Mapping of micro-meteorological conditions using statistical approaches – The example of Stuttgart

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1. Introduction

The majority of the world's population lives in cities. Health, well-being and productivity of people in urban areas depends also on meteorological conditions (Curriero, 2002; Nastos and Matzarakis, 2012), which differ significantly from those at rural areas. Up to 70,000 people died in Western Europe during the very hot summer in 2003 (Robine et al., 2008). It was estimated that heat stress and heat waves would occur more frequent, intense and longer lasting due to anthropogenic climate change in the 21st century (Beniston, 2004; Meehl and Tebaldi, 2004; Schär et al., 2004). Thus, the aim of city planners and officials is the implementation of adaptation measures in cities to counteract the increase in frequency of heat stress in the 21st century. To do so, city planners and officials need to know about the spatial and temporal dimensions of the meteorological conditions and their impact on humans in a city. As human beings do not have a sensor for air temperature, the thermal feeling depends on the integral effect of air temperature, air humidity, wind speed and radiation fluxes. Hence, modern human-biometeorological methods were applied for the quantification of thermal conditions in urban areas (Höppe, 1993).

Mapping of the urban biometeorological conditions is important to identify areas with high thermal load. The micro-meteorological conditions in these areas could be improved by city planners using adaptation measures as vegetation and trees. The requirements of these thermal maps are a high resolution and extension over the whole city or urban quarters.

The aim of the study was to quantify the current meteorological conditions in Stuttgart using hourly data of five meteorological stations for the period 2000 – 2010. In order to provide meaningful results, a frequency analysis was made to answer questions as "How often does heat stress occur? How often is the intensity of the urban heat island (UHI) higher than 4 K?" To mark areas with high thermal load, a high-resolution map of the UHI, air temperature and Physiologically Equivalent Temperature were created using artificial neural nets. Furthermore, the frequency of heat stress was analyzed using data of regional climate models (e.g. REMO and ENSEMBLE Rt2b) for the 21st century. In a final step, possibilities for the reduction of negative factors in order to counteract negative environmental factors as heat stress were quantified for idealized and exiting locations.

2. Data and methods

2.1 Data

Hourly data of four urban and one rural measurement stations were used to quantify the meteorological characteristics in Stuttgart over 10 years (Table 1).

Tab. 1 Coordinates and altitude of the meteorological stations.

Measuring station	Longitude	Latitude	Altitude
Neckartal	48:47	9:13	224
Schwabenzentrum	48:46	9:10	250
Schnarrenberg	48:50	9:12	314
Hohenheim	48:42	9:02	405
Echterdingen (rural)	48:41	9:14	371

Car traverses were conducted in Stuttgart on 3rd – 4th July 2014. The duration was about 60 to 90 minutes depending on traffic, with a constant speed of 30 kmh^{-1}. The route, in form of an eight started and ended at the main station which was also reached after 30 minutes. The position of the car was logged by a GPS with an accuracy of ±1.5 m. An Omega Humidity Temperature Meter HH314A was fixed at the car at 1.8 m above ground and measured every 10 sec air temperature and air humidity. The measurements were detrended according to the measurements at the beginning, the middle and at the end of the car traverse at the main station using linear regression.

Spatial dataset about land use and land cover, buildings, vegetation and topography was provided as shapefiles or raster data by the land surveying office of Stuttgart.

The regional climate model REMO (Jacob, 2001) providing hourly data with a spatial resolution of 10 km and the ensemble model ENSEMBLE Rt2b with a spatial resolution of 22° (see http://ensembles-eu.meto_ce.com) were used to quantify the impact of climate change on the background conditions of Stuttgart.

2.2 Methods

Human beings experience meteorological conditions by the combined impact of air temperature, air humidity wind speed and radiation fluxes. Furthermore, activity, clothing and other physical parameters such as age, weight and gender are of importance in order to quantify the thermal conditions of human beings (Höppe, 1993). The Physiologically Equivalent Temperature (Höppe, 1999; Matzarakis et al., 1999; Mayer and Höppe, 1987) is one of those thermal indices that is based on the human energy balance in terms of the Munich Energy Balance for Individuals (Höppe, 1984). The assessment scale of Matzarakis and Mayer (1997) was applied. The radiation fluxes for complex three-dimensional urban areas are expressed as mean radiant temperature and calculated using SkyHelios.

