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Evaluation of the health-risk reduction potential of countermeasures to urban heat islands

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ABSTRACT

Traditional assessment of heat-related health risks neglects the influence of the building physics as outdoor conditions are used as predictor variables. Data on heat-related mortality from Berlin, Germany and from the US are evaluated with a risk concept which differentiates between outdoor and indoor hazards. Such, the influence of non-linear building physics on heat-related risks can be considered and the impact of adaptation strategies can be examined.

The number of heat-related deaths in the age-group 65+ for Berlin is expected to double with each 1 K increase in ambient temperature. It can be reduced by 50% with a mean ambient air-temperature reduction of 0.8 K. Countermeasures to urban heat islands are evaluated according to their reduction potential on hazards, both indoors and outdoors. The analysis shows that classic UHI countermeasures, which are effective in reducing air-temperatures outdoors, do not necessarily reduce the indoor hazard. Regarding indoor heat-related hazards, trees, façade and roof greening, cool roofs and cool pavements have a low impact only. Measures at the building level, namely cool roofs and façade greening perform best, however, passive cooling and air-conditioning are most effective. To reduce the number of excess deaths in a changing climate, combined measures are necessary.

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1. Introduction

The urban heat island (UHI) effect is a localized anthropogenic climate modification in the canopy layer of the urban atmosphere where almost all daily human activities take place [19,41]. At the individual level, increased temperatures promote the inability to balance the heat flows from the human body by the thermoregulation system. This leads to health risks ranging from heat rash and heat cramps, through heat exhaustion, heat stroke, to death. Furthermore, pre-existing medical conditions, such as heart or lung diseases, may be exacerbated. Thus, especially elderly people are at risk [2,61].

A significant increase in heat-related health risks (mortality and morbidity) is projected for many mid-latitude cities if no adaptation and mitigation strategies are implemented [26,34,64]. The amplification of the occurrence of extreme temperatures, due to the UHI effect or climate change, will lead to elevated heat-related risks, especially in urban areas. The relevance will increase even without the external driving factors, due to demographic change in many mid-latitude cities. Obviously, mitigation strategies to reduce absorption of radiation and storage of heat (e.g. cool roofs and cool pavements), or to increase evaporation, transpiration, and biomass production (green roofs, urban green) on a region or city-wide implementation, which are referenced to as countermeasures to UHI, seem to impose a reduction potential for health risks. However, even a qualitative assessment or estimate of the risk reduction potential of the countermeasures is missing, as necessary knowledge and data is distributed across several disciplines (climatology, epidemiology, social sciences, building physics, horticulture, and engineering).

Statistical evaluation in the form of risk assessment at population level has been established within the climate change adaptation community [17]. Heat-related risks in cities were addressed by various studies in recent years (see reviews of [51,29,21]), with heat-related mortality being one of the most researched heat-stress related risks due to its drastic impact and availability of reliable time-series data. However, there is disagreement concerning epidemiological studies on heat-related risks, and appropriate concepts and methods for quantifying heat-stress

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related hazards, vulnerabilities, and risks are still under development and discussion. Disagreement in heat-related mortality data is due to the methods to define days or episodes of heat stress, the use of different types of mortality data, methods to account for displaced deaths, or the methods to estimate base mortality rates [51]. Furthermore, risks vary substantially between and within cities, since both hazard and vulnerability display strong spatial and temporal patterns [42,23,45,55,10].

On a spatial scale, climate variability between different building types is often higher than the one originating from the outdoor climate on the mesoscale [40]. However, due to the heterogeneity of the building stock (and the missing involvement of the building experts), heat-related risk assessment is often based on outdoor climate only.

On the contrary, it is well known that the living conditions, especially building structure and air conditioning, have a significant effect on the risk. Many studies have documented statistically significant higher mortality rates of residents in top-floor apartments or in buildings with poor insulation or high glazing fraction [56,62]. Reduced risk is documented for people with access to air conditioning [56,27,13,43]. A statistically sound explanation of heat-related mortality, with elevated indoor temperatures calculated with a building model, was presented for Frankfurt, Germany [8] and for Berlin, Germany [9].

