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The role of building models in the evaluation of heat-related risks

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Abstract

Existing concepts to evaluate heat-related risks are based on outdoor climates only. However, vulnerable groups are most of their time exposed to indoor climates. To allow for a distinct evaluation of mitigation and adaptation strategies against adverse impacts of heat waves a novel indoor/outdoor risk concept is required.

By coupling indoor and outdoor climates using a building model, the developed indoor/outdoor risk concept can still be based on the outdoor conditions but includes exposure to the indoor climate. The influence of nonlinearities due to building physics and the impact of air-conditioning on heat-related risks can easily discussed with this risk concept.

For proof of concept the proposed risk concept is compared to a traditional risk analysis. Exemplary, we use time-series data of mortality of Berlin, Germany, for the years 2001–2010. Three simplified building models are parametrized with data of a detailed building model and used in a time-series regression analysis. Indoor hazards calculated in this way better explain the variability in the risk data compared to outdoor hazards, depending on the kind of building model. Furthermore, part of the time-lag between heat-wave events and elevated risks can be explained with the indoor/outdoor risk concept and a nonlinear building model.

1 Introduction

Climate projections indicate that frequency, intensity and duration of extreme heat waves are likely to increase (Meehl, 2004; Field, 2012; Coumou and Robinson, 2013). Therefore, significant increase in heat-related mortality and morbidity can be expected. Especially the amplification of extreme temperatures due to the urban heat island effect will lead to elevated heat-related risks in urban areas.

The living conditions, especially building structure and air conditioning, have a significant effect on the individual risk. A statistically significant relation of increased mortality for residents in top-floor apartments and reduced risk for people with access to air conditioning for the 1995 heat wave in Chicago was evaluated by Semenza et al. (1996) in a case-control study. Similar studies show increased mortality for the 2003 heat wave in France for peoples living in buildings built prior to 1975, and for buildings with poor insulation and high glazing fraction (Vandentorren et al., 2006). Reduced heat-stroke risks could be statistically attributed to access to air conditioning (Kilbourne, 1997). Also the longterm decline in heat-related mortality in 19 out of 28 cities in the United States of America is primarily attributed to increased access to air conditioning (Davis et al., 2003). Disparities by race in heat-related mortality in four US cities for the years 1986 to 1993 could be attributed to differences in central air-conditioning prevalence (O'Neill et al., 2005). A statistically sound explanation of heat-related mortality with elevated indoor temperatures calculated with a building model was presented by Brandt (2006). The inclusion of a detailed building model in the German heat-health warning system and the influence of user behavior on indoor temperatures was discussed by Pfafferott and Becker (2008).

Despite the qualitative and quantitative evidence on the influence of the building parameters and air conditioning on the heat-related risks, these are not covered systematically in traditional risk analyses and thus cannot be implemented in a reliable projection.

The objective of this study is the development of an indoor/outdoor risk concept, which considers building physics and indoor climate conditions. The risk concept follows the one introduced by the Research Unit 1736 "Urban Climate and Heat Stress in mid-latitude cities in view of climate change (UCaHS)" (Scherer et al., 2014). Three different building models that vary in their complexity are evaluated concerning their applicability in such a concept. The indoor concept is tested with a time-series based risk analysis method.

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2 Methods and materials

2.1 General risk concept

A general risk concept is based on a functional interrelation of risk r, hazard h and vulnerability v. The product of hazard and vulnerability defines the risk:

$$r_{\mathrm{e,\,p,\,s}} = h_{\mathrm{p,\,s}} v_{\mathrm{e,\,p,\,s}}. \tag{1}$$

Generally, a risk approach like this allows for a projection of future risks as it is differentiated between external driving processes and a hazard-independent vulnerability. At constant vulnerability the risk for changing hazard magnitudes and time spans can be calculated or vice versa.

The nomenclature follows the one proposed by Scherer et al. (2014) for an event based risk analysis. The subscripts indicate the effect (e) which is caused by a hazardous process (p) on a specific system (s). In general, a system is defined by its elements (e.g. a group of inhabitants or objects) and its spatial distribution (e.g. country, city or an urban quarter). For instance, $r_{\mathrm{mortality,\,heat\text{-}stress,\,65+}}$ represents the excess mortality related to heat stress for the group of inhabitants aged 65+ in Berlin.

Risk and hazard are mean intensities within a time span and within the spatial extent of the system group.

The hazard has to be defined such that it is independent of the effect. A hazard definition function (HDF) is used to calculate the mean intensity of the hazard from a hazard signal (HS);

$$h = \mathrm{HDF(HS)}. \tag{2}$$

For instance, the hazard signal can be a time series of outdoor air temperature or human bio-meteorological indices, such as Predicted Mean Vote (PMV) or Universal Thermal Climate Index (UTCI).

