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Multiphysics Modeling of Materials, Assemblies, Buildings and Cities

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ABSTRACT

There is growing evidence that heat waves are becoming more frequent under increased greenhouse forcing, associated with higher daytime temperatures and reduced night-time cooling, which might exceed the limits of thermoregulation of the human body and affect dramatically human health. Especially urban areas are affected, since these regions in addition experience an urban heat island (UHI) effect characterized by higher air temperatures compared to the surrounding rural environment. A necessary breakthrough is a shift away from a fragmented approach towards an integrated multiscale urban climate analysis. This type of research is a rather new domain of research and might be based on an all-physics understanding and modeling of the urban climate ranging from the scales of material and buildings, to the scales of a group of several buildings, street canyons, neighbourhoods, cities and urban regions, referred to as multiscale building physics. To adequately cover global and local urban heat island effect, regional and mesoscale climate analyses have to be downscaled to sub-kilometer resolution and linked with urban climate models at neighborhood and street canyon scales. Such a multiscale urban climate model allows to analyze the influence of urban and building parameters on thermal comfort and the building cooling demand. The importance of accounting for the local urban climate when quantifying the space cooling demands of buildings in an urban environment is demonstrated. The heat-moisture transport model for building materials allows the design of new building materials, which can help in the mitigation of local heat islands. With respect to evaporative cooling materials, we need to optimize their water retention and evaporative cooling by tailoring their pore structure. The understanding and information obtained from pore-scale investigations enables to understand macro-scale transport processes, and enabling us to explore the potential of new evaporative cooling materials at local urban scale.

KEYWORDS

IBPC 2018, building and urban physics, multiscale modelling, building energy demand, pore scale modelling

THE BROAD VIEW: URBAN CLIMATE AND CLIMATE CHANGE

There is growing evidence that heat waves are becoming more frequent under increased greenhouse forcing (e.g. Seneviratne et al. 2012, Hartmann et al. 2013, Schleussner et al. 2017). Climate simulations project an increase of the number and intensity of heatwaves and hot extremes in many regions in the world (Sillmann et al. 2013, Fischer et al. 2014) even for moderate scenarios of global warming of 1.5°C or 2°C (Seneviratne et al. 2016, Wartenburger et al. 2017, Dosio et al. 2018). In future, heat waves associated with higher daytime temperatures and reduced nighttime cooling might exceed the limits of thermoregulation of the human body and affect dramatically human health. Switzerland experienced important heat waves during the 2003 and 2015 summers, which were the two warmest summers over more than 150 years. For these summers, an excess mortality of 6.9% and 5.9% respectively

was estimated corresponding to 975 and 804 extra deaths for these years, see Figure 1a (Vicedo-Cabrera et al. 2016).

Urban areas are especially affected, since these regions, in addition, experience an urban heat island (UHI) effect characterized by higher air temperatures compared to the surrounding rural environment (Oke 1987, Moonen et al 2012b). Urban heat islands in cities have been reported for more than 400 cities around the world (Santamouris and Kolokotas 2016). The magnitude of UHI is found to vary from place to place with urban heat island intensities up to 6 - 7°C (Santamouris and Kolokotsa, 2016). For Zurich, we found an urban heat island intensity of around 4.5 degrees during the heat wave of 2015 (see Figure 1b-c, Mussetti et al. 2016). Li and Bou-Zeid (2013) showed that the combined effect of UHI and heat waves is larger than the sum of the two individual effects.

The UHI leads not only to a reduction of urban thermal comfort, but also to an increase in building energy demand, especially in space cooling demand during warm periods. Due to local and global climate change and growth of world's population and economic, the world global space cooling demand for buildings is expected to strongly increase in future. In 2010 the global cooling consumption of the residential sector represented 4.4 % of the total space conditioning of buildings. This number is expected to increase to 35 % in 2050 and 61% in 2100 (Santamouris 2016, Isaac and van Vuuren 2009). Not only the annual but also the peak cooling demands will strongly increase. This means that also the power capacity for cooling, and thus electricity, may have to be strongly increased to satisfy future peak energy needs (Santamouris 2016). Santamouris (2016) proposed three main actions to face the problem with the increase in cooling demands: (1) mitigation of the global and local climate change, (2) adaptation of the building sector and improvement of its energy performance and (3) improvement of mechanical air conditioning and alternative cooling technologies.

