How to bring urban climate studies to application – A meteorological view from five decades of urban climate research and results from a current study

Related study: Fallmann, J. and Emeis, S. (2020) How to Bring Urban and Global Climate Studies together with Urban Planning and Architecture? *Developments in the Built Environment*, 4, 100023.

Atmospheric sciences have dealt with the special features of urban climate for about 200 years, starting with the seminal book of Howard. It therefore has been long understood that urban areas govern the dynamics and air chemistry of the atmospheric boundary layer, they are key drivers for the development of local circulation patterns and can modify local and regional weather and climate. On the other hand, local meteorological conditions and large-scale weather patterns drive the formation of the urban heat island, can modify microclimate conditions and affect air quality regionally and locally. As such, holistic models have to be developed in order to properly represent interactions along both time and spatial scales and preferably have to incorporate both dynamics and air chemistry. A large amount of studies exist already, which highlight the importance of properly representing urban areas within mesoscale models via urban canopy parametrizations. Current coordinated model activities try to assess these parametrizations to be included e.g. in regional climate models as being considered within Cordex FPS URB-RCC. More information on that activity can be found in the contribution of Gaby Langendijk and Tomas Halenka within this issue.

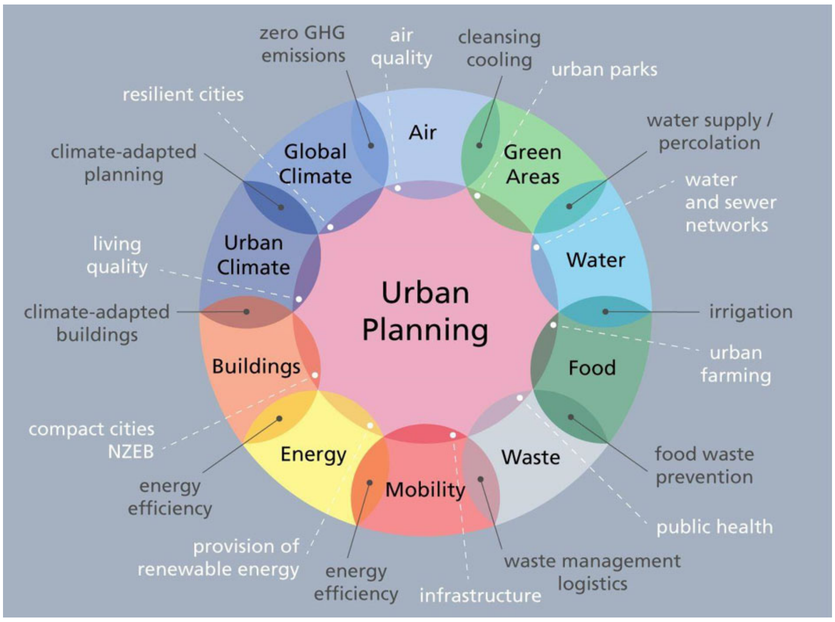

Figure 1. Interrelations among urban issues towards sustainability. The bubbles depict mutual overlaps among the urban issues and one example for each overlap is provided (white dashed lines point to overlaps with the central bubble and black full lines to overlaps between neighbouring outer bubbles). NZEB = "nearly zero-energy building". (Copyright: IMK-IFU of KIT, Petra Guppenberger)

For properly incorporating the findings and perspectives from meteorological and urban climate studies into dedicated urban planning actions, scientific information has to be condensed to a level that can be understood and used by local stakeholders. In addition, the broad amount of urban climate literature has to be summarized in a way that provides an applicable hands-on for urban practitioners allowing them to select measures which best fit their specific city regarding its morphological, social, political and legal framework. Transferring scientific and often theoretical knowledge into actual urban planning, however, necessarily involves an interdisciplinary dialogue, which links urban and global climate to e.g. urban planning and building design.

In our recent literature review (Fallmann and Emeis, 2020) we aim to provide suggestions for sustainable urban planning under present and future climate conditions. By this, we display and offer a pool of efforts and ideas summarizing results from five decades of scientific research in the field of urban planning with regard to local air quality and to local and global climate. As such, the term 'Smart' often appears in the context of city design, with regard to better information and communication infrastructure. In our perspective, however, that term does not necessarily incorporate all facets of sustainability. Based on that review, we propose a new way of thinking towards the Smart-City term, with urban planning being embedded in an interconnected framework of specific fields and their effect on urban sustainability (Figure 1).

