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Investigating public places and impacts of heat stress in the city of Aachen, Germany

Isabell Maras[1,2], Mareike Buttstädt[2], Julia Hahmann[3], Heather Hofmeister[4], Christoph Schneider[2]

[1] *Human Technology Centre, RWTH Aachen University, Theaterplatz 14, 52062 Aachen, Germany, maras@humtec.rwth-aachen.de*

[2] *Geographisches Institut, RWTH Aachen University, Wüllnerstr. 5b, 52056 Aachen, Germany, mareike.buttstaedt@geo.rwth-aachen.de; christoph.schneider@geo.rwth-aachen.de*

[3] *Institut für Gerontologie, Arbeitsgebiet Empirische Alternsforschung und Forschungsmethoden, Universität Vechta, Driverstr. 22, 49377 Vechta, Germany, julia.hahmann@uni-vechta.de*

[4] *Institut für Soziologie, Professur für Soziologie mit Schwerpunkt Arbeitssoziologie, Goethe-Universität Frankfurt, Grüneburgplatz 1, 60323 Frankfurt am Main, Germany, h.hofmeister@soz.uni-frankfurt.de*

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Abstract

Understanding the role of structure and social aspects regarding heat stress of people in urban areas requires an interdisciplinary scientific approach that connects methods from both natural sciences and social sciences. In this study, we combine three approaches to provide an interdisciplinary analysis of the structure and social components of heat stress in the city of Aachen, Germany. First, we assess the overall spatial structure of the urban heat island using spatially distributed measurements from mobile air temperature recordings on public transport units combined with spatially distributed geo-statistical data. The results indicate that the time of day matters: During the afternoon, areas with a relative low building density, like the industrial area northeast of the inner city, are the warmest, while surfaces in high-building-density areas like the inner city heat up faster during the evening. Second, we combine these measurements with place-based survey data collected in 2010 from residents aged 50 to 92 regarding their individual housing conditions, medical history and social integration to examine the match among heat-based stress of older residents, social conditions and elevated temperatures in their residential quarter. We identify disadvantaged areas for specific already-disadvantaged demographic groups in the city, pointing to a cumulation of inequalities, including heat stress among the most vulnerable. Third, we compare data of biometeorological measurements on urban public squares during the afternoon with results of the micrometeorological model ENVI-met to examine the spatial variability of the inner-city heat load. We complement the modelling results with on-site interviews to evaluate people's heat perception at the same public places. A simulation shows that additional vegetation would increase thermal comfort at these public places, whereby the heat load assessed using the predicted mean vote (PMV) value would decrease by approximately 60 %. Furthermore, we demonstrate the strengths and weaknesses of heat stress simulation. ENVI-met allows for an overall reasonable representation of heat load during stable atmospheric conditions. However, due to the setup and structure of ENVI-met, large-scale atmospheric changes that occur during the day cannot readily be integrated into ENVI-met simulations.

Zusammenfassung

Der hier präsentierten Studie liegt die Annahme zugrunde, dass Hitzestress des Menschen in urbanen Räumen eine interdisziplinäre Herangehensweise erfordert, die sowohl naturwissenschaftliche als auch sozialwissen-

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schaftliche Methoden miteinander verbindet. Wir kombinieren drei Untersuchungsansätze als interdisziplinäre Analyse, die die Struktur und Wahrnehmung sommerlicher Wärmebelastung in der Stadt Aachen aufzeigen. Mittels mobiler Messungen der Lufttemperatur, unter Verwendung öffentlicher Linienbusse, bei gleichzeitiger Erfassung geostatistischer Daten, wird zuerst die großräumige Struktur der städtischen Wärmeinsel bewertet. Während der Nachmittagsstunden stellen sich Gebiete mit einer relativ geringen Gebäudedichte, wie das Industriegebiet nordöstlich der Innenstadt, als die wärmsten Areale heraus. In den Abendstunden verlagern sich diese in Gebiete des Innenstadtbereiches mit hoher Gebäudedichte. Wir verknüpfen diese Werte mit raumbezogenen Daten aus einer Befragung von 50- bis 92-jährigen Einwohnern/-innen der Stadt Aachen aus dem Jahr 2010. Anhand der Befragungsergebnisse lassen sich in Verbindung mit der Analyse der Temperaturentwicklung kumulativ benachteiligte Räume und soziale Gruppen innerhalb des Stadtgebiets ausmachen, die aufgrund sozialer Faktoren wie ungleicher Temperaturbelastung in Hitzephasen besonders hohem Stress ausgesetzt sind. Ergänzend erfolgt ein Vergleich biometeorologisch erhobener Daten von öffentlichen innerstädtischen Plätzen mit Ergebnissen von Simulationen mit dem mikrometeorologischen Modell ENVI-met, um die räumliche Variabilität von Wärmebelastung zu betrachten. Weiterhin wird die Wahrnehmung von Wärmebelastung einzelner Passanten durch Befragungen auf denselben öffentlichen Plätzen untersucht. Eine Simulation mit zusätzlicher Begrünung zeigt, dass der thermische Komfort deutlich steigt und die Werte des *predicted mean vote (PMV)* um etwa 60 % gesenkt werden. Es lassen sich zudem die Stärken und Schwächen bei der Simulation von Wärmebelastung mit ENVI-met aufzeigen. Bei stabilen atmosphärischen Bedingungen kann eine realistische Reproduktion der Wärmebelastungsintensität erzielt werden, während großräumige atmosphärische Veränderungen im Tagesverlauf, aufgrund des Konzepts und der Struktur von ENVI-met, nicht integriert werden können.

Keywords Urban Heat Island, Heat stress, Atmospheric modeling, Social isolation

1. Introduction

Rising temperatures caused by globally increased levels of green-house gases may disproportionately impact urban areas, according to the United Nations Intergovernmental Panel on Climate Change (IPCC) Assessment Report 2007. Reasons for the extra intensity in cities are surface sealing, anthropogenic heat release, and dense building structures, all of which compound to the urban heat island effect. These higher temperatures can result in negative health consequences that are associated with the body's ability to regulate the temperature balance in extreme situations, e.g. heat cramps or heat strokes (*McGeehin* and *Mirabelli* 2001). Health risks result in morbidity and even mortality for urban residents during heat waves. The risks are moderated by sociodemographic conditions such as social embeddedness and exacerbated by other forms of social inequality such as poor health or poverty. Therefore, investigations on urban heat island (UHI) effects as well as people's perception of heat load need combined and interdisciplinary approaches for a holistic perspective.

1.1 Urban heat island effects

The intensity and extent of the UHI especially depend on the sky view factor and the albedo (reflection coefficient) due to the building design and construction materials in agglomerations (*Aida* and *Gotoh* 1982, *Chen* et al. 2012, *Ryu* and *Baik* 2012). Additional parameters which influence the UHI are the city population (*Oke* 1973), the proportion of surface sealing, and the presence and amount of green spaces and water bodies (*Taha* 1997, *Kuttler* 1998). As a consequence, urban areas do not heat up homogeneously; rather, UHIs differ in their temporal and spatial characteristics. They may show one or more cores and varying intensity due to different land use and terrain (*Helbig* et al. 1999). These thermal hot spots are usually identified by mobile measurements or satellite imagery (*Mirzaei* and *Haghighat* 2010).