In addition to the global UHI effect, heat waves are accompanied with local hot spots in cities, called local heat islands (LHI), see Figure 1d (Allegrini and Carmeliet, 2016). Certain city quarters or zones between individual buildings may show much higher air temperatures compared to neighboring urban areas, due to lower wind speeds by wind sheltering leading to less removal of heat. On the other hand, at low wind speeds, higher urban surface temperatures due to solar radiation may lead to more buoyancy enhancing heat removal. As a result, the origin of LHIs is a complex phenomenon depending on a set of parameters such as lack of urban ventilation, lack of vegetation, densification and urban morphology.

The continuing spread of urban areas and the growing fraction of people living in cities direct nowadays a particular spotlight on urban climate and urban heat islands, and the corresponding effects on thermal comfort and heat stress during heat waves. As a result, many research teams worldwide aim at formulating adequate measures to adapt to and/or mitigate these threats, but most approaches remain fragmented focusing on specific scales or topics of the urban climate.

A necessary breakthrough is a shift away from a fragmented approach towards an integrated multiscale urban climate analysis. This type of urban climate research is a rather new domain of research and might be based on an all-physics understanding and modeling of the urban climate ranging from the scales of material and buildings, to the scales of a group of several buildings, street canyons, neighbourhoods, cities and urban regions. The final aim is to propose adequate urban adaptation measures for climate change (CC) at regional scale in view of different CC scenarios and to develop adequate UHI mitigation measures. Such an approach for urban heat island mitigation allows communities to identify spots of local heat islands, reduced urban comfort and increased health risks, to pinpoint the causes for the appearance of local urban heat islands, and to propose possible mitigation measures using high-resolution urban mapping techniques.

Figure 1. (a) All-cause daily mortality (number of deaths) in Switzerland in 2003, from 2005 to 2014 and in 2015. Two prominent mortality peaks in the summer months, July 2015 and August 2003. (b) Global heat island in Zurich during the heat wave of 2013: map of air temperatures at 2 m height at 12 pm averaged over 5 consecutive days. (c) Urban mapping of air temperatures at 2 m height at 6 am in city of Zürich showing higher air temperatures during the night. (d) Local climate at a neighborhood in Zurich determined with coupled Building Energy - CFD simulations. Selected streamlines where colours indicate local temperature increase due to new buildings (Allegrini and Carmeliet 2016).

WHY MULTISCALE BUILDING PHYSICS ? WHICH SCALES TO CONSIDER?

Traditional building physics focusses on the scales of materials towards building components and buildings systems, and finally whole buildings. The aim of building physics is assuring a correct indoor comfort with minimal building energy consumption, while guaranteeing a correct hygrothermal and acoustic performance, maintenance and durability. Urban physics focusses on physical processes from the scales of urban materials, to the scales of a group several buildings, street canyons, neighbourhoods and total cities. Urban physics can be seen as a complement to building physics, filling the missing link between studies at meteorological and climate scales and building physics. There is nowadays not only a high need of integrating urban and building physics, but also to develop a new discipline, called multiscale building physics. The challenge for multiscale building physics is not only to broaden its field over different scales from material to city scale, but also to link up with other fields. From one side urban climate scientists and planners generally consider only UHI mitigation measures to limit the negative impact of local heat islands. Climate model scientists on the other hand mainly focus on the effects of greenhouse gas mitigation to limit the climate change impact globally. A necessary breakthrough consists in the combination of regional climate modeling combining the effects of greenhouse gas forcing on larger scales with the assessment of UHI mitigation measures on smaller scales for local heat islands during heat waves, and the analysis of their interaction. Such a global approach allows the

formulation of more general UHI mitigation measures integrating the use of materials, energy and water on different scales, which can be considered in climate change projections and climate change adaptation.

Scales in urban climate analysis

To adequately cover global and local urban heat island effects, regional and mesoscale climate analyses have to be downscaled to sub-kilometer resolution and linked with urban climate models at neighborhood and street canyon scales. The scales to be considered are represented in Figure 2. We start from global climate models and scale them down to the European (~25 km resolution) and further to the regional scale (entire Switzerland and a portion of central Europe at 1-2 km resolution) using a regional/mesoscale climate model. The regional climate model is further downscaled for selected cities to resolve small-scale thermal circulations and intra-urban variability at sub-kilometer resolution (~200 m). At the urban level, we consider city, neighborhood and street canyon scales.

Figure 2. Different scales in urban climate modelling and multiscale building physics (photos from Christen 2005).

MULTISCALE MODELING?

