

## MODELLING THE URBAN MICROCLIMATE AND ITS IMPACT ON THE ENERGY DEMAND OF BUILDINGS AND BUILDING CLUSTERS

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### ABSTRACT

The urban microclimate (UMC) can strongly affect the building energy demand. In this paper, the impact of the UMC on the space heating and cooling energy demand of buildings is analysed for typical office buildings in street canyon configurations, using detailed building energy simulations (BES). Convective aspects of the UMC are modelled using computational fluid dynamics (CFD) and data are transferred to BES, either by convective heat transfer coefficients or by directly coupling CFD and BES. Measured urban heat island intensities are additionally considered. Comparisons to stand-alone buildings show the large influence of the urban situation. We then outline multi-scale modelling concepts to consider UMC effects at larger urban scales, using a city energy simulation model and an adapted UMC model.

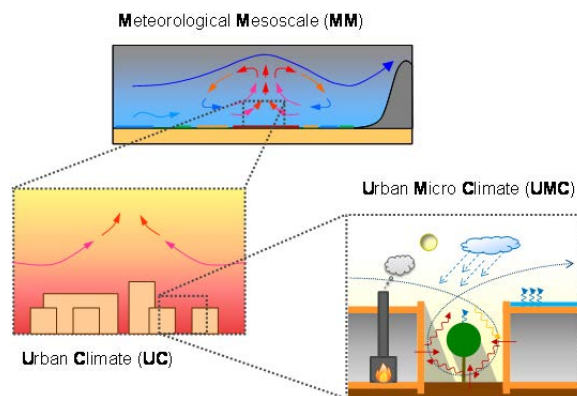


Figure 1 Multi-scale approach for urban microclimate modelling

### INTRODUCTION

A significant part of the world's energy consumption is used for heating and cooling of buildings. With the global trend towards urbanization, the minimization of the energy consumption of buildings in urban areas has a great energy-saving potential. The microclimate in urban areas differs significantly from the climate in rural areas. The air temperatures are higher due to the urban heat island (UHI) effect and the wind speeds are lower due to wind sheltering by buildings. Due to the UHI effect, the energy demand for space cooling in buildings can increase significantly, as studied by authors such as Santamouris et al. (2001) for Athens, or Kolokotroni et al. (2012) for London.

UHI have to be modelled in a multi-scale approach ranging from meteorological mesoscale (MM) down to the urban microclimate (figure 1).

The urban microclimate is determined by (i) local air velocity, temperature and humidity; (ii) solar irradiation and specular and diffuse reflections; (iii) surface temperatures of building and ground, and the respective long-wave radiation exchange, also with the sky (figure 2).

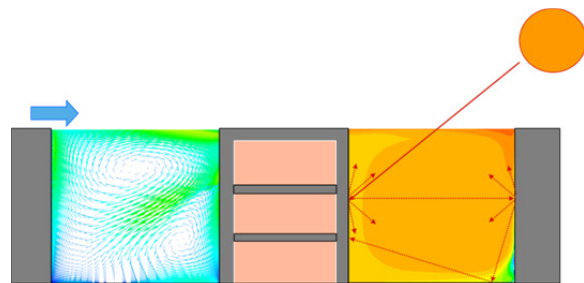


Figure 2 Local phenomena of the urban microclimate affecting heat fluxes at building surfaces

Even for buildings in an urban context, common practice in detailed building energy simulation (BES) still relies on stand-alone building configurations, not accounting for the influence of neighbouring buildings, except perhaps for shading. However, the urban climate and microclimate can strongly affect the building energy demand. Compared to stand-alone buildings, buildings in urban context experience higher ambient temperatures due to urban heat island effects and local heat rejection from other buildings, an altered radiation balance, due to the presence of surrounding buildings, and changed convective heat exchange, due to the different wind flow pattern. Thus, BES has to be coupled with an UMC model.

