



## Research paper

# Research note. Visualisation of summer heat intensity for different settlement types and varying surface fraction partitioning



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## HIGHLIGHTS

- Micro-scale simulations of idealised squared cities with different settlement types.
- Sensitivity studies relating to building surface and impervious surface fractions.
- Ternary plots with 3 axes for built-up, impervious and pervious surface fractions.
- Dependency of summer heat intensity on settlement type and surface partitioning.
- Novel approach to summarise model results in support of urban planning.

## ARTICLE INFO

### Article history:

Received 13 January 2015

Received in revised form 17 June 2015

Accepted 5 August 2015

Available online 10 September 2015

### Keywords:

Climate adaptation

Ternary diagrams

Micro-scale numerical model

MUKLIMO.3

Urban planning

Idealised cities

## ABSTRACT

Urban planners and stakeholders require knowledge about the effectiveness of city-scale climate adaptation measures in order to develop climate resilient cities and to push forward the political process for the implementation of climate adaptation strategies in cities. This study examines the impact of modifications in urban surface fractions of buildings, impervious and pervious surfaces on summer air temperatures using urban climate modelling of idealised cities. Sensitivity tests are performed for nine typical settlement types in Germany. The results for minimum and maximum temperatures are analysed and plotted in a ternary diagram. The novel approach of using ternary diagrams for the aggregation and visualisation of modelling results clearly identifies thermally unfavourable ranges of urban surface partitioning that should be avoided for urban settlements. Furthermore, the diagrams are used to derive quantitative recommendations for the most effective reduction of summer heat intensity.

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## 1. Introduction

The urban heat island, defined as the air temperature difference between cities and their surrounding countryside, can increase discomfort and potentially increase the threat of heat stress and the mortality of city dwellers (Stewart & Oke, 2012). Furthermore, elevated air temperatures in cities also increase the demand for energy and the cost of air conditioning during hot seasons (Lemonsu, Koukou-Arnaud, Desplat, Salagnac, & Masson, 2012; Martilli, 2014). The diurnal maximum and minimum air temperatures in cities depend on the values of geometric, thermal, radiative, metabolic and surface cover properties (Barlow, 2014). Climate specific classification systems, such as local climate zones

(Stewart & Oke, 2012), are important for comparing and interpreting the urban heat island measured or modelled in different research studies. Conversely, classification systems are used as a rule of thumb to estimate the urban heat risk of a specific building type ensemble. Usually, a few levels ranging from low risk to high risk are distinguished. This information is essential and a good first estimate for urban planners helping to design climate resilient cities.

Although a large number of thermal urban climate studies are available, the results are (i) difficult to compare, (ii) difficult to transfer to other real world examples and, even more important, (iii) difficult to standardise. This compromises their usefulness for urban planning. Urban planners require urban climate information which is visualised in standardised figures (e.g. nomogram) to enable the urban heat intensity for a certain settlement type to be determined easily based on key parameters. Furthermore, the climate information should be based on values which exceed critical thresholds (e.g. 30 °C) and which are therefore easier to communicate within the political process of climate resilient planning.

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Standardised sensitivity tests for idealised cities with different urban morphology characteristics are carried out with the 3-dimensional micro-scale urban climate model MUKLIMO\_3. The results of the sensitivity tests are used to develop a ternary plot based on the three surface fractions built-up, impervious and pervious. While ternary plots have been used widely in other disciplines such as mineralogy or physical chemistry (Howarth, 1996), the approach to present urban climate model results within a ternary plot is novel and promising as it considers different requirements of urban planners. The ternary plot can be used as a nomogram for climate resilient planning against summer heat. Furthermore, the results can confirm or disprove the rule of thumb estimates for the urban heat intensity of different settlement types.

## 2. Methods

### 2.1. MUKLIMO\_3 model and simulation setup

The 3-dimensional micro-scale urban climate model MUKLIMO\_3 (Sievers, 1995; Sievers & Früh, 2012; Sievers & Zdunkowski, 1986; Sievers, Forkel, & Zdunkowski, 1983) was used for sensitivity studies of idealised squared cities similar to Theeuwes, Solcerova, and Steeneveld (2013) or Martilli (2014). MUKLIMO\_3 solves the Reynolds-averaged non-hydrostatic Navier–Stokes equations in the presence of buildings with a generalisation of the stream function–vorticity method to three dimensions. Model physics include prognostic equations for atmospheric temperature and humidity, the parameterisation of unresolved buildings, short-wave and long-wave radiation, balanced heat and moisture budgets in the soil (Sievers et al., 1983) and a vegetation model based on Siebert, Sievers, and Zdunkowski (1992). The model utilises sub-grid scale surface fraction partitioning into built-up, impervious and pervious (vegetation canopy and bare soil) surface fractions (more details in Appendix A).

