Assessment of human-biometeorological conditions in urban areas embedded in complex topographies – The example of Stuttgart

Ketterer C., Matzarakis A.

The region of Stuttgart, located in the south-western part of Germany, favors warm and humid climate accompanied by a low wind speed. Stuttgart lies in a basin-like sink and is surrounded by hills, a fact, which enforces the specific formation of these thermal and air quality conditions. The Urban Heat Island (UHI) of Stuttgart and its spatial distribution were assessed using thermal indices Physiologically Equivalent Temperature (PET) for different time of the year and for day and night situations.Urban-rural PET differences are highest in daytime, while air temperature UHI is highest during night-time. The UHI is mostly enhanced due to topography, besides during periods with inversions. The highest hourly UHI appears during summer as it is strongly radiation driven.

Ketterer C, Matzarakis A.*

Chair of Meteorology and Climatology, Albert-Ludwigs-University Freiburg, Germany

***corresponding author e-mail:** **andreas.matzarakis@meteo.uni-freiburg.de**

1 Introduction

Spatial and temporal differences of meteorological parameters between neighboring urban and rural areas develop due to changes of aerodynamic surface structure and radiation fluxes (Landsberg 1981, Oke 1982). Thereby, the urban heat island (UHI) expressed by air and surface temperature differences are the most prominent and world-wide studied characteristics (Alcoforado and Andrade 2006, Bejaran and Camilloni 2003, Katsoulis and Theoharatos 1985, Ren et al. 2013, Runnalls and Oke 2000). The urban heat island in Stuttgart, Germany is analyzed within the project "Mitigation and Adaptation of the Urban Heat Island" (www.eu-uhi.eu).

Human-biometeorological methods are used to analyze UHI in matters of city dwellers and in support of city planners. Thereby, the thermal perception of humans is considered as the integral effect of air temperature, wind speed, air humidity and radiation fluxes and expressed by thermal indices (Höppe 1993).

The aim of this study is the human-biometeorological quantification of the urban heat island as well as the analysis of its spatial distribution.

2 Data and Methodology

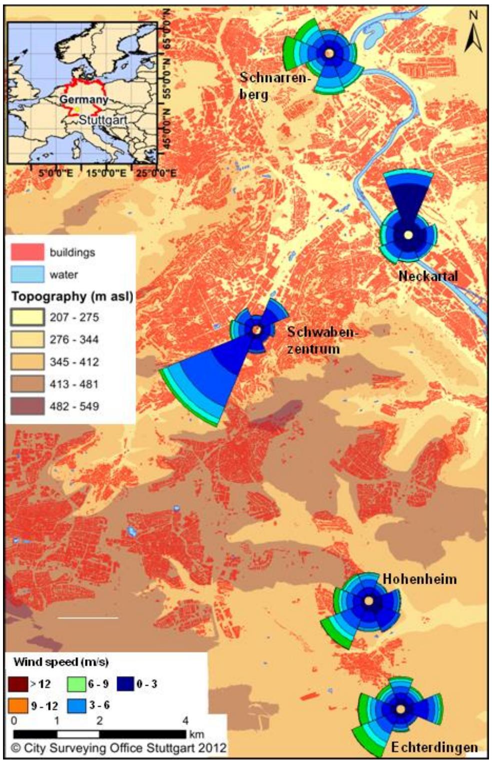

Fig. 1. Map of Stuttgart with wind roses of every measurement station Echterdingen (rural), Hohenheim (suburban), Schwabenzentrum (city centre), Neckartal and Schnarrenberg (both urban). The wind roses depict the frequency of a wind direction and according wind speed (see *color code*).

Stuttgart (Fig. 1) is located in complex topography in the south western part of Germany, which is also one of the warmest areas of Germany. While the city center is located in a sink-like basin, urban quarters are spread across several hills. Stuttgart is the capital city of Baden-Württemberg constituting its industrial, educational, cultural and political center. Subsequently, Stuttgart experiences population growth in recent years, after some decades of weak depopulation tendencies. The average temperature was 11.8 °C in the city center and 9.8 °C at the airport in Stuttgart-Echterdingen. The average annual precipitation was 732 mm in the surroundings while in the city center it is about 60 mm less. Stuttgart's city dwellers suffer from strong daytime heat load, high UHI intensity, and also from strong air pollution caused by frequent weather conditions with low wind speed and air temperature inversions (Ketterer and Matzarakis 2014).

