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

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\textbf{A B S T R A C T}

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 outdoors and indoors. 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 effects have been implemented [26,34,64].

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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.

$$ r = h \cdot v. \quad (1) $$

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, $r_{\text{mortality,heat-stress,65+Berlin}}$ 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 $N_{\text{tot}}$ according to their exposure into three groups. There is one group $N_{\text{out}}$, which is predominantly exposed to outdoor conditions, whilst the others are exposed to the indoors, either in unconditioned ($N_{\text{in,uc}}$) or air-conditioned ($N_{\text{in,ac}}$) climates. A plausible implementation is additive as follows:

$$ r = \frac{N_{\text{out}} \cdot h_{\text{out}} \cdot v + N_{\text{in,uc}} \cdot h_{\text{in,uc}} \cdot v + N_{\text{in,ac}} \cdot h_{\text{in,ac}} \cdot v}{N_{\text{tot}}} . \quad (2) $$

In Eq. (2) the vulnerability $v$ 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 ($a = N_{\text{in,ac}}/N_{\text{in}}$); $e$ is an exposure-parameter describing the mean exposure of the group at risk towards the outdoor hazard ($e = N_{\text{out}}/N_{\text{tot}}$). With this Eq. (2) reads:

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

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 $h_{\text{in,uc}}$ 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 fulfills comfort criteria and does not promote heat-related risks. Thus, it can be neglected ($h_{\text{in,ac}} = 0$) and Eq. (3) is reduced to:

$$ r = ((1-e)(1-a)h_{\text{in,uc}} + e \cdot h_{\text{out}}) \cdot v. \quad (4) $$

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:

$$ r = (1-a)h_{\text{in,uc}} \cdot v. \quad (5) $$

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:

$$ h = T - T_{\text{th}} \quad \text{if} \quad T - T_{\text{th}} > 0, \quad (6) $$

$$ h = 0 \quad \text{otherwise}. $$

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 $r$ and $\lambda$ is used to calculate a time-series of a representative indoor temperature $T_{\text{in}}$ from a
time-series of outdoor air temperature $T_{out}$ and global horizontal irradiance $I$. The following equation is derived by Buchin et al. [9]:

$$T_{in}(t + \Delta t) = \max \left[ T_{out} + \lambda t + \left( T_{in}(t) + T_{out}(t + \Delta t) - T_{in}(t) \right) e^{-\Delta t/\tau}, T_{heat} \right].$$  

(7)

$\tau$ is a time constant which is a measure for the thermal inertia of the building, $\lambda$ covers the temperature elevation due to solar gains. For the cold season, it can be assumed that the indoor temperature does not fall below a minimum temperature $T_{heat}$, which is set by the heating system. For the warm season, it can be assumed that internal heat sources are negligible compared to the solar heat flux into the zone. $T_{in}(t)$ is the initial indoor temperature for the time interval $\Delta t$. The time-series of $T_{in}$ is calculated in a forward scheme with an initial starting value for $T_{in}(t=0)$ and arithmetic mean values for the ambient climate data (e.g. $\bar{T}_{out} = 0.5 \cdot T_{out}(t) + 0.5 \cdot T_{out}(t + \Delta t)$). The temporal resolution of the climate data determining the time step $\Delta t$ has to be set high enough, so that the outdoor climate conditions can be assumed constant during this time step. Of course, the building model parametrization has to be representative for the building stock in the region for which risk data is available.

2.3. Vulnerability calculation

The influence of rising temperatures on the risk can be modelled to be linear above the threshold temperature $T_{th}$ used in the hazard definition. If vulnerability is assumed to be constant, it can be calculated as slope of the regression curve:

$$\nu = \frac{dr}{dh} = \frac{dr}{dT} \quad \text{for} \quad T > T_{th}. \quad (8)$$

Finally, it can be stated that the risk is dependent on three variables ($h, T_{out}, I$) and four parameters ($a, T_{th}, \tau, \lambda$). Section 3 will elaborate on the plausibility of the parameters and on their influence on the regression analysis. The analysis will be based on the exemplary data described in the following subsection.

2.4. Data

2.4.1. Climate data

A time-series of outdoor air temperature from Berlin-Tempelhof during the period from 01.01.2001 to 31.12.2010 in hourly resolution [15] is used for the hazard calculation (see Fig. 1 (top)). Furthermore hourly data of global horizontal irradiation from the urban climate observation network operated by Technische Universität Berlin [16] is used for the application of the simplified building model. The daily sums of global horizontal irradiation observed at site Rothenburgstraße in Berlin-Steglitz are shown in Fig. 1 (bottom).