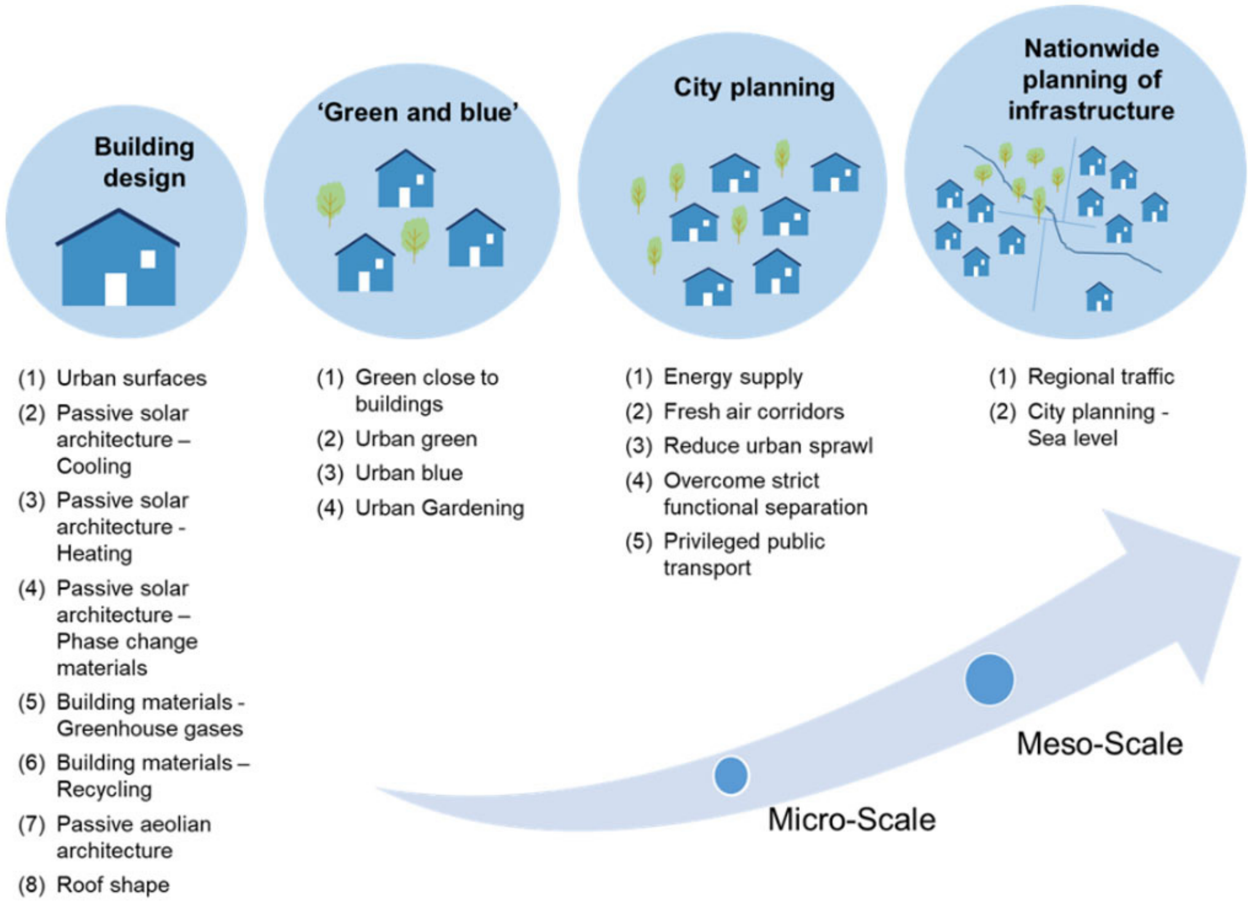

Figure 2. Action fields in ascending order according to the spatial scale. Within each field, activities are ranked due to the amount of studies found in the literature review.

Figure1 links planning and building requirements (clockwise from "Green areas" (upper right) to "Buildings" (left)) with atmospheric and climatic issues ("Urban Climate" to "Air"). The outer bubbles are linked with the central bubble "Urban Planning" by exemplary action fields given in white letters, while selected action fields connecting neighbouring outer bubbles are given in black. There are definitely further action fields, also between non-neighbouring bubbles, which have been skipped from the graph for the sake of simplicity. The legacy to be conveyed by Figure 1 is that urban and global climate issues and air quality are equally ranking issues in smart planning processes for sustainable cities.

