Modelling the impact of climate change on heat load increase in Central European cities

Anita Bokwa[1], Petr Dobrovolny[2], Tamas Gal[3], Jan Geletic[2], Agnes Gulyas[3], Monika J. Hajto[4], Brigitte Hollosi[5], Rafal Kielar[4], Michal Lehnert[6], Nora Skarbit[3], Pavel Stastny[7], Marek Svec[7], Janos Unger[3], Miroslav Vysoudil[6], Jakub P. Walawender[4,1], Maja Zuvela-Aloise[5]
[1]Jagiellonian University, Institute of Geography and Spatial Management, 7 Gronostajowa St., 30-387 Krakow, Poland, anita.bokwa@uj.edu.pl, Jakub.Walawender@imgw.pl
[2]Global Change Research Centre AS CR, 986/4a Belidla St., 603 00 Brno, Czech Republic, dobro@sci.muni.cz, geletic.jan@gmail.com
[3]University of Szeged, 13 Dugonics ter St., Szeged H-6720, Hungary, tgal@geo.u-szeged.hu, agulyas@geo.u-szeged.hu, skarbitnora@gmail.com, unger@geo.u-szeged.hu
[4]Institute of Meteorology and Water Management - National Research Institute, Branch Krakow, 14 Piotra Borowego St., 30-215 Krakow, Poland, Monika.Hajto@imgw.pl, Rafal.Kielar@imgw.pl, Jakub.Walawender@imgw.pl
[5]Central Institute for Meteorology and Geodynamics, 38 Hohe Warte St., 1190 Vienna, Austria, brigitta.hollosi@zamg.ac.at, maja.zuvela-aloise@zamg.ac.at
[6]Palacky University Olomouc, 511/8 Krizkovskeho St., 77147 Olomouc, Czech Republic, michal.lehnert@gmail.com, vysoudil@prfnw.upol.cz
[7]Slovak Hydrometeorological Institute, 17 Jeseniova St., 83315 Bratislava, Slovakia, pavel.stastny@shmu.sk, marek.svec@shmu.sk

dated: 15 June 2015

1. Introduction

The global mean surface temperature change for the period 2016–2035 relative to 1986–2005 will likely be in the range of 0.3°C to 0.7°C, and relative to the average from year 1850 to 1900, global surface temperature change by the end of the 21st century is projected to likely exceed 1.5°C (IPCC 2013). Urban areas are among those most endangered with the potential global climate changes as the heat load in urban areas is supposed to increase. Therefore, the studies concerning the impact of global changes on local climate of cities are of a high significance for the urban inhabitants' health and wellbeing. In order to plan and undertake the mitigation actions in particular cities, it is necessary to recognize the possible range of heat load increase, in terms of both its magnitude and spatial extent. Therefore, not only land use but also land form influences should be included. The present study shows preliminary results of an international project “Urban climate in Central European cities and global climate change” aimed to evaluate the expected heat load increase in the following Central European cities: Krakow, Poland (inhabitants: 760 000, population density: 2300/km^2, elevation: 150–460 m); Bratislava, Slovakia (inhabitants: 500 000, population density: 1300/km^2, elevation: 120-440 m); Brno, Czech Republic (inhabitants: 380 000, population density: 1600/km^2, elevation: 200-525 m); Szeged, Hungary (inhabitants: 170 000, population density: 606/km^2, elevation: 50-140 m) and Vienna (inhabitants: 1 800 000, population density: 4000/km^2, elevation: 140-580 m). The four Visegrad cities have the spatial structure typical for post-communistic urban areas. Additionally, Krakow, Bratislava and Brno are located in large river valleys, in concave land forms, while Szeged is located in a flat area.

2. Methods

Within the study, complex data concerning local geomorphological features, land use and long-term climatological data are used to perform the climate modelling analyses using the non-hydrostatic MUKLIMO_3 model provided by the German (DWD) and Austrian (ZAMG) weather services for micro-scale urban climate and planning applications (Sievers and Zdunkowski 1986, Sievers 1990, Sievers 2012, 2014). The modelling approach is designed to evaluate possible changes in urban heat load under future climate conditions. The MUKLIMO_3 model is able to include the role of the relief in controlling the urban climate which is a unique feature comparing to other similar tools available.

