Urban climate impact on indoor overheating – a model chain approach from urban climate to thermal building simulation

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Abstract
Does microscale climate conditions in urban districts vary severe enough that indoor overheating depends on the location of the building within the district? Especially in big cities heat stress for residents will increase in future summers in intensity and duration caused by the global warming trend. To quantify this load for urban dwellers, the resulting room temperatures in residential buildings are to be evaluated. More precisely, the possibility of passive cooling measures, especially nighttime cooling by window opening and cross ventilation, applicable for typical Central European summers, is to be analysed. To evaluate the impacts of nighttime cooling, the knowledge about the diurnal variation of outdoor air temperature and wind speed at the facade of the individual dwelling is highly relevant and depends on window orientation, floor level of the dwelling and the location in the urban setting. To provide the required data, we present a method of combining two time-resolving simulation techniques: First, calculating the diurnal variation of meteorological quantities like the local air temperature and wind vector near the building applying the urban climate model ENVI-met to the interaction between the 3D modelled environment with buildings, vegetation, soil and atmosphere. Second, implement the obtained local meteorological data as input for a 3D building model in the thermal building simulation tool IDA ICE evaluating the thermal comfort of residents in the individual rooms of the dwelling. As reference, a five storey multi-family house from the „Gründerzeit“ epoch in Erfurt (Germany) was chosen and simulated for the daily course of a hot summer day. The district of the building was modelled in the 3D urban climate simulation, taken into account surrounding buildings, trees and infrastructure with a high horizontal resolution of 4 m. Combining both simulation tools, we are able to show that the low differences in outdoor air temperature within the district (around 1 K) shows only low impact of the room temperatures in the building. However, the wind speed variation of West-East wind component in the district is more significant (0.3 m/s to 1.4 m/s in 16 m height above ground) depending on the orientation of obstacles and lead to high differentiations in nighttime cooling efficiency by window ventilation in combination with cross-ventilation. Thus, the indoor temperatures and overheating depends on the location of the building in the city and the orientation of windows, especially when cross ventilation is applied. Finally, the wider opportunities as well as limitations of the applied model chain from urban climate to thermal building simulations are discussed.

Keywords: Model chain, urban climate simulation, thermal building simulation, overheating

1. Introduction

The global warming trend will lead to heat wave events projected to increase in frequency and severity in future (IPCC, 2014). Hence, overheating risk in buildings is expected to increase in strength and duration in the next decades leading to discomfort, restricted concentration abilities, increase in health risk up to heat mortality (Head et al., 2018; Toulemon & Barbieri, 2008). Especially in large cities with a high degree of sealed surfaces additional heat burden by high night outdoor air temperature for inhabitants is induced by the urban heat islands (Manoli et al., 2019; Mohajerani, Bakaric, & Jeffrey-Bailey, 2017). This is particularly critical because residential buildings in urban settings located in moderate climate are usually cooled not mechanically but by passive measures, especially nighttime cooling. The efficacy of this measure depends on various conditions like opening profile of the windows and opportunities for cross ventilation on the building side or wind speed, wind direction and outdoor temperature at the individual window position of the dwelling.

However, recent overheating analysis by thermal building simulation commonly uses meteorological input from hourly resolved meteorological data of test reference or design years (Brotas & Nicol, 2017; Hamdy, Carlucci, Hoes, & Hensen, 2016; Schünemann, Olfert, Schiela, Gruhler, & Ortlepp, 2020) or from meteorological measurement stations (Taylor et al., 2014). On the one hand, this method is accurate enough when comparison of overheating risk of different building types, inhabitant behaviour or climate conditions are in focus. On the other hand, this approach is insufficient to examine the impact of urban structure on overheating risk in buildings. For this reason, we extend overheating analysis by applying a model chain method starting from urban climate simulation for 3D modelling of the district and implement the local meteorological data into the thermal building simulation for 3D modelling of a residential building. The focus of this article is to present the details of this method, its opportunities and limitations.

For our study we model a district of the city of Erfurt (Germany, 50°58’43.5’’ N, 11°02’44.3’’ E) using the micro-scale climate model ENVI-met (Bruse & Fleer, 1998; ENVI-met, 2020) with a horizontal resolution of 4 m and an increasing vertical resolution with increasing height (beginning with 1 m above the soil surface). The Federal State of Thuringia, where the city of Erfurt is located in, was hit by strong heat and drought waves in 2018 and 2019 and increasing summer temperatures are projected for the next decades (TLUBN, 2020). Based on the fact that most residential buildings in big city centres are multi-family housings (MFH), we chose this building type for the indoor temperature analysis in building simulation. A common building type of MFH in Central Europe is the so-called “Gründerzeithaus” (GZH), erected in the “Gründerzeit” epoch between the years 1870-1918 especially in old town centres and originally equipped with stucco facade and saddle roof with dormers. This building was modelled in 3D in the thermal building simulation IDA ICE (EQUA, 2018). The procedure of generating the daily course of meteorological data by ENVI-met, subsequent transfer of the data as meteorological input to IDA ICE and indoor overheating analysis using this tool is described in detail in the method section.

2. Methods

2.1. Reference district and building

The city of Erfurt is located in the middle of Germany in a moderate cooling load zone (category B in DIN 4108-2 (DIN4108, 2013)). The urban district in the eastern part of Erfurt, see Figure 1, was selected to be modelled in the urban climate model ENVI-met. The model domain is about 950 m from West to East and 970 m from North to South. The western part of the district is dominated by MFH of the GZH type constructed in the turn of the 20th century in closed block development. The south-eastern part represents a mixed building area with different new and old MFH types, office, industry and public buildings. In Figure 1, the location of the GZH reference building chosen for building simulation is marked at receptor point 1. The other two markings in the figure represent positions where the GZH building from receptor point 1 is virtually positioned to investigate the impact of higher outdoor temperatures and different building orientation (receptor point 2) and higher wind speed (receptor point 3) in the district on the overheating intensity in the dwellings of the MFH. Thus, we can discuss the influence of different location in the district on indoor overheating.