Individuals in cities are affected by the UHI effect to varying degrees based on their living and working conditions. Because the distribution of living and working space is systematically biased by socioeconomic and socio-demographic positions, people in different socio-demographic groups are likely to experience different levels of heat stress from the UHI based partly on their social position. Microclimatological conditions need to be linked to social structures to better understand the impact of uncommonly high temperatures on residents with different social and living situations.

1.2 Linkage between social factors and heat stress

Hot summer spells and the exposure to high temperatures are a threat to human health and well-being and result in a higher risk of mortality for vulnerable population groups such as persons with cardiovascular diseases, older people and children (*Harlan* et al. 2006). Diverse social factors influence the social, financial and cognitive resources that moderate individuals' capacities to develop adequate coping strategies in times of (heat) stress. The 'social vulnerability' of some people takes on a spatial component due to place-based inequalities (*Aubrecht* and *Özceylan* 2013, *Cutter* et al. 2003). Research from the 1995 Chicago heat wave and the European heat wave in 2003 identified living conditions, social inequalities and social embeddedness as additional factors that increase or decrease mortality risk in heat waves. *Klinenberg* (2002) concentrated on social integration aspects and found that a lack of social embeddedness – such as living alone, being isolated and being reclusive – explains death rates during heat waves. The analysis of *Semenza* et al. (1996) showed that living alone doubled the risk of death during the hot summer spell in 1995 in Chicago. These findings have been replicated in diverse cultural contexts in industrialised countries (*Bouchama* 2004, *Vaneckova* et al. 2010, *Wolf* et al. 2010). Strong personal community networks moderate the effects of stressful events (*Cohen* and *McKay* 1984) such as heat waves because they provide a sense of belongingness and concrete social support in diverse ways (*Hahmann* 2013). In contrast, social isolation puts individuals at additional risk during high temperature events. The analytical combination of environmental burdens and socio-structural variables that reflect social hierarchy allows the detection of environmental or spatial inequality which "include[s] any form of environmental hazard that burdens a particular social group" (*Pellow* 2000: 582).

1.3 Biometeorological Approach

Although the most pronounced temperature anomalies between urban and rural sites occur during evenings with clear sky conditions (*Arnfield* 2003), and therefore imply a higher danger for city residents in the evening in comparison to rural residents, heat load during the day also impinges on human health. Heat fatigue, heat exhaustion or even heat stroke might occur due to a failure in a person's thermoregulatory regulation system (*Koppe* et al. 2004).

Air temperature and surface temperature are the most direct variables for quantifying heat stress. However, these do not provide the full range of information regarding heat stress; biometeorological analyses and personal data need to complement the evaluation. In comparative studies using Hongkong, Freiburg and Kassel, researchers examined the difference between actual inner-city urban temperatures using biometeorological mobile measurements and the perception of heat by individuals in the same inner-city urban squares using on-site interviews (*Katzschner* 2006, *Katzschner* 2010). Both data sets permit an estimation of individual heat perception and allow for a comparison with modelled data. Comparing the predicted mean vote (PMV) with measurement and results from simulations using the three-dimensional micrometeorological hydrostatic model ENVI-met (*Bruse* 2007, *Huttner* et al. 2009) allows researchers to evaluate whether the model can sufficiently reproduce the temporal and spatial evolution of heat load on open squares. Furthermore, such a method can identify differences between the individual perception of heat and the actual situation both in the model and according to the measurements. We use this method here.

2. Study site description

The interdisciplinary projects 'City 2020+' (http://www.humtec.rwth-aachen.de/index.php?article_id=11& clang=1) and 'U-Turn' (http://www.humtec.rwth-aachen.de/index.php?article_id=881&clang=1) at RWTH Aachen University use the city of Aachen, Germany as a case study to work on questions regarding the effects of climatic and demographic change. Aachen is situated at the border to Belgium and the Netherlands in North Rhine-Westphalia and is a medium-sized German city (160 km^2) with an approximate population of 250.000 residents. It is situated in a basin with differences in altitude of up to 120 m, causing significant local climate differences during situations with low wind speed. In the national context, the annual mean air temperature of 10.5°C in Aachen is comparatively high mainly due to relatively moderate winter air temperatures (*Havlik* 2002). *Buttstädt* et al. (2009) observed a temperature increase of 1.2 K in Aachen between the decades 1980-1989 and 2000-2009. According to this temperature trend, summer days, hot days and extreme hot days are increasing for Aachen. The number of tropical nights (overnight temperatures that do not drop below 25°C) have remained rather constant, with a slight trend towards a rising frequency.

3. Methods and data

3.1 Temperature data and structure of the UHI

We collected temperature data for Aachen by mounting temperature and GPS loggers on local public transport buses along four routes for 44 days in 2010 and 2011, selecting days with a diurnal temperature amplitude of at least 7 K. We measured the air temperature from about 4:00 until midnight every 5 seconds, ascribed to 256 predefined points in the city (*Buttstädt* et al. 2011). We analysed these data in association with a land-use classification according to *Merbitz* et al. (2012). The 10-category classification comprises three land-use classes differentiated by the degree of surface sealing, five unsealed land-use classes, and two building classes (residential and industrial) for the whole city area (*Fig. 1*). We performed a multiple regression analysis with observed air temperature data and described land-use classes for radii of 50, 100, 250, 500 and 1000 m. Given that the area of investigation is characterised by altitude differences of up to about 120 m, the altitude needed to be taken into account. As the vertical temperature gradient is expected to differ strongly in the course of the day, we included altitude as a parameter based on the ASTER Digital Elevation Model (NASA 2004). The results of the multiple regression analysis with the highest explained variance (R^2) and statistical significance were integrated into a GIS model. The model allowed us to calculate the temperature distribution for the whole city area in order to determine the formation of an UHI and its intensity and extent for two different times of day.

3.2 Social factors

The sociological data reported here originate from a postal questionnaire from 2010 that was sent to 8500 inhabitants of Aachen, all aged 50 and older. We received 2180 completed questionnaires (response rate: 26 %). We used the results to describe the social situation of the older inhabitants of the city of Aachen by giving insights on living conditions, social context, health and financial status, and basic socio-demographic variables.

To measure the social embeddedness of Aachen's population, we divided our analyses in two parts: First, we described the situation of older inhabitants in inner-city, outer-city and suburban areas to discover aspects of social vulnerability that might be a sign of a general spatial inequality in Aachen. Second, we concentrated on the combination of heat stress and social isolation. We measured social isolation in three ways. First, we measured the size of the household (*Harlan* et al. 2006). Second, we asked for the number of close friends and family members. A small number of social ties can result in a lack of companionship and a feeling

Fig. 1 Land-use classes and locations of mobile measurements (small white circles) for the enlarged inner-city district of Aachen; the two squares used for micro-scale assessment of heat load are indicated as white-red circles with numbering: (1) Main train station (hereafter 'Main Station') and (2) Elisenbrunnen square; number 3 indicates the location of the permanent weather station of RWTH Aachen University.

of loneliness. Respondents having ≤ 5 close contacts – either family or friends – are identified as being socially isolated concerning their close social relationships. The absence of social support is our third measure of risk of social isolation. Respondents were asked to identify possible support givers by type of relationship for 12 common situations that reflect different dimensions of support; social companionship (e.g., a person to spend time with), instrumental support (e.g., a person who gives a ride to the doctor), and emotional support (e.g., a person to discuss personal matters with). Response categories included the option that nobody is available for support in these situations. Respondents who could not identify at least one more support person for each of the 12 situations are identified as being at risk of social isolation. The three variables together create an additive index with a range from 0 to 3, where 0 corresponds to the lowest and 3 to the highest risk of social isolation. Due to the severity of the consequences of social isolation for coping strategies, we classified individuals with a value of 2 or higher to be vulnerable to social isolation. The allocation of social factors allows a deeper understanding of the heterogeneity of risk scenarios in the urban area of Aachen.

