

Urban climate simulation: coupling of mesoscale meteorological model with building-resolved neighbourhood CFD simulation

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Abstract

The understanding of the local urban climate requires the resolved representation of the built environment and must consider explicitly all environmental loading. To do so, we present a CFD-based computational framework that includes comprehensively all relevant physical processes (sun, wind, rain, etc.) at local scale including a coupling methodology to meteorological modelling at mesoscale to obtain appropriate boundary conditions. We present the concept and implementation of this approach. Modelling results of the impact of trees in urban climate are presented in terms of wind flow patterns and air temperature difference. This paper convincingly proposes an avenue for fully-resolved modelling of the urban climate, a much required tool to propose and study valuable solutions for cities faced with climate change and increased frequency of heat waves.

Key Innovations

- Local urban climate modelling with explicit geometry and physics including boundary conditions from meteorological simulations at mesoscale
- Modelling environment to support design of urban solutions to mitigate the effects of heat waves

Practical Implications

The urban climate model allows to simulate the local urban climate and provide complete information on the exterior environment to which buildings are exposed. This can yield guidance to urban planners and design teams to assess their designs with respect to the impact of local climate on urban climate, comfort and energy, adaptive measures to climate change and mitigation measures of urban heat islands.

Introduction

Cities show an urban heat island (UHI) effect, where night temperatures are markedly higher in urban areas than rural ones. Cities are thus particularly affected when struck by heatwaves, which are, amongst others, climate extremes occurring at increasing frequency due to climate change. It is imperative to understand by how much the negative impact of urban climate during heat waves could

be mitigated using different solutions. Such solutions can be permanently in place, like evaporative cooling pavement materials or trees (Ferrari et al. 2020, Kubilay et al. 2019ab, Zhou et al. 2020a), or seasonal, like awnings and sun shading devices, to temporary interventions synchronously with heat waves, such as watering and irrigation interventions.

Simulations of the local urban climate at the scale of a few buildings to a full neighbourhood must consider the following physical processes: local wind dynamics, urban ventilation, solar radiation entrapment and local shading, evapo-transpiration of vegetation, heat and mass transport in porous media lining the streets (Carmeliet et al. 2011, Kubilay et al. 2019, Zhou et al. 2020b), wind-driven rain deposition and run-off (Kubilay et al. 2013, 2014ab, 2015ab, 2017ab, Derome et al. 2017) and local anthropogenic heat sources.

To do so, we model local urban climate by coupling mesoscale meteorological simulation results to building-resolved computational fluid dynamics, coupled to radiation, heat-air-moisture transport model and building energy simulation.

This paper shows the potential of this approach, which has a reasonable level of computational cost while preserving necessary resolution across the scales, from meteorological data at mesoscale to heat and moisture transport at building- and material-scale.

Methodology of multiscale modelling

With the aim of modelling the local urban climate, a rational approach is to couple mesoscale meteorological models (MMM) to building-resolved computational fluid dynamics (CFD), heat-air-moisture (HAM) transport model and building energy simulation (BES). In the work presented here, we use COSMO (Consortium for Small-scale Modelling) (Doms and Baldauf 2011) using a Double Canyon Effect Parametrization (DCEP) (Schubert et al. 2012). However, other meteorological models could be used such as WRF (Advanced Weather and Research Model) (Shamrock et al. 2019) as well as LES models like PALM and the urban module PALM-4U (Maronga et al. 2015).