Regional and urban climate interactions

Urban surfaces interact with mesoscale meteorology and climate in several different ways (Roth 2000; Masson 2006; Martilli 2007). Their roughness exerts enhanced drag on the flow and they alter the surface energy balance by trapping radiation, storing heat in urban materials, changing the ratio between sensible and latent heat fluxes, and releasing additional heat due to human activities. These interactions motivated the development of urban canopy parameterizations in atmospheric models enabling a better representation of the mesoscale forcing of urban weather and climate. These models describe the sub-grid scale effects of buildings and urban surfaces on the flow and on surface heat exchange in a parameterized fashion, for example by representing buildings within a grid cell as a statistical ensemble of

street canyons of different orientations and dimensions and calculating radiative transfer (including multiple reflections between surfaces) and energy and water vapor exchange between atmosphere and building and street surfaces in each canyon separately.

As an example, the urban heat island effect in Zurich was simulated with the climate version of COSMO in order to capture the local atmospheric circulation influenced by the orography and the presence of Lake Zurich, see Figures 1b-c (Mussetti et al. 2016). The model has currently been extended with the representation of street trees and a detailed representation of short- and long-wave radiation in the street canyons by ray tracing.

From urban to building scale: building-resolved analysis

At city scale, a CFD based urban climate model is used which, in contrast to mesoscale models, also resolves the physical phenomena at street canyon scale. These models take into account accurately the building and street geometry, where buildings are geometrically resolved in computational fluid dynamics (CFD) (figure 3a). They also take into account the used urban materials, particular weather conditions (wind, sunshine, rain, temperature, relative humidity), shadowing, as well as the local urban water cycle.

The influence of higher scales such as the global urban heat island are modeled via appropriate boundary conditions (wind velocity and orientation, surface temperatures) from simulations at sub-kilometer resolution using a nesting approach (Vonlanthen et al. 2017). In order to solve the mismatch between different scales and physics involved in the two models, we apply a blending layer. Transpirative cooling and shadowing effects from trees as well as the evaporative cooling effects of water bodies or absorbed water (by rain or spraying) can be considered. Figure 3b gives an example of the air temperatures at 3 m height in downtown Zurich during a heat wave day.

These models at city scale are further downscaled to neighborhood and street canyon scales for selected parts of a city. At this scale, an all-physics model is used considering solar and longwave radiation, three-dimensional turbulent wind flow and buoyancy, temperature and relative humidity in the air domain and heat and moisture transport in the porous domains of urban surfaces (see Figure 3c, Kubilay et al. 2016). The surface temperatures are determined by a thermal balance of solar and longwave radiation, convective heat transport at surfaces, heat conduction and storage of heat in the building materials and soil, and evaporative cooling effects. The urban climate model is extended with vegetation using a porous media approach with sink and source terms for moisture and heat to model the transpiration and the related transpirative cooling effect. The vegetation model includes moisture transport within the soil/roots, tree, stem, branches and leaves, allowing the consideration of the complete water cycle at street canyon scale between air, soil and tree. A multiphase Eulerian model for wind driven rain has been developed and validated in order to accurately determine the wetting of the building surfaces and soil, see Figure 3d (Kubilay et al. 2013). The wind driven rain model is able to predict the rain load and wetting of all urban surfaces including roofs, facades, pavements, streets, soils and other surfaces. The porous heat-moisture transport model allows the determination of the heat and moisture transport and storage in these materials. When evaporation occurs, evaporative cooling is considered.

The urban climate model is further integrated with an urban water cycle model including rain and drainage systems at city scale in order to explore the potential of using urban water resources locally for UHI mitigation, especially during heat waves. This enables the assessment of when stormwater can be used to reduce the local heat island effects via evaporative cooling. A thorough analysis on stormwater availability and storage potential in cities can then be performed. This provides answers to questions such as: Is the stormwater volume sufficient and available when required to mitigate urban heat island effects? How does

dedicated stormwater storage solutions compare with other existing urban water infrastructure in terms of city infrastructure retrofitting possibilities and costs?

Figure 3. (a) CFD mesh for the old city of Zurich. The area of interest is represented with more geometric details (roofs), while the surrounding neighborhood is represented by simplified building blocks. (b) Air temperature at 3 m height in downtown Zurich during heat wave day June 23 2015 at 2 pm. (c) Annual space cooling demands for different building configurations and using different modelling approaches (Allegrini 2012). (d) All-physics approach of local urban climate model. The momentum, heat and moisture transport in the air domain is solved using computational fluid dynamics (CFD). Wind driven rain is modelled using an Eulerian Multiphase method. Results from the CFD simulation are exchanged with a model for heat and moisture transport (HAM) in urban materials like facades, roofs, pavements and soils. A radiation model solves for the solar radiation, shadowing and thermal radiation between the different surfaces and the environment. (e) Universal Thermal Climate Index (UTCI) for a person (red box) standing below a tree (green box) showing the positive effect of a tree mainly through shadowing on the thermal comfort. (f) top: Liquid distribution in micro-fluid device representing porous asphalt during drainage. bottom: PM-LBM simulation of drainage in porous asphalt (Son et al. 2016).