3.3 Biometeorological assessment

Biometeorological assessment is based on meteorological measurements and on-site interviews in the city of Aachen. Results are compared with values of PMV modelled with ENVI-met, which is used to simulate the interaction between surface, vegetation and atmosphere in the urban environment (*Huttner* et al. 2008). We used measurements of air temperature, wind, humidity and solar radiation to determine the thermal comfort which can be expressed by the predicted mean vote (PMV), an integral index indicating the thermal sensation of a larger group of people on a scale from -4 (cool) to +4 (hot) (*Jendritzky* 1993). The PMV value of 0 indicates thermal comfort and no heat load for the human body: the case where the heat released by the human body is in equilibrium with its heat production (*Turowski* 2002). Consequently, PMV combines the heat balance equation of the human body with meteorological parameters.

Four places in Aachen were selected due to their relevance as public open spaces. However, in this study we focused on two places (see *Fig. 1*). We investigated the central square in front of the Main (train) Station as a sealed place on the edge of the city centre, strongly frequented by people of all ages for short-term stopovers. The second location is 'Elisenbrunnen', a partly green urban area in the centre of Aachen. Between 13:00 and 17:00, 20 persons of all ages were interviewed at the Main Station on June 28th 2011 and 17 persons at Elisenbrunnen on August 4th 2011 concerning their individual reason for their visit, their heat perception and personal data

Photo 1 Mobile weather station with multisensor WXT520 (Vaisala), CNR1 radiometer (Kipp and Zonen) and data logger (Campbell Scientific)

such as age, personal habits and health status. We did not require any professional knowledge about atmospheric processes and physical details because we were interested in the opinions and perceptions of lay people who were incidentally present in these locations. Micro-climatic measurements with a mobile weather station were carried out on the same dates and same times, June 28th and August 4th 2011, from 13:00 to 17:00. These days showed different atmospheric conditions which are strongly reflected in the results. While on June 28th, the air temperature exceeded +30°C without any clouds, on August 4th the maximal air temperature did not exceed +27°C also due to a rising degree of cloudiness over the course of the day. The mobile weather station consists of two main parts which are both installed at a biometeorological standard distance to the ground of 1.1 metres (see *Photo 1*).

The multisensor Vaisala weather transmitter WXT520 was used to measure the relevant parameters air temperature (T), relative humidity (RH) and wind speed (U). An Kipp & Zonen CNR 1 radiometer was used to measure radiation fluxes in a three-dimensional way according to *Höppe* (1992) and comparative studies (*Ali-Toudert* and *Mayer* 2007, *Thorsson* et al. 2007). All values were collected by a CR1000 measurement and control datalogger by Campbell Scientific with a one-minute recording interval.

To reduce measurement errors and increase flexibility as well as stability, the CNR1 was installed on a telescope bar. Thus, we ensured that the CNR1 can easily be turned from vertical to horizontal alignment every 20 minutes. According to *Höppe* (1992) the three-dimensional radiation fluxes serve as input for the determination of the mean radiant temperature T_{mrt}

$$T_{mrt} = \sqrt[4]{\frac{S_{str}}{a_l \cdot \sigma}} - 273.15$$

where S_{str} (Wm^{-2}) are the mean radiant flux densities of the human body, a_l is the absorption coefficient for longwave radiation and σ is the Stefan-Boltzmann constant ($5.67*10^{-8}$ W $(m^2K^4)^{-1}$). The calculated T_{mrt} and measured data further allowed for the estimation of PMV values by the model RayMan (*Matzarakis* and *Rutz* 2005). However, as there is no availability of three CNR1, it is not possible to determine T_{mrt} and PMV values for every minute. Therefore, the 20-minute values of radiation flux for every dimension are used to generate mean hourly values.

By using the three dimensional micrometeorological hydrostatic model ENVI-met, an immediate comparison between measured data, e.g. PMV values, results of the on-site interviews and model results was possible and allowed us to identify potential heat stress in urban public squares by combining social and physical approaches. ENVI-met can be used for micro-climate modelling in urban areas (*Bruse* and *Fleer* 1998). It combines air flow, thermodynamics, radiation balance and the physiological response of vegetation (*Bruse* 2001). The model enables a complete simulation of urban micro-climate and the influence of vegetation in diurnal course (*Huttner* et al. 2008). Furthermore, ENVI-met allows us to produce an assessment of the temporal and spatial distribution of heat stress on the investigated public places, while biometeorological measurements were carried out at a single spot within the squares only. Therefore, the open public squares Elisenbrunnen and Aachen's Main Station are constructed with the ENVI-met Editor to simulate the weather conditions for both June 28th and August 4th 2011.

4. Results

4.1 Spatial structure of the urban heat island

The UHI is well reproduced by the GIS based model, showing positive air temperature anomalies of up to approximately 1.5 K compared to the permanent weather station of RWTH Aachen University (WS Aachen-Hörn), which we use as reference station in this study (*Fig. 2*). The temperature distribution for the afternoon situation showed the highest temperature differential in the industrial area northeast of the inner city due to the high degree of surface sealing. Differentiated air temperature patterns arose during the evening. Building densities gained influence and contributed significantly to an UHI in the city centre. By contrast, grassland and forest showed an increased cooling with air temperature differences to the inner city of about -1.5 K compared to WS Aachen-Hörn. For the afternoon situation, surface sealing (> 90 %) in a 250 m radius of the measurement points, green spaces and forest in a 500 m radius and altitude resulted in an explained variance R^2 of 0.82 in spatial air temperature variability. For the evening, less data were available because the driving cycle of the employed buses ended in some cases before 20:00. As the measurements in the evening did not include the south of Aachen, large areas covered by green spaces are not well represented. Even though most influenc-

Tab. 1 Descriptive statistics of the survey data by degree of urbanisation of living area, including subjective evaluation of health status reported as being poor or very poor, subjective evaluation of financial status reported as being poor or very poor, N=2181. Source: City 2020+ Survey of Residents aged 50+ in Aachen, Germany, 2011

Measures		Inner-city	Outer-city	Suburban
N (and as % of total sample)		489 (22.5)	913 (41.9)	776 (36.6)
Gender (%)	Women	55.8	54.1	56.5
	Men	44.2	45.9	43.5
Mean age (in years)		67.0	66.7	66.3
Relationship status (%)	Married	55.4	69.6	71.2
	Single	14.2	6.7	5.5
	Widowed	12.1	11.7	11.6
	Divorced or separated	18.2	12.0	11.8
% reporting poor health status		12.8	6.2	6.3
% reporting poor financial status		14.8	8.6	5.5
% living alone		36.7	21.1	18.9
% with nobody to give support		21.9	14.9	12.8
% with 5 or fewer close friends and/or family members		15.8	5.9	10.2
% at risk for social isolation		20.7	9.0	8.9

ing factors are thus limited to buildings and forest in a 500 m radius and altitude, the temperature distribution within the inner city is reflected well, with spatial variance being well explained (R^2 = 0.81).

