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Research paper

Mapping the Physiologically Equivalent Temperature in urban areas using artificial neural network

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HIGHLIGHTS

- Spatial distribution of PET in a city of complex topography.
- Transfer from discrete measuring to continuous data.
- Application of artificial neural network for mapping.
- Mapping of day- and nighttime heat stress.
- Mapping of the urban heat island.

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ABSTRACT

The gap between point measurements made during a measurement campaign and the required discrete data of human thermal comfort in the form of maps could be overcome by statistical or numerical models. City planners usually demand thermal maps with a resolution below 50 m. The required input data for the statistical models were meteorological data at high resolution as well as land use and land cover data including morphological data. Meteorological data were obtained through car traverses on a measuring campaign on hot summer days in July 2014. The chosen statistical approaches of stepwise multiple linear regression and artificial neural network were compared for the case study area Stuttgart, Germany. The Physiologically Equivalent Temperature (PET) was applied to analyse the human thermal conditions taking into account both the meteorological environment and the thermo-physiological parameters including the human energy balance. The polycentric and complex spatial distribution of heat stress and heat load is clearly visible in the created maps. One hot spot is the city centre and its surrounding residential neighbourhood, the other hot spot can be detected in Bad Cannstatt (easterly of the Neckar river valley), including industrial and residential areas. Thereby, the non-linear artificial neural network model delivers better results than the stepwise multiple linear regression model. Advantages of the artificial neural network arise from the possibility to reveal non-linear dependencies and interactions between the variables resulting in a better model fit.

1. Introduction

More than 50% of the world population are currently living in cities and it is projected that this percentage will increase to 70% in 2050 (United Nations, 2014). An increase in urban population and its associated horizontal extension of urban areas modifies urban micro-climate. This is well illustrated by the occurrence of an urban heat island (UHI) effect (Oke, 1980).

City planners, architects and authorities aim to design healthier, sustainable and more comfortable cities (Schwela, 2000). So, they need well processed, easily understandable information about urban climate and micro-meteorological conditions (Eliasson, 2000; Fanger, 1970). Thus, climatic knowledge has to be transferred into the language of planners, architects and authorities by easily understandable graphs or maps of meteorological conditions (Matzarakis et al., 2008). Maps dealing with urban climate can be divided into four groups: (1) analytical maps showing geographical distribution of various elements of climate, (2) synthetic maps showing the division of areas investigated into particular topoclimates, (3) applied maps showing the usefulness of existing

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topoclimatic conditions for practical purposes, and (4) prognostic maps showing expected modifications of local climate (Paszynski, 1991).

Datasets about urban morphology, land use and land cover (LULC) or surface properties are used to calculate the sky-view-factor (SVF) or roughness (Gál & Unger, 2009; Matzarakis & Matuschek, 2011). Analytical maps of meteorological parameters such as air temperature could be produced by data collected through car traverses (Hamm, 1969; Saaroni, Ben-Dor, Bitan, & Potchter, 2000), using statistical approaches or numerical modelling. Besides several statistical approaches were applied to analyse the spatial extent of the urban heat island in Wroclaw, Poland, including different kinds of multivariate interpolation (inverse distance weighting, regularized spline with tension), linear regressions and kriging methods (Szymanowski & Kryza, 2009, 2012).

Interestingly, Szymanowski & Kryza (2009, 2012) found that the inverse distance weighting method had the poorest model fit while the geographically weighted regression in combination with residual kriging offered the best performance of the presented models. However, the widely used statistical approach for mapping single variables is a multiple linear regression (MLR) (Szymanowski & Kryza, 2009; Unger, 2006; Unger, Sümeghy, Szegedi, Kiss, & Géczi, 2010). Hart and Sailor (2009) used a tree structured regression model. Whereas Svensson, Thorsson and Lindqvist (2003) classified the Physiologically Equivalent Temperature (PET) according to LULC zones in Göteborg. In general, the predictors used are often LULC classifications, vegetation, SVF, building density and roughness. However, the resolution of these mentioned maps varies between 100 and 1000 m. Numerical models used for the mapping of micro-climate conditions in urban areas are for example MUKLIMO_3 (Sievers, 2012), ENVI-met (Bruse & Fleer, 1998; Huttner, 2012), UBIKLIM (Friedrich, Grätz, & Jendritzky, 2001). Depending on the model and its solution, the model area and model time might be very limited.

On the other hand, synthetic maps consider all relevant climatological issues, such as surface temperature, cold air production areas and flow, wind field, portion of green area, built-up areas, soil sealing and roughness (Bründl, 1988; Kuttler, 1997; Scherer, Fehrenbach, Beha, & Parlow, 1999). Basic datasets are digital terrain and elevation model and LULC types. Moriyama and Takebayashi (1999) made a *Klimatope* (VDI, 1997) map for Kobe using heat balance modelling, considering also anthropogenic heat production, aerodynamic roughness and normalized vegetation index.

