

## 74: Modeling of the Urban Heat Island using WRF comparing different urban parameterization schemes

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### Abstract

In 2050 the global fraction of urban population will grow up to over 69%, which means that around 6.3 billion people are expected to live in urban areas [1]. Improving the living conditions for this population is a major future task in a world under changing climate.

Urban Heat Island (UHI) describes the tendency for an urbanized area to remain warmer than its surroundings and thus generating its own microclimate. Next to health problems through rising temperature itself, stands the effect of accelerating photochemical reaction rates, in turn worsening the inner-city air quality [2]. Modeling the link between increasing temperature and air quality in an urban environment within a complex topographical terrain, is the innovative approach within this study.

The Weather Research and Forecasting Model (WRF) is an instrument to simulate and assess this phenomenon based on boundary conditions from observations and global climate models. This study deals as preliminary work for air quality modeling and is conducted for the area of Stuttgart, South West Germany. Different urban parameterization schemes are tested and results are compared against ground measurements.

Keywords: Urban Heat Island, WRF/chem, urban canopy parameterization, complex terrain, land use change, Stuttgart

### 1. Introduction

Affecting the local climate within and in the surrounding of an urban area, the formation of an Urban Heat Island plays an outstanding role in urban environments. The annual mean temperature of a large city is about 1°–3°C higher than in the outer areas, on individual calm, clear nights even up to 12°C (UHI intensity). Additional heat sources, roughness effects and albedo of urban surfaces (concrete, walls...), 'design' specific atmospheric dynamics. A warmer environment and modified chemical reactions effect air quality and thus human health [2]. This study about modeling the UHI of a densely populated urban area in Central Europe is conducted with the Weather Research and Forecasting Model WRF and its chemical part WRF/chem. Long term measurement data for the area offers a possibility to validate modeling results against measured variables. This study can be seen as preparatory work for modeling the impact of different surface properties on UHI formation and especially on urban air quality. The first WRF runs are carried out without coupling the chemical part to check if the model can reproduce local meteorological circulation patterns, occurring through urban-rural interactions. Based on WRF modeling results, simple mitigation and adaptation strategies counteracting the UHI-formation are to be discussed. For that reason, certain surface properties are modified, e.g. surface albedo, vegetation fraction, building density, to examine the measures most

suitable for minimizing the UHI. The time period Aug 11 – Aug 18, 2003 was chosen as reference period, also to have an example for an extreme case scenario – namely the European heat wave summer 2003.

### 2. Data and Methods

#### 2.1 Area of Interest

Stuttgart is the capital City of the federal state Baden-Württemberg located in the south-western part of Germany. With around 600000 inhabitants it's the centre of a metropolitan region of about 2.7 million people. The topographical situation of the city located within a 'pan' causes the air to be trapped and pollutants to remain longer in the urban atmosphere. The climate of Stuttgart is characterized by a great number of sunshine days and mild weather with weak winds coming from south western direction. Next to the Upper Rhine Rift, the greater area of Stuttgart is one of the warmest areas all over Germany.

Measurements at the inner city meteorological measurement station *Stuttgart-Schwabenzentrum* (Source: environmental agency of Stuttgart) show an annual mean air temperature of 10°C, a mean wind speed of 2 m/s and an average yearly precipitation sum of 573 mm [3]. The urban area of Stuttgart roughly covers 200 km<sup>2</sup>, whereas about 42% can be classified as 'urban'[4]. Low wind speed throughout the year leads to weak air mixing intensity. This becomes important

especially during inversion conditions worsening the inner city air quality. Next to high temperatures during heat waves, that issue becomes harmful for human health [3].

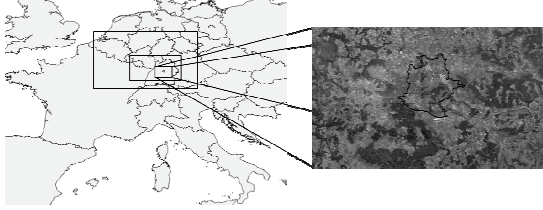


Fig. 1 Location of modelling domains (left) and snapshot of the urban area of Stuttgart, equal to size of domain 3 (right) (Source: Google Earth)

## 2.2 Modelling approach

### 2.2.1 Configurations

For modelling the local meteorological conditions over a certain period for the urban area of Stuttgart and rural surroundings, the numerical Weather Research and Forecasting model WRF was used. Downscaling techniques allowed reaching resolutions down to 1km.