4.2 Spatial social inequality and heat stress

In order to obtain a measure for signs of spatial social inequality, we divided the city of Aachen into three sectors, comprising living areas in the inner city, the outer city and in suburban districts. As can be seen in *Table 1*, mean age of residents does not differ among living areas and neither does gender distribution within the data from the survey. Therefore, we ruled out compositional effects (e.g., a higher density of, for example, widows due to a greater concentration of older women in certain areas) when considering the data on relationship status or social isolation regarding heat stress.

The relationship status of residents aged 50 and above differed by degree of urbanisation of the living area. The number of single and divorced or separated individuals was clearly higher in inner-city areas than in the rest of Aachen. By contrast, residents aged 50+ in outer districts were more likely to be married, especially in the suburban areas, even when controlled for age. In the next step, we analysed two measures of social inequality: financial and health status. The data showed an unequal distribution of respondents reporting a poor health and finances according to their residential status: Inhabitants of inner-city districts are clearly more likely to report poor health and a poor financial status than those in outer-city or suburban areas. The disparity is repeated on the level of social-contextual factors. Respondents residing in the city centre were more likely to live alone, which is directly related to the higher number of separated, divorced and single individuals in this area. Every fifth inner-city inhabitant reported at least one everyday life or emergency situation in which he or she has nobody to receive support from. Every sixth person had five or fewer close relationships to friends and/or family members. Both these measures – nobody to give support and five or fewer close contacts – were less likely to apply for inhabitants of outer-city or suburban districts. These results thus show an unequal distribution of social isolation in the three sectors:

20 % of the respondents who live in the inner city are defined as being socially isolated while less than ten percent were at risk in the other parts of Aachen. We therefore see evidence for spatially distributed social inequality on two levels: living conditions (e.g. health status and financial status) and social isolation that differ by degree of urbanisation.

Figure 2 shows a combination of temperature differences and the percentage of respondents within an area who have a social isolation index value of 2 or more, which means that they were socially isolated in at least two of three ways: living alone, having a small number of close social ties, and having only little social support in a small-scale range of 41 city districts. We ranked the proportions of isolated individuals from 1 to 4. Category 4 indicates the highest number of socially isolated persons, 1 the lowest. Most of the socially vulnerable individuals live in inner-city districts and especially in the city centre. These districts are associated with a high building density and relative high temperatures for the period from 20:00 to 24:00, precisely when heat-related morbidity and mortality are high. Additionally, the number of residents aged 80 or older and the proportion of residents reporting cardio-vascular diseases was especially high in the city centre around the market square and the cathedral (the same area where the UHI is most intense in *Figure 2*) (*Siuda* et al. 2010). *Figure 2* shows a clear correspondence between two of three areas with the highest percentage of isolated residents (Category 4) and the greatest evening UHI.

4.3 Comparison of biometeorological measurements, modelling and on-site interviews

We investigated the heat load on urban public spaces in the city centre in more detail by measuring and modelling PMV values both in time and space. For the Main Station, PMV values at 15:00 on June 28th 2011 showed an average perception of extremely high temperatures (purple areas, see *Fig. 3*) for a large portion of the investigated area, while blue colors indicated lowest PMV values. The latter applies to shadows of buildings and very dense trees (*Fig. 3*). While the left simulation in *Figure 3* shows the present situation, the right one includes an improved vegetation structure. It can be demonstrated, that this additional vegetation would increase thermal comfort at these public places, whereby the heat load assessed using the predicted mean vote (PMV) value would decrease by approximately 60 %.

A closer examination of the comparison between modelled and measured PMV values, and in particular at the specific point of measurement in front of the Main Station, shows that these are in good agreement (see *Fig. 4*). At 15:00 on June 28th 2011 both ENVI-met and measurement results showed a PMV value of 4.3. Looking at the remaining meas-

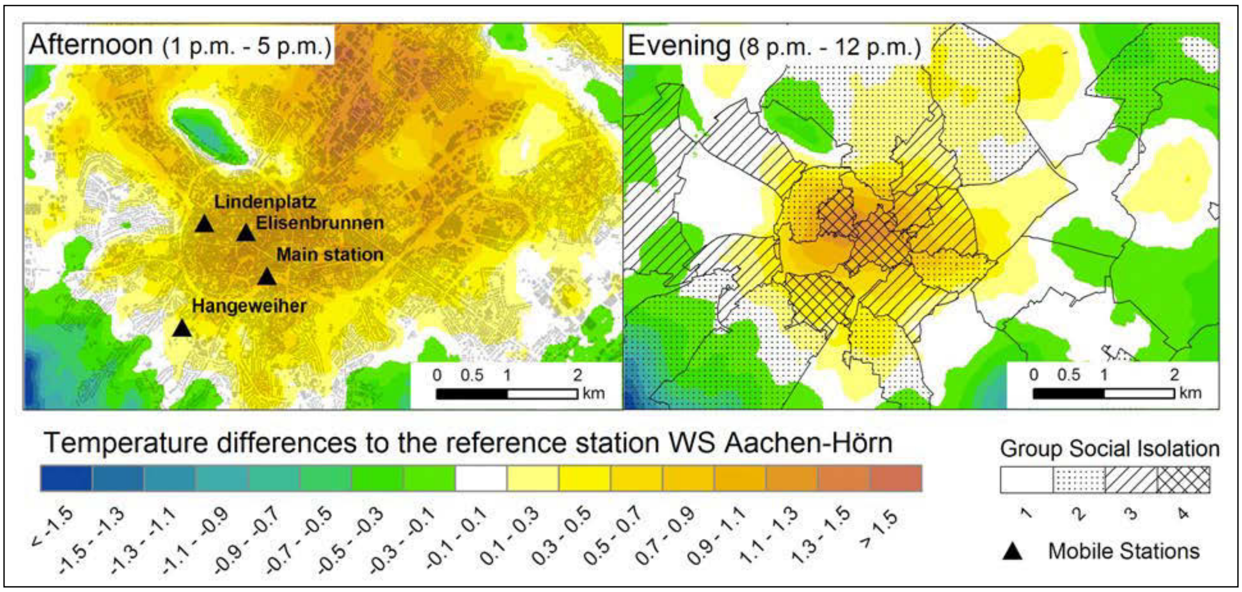

Fig. 2 Modelled temperature anomalies to the reference station Aachen-Hörn for the afternoon (left) and evening (right) situation, mapped with city areas describing the proportion of isolated persons in a particular district: 1: 0-10 % isolated; 2: 10.1-20 % isolated; 3: 20.1-30 % isolated; 4: > 30 % isolated residents