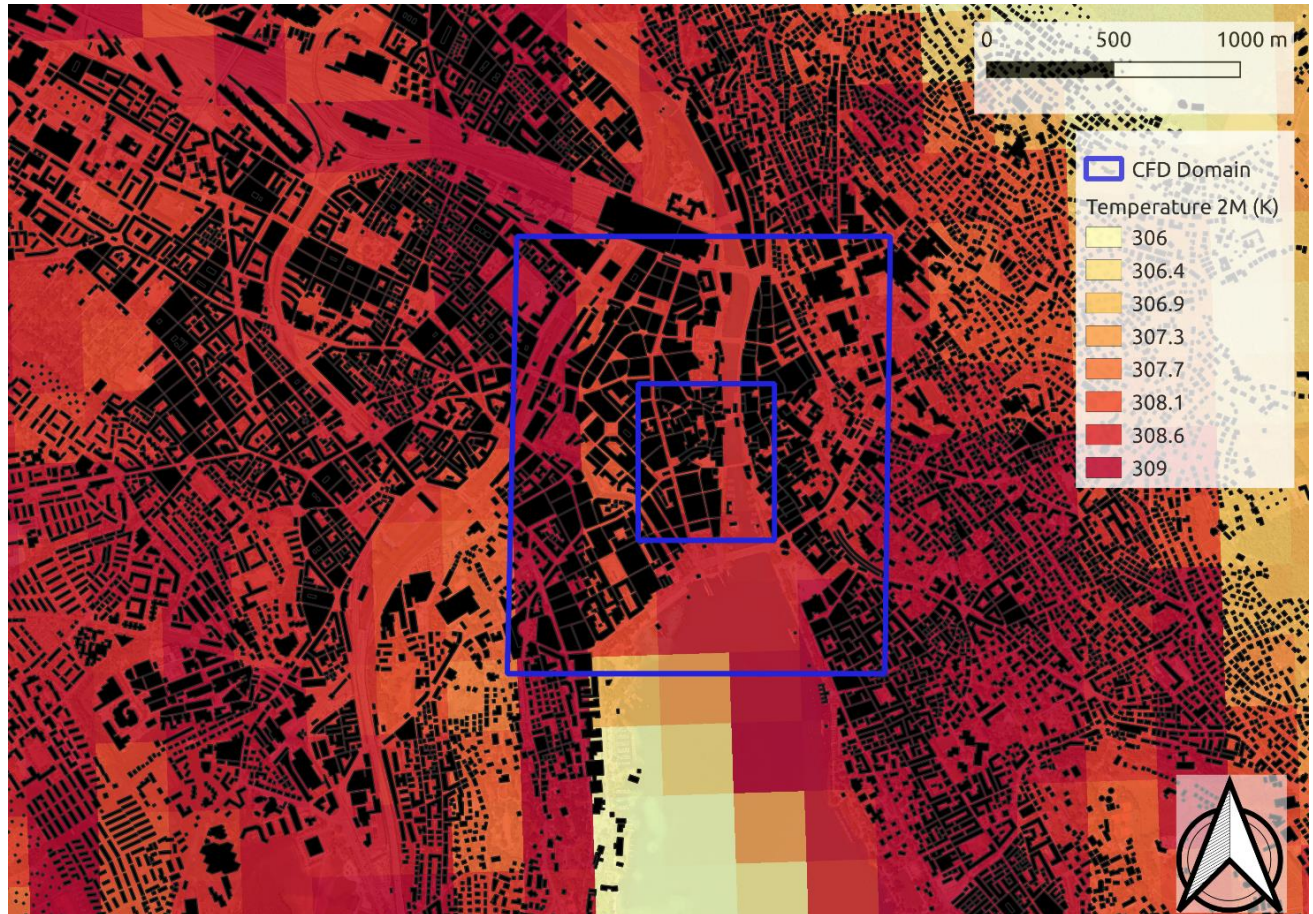


Figure 1: Distribution of air temperature at 2 m from COSMO-DCEP simulations in Zurich City on 2019-06-26 15:00 UTC and the CFD domain size, top pointing north (Kubilay et al. 2020).

Such coupling of models provides a balance between computational cost and resolution at the respective scales. Our methodological framework can be thought of having four scales covered by coupling MMM and CFD:

1. meteorological data at mesoscale with domain sizes of less than 200 km (MMM)
2. heat and moisture transport at city scale, where the buildings are not resolved but their effect is parametrized, with domain sizes of less than 15 km (COSMO-DCEP)
3. neighbourhood scale with fully resolved buildings and urban features, with domain sizes of less than 2 km (CFD) and
4. local scale with fully resolved buildings and urban features, with transport in the porous media lining the urban environment (CFD-HAM), with domain sizes of less than 100 m) and, when necessary, there exists the possibility to go down to material scale (less than 1 m).