The chosen GZH building type is a common representative for MFH types (Schünemann et al., 2020) in Central European cities without the use of mechanical cooling systems. Figure 2 illustrates the West and East façade of the selected GZH reference building including the floor plan of the attic floor. The MFH consists of eight dwellings on four full floors and the converted attic floor. On the courtyard (west) side, balconies have subsequently been installed for each floor ensure window shading on this façade for the four full floors. In this article we only focus on the room temperatures resulting in the attic floor because previous investigations show that overheating in this GZH building type is most relevant for this top floor, caused by low thermal storage capacities and solar heat gains transmitted through the roof and by the unshaded window front at west façade (Schünemann et al., 2020). Further details like structural components of the building can be found elsewhere (Schünemann et al., 2020). Here, we present a detailed overheating analysis of the bedroom (east façade) and the kitchen living room (west façade) of the attic dwelling (cf. Figure 2c). As shown previously, applying nighttime cooling of the room by opening windows during chilly nights is very effective to keep the overheating in the dwelling at a low level (Schünemann et al., 2020), best combined with cross ventilation by opening the room door. Both scenarios have been evaluated by implementing wind and temperature gradient driven window ventilation in the building simulation IDA ICE.

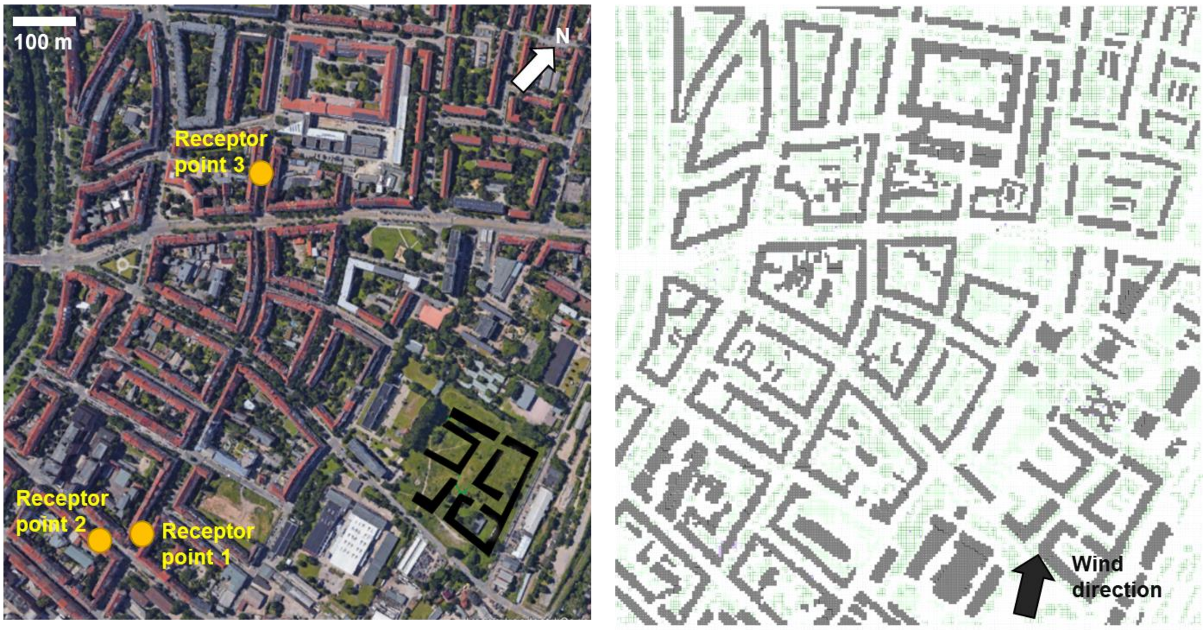

Figure 1: *Aerial photograph (left, Google Earth, downloaded at 2020-04-03) and ENVI-met overview of the area input file with environmental information (right: grey - building, green - vegetation) of the investigated district in the eastern part of Erfurt (Germany). At position 1 the GZH reference building is located. Position 2 marks the virtual location of the GZH with high outdoor temperature and position 3 of high wind speed. The building textures in black located South-East in the district represents a new development area for MFH completed in the year 2020 and thus already implemented in the ENVI-met model.*

Figure 2: *a) East-facing and b) west-facing façade of the GZH building; b) floor plan of the attic floor of the GZH.*

2.2. Climate simulation within an urban environment

To investigate the impact of climatic effects on the district scale on thermal building simulations, the urban climate model ENVI-met (Bruse & Fleer, 1998; ENVI-met, 2020) was applied. ENVI-met is a three-dimensional small-scale model of the atmosphere solving the basic equations of flow mechanics and thermodynamics. It was developed to simulate the interaction between urban structures like buildings, trees and other kinds of vegetation and the micro-climatic situation. ENVI-met has been used and validated in recent studies (Goldberg, Kurbjuhn, & Bernhofer, 2013).

In the presented study, ENVI-met was used to generate a typical daily cycle of meteorological variables at a hot summer day. The investigations are adapted to one district of Erfurt. The model input datasets were the spatial arrangement of buildings with realistic building heights, the vegetation structure in its spatial extent and with different vegetation parameters (different kinds of trees, shrubs, grassland), as well as sealed areas considered as asphalted surfaces, partly sealed areas as cobbled, paved or gravel covered, and unsealed surfaces as areas of loam. Freely available object model data and Aerial pictures (data source 'Geoportal Thueringen': https://www.geoportal-th.de/de-de/) as well as satellite pictures (Google Earth) were used as data base for the manual digitalization of al environmental objects. Figure 1 (right side) shows the prepared area input file for model simulations with ENVI-met using a horizontal resolution of 4 m.