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Many authors suggest a positive temperature deviation from a threshold temperature to be an appropriate hazard intensity (see Gosling et al. (2009) for an extensive literature survey):

$$h = \mathrm{HDF}(T, T_{\mathrm{Th}}) = \begin{cases} T - T_{\mathrm{Th}}, & \text{if} \quad T - T_{\mathrm{Th}} > 0 \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

In this case the hazard signal is directly proportional to the hazard intensity h. In this kind of time-series approach retardation effects have to be covered separately. It is therefore practical to use hazard or vulnerability definitions that incorporate these retardation effects. Scherer et al. (2014) covers retardation effects in an event based approach and includes lag-duration in a regression analysis. Huynen et al. (2001) define lag periods to differentiate between short- and longterm retardation effects. Furthermore, moving average approaches, logarithmic functions etc. have been discussed in literature as suitable HDF.

Actions for risk reduction can be aimed at the hazardous process, e.g. reducing urban heat island effects on the city scale, or by influencing vulnerability. Vulnerability in a traditional understanding incorporates all effects that are not covered by the outdoor hazard definition, e.g. social measures, building design, and air conditioning.

2.2 Indoor/outdoor risk concept

In a traditional risk evaluation the hazard is based on the outdoor climate only. Nonetheless, many persons at risk are subjected to indoor conditions, which might be dependent on the outdoor climate but can also be independent from the outdoor conditions by means of air conditioning. Studies suggest that the nightly recreation is very important to reduce heat stress and it is therefore necessary to consider the indoor environment in the risk assessment (Franck et al., 2013; Wright et al., 2005). Furthermore, there might be a time lag between indoor and outdoor hazard, which has to be accounted for. Following this argumentation, an appropriate risk concept has to differentiate be-

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tween indoor and outdoor hazard. A plausible implementation might be additive as follows:

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

Note that the indoor hazard h_{in} in Eq. (4) is considered to be valid for the building stock without air conditioning. We added two parameters: a is the air-conditioning ratio and e is an exposition-parameter describing the mean exposition of the group at risk towards the outdoor hazard.

Air-conditioned indoor environments can be excluded from the hazard prone spaces as the indoor climate conditioned according to common comfort criteria does not impose a heat-stress hazard. Thus, the fraction of individuals in air-conditioned spaces $N_{\mathrm{in,AC}}$ to the total number of individuals N_{in} is introduced by the air-conditioning ratio a:

$$a = \frac{N_{\mathrm{in,AC}}}{N_{\mathrm{in}}}. \tag{5}$$

The exposition parameter e is defined as:

$$e = \frac{N_{\mathrm{out}}}{N}. \tag{6}$$

The exposition 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 exposition to the indoor hazard. Deviating from a common definition of exposition as degree of exposure between a hazardous process and no hazard, we consider exposition as degree of exposure between outdoor and indoor hazard.

The ratios e and a are determined by the number of individuals in the system exposed to the outdoor hazard or air-conditioned climate, so these are system specific parameter also.

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2.3 Simplified indoor/outdoor risk concept

To compare the traditional risk concept and the indoor/outdoor risk concept on a theoretical level it is useful to assume a linear correlation between indoor and outdoor hazard, $h_{in} = ch_{out}$. We can rearrange Eq. (4), with parameter c describing the outdoor hazard transformation by the building stock:

$$r = h_{out}\left((1-a)(1-e)c + e\right)v. \tag{7}$$

We can interpret the term $((1-a)(1-e)c+e)v$ as a corrected vulnerability in the traditional risk approach, or the term $h_{out}((1-a)(1-e)c+e)$ as effective indoor hazard, arbitrarily. The simplified indoor/outdoor risk concept will fail if the assumption of linearity between indoor and outdoor hazard is not fulfilled. Conditions with indoor hazard but no outdoor hazard, e.g. elevated indoor temperatures in glazed rooms with high internal loads, or vice versa, obviously contradict linearity.

2.4 Building models

Within this study we will use a complex numerical building model to parameterize three simplified building models. The three building models are based on either an empiric linear relation between indoor and outdoor temperatures (linear building model), or on the analytical solution of a simplified capacitance-resistance-transmittance model (physical building model), or on an empiric recursive modelling approach (recursive building model).

2.4.1 Numerical building model

Sophisticated building models are based on energy balances of building components and zones. As the models cannot be solved analytically numerical solvers are used. We use EnergyPlus software (version 8.1) to model a representative building (EnergyPlus, 2013). The results of this numerical model are used to parameterize the following simplified building models.

2.4.2 Linear building model

A simple quasi-linear approach with a lower threshold and two coefficients k_1 and k_2 can be used to describe the relation between indoor and outdoor temperatures:

$$T_{in} = \max(k_1 T_{out} + k_2; T_{heat}). \tag{8}$$

For the cold season it can be assumed that the indoor temperature in the building does not fall below a minimum temperature T_{heat}, which is controlled by the heating system. Linear temperature relations are widely used in the analysis of indoor comfort conditions for naturally ventilated buildings (EN 15251:2012, ANSI/ASHRAE Standard 55-2013). We will use this model to foster understanding of the influence of buildings in a traditional risk approach.