Urban microclimate effects on energy demand were analysed by authors such as Yang et al. (2012), who used the urban microclimate model *ENVI-met* (ENVI-met, 2009) and the building energy software *EnergyPlus* (Crawley et al., 2004) within the co-simulation platform Building Controls Virtual Test Bed (BCVTB). Modelling the urban microclimate with its interactions to building energy is also important for topics such as: electricity demand for lighting (Strømman-Andersen and Sattrup, 2011); impact of heat rejection from local air conditioner devices (Hsieh et al., 2007); cool or green roof and pavement (Akbari and Matthews, 2012) or other UHI mitigation techniques; and performance of building integrated photovoltaics (Scherba et al., 2011).

In this study, we first analyse the impact of the UMC on building energy at the level of street canyon cases and then outline approaches for larger urban configurations.

## STREET CANYON CASES - MODELLING

First, the impact of the urban microclimate on the space heating and cooling energy demand of buildings is demonstrated and quantified for typical office buildings in street canyon configurations (Allegrini et al., 2012a). Street canyons are chosen as a generic urban configuration. For this study, the transient 3D single building multi-zone BES software *TRNSYS 17.0* (TRNSYS 17.0, 2010) is employed and adapted to account for the following three aspects of urban microclimate: (i) the radiation exchange between neighbouring buildings, (ii) the convective heat transfer adapted to the local flow field, and (iii) the UHI effect.

### Radiation exchange

In classical BES of stand-alone buildings, solar irradiation on façades is considered as a gain and long-wave radiation as a heat loss to the cold sky. In street canyon configurations, however, the solar and long-wave radiation fluxes are characterized by multiple diffuse and specular reflections at the building surfaces. In *TRNSYS 17*, the 3D radiation model that accounts for these reflections normally is only used for interior zones. Therefore, in this study, the outdoor space between buildings is modelled as an atrium with an open ceiling. In this way, the shadowing by the neighbouring buildings and the exchange of long-wave and solar radiation between the different buildings is considered. The exchange of solar diffuse and long-wave radiation is determined using Gebhart factors, which basically are view factors, corrected to include the effect of multiple reflections.

### Convective heat transfer

The convective heat transfer at the building envelope is modelled using convective heat transfer

coefficients (CHTCs). Usually the CHTCs are based on measurements at façades of stand-alone buildings. For BES of buildings in urban areas CHTCs derived for stand-alone buildings can lead to inaccurate convective heat transfer predictions. To consider the reduced convective heat transfer at the building façades, computational fluid dynamic (CFD) simulations were conducted, for which specific temperature wall functions were derived (Allegrini et al., 2012b). Then CHTC vs. reference wind speed correlations were derived for different stand-alone and urban building configurations and used in BES for the specific urban geometries considered. These CFD simulations were also validated by wind tunnel measurements (Allegrini et al., 2013). Figure 3 gives examples of CHTC correlations for different building configurations.

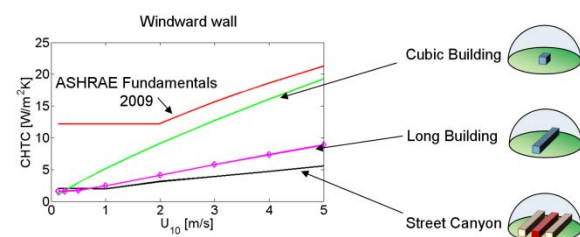


Figure 3 CHTC vs. wind speed at the windward wall for different building configurations

### Urban heat island intensity

The climatic data for the Swiss city of Basel are used as input for the BES. An UHI intensity approximation was developed based on measured data of the BUBBLE project (Rotach et al., 2005).