2.4.2. Risk data

The database is the age-classified number of deaths in Berlin in daily resolution and the half-yearly population data interpolated to daily resolution. Both data sets are valid for the group of people in the age of 65 years and older and for the period 01.01.2001 to 31.12.2010 [60]. The data are presented in Fig. 2. Obviously, death rates are elevated during the winter season, but also during summer. The heat waves of 2006 and 2010 can easily be detected in the time-series data with 2010 exceeding even the maximum winter season death-rates.

All-cause mortality rates are calculated as risk data:

$$r_{mortality,65+} = \frac{\text{Nr of Deaths}_{65+}}{\text{Population}_{65+}}. \quad (9)$$

The heat-related excess mortality $r$ is calculated from the risk data by subtracting the base mortality rate $r_0$. It is the mean mortality rate at temperatures below the threshold temperature which cannot be associated to the heat. To withdraw the effect of the elevated mortality during the winter season only risk data associated to daily mean outdoor temperatures above 15°C and to daily mean indoor temperatures above 22°C are evaluated (see also Section 3).

3. Analysis

3.1. Parametrization of the building model and threshold temperature

The system group is assumed to be fully exposed to the indoor climate ($e=0$) without air conditioning ($a=0$) which is a good approximation for the Berlin region where air-conditioning is only prevalent in some offices and in automobiles.

The climate data are available in hourly resolution and are transformed to indoor temperatures with the simplified building model. The minimum temperature $T_{heat}$ and $T_{in}(t=0)$ is set to 20°C. The building model was parametrized with $\tau = 100$ h and $\lambda = 0.0175$ W/K m² according to its calibration using simulation results for a typical residential building for the Berlin region done with a detailed EnergyPlus building model (for details see [9]).

![Fig. 1](image1.png)

**Fig. 1.** Top: daily mean of air-temperature at Berlin-Tempelhof from 01.01.2001 to 31.12.2010. Bottom: daily sums of global horizontal irradiation at a weather station in Berlin-Steglitz from 01.01.2001 to 31.12.2010.

![Fig. 2](image2.png)

**Fig. 2.** Number of deaths and population for the group of people in the age of 65 years and older in Berlin from 01.01.2001 to 31.12.2010.
The relation between the risk and daily mean of the outdoor air temperature and the modelled indoor air temperature is depicted in Fig. 3. Boxplot diagrams are prepared in 1 K intervals and show the median, 25th and 75th percentiles (boxes), and range (whiskers) of the mortality data. Outliers are defined as being outside of 1.5 times the interquartile range above or below the quartiles.

The median mortality, and the lower and upper quartiles, increase for outdoor temperatures above 20°C. At outdoor temperatures exceeding 27°C no clear trend can be detected. The median mortality, and the quartiles, increase as well for high indoor temperatures (>28°C). Obviously the high mortality rates correspond better to indoor than to outdoor temperatures.

The breakpoint in the underlying data can be detected by a comparative regression analysis with changing threshold temperatures. Higher threshold temperatures yield higher coefficients of determination $R^2$ as long as data before the breakpoint are influencing the regression. When the threshold temperature exceeds the breakpoint, $R^2$ remains at a constant level as the rising trend is covered and uncertainty $\sigma$ is increasing as the number of data points is reduced. The coefficient of determination $R^2$ can be interpreted as explained variance in the given data. Note that deviating from a standard segmented regression analysis only the sloped part of the regression curve above the breakpoint temperature is used to determine $R^2$ and $\sigma$ as it is essential to describe the extreme risk data with high accuracy. The slope of the regression curve yields the vulnerability $r$.

For instance, a threshold temperature of 26°C yields a vulnerability of $7.3 \times 10^{-6} \text{ d}^{-1} \text{ K}^{-1}$ at a base mortality rate of $1.15 \times 10^{-4} \text{ d}^{-1}$ with $R^2 = 0.23$ and $\sigma = 0.097$. A threshold temperature of 29°C yields a vulnerability of $2.4 \times 10^{-5} \text{ d}^{-1} \text{ K}^{-1}$ at a base mortality rate of $1.15 \times 10^{-4} \text{ d}^{-1}$ with $R^2 = 0.49$ and $\sigma = 0.12$. Obviously, the choice of an appropriate threshold temperature significantly influences the vulnerability whilst the base rate is not significantly affected. The regression curves of the two examples are depicted in Fig. 4. The estimation of the breakpoint from the given data is described in the following section.

The regression performance is not only dependent on the threshold temperatures but also on the representativeness of the underlying building which is characterized by the two parameters $\tau$ and $\lambda$. The accuracy of the chosen parametrization and the sensitivity of the regression on the model parameters is evaluated for the given risk data. The dependence of the coefficient of determination $R^2$ and the uncertainty $\sigma$ for changes in $\tau$ is presented in Fig. 5 (top).