The urban climate model allows to analyze the influence of urban parameters on thermal comfort by determining the variables at a certain location in the street canyon, such as air temperature, air speed, radiant temperature and relative humidity. These variables are used to determine thermal comfort/heat stress using a common thermal comfort indicator, such as the UTCI (Universal Thermal Climate Index, Bröde et al., 2018). As an example we show the influence of a tree on the UTCI for a person (red box) standing below a tree (green box), showing the positive effect of a tree mainly through shadowing on the thermal comfort.

COUPLING URBAN CLIMATE AND BUILDING ENERGY

It is clear that space cooling demands of buildings in urban environments exposed to climate change and heat waves will increase in future due to hotter urban climates.

To propose new building designs and/or building energy systems and to adapt existing buildings to future urban climates, the impact of the local urban climate on the space cooling

demands of buildings has to be better understood. At the moment, no full scale studies where models for the different scales of the urban climate are coupled to accurately simulate the local urban climate for building energy simulations taking into account all interactions between the scales, exist. There is a strong need for a better understanding and quantification of the impact of local urban climate, its modification due to climate change as well as possible urban mitigation measures on the cooling demand of buildings in cities. Such knowledge will allow proposing new solutions to improve the energy performance of buildings taking into account their local urban climate.

Most of the building energy simulation models, which are used to predict energy demands of buildings, were originally developed for stand-alone buildings (Hensen 2011). For buildings in urban environments, the space cooling demand is strongly influenced by the local urban climate (Figure 3e) and can be quite different to buildings in rural areas (Allegrini et al. 2012a). The short and longwave radiation exchange between buildings in dense urban areas has a strong impact on the building performance (Allegrini et al. 2012a, Allegrini et al. 2016). The shortwave radiation entering the street canyons is entrapped between the buildings due to multiple reflections between the buildings. Additionally sunlit surfaces exchange hot and radiate longwave radiation with non-sunlit surfaces and heat them up. These increased surface temperatures have a direct impact on the energy performance of the buildings and on the local air temperatures. Another important impact is the increased local air temperatures due to the urban heat island effect. The lowest impact comes from the convective heat transfer coefficients. This study showed clearly the importance of accounting for the local urban climate when quantifying the space cooling demands of buildings in an urban environment.

DOWN TO MATERIAL SCALE

The multiscale urban climate model can be used to understand the impact of different urban parameters on the local heat island effect and to propose adequate mitigation measures. Especially one can study the impact of (1) radiation properties of building surfaces (albedo value), (2) the heat-moisture transport and capacity properties of building materials, (3) the presence of vegetation such as green roofs and facades, (4) the role of impervious versus porous substrates (different pavements and sublayers, different soils, cover ratio), (5) the presence of urban shadowing devices, (6) the role of active evaporative cooling by water spraying during heat waves of collected urban water.

The heat-moisture transport model allows the design of new building materials, which can help in the mitigation of local heat islands. With respect to evaporative cooling materials, we need to optimize their water retention tailoring their pore structure. This requires the use of pore-scale simulation of two-phase flow in porous media and an upscaling using pore-network models for the determination of the macroscopic fluid transport properties

As an example, we recently showed that hydrophobic macro-porous materials, such as porous asphalt with pore sizes ranging from micron to millimeter size, can retain water in their pore structure for long time after wetting by rain or artificial wetting (spraying), as such opening potentials for new evaporative cooling materials (Lal 2016). To study the two-phase flow in such complex materials, we developed a pseudopotential multiphase lattice Boltzmann model (PM-LBM). The use of LBM was motivated by the need for the explicit tracking of the liquid-vapor interface during gravity-driven drainage in macro-porous asphalt as well as the drying process. The PM-LBM was validated with micro-fluidic measurements, where liquid distributions were monitored by high speed camera on quasi-2D transparent micro-fluidic devices, where the porous structure was printed by additive manufacturing (Figure 3e-f) (Son 2016). To predict the unsaturated permeability of building materials, pore-network modeling

was used (Carmeliet et al. 1999, 2004, Vandersteen et al. 2003). The understanding and information obtained from pore-scale investigations enables to understand macro-scale transport processes, and to explore the potential of new evaporative cooling materials.

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