](image)

For each of the “exchange timesteps” n in figure 1, a separate steady RANS simulation is performed where the inlet boundary conditions and the temperature and humidity at urban surfaces are updated. In
between each exchange timestep, transient HAM simulations are performed with adaptive timesteps using the Picard iterative scheme \[5,6\]. Timestep of the HAM model is increased if the Picard iteration converges successfully, i.e. the maximum change in moisture content or temperature is smaller than a user-defined tolerance, and decreased otherwise.

2.2. Modeling of artificial wetting of pavements

The coupled CFD-HAM approach presented in section 2.1 is able to resolve and track the moisture content available within porous urban materials. This allows for the accurate representation of evaporative cooling from a wetted surface, where the convective heat and moisture fluxes are calculated by the local flow field in the CFD subdomain. Previous research investigated the evaporative cooling potential of porous pavements in a street canyon, which showed strong dependence on layer configuration of pavements with different porosity \[8\] and the moisture retention and transport properties of the pavement materials \[8,9\]. Afterwards, using a porous pavement configuration optimized for evaporative cooling, parametric analyses are performed to find out optimal wetting amount, wetting period and wetting duration by artificial spraying of stored rain water \[7,9\]. It was found that, when using a porous pavement effective at keeping liquid water near the surface after artificial wetting, a single wetting application of 6 mm in the morning provides sufficient cooling for a day and night during a heat wave \[7\]. A similar setup is used in terms of pavement configuration and wetting strategy in a realistic case study described in section 3.

2.3. Modeling of vegetation

Trees are modeled as porous zones with a given leaf area density (LAD). Based on the LAD distribution, the vegetation model takes into account the aerodynamic effects and shadowing of the trees and the long-wave radiation exchange between the trees and the surroundings. Porous zones representing trees introduce source/sink terms for the mass, momentum and heat transport in the CFD model. Transmissivity of short-wave radiation through the vegetation is modeled based on the Beer-Lambert law, with an extinction coefficient for solar radiation and a leaf area index (LAI). Leaf temperature is calculated with an iterative energy balance calculation considering short-wave and long-wave radiation, sensible heat flux and latent heat flux \[10\]. Sensible heat flux depends on the aerodynamic resistance of leaves and the temperature difference between air and leaf surface. Evapotranspiration, and thus latent heat flux, depends on both the aerodynamic resistance and the stomatal resistance, controlled by physiological response of the tree and which is a function of solar radiative flux, vapor pressure deficit in the air and tree species.

3. Description of case study

The present study applies the coupled microclimate model to analyze the thermal comfort in a historic public square in the middle of the City of Zurich, Switzerland. The square is highly exposed to solar radiation and currently without permanent vegetation. The computational domain for the CFD simulations is provided in figure 2a. Only the buildings within a certain distance of Münsterhof are modeled explicitly, with building shapes captured more accurately in the immediate surroundings of the square (buildings indicated in blue). Building groups indicated in yellow are modeled with less detailed shapes and coarser grid refinement, while the ones in green are clustered together to avoid unnecessarily high total grid cell count. Buildings even further away are modeled with ground roughness. At the lateral boundaries of the domain, boundary conditions of air temperature and air velocity are provided by pre-calculated COSMO simulations.

Figure 2b shows the computational domain for the HAM simulations, where the coupling with the CFD simulations is described in figure 1. The facades facing the square and the pavement surface within the square are selected as coupled boundaries. At these coupled boundaries, the calculated temperature and humidity values in the HAM domain are imposed as boundary conditions in the CFD domain. In the opposite direction, the calculated heat and moisture fluxes in the CFD domain are imposed as boundary conditions in the HAM domain. The thickness of the facades in figure 2b is 10 cm, which
represents the active part of the façade for storage, while the remaining part is modeled by a thermal resistance. The total ground thickness is 2 m, composed of a 30-cm impervious pavement layer at the top and 1.7 m soil layer underneath. For all the remaining wall surfaces within the CFD domain, the surface temperatures are obtained from the COSMO urban parametrization (DCEP).

Figure 2. Computational domains for a) the CFD simulations of air flow and b) the HAM simulations within the facades looking towards Münsterhof and within the ground.

In order to compare with the existing situation within the Münsterhof, two mitigation measures are considered. In the first case, the impervious pavement inside the area outlined in blue in figure 3a is replaced with porous pavement based on the earlier study in a street canyon [7]. A two-layer porous pavement configuration is considered, with a fine-porous layer at the top and a coarse-porous layer at the bottom. The top layer acts as a capillary pump, sucking up the moisture to the surface, while the bottom layer acts as a capillary break, preventing water loss into the subsoil. The porous pavement is wetted in the morning between 8:00 and 8:20 UTC with a total water amount of 6 mm. In the second case, two different species of trees are used as shown in figure 3b. The taller trees indicated with dark green color are silver lindens (Tilia tomentosa), with a uniform LAD value of 4 m²/m³. The shorter ones with light green color are field maples (Acer campestre), with a uniform LAD value of 2 m²/m³.