A three way basic nesting approach was conducted to represent the urban area of Stuttgart (Fig 1), with three domains of 15, 3 and 1 km resolution respectively.

Table 1: Spatial statistics of model domains one, two and three showing resolution of WRF input data, horizontal resolution east-west, south-north extent and total area of the domain

Domain	D01	D02	D03
Input [km]	1	1	1
dx/dy	15	3	1
e_we [km]	43	76	61
e_sn [km]	34	56	49
Total [km <sup>2</sup> ]	328950	38304	2989

36 vertical levels were chosen and placed manually with the lowest model layer in 12 m over ground. The most important model configurations are:

- WSM 3-class scheme for D01 and D02 and Thomson scheme for D03 for microphysics
- RRTM longwave-/ Dudhia shortwave
- Eta similarity surface layer
- NOAH Land Surface Model
- Mellor-Yamada-Janjic (MYJ) boundary layer
- Kain-Fritsch scheme (only D03)
- Single Layer Urban Canopy Model (SLUCM)
- Building Energy Parameterization (BEP)
- 30" resolution geographical input data reclassified to 33 class corine land use classification [4]; with three urban classes incorporated (31: low density residential, 32: high density residential, 33: commercial)

We used ECMWF ERA Interim 0.5° Reanalysis Data as boundary conditions. For reasons of homogeneity a time period with stable weather conditions was chosen, meaning clear sky, weak

wind speeds and regular incoming solar radiation (Aug 11 – Aug 18, 2003). The default USGS land use classification was replaced by CORINE land cover [4] using ArcGIS software and transformed to WRF geogrid-readable data. Parameters like albedo and emissivity were retrieved from MODIS- and LANDSAT data with ERDAS Imagine and ArcGIS, roughness information from literature [5], LAI and vegetation fraction were estimated. The parameters in the URPARM.TBL were set as WRFV 3.3 default. For urban modelling efforts we coupled two different urban canopy models (UCMs) with NOAA land surface model in WRF. With urban fraction,  $F_{urb}$  representing the proportion of impervious surfaces in the WRF grid, NOAA then calculates fluxes for vegetated areas, whereas the UCM treats anthropogenic surfaces. The total grid-scale sensible heat flux can be estimated as sum of fluxes from natural and anthropogenic surfaces multiplied with each fractional cover [6].

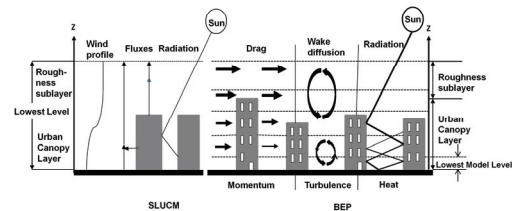


Fig. 2 Schematic figure of SLUCM (left) and BEP multi-layer model right (changed from CHEN, 2011)

### 2.2.2 Single Layer Urban Canopy Model

The SLUCM assumes infinitely long street canyons, representing shadowing, reflecting and radiation trapping in the street canyon and specifies an exponential wind profile. Temperatures of urban surfaces are calculated from surface energy budgets and thermal conduction equations. Calculation of surface sensible heat flux is done by using Monin-Obukhov similarity theory. Canyon drag coefficient and friction velocity is approximated by a similarity stability function for momentum. SLUCM has about 20 parameters, which should be adapted to the urban area of interest. In that study the parameters of CHEN, 2011 are used [6].

### 2.2.3 Multi-layer urban canopy model (BEP)

The Building Effect Parameterization approach accounts for the three-dimensional nature of urban surfaces and treats the buildings as sources and sinks of heat, moisture and momentum, in vertical distribution. Thus impacting the thermodynamic structure of the urban roughness sub-layer meaning the lower part of the urban boundary layer, BEP allows a direct interaction with the PBL. Effects of horizontal and vertical surfaces on turbulent kinetic energy (TKE), potential temperature and momentum are covered by that model. Both aspects enable a high vertical resolution close to the ground. In that case, internal temperatures of the buildings are kept constant [5].

### 2.2.4 Modelling

To test, which of the two schemes, SLUCM or BEP was more suitable to account for regional climate interactions and UHI-formation in the area of Stuttgart, results from both runs were compared against measurements. A measurement station in high density residential environment was chosen for comparison. To test the reliability of the model, measured and simulated 2m temperatures were correlated. The approach with the higher R<sup>2</sup> was chosen for further proceedings.