2.1. MUKLIMO_3

MUKLIMO_3 simulates the atmospheric temperature, humidity and wind field on a three dimensional model grid. For this purpose, the basic model MUKLIMO was generalized with the stream function-vorticity method to three dimensions (Sievers 1995). The model is augmented with prognostic equations for atmospheric temperature and humidity, balanced heat and moisture budgets in the soil (Sievers et al. 1983) and a sophisticated vegetation model (Siebert et al. 1992). Cloud processes and precipitation are not considered, which limits the model application to days without precipitation. MUKLIMO_3 simulates idealized atmospheric conditions with pronounced influence of local land-use properties. Typical integration times reach from several hours up to one day. In MUKLIMO_3 special attention is dedicated to interactions between the buildings and the atmosphere. A fundamental feature of MUKLIMO_3 is, thus, the parameterization of unresolved buildings. The need for such parameterization arises for scales in which buildings are resolved vertically but not horizontally. To account for the interaction between the atmosphere and the buildings, the structural properties of the buildings within a grid cell are described by three statistical parameters: the building density, their wall area per grid volume, and their mean height (Früh et al. 2011). The model's horizontal resolution is 100 m, vertical resolution: 10–100 m, with finer resolution near surface. Initial and boundary conditions are 1D vertical profile of time-varying atmospheric conditions at the referent station. Additionally, 3-layered vegetation model and 15-layered soil model are used. MUKLIMO_3 was applied in the studies for Frankfurt (Früh et al. 2011) and Vienna (Zuvela-Aloise et al. 2014).

2.2. Land use/land cover data

In order to allow comparison of modeling results between the cities, the model setup uses standardize classification of land use properties based on local climate zones (Stewart and Oke, 2012) derived from remote sensing images (Bechtel and Daneke, 2012). The comparative analysis allows the study of spatial patterns in urban heat distribution. The Landsat satellite images are used to identify typical land use classes in all the cities (Fig 1).

The mapping procedure was carried out with the methodology proposed by the World Urban Database and Access Portal Tools (WUDAPT) (Bechtel et al. 2015). As an input data several Landsat 7 images were used, the number of the applied scenes varied between 4-7, depend of the cloud cover and data availability in the different cities. The use of multiple images from different time (seasons) is advantageous thus using more spectral information the classification gives better results. The scenes obtained from USGS (earthexplorer.usgs.gov).

For the five cities, first typical LCZ areas (training areas) were located in the study areas; this part was carried out in Google Earth. Then the Landsat images and the vector file (containing the training areas) were preprocessed in SAGA-GIS. The classification was conducted with the built in random forest classifier based on the Landsat images and the training area polygons. The classifier calculates the most likely LCZ type and the probabilities for all LCZ classes for each pixel.

For the setup of the input parameters for the model, the available land use and building height data from the study areas were gathered and additionally the thresholds for land use and built-up parameters defined by Stewart and Oke (2012) were applied. For each LCZ class, a common value was assigned for all of the necessary input parameters of MUKLIMO for all the cities.