There seems to be consensus amongst existing literature, that only a small number of previous urban climate studies had considerable influence on actual city planning and/or building design so far (Eliasson 2000; Mills et al. 2010; Parsaee et al. 2019). Some progressive ideas however found widespread interest for instance in the field of biophilic designs (e.g. Bosco Verticale in Milan or Kö-Bogen in Düsseldorf). Another trend mirroring sustainable building design is using wood as a building material (Tupėnaitė et al. 2020), which involves less concrete and eventually stores biologically extracted carbon from the atmosphere for a long time (Churkina et al. 2020).

As a result of the literature review, we defined four action fields from the building to the national scale:

a) measures to modify building design

b) measures to enhance urban green and blue

c) measures to re-plan cities

d) measures to secure the overall resilience of urban areas.

These points intend to provide a guideline for both resilient building and city design but also should set a basis for the definition of dedicated urban climate studies within both meso- and microscale resolution. Figure 2 summarizes the four action fields and ranks the subtopics in each field according to their importance from an atmospheric scientist point of view (according to the amount of studies found in the review). More details can be found in Fallmann and Emeis (2020).

From a scientific point of view, the first action point necessarily has to be addressed by dedicated micro-climate modelling studies or focused observation campaigns. Action points two to four however include city wide to regional effects, which can be assessed already with convective scale atmospheric, or chemical transport models. These models in turn have to be developed towards earth system models and necessarily have to involve a proper representation of urban geometries, anthropogenic heating and emissions. Getting these larger scale meteorological and air chemical conditions right, sets the basis for the coupling to highly resolved street scale models.

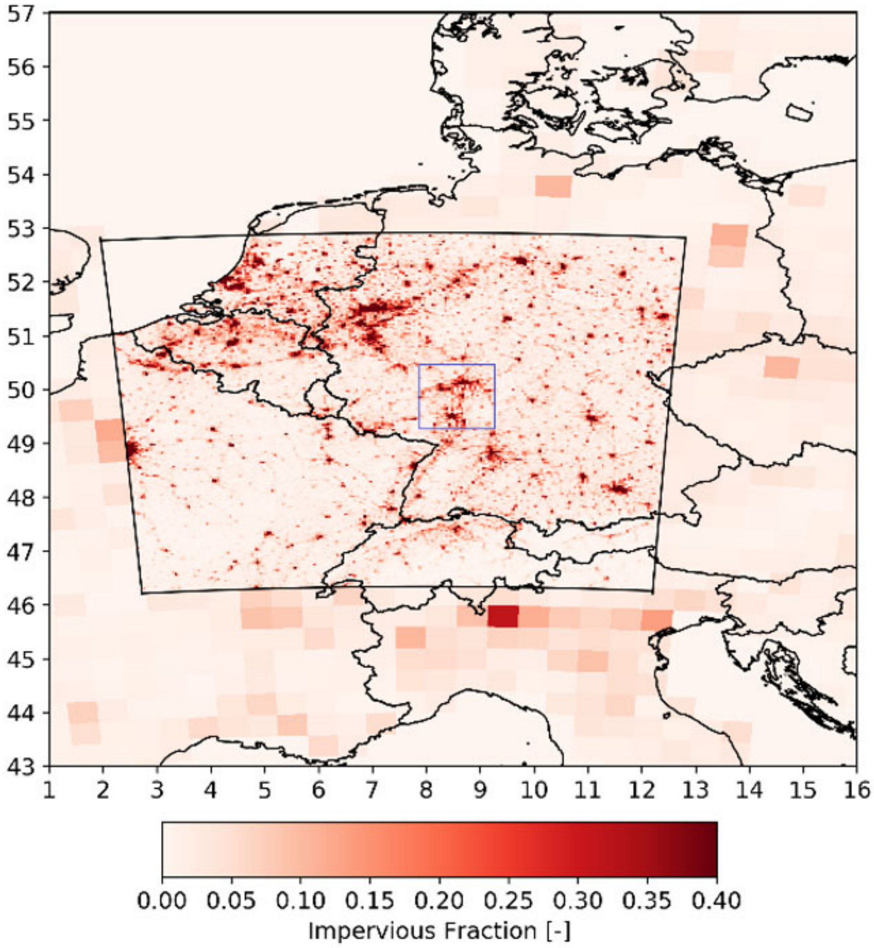

Figure 3. MECO(n) model domain CM40 (40 km) and CM3 (2.8 km) embedded. Colour shading indicates impervious surface area fraction per grid cell.

