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Editorial: Urban climate and heat stress – Part 1

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A brief review of research on urban climate and heat stress

Today, more than 50 % of all humans live in cities, and the continuing trend towards urbanisation will increase the fraction of urban residents to over 69 % in 2050 (UN 2011). Thus, research on natural hazards in urban regions is of particular importance since a high number of people concentrated within comparably small areas is exposed to them, substantially increasing natural risks in cities relative to rural areas. This holds also true for heat-stress related risks in the built environment of cities.

A large number of studies have addressed the challenge of heat stress for human health in recent years (e.g. *Jendritzky* and *Koppe* 2008; *Bassil* et al. 2009; *Anderson* and *Bell* 2011; *Gabriel* and *Endlicher* 2011; *Yardley* et al. 2011; *Montero* et al. 2012; *Burkart* et al. 2013). Recent reviews on this field of research are given by *Kovats* and *Hajat* (2008) and by *Gosling* et al. (2009), among others. These studies have shown that heat stress is caused by ambient atmospheric conditions making it difficult if not impossible to humans releasing enough energy to the environment to prevent the body temperature to rise to hazardous levels. Besides air temperature, humidity, wind speed and radiation are the main atmospheric controls of energy exchange between humans and their atmospheric environment. In many human-scale biometeorological studies, these energy exchange processes were investigated in detail, while in epidemiological studies heat-stress related risks were often addressed by investigating adverse effects of elevated air temperatures on public health, particularly on mortality and morbidity (*Kovats* and *Hajat* 2008; *Aubrecht* and *Özceylan* 2013). Other studies investigated adverse effects threatening larger groups of individuals on a statistical basis using sophisticated biometeorological approaches (see e.g. VDI 2008).

Cities are, however, not only areas in which population concentrate, but themselves modify the environmental conditions. Micro- to meso-scale climate modifications by urban structures and human activities in cities lead to urban climates that show specific characteristics relative to the original non-urban climates (e.g. *Howard* 1833; *Landsberg* 1981; *Oke* 1982; *Arnfield* 2003). Since all climate elements are affected, urban climates also modify heat-stress

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hazards. The most intensively studied but yet insufficiently understood urban climate phenomenon is the so-called urban heat island (UHI) effect. Urban land use and related human activities influence radiation geometries and radiative surface properties, wind and turbulence, heat and water storage and exchange processes, additional release of heat and water from anthropogenic sources, such that the energy and water balance of urban areas is strongly different from non-urban areas under similar regional climates (e.g. *Oke* 1982; *Taha* 1997; *Arnfield* 2003; *Christen* and *Vogt* 2004; *Grimmond* 2005).

As many studies have shown, these modifications lead to near-surface air temperatures that are generally about 1 to 3 K higher in cities than in adjacent open areas, when averaged over one year. The difference in near-surface air temperature between urban and rural areas within and nearby a city is called the UHI intensity. In larger cities mean annual UHI intensity may be even higher (e.g. *Oke* 1982). The UHI intensity shows seasonal and diurnal variations. Commonly, UHI intensity is higher during the evening and throughout the night, while no UHI effect or even negative UHI intensities are observed during the morning and throughout daytime. Diurnal variations are often most pronounced during the warmer seasons, and UHI intensities may reach very high positive values during nighttime. In a recent study *Fenner* et al. (2014) show that nocturnal UHI intensity in Berlin, Germany, is, on average, about 4 to 5 K during summer days (maximum air temperature exceeds 25 °C), sometimes reaching values higher than 11 K.

Despite the multitude of UHI-related studies there is an ongoing scientific debate on the causes, which may differ from city to city and between different regional climate conditions (e.g. *Wienert* and *Kuttler* 2005) making more studies on urban climate necessary. There is also some debate on the appropriateness of urban and rural sites for deriving the UHI intensity from air-temperature measurements. The concept of local climate zones (LCZ) has been introduced by *Stewart* and *Oke* (2012) to overcome the limitations of urban and rural site selection, and to standardise meta-data protocols with respect to site descriptions.