The model was set up for July 15, a rather hot, cloudless midsummer-day with high potential for solar irradiation and the development of an autochthonous weather situation. The following initial and boundary conditions were used for the model simulations with ENVI-met: soil temperature (0-50 cm depth) 294 K (21 °C), soil moisture (0-50 cm depth) 20 % (related to field capacity), soil type: loam, air temperature in 2 meters above the ground 301 K (28°C), air humidity in 2 meters above the ground 50 %, horizontal wind speed in 10 m above ground 3 m/s, wind direction of 150 degrees (i.e., south-east wind direction, see Figure 1b), initial time: 20:00 local time (due to nearly neutral stratification of the atmosphere for initialization). The model runtime was set to 28 simulation hours, starting in the evening, whereby the first hours were needed to adapt the model to the environmental set-up.

Especially the daily course of air temperature, wind speed and wind direction was evaluated at different receptor points for different heights above ground every five simulated minutes as well as for the total model area every simulated hour. A data set of 237x243x29 (x-y-z direction in a Cartesian coordinate system) spatial points in horizontal and vertical direction results for one meteorological variable at one output time step (one hour). To optimise the data amount, receptor points near the reference buildings were used with a higher time step of generating output data for one grid cell (4 x 4 m²) and at all simulated height levels (number of height levels: 29, central height of the level above ground surface: 1.00, 3.00, 5.12, 7.49, 10.15, 13.13, 16.47 ,…, 362.07 m).

2.3. Data transfer from local urban climate to building simulation

As the models of urban climate and thermal building simulation are not directly linkable in sense of interaction and feedback, the data output of ENVI-met is transferred into IDA ICE in a non-automated procedure. More precisely, the meteorological data of the receptor points in the district generated by ENVI-met were manually implemented into IDA ICE. These meteorological data are direct solar irradiation, indirect solar irradiation, both to the horizontal surface, outdoor air temperature as well as wind speed and wind direction. In more detail, the following steps were done:

1. Time step adjustment of meteorological output from ENVI-met:
   Averaging of the meteorological results from the time step size of 5 min (defined step width of the results in ENVI-met) to 1 h was done which is the desired meteorological input data step width for IDA ICE, although the step width of simulation in IDA ICE and ENVI-met is much lower. The effect of the averaging on the meteorological data is negligible because the daily course of the meteorological data show smooth progression.
2. Chosen height of meteorological data from ENVI-met for IDA ICE:
   Receptor points of ENVI-met contain meteorological data in the different vertical layers of the 3D model. Figure 3 shows the low variability of the outdoor air temperature and wind direction with the height above ground. Contrasting, the wind speed significantly increases with height, expected and caused by the 3D elements in the model. Translated to the building, this implies low wind speed for the first floor of around 1.0 m/s and higher wind speed for the top floor (16 m height) of around 1.7 m/s. As a result lower air exchange of dwellings in the first compared to the top floor. As mentioned, we focus on the dwellings at the top/attic floor. Thus, the meteorological data of the receptor points from ENVI-met at 16 m height above ground, corresponding to the altitude of the top floor, was used for implementation into IDA ICE. Deviating from this, the solar irradiation data was used from the height of 20 m to avoid the reduction of irradiation by shadings in ENVI-met (for some receptor points obtained up to 16 m due to, e.g., trees) into IDA ICE. Shading effects on the building were considered in the building simulation and set equal for the receptor point comparison in this article.
3. Synthetic meteorological data set for month of July:
   Overheating assessment using thermal building simulation is typically done for a whole summer period or year. However, the model structure (ENVI-met is not running in a climate mode) as well as the CPU-intensive calculations of the 3D atmospheric flow model of ENVI-met limit the meteorological data output to one day. Thereby, we are focusing on a warm summer day with maximum temperature near 30 °C to study general processes and dependencies between the outdoor meteorological situation and the indoor temperature development. However, the simulation of the building for one day would be unreasonable since thermal inertia of buildings are not represent in a realistic modality. Thus, we created a synthetic month (July) consisting of the meteorological daily data of the simulated day in ENVI-met. Accordingly, every day of this month is equal. This data set was imported into IDA ICE for building simulation. The results show that after one week of daily increase in room temperature (caused by thermal inertia of the building components), the room temperature curve was the same each day. Finally, the 14th simulation day in the thermal building simulation was used as result and for further comparison.
4. Wind driven air exchange parameters in IDA ICE:
   The air exchange of rooms driven by horizontal and vertical wind as well as temperature gradient at building openings must be represented as realistically as possible for the analysis. Therefore, IDA ICE enables the opportunity to take into account wind flows in or through a building by considering pressure coefficient (calculated by a simplified algorithm using the method of the AIVC (Air Infiltration and Ventilation Centre) (Cóstola et al., 2009) in IDA ICE) of the façade and roof elements based on the air exchange modelling used also for COMIS (Feustel, 1999). The location of the investigated GZH building was assumed to be semi-exposed for the calculation of the pressure coefficients according the method of the AIVC. The pressure coefficients calculated for the façade and the approach enables the opportunity to evaluate wind driven air exchanges in the building as well as the effect of cross ventilation. Besides this, temperature gradient driven air exchange by different indoor to outdoor or adjacent room air temperatures was considered as well (according to air exchange modelling used also for COMIS (Feustel, 1999). The validation of the air exchange was proven by comparing simulation with measured temperature data of individual rooms with natural ventilation (Schünemann et al., 2020). Finally, in IDA ICE the parameter “wind measurement height” had to be set to the same height as the layer height of the implemented meteorological data from ENVI-met, in this case 16 m, because a height dependent wind profile was used in IDA ICE.