It can be seen that for the reference model ($\tau = 100$ h, $\lambda = 0.0175 \text{ kW}^{-1} \text{ m}^2$) and threshold temperatures above 22°C the explained variability in the data is steadily rising until it flattens at values of about 0.5 at temperatures of 28–29°C. The uncertainty remains at a level of about 0.1. The flattening behaviour can be associated with exceeding of the breakpoint in the data. For higher temperatures, the behaviour is unsteady and uncertainty is increasing at temperatures above 30°C, as data are removed from the segment. For lower and higher values of $\tau$ (50 h and 150 h), the flattening region indicating the breakpoint is in a similar temperature range, however, with a lower coefficient of determination. So, $\tau = 100$ h is a good choice with a breakpoint of about 28–29°C at $\lambda = 0.0175 \text{ kW}^{-1} \text{ m}^2$.

Fig. 5 (bottom) shows the influence of $\lambda$ on the regression performance. This parameter covers the temperature elevation due to solar gains. For $\lambda = 0.0125 \text{ kW}^{-1} \text{ m}^2$ the range in which the curve of $R^2$ flattens is starting at about 26°C, whilst at $\lambda = 0.025 \text{ kW}^{-1} \text{ m}^2$ this region is shifted to 30°C. The coefficient of determination $R^2$ decreases with increasing $\lambda$.
in these regions is comparable for all three curves with values of approximately 0.5.

This temperature offset in the regression curves can be explained with the effect of \( \lambda \) in Eq. (7):
\[
T_{in} = T_0 e^{-\Delta t/\tau} + T_{out}(1 - e^{-\Delta t/\tau}) + \lambda(1 - e^{-\Delta t/\tau}),
\]

At elevated indoor air temperatures, shifted thresholds can be explained if the daily mean radiation is at a constant level. In this case \( \lambda \) just scales a temperature offset. Especially during heat event days, at clear sky conditions during the summer months, the mean daily irradiation rate is on a comparable level.

From the analysis we learn, firstly, that the time constant \( \tau \) is significant for the regression performance and the values which do explain the data best are consistent to the ones obtained from the reference building and its underlying detailed building simulation. Secondly, for a given representative model, the accuracy of the threshold temperature obtained from the regression analysis is influenced by the accuracy of the solar gain parameter (\( \lambda \)) of the simple building model. Finally, we see that countermeasures aiming at the reduction of solar gains will be of high importance, as these directly influence the general temperature level within the zone.

The regression curve for a threshold temperature of 29 °C and a building model with the reference parametrization of \( \tau = 100 \) h and \( \lambda = 0.0175 \text{KW}^{-1} \text{m}^2 \) is used in the subsequent section (see Fig. 4). This regression curve yields \( R^2 = 0.49 \), \( \sigma = 0.12 \), a vulnerability of \( 2.4 \times 10^{-2} \text{d}^{-1} \text{K}^{-1} \) at a base mortality rate of \( 1.5 \times 10^{-4} \text{d}^{-1} \).

3.2. Mortality in regions with prevalent air-conditioning

If the above assumptions of Eq. (5) hold true, data on the development of risks at changing fractions of air-conditioned buildings during the years should fulfil Eq. (5) and relative risks \( r/\left(b_{in,UCV} \right) \) have to show a linear dependence with respect to \( a \).

The assumptions are exemplarily applied to data of heat-related excess mortality from different decades extracted from [13, Fig. 4]. These data were collected for 28 cities in the United States and grouped in eight regional clusters for the decades 1980 and 1990. For these clusters, the percentage of homes with air conditioning was available which can be interpreted as air-conditioning fraction \( a \). To allow for comparison of the trends within the different clusters, relative annual excess mortality rates \( r_{rel} \) are defined:
\[
r_{rel} = \frac{r}{\bar{r}_{in}} = \frac{r \left( 1 - \overline{\Delta} \right)}{\overline{\hat{r}}},
\]

\( \bar{r}_{in} \) represents the expected risk for the persons exposed to a fully unconditioned building stock (a = 0). Assuming that mean vulnerability and mean hazards were constant during the decades, \( \bar{r}_{in} \) can be estimated for each cluster from the mean mortality rate \( \overline{\hat{r}} = 0.5(r_{1980} + r_{1990}) \) and the mean air-conditioning fraction \( \Delta = 0.5(t_{1980} + t_{1990}) \); \( \bar{r}_{in} = \overline{\hat{r}}/\left(1 - \Delta \right) \). Fig. 6 shows the proportional decrease of the risk with an increase in air-conditioning coverage according to Eq. (11). For \( a = 1 \), no relative risk is expected, whilst at \( a = 0 \) it is 1. As can be seen, this general behaviour is in accordance to the risk data of [13, Fig. 4].

Of course, deviations from the expected slope exist and are possibly due to a decadal change in hazards and vulnerabilities, which are influenced by e.g. migration, demographic change, or changes in medical care. Unfortunately, it is not possible to extract these influences from the underlying data. Note, that one cluster (MT) with the cities of Phoenix and Denver shows an increasing trend. However, the data on the excess mortality rate for these hot climates is at a very low level, between 4 and \( 10 \times 10^{-6} \text{d}^{-1} \) [13] and the underlying data for this cluster is not in accordance with further data in the same publication.