Towards application – Impact of urban imperviousness on dynamic and chemistry at a regional scale (Fallmann et al. 2021)

As one example in the atmospheric modelling community, the COSMO-CLM model, coupled to the urban canopy model (UCM) TERRA-URB (Wouters et al. 2015; Wouters et al. 2016), has been proven to be suitable for mesoscale urban studies. Studies with that regard exist for e.g. Berlin (Trusilova et al. 2016) or Moscow (Ginzburg und Dokukin 2019) for the meteorological perspective only. Here, we present a current study assessing that UCM being implemented in the regional climate air chemistry model system MECO(n) (Kerkweg und Jöckel 2012). The way urban areas are incorporated within these kinds of model systems governs exchange processes in the urban boundary layer, thus effecting both dynamics and air chemistry. In this work, we compare both 2-m temperature and near surface NO_2 concentrations against urban background observations at six different cities within the model domain (Figure 3). Receiving global boundary conditions from the ECHAM5 global model at T106 resolution, we come up with a 3-domain model chain from ~200 km to 40 km down to 3 km. The emissions are retrieved from TNO-MACCIII dataset with 7 km horizontal resolution. The presence of urban areas within a grid cell is translated to the land surface model via the variables impervious surface area fraction (ISA) and anthropogenic heating factor (AHF). Figure 3 shows the variable ISA for the 3 km model domain embedded in the underlying 40 km Central European domain.

Focusing on an extreme climate scenario, rather than a full 30-year climate run, this study analyzes 10 days in July 2018 (1.7.-10.7.2018) centred around the metropolitan area Rhine-Main in Germany, with its main cities Frankfurt, Mainz, Mannheim and Heidelberg. In order to assess the model sensitivity we compare a default configuration (BASE) with TERRA_URB and a version with TERRA_URB switched off (NO_URB) with observations from satellite and urban background stations. Urban parameters have been set according to Wouters et al. (2015). Compared to MODIS TERRA land surface temperature (LST) (for 1 July 2018 21:15 UTC), we find a bias reduction for mean surface temperature averaged over the urban grid cells within the vicinity of the borders of the metropolitan area Rhine Main. Hence, BASE underestimates MODIS LST by -0.5 K and NO_URB by -1.4 K respectively. Averaged over 6 selected urban areas and model period, 2-m

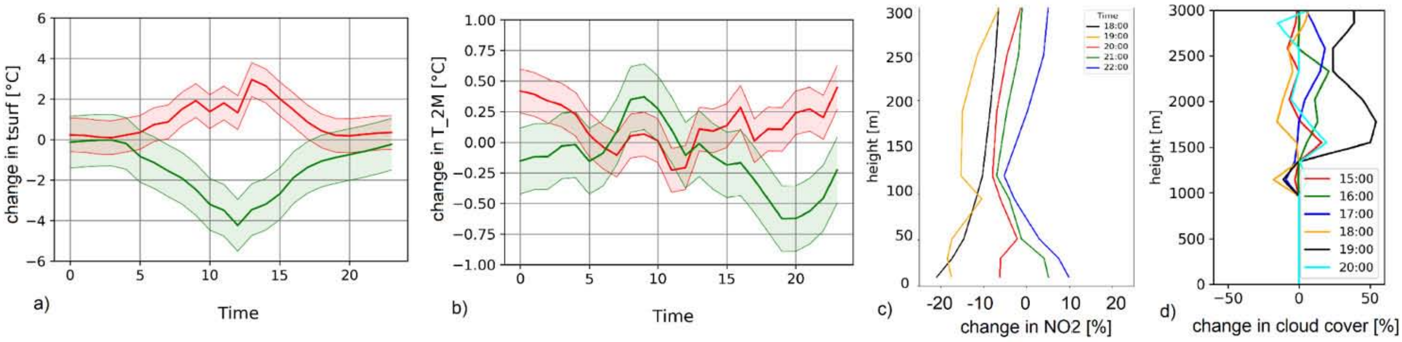

Figure 4: Diurnal difference ISA_plus-BASE (red) and ISA_minus-BASE (green) averaged over model period and urban area as marked in Figure 3 for (a) surface temperature and (b) air temperature. Relative change ISA_plus-BASE in (c) NO_2 concentration and (d) cloud fraction averaged over the urban area.