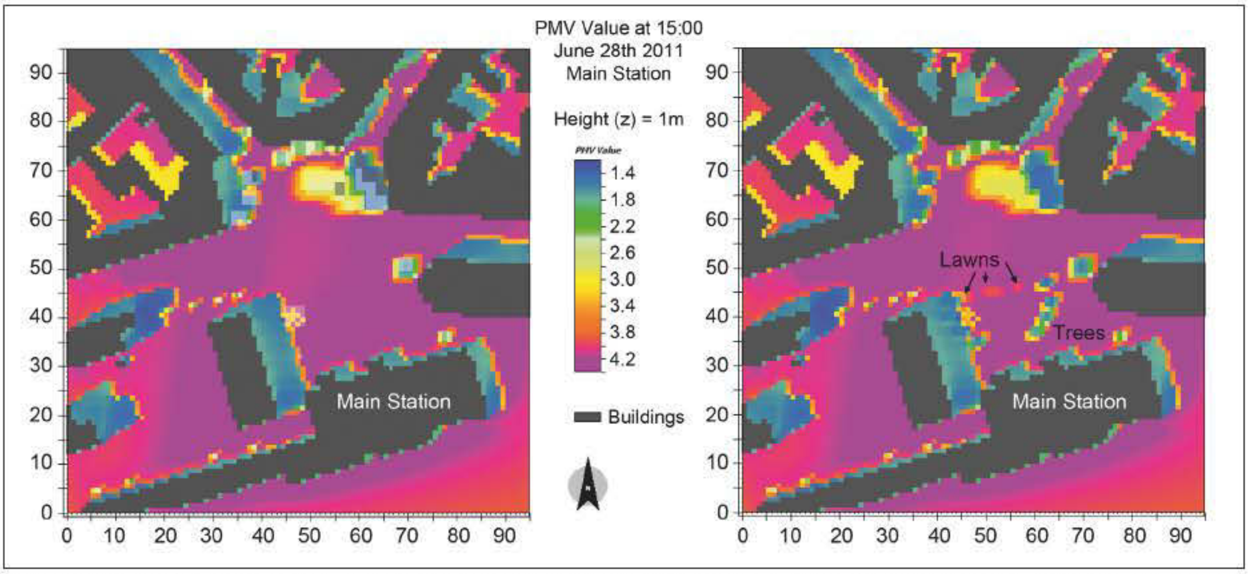

Fig. 3 Simulated PMV values using the ENVI-met model for the Main Station at 15:00 on June 28th 2011. Left: present situation, right: with improved vegetation

urement period of this day, we observed only a small difference (approx. 0.3 PMV) between modelled and measured data. In the model as well as in the measurements, PMV values indicate heat load level four. The data for Elisenbrunnen show a different situation. At 15:00, ENVI-met results revealed a modelled PMV value of 1.7 for the selected point of measurement in front of Elisenbrunnen. However, the actual measurements indicated a much higher value of 2.3. It can therefore be noted that the model for the situations documented in this study tends to underestimate the PMV values, which is more obvious in the case of the Elisenbrunnen location.

The comparison between the spatial distribution of PMV values of the Main Station on June 28th 2011 and

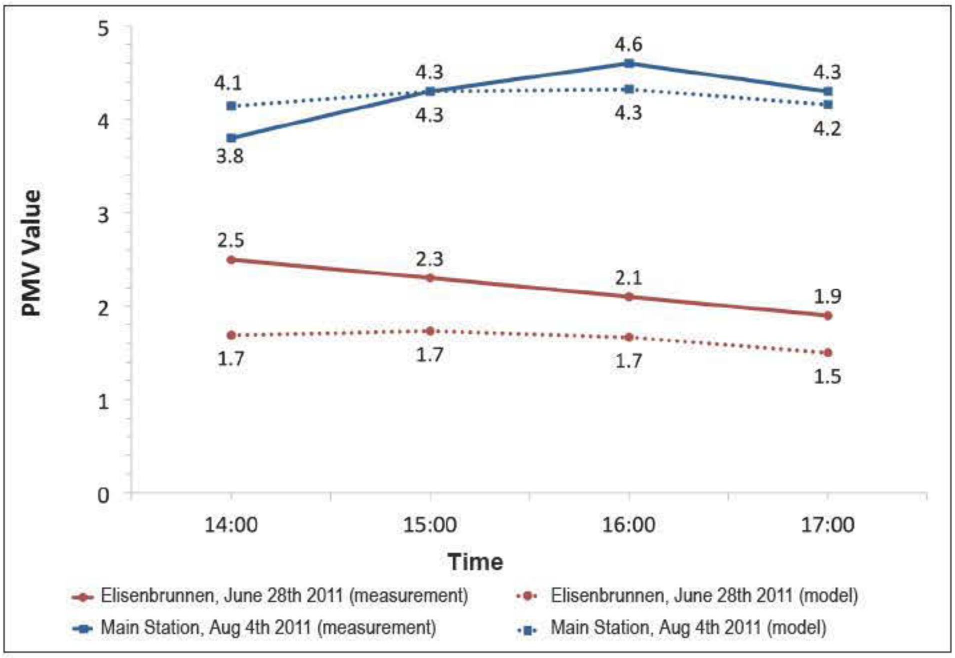

Fig. 4 Comparison between measured and modelled PMV values of the two open public squares, Main Station (June 28th 2011) and Elisenbrunnen (August 4th 2011) for afternoon hours

Elisenbrunnen on August 4th 2011 showed a number of differences. While the Main Station was characterised by very high heat load levels excluding the shaded areas, the PMV values for Elisenbrunnen showed much larger spatial variability. The centre of Elisenbrunnen offered a range of PMV values between 0.6 and 1.0. In contrast, the surrounding streets indicated higher PMV values between 1.5 and 2.2 (*Fig. 5*).

Conducting on-site interviews, in contrast to ENVI-met and biometeorological measurements, offered an assessment of heat load on the urban public places based on individual subjective perception. The evaluation of the on-site interviews at the Main Station did not reveal significant differences in heat perception of people based on age or gender differences. In the results for the Main Station, individual discontent was expressed by a general desire for a modified public place: 70 % of the 20 people interviewed would prefer more vegetation and/or shading, as the sealed surface in front of the Main Station promotes noticeably high air temperature values on hot days. This result is confirmed by the broader survey: Inner-city inhabitants were significantly less content with the vegetation in their residential areas compared to respondents living in suburban areas. In contrast to the high levels of discomfort with temperature, 45 % of the respondents at the Main Station felt comfortable with the local solar radiation, 20 % felt very comfortable, and 15 % were neutral, while only one in five reported feeling uncomfortable or very uncomfortable. While measurement and model results revealed high heat load levels for the Main Station, only 30 % of the 20 people interviewed reported not feeling exhausted with the general weather conditions.

Based on the results from the interviews, we simulated a redesigned vegetation alignment in front of the Main Station. Trees with leafless base, dense crown and 10 m in height are added as well as three dense lawns with a height of 50 cm (see *Fig. 3*, right side).

The results of the on-site interviews of Elisenbrunnen differed from the results of the Main Station. Only 24 % of the 17 people interviewed preferred more vegetation and 12 % opted for more shade. Accordingly, 41 % of the respondents felt comfortable with the local solar radiation and 29 % reported feeling very comfortable. Furthermore, 59 % of the respondents reported feeling 'not exhausted' by the local weather conditions while only 6 % (one respondent) reported feeling 'very exhausted'.