From Fig. 6 it is obvious that the heat-related risk is highly influenced by indoor conditions, otherwise the impact of air conditioning on mortality rates could not be explained. Thus, for evaluation of the risk reduction potential of countermeasures to UHI the specific influence on the indoor conditions has to be considered.

3.3. Countermeasures to UHI and hazard reduction

Countermeasures to UHI change the urban atmosphere and thus the heat-stress related hazard, both outdoors and indoors. Many quantitative studies on countermeasures document the influence on energetic fluxes, temperatures, or bioclimatic indices in the outdoors. However, the influence of countermeasures on the indoor climate is often not addressed or research is focussed on a specific region, climate time-series, or building type. To allow, despite the missing data, for a general conclusion on the health risk reduction potentials, the following evaluation considers the physical processes of sensible heat transfer, short-wave and long-wave radiation, and latent fluxes in a qualitative manner. The qualitative evaluation of the UHI countermeasure in terms of a hazard reduction primarily concerns their effect on outdoor and indoor air temperature.

A qualitative scaling is applied to differentiate the measures. It comprises three levels for positive impacts on the hazard, a neutral level, and one negative level (+++; ++; +; −). The highest positive scale (+++) is used for measures which always provide comfort, whilst the negative scale (−) is used for measures which increase the hazard. Furthermore, heat wave resilience is classified, describing the potential indoor hazard reduction potential during long-term adverse climate conditions. Finally, resource demand (water, electricity, and heat) is considered for a concise discussion.

The following short review on the specific countermeasures is clustered into the spatial scale of implementation (mesoscale, building scale, room scale) and it is summarized in Table 1. The objective of this summary is to visualize a general trend of the hazard reduction potential of countermeasures to UHI effect. The given classification might change in dependence on regional influences, the existing building stock, and pre-existing implementations of countermeasures.

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3.3.1. Cool pavements

Materials that have high solar reflectance (spectrum 0.3–2.5 μm) and high thermal emittance (spectrum 4–80 μm) maintain low surface temperatures. These “cool” or “reflective” materials reduce the surface-to-air temperature difference and therefore the sensible heat flux into the urban atmosphere [33]. These materials reduce also the heat transport from the surface into the ground or wall at direct sun exposure. Thus, the sensible heat flux and heat storage are reduced resulting in a general air temperature reduction if applied on city scale.

A review of measurements and simulation studies was given by [47] and serves as a basis for classification according to the physical contribution of albedo and emissivity. Whilst the influence of reflectivity on surface temperatures is significant for daytime, emissivity is important for the nocturnal temperature depression. Temperature differences between black (α = 0.03) and white (α = 0.45) asphalt surfaces are reported to reach 12 K during daytime [47]. Even though peak surface-temperature reduction is documented to be high, the general contribution on hazard reduction is limited, as the effect is highest for open spaces exposed to direct radiation. Furthermore, increased reflectivity (albedo) increases the heat input on the nearby individual and dwellings during daytime due to the reflected radiation. Nonetheless, the general temperature reduction reduces the flow into the thermal storage and therefore reduces also night-time temperatures. In addition to the reflective characteristics, the pavers can be constructed to be porous or the pavement geometry can be designed to store water at the surface [38]. Both characteristics would add the cooling effect of evaporation if water is available. This effect can turn into a disadvantage when the evaporation leads to high air humidities in the surface near atmosphere (2 m) where pedestrians regularly suffer from high sultriness after summer rainfall events. Considering these effects, the overall outdoor and indoor hazard reduction potential is considered to be low (+) with its effectiveness depending on water availability in the pavement. The performance of cool pavements can be maintained also during hazardous conditions (+).

3.3.2. Urban green

This countermeasure encompasses high (trees) and low vegetation (lawn, bushes). Urban green modifies the urban atmosphere through evapotranspiration, shading and photosynthetic energy conversion. These processes reduce the energy flux into the built environment. The theoretical maximum of the photosynthetic conversion efficiency is in the order of 4.6% for C3-photosynthesis at 30 °C and 380 ppm CO₂ [65]. Due to the low efficiency of the conversion process, this effect can be considered to be negligible in terms of hazard reduction. Evapotranspiration reduces the surface temperature of leaves [36] and the temperature of surfaces beneath trees. Low moisture availability and predominately impervious surfaces reduce the evapotranspirative effect in areas with high-rise buildings [28] and during heat waves [12]. On average, the cooling effect of parks compared to urban surroundings is about 0.9 K during day and 1.2 K during night as reviewed by [4]. However, strength of cooling effects varies largely [58]. The simulations for the city of Berlin [53] show an air temperature reduction during extreme heat events of up to 0.5 K for an increase of the natural surface fraction by 15%.