Meteorological modelling and building-resolved CFD

Mesoscale meteorological models (MMM) are commonly used for weather prediction, having the possibility to consider phenomena such as sea breeze, rain, cloud clusters, thunderstorms, etc. (Orlanski 1975). Such models cannot resolve phenomena that are too complex or occur at smaller scales given their grid resolution. Therefore, these processes are modelled by parameterisations. Of relevance to our work, is the parameterisation for simulating the influence of the presence of buildings. Since buildings are not resolved at the scale used in meteorological modelling, the urban environment is parametrised using a statistical model assuming a distribution of street canyons. An example of the possible simulation results by MMM using DCEP as urban parametrization is shown in Figure 1 (at the end of the paper).

Available measurements, such as shown in Figure 2, are used to validate the results of the meteorological model. Shown are the air temperatures in rural (Kloten) and urban environment and UHI intensity during a specific heat wave period in Zurich, here between June 24 and July 1, 2019. The heat wave led to seven consecutive days with maximum daily temperatures over 30 °C. Comparing measurements in the city centre and at the Kloten airport, the difference between the urban and rural values yields

the urban heat island intensity, showing a maximum of 8.0 °C and an average of 3.1 °C.

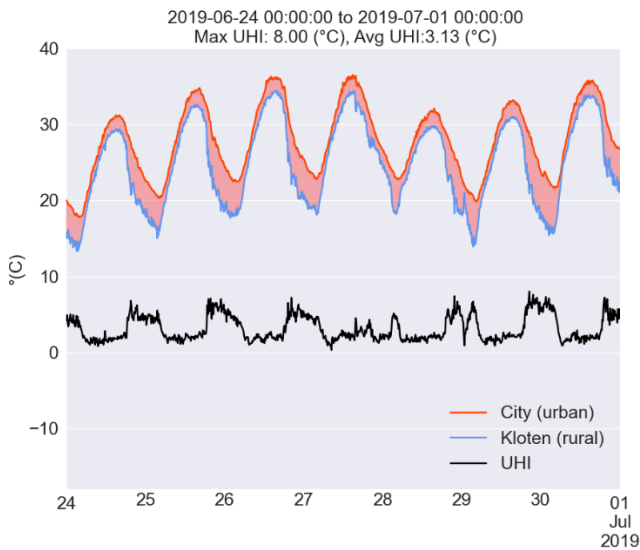


Figure 2: Measured air temperature values at 2 m height during the heat wave between June 24 and July 1, 2019 in Zurich and the associated urban heat island (UHI) intensity based on urban and rural temperatures. Datasource: MeteoSwiss (Kloten) and Swiss National Air Pollution Monitoring Network (NABEL).

Meteorological models provide boundary conditions that are realistic, as they use the state of the atmosphere, local topography and integrate land-use models. However, their local precision is limited by many factors: coarse resolution, parametrization of different phenomena and computational limitations. Coupling of meteorological models, to provide the boundary conditions of CFD models, which resolve a full neighbourhood spatially, is an on-going research field, where multiple approaches exist with different advantages and computational cost.

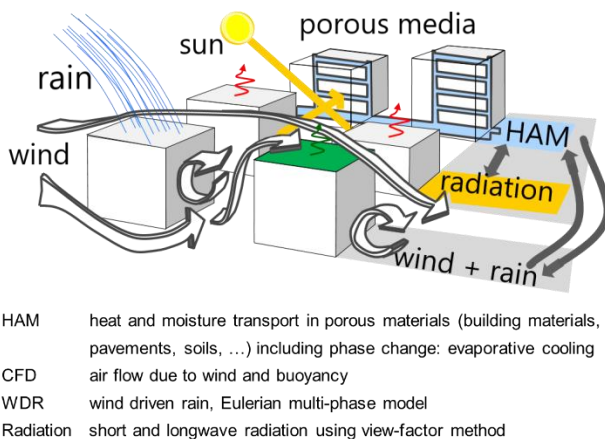


Figure 3: Schematic representation of couplings in local urban climate model (adapted from Kubilay et al. (2018) with permission).

At neighbourhood scale, our CFD model is coupled to a radiation exchange model and a heat and mass transport model for urban materials, allowing to take into account all the required physics (Kubilay et al. 2018, 2020), see its schematic representation in Figure 3. The development of

methodologies incorporating all relevant urban elements under realistic climate loading should be accompanied by interface with a comfort and physiological models of occupants, as well as methods for health impact assessment. These assessments have to be done under different scenarios of future climate conditions.