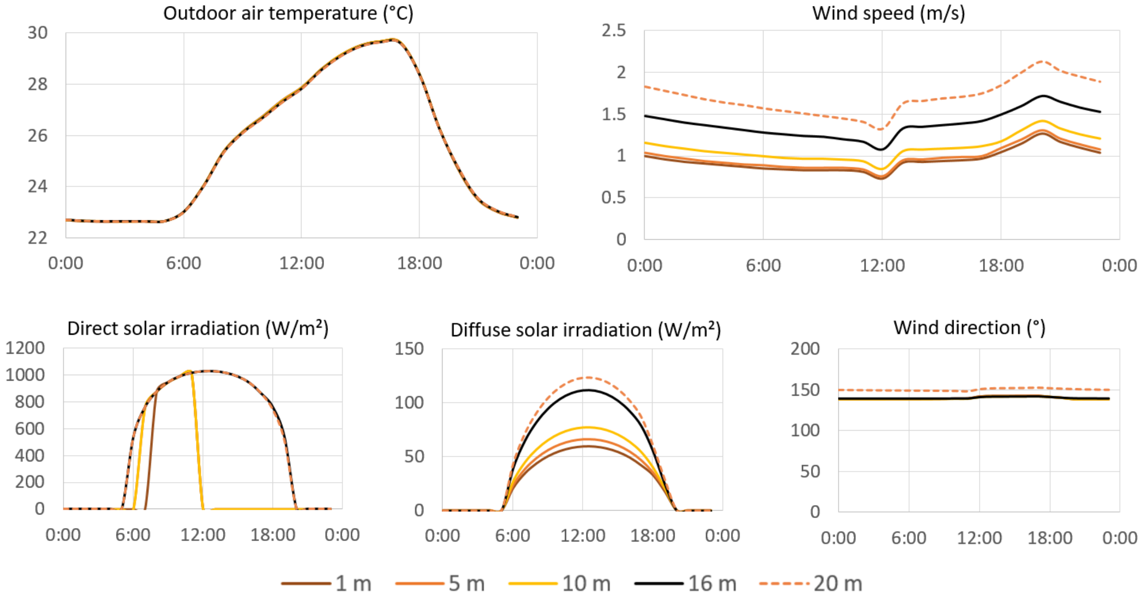

Figure 3: *Height dependent meteorological data of the receptor point 3 gained by ENVI-met simulation (heights above ground 1/5/10/16/20 m).*

2.4. Thermal building simulation

To analyse the evolving indoor room temperatures by the outdoor meteorological conditions gained from the outdoor urban climate simulation, the GZH was modelled including all rooms using the validated and certificated thermal building simulation software IDA ICE 4.8 (EQUA, 2018, 2020). Figure 4 illustrates the 3D model of the GZH building in IDA ICE. The simulations were run at a time step of less than one hour to allow detailed analysis of the evolving operative room temperatures for each room. Building components and material layers of the GZH were implemented to gain realistic heat storage capacities and transmissions of each room to the building exterior as well as to neighbouring rooms. For the thermal building simulation, the following general boundary conditions were applied:

- Buildings location: Erfurt, Germany
- Shading: the neighboured building on the opposite side of the street (east façade) was taken into account; shading of trees are not considered
- Minimum room air temperature (heating): 20 °C except unheated corridors, staircases and bedrooms
- Local meteorological data in the district gained from receptor points in ENVI-met

The individual internal loads from the presence of inhabitants and electrical devices depends on the room use. We assumed that two adult persons inhabit the dwelling, sleeping from 22:00 to 6:00 and are outside the home from 8:00 to 16:00. The course of the day for the assumed hourly defined heat gains for the presented bedroom and kitchen living room are depicted in Figure 5.

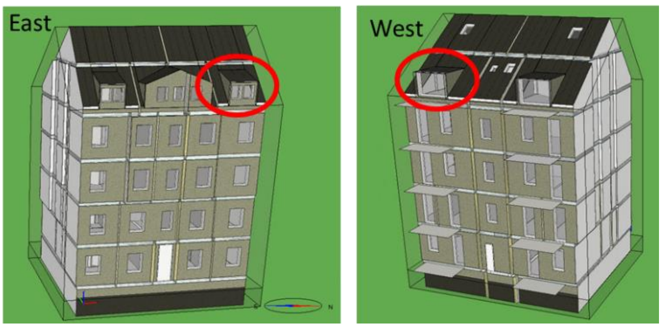

Figure 4: *3D model of the selected GZH building in the thermal building simulation tool IDA ICE. The analysed bedroom (east façade) and kitchen living room (west façade) are labelled with red circles*

As mentioned earlier the kind (tilted, fully open) and duration of window ventilation during chilly nights has significant impact on the overheating of rooms. IDA ICE enables the opportunity to depict realistic wind- and temperature gradient driven air exchange through windows and room doors, taken into account the pressure coefficient of the façades and the altitude layering of the wind speed. That this has been done in a realistically was proven by comparing modelled room temperatures and measured room temperatures of the GZH building in the kitchen living and bedroom on different storeys (Schünemann et al., 2020). The assumed window ventilation conditions are:

- Windows fully open in both kitchen living room and bedroom during the whole night from 18:00 to 7:00
- Degree of window opening: defined by opening profiles of the installed windows (ventilation area in kitchen living room 1.62 m² and in bedroom 1.04 m²)
- Cross ventilation: room door between kitchen living room and bedroom only open in the scenario of cross ventilation during bedtime from 22:00 to 6:00

According to own surveys on ventilation behaviour of residents in MFH (publication in progress), the assumed ventilation behaviour can be definitely regarded as above average and as exemplary behaviour to expect the full potential of nighttime cooling. This behaviour was chosen to illustrate the potential of different climatic conditions in the district gained by ENVI-met. Of course, the difference between the locations in the district will decrease if window ventilation is or can be implemented only at a lower level.