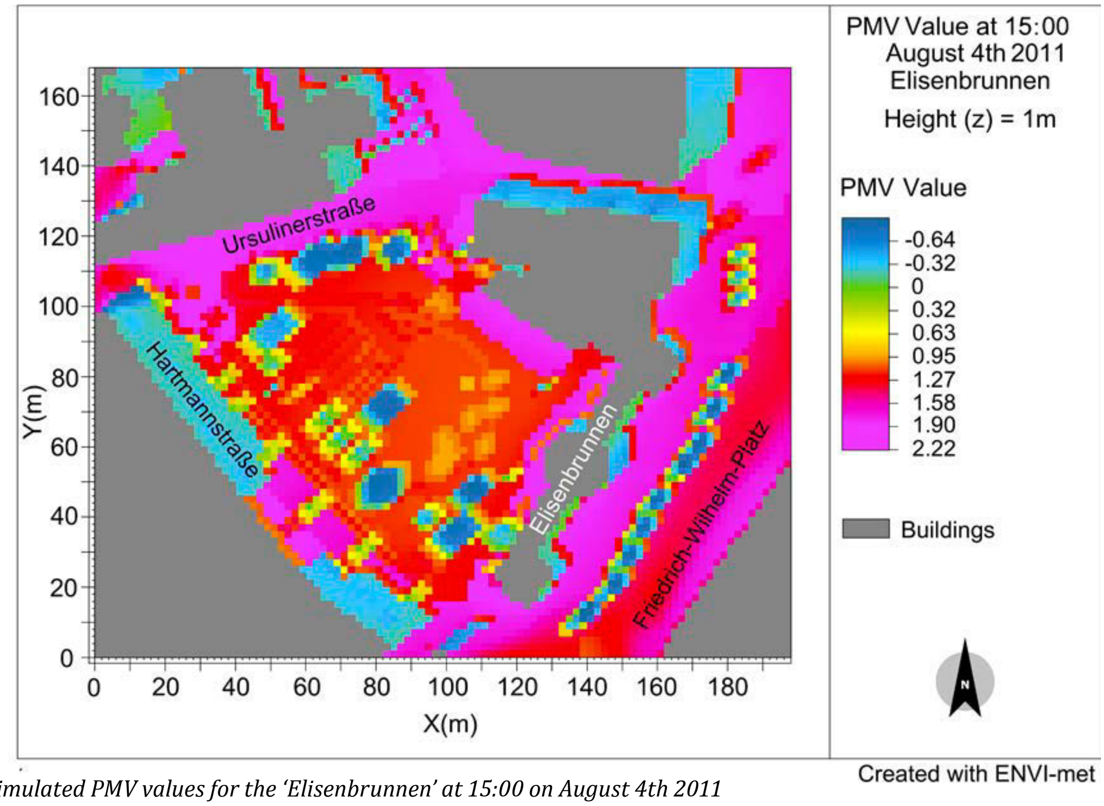

Fig. 5 Simulated PMV values for the 'Elisenbrunnen' at 15:00 on August 4th 2011

5. Discussion

5.1 Spatial distribution of the urban heat island

During the afternoon, outdoor thermal load did not prevail in the inner city, where public places are widely spread, but rather dominated in the industrial area, an area which does not include leisure facilities. Nevertheless, a lack of green spaces in the inner city and an abundance of surface materials that promote high air temperatures is likely to produce uncomfortable temperature conditions in open spaces, even though these locations do not represent the highest temperature anomalies. For the afternoon situation, the UHI was most pronounced in industrial areas, affecting the working population by heat load. Air conditioning indoors often reduces negative health consequences, but it also increases the air temperature in streets and therefore the cooling demand (*Tremeac* et al. 2012). More relevant, especially in the context of social inequality within the city, is clearly the overheating of the city centre during evening hours. While this inequality may be irrelevant during most periods of the year and does not disturb evening visitors who are voluntarily in the streets on hot summer days, it matters greatly for residents in these city centre quarters. The reason is that this part of the population will be at risk of adverse effects of heat waves without appropriate relief and possibilities for relaxation during evening hours and at night, especially for those living in poorly ventilated homes or flats without any active air-conditioning.

5.2 Analysis of spatial inequality

The results of the social factors show that individuals differ in the compared residential areas of the city of Aachen by their relationship status, regarding their subjective evaluation of health and finances, but also by different aspects of social embeddedness that result in a risk for social isolation. The combination of reported poor health and social isolation is especially dangerous in times of heat waves. Exceptionally vulnerable individuals lacked highly needed assistance for example in situations of heat-related fainting. Additionally, these individuals reported having fewer financial resources. Those with better finances have more resources to cope with stressful situations, for example paying for comfortable alternative housing (such as a hotel) during a heat wave, investing in an air-conditioning unit, having travel resources to visit cool green areas, and obtaining high quality health care. We therefore see evidence for a concentration of socially vulnerable individuals in the inner-city districts and especially in the city centre of Aachen. Since the UHI is most pronounced between the late evening and the early morning (*Oke* 1982, *Klysik* and *Fortuniak 1999*, *Montávez* et al. 2000, *Unger* et al. 2001), the exposure of urban dwellers to exceptionally high overnight temperatures hampers relief at night and results in a strengthening of thermal load situations. Small case numbers limit the small-scale comparison among the 41 districts of Aachen. Nevertheless, we see evidence for a combination of heat stress, social isolation and other factors of social vulnerability such as health and financial disadvantage for residents of the city centre around the market square and the cathedral, a combination that compounds and exacerbates the negative effects of any one of these stressors. The exceptionally high risks for residents of the most urbanised districts of Aachen on all dimensions of inequality point to the need for acute public and policy attention to this kind of urban area, including measures to alleviate the negative effects of, or reduce, UHI.

5.3 The analysis of biometeorological results

The analysis of the results of the measured and modelled data reveals different levels of discrepancy. Due to the fact that diurnal variations were only computed by using initial values to internally calculate the temporal evolution of energy fluxes, ENVI-met systematically underestimated PMV values for the Elisenbrunnen square while it more accurately reproduced heat load levels for the Main Station. The reason for this deviations is that initial conditions are the basis for proposed further development of the model output. Large-scale atmospheric changes in the course of the day cannot be integrated into this kind of atmospheric simulation. On a cloudless day with high pressure conditions without large-scale atmospheric forcing like on June 28th, 2011 (Main Station), model output from ENVI-met and measurements were in good agreement. Therefore, it is reasonable to expect that there was considerable underestimation of modelled PMV values for Elisenbrunnen during a situation with advection of warm and moist air on August 4th, 2011, with an increasing degree of cloudiness during the afternoon. There is indication that the ENVI-met model cannot reproduce absolute values especially under labile atmospheric conditions. However, ENVI-met provides the possibility to show the detailed spatial and temporal distribution of heat load, in particular for simulating different urban planning concepts.

For the example of the Main Station, this possibility is evident in *Figure 3*. This modelling effort led to decreasing PMV values in the adjacencies of the simulated trees from 4 to a range of 3.6 to 1.4. The effect from additional simulated lawns was small in comparison.

For Elisenbrunnen, lower temperatures on the day of measurement caused an overall lower level of heat load. Additionally, the structure of the square incorporating a variety of trees with different densities as well as a lawn and some hedges principally led to lower PMV values.