Table 1. Location, altitude and features of the considered measuring stations in Stuttgart.

Measurement station	Latitude	Longitude	Altitude	Feature
Schwabenzentrum	48:46	09:10	250 m asl	City center; on the top of a 25 m high building
Schnarrenberg	48:50	09:12	314 m asl	Vineyard, SW-exposed
Neckar valley	48:47	09:13	224 m asl	River valley, urban
Hohenheim	48:42	09:02	405 m asl	Suburb
Echterdingen	48:41	09:14	371 m asl	Airport

Four measurement stations in Stuttgart are used in this study: Schwabenzentrum (city center, 250 m asl), Schnarrenberg (vineyard, 314 m asl), Neckar valley (224 m asl) and Hohenheim (suburb, 405 m asl). The rural reference station is located at the airport in Echterdingen at 371 m asl (Table 1).

The Physiologically Equivalent Temperature (PET) (Mayer and Höppe 1987, Höppe 1999, Matzarakis et al. 1999) follows the concept of an equivalent temperature and is based on the Munich Energy Balance Model for Individuals (Höppe 1993). The assessment scale of PET is described in Matzarakis and Mayer (1996) who describe the thermal comfort zone between 18- 23 °C and the wider comfort zone between 13 -29 °C.

3 Results

Low wind speed is characteristic for Stuttgart region due to its sheltered position. Wind speed is lower than 3 ms^{-1} in the Neckar valley by 80 % of the time period 2000-2010 (Fig. 1). In the city center, the wind speed rarely (2 %) exceeds 6 ms^{-1}. Wind direction is determined by the alignment of the underlying topography and the morphology of the city. Hence, thermal-induced local wind systems, like the nocturnal "Nesenbachtäler" wind system usually occurring at a frequency of 63 % in Stuttgart-West, are often dominant. Wind measurements in Echterdingen and Hohenheim are rather representative for the greater region of Stuttgart. The most frequent wind direction is the south and south-west, followed by south-east and north. But even in Echterdingen, wind speed is lower than 3 ms^{-1}by almost 75 % of the time.

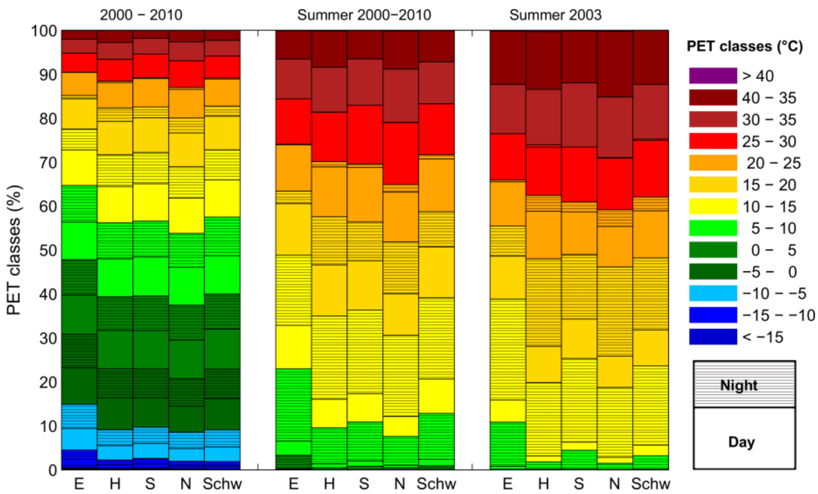

Fig. 2. Frequency of different air temperature classes at the measuring stations Echterdingen (E), Hohenheim (H), Neckar (N), Schnarrenberg (S) und Schwabenzentrum (Schw) for the period years 2000-2010 (left), during summer, 2000 to 2010 (middle) and during summer of 2003 (right).