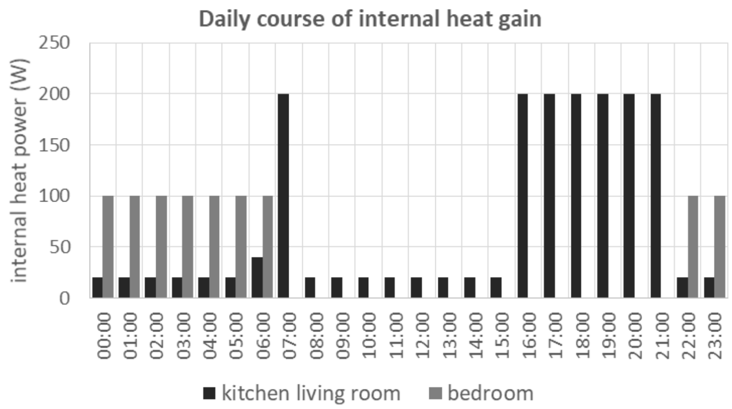

***Figure 5**: Daily course of the assumed heat gains from occupants and electronic devices for the analysed bedroom and kitchen living room.*

3. Results and Discussion

3.1. Urban climate simulation

The daily course of meteorological variables was simulated by ENVI-met and evaluated for the district at every full hour of the 15th July. Figure 6 demonstrates exemplarily the spatial variability of the temperature and wind field in the early morning (temperature minimum) and in the afternoon during the temperature maximum at a height of 1 m above ground (first grid layer of ENVI-met with a height level between 0-2 m).

The air temperature varies rather slightly throughout the district: ca. 0.7 K at 4:00 in the morning up to 1.4 K in the afternoon at 16:00. The largest contrast between night- and daytime temperature can be found over short grassland sites without shaded areas and without limitations of horizon. At such places, the air temperature is minimal at night because the outgoing radiation leads to air temperature values smaller than between buildings and over sealed areas with a higher heat capacity. The thermal stress at night is maximum in densely built and sealed areas with great limitations of horizon (decreasing outgoing radiation caused by surrounding objects). A secondary maximum of air temperature occurs during the day between buildings where the ventilation is additionally very small. In general, it has to be noted, that the expected impact of air temperature differences on the thermal building simulation would be low due to the small spatial contrast of air temperature.

In comparison to the temperature, the wind field shows more spatial variability. The wind field in Figure 6 illustrates the inflow at the boundaries of the modelled area (horizontal wind speed: 3 m/s, South-East direction). Please note, that the first grid cells around the simulated area are unsealed and undeveloped. Due to the mechanical roughness of the urban structures within the district, especially buildings and trees, the wind speed is decreasing significantly. The smallest wind speed values occur between buildings and at backyards. Depending on the orientation streets with respect to the wind direction, the wind speed is significantly decreased, especially for streets in West-East direction. The incoming airflow is significantly slow down up to values of 0.5 m/s for horizontal wind speed due to higher buildings. This influence of street canyon orientation on the properties of the wind field can also be studied at single receptor points, see Figure 7. It is expected that the spatial differences in wind field influence significantly the thermal building simulation especially in the case of nighttime ventilation (see section 3.1).

Compared to the spatial variability, the daily cycle of the wind speed was found to be rather smooth for the total district.