The input parameters for the calculation of PET for the measurement locations during the car traverse are the measured air temperature and air humidity, whereas the mean radiant temperature and wind speed was calculated and simulated by different models. The mean radiant temperature was calculated for the same points using SkyHelios considering the 3-dimensional urban morphology and vegetation. Wind speed was simulated by the combination of a meso-scale model in 200 m resolution and a micro-scale model DULAN (Röckle 2014). The influence of the complex topography together with the 3-dimensional urban surface could only be considered by the combination of the meso-scale model for topography and the micro-scale model for trees and buildings.

Based on the original spatial data more meaningful datasets were calculated and generated: I) slope and aspect, II) Local Climate Zones (Stewart and Oke, 2012), III) building volume and density, IV) Sky View Factor (SVF), and V) roughness (Bottema, 1997; Bottema and Mestayer, 1998).

Different statistical approaches as artificial neural network (ANN) and stepwise multiple linear regression were applied and compared for mapping thermal conditions in Stuttgart at day- and nighttime. The artificial neural network has the advantage of being a non-linear approach. The input dataset was split into three different datasets for training (60 %), testing (20 %) and validating (20%) the ANN. Various ANN model configurations with different configurations were compared with respect to the mean square error. The created maps of air temperature and PET have a resolution of 10 m.

Micro-scale models ENVI-met 3.5 (Bruse and Fleer, 1998) and RayMan Pro (Matzarakis et al., 2007, 2010) were applied to analyze the human-biometeorological conditions and their changes due to redesign within an urban quarter as well as for the quantification of adaptation measures. The micro-scale model ENVI-met 3.5 (Bruse and Fleer, 1998) calculates micro-scale surface-air-plant interactions inside complex urban structures in a three-dimensional nonhydrostatic way. Its high spatial and temporal resolution provides a good basis for quantification of changes due to redesign. The current state of the Olga Hospital and several future scenarios were simulated. These are a planned housing area, different park scenarios, a forest, and a sealed multi-use place. Measurements on 22nd June 2003, a summer day with high pressure, were taken as input parameters.

The micro-scale model RayMan is developed to calculate the thermal comfort of human beings in complex urban areas (Matzarakis et al., 2007, 2010). RayMan estimates long- and shortwave radiation flux densities from the three dimensional urban surroundings for the calculation of the mean radiant temperature and thermal indices as PET. Data of the nearby background station Stuttgart-Schwabenzentrum was used for the initialization of ENVI-met and as input data in RayMan.

2.3 Study area

European metropolitan region Stuttgart (48°47’ N, 9°10’ E) has 5.2 million inhabitants and is the fourth largest metropolitan region of Germany. Stuttgart is located in the southwestern part of Germany in complex topography. The city is spread over various hills and valleys between 207 m and 511 m asl. The annual mean air temperature is 10.6 °C from 1961-1990 and the urban-rural air temperature differences (UHI) between city center and the airport are in average 2 °C but ranges to 12 °C. The annual precipitation is 664 mm in the city center, 50 mm less than at the airport. The sunshine duration is in the city center about 50 h lower than at the airport (1740 h).

3. Results and discussion

3.1 Intra-urban temperature differences and the urban heat island

The city dwellers in Stuttgart experience heat stress (PET > 35 °C) during 7-10 % and cold stress (PET < 8°C) during 62 - 72% in the period 2000 – 2010 (Fig. 1). Heat stress occurred at about 250 h but only at daytime during an average summer 2000 – 2010. However, in summer 2003 the frequency of heat stress increased to 23 % in the city center. Thereby, thermal uncomfortable conditions occur also at nighttime.