Despite the qualitative and quantitative evidence of the influence of the building parameters and air conditioning on the heat-related risks, these are not yet covered systematically in traditional risk analysis, and thus are not implemented in respective projections. A concise evaluation of risk reduction potentials has to differentiate between the actual risk and the underlying hazard, both indoors and outdoors. Outdoor health risks are often due to direct exposure to sun, such as sunburn or heat stroke, whilst heat-related mortality and exacerbated diseases are associated with elevated indoor temperatures and reduced recreation due to elevated night-time indoor temperatures. Buchin et al. [9] have shown that it is very suitable to evaluate heat-related mortality with indoor hazards as vulnerable groups are mainly subjected to indoor conditions and the lag in risk development during heat events can be explained with the thermal inertia of the building stock. The objective of this study is the qualitative evaluation of the risk reduction potential of several countermeasures to urban heat islands, applying a risk concept with differentiated indoor and outdoor hazards developed by Buchin et al. [9]. The concept was developed within the DFG Research Unit 1736 “Urban Climate and Heat Stress in mid-latitude cities in view of climate change (UCaHS)”. It considers building physics and indoor climate conditions. Countermeasures to UHI are compared to passive and active adaptation measures on the building level.

The paper first explains the risk concept and analyses the validity of the main influential parameters. The validity for the indoor hazard on indoor risk is tested with data on mortality of Berlin. Different countermeasures to UHI are analysed concerning their potential of hazard and risk reduction and are compared on a qualitative basis with further adaptive measures. Suggestions for concrete measures and further research conclude the paper.

2. Methods and data

2.1. Heat-related risk concept

The detailed description of the heat-related risk concept in this subsection is based on a previous work of the research group [9]. The risk r of a specific effect during a hazardous process, e.g. heat-related excess mortality at a day during a heat wave, can be described by the product of a hazard value h representing a hazardous process and the vulnerability v to this effect.

$$r = h \cdot v. \tag{1}$$

The advantage of a risk concept like this is that it is differentiated between external driving factors and a hazard-independent vulnerability. In general, all variables are specific for one system, which is defined by its elements (e.g. a sub-group of inhabitants) and its spatial distribution (e.g. an urban district). For instance, $r_{\text{mortalityheat-stress,65+Berlin}}$ represents the excess mortality related to heat stress for the group of inhabitants in the age of 65 years and older in Berlin.

Nonetheless, it is useful to differentiate the total number of persons at risk N_{tot} according to their exposure into three groups. There is one group N_{out}, which is predominantly exposed to outdoor conditions, whilst the others are exposed to the indoors, either in unconditioned ($N_{in,uc}$) or air-conditioned ($N_{in,ac}$) climates. A plausible implementation is additive as follows:

$$r = \frac{N_{out}}{N_{tot}} h_{out} v + \frac{N_{in,uc}}{N_{tot}} h_{in,uc} v + \frac{N_{in,ac}}{N_{tot}} h_{in,ac} v. \tag{2}$$

In Eq. (2) the vulnerabilty v in the different environments is assumed to be equal, although there are hints that people with pre-existing health issues tend to be more restricted to indoor climates.

Two new parameters are defined: a is an air-conditioning ratio which describes the fraction of inhabitants in air conditioned environments to the total number of individuals indoors ($a = N_{in,ac}/N_{in}$); e is an exposure-parameter describing the mean exposure of the group at risk towards the outdoor hazard ($e = N_{out}/N_{tot}$). With this Eq. (2) reads:

$$r = (e h_{out} + (1 - e)(a h_{in,ac} + (1 - a) h_{in,uc})) v. \tag{3}$$

The exposure e varies between 0 and 1 with $e = 1$ meaning that the system group is exposed to the outdoor hazard only, whilst $e = 0$ describes the full exposure to the indoor hazard. The indoor hazard $h_{in,uc}$ in Eq. (3) is considered to be valid for the building stock without air conditioning. It is assumed that the climate of the air-conditioned space generally fulfils comfort criteria and does not promote heat-related risks. Thus, it can be neglected ($h_{in,ac} = 0$) and Eq. (3) is reduced to:

$$r = \left((1 - e)(1 - a) h_{in,uc} + e h_{out}\right) v. \tag{4}$$

Furthermore, it can be assumed that most people in mid-latitude cities are subjected to indoor conditions during more than 80% of their time, even during the summer season [30], and e can be approximated to be negligible ($e = 0$). Eq. (4) then reads:

$$r = (1 - a) h_{in,UC} v. \tag{5}$$

2.2. Hazard calculation

The hazard intensity h has to be based on variables that are available to measure. To simplify the analysis we use a hazard definition based on excess-temperature:

$$\begin{aligned} h &= T - T_{Th} \quad \text{if} \quad T - T_{Th} > 0, \\ h &= 0 \quad \text{otherwise}. \end{aligned} \tag{6}$$

The hazard intensity has to be representative for the spatial and temporal resolution of the risk data, which is often coarse due to data collection or data privacy protection. Therefore, indoor hazards can be calculated with a simplified building model. A building model with two parameters τ and λ is used to calculate a time-series of a representative indoor temperature T_{in} from a

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