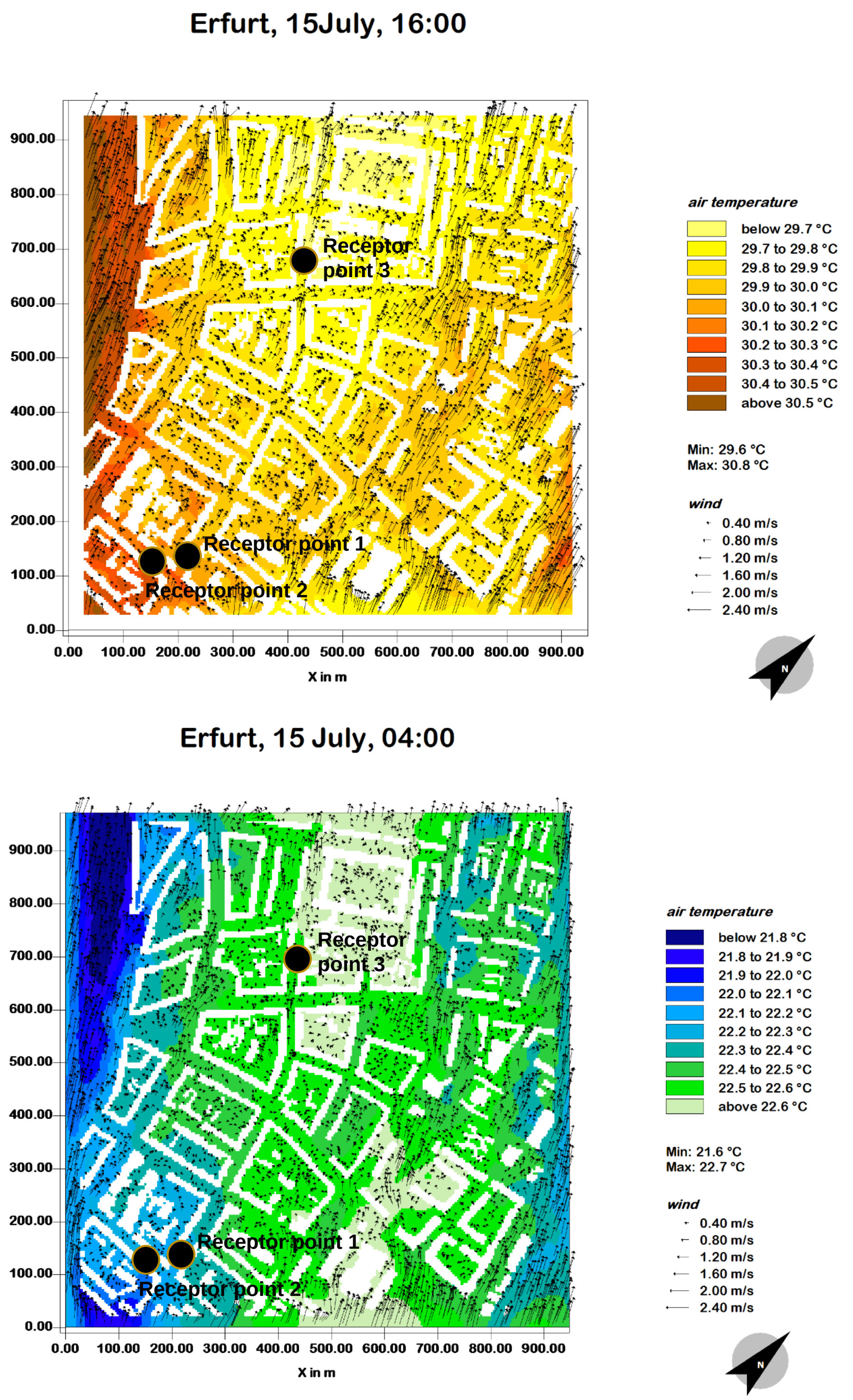

Figure 6: *Meteorological conditions in the district of Erfurt: Air temperature (potential temperature in Kelvin) and wind field (arrows for wind vector, length/direction of the arrow shows horizontal wind speed/wind direction) near the ground surface simulated by ENVI-met (first model level at 1 m) on the 15th of July at 04:00 and 16:00 Local Time. Please note the different range of air temperature values at 04:00 and 16:00 due to small spatial variability. The three receptor points are highlighted.*

3.2. Thermal building simulation

In the urban climate model more than 40 receptor points were analysed. Three receptor points (location see Figure 1) with different meteorological conditions were selected for further investigations:

- Receptor point **1** located at the east (street) side of the reference GZH building
- Receptor point **2** located in front of a south façade of a building block of comparable GZH buildings. For this receptor point the GZH reference building was tilted horizontally by 90° clockwise to its original position of receptor point 1 to be aligned to the other buildings of the block (the east façade at receptor 1 now facing to the street turned into a south façade).
- Receptor point **3** showing one of the highest wind speed in the urban climate model, situated in front of an east façade of a building block of GZH types. Here, the orientation of the GZH was set the same as for receptor point 1 for simplification

While wind direction and solar irradiation are comparable at 16 m height for all receptor points, Figure 7 illustrates the small differences of outdoor air temperature of max. 0.5 K for the different receptor points. For all receptor points, the temperature rises from around 22 °C in the (tropical) night to 30 °C at 16:00 in the evening. In contrast to the small local differences in air temperature, the wind speed varies significantly between receptor point 1 and 2 with 0.3 m/s and receptor 3 with 1.4 m/s as a daily average without strong intraday changes.

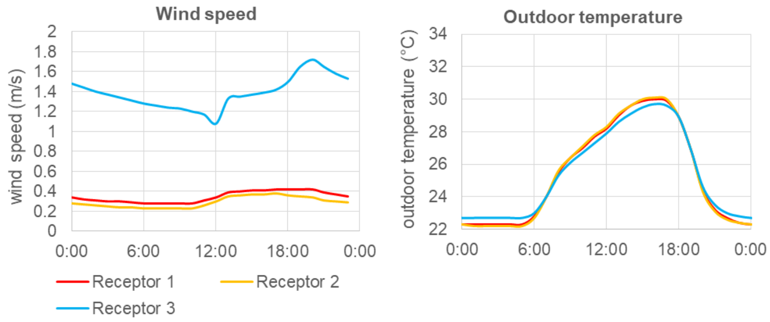

Figure 7: *Meteorological conditions at three receptor points in the district: Wind speed and outdoor air temperature in 16 m height above ground (position of the attic dwellings).*

To estimate the impact of the spatial differences in outdoor temperature and wind conditions, the meteorological data of these three receptor points were implemented into the thermal building simulation and the resulting temperatures of the bedroom and kitchen living room of the attic dwelling in the GZH building were analysed. Two scenarios were distinguished: a) without the use of cross ventilation by keeping the room door of the bedroom closed and b) applying cross ventilation by open the door when windows in kitchen living and bedroom are opened between 18:00 and 7:00. The results are compared in Figure 8 a) and b).