The validation of such coupling is complex and could use, for example, large datasets of careful urban measurement campaigns as shown in Figure 2. We note that the components of this modelling strategy have been validated against field and wind tunnel experimental data. For example, Kubilay et al. (2014b, 2015b) present detailed comparison of the wind flow and wind-driven rain deposition modelling data with results from extensive field measurement campaigns, on two building configurations. Wind flow and air temperature by CFD were compared with wind tunnel experiments. The heat and mass transport modelling approach has been validated several times with comparison with experimental data, a recent example being (Zhou et al 2020c) for liquid uptake in masonry, compared with neutron radiography.

Coupling approach

The neighbourhood of interest is positioned in the center of a meteorological computational domain, which should have dimensions of at least 100x100 grid cells to allow proper model spinup. The horizontal dimensions of the computational cells in the mesoscale domain in our case study are $250 \times 250 \text{ m}^2$. The boundary conditions for the detailed CFD simulations are provided by MeteoSwiss COSMO-1 analysis dataset, at the edge of the CFD domain, for example, shown in the larger blue square in Figure 1. The smaller blue rectangle indicates the area where the buildings are explicitly modelled within the CFD domain. Samples of such boundary conditions, air temperature and wind direction, provided by COSMO calculations are given in Figure 4 (at the end of the paper).

The computational domain for CFD is much larger than the group of explicitly modelled buildings. Buildings have different resolution in the different zones of the domain in terms of the geometric details and computational grid. The computational grid is more refined and the building shapes are more accurately modelled in the center of the domain, for the case of this paper the center is an open square in Zurich, named Münsterhof (Figure 5). Buildings located further away are not resolved and modelled only as a surface roughness on the ground. In between the two zones, an intermediate layer of buildings is modelled with a simplified geometry. In this example, the building facades facing the square and the pavement surfaces are modelled as coupled boundaries between the CFD and HAM domains (Figure 5). Three-dimensional computational domains for the HAM model are generated by extruding the coupled boundaries in their normal direction for which the surface temperature is calculated. The temperature of the remaining surfaces in the CFD domain, such as the ground, building facades and roofs outside Münsterhof, is obtained from COSMO-DCEP simulations.