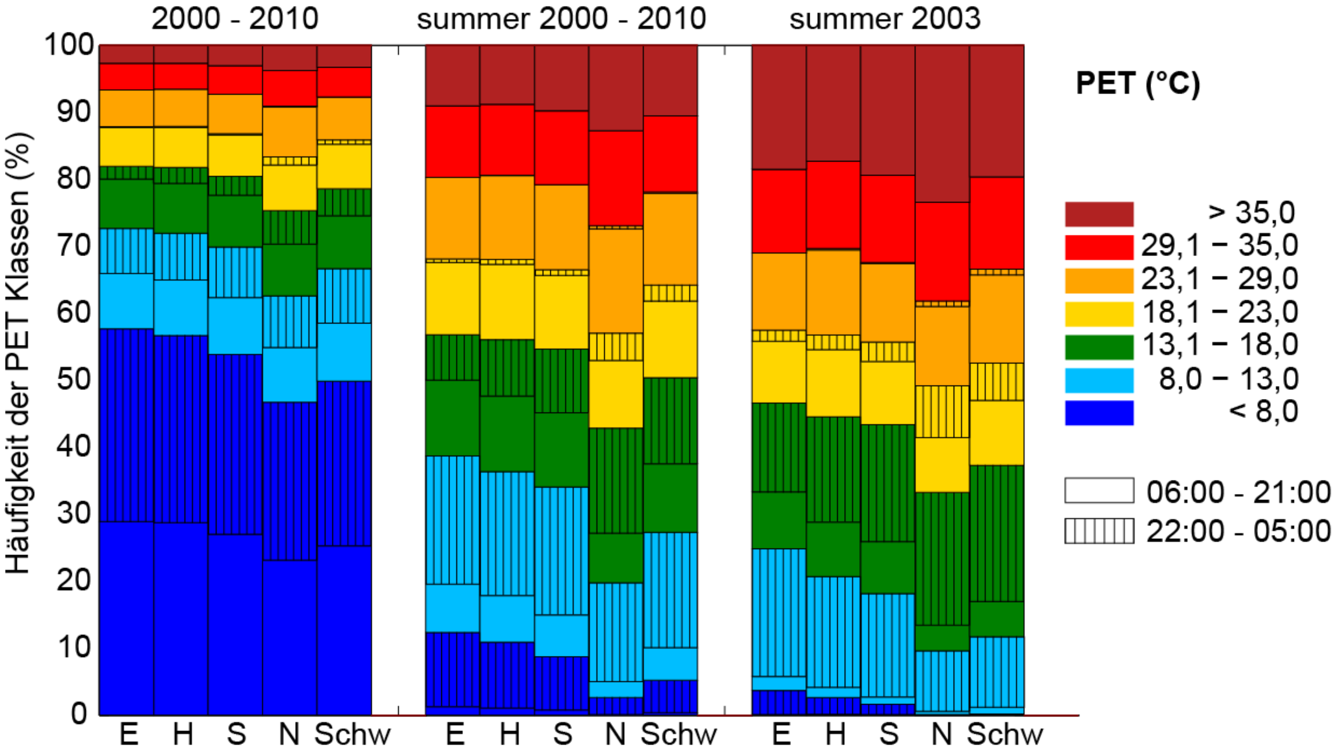

Fig. 1 Frequency diagram of hourly averages of air temperature Ta following different measuring stations in Stuttgart for the period 2000 – 2011 (left): Echterdingen (E), Hohenheim (H), Neckar valley (N), Schnarrenberg (S), and Schwabenzentrum (Schw).The frequency of PET is depicted for an average summer (2000 – 2010) over the 11 years and in 2003 (right).

The urban heat island (UHI), analyzed using PET, is during 46 % in summer and 64 % in winter between 0 – 2.0 K. The UHI intensity is higher than 4 K during 4 % in winter and 15 % during summer. Thus, city dweller experience additional heat load especially in the evening compared to people living in rural areas. However, the location of the measuring stations has a big influence on thermal conditions in Stuttgart. For this reason an analysis of the urban heat island by the comparison of one rural and one urban station is not meaningful for a city located in complex topography, even if the sites are described. Furthermore, mapping of the thermal conditions is important in order to identify areas with high thermal load.

In the course of climate change, the ENSEMBLE model predicts an increase in the number of heat waves from 0.8 ± 1.2 to 2.4 ± 2.4 heat waves per year until the end of the 21st century. The average duration should increase from 3.8 ± 1.8 days to 5.1 ±3.2 days.

3.2 Mapping the thermal conditions

The spatial distribution of air temperature and urban heat island shows a maximum in the city center and along the low-lying areas of the Neckar river at 14:00 CET (Fig. 2). The decrease in PET as well as in air temperature goes along with an increase in altitude, green areas and number of trees as well as a decrease in built-up ratio and sealed areas.

Artificial Neural Network allows a good estimation of the spatial distribution of PET due to its nonlinearity with an R-squared of 0.94 and a root mean square error of 1.8 K. Although the maps should be analyzed carefully in quantitative manner, they provide an indication of the thermal conditions in a city. According to the definition of urban climate by Lowry (1977) the generated statistical model or ANN is only valid for the defined time and city under the same atmospheric conditions as during the measurements.