Guidelines for planners are depicted in applied maps, which can be based on homogeneous climate-response units representing the feature that influence climate (Alcoforado, Andrade, Lopes, & Vasconcelos, 2009; Lazar & Podesser, 1999).

The aim of this paper is therefore to develop a thermal map at micro-scale for Stuttgart, Germany, using SMLR and artificial neural network (ANN). These methods were both applied and compared. Thermal conditions were quantified in terms of PET (Höppe, 1999; Matzarakis, Mayer, & Iziomon, 1999; Mayer & Höppe, 1987) to describe the integral effect of the thermal atmosphere on humans. The resulting maps present information about thermal perception of city dwellers during a hot summer day. With the help of these maps, areas of intense heat load can be detected. They are of importance for developing and implementing adaptation measures facing climate change particularly in urban areas.

2. Study area and methods

2.1. Study area

Stuttgart is the fourth largest metropolitan area in Germany, with a population of about 5.2 millions in 2013. It is the most important city for industry, education, culture and policy in the south-western part of Germany (Fig. 1). The city itself had a population growth rate of 4.7% from 2010 to 2014 (Regional Bureau of Statistics, retrieved September 4, 2015 http://www.statistik.baden-wuerttemberg.de/Veroeffentl/Monatshefte/PDF/Beitrag15_08_11.pdfhttp://www.statistik.baden-wuerttemberg.de/Veroeffentl/Monatshefte/PDF/Beitrag15_08_11.pdf).

The mean air temperature was 9.5 °C and the average precipitation was 660 mm in Stuttgart-Schnarrenberg from 1961 to 1990. The relatively low precipitation arises from the city's location in the lee of the Black Forest. Stuttgart's city centre lies in a sink like basin, while the urban quarters are spread across hills and valleys. Air temperature is about 2 °C warmer in the city centre than in the surroundings (Ketterer & Matzarakis, 2014a) due to the urban heat island effect as well as topography (Fig. 1b). Thermal inversions are frequent during winter. Stuttgart's city dwellers suffer from a nocturnal urban heat island (UHI), frequent heat stress in daytime during late spring and summer. Relatively strong air pollution episodes are aggravated by weather conditions associated with a low wind speed, mostly less than 3 ms^{-1}. The wind speed in the city centre and the Neckar valley is particularly very low (Ketterer & Matzarakis, 2014a). On the other hand, cold stress prevails in Stuttgart at about 64–75% of the year, while the increased thermal level is an advantage.

2.2. Methods

2.2.1. Physiologically Equivalent Temperature

The Physiologically Equivalent Temperature (PET) was applied to evaluate humans' perception on the thermal environment (Höppe, 1999; Matzarakis et al., 1999; Mayer & Höppe, 1987). PET by itself takes into account of the thermo-physiology of the human body (sex, height, activity, clothing resistance for heat transfer, shortwave albedo and long wave emissivity of the surface) and the integral effect of the meteorological parameters namely air temperature, air humidity, wind velocity and radiation fluxes. The thermal impact of these radiation fluxes from lower and upper hemisphere on the human energy balance is parameterized as mean radiant temperature T_{mrt} (Höppe, 1999, 1993). The assessment scale used in this study to classify cold stress (PET < 13 °C), thermal comfort (13 ≤ PET ≤ 29) and heat stress (PET > 35 °C) is described in Matzarakis et al. (1999).

2.2.2. Measuring campaign

A measuring campaign was conducted on July 3 and 4, 2014. The average air temperature was about 22.0 °C and 24.2 °C while the maximum air temperature measured in the city centre was about 30 °C and 32 °C. The wind speed was as low as 1.5 ms^{-1} and 1.7 ms^{-1}. Atmospheric conditions were representative for typical summer conditions in Stuttgart. Similar conditions occurred at about 41.2% during summer (JJA) for the years 2000–2010 (Ketterer & Matzarakis, 2014a,b). The car traverses started from the main train station eastwards to Stuttgart-East then north through the Neckar valley, back to the main station. The second half of the car traverses started at the main station through Stuttgart-North up to Stuttgart-West and back to the main station again (see Fig. 1a–c). Thus, the driven route draws a figure of eight. Air temperature and relative humidity were measured at every 10 s during the campaign by the device Humidity–Temperature-Meter HH314A which was mounted in a radiation-shield. The measuring instrument was mounted 30 cm above a white car with a horizontal offset of 30 cm and the set-up was approximately to a height of 2 m from the ground. The uncertainties of the Humidity–Temperature-Meter HH314A are ±0.7 K and ±2.5% relative humidity. The measurements started at 14:00CET (Central European Time) and at 21:30CET with a duration of 1 h 20 min and