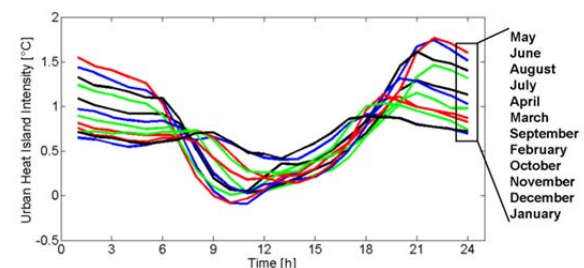


Figure 4 Average diurnal UHI intensity schedules for each month of a year

A diurnal schedule of the temperature difference between the rural (here Basel-Binningen) and the urban (here Basel-Spalenring) air temperature was specified for each month. For each hour of the day, the temperature differences are averaged for a time period of 7 years. The profiles are given in figure 4. For the BES, these hourly intensity values are then added to the basic weather file of the rural station.

### Buildings

In this study, three-storey buildings with different surroundings are analysed. BESs are performed for

stand-alone buildings in an open field and for the same buildings with street canyons in front and behind the buildings. Street canyons with aspect ratios of 0.5, 1 and 2 are considered (aspect ratio  $H/W$  with  $H$ : height of the building,  $W$ : street canyon width). Figure 5 depicts the studied building surrounded by street canyons with aspect ratios of one. The studied building has a length of 110.5m (to minimize lateral boundary effects in the radiation model) and a total height and width of 13.5m.

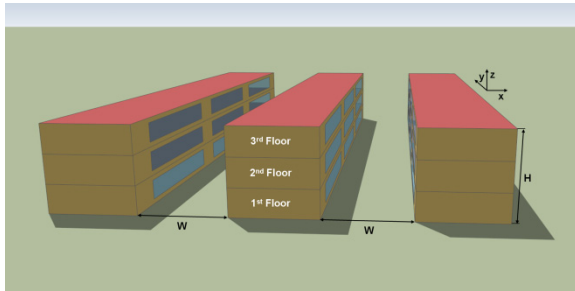


Figure 5 The building of interest in the middle, surrounded by street canyons with aspect ratios of 1 ( $H/W$ )

The building is well insulated externally with a U-value for the walls of  $0.26\text{W/m}^2\text{K}$ , roof of  $0.15\text{W/m}^2\text{K}$  and ground floor of  $0.30\text{W/m}^2\text{K}$  (no basement considered). The glazing fraction is 50% and windows with double-glazing (U-value  $1.4\text{W/m}^2\text{K}$ , g-value 0.589) are assumed. Internal gains by lights, devices and persons and occupancies are set according to (SIA 2024, 2006) (standard values for offices are used). Light control is as follows: lights are on when the building is occupied and the solar radiation on the corresponding façades is  $<70\text{W/m}^2$ . External shading devices are closed when solar radiation on the corresponding façades is  $>120\text{W/m}^2$ . The building has an orientation showing a north and south façade, lateral façades are modelled as adiabatic. A mechanical ventilation system is used (Day-time: airflow rate  $30\text{m}^3/\text{h}$  per person, heat recovery with 80% efficiency, ambient air is not heated to temperatures above  $21^\circ\text{C}$ ; Night-time: air change of  $1\text{h}^{-1}$  if building needs to be cooled).

Space cooling and space heating demands were determined for room air temperatures controlled to remain between  $21^\circ\text{C}$  and  $26^\circ\text{C}$  by heating or cooling. The change in e.g. electricity demand due to changed artificial lighting demands, caused by shadowing, is not considered.

The street canyon building studied is surrounded by two other rows of buildings, which have the same properties as the studied building. The energy demands of these two buildings are not evaluated.