To test the effect of land use change on the UHI formation, a 'zero case' was conducted. By using ArcGIS techniques, the urban classes in the land use data (83 grid cells a 1x1km) were replaced by natural vegetation (grassland). By subtracting the zero-case from the full urban canopy model run, the effects of the city on local circulation patterns can be visible. To simulate simple mitigation strategies, we changed the albedo of impervious surfaces throughout the modelling domain from 0.25 to 0.7 (in LANDUSE.TBL, VEGPARM.TBL and URPARM.TBL) – which can be compared to a 'white-colouring'. This modified parameters then served as input for the urban canopy model.

## 3. Results

### 3.1 Pre-Processing

To represent the urban surface in the mesoscale forecasting model, it's for great importance to select the urban scheme which can reproduce the local conditions the best.

To check, which urban canopy parameterization fits best to the modelling approach, results from BEP and SLUCM were validated against a single point measurement for a station located in Stuttgart's city centre (Bad Cannstadt, Fig 3).

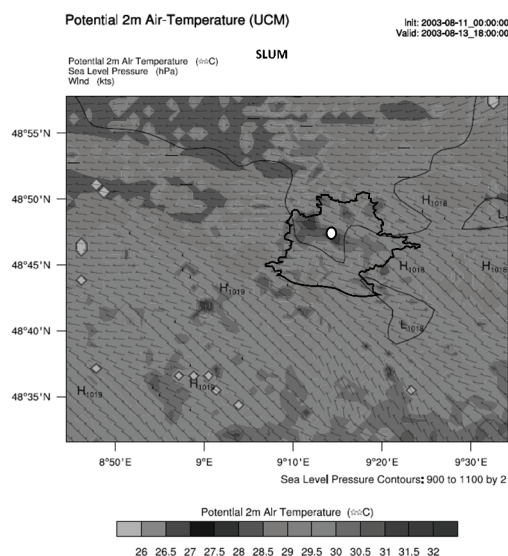


Fig. 3 Simulated 2m potential temperature using single layer urban canopy model (SLUCM)

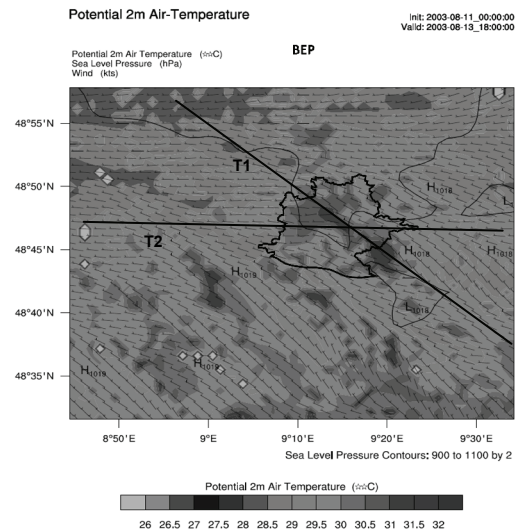


Fig. 4 Simulated 2m potential temperature using Building Energy Parameterization (BEP)

Looking at the correlation coefficient R<sup>2</sup> between measured and modelled temperature for both urban parameterizations, we decided which approach we would use for further proceedings

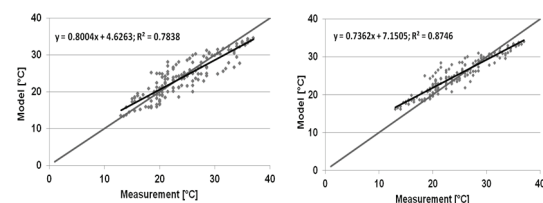


Fig.5 Correlation of SLUCM (left) and BEP (right) with ground measured 2m temperature

### 3.2 Model application

Based on a R<sup>2</sup> of 0.87 the BEP-approach was used to model the urban heat island intensity for the test period. On a characteristic 'UHI-Day' with clear sky, calm conditions, the difference between 2m air temperature modelled for an urban and a rural stations had a maximum of up to 5°C in night-time hours.