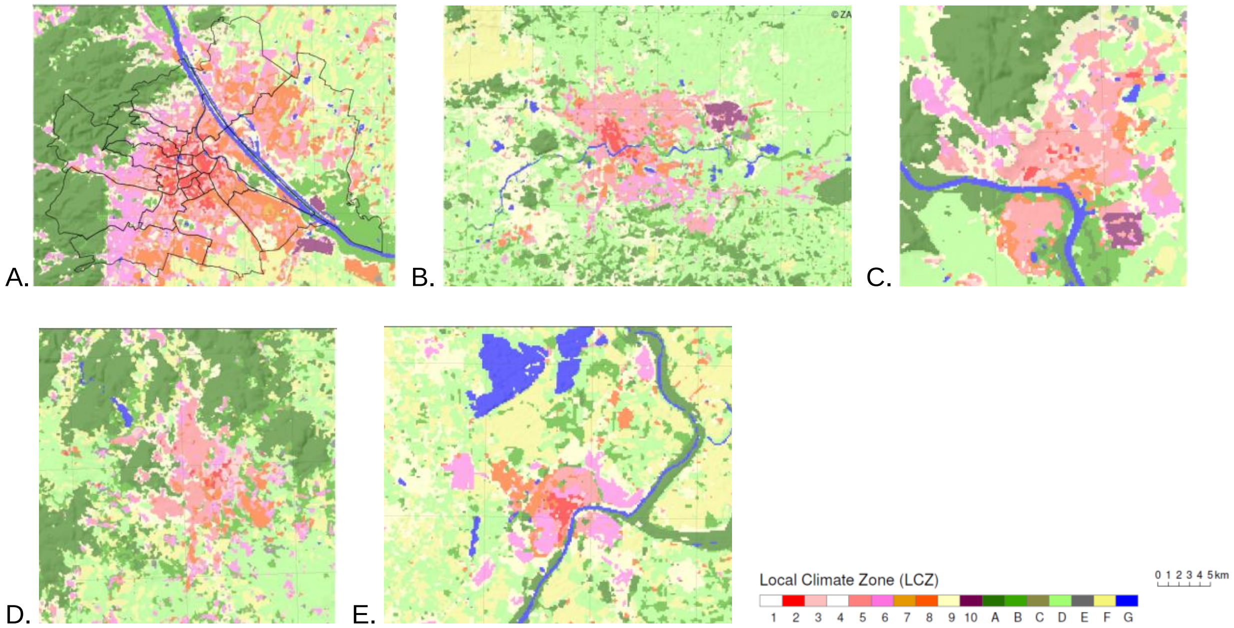

Fig. 1. Local Climate Zones in Central European cities: A.: Vienna (grid size: 316x247x39); B.: Krakow (grid size: 389x275x39); C.: Bratislava (grid size: 160x160x39); D.: Brno (grid size: 250x250x39), E.: Szeged (grid size: 213x181x25)

2.3. Cuboid method

The possible climatological changes in urban heat load under future climate conditions are evaluated in terms of expected increase in the number of days with maximum air temperature exceeding 25 centigrade (i.e. summer days). To conduct urban scale simulations for several 30-yr time periods would lead to an enormous computational effort. Therefore, the cuboid method (Fig. 2) is used to derive the actual conditions of a specific day by means of interpolation. Calculation of mean annual number of summer days for 30-year climatic periods is based on maximum temperature fields derived by a tri-linear interpolation between the 8 single-day simulations using daily meteorological data from a reference station as input. It is assumed that conditions potentially leading to heat stress can be characterized by near surface values of three meteorological parameters, namely air temperature (T), relative humidity (rh) and wind speed (v). The three parameters (T, rh, v) are representing the 3 dimensions of a cuboid structure. In order to avoid extrapolation, the limits of the cuboid (i.e. the range of T, rh, v values inside the cuboid) are chosen to encompass almost all regional climate conditions favorable for the occurrence of urban heat load situations. For each of the 8 regional climate conditions represented by the cuboid corners, the daily cycle of atmospheric conditions in the study area was simulated with the microscale urban climate model MUKLIMO_3 for each prevailing wind direction. The simulations represent the cuboid corners. Assuming a linear relationship between the three atmospheric parameters, tri-linear interpolation can be used to assign a value to any data point Ci (Ti, rhi, vi) within the cuboid as a weighted average of the values simulated for the surrounding cuboid corner points. The interpolation weight wi is computed from the distance of Ti to the two fixed points Tc,min and Tc,max and applied to the simulated urban scale MUKLIMO_3 fields to yield the interpolated urban scale fields of Tint, Tint,max or Tint,min. The relationship between T, rh, and v has been tested for the given ranges and showed no basis for rejecting the hypothesis of approximate linearity.

The future climate signal is based on the data from regional climate projections of the EURO-CORDEX project. In order to identify thermally sensitive areas within the city, idealized simulations of temperature, wind and relative humidity in the urban area are performed based on the orography and land use data with 100 m resolution. The climatological changes in urban heat load are evaluated in terms of expected increase in the mean annual number of summer days (Früh et al. 2011, Zuvela-Aloise et al. 2014).

For the analysis of the future climate change, 15 different climate predictions were used. The data were prepared with 5 global (CNRM-CM5, EC-EARTH, IPSL-CM5A, HadGEM2-ES, MPI-ESM-LR), 3 regional climate models (RCA4, RACMO22, HIRHAM5), and for two emission scenarios (RCP 2.6, RCP 4.5, RCP 8.5). The model outputs were corrected using orography and the measurement data of 1971-2000 in order to avoid the systematic errors.