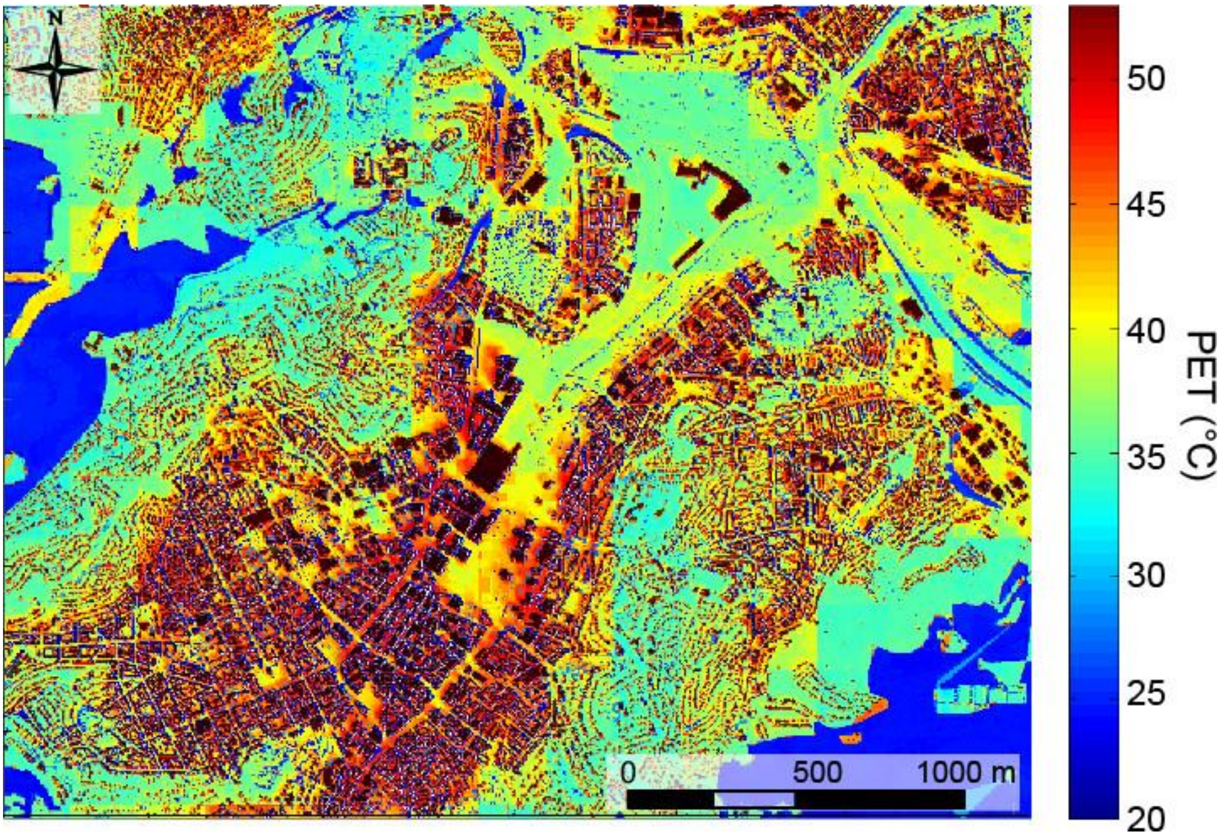

Fig. 2 Map of PET for Stuttgart based on the data of the measuring campaign on 3rd July 2014, 14 CET.

3.4 Adaptation measures

The impact of different planning scenarios and adaptation measures (e.g. trees, green areas) on micro-climatic conditions was analyzed and quantified for the area of the Olga-hospital in Stuttgart-West. This area should be rebuilt during the next years and a residential area should be constructed. The average PET is estimated to increase by 2 K in this area with the erection of the residential buildings. Especially the paved courtyards are estimated to create very hot PET up to 62 K on hot summer days. Trees can improve the thermal conditions especially in their shadow by 24 K compared to paved areas. However, the establishment of a park or the increase of the number of trees can be seen as a local improvement of the micro-meteorological conditions, but the impact on the whole examined area is limited. During summer it is important to reduce energy input by shading in order to reduce thermal conditions to a comfortable level at nighttime.

ENVI-met was used to quantify the change in micro-meteorological conditions on a small for one day, whereas RayMan can be used to quantify alterations generated at one single point over several decades. This is important to quantify the effect of adaptation measures on thermal conditions as well as sunshine duration throughout the year. Cold stress is predominant in Central Europe and sunlight is most welcome during about three quarters of the year. Shading by deciduous trees are therefore a good adaptation measure, whereas street canyons with an H/W ratio of 3.5 and a west-east orientation decrease on the one hand heat stress, but these streets limit sunshine significantly during winter.