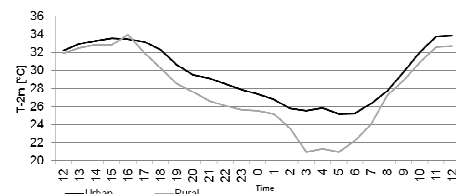


Fig. 6 Typical characteristic of difference in urban and rural air temperature during a summer day; modelled with WRF BEP

The following steps were executed to simulate certain changes of the surface properties. This was done by a) replacing urban surface by grassland and (b) enlarging the albedo of roof and road surfaces from 0.2 to 0.7 – which can be compared to white colouring.

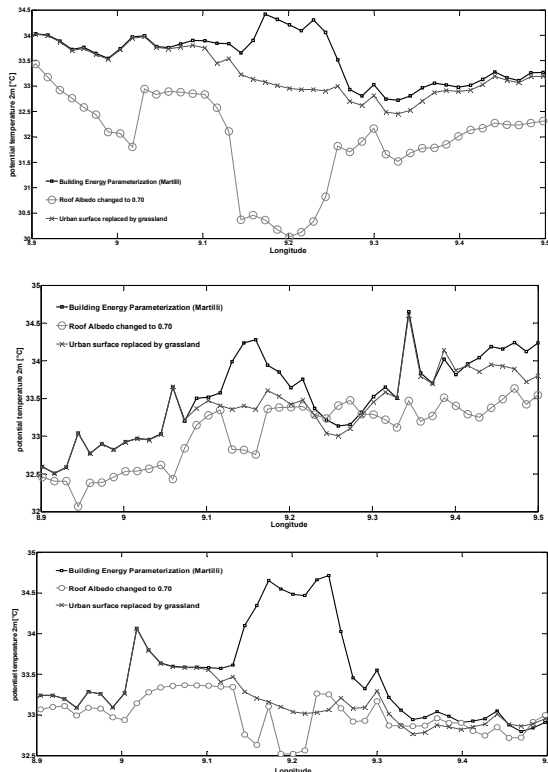


Fig. 7 Development of potential 2m temperature over given transect (Fig4) – T1 (wind direction) 12:00 UTC (top); 18 UTC (middle) and T2 (horizontal) 18:00 UTC (bottom)

To identify the urban-rural circulation patterns occurring through the presence of urban surfaces we carved out the difference in vertical velocity  $W$  between the 'real case' and the scenario case, where urban surface in between the city borders was replaced by grassland. A positive value of  $\Delta W$  was seen as uplift of air masses and a negative  $\Delta W$  as downdraft.

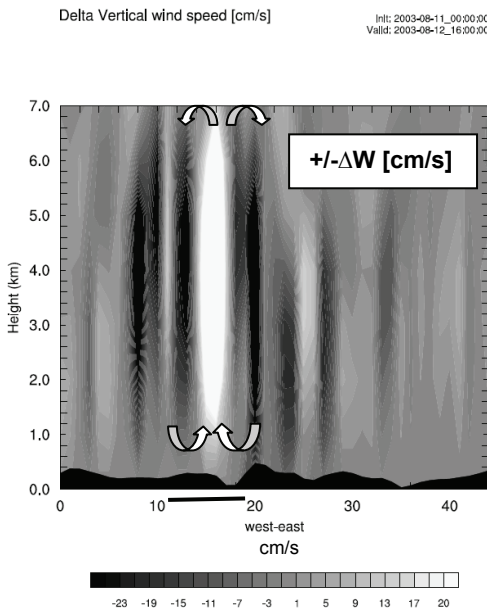


Fig. 7 Cross section for transect T1 (Fig 3) showing the difference in vertical velocity [cm/s] between BEP and zero-case run

## 5. Conclusions

The goal of this study was, to identify the UHI for the urban region of Stuttgart by downscaling the model to local scale, testing the effect of land use changes on modeling results and identify secondary circulation as preparation for air quality modeling. By replacing certain surface properties, different mitigation and adaptation strategies can be tested and the effect of Stuttgart on the local climate can be worked out. Configurations of WRF should be used for following proceedings testing different scenarios. The insights from that preparatory work will be used for analyzing the connection between urban heat island and air quality. For that reason, the coupling with WRF/chem is planned. Although WRF alone is obviously not suitable for street scale modeling, it seems to be well suitable for displaying regional climate patterns occurring through the difference between urban and rural environments.

## 6. Acknowledgements

This work is funded by the EU- Project "UHI - Development and application of mitigation and adaptation strategies and measures for counteracting the global UHI phenomenon" (3CE292P3) – CENTRAL Europe. (2011-2014).

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