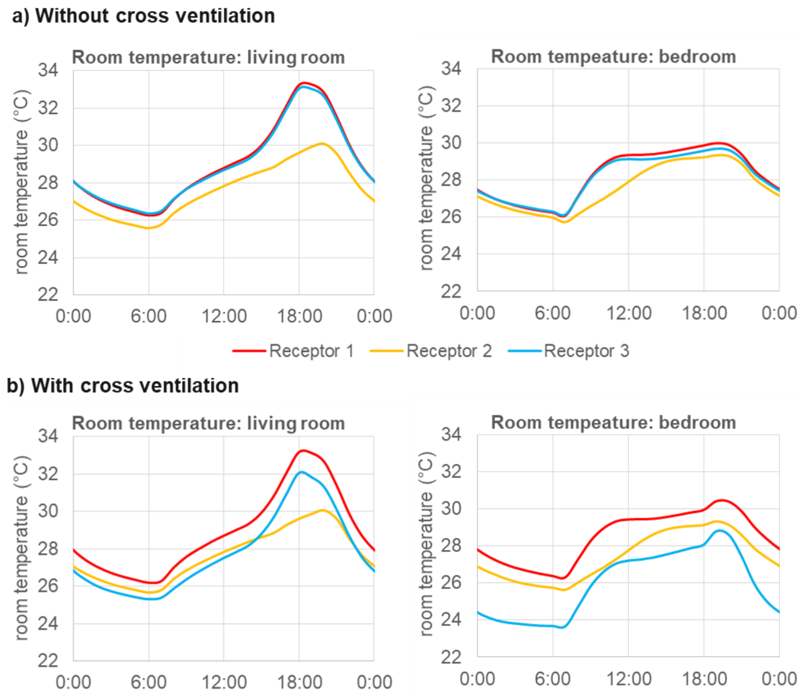

Figure 8*: Room temperature of kitchen living room (left) and bedroom (right) for the GZH attic dwelling virtually located at three different receptor points in the district a) without cross ventilation and b) with window cross ventilation applied.*

Without cross ventilation the differences in room temperature caused by variations in wind speed and outdoor air temperature of receptor 1 and 3 are negligible. However, the changed orientation of the building from east-west façades for receptor 1 and 3 to south-west façades for receptor 2 shows remarkable influence. Here, the lower room temperatures of the kitchen living room are caused by lower solar irradiation through the north oriented windows. For the bedroom with south oriented windows (at receptor 2 position) the more evenly distributed solar irradiation results in a lower increase in room temperature in the morning but saturates nearly at the same room temperature level as for receptor 1 and 3.
Contrasting, if cross ventilation between both rooms is realised (Figure 8b), the small differences in wind strength lead to significant differences in room temperature and overheating of the rooms. For receptor 1 and 2 with almost calm wind conditions (see Figure 7) the temperature course is comparable to the case without using cross ventilation in Figure 8a. In contrast, for receptor 3 the higher (but still low) wind speed of around 1.4 m/s leads to a significant increase in air exchange if cross ventilation is applied. Thus the room temperatures in the small bedroom is around 2 K lower and in the kitchen living room around 1 K lower compared to the case without cross ventilation. This underlines that cross ventilation is very effective even for low wind at nearly calm summer nights.
The receptor points 1 and 3 differs in both, outdoor air temperature and wind speed. To analyse the sole impact of different outdoor air temperature (without wind influence) within the district, the meteorological conditions of receptor 1 were modified by exchanging the outdoor air temperature from receptor 3. Thus, the meteorological input for the comparison in Figure 9 only differed by the outdoor temperature, not by wind. As discussed above, the impact of the small differences of outdoor air temperature in the district on room temperatures is negligible. More precisely, the differences in room temperature are even smaller (less than 0.5 K) than the differences in outdoor air temperature. Thus, the differences in outdoor air temperature on indoor climate are negligible for the chosen district.

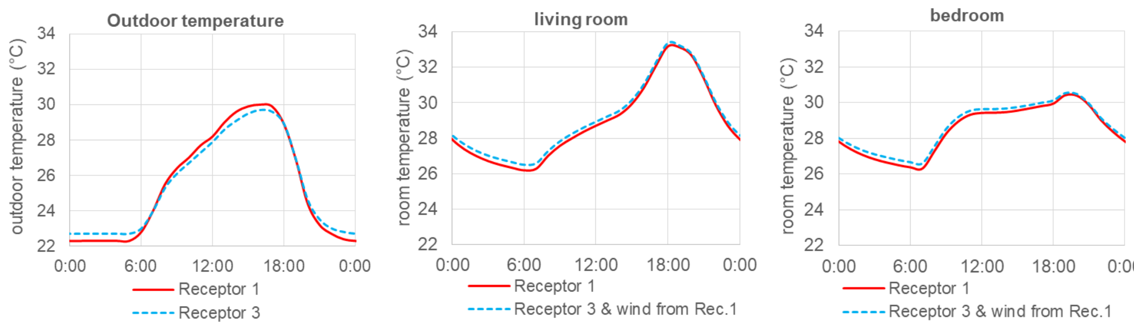

Figure 9*: Outdoor temperature (left) influence on the resulting room temperature for kitchen living room (middle) and bedroom (right) for the GZH attic dwelling by comparison of receptor 1 with receptor point 3 but with same wind conditions as receptor 1 to equalize the different wind conditions on the receptors (using cross ventilation).*

For analysis of the sole impact of different wind conditions in the district, the meteorological conditions of receptor 1 were modified by exchanging the wind conditions from receptor 3 with higher wind speed. Figure 10 underlines, that the effect of small changes in wind conditions in the district shows a distinct impact on the resulting room temperatures using cross ventilation, even for low wind speeds of around 1.4 m/s.

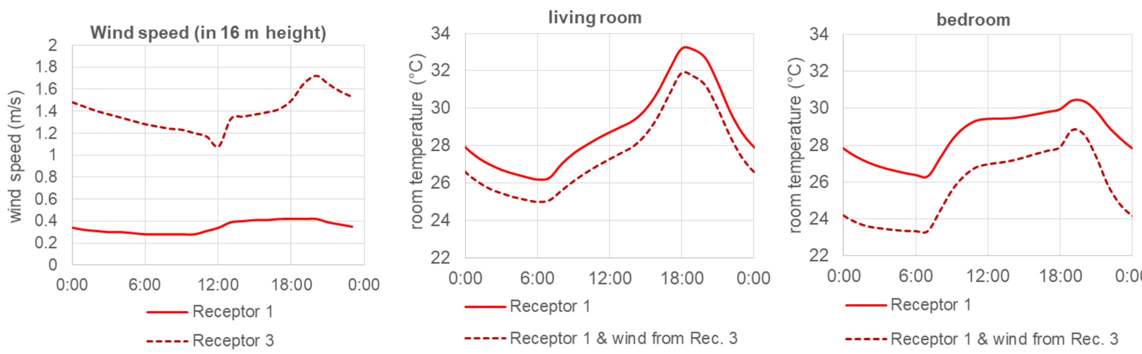

Figure 10*: Wind speed (left) influence on the resulting room temperature of kitchen living room (middle) and bedroom (right) for the GZH attic dwelling by comparison of receptor 1 with wind input from receptor point 3 but (both have same outdoor temperature conditions) using cross ventilation.*