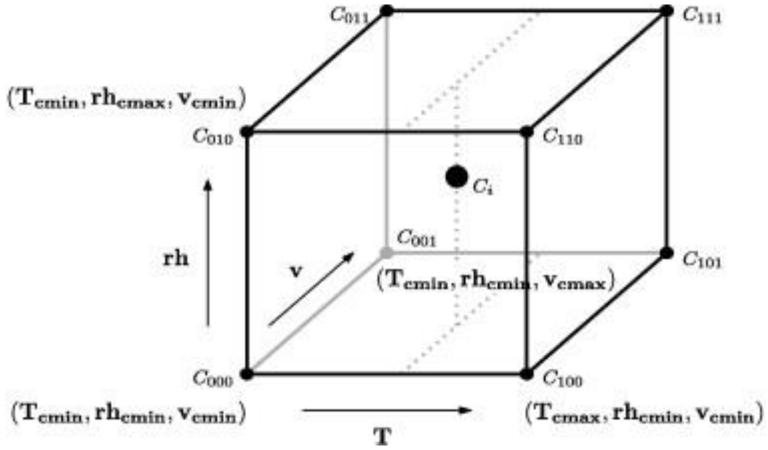

Fig. 2. Illustration of the tri-linear interpolation of the cuboid method (Früh et al. 2011). The cuboid corners (C_{xyz}) define the range of regional daily mean values of near surface air temperature (T), relative humidity (rh), and wind speed (v), potentially leading to heat load situations within the city. The limits of the cuboid are defined with cuboid minimum (cmin) and maximum (cmax) values for parameters (T, rh, v). The actual conditions for a specific day represented by a data point C_i (T_i, rh_i, v_i) are obtained by a tri-linear interpolation using the conditions simulated for the 8 cuboid corners (C_{xyz}). (Zuvela-Aloise et al. 2014)

3. Preliminary results

The preliminary results obtained so far consist of modelling air temperatures and wind fields for all cities considered for an idealized case. The model was initiated with the same meteorological profiles for all cities and the reference conditions were the following: mean daily air temperature: 25°C, mean daily relative humidity: 40%, mean daily wind speed: 3 $m \cdot s^{-1}$. It means that the simulations were prepared for the conditions corresponding to the cuboid point 101, i.e. a hot and dry day (please see Fig. 2). The upper wind direction was NW, except Krakow for which it was NE. Figure 3 presents idealized simulations for air temperatures and wind fields at h=5 m, at t=1600h MESZ (UTC + 2 h), i.e. in the afternoon, when the largest heat load is expected. The results obtained show the impact of geographic position of a city, orography and urban structure on the day time urban heat island's (UHI's) extent and intensity, and on the modification of the wind field. The connection between land use/land cover and air temperature, but also land form and air temperature can be seen when Fig. 3 is compared with Fig. 1. In rural areas, the air temperature decreases with altitude. Further studies are needed for the night time period when UHI is best developed but parallel air temperature inversions develop in cities located in concave land forms. In urban areas, rivers and water bodies have significant cooling effect and the built-up areas show some spatial diversity in air temperature values, i.e. the areas with the highest air temperatures can be found in various parts of the cities. As the urban structure of post-communistic cities is different from the structure of e.g. American cities, the spatial pattern of UHI does not follow the well-known general scheme (Oke 1987) in all cases. The simulations for other points in the cuboid method (see Fig. 2) will be used to obtain the final results on the future heat load increase.