UHI effects were also studied by using thermal remote sensing data both from air- and space-borne platforms (e.g. *Voogt* and *Oke* 2003). Thermal remote sensing provides data on surface temperatures, which also show systematic differences between built-up areas and other land-cover types. The term 'surface UHI (SUHI)' was introduced to distinguish remotely sensed surface temperature differences from air temperature differences. This is particularly important during daytime, when SUHI and UHI intensities are generally not in accordance, since thermal contrasts in surface temperatures are largest, while spatial air temperature variations and thus UHI intensity are smallest or even negative.

Summarising the results from urban climate studies, UHI phenomena cause significant negative environmental and economic impacts, e.g. on thermal comfort and, more seriously, on the health of the cities' inhabitants, but also on cooling energy demand (e.g. *Gartland* 2008). The impact of higher air temperatures in cities is further aggravated by severe heat-stress events caused by heat waves as the ones in Europe during 2003 (e.g. *Schär* and *Jendritzky* 2004; *Robine* et al. 2008), during 2006 (e.g. *Fouillet* et al. 2008), or during 2010 (e.g. *Barriopedro* et al. 2011), which are projected to increase in frequency and intensity in the 21st century (e.g. *Meehl* and *Tebaldi* 2004; *Solomon* et al. 2007). Therefore, research on strategies to reduce current and future heat-stress related risks is of great relevance for public health.

So far, most urban climate studies related to heat stress have focused on outdoor climate conditions. However, since humans spend much time within buildings, research on indoor climates and subsequent heat-stress related risks is also required. Indoor atmospheric conditions depend on outdoor weather conditions, structural characteristics of city quarters and building properties, such that exposure to hazardous urban weather conditions will show strong spatio-temporal variations between and within cities.

In addition, many studies have revealed that health burdens apply most often to physiologically susceptible and economically underprivileged persons in unfavourable environmental conditions (e.g. *Harlan* et al. 2006). Elderly people and those suffering from chronic diseases were often reported to be particularly sensitive to heat stress. For instance, respiratory morbidity showed significant heat effects in European cities. An epidemiological study of high-temperature impacts on morbidity in twelve European cities revealed that extreme heat events increase hospital admissions for respiratory diseases, particularly in the elderly population (*Michelozzi* et al. 2009). Thus, heat-stress related risks vary substantially between and within cities since both hazard and vulnerability display strong spatio-temporal patterns. For these reasons, interdisciplinary research linking natural and social sciences is prerequisite to deepen our understanding of the complex interactions between urban climate and heat stress.

Risk assessments are well established in the field of disaster risk reduction, and have been adopted within the climate change adaptation community (IPCC 2012; *Suroso* et al. 2013). Both communities share a common notion of key theoretical aspects and components (*Solecki* et al. 2011). However, appropriate concepts and methods for quantifying heat-stress related hazards, vulnerabilities and risks are yet under development and discussion. Differences in epidemiological studies on heat-stress related mortality are particularly due to the strong dependency of the number of excess deaths related to elevated air temperatures on the methods to define days or episodes (events) of heat stress, on the use of different types of mortality data, or on the methods to estimate base mortality rates (e.g. *Kovats* and *Hajat* 2008; *Gosling* et al. 2009; *Anderson* and *Bell* 2011).

As long as the potential benefits of actions for reducing such risks are only known on a qualitative level, it is difficult to convince stakeholders to design and implement climate-responsive actions with respect to present and future climates (e.g. *Gill* et al. 2007). Analysis of cause-effect relationships helps to design responsive actions for impact mitigation more precisely (e.g. *Renn* 1998).