## STREET CANYON CASES - RESULTS

### Annual space cooling demands

Figure 6 shows the annual space cooling demands for a stand-alone building and a building surrounded by

street canyons with different aspect ratios. In modelling case 1 (“radiation effects”), the same CHTC correlations are used for the stand-alone as well as for the street canyon configurations, namely CHTC correlations that were derived for stand-alone buildings. In case 2 (“+dynamic CHTC”), CHTC correlations derived by CFD (Allegrini et al., 2012b) are used for the street canyon. Case 3 (“+heat island effect”) is identical to case 2, but with the UHI intensities considered. The space cooling demand for the stand-alone buildings is much lower compared to the buildings situated in the street canyons. For wider street canyons, the cooling demand is higher, because more solar and thermal radiation is entrapped, mainly due to multiple reflections. In narrow street canyons, the cooling demand is lower due to less solar radiation entering the street canyon. The different CHTC correlations become only important for narrow street canyons. The UHI effect significantly increases the space cooling demand for all cases. The differences in space cooling demands between stand-alone and street canyon buildings are rather high due to the fact that the space cooling demands for the former are very low (for the climate of Basel). Therefore, already moderate changes of the absolute values cause rather high relative differences.

For the space heating demand the differences between the different cases are much lower than for the cooling. In general, higher surface and air temperatures cause a decrease of the heating demands.

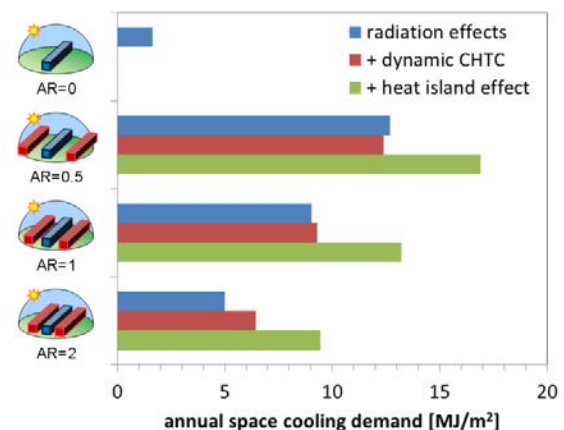


Figure 6 Annual space cooling demands for different modelling cases and different street canyon aspect ratios

### Heat fluxes

As shown, one of the reasons for cooling loads being higher in the urban configuration is the fact that total radiation gains are higher, especially when looking at north façades. The amounts of total absorbed radiative heat flux (solar plus long-wave radiation) on the north and the south façade of the first floor are illustrated in figure 7. On both façades (but more pronounced on the north façade), the radiative heat gains for the street canyon buildings are significantly



higher than for the stand-alone building. This is due to the higher solar gains and the fact that the stand-alone building can radiate much more heat to the cold sky and receives no long-wave radiation from the neighbouring building across the street.

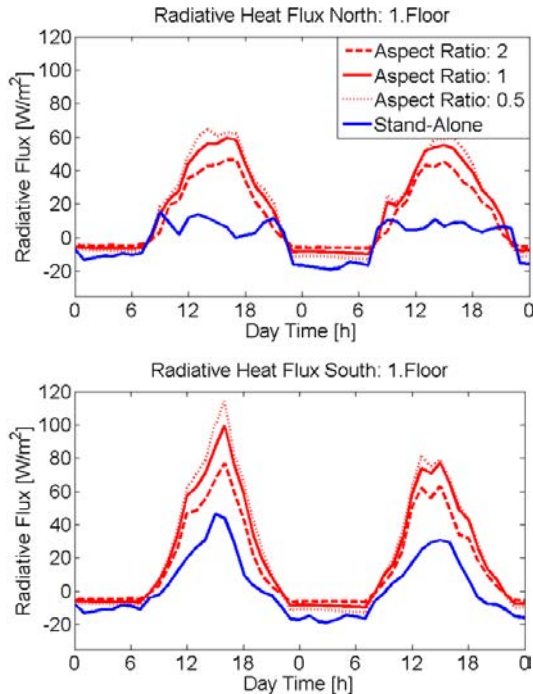


Figure 7 Absorbed radiation (solar plus long-wave) on the north (top) and south (bottom) façades of the first floor for a stand-alone building and buildings surrounded by street canyons with different aspect ratios (0.5, 1, 2)

Not only heat fluxes on building surfaces are influenced by the flow pattern, but also the convective heat exchange at the street canyon – free-stream shear layer. Due to buoyancy, there is a strong coupling between the flow field inside the street canyon and the heat fluxes at the boundaries of the street canyon, as demonstrated by Allegrini (2012) by CFD simulations and wind tunnel tests. The air temperature distribution inside the street canyon is strongly dependent on these heat fluxes, and consequently also e.g. the potential for passive cooling by night-time ventilation.