The urban climate conditions are analyzed using air temperature (not shown) and PET (Fig. 2) throughout the years 2000-2010 in terms of frequencies. Additionally, the summer of 2003, characterized by two strong heat waves, is compared to the average conditions in the period 2000-2010 (Figure 2). During summer 2003, air temperature was over 60 % higher than 20 °C in Neckartal and at Schwabenzentrum while in a normal summer, this is only 40 %. The air temperature is highest at Schwabenzentrum, followed by Neckartal, Schnarrenberg, Hohenheim and Echterdingen. However, PET is higher at Neckartal, followed by Schnarrenberg, Schwabenzentrum, Hohenheim and finally Echterdingen. PET higher than 25 °C indicates heat stress according to Matzarakis and Mayer (1996). Heat stress occurs by 34 % during a normal summer, but by 41 % in summer of 2003. This means additional 110 hours of heat stress from June to August in summer 2003 compared to an ordinary summer. On the other hand, PET smaller than 0 °C occurs by an average 10 % less in urban areas compared to Echterdingen.

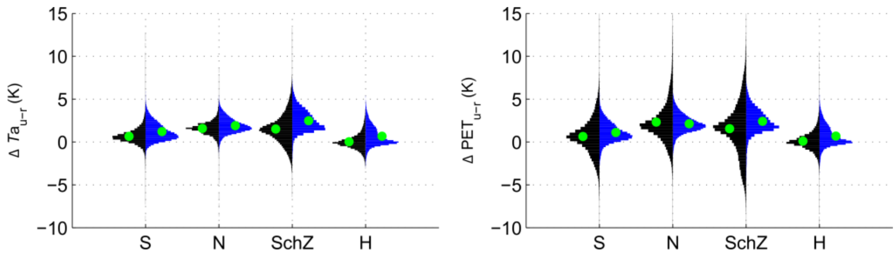

Fig. 3. Frequency distribution in form of boxplots of the urban-rural air temperature (*left*) and PET (*right*) differences between the four urban measuring stations (see *legend*) and rural station Echterdingen at day- (*black*) and night-time (*blue*) 2000 to 2010.

At night-time, the average air temperature differences are largest at Schwabenzentrum (2.5 K), followed by Neckartal (2.1 K), Schnarrenberg (1.2 K) and Hohenheim (0.7 K). At Neckartal, the nocturnal air temperature differences are only slightly higher than at daytime. Neckartal is the lowest measuring site and features very low wind speed. During daytime, lower air temperature and PET are observed frequently in Neckartal and Schwabenzentrum compared to their neighboring rural surroundings. This is due to air temperature inversions and frequent urban cooling island occurring in summer between 9 to 11 AM. The air temperature and PET differences between Hohenheim and Echterdingen have a small standard deviation and they are larger at night-time than at daytime. In Hohenheim, UHI_{PET} is negative almost by 50 % of the time due its higher elevation compared to Echterdingen. The urban-rural PET differences are highest in daytime, while UHI_{Ta} is highest during night-time. During night-time, UHI_{PET} is comparable to UHI_{Ta}.

4 Conclusions

The urban heat island and its spatial and temporal characteristics were studied in Stuttgart using human-biometeorological methods. The frequent occurrence of local, thermally induced wind like the "Nesenbachtäler" in Stuttgart is due to the prevailing low wind speed. The average urban heat island expressed in air temperature is about 2 K between city center and the rural reference station in Echterdingen and only 0.3 K between the suburbs on the hills.

The maximum urban heat island is up to 12 K. The UHIPET is in average 3.3 K and maximum 20 K. The spatial distribution of the UHI is governed by topography, land use and structure of urban morphology. The heat stress occurs more frequent at Neckartal as a daytime phenomenon, but the nocturnal urban heat island is higher and more frequent at Schwabenzentrum. At Schwabenzentrum, the UHI is between 0 - 5 K by 97 % of the time. Anyway, the assessment of the UHI frequencies is preferable and more meaningful as the urban-rural temperature differences are not normal distributed. Furthermore, the heat stress occurs in the daytime, for which reason the nocturnal UHI is less harmful to city dwellers in Stuttgart.

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