3.3. Opportunities and Limitations of the model chain approach

The applied model chain of implementing meteorological conditions from urban climate simulations of districts to thermal building simulation of residential buildings provides new understandings of the impact of spatial variations in urban climate on the efficacy of night cooling in buildings and thus on thermal comfort of residents. The scheme in Figure 11 visualises the model chain approach.

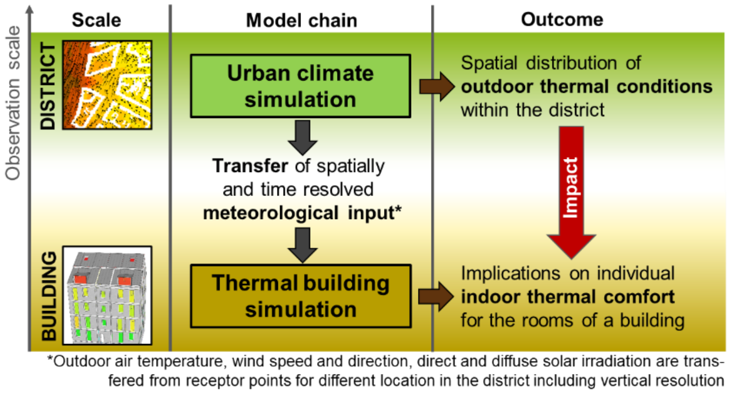

Figure 11: *Schema of the developed model chain approach, starting from urban climate simulation of a district and transferring the resulting local meteorological conditions into thermal building simulation. The model chain enables the opportunity to investigate the impact of urban structures and resulting microscale climate on indoor thermal comfort conditions (including overheating) in buildings.*

However, also for this approach feasible conclusions are limited caused by different model approaches. Here, we state the opportunities and limitations of the model chain.

Opportunities of the urban climate – building simulation – model chain:

- The impact of urban climate on resulting room temperatures (indoor thermal comfort) can be analysed in high spatial and temporal resolution. Thus, the effect of small differences in outdoor air temperature and wind on overheating in buildings can be demonstrated in a realistically manner.
- The described model chain allows sensitivity studies of parameters or variables within a kind of a 'virtual' laboratory.
- Using urban climate simulation, the influence of urban structures like buildings, sealed surfaces or trees on thermal performance in buildings can be examined. The closer the information to urban structures are to reality, the smaller are the uncertainties of estimating the interaction between structural factors, airflow and energy exchange.
- The model chain can assist planners to estimate the impact of projects on the thermal comfort for inhabitants in the district as well as in its buildings. This might help to develop locally adapted measures for heat resilient cities.

Limitations of the urban climate – building simulation – model chain:

- Using ENVI-met, only short periods (usually one or two days) can be simulated as connected time series and used for the thermal building simulation. Nevertheless, for building simulation the analysis of the whole summer or at least heat waves is more reasonable but not possible with this approach.
- The impact of urban climate on indoor temperatures depends on numerous conditions in the thermal building simulation like window ventilation behaviour, the use of cross ventilation, building type or storey as well as in the urban climate simulation like initial parameter setting, resolution, model size.
- Even if the horizontal resolution in the urban climate simulation is high (4 m x 4 m), the effect of high temperatures developing on surfaces with high solar irradiation and its effect for window ventilation of such heated façades or roofs is irresolvable with this method.
- In ENVI-met TKE-epsilon turbulence closure is used (i.e., equations for turbulent kinetic energy and turbulent energy dissipation are solved) producing strong mixing of the lowest atmospheric boundary layer. This fact combined with a rather coarse vertical resolution of the laminar boundary layer above the ground leads to an underestimation of daily cycles of temperature and humidity in the lower urban canopy.

4. Conclusions and outlook

The focus of this article is to introduce a method of applying a model chain, starting from urban climate simulation of a district and implementing the resulting local meteorological conditions in the thermal building simulation, depicted in Figure 11. Using this method it is possible to investigate the impact of spatial climate differences in a district on thermal comfort for different rooms of buildings. This was done combining the simulation tools ENVI-met and IDA-ICE. The practicability is demonstrated by comparing the effect of different meteorological conditions for several receptor points in a district of Erfurt (Germany) for a GZH MFH type. Doing this enables opportunities to examine the implications of spatial differences in wind and outdoor air temperature conditions on the building. As first results of this model chain, it was found that small differences in outdoor air temperatures in the district have negligible influence on the room temperature, whereas different wind conditions even for low wind speed of around 1.4 m/s lead to significant changes in indoor thermal comfort by using window and cross ventilation. The orientation of the building also plays a decisive role mainly caused by changed solar irradiation and wind flow. In sum, the proof of concept of urban climate to building simulation model chain is performed successfully and more profound investigations applying this model chain are intended. As an example, analysing the impact of different ventilation behaviour will lead to significant changes. In this article, the assumed ventilation behaviour is nearly ideal for effective nighttime cooling. Also comparing different district types or changes in urban structure can help to generalise the findings and understand the urban climate – indoor climate correlation.

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