Some of the on-site interview results were a contrast to the results from the measurement and the model. While for the Elisenbrunnen square we found a good concordance between individual responses and technical measurements, the results for the Main Station showed significant differences. The reasons may be due to the different locations themselves. The Main Station is a sealed place with only very little vegetation. It can be characterised as a short-term stopover place for pedestrians. The Elisenbrunnen area with the Elisengarten restaurant and terraces and greens is an urban green area in the middle of the city centre. Therefore, it is frequently used for recreational activities. Nevertheless, we expected more negative responses to questions regarding the well-being of the interviewed people at the Main Station. Unexpected positive results might be attributed to weather conditions and expectations prior to the day of measurements. June 28th, 2011 was the first hot summer day since April 2011. It is likely that residents reported unexpectedly positive results because they were finally experiencing the onset of generally warm summer weather conditions. Nevertheless, and in the light of principal agreement between modelled data, measured PMV and on-site inquiry, it appears that the subjective component of heat stress – as measured in PMV – is an important measurement strategy when evaluating heat stress effects in cities (*Huttner* et al. 2009, *Katzschner* 2006, *Knez* and *Thorsson* 2008).

6. Conclusion

We present three complementary analyses that point out a consistent insight on the spatial and temporal structure and significance of UHI and heat load levels as well as vulnerable areas in the city of Aachen. We show in this interdisciplinary approach that highest temperature anomalies in the evening hours occurred in the inner-city residential districts that concurrently have an overrepresentation of vulnerable population groups. These inner-city residential districts are especially affected by thermal load in the evening. We have combined these findings with biometeorological measurements and on-site interviews on urban public squares in Aachen as well as with results of the hydrostatic model ENVI-met showing that urban greening would likely be an effective measure to provide low heat stress environments for the public in the inner-city centre.

Industrial areas show the highest temperature anomalies in the afternoon, whereas vulnerable population groups in inner-city residential districts are especially affected by thermal load in the evening. The descriptive analyses show that the spatial distribution of residents in urban and suburban areas is not determined by random chance but is strongly correlated with social inequalities in economic resources, health and social embeddedness. Specific groups are thus subject to an accumulation of disadvantages, as illustrated in our data for individuals in inner-city districts who experience a combination of poor health and poor financial status, are at a high risk for social isolation and reside in areas with a stronger UHI effect. Our findings may be a starting point for a broader debate regarding the political and social implications of climate change in urban areas and the need for environmental justice (*Szasz* and *Meuser* 1997, *Reed* and *George* 2011). Adequate insulation, ventilation, shade facilities and professional support that compensates for social isolation could reduce the burden for especially vulnerable older inhabitants of urban districts during hot summer spells. Estimates of future temperature change must be incorporated and, subsequently, possible planning measures ought to be analysed in more detail with an eye on the social inequalities in cities. Supportive policy strategies and the provision of thermally comfortable conditions are especially necessary for socially vulnerable individuals and should therefore be prioritised in areas where residents suffer from multiple social and structural disadvantages.

By investigating thermal comfort during hot days in two exemplary open public squares in the inner city, we demonstrate the importance of urban green spaces and a low sealing ratio. The important connections between UHI, thermal comfort and heat load as well as social inequality are illustrated through the interdisciplinary approach of this study. An investigation of more urban open public squares in prospective studies by using biometeorological approaches could help to specify the heat load and thermal comfort situation in the city of Aachen and other cities. Furthermore, a larger sample of on-site interviews would allow us to draw conclusions concerning differences in heat perception among people in different social groups and how these perceptions correspond to not only characteristics such as age and gender but also the duration of time spent in the place as well as seasonal expectations.

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8. References

Aida, M. and *K. Gotoh* 1982: Urban albedo as a function of the urban structure – A two-dimensional numerical simulation. – Boundary-Layer Meteorology **23** (4): 415-424

Ali-Toudert, F. and *H. Mayer* 2007: Thermal comfort in an east-west oriented street canyon in Freiburg (Germany) under hot summer conditions. – Theoretical and Applied Climatology **87** (1-4): 223-237

Arnfield, A.J. 2003: Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. – International Journal of Climatology **23** (1): 1-26

Aubrecht, C. and *D. Özceylan* 2013: Identification of heat risk patterns in the U.S. National Capital Region by integrating heat stress and related vulnerability. – Environment International **56**: 65-77

Bouchama, A. 2004: The 2003 European heat wave. – Intensive Care Medicine **30** (1): 1-3

Bruse, M. and *H. Fleer* 1998: Simulating surface-plant-air interactions inside urban environments with a three dimensional numerical model. – Environmental Modelling & Software **13** (3-4): 373-384

Bruse, M. 2001: Anwendung von mikroskaligen Simulationsmodellen in der Stadtplanung. – In: *Bernard, L.* und *T. Krüger* (Hrsg.): Simulation raumbezogener Prozesse: Methoden und Anwendungen. Beiträge zum 1. GeoSim-Workshop, 26. September 2000. – ifgi-Prints **9**. – Solingen: 1-20

Bruse, M. 2007: Simulating human thermal comfort and resulting usage patterns of urban open spaces with a multi-agent system. – In: *Wittkopf, S.* and *B.K. Tan* (eds.): Sun, wind and architecture. Proceedings of the 24th International Conference on Passive and Low Energy Architecture, PLEA 2007, 22-24 November, National University of Singapore. – Singapore: 699-706

Buttstädt, M., G. Ketzler und *C. Schneider* 2009: Ergebnisse der 30-jährigen Klimamessungen an der Klimamessstation Aachen-Hörn. – In: *Schneider, C* und *G. Ketzler* (Hrsg.): Sonderausgabe zum 30-jährigen Bestehen der Klimamessstation Aachen-Hörn des Geographischen Instituts der RWTH Aachen. – Klimamessstation Aachen-Hörn, Monatsberichte **359a**, 13/2009, Jahresbericht 2009. – Aachen: 18-25

Buttstädt, M., T. Sachsen, G. Ketzler, H. Merbitz and *C. Schneider* 2011: A new approach for highly resolved air temperature measurements in urban areas. – Atmospheric Measurement Techniques Discussion **4** (1): 1001-1019

Chen, L., E. Ng, X. An, C. Ren, M. Lee, U. Wang and *Z. He* 2012: Sky view factor analysis of street canyons and its implications for daytime intra-urban air temperature differentials in high-rise, high-density urban areas of Hong Kong: A GIS-based simulation approach. – International Journal of Climatology **32** (1): 121-136

Cohen, S. and *G. McKay* 1984: Social support, stress and the buffering hypothesis: A theoretical analysis. – In: *Baum, A., S.E. Taylor* and *J.E. Singer* (eds.): Handbook of Psychology and Health. – Hillsdale: 253-267

Cutter, S.L., B.J. Boruff and *W.L. Shirley* 2003: Social vulnerability to environmental hazards. – Social Science Quarterly **84** (2): 242-261

Hahmann, J. 2013: "She's like family to me!" Family and friends in the personal communities of older adults. – Accepted full paper for the Annual Meeting of the American Sociological Association. – New York