The idealised city of 5 km by 5 km was located in the centre of the model domain, which extends 10 km in south–north and west–east direction with a horizontal grid resolution of 100 m (Fig. A1 in Appendix A). The vertical extension of the 3-dimensional model reaches 870 m with 25 vertical levels of 10 m spacing at the surface to 50 m at the top of the model. A 1-dimensional model with rural surface characteristics extending up to the height of 2120 m provides diurnally varying boundary conditions for the 3-dimensional model.

Each idealised city comprises one of nine settlement types (Table 1) known to be typical for Germany (BMBAU, 1980). The surface of model grid cells with buildings is subdivided into the surface fraction of buildings ( $a_b$ ), the fraction of impervious surfaces without buildings ( $a_i$ ) and the fraction of pervious surfaces ( $a_p$ ), which is further distinguished into bare soil ( $a_s$ ) and low canopy vegetation ( $a_{ca}$ ) surface fractions (Fig. A1 in Appendix A). The building surface fraction and building characteristics (mean building height and wall area index) listed in Table 1 are derived from BMBAU (1980) as described in Früh et al. (2011). The surface fractions of impervious and pervious surfaces are based on expert knowledge. MUKLIMO\_3 applies a porous media approach, which requires additional information about the wall area density and the mean building height ( $h_b$ ) in order to calculate the effects of buildings on airflow, heat and radiation transfer. The wall area density, defined as the sum of all wall areas per grid volume, is derived from the wall area index (wai), which is defined as the relationship between the wall area and the base area of a typical building. Up to two different building types can be considered in one land use class (Table 1). The rural area around the idealised city is modelled as 80% pervious surface with low canopy vegetation and 20% bare soil (Table 1).

In this study model simulations are performed for a constant terrain height and a location in central Germany (latitude 50.66N). The 1-dimensional model simulations started at 9 am on July 15 Central European Summer Time (CEST). The 3-dimensional model simulations started at 9 am on July 17 CEST and ended at 9 am on July 18 CEST. The model results used for analysis refer to the 24 h period between 10 am CEST on July 17 and 9 am CEST on July 18. The forcing wind at the model boundaries was set to  $1 \text{ m s}^{-1}$  at 100 m height from southwest ( $225^\circ$ ) resulting in a mean daily wind speed of  $0.7 \text{ m s}^{-1}$  near the surface. The 1-dimensional simulations with an open country land cover result in a mean air temperature of  $22.9^\circ\text{C}$  and a maximum air temperature of  $28.3^\circ\text{C}$  near the surface. The size and dimension of the city and model domain, as well as the meteorological conditions are kept constant in all simulations.

### 2.2. Sensitivity studies and analysis

Two sensitivity tests are conducted for each idealised city with one out of the nine reference settlement types of Table 1. The first sensitivity test includes the change of the building surface fraction between 10% and 70% compensated by a proportional change in pervious and impervious surface fractions. An increase of the building surface fraction above 70% of a grid cell was not modelled, since the porous media approach strictly needs a minimum amount of porosity to model the airflow. The second sensitivity test examines the change of the relative impervious surface fraction between buildings from 10% to 90% compensated by a variation in pervious surface fraction (assuming no change in building surface fraction, see Appendix A). Together with model runs for the reference settings listed in Table 1, a total number of 152 model simulations are analysed and visualised with ternary plots.

The ternary plot is a barycentric plot of three variables which sum to a constant. It graphically depicts the ratios of the three variables as positions in an equilateral triangle. In our case, the constant is the total area of each grid cell representing 100% and the three variables are the surface fractions taken by buildings, impervious and pervious surfaces. Within the ternary the simulated spatial median 2 m minimum and maximum air temperature in the idealised city domain (excluding the rural surroundings) are drawn as individual values from selected sensitivity simulations of one settlement type (Fig. 1) or as contour lines to aggregate all simulations for a joint analysis (Fig. 2). For the latter purpose, the median minimum and median maximum air temperature are shown as differences to typical heat related air temperature thresholds. The threshold chosen for the minimum temperature is the tropical night criterion (minimum temperature  $\geq 20^\circ\text{C}$ ; DWD, 2015; Klein Tank, Zwiers, & Zhang, 2009). The threshold applied to the maximum temperature is the hot day criterion (maximum temperature  $\geq 30^\circ\text{C}$ ; DWD, 2015; Emeis, 2000).

## 3. Results

A linear relationship between impervious surface fraction without buildings and maximum air temperature is found by linear regression analysis for all settlement types with  $R^2$  values above 0.99. This linear relationship is visualised in a ternary plot and a linear regression plot for the examples of single- and multifamily residential and tenement block residential (Fig. 1). A decrease in the impervious surface fraction without buildings of about 10% results in a decrease of maximum temperature between 0.05 K (medieval city) and 0.2 K (terrace houses and high-rise buildings) ( $\sim 0.15 \text{ K}$  for single- and multifamily residential and tenement block residential). The reduction of the maximum temperature is related to an increase in evaporation and transpiration over the mainly

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