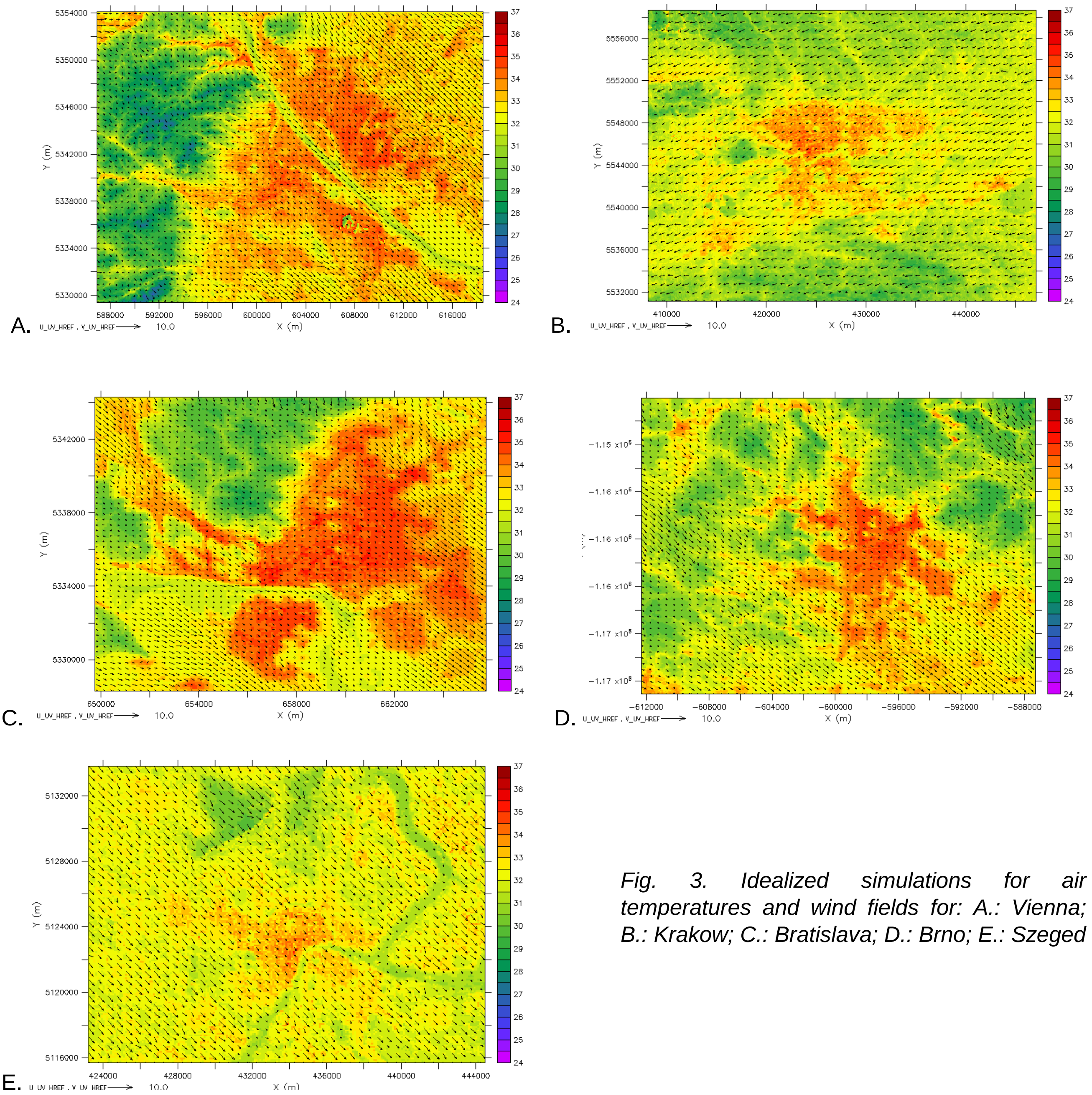

Fig. 3. Idealized simulations for air temperatures and wind fields for: A.: Vienna; B.: Krakow; C.: Bratislava; D.: Brno; E.: Szeged

The results for the future climate change impact are available for Szeged only at this stage of the analysis, but the first result can show the importance of this work and the use of a local scale urban climate model (Fig. 4.)