Some studies highlight the relevance of shading rather than evapotranspiration [22,46]. Therefore, it is useful to differentiate the hazard reduction potential for high and low vegetation. The highest hazard reduction potential (++) can be attributed to a reduction of direct short-wave radiation by the shading effect of high vegetation [57]. It is considered to be low (+) for the low vegetation as the net energy flux is not significantly reduced. Shading can reduce both indoor [37] and outdoor heat-stress hazards [3,22,46,57]. High vegetation can reduce ventilation and trap long-wave radiation during the night and such curtails its hazard reduction potential. Furthermore, urban green cannot be established everywhere in the city due to a lack of available ground area and a high use concurrence in inner city quarters, where urban green would be most important. Moreover, evapotranspiration increases atmospheric water vapour and relative humidity, which weakens the cooling effect for the human body, as the thermoregulation via sweat evaporation is reduced. However, epidemiological studies on the effect of humidity on mortality show no clear trend [6]. Water scarcity and drought reduce the evapotranspirative effect of urban green especially during heat waves [12] and lowers its indoor hazard reduction potential to a low level (+) for high vegetation (trees) and to a negligible level (0) for low vegetation.

3.3.3. Cool roofs

The outdoor hazard reduction potential of cool roofs is comparable to the implementation of cool pavements. However, the influence on the street level can be considered to be negligible for high rise buildings [48]. In a meta-study of [48] an ambient temperature reduction in the range of 0.3 K per 0.1 increase in overall albedo is calculated. Krayenhoff and Voogt [31] modelled the impact of this countermeasure and their review suggests that a 0.10 average increase in urban albedo (equivalent to a 0.40 roof albedo increase for a roof area plan fraction of 0.25) will generate a peak daytime air temperature reduction on the order of 0.5 K for typical clear-sky mid-latitude summer conditions. Overall, the ambient air-temperature reduction can be considered to be low (+). However, the application of cool materials at the roof or façade surface also has a direct effect on the indoors: reduced indoor temperatures for non-conditioned buildings or a reduced cooling demand in air-conditioned buildings. Exemplarily, an average decrease in indoor air temperatures of about 8 K for the non-insulated attic of a roof painted with cool color compared to the blank asphalt roof was reported [5]. The adjacent top-floor room still benefited by an average 0.7 K decrease in indoor air temperatures. Obviously, the indoor temperature reduction is greatest in the top-floor apartments which impose also the highest hazard potential. However, the effect is reduced for new buildings with improved insulation standards. The adaptive effect is maintained during heat-waves (+).

3.3.4. Green roofs and green façades

The outdoor hazard reduction potential of extensive, meaning not irrigated green roofs and green façades is comparable to the
implementation of urban green. The effects of actively managed systems like irrigated green roofs and irrigated façade greening add a higher evapotranspirative cooling to the anyway given shading effect. Obviously, the indoor hazard reduction potential is higher. However, for green roofs a separate discussion of the contribution of insulation, evapotranspiration, and shading is often missing in comparative studies and the main effect might often be contributed to a change of insulation [48], which is not considered in this evaluation. Comparing green roofs to cool roofs, the former can often not compensate the reflective advantage of cool roofs by latent heat rejection [48]. Furthermore, the cooling effect of evaporation on green roofs can also be obtained within a non-vegetated drainage layer, and its performance is limited during hazardous conditions if irrigation is a problem or if the drainage layer is dry [50]. Therefore, the hazard reduction potential is considered to be low (+), indoors and outdoors. The effect of the greened roof on the street level is negligible in areas with medium and high rise buildings [11].

Observations of mean radiant temperature in front of a building façade in Berlin reveal that façade greening contributes only slightly to a reduction of heat-stress hazards outdoors [25]. Hoeslischer et al. [24] separated cooling effects of vertical façade greening through transpiration and shading in an experimental study. Surface temperatures of the building walls were decreased by the greening up to 15.5 K for the exterior side, and up to 1.7 K for interior side. The measurements have shown that façade greening is effective on indoor temperatures during night-time, which can be predominately attributed to the shading effect during the day. Only a lower proportion was due to transpiration. However, the actual effectiveness is highly dependent on the thermal design of and thermal retardation in the adjacent walls. The nightly heat loss by long-wave emittance and convective heat flux from the walls may be reduced by an insulating effect of the leaf-layer, which depends on the vegetation density and greening design [24]. Thus, the overall potential to reduce the hazard indoors and outdoors is low (+).