4. Conclusion

Analysis of the thermal conditions for urban planners and architects requires thermal indices. While mean and maximum values of the urban heat island are not meaningful, frequency analyses has to be executed based on long-term datasets. Following, the identification of thermal load in a city is a basic need for city planners in order to counteract high thermal load in cities. This should be done in form of high- resolution maps for urban quarters or even a city. Artificial neural networks are an appropriate method to generate high-resolution maps of the micro-meteorological conditions. Essential requirements are high-resolution basic spatial and meteorological datasets that cover different combinations of land use types and morphological types. Case studies was linked to the context of long-term conditions in terms of frequency analyses. The quantification of adaptation measures related to climate in cities requires the use of thermal indices and the impact on micro-meteorological conditions throughout the year. Using trees and establishing green areas could significantly reduce heat stress at daytime in order to create thermal comfortable conditions at night-time, too.

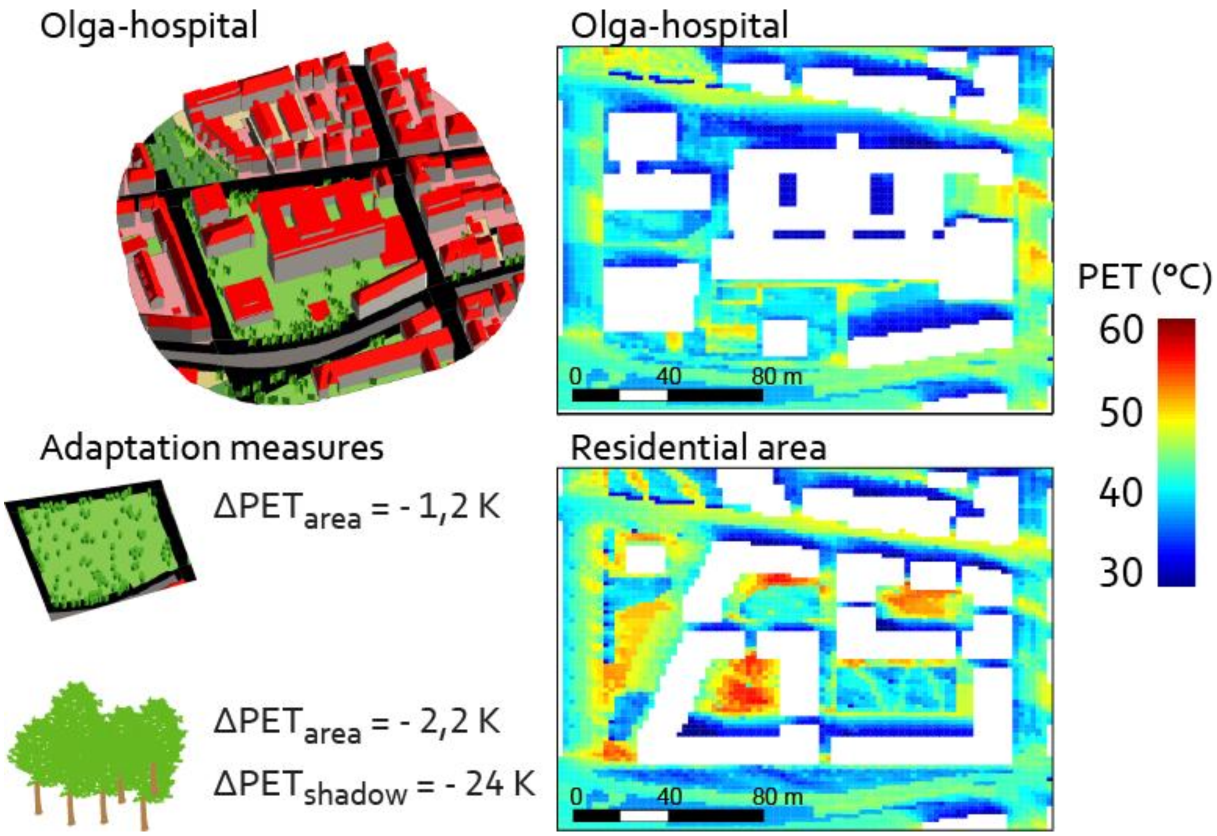

Fig. 3 Simulations of PET using micro-scale models ENVI-met 3.5 and RayMan Pro for a hot summer day averaged from 10:00 – 17:00. A residential area is planned to be build.

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