Harlan, S.L., A.J. Brazel, L. Prashad, W.L. Stefanov and *L. Larsen* 2006: Neighborhood microclimates and vulnerability to heat stress. – Social Science and Medicine **63** (11): 2847-2863

Havlik, D. 2002: Das Klima von Aachen. – In: *Juchelka, R.* und *A. Koch* (Hrsg.): Forschungen aus dem Geographischen Institut der RWTH Aachen. – Aachener Geographische Arbeiten **36**: 1-20

Helbig, A., J. Baumüller and *M.J. Kerschgens* 1999: Stadtklima und Luftreinhaltung. – 2. Auflage. – Heidelberg

Höppe, P. 1992: Ein neues Verfahren zur Bestimmung der mittleren Strahlungstemperatur im Freien. – Wetter und Leben **44**: 147-151

Huttner, S., M. Bruse and *P. Dostal* 2008: Using ENVI-met to simulate the impact of global warming on the microclimate in central European cities. – In: *Mayer, H.* und *A. Matzarakis* (Hrsg.): Berichte des Meteorologischen Instituts der Albert-Ludwigs-Universität Freiburg **18**: 307-312

Huttner, S., M. Bruse, P. Dostal and *A. Katzschner* 2009: Strategies for mitigating thermal heat stress in central European cities: The project Klimes. – In: The Seventh International Conference on Urban Climate ICUC-7, 29 June - 3 July 2009. – Yokohama

Jendritzky, G. 1993: The atmospheric environment. An introduction. – Experientia **49** (9): 733-740

Katzschner, L. 2006: Behaviour of people in open spaces in dependence of thermal comfort conditions. – In: PLEA 2006. The 23rd conference on Passive and Low Energy Architecture, 6-8 September 2006. – Geneva: 505-510

Katzschner, L. 2010: Outdoor thermal comfort under consideration of global climate change and urban development strategies. – In: Proceedings of the conference: Adapting to change: New thinking on comfort. Cumberland Lodge, Windsor, UK, 9-11 April 2010. – London

Klinenberg, E. 2002: Heat wave. A social autopsy of disaster in Chicago. – Chicago

Klysik, K. and *K. Fortuniak* 1999: Temporal and spatial characteristics of the urban heat island of Lodz, Poland. – Atmospheric Environment **33** (24): 3885-3895

Knez, I. and *S. Thorsson* 2008: Thermal, emotional and perceptual evaluations of a park: Cross-cultural and environmental attitude comparisons. – Building and Environment **43** (9): 1483-1490

Koppe, C., S. Kovats, G. Jendritzky and *B. Menne* 2004: Heat waves: Risks and responses. – Copenhagen

Kuttler, W. 1998: Stadtklima. – In: *Sukopp, H.* und *R. Wittig* (Hrsg.): Stadtökologie. Ein Fachbuch für Studium und Praxis. – 2. Auflage. – Stuttgart et al.: 125-167

Matzarakis, A. and *F. Rutz* 2005: Application of RayMan for tourism and climate investigations. – Annalen der Meteorologie **41** (2): 631-636

McGeehin, M.A. and *M. Mirabelli* 2001: The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States. – Environmental Health Perspectives **109** (2): 185-189

Merbitz, H., M. Buttstädt, S. Michael, W. Dott and *C. Schneider* 2012: GIS-based identification of spatial variables enhancing heat and poor air quality in urban areas. – Applied Geography **33** (4): 94-106

Mirzaei, P.A. and *F. Haghighat* 2010: Approaches to study urban heat island. Abilities and limitations. – Building and Environment **45** (10): 2192-2201

Montávez, J. P., A. Rodríguez and *L.J. Jiménez* 2000: A study of the urban heat island of Granada. – International Journal of Climatology **20** (8): 899-911

NASA (2004): ASTER global digital elevation map announcement. – Online available at: http://asterweb.jpl.nasa.gov/gdem.asp, 08/07/2011

Oke, T.R. 1973: City size and the urban heat island. – Atmospheric Environment **7** (8): 769-779

Oke, T.R. 1982: The energetic basis of the urban heat island. – Quarterly Journal of the Royal Meteorological Society **108** (455): 1-24

Pellow, D.N. 2000: Environmental inequality formation. Toward a theory of environmental injustice. – American Behavioral Scientist **43** (4): 581-601

Reed, M. G. and *C. George* 2011: Where in the world is environmental justice? – Progress in Human Geography **35** (6): 835–842

Ryu,Y.-H. and *J.-J. Baik* 2012: Quantitative analysis of factors contributing to urban heat island intensity. – Journal of Applied Meteorology and Climatology **51** (5): 842-854

Semenza, J.C., C.H. Rubin, K.H. Falter, J.D. Selanikio, W.D. Flanders, H.L. Howe and *J.L. Wilhelm* 1996: Heat-related deaths during the July 1995 heat wave in Chicago. – New England Journal of Medicine **335** (2): 84-90

Siuda, A., J. Hahmann, H. Hofmeister und *C. Pfaffenbach* 2010: Hitzegefährdete Bevölkerungsgruppen in Aachen. – In: *Schneider, C.* und *G. Ketzler* (Hrsg.): Sonderband: 30 Jahre Klimamessstation Aachen-Hörn des Geographischen Instituts. Beiträge zu Geschichte und Regionalbezug der Klimaforschung in Aachen. – Aachener Geographische Arbeiten **47**: 69-76

Szasz, A. and *M. Meuser* 1997: Environmental inequalities: Literature review and proposals for new directions in research and theory. – Current Sociology **45** (3): 99-120

Taha, H. 1997: Urban climates and heat islands: Albedo, evapotranspiration, and anthropogenic heat. – Energy and Buildings **25** (2): 99-103

Thorsson, S., F. Lindberg, I. Eliasson and *B. Holmer* 2007: Measurements of mean radiant temperature in different urban structures. – In: Sixth International Conference on Urban Climate, June 12-16 2006, Göteborg, Sweden. – Göteburg: 867-870

Tremeac, B., P. Bousquet, C. de Munck, G. Pigeon, V. Masson, C. Marchadier, M. Merchat, P. Poeuf and *F. Meunier* 2012: Influence of air conditioning management on heat island in Paris air street temperatures. – Applied Energy **95**: 102-110

Turowski, E. 2002: Das Bioklima – Die Wirkung des Bioklimas und die bioklimatischen Wirkungskomplexe. – In: *Moriske, H.-J., E. Turowski, G. Jendritzky* und *T. Salthammer* (Hrsg.): Handbuch für Bioklima und Lufthygiene **2-3** – Landsberg: 1-32

Unger, J., Z. Sümeghy, L. Mucsi, V. Pál, E. Kádár and *I. Kevei-Bárány* 2001: Urban temperature excess as a function of urban parameters in Szeged, Part 1: Seasonal patterns. – Acta climatologica et chorological **34**-35: 5-14

Vaneckova, P., P.J. Beggs and *C.R. Jacobson* 2010: Spatial analysis of heat-related mortality among the elderly between 1993 and 2004 in Sidney, Australia. – Social Science & Medicine **70** (2): 293-304

Wolf, J., W.N. Adger, I. Lorenzoni, V. Abrahamson and *R. Raine* 2010: Social capital, individual responses to heat waves and climate change adaptation: An empirical study of two UK cities. – Global Environmental Change **20** (1): 44-52