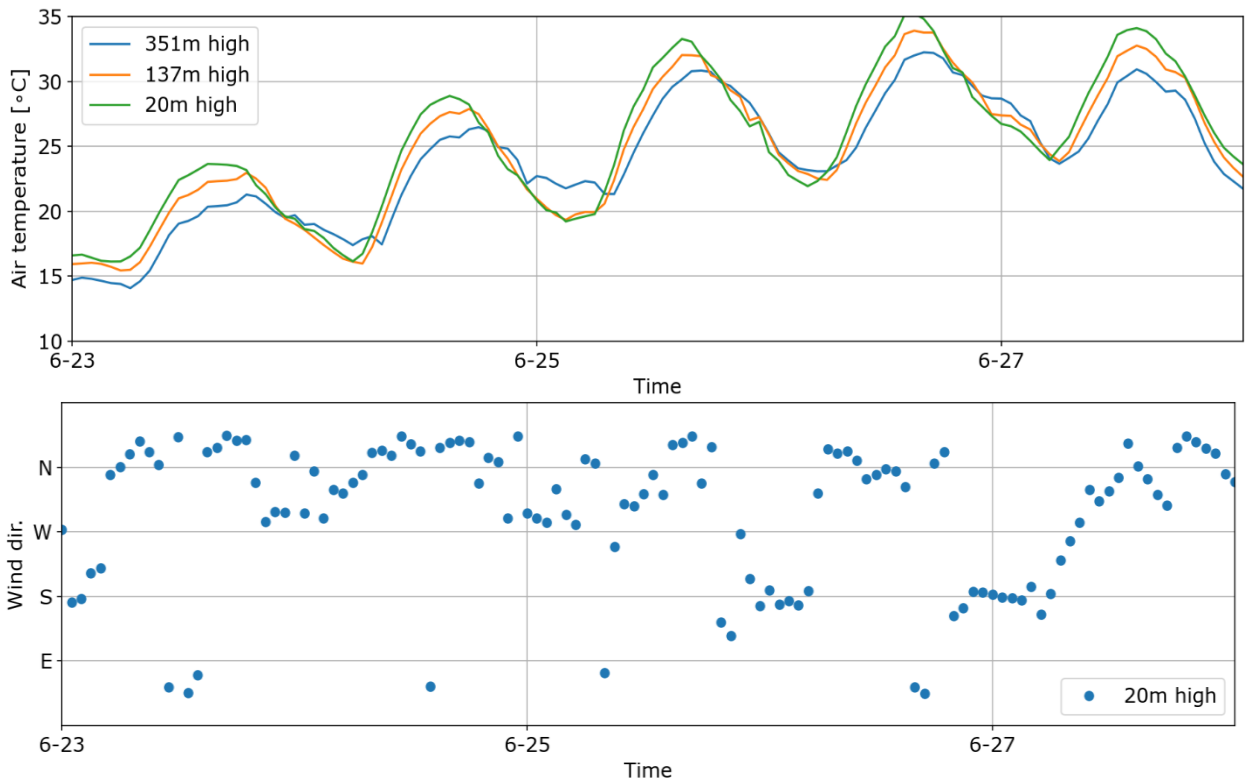


Figure 4: Meteorological conditions 2019: above) air temperature and below) wind direction, from COSMO at different heights near Münsterhof.

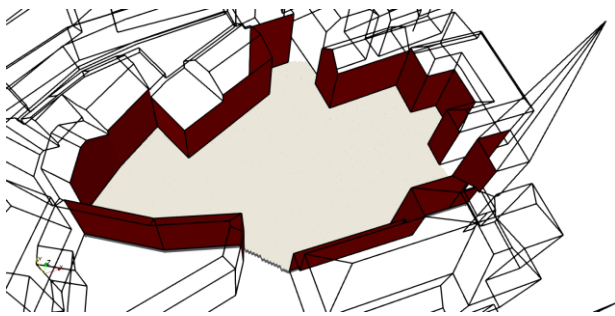


Figure 5: Close-up of the computational domain used, showing the configuration of the chosen urban square, Münsterhof, Zurich. Dark façade surfaces and square indicate surfaces modelled as coupled boundaries between the CFD and HAM domains.

The square is highly exposed to solar radiation and currently without permanent vegetation. This situation is considered as the reference case and we compare the behaviour by adding several trees planted in the square. Trees are modelled as porous media, where the leaves can undergo evapotranspiration when the proper conditions of direct solar radiation and availability of water allow it

Results

The proposed computational framework allows analyzing the urban climate at urban square scale evaluating the different contributions of phenomena such as convective cooling, sensible heat transfer due to rain, evaporative cooling, thermal storage throughout the day, in addition to shadowing and transpirative cooling by vegetation to the urban thermal comfort.

We model the behaviour of the square all paved and with the addition of nine trees. We consider leaf area density, an indication of the foliage density, of $4 \text{ m}^2/\text{m}^3$ for the taller trees and of $2 \text{ m}^2/\text{m}^3$ for the shorter trees as appropriate for several common deciduous trees. Stomatal resistance is function of solar radiation, vapor pressure deficit and plant type, here a deciduous tree.

We present the results of the local air flow at midnight when the predominant wind direction is from south, in terms of air velocity magnitude and direction in horizontal plane at 3 m height within the urban square in Figure 6. In the base case without trees shown in Figure 6a, strong inflow is observed from the river side located to the east of the Münsterhof. Several counter-rotating vortices are visible within the horizontal plane as a result of wind streams approaching from different alleys. The presence of trees clearly causes a different local flow field as shown in Figure 6b. Inflow from the east side is weaker, as well as the overall wind speed within the Münsterhof.