3.3.5. Passive cooling
Passive cooling covers all processes of heat control and dissipation without or only with minor usage of energy [20]. Following this general definition, all countermeasures to UHI which focus on the microclimate can be considered as passive cooling strategies. However, within this section only measures which can be influenced by the user on the room scale are addressed, namely solar control and night ventilation. The effect of these measures on the outdoor climate can be considered to be neutral (0), as the energy fluxes remain within the urban microclimate. Insulation, solar control and ventilation techniques were evaluated in a simulation study for typical end and mid terrace houses in Greater London, UK for different occupancy profiles [44]. In general, preventive techniques are much more efficient than dissipation of the heat into the microclimate. The reduction of solar gains is most important and can be realized with overhangs, shutters, blinds, or curtains. Shading elements at the external side of the room, such as shutters, are more effective (+) than internal shading elements (+), such as curtains, as the absorbed heat is partially released at the shading element. However, orientation of the room and occupant behaviour are often more influential [44,35]. Night ventilation is documented to have a high potential for temperature reduction (+) [44,49]. However, during hazardous conditions its effectiveness is limited (+), as the diurnal driving potentials (wind, temperature difference) are often not pronounced.

3.3.6. Active cooling
Active cooling measures, namely all types of air-conditioning, are effective, as these provide a comfortable indoor climate (+++), albeit at the cost of electrical or thermal energy. In most cases electrically driven vapour compression systems are installed either in centralized or decentralized form. Thermally driven systems are predominantly used in centralized systems and if (low-grade) heat is available. While all these systems improve the indoor climate, the heat rejection increases outdoor ambient temperatures (−). The systems are dependent on energy, either electricity or heat, which is a possible means for reduced effectiveness during heat waves, as the system efficiency is reduced and power shortages are more probable. However, the stability of the underlying electricity network is not under consideration in this study, and the effectiveness of the cooling systems is considered to be maintained also during heat waves (+++).

E evaporative cooling has a positive cooling effect, especially at dry outdoor conditions, however, its effectiveness is highly dependent on the outdoor climate. Therefore, its indoor hazard reduction potential is considered to be at a medium level (++). Despite the released humidity, its effect on the outdoor hazard is considered to be neutral (0). Effectiveness is reduced at humid outdoor conditions and might be effected by water shortages during heat waves. However, the spatially confined use of water can be seen as being superior to the use of the same amount of water in the outdoor environment for urban green, keeping the hazard reduction potential at a medium level (+++).

3.3.7. Comparison
The qualitative contribution of the different countermeasures on the hazard reduction is represented in Fig. 7. The classification levels for outdoor hazard reduction potential and indoor hazard reduction during heat waves of Table 1 is used. Further positioning between the measures is based on the above qualitative evaluation. It can be seen that measures focussing on attenuation or reflection of short-wave radiation perform best outdoors. Trees thus impose the highest hazard (and risk) reduction potential outdoors. If placed in vicinity of the buildings, it can also have a significant effect on the indoors. However, the effect of measures at the building scale, façade greening and cool roofs, is higher. Air-conditioning has the best hazard reduction potential indoors, however, at the cost of deteriorated outdoor conditions. Passive cooling and evaporative cooling also has a significant hazard reduction potential indoors, without deteriorated outdoor conditions.

3.4. Risk reduction potential
The effect of the hazard reduction potential of the adaptation measures on mortality is evaluated for the group of persons aged 65 and older in Berlin. The functional interrelation of hazard and risk and the parametrized building model as derived in Section 3 are used. The analysis is restricted to the influence of air temperature as this can be considered to be the most influential climate variable. The influence is modelled with a general offset of ΔT on the given
time-series of ambient air-temperature for the years 2001–2010. This temperature difference can be interpreted as being determined by either climate change, or by implemented countermeasures.

Rising ambient air temperature has a progressive influence on mortality. The influence on the relative change in the heat-related number of deaths (age group 65+) is calculated for a risk function as determined from the risk data (threshold temperature 29°C). The heat-related number of deaths is calculated from the risk data with the modified time-series of the weather and the population at the end of 2010 as presented in the above sections. It is related to the heat-related number of deaths calculated with the original weather and the population at the end of 2010 (45.7±5.3 deaths/year). Results are presented in Fig. 8. Additionally, several development paths of countermeasures A to E are given.

Several studies have projected a climate-change induces increase in ambient air temperatures. The ENSEMBLES-project reported on a shifting probability density function with a mean offset of about 1 K for the summer months for the projection period 2021–2050 compared to the reference period 1961–1990 for the Berlin region [14]. A 1.8–2.3 K increase in mean annual temperatures for scenarios A1B and B1 (IPCC) calculated with a regional downscaling model (WETTREG) was reported for Germany for the projection period 2071–2100 [63]. The analysis yields that an increase by 0.5 K in ambient temperatures increases the number of heat-related deaths by 46% (development A), whilst at 1 K it is doubled, at 1.5 K it is tripled, and at 2.0 K it is quadrupled. This progressive behaviour is driven by more days exceeding the threshold temperature and by the linearly increasing risk magnitude above the threshold temperature (see Fig. 4). Given these findings it is obvious that rising temperatures, either by increasing UHI-effect or climate change will result in rising risks and adaptation and mitigation strategies have to be evaluated in scope of increasing regional temperatures.