### MODELLING OF BUILDING QUARTERS AND CITIES

For the analysis of larger urban arrays of buildings up to cities, linking the models of the scale of individual buildings up to the meteorological mesoscale is needed.

Respective models for the urban environment and the energy simulations are needed at each scale. The urban climate (UC) model acts as the link between

the boundary conditions, stemming from the MM model, and the individual buildings, which are modelled by city energy simulation (CES) or BES. The UMC models in detail the urban environment at building block/street canyon level. Both the radiative and convective aspects of the interaction between urban environment and building are to be considered in the UC and UMC models. At all modelling levels there are connections to a database platform, providing meteorological, geographic, morphological and building information (figure 8). The modelling options and the models used at the different scales are described below.

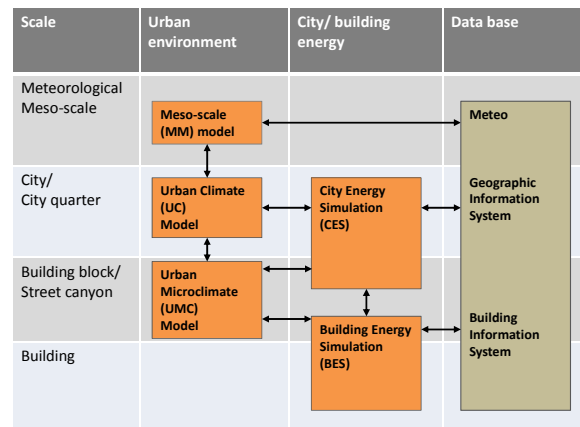


Figure 8 The models for urban environment and building energy for the different urban scales, with their respective databases

### Urban climate modelling

Boundary conditions for the UC model are determined using site specific simulation results of MM models such as COSMO (Consortium for Small-scale Modelling), or more specifically COSMO-CML (Rockel et al., 2008).

For more detailed and accurate UMC modelling, parameters gained by the MM model may not be directly adapted and transferred to the UMC model. Considering effects of the urban built environment around the UMC model domain, such as surface roughness and related wind and turbulence characteristics as well as UHI intensities, requires the use of an intermediate scale model, the UC model (figure 9). Such UC model may be based on urban canopy parameterisation or on a CFD based model.

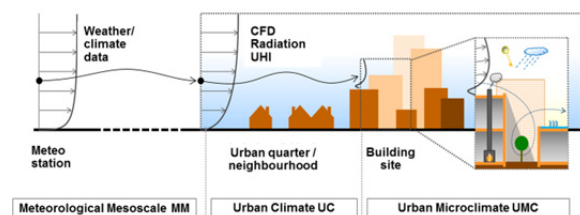


Figure 9 The UC model as the link between MM and UMC model

Urban canopy layer (UCL) parameterization can fill the gap between the grid scale of a mesoscale model and the building scale. Single-layer models such as the town energy balance (TEB) model (Masson 2000) provide a direct exchange between surfaces and one single atmospheric layer above the street canyon. These models have the advantage that they are computationally efficient, but e.g. in TEB the city is represented only as an average oriented urban street canyon, and air conditions (temperature, humidity and wind velocity) inside the urban canyon are represented only by a single value. Multi-layer models (e.g. Martilli et al., 2002) consider boundary conditions at several atmospheric levels, but require a higher discretization of the mesoscale model near the surface, which significantly increases computational costs. Martilli's original as well as extended models (Schubert et al., 2012) are implemented in *COSMO-CLM*.