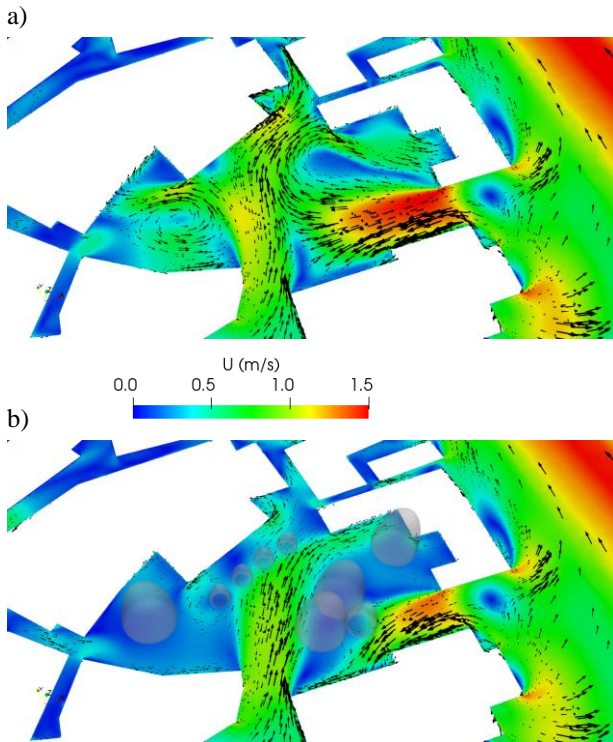


Figure 6: Wind flow field at 3 m height within the Münsterhof square for a) the base case without trees and b) with trees, at midnight with prevailing winds from south.

Next, we present, for the same time instant, the temperature difference at a height of 3m throughout the Münsterhof in Figure 7. The temperature difference is calculated as the temperature in presence of trees minus the temperature of the base case. We see cooler zones that are protected by the trees and where the wind speeds are lower, especially around the taller trees. The observed difference is mainly due to the effect of evapotranspiration by the foliage of trees, change in flow incurred by the presence of porous foliage and the occurrence of much more shading in the day leading to reduced heat storage.

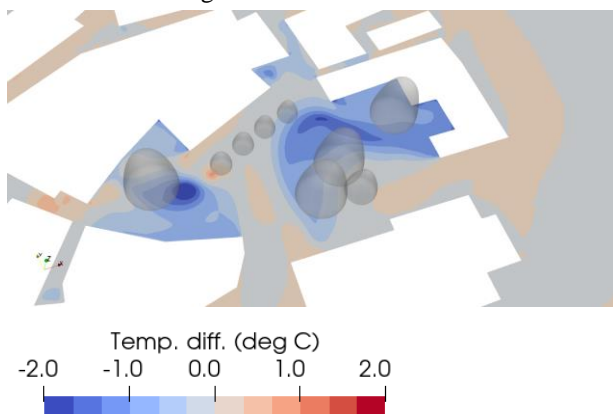


Figure 7: Air temperature difference (i.e. the temperature in presence of trees minus the temperature of the base case) at 3 m height showing the impact of the presence of trees within the Münsterhof square at midnight with prevailing winds from south.

Conclusion

In this paper, we present a multiscale framework for predicting the local urban climate including different sub-models and couplings strategies and provide one example of its application for an urban square in Zurich in terms of the impacts of adding vegetation.

The integrated approach presented here, coupling meteorological models at mesoscale with CFD, heat and mass transport and radiation at local scale, is appropriate for a neighborhood-scale urban climate analysis and provides capacities to assess the potential of mitigation solutions for heat waves. Sustainable mitigation solutions to local urban heat islands, especially in case of heat waves, are expected to require a combination of measures such as the use of ventilation lanes, shadowing, evaporative cooling, vegetation, reflective surfaces. Realistic climate boundary conditions coming from meteorological simulations are necessary to deal with such extreme cases and analyses at local scale are required in order to assess the local heat islands and assess correctly the impact of these mitigation measures. The proposed coupled simulation approach is a carefully developed modular framework, providing a physically sound and validated representation of the complex local urban climate. In future, the coupling between the different models will be further validated.

Acknowledgement

This research project is supported by the Swiss Competence Center for Energy Research SCCER FEEB&D of the Swiss Innovation Agency Innosuisse CTI.1155002539, the Swiss National Science Foundation (SNF)—Project No. 200021_169323 and the ETH Research Grant ETH-08 16-2. We also acknowledge the support of CSCS, where simulations were performed.

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