Short presentation of the articles

DIE ERDE's special issue on urban climate and heat stress is published in two parts, of which the first one is presented here. It comprises seven articles on research carried out for four German cities. Countermeasures against heat stress in cities were examined for the example of Gelsenkirchen by *Dirk Dütemeyer, Andreas-Bent Barlag, Wilhelm Kuttler* and *Ulrich Axt-Kittner*. A modelling case study for Stuttgart with respect to mitigation of urban heat stress is presented by *Joachim Fallmann, Stefan Emeis* and *Peter Suppan*. Urban climate and heat stress in Berlin are subject of three articles. *Katharina Scherber, Marcel Langner* and *Wilfried Endlicher* carried out a spatial analysis of hospital admissions for respiratory diseases during summer months taking bioclimatic and socio-economic aspects into account. *Dieter Scherer, Ute Fehrenbach, Tobia Lakes, Steffen Lauf, Fred Meier* and *Christian Schuster* quantified heat-stress related mortality hazard, vulnerability and risk. An assessment of human bioclimate using the Universal Thermal Climate Index (UTCI) in different buildings with respect to indoor heat stress is presented by *Marcel Langner, Katharina Scherber* and *Wilfried Endlicher*. Finally, two articles by *Timo Sachsen, Gunnar Ketzler, Achim Knörchen* and *Christoph Schneider*, and by *Isabell Maras, Mareike Buttstädt, Julia Hahmann, Heather Hofmeister* and *Christoph Schneider* cover studies carried out in Aachen. While *Sachsen* et al. investigated past and future evolution of nighttime urban cooling by suburban cold-air drainage, the article of *Maras* et al. presents an investigation of public places and the impacts of heat stress.

The thematic focus of the seven articles displays a broad spectrum, spanning from heat waves and urban heat islands and subsequent heat-stress hazards, which are addressed by all articles, over excess morbidity risks (*Scherber* et al.) and excess mortality risks (*Scherer* et al.) including vulnerability issues (*Dütemeyer* et al., *Scherber* et al., *Scherer* et al., *Maras* et al.), to actions for mitigation of and adaptation to heat stress (*Dütemeyer* et al., *Fallmann* et al., *Sachsen* et al.).

The studies address different spatial scales, from regional scales (*Fallmann* et al.), over city scales (*Dütemeyer* et al., *Fallmann* et al., *Scherber* et al., *Scherer* et al., *Sachsen* et al., *Maras* et al.) to local scales (*Dütemeyer* et al., *Scherber* et al., *Sachsen* et al., *Maras* et al.), and even micro-scales (*Dütemeyer* et al., *Langner* et al.). While some articles concentrate on outdoor climates (*Dütemeyer* et al., *Fallmann* et al., *Sachsen* et al.), others refer to indoor climates (*Langner* et al.), or to both (*Scherber* et al., *Scherer* et al., *Maras* et al.). The approaches vary from spatially aggregated investigations (*Scherer* et al.) and comparisons of different locations (*Langner* et al.), while spatially distributed data has been used in the other studies (*Dütemeyer* et al., *Fallmann* et al., *Scherber* et al., *Sachsen* et al., *Maras* et al.).

Past and present urban climates are addressed by all studies, while climate-change issues are discussed in three articles (*Dütemeyer* et al., *Fallmann* et al., *Sachsen* et al.). One study covers a time period of more than 30 years (*Sachsen* et al.), while two studies analyse data from one decade (*Scherber* et al., *Scherer* et al.). Two years are analysed by *Langner* et al., while *Fallmann* et al. study a short period within a single year.

Two epidemiological studies target on hazard and risk assessment (*Scherber* et al., *Scherer* et al.), while three studies focus on mapping urban climate features (*Dütemeyer* et al., *Scherber* et al., *Maras* et al.). A sensitivity study (*Fallmann* et al.) and an investigation using surveys and interviews (*Maras* et al.) complement the spectrum of approaches followed in the seven articles. A variety of methods are applied. Data from weather observations are used by *Dütemeyer* et al., *Scherber* et al., *Scherer* et al., *Langner* et al., *Sachsen* et al., and by *Maras* et al.. Other studies employ atmospheric modelling (*Dütemeyer* et al., *Fallmann* et al., *Sachsen* et al., *Maras* et al.). *Dütemeyer* et al. and *Sachsen* et al. analyse remote-sensing data using Geographic Information Systems (GIS). Human biometeorological indexes are applied in three studies (*Dütemeyer* et al., *Langner* et al., *Maras* et al.). The two epidemiological studies (*Scherber* et al., *Scherer* et al.) are based on statistical analyses of meteorological and social/medical data, the latter ones also used by *Dütemeyer* et al. and *Maras* et al.. Four studies deal with real-case weather situations (*Scherber* et al., *Scherer* et al., *Langner* et al., *Maras* et al.), while the other studies consider idealised weather situations (*Dütemeyer* et al., *Fallmann* et al., *Sachsen* et al.).