For the UC model, the use of a Reynolds-averaged equations (RANS) based CFD model is envisaged, considering also radiation processes. The link to the *COSMO-CML* model is established on the basis of a time-slice approach (Schlünzen et al., 2011), where information from the MM model is transferred only at fixed times. However, this CFD approach soon becomes computationally quite demanding, as e.g. shown by Ashie and Kono (2011) who recently simulated the UHI effect in the city of Tokyo, also imposing results from MM models as boundary conditions. Therefore, we simplify the urban structures in the UC model domain. Methods for representative data reduction for complex urban structures are given e.g. by Rasheed et al. (2011).

### Urban micro climate modelling

Different concepts for an UMC model exist: (i) integral modelling of radiation and convection, using models such as *ENVt-met*, or (ii) separate treatment of radiation and convection.

In our approach, the radiative aspects of the UMC modelling are treated within the CES model *CitySim*, see below. The embedded radiation model simulates solar irradiation and the short- and long-wave radiation distribution and exchange between buildings and sky.

Thus, only the convective part has to be modelled separately in the UMC module. Several approaches for the coupling are used: (a) direct coupling of CFD and CES; (b) an UMC emulator is established, which provides data to CES based on parameterised results from CFD simulations. From the results of the street canyon case, one could argue that convective modelling is of less importance than radiative modelling. However, information of local air temperature is not only important for the determination of convective heat fluxes at building surfaces, but also for the modelling of ventilation and active and passive cooling techniques, and also to

consider heat rejected into the urban environment, e.g. from air conditioning systems.

In our projects, CFD simulations are performed using the RANS models of the open source CFD software package *OpenFoam* (OpenFoam, 2012). CFD simulations are performed, either for the actual setting or for typical urban morphology types, such as the Local Climate Zones described by Stewart and Oke (2009) for detailed UHI modelling.

Results for these typical area types are then applied in a matching process to the actual urban morphologic setting.

### Building energy modelling

In our projects, *CitySim* (Kämpf, 2009) is selected as the CES model. *CitySim* is a simulation model predicting energy fluxes at various scales, from a small neighbourhood to an entire city. It includes a radiation model based on the Perez All Weather and Simple Radiosity algorithm to compute the hourly irradiation on the building surfaces, a building thermal model, as well as HVAC and energy conversion system models (Robinson, 2011). Figure 10 presents a screen shot of a case study (Martigny, Switzerland) performed with *CitySim*, which shows the annual irradiation on the building surfaces (top) and the annual space heating demand (bottom). In this case, the stand-alone buildings on the left-hand side have less heating demand compared to the obstructed buildings, due to higher irradiation on the façades facing south direction.

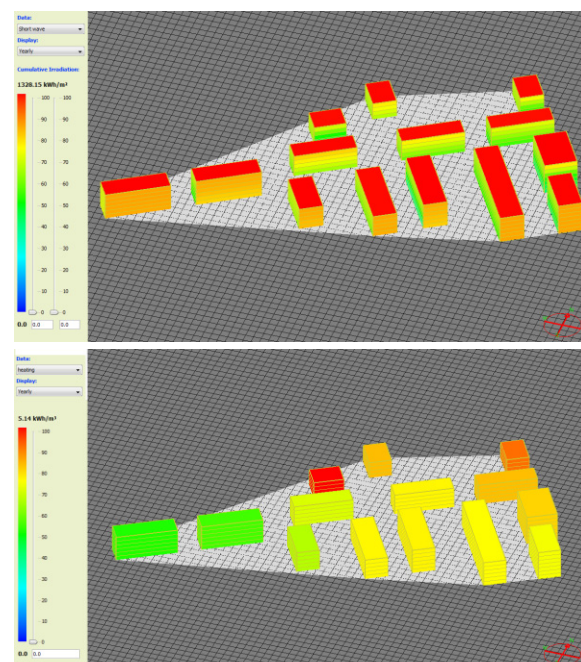


Figure 10 A screenshot from a case study performed with *CitySim*. Top: Annual irradiation on the surfaces. Bottom: Annual space heating demand for the individual buildings

For a more detailed analysis of individual buildings, the *Design Performance Viewer (DPV)* (Schlueter and Thesseling, 2010) and the *EnergyPlus* models are employed. Via the database, the UMC model can also provide local climate data for a comprehensive building stock model. This model can perform energy demand simulations and is used for the long-term development planning of city quarters and cities (Heeren et al., 2013).