Considering the countermeasures, a 50% fraction of buildings with air-conditioning or a reduction of effective irradiation by 20% will stabilize the number of excess deaths at the same level even at a 1 K increase in ambient air temperatures. If air conditioning coverage is increasing to 50% of the buildings this will result in a slight increase in outdoor temperatures indicated by development path B. The projected change in relative excess deaths for this path accounts to a decrease by 44%. Applying passive cooling on the building scale (development path C) has a neutral impact on the ambient climate. A reduction of the effective irradiation by 20% is projected to reduce the number of excess deaths by 58%. The risk development with measures that additionally have an impact on the outdoor climate, such as trees or cool roofs, is depicted with path D with a risk reduction of 52%. Heat-related mortality reduction by 32% is possible if the ambient temperature is lowered by 0.5 K only (development path E). This might be accomplished by measures which only affect outdoor air temperatures, such as cool pavements or urban green. It is noteworthy that measures reducing the effective radiation on the buildings by about 40% allow for a quasi-elimination of the heat-related mortality under present conditions. This is equivalent to the effect of a mean ambient air temperature reduction of 2 K.

4. Discussion

4.1. Countermeasures to UHI and risk reduction

Following the risk concept of this paper, the highest hazard (and risk) reduction potential for urgent heat-risks, such as mortality, lies in the indoor environment. Classical UHI countermeasures focusing on the urban scale often do only have a marginal direct effect on the indoor climate. Of course, the outdoor environment is an important driver with outdoor temperatures being the most discussed climate variable in UHI research. However, the actual risk reduction potential of measures which predominantly influence the outdoor air temperature (cool pavements, grass areas, etc.) can be considered to be small as the cooling effect is spatially confined [4]. This study suggests that measures on the building level, cool roofs, green façades, or nearby trees have the highest potential on the indoor environment. However, direct measures on the room scale, either passive or active, have a larger effect and are favourable if decisions on measures have to be exclusive. The indoor based risk concept estimates a lower hazard reduction potential to urban green, as the indoor climate is not directly affected and evapotranspiration is limited during hazardous conditions. Only if directly installed in the vicinity of dwellings (façade greening or trees) a risk reduction for the inhabitants can be maintained by shading effects.

The absolute risk reduction potential has to be discussed in relation to the fraction of air-conditioning. It was shown that the approximation of the linear influence of the fraction of air-conditioned buildings can explain the risk reduction in the given data. However, reliable data on the distribution of air-conditioning is often not available. Furthermore, the linear approach neglects the underlying adaptive behaviour driving air conditioning installations. At low levels of a the installation of air-conditioning equipment is directly focussed on the temperature reduction in overheated rooms, whilst at highly saturated levels, accessibility to air conditioning is determined by the socio-economic status [43]. Therefore, the overall risk-magnitude will possibly decrease with larger slope at small fractions of air-conditioning and with flattening slope at saturated regions. In many U.S. cities, the fraction of air-conditioning is already very high and absolute heat-related risks are low [13]. Under such conditions, mitigation strategies have to directly address the remaining groups at risk, often homeless or socially poor classes which cannot afford air-conditioning [23]. In these cases, special focus has to be put on the education of these groups. Furthermore, it is necessary to identify the buildings with the most hazardous indoor climates by research on the spatial indoor climate distribution within a city [59].

Personal adaptation, both physically and psychologically, is evidently an important factor and has to be considered. Physical adaptation covers variation of clothing, changes in activity levels and choice of exposure to specific environments. Psychological adaptation is documented to depend on recent experience, expectations and degree of freedom to expose oneself to a certain
The adaptation potential is higher outdoors as there normally exist many possibilities to change between spaces of different climate conditions. Indoors, the physical and psychological adaptation potential is limited and highly dependent on the thermal quality of the building and possibilities to influence overheating. Thus, the evaluation of specific countermeasures on the outdoor climate has to focus on the activity and adaptation patterns of the persons at risk. For instance, cool pavement might increase the overall heat flux to the human body during sunny days due to the reflected short-wave radiation which promotes heat-stress despite decreased surface temperatures. But such places can be avoided during daytime and impose reduced hazards during the evening hours due to the lower surface temperatures and less stored energy. Due to the reduced net heat flux into the city, an additional positive net effect on the outdoors can be expected.

[54] investigated the perception of heat in the urban population in a cross-sectional household survey. Individual physical constitution, mainly determined by health status and physical fitness, was identified as major determinant of individual vulnerability and the authors identified active mobility concepts (walking, cycling) as highly effective adaptation (and mitigation) strategies. As the metabolic rate is higher e.g. for cyclists and attractiveness of the transport routes is essential for transition from passive vehicle based mobility to sustainable mobility [1], it is necessary to focus on the climate conditions along main transportation routes. Shading by trees or canopies along with greened areas have a hazard reducing effect and can additionally encourage shifting from passive to active mobility by increased climatic attractiveness.