The simulations for the existing situation and the two modified cases are performed for 25 June 2019, which is a hot day during a heat wave in the city of Zurich. In the first case with porous pavement, the liquid water content near the porous pavement surface is calculated with the unsteady HAM model, allowing for the estimation of the duration of evaporative cooling. Remaining surfaces are assumed impermeable, where the HAM model reduces to pure heat conduction, calculating the dynamic thermal storage and temperature distribution. For the trees in the second case, the transpiration rate is calculated based on the assumption that enough moisture is available in the soil for root water uptake, considering that the location is near the lake and river.

Figure 3. Mitigation measures implemented in Münsterhof. a) Artificial wetting on porous pavement and b) configuration with street trees (Figure from [2] with permission).
4. Results
The impact of the trees on the local air flow is shown in figure 4 when the predominant wind direction is from south at midnight. The horizontal plane is at 3 m height, which corresponds to the lower part of the tree foliage. In the case without trees, inflow into Münsterhof from the eastern side is visible, where the River Limmat is located. This inflow is physically directed into the square by the building on the eastern side of Münsterhof. Locally, several counter-rotating vortices are visible as a result of other wind streams approaching from different alleys. The presence of trees in figure 4b clearly causes a different local flow field, where the inflow from the east side is weaker. Furthermore, the overall wind speed is reduced within the square.

Figure 4. Magnitude of wind velocity at 3 m height within the Münsterhof for a) the existing conditions without vegetation and b) the case with trees.

As a next step, pedestrian thermal comfort is evaluated using the UTCI [1]. The reduction of wind speed due to the presence of trees leads to worsened conditions in terms of thermal comfort, but, at the same time, trees provide shading, i.e. a reduction in nearby surface temperature, and cooling by evapotranspiration, while increasing relative humidity in the air. UTCI considers these variations and provides an equivalent temperature perceived by a pedestrian based on local values for air temperature, relative humidity, wind speed and mean radiant temperature.

Figure 5 shows the obtained UTCI values at pedestrian height at different positions in the square at 12:00 UTC, when the sun is high in the sky. In the existing situation, figure 5a shows UTCI values above 37°C in a large part of the square. This value corresponds to very strong heat stress based on the classification of UTCI values provided in Bröde et al. [11]. There is a reduction by up to 2.5°C in UTCI values at the central part when artificial wetting is applied (Figure 5b). In this case, the improvement in thermal comfort is due to the lower pavement temperatures obtained via evaporative cooling at the center part, reducing the mean radiant temperature. While the increase in relative humidity has an adverse impact on thermal comfort, there is an overall improvement. In the presence of trees, as shown in figure 5c, the impact is larger with additional cool zones directly under the trees due to shadowing. The cooling effect is particularly large under and around the larger trees, where lower air temperatures are observed. In this case, the reduction in UTCI values reaches lower heat stress levels, e.g. moderate heat stress or lower range of strong heat stress.

Results show that the cooling provided by trees is large enough to reduce the thermal stress during daytime, in some cases until moderate levels with a reduction in UTCI by up to 7 °C. Without any additional shadowing, cooling provided by artificial wetting is more limited, with a maximum reduction of 2.5 °C in UTCI. The effective duration of cooling is found to be shorter in time for a square due to a higher exposure to solar radiation compared to the case of a street canyon.
Figure 5. Spatial variation of UTCI at pedestrian height for a) existing situation without vegetation, b) the case with artificial wetting and c) the case with trees at 12:00 UTC (Figure from [2] with permission).

5. Discussion and conclusions

A coupled urban climate model is applied in a case study to analyze the effect of UHI mitigation measures on thermal comfort, taking into account the resolved wind-flow field and buoyancy with radiative exchange, heat and mass transport in porous materials and vegetation. Two mitigation solutions during heat wave conditions are evaluated in terms of their local impact on pedestrian thermal comfort. Thermal comfort analysis shows that the cooling achieved by trees is more efficient than artificial wetting in this particular study. The main factors here are the shadowing provided by the trees and, to a lower extent, transpiration. Although providing comparatively less cooling, artificial wetting can be considered in locations where vegetation is not an option.

The present study provides some insight into the complex behavior of the influencing factors on thermal comfort for different mitigation measures. However, it should be mentioned that the obtained results cannot be generalized, especially when different climates are considered, e.g. coastal or tropical climates where humidity is higher. Additionally, in cases with reliance on ventilation for heat removal, e.g. the use of ventilation corridors, the reduction in wind speed due to the presence of trees can lead to worse conditions than in this particular case study. Note also that the UTCI provides a means to the comparison of thermal comfort levels at different conditions. However, this comparison is by itself mainly instantaneous, where no information is acquired related to the duration of exposure to a high thermal stress level. For example, the improvement in thermal comfort may be at a similar level for certain conditions, but a prolonged impact may have a better benefit over time.

Further work is planned related to the identification of the relative influence of different factors by vegetation, e.g. the relative contributions of shadowing and evapotranspiration, reduction of sky view factor at night in the presence of trees and conditions with water stress, where the available water for transpiration is limited.

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