In the present version of *CitySim*, wind speed, wind direction and the external ambient temperature values are taken from the meteo file and are assumed identical for all the surfaces in the scene. For the link to the UMC model, the *CitySim* model is adapted, allowing for the allocation of individual outdoor air and heat flux parameters to each surface element of building envelope as well as the ground (figure 11).

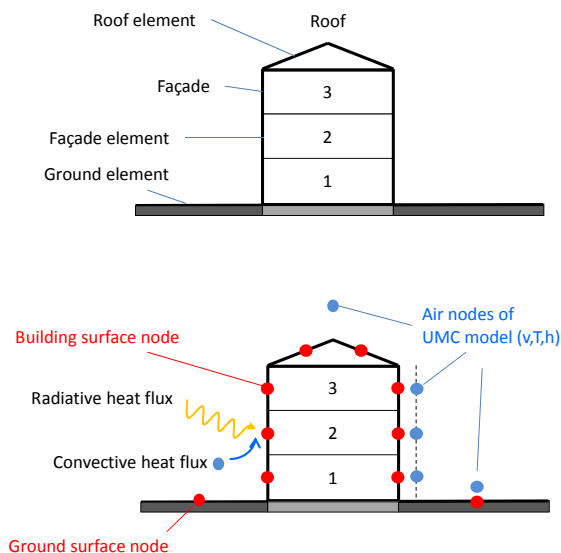


Figure 11 Discretisation and respective node points for data transfer between UMC (blue) and CES (red) model

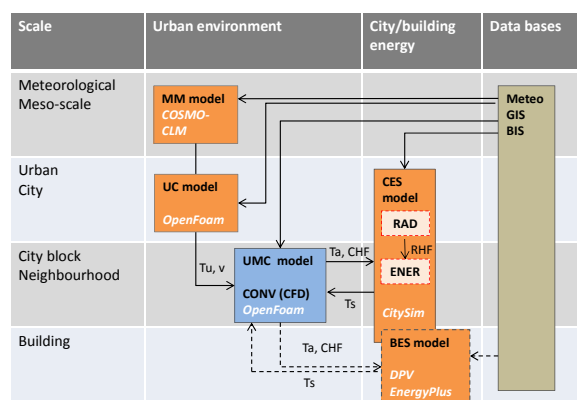


Figure 12 Actual modelling and data transfer approach. Abbreviations see text.

### Modelling approach and model interactions

The present concept of models and data transfer is depicted in figure 12, with GIS/BIS: Geographic/ Building information system; CONV: Convection model; RAD: Radiation model; ENER: Energy model; Tu/Ta: Urban/Local air temperature and humidity values; Ts: Surface temperatures, v: Urban wind velocity and turbulence parameters; CHF/RHF: Convective/ radiative heat fluxes.

### CONCLUSIONS AND OUTLOOK

The results of the project show that for buildings in an urban setting (compared to stand-alone buildings) the urban microclimate can have a significant impact on the heat exchange and thus on the energy demand of buildings, depending on building geometries and constructions. In the street canyon case presented, solar and long-wave radiation effects had the greatest impact, followed by the UHI effects and the convective heat exchange both at the surfaces and in the canyon to free-stream shear layer.

For the climate modelling of larger urban areas, a multi-scale approach is proposed, ranging from models at the meteorological mesoscale down to a detailed modelling of radiative and convective heat exchange at microscale, with the respective links to the individual building and ground surface elements in building and city energy simulation.

### ACKNOWLEDGEMENTS

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