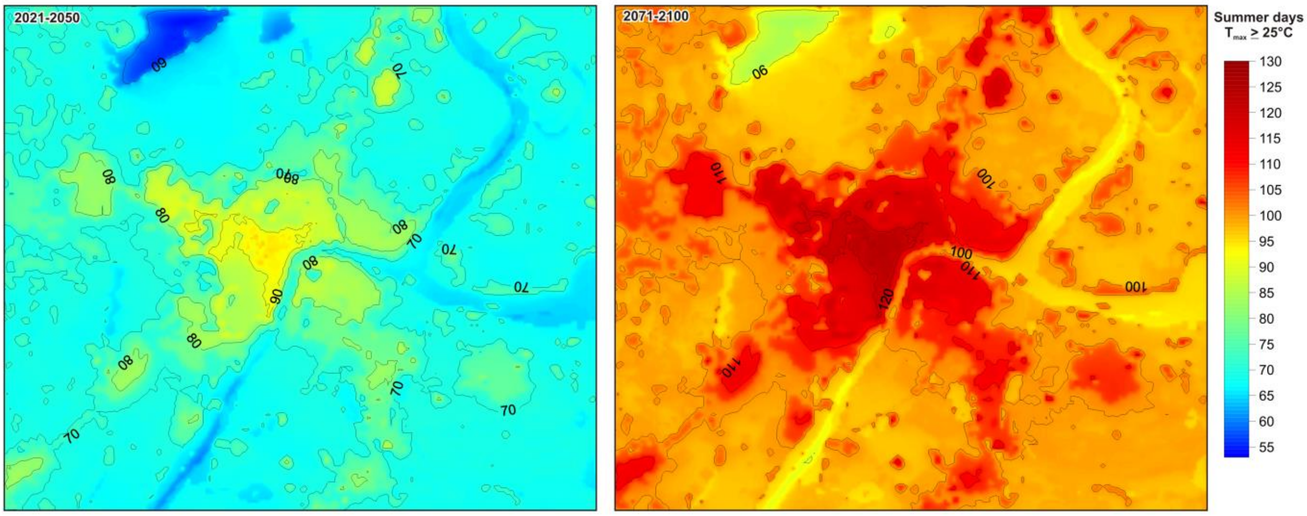

Fig. 4. The number of summer days in Szeged at 2021-2050 and 2071-2100 in case of RCP 8.5 scenario

Acknowledgment

The project “Urban climate in Central European cities and global climate change” (http://www.klimat.geo.uj.edu.pl/urbanclimate/index.html) is being realized within the framework of the International Visegrad Fund’s Standard Grant No. 21410222 in the years 2014-2015.

References

Bechtel B., Daneke C., 2012: Classification of local Climate Zones based on multiple Earth Observation Data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing,* **5(4)**, 1191-1202

Bechtel B., Alexander P.J., Böhner J., Ching J., Conrad O., Feddema J., Mills G., See L., Stewart I., 2015: Mapping local climate zones for a worldwide database of the form and function of cities. *ISPRS International Journal of Geo-Information* **4(1)**, 199–219

Früh B., Becker P., Deutschländer T., Hessel J.-D., Koßmann M. , Mieskes I., Namyslo J., Roos M., Sievers U., Steigerwald T., Turau H., Wienert U., 2011: Estimation of climate change impacts on the urban heat load using an urban climate model and regional climate projections, *Journal Applied Meteorology and Climatology*, **50(1)**, 167-184

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Oke T.R., 1987: Boundary layer climates. Methuen, London.

Siebert J., Sievers U., Zdunkowski W., 1992: A one-dimensional simulation of the interaction between land surface processes and the atmosphere, *Boundary-Layer Meteorology,* **59**, 1-34

Sievers U., 1990: Dreidimensionale Simulationen in Stadtgebieten. Umweltmeteorologie,Schriftenreihe Band 15: Sitzung des Hauptausschusses II am 7. und 8. Juni in Lahnstein. Kommission Reinhaltung der Luft im VDI und DIN, Düsseldorf. p. 92-105 (in German)

Sievers U., 1995: Verallgemeinerung der Stromfunktionsmethode auf drei Dimensionen, *Meteorol. Zeitschrift*, **N. F. 4**, 3-15 (in German)

Sievers U., 2012: Das kleinskalige Strömungsmodell MUKLIMO_3 Teil 1: Theoretische Grundlagen, PC-Basisversion und Validierung. *Berichte des Deutschen Wetterdienstes,* **240**, Offenbach am Main, Germany (in German)

Sievers, U., 2014: Das kleinskalige Strömungsmodell MUKLIMO_3 Teil 2: Thermodynamische Erweiterungen. *Berichte des Deutschen Wetterdienstes Entwurf*, Offenbach am Main, Germany (in German)

Sievers U., Forkel R., Zdunkowski W., 1983: Transport equations for heat and moisture in the soil and their application to boundary layer problems, *Beitr. Phys. Atmosph*., **56**, 58-83

Sievers U., Zdunkowski W., 1986: A microscale urban climate model, *Beitr. Phys. Atmosph.*, **59**, 13-40

Stewart I.D., Oke T.R., 2012: Local Climate Zones for Urban Temperature Studies. *Bull. Amer. Meteor. Soc*., **93**, 1879–1900

Zuvela-Aloise M., Koch R., Neureiter A., Böhm R., Buchholz S., 2014: Reconstructing urban climate of Vienna based on historical maps dating to the early instrumental period. *Urban Climate*, **10**, 490–508