air temperature bias is reduced from -1.6 K (NO_URB) to -0.8 K (BASE). For gaseous pollutants such as NO_2, bias reduction is mainly found for the 95th percentile of concentrations (traffic peaks in the morning and evening), with a relative bias of +31% (NO_URB) and +23% (BASE). Using data from a passive microwave radiometer in the urban centre, we found a noticeable effect of the urban canopy on air temperature up to a height of approximately 120 above roof level. Detailed results can be found in Fallmann et al. (2021).

The existing model configuration allows for case study experiments of two scenarios of urban development, a re-densification of the urban centre or a push towards the close vicinity, symbolizing an urban sprawl. The latter scenario necessarily has to happen at the cost of natural land in the vicinity of the city borders. Both experiments are controlled via the variables 'ISA' and 'URBAN', representing the fraction of impervious surface and the fraction of urban classified area in a 3x3 km grid cell. For highly impervious urban grid cells (ISA>0.4), ISA_plus considers an increase of impervious surface area fraction per grid cell by 50%, which is equivalent to a 50% decrease of natural land cover in the same cell. ISA_minus considers a decentralization of urban space with an increase in the closest rural surrounding at the simultaneous decrease in the urban centre. The experiment is realized, decreasing the impervious fraction in the core urban grid cells by 30% and increasing the impervious fraction by 80% for the grid cells in close vicinity where ISA is in the range of [0.1,0.3] in the BASE simulation.

Considering the relatively coarse resolution within an urban context, the model results however allow for following first and second order conclusions.

1st order:

• City-wide densification of urban areas results in an increase of surface temperature. This aspect is most pronounced in the daytime. Equivalent temperature reduction is simulated when impervious surface is replaced by vegetation (Figure 4a)

2nd order

• 2-m air temperature is increased for denser – and decreased for 'greener' – grid cells. There is an exemption however in the morning hours, when flat incoming radiation can penetrate deeper into the urban canopy due to increased sky view factor in ISA_minus. For about two hours, we find a relative increase of air temperature compared to BASE, which is not seen in ISA_plus (4b)

• Using the urban heat island intensity does not seem to be a proper indicator for evaluating the mitigation potential of the selected measures, as model results indicate the rate of change in urban 2-m temperature being larger than the change in UHI intensity (see also Martilli et al. 2020)

• Increased mixing over warmer urban surfaces in ISA_plus reduces the near surface NO_2 concentration by up to 20%. This assumption however is not true at nighttime hours, when a denser urban canopy blocks natural ventilation, once convective mixing is dying back. Surface levels of NO_2 increase by up to 10% (4c - blue, green)

• Increased convection from a warmer surface into the urban boundary layer triggers the formation of shallow clouds over the denser area (4d). This is well in line with other studies e.g. Theeuwes et al. (2019)

Referring back to the beginning, these model studies could help to get a first impression of potential (unwanted) consequences, which can succeed a specific measure to reduce urban heat levels. Aside from that, they can assist coordinated modelling exercises, such as Cordex FPS URB-RCC as mentioned above.

Linking results of these kinds of models to microscale modelling systems such as ENVI-met, either via direct coupling or using selected modules only, envisage the transfer to the applied scale considering e.g. street levels. Simon et al (2019), who analyzed the impact of certain tree species on local air quality, have done the latter. Combining MECO(n) and ENVI-met, they found certain tree species to emit a large amount of biogenic volatile organic compounds (BVOCs), which accelerate near surface ozone formation in selected street canyons due to both high temperatures and the presence of vehicle emissions (NO_2).

First steps towards a holistic street-scale and building-resolving urban climate model covering spatial scales from metres to many kilometres and temporal scales from seconds to years have recently been made in Germany (Scherer et al. 2019; Maronga et al. 2019). This microscale model, PALM4U, can be coupled to mesoscale models, such as COSMO or WRF and hence can be used for simulating the impact of realistic weather events on the city at the street-scale (Kadasch et al. 2020; Lin et al. 2020; Resler et al. 2020). Also including air chemistry, such a model can simulate the interactions between buildings and the atmospheric flow, the urban radiation and heat budget, and the urban air quality (Khan et al. 2021).

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