The main results are briefly described in the following paragraphs.

Dütemeyer et al. show that dense built-up areas in Gelsenkirchen are most affected by heat stress, thus countermeasures in these areas are required under present-day climate conditions. In addition, they also find that urban areas on the outskirts of cities currently not strongly affected by heat-stress problems should also be considered since climate change is expected to increase the problem area.

Fallmann et al. demonstrate that the Weather Research & Forecasting (WRF) model is able to simulate UHI characteristics for Stuttgart during the heat wave in 2003. Based on this result, they compared the effect of various countermeasures, i.e., increasing albedo, increasing urban green and decreasing building density, on near-surface air temperatures. Their results show that increasing albedo would reduce the UHI intensity in Stuttgart by 2 K, whereas the other two countermeasures would only lead to a reduction of about 1 K.

The study by *Scherber* et al. reveals significant intra-urban disparities in Berlin in the relative risks for hospital admissions among elderly people (above 64 years) with respiratory diseases during the summer months (June-September) from 2000 to 2009. Hot spots of relative risk are found in north-western and south-eastern areas of the city centre. Population density, socio-economic conditions and annual mean number of days with heat load could be used as predictors for the spatial variability of the relative risk at the zip-code level in Berlin.

Scherer et al.'s study reveals that about 5 % of all deaths between 2001 and 2010 in Berlin can statistically be related to elevated air temperatures. Most of the affected people are 65 years or older. The results demonstrate that their approach for quantitative risk analysis delivers statistically highly significant results on the city scale when analysing heat stress on an event basis.

The study of *Langner* et al. could find only minor differences between rooms located within comparable buildings in different districts of Berlin, while pronounced variations of UTCI values were detected in two adjoining buildings. They explain these variations by differences in the structures of the two buildings, floor level and aspect. Only two rooms showed no thermal stress, while strong heat stress was detected in three rooms.

The results of *Sachsen* et al. show distinctive effects of accumulated long-term urban land-use changes on suburban cold-air drainage flow. Using a model-based approach they are able to demonstrate for the city centre of Aachen that the mean cooling rate decreased from 3.6 K in 1810 to 2.8 K in 1910, and to 2.4 K in 2010. They conclude that intensified urban cooling by nocturnal cold-air drainage can contribute to mitigating probable future global warming effects.

Maras et al. show that during the afternoon areas in Aachen with low building density are warmest, whereas high density areas start to become warmer than other areas in the evening. The authors could identify areas of specifically high vulnerability to heat stress. Additional vegetation would be able to substantially reduce heat loads in public places as ENVI-met simulations revealed. However, they point to unsolved problems in local-scale ENVI-met applications due to large-scale atmospheric influences that are not yet considered in such simulations.

Conclusions

The studies presented in Part 1 of the special issues of DIE ERDE on urban climate and heat stress accordingly reveal that heat stress is a serious problem of German cities already under present-day climate conditions, which are expected to increase due to climate change (IPCC 2013; *Coumou* and *Robinson* 2013). There is consensus that nocturnal UHI effects and indoor climate conditions have to be addressed when investigating heat stress risks in cities. Risk assessments have not only to analyse heat stress hazards but also to consider spatial variations of vulnerability to heat stress. Public institutions (urban planning, public health etc.) as well as city residents will have to act to reduce present-day and future heat-stress related risks.

There are also some findings reported in the articles that lead to open scientific questions. In particular, the role of building density for mitigating UHI effects remains unclear. The effectiveness of green versus white city concepts is also not yet known at a level of detail that would enable city planners to carry out and rely on cost-benefit analyses of countermeasures against heat-stress, also due to the fact that heat-stress related risks are not yet known in their full quantities, and may probably be substantially underestimated.

The second part of the special issue on urban climate and heat stress will present articles for cities in countries other than Germany. It will be of great interest to compare these studies with those presented here. The by far larger variability of regional climate conditions will allow to address the open scientific question how the specific climate controls of urban regions interact with different regional climates with respect to heat stress in cities (e.g. review by *Burkart* et al. 2014).

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