Combined adaptation on all scales, on the building scale with passive building design and on the micro-climate scale, might be a useful alternative to adaptation by air-conditioning. However, the effective potential is dependent on the actual climate and existing building design. At the city level, the increase in outdoor air temperature during to air-conditioning might be in the same order of magnitude as the reduction potential of UHI countermeasures. Therefore, to reduce heat-related risks efficiently it is essential to support UHI countermeasures and passive cooling especially in regions where air conditioning is not yet common practice. A combined mitigation strategy implementing outdoor measures and supporting passive cooling might maintain indoor temperatures below hazardous thresholds.

The design of urban spaces on the basis of microclimate studies with bioclimatic evaluation of comfort is intended to foster the social interaction and life during normal summer conditions and extreme conditions are often out of focus. Obviously, at extreme conditions people can easily adapt outdoors by avoiding these places. However, it is necessary to quantify the effect of the countermeasures on the indoors also at extreme condition to implement efficient strategies.

Finally, it has to be mentioned that additional positive and negative feedback has to be weighted before implementation. In many mid-latitude cities the cold-related number of deaths often exceeds the heat-related number [18,34]. Thus, a thorough analysis has to address the impact on the winter-season risks also. Obviously, the application of the indoor risk concept with indoor temperatures will fail under these conditions, as the elevated winter mortality cannot be explained with the constant indoor temperatures. For heat-related mortality, direct effects on the respiratory system are probably more important, while for cold-related mortality, analysis yielded evidence of indirect effects involving increased incidence of influenza and other respiratory infections [32]. Furthermore, implications on water run-off management, energy consumption, or urban biodiversity as well as cost effectiveness have to be balanced in a sound management process [42].

4.2. Further research topics

The qualitative analysis has shown that the physical interpretation of the energy fluxes is important to evaluate and compare different measures. However, research on specific measures often only documents the resulting effect: temperature reduction. A differentiation in the energetic fluxes (irradiation, radiative emission, evapotranspiration, storage) is essential to quantify their impact on micro- and building scale and foster comparability of the measurements.

The analysis has shown that it is important to include the exposure and adaptation patterns of the persons at risk and the design of urban microclimate has to address the underlying activity patterns. Projections on the development of heat-related health risks in a changing climate often exclude the adaptation of the individuals. To make projections more reliable, research has to address the underlying decision making on the individual level and quantify climatic thresholds which trigger adaptive measures, e.g. the installation of air-conditioning.

The paper has focussed on indoor air temperature as predictive hazard variable. It is well known that temperature is the predominant variable to describe heat-stress indoors, however, bioclimatic indices which are based on the thermoregulation and adaptation of the human body possibly increase the quality of the risk concept. Considering that the reference ambient temperature is measured at Tempelhof weather station, at the former airport area, which does not necessarily include the UHI effect [52] the effective threshold temperatures might be even shifted by the mean UHI island intensity. To allow for a concise implementation of bioclimatic indices, their applicability on the indoor climate and their validity for the groups under consideration has to be assured.

5. Conclusions

This study presents a risk concept, which differentiates between heat-stress hazards within indoor and outdoor environments. It is shown that a separate focus on indoor and outdoor hazards is necessary to discuss efficient mitigation strategies and evaluate risk reduction potentials.

Indoor hazards can be calculated from the outdoor climate with a simple building model. The analysis has shown that it is important to parametrize the building with a representative time constant τ. Uncertainties in the parameter λ, which covers the temperature elevation due to solar irradiation, can be compensated with a change in the threshold temperature of the risk assessment. Mortality data from Berlin, Germany for the age group 65+ was evaluated with calculated indoor temperatures from the building model. The analysis has shown that the relative risk increases progressively with rising temperatures and doubles approximately with each 1 K increase in ambient temperature. Considering the reduction potential indoors, it is necessary to focus on the air-conditioning coverage. For cities in which air-conditioning coverage is saturated, the risk reduction potential by UHI countermeasures is negligible. For cities in which air-conditioning coverage is low, classic UHI countermeasures and passive cooling measures on the building level are more effective. Especially shading measures and cool roofs, might be sufficient to reduce overheating and an associated increase in indoor based risks.

A future diffusion of air-conditioning will decrease risks. At the same time additional energy consumption should be avoided. So, also air-conditioning should be avoided or based on regenerative sources if possible. Therefore, the implementation of passive measures on the room level should be a major focus of urban planning and policy. Possibly only a combination of a rigorous passively
cooled building design and countermeasures on the urban scale will keep indoor temperatures below critical thresholds.

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References