2.4.3 Physical building model

We can understand the indoor climate as a function of the outdoor climate, the functional relation being described by the building parameters. A very simple 1-zonal energy-balance model of the building (or room) can be solved analytically:

$$C\frac{dT_{in}}{dt} = \frac{1}{R}(T_{out} - T_{in}) + g\dot{I} + \dot{Q}. \tag{9}$$

Equation (9) is an inhomogeneous first order differential equation with thermal capacity $C\,[\mathrm{J\,K^{-1}}]$, building envelope resistance $R\,[\mathrm{K\,W^{-1}}]$, transmittance of radiation $g\,[\mathrm{m^2}]$, and internal heat source $\dot{Q}$. Ventilation is neglected in this model. Assuming constant outdoor climate conditions (temperature T_{out} and global horizontal irradiance $\dot{I}$) during the time step Δt the analytical solution of Eq. (9) for the indoor temperature yields:

$$T_{in} = T_{out} + \lambda\dot{I} + R\dot{Q} + \left(T_0 - T_{out} - \lambda\dot{I} - R\dot{Q}\right)e^{-\Delta t/\tau}. \tag{10}$$

The remaining parameters characterizing the building are $\tau = RC$ and $\lambda = gR$. τ represents a time constant being a measure for the thermal inertia of the building, λ covers

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the temperature elevation due to solar gains. T_0 is the initial indoor temperature for the time interval Δt.

For the cold season T_{heat} is motivated with the same reason as in the linear building model. For the warm season we assume that internal heat sources are negligible compared to the solar heat flux into the zone. Therefore, Eq. (10) can be simplified:

$$T_{in} = \max\left(T_{out} + \lambda I + \left(T_0 - T_{out} - \lambda I\right)e^{-\Delta t/\tau}; T_{heat}\right). \quad (11)$$

We will use this model to simulate the indoor temperature for a restricted climate data set, which only consists of outdoor air temperature and global horizontal radiation.

2.4.4 Recursive building model

A simple recursive model was used by Wright et al. (2005) to cover the thermal inertia of the building structure:

$$T_{in} = \max(b_1 T_{hist} + b_2; T_{heat}). \quad (12)$$

$$T_{hist}(t + \Delta t) = \alpha T_{out}(t + \Delta t) + (1 - \alpha) T_{hist}(t). \quad (13)$$

This model is similar to the physical model for constant time steps and $b_1 = 1$. In this case the parameter α represents the thermal inertia and parameter b_2 includes the temperature elevation due to constant internal loads. This model is only based on temperatures and does not cover radiation effects directly. We will use this model to evaluate the applicability of outdoor temperature as one single climate datum in the indoor/outdoor risk concept.

2.4.5 Parameterization data

As the hazard is defined as an integral value for the system, the building model has to be parameterized with data of a representative building for the system on the same spatial scale. We use a data set of simulation results of a detailed numerical building model (multizone, EnergyPlus, Fig. 1). The model is representing a typical Berlin residential building according to the Promoterism and Art Nouveu block development periods from 1860 to 1918 (IWU, 2011, code DE.N.AB.02.Gen). This type is one of the major types in the Berlin building stock (SDUDE, 2011) and therefore used as representative building model. The building geometry was simplified concerning window partitioning and existence of balconies and oriels. See Fig. 1 for the implemented exemplary zone structure. Technical specifications were extracted from the building typology and implemented in the numerical model for an east–west oriented building (see Table 1). The typical shading in urban areas by other buildings was implemented in the domain of the model. The minimum indoor temperature for heating is assumed to be $T_{\text{heat}} = 19\,^{\circ}\text{C}$.

2.5 Climate and risk data

For simulation of the the indoor climate with the numerical building model we use weather data (air temperature, humidity, wind velocity and direction, diffuse and direct horizontal radiation) from Potsdam, ~ 25 km from the center of Berlin, for the time period 2003 to 2010 (DWD, 2014a). Simulation results of an upper zone (4th floor, east oriented) of this model are used for parameterization of the linear, physical, and recursive building model with a trust region method.

Time series data for the period from 1 January 2001 to 31 December 2010 of air temperature from a weather station in Berlin Tempelhof operated by the German Weather Service are used for hazard calculation (DWD, 2014b) along with global horizontal irradiance data from a weather station of Technische Universität Berlin in Berlin Steglitz. The climate data are available in hourly resolution and are transformed to indoor temperatures with the linear, physical, and recursive building models. Consecutively, the daily arithmetic mean indoor temperature is used as hazard signal.

All-cause mortality rates are used as heat-related risk data and are derived from the age-classified number of deaths in Berlin in daily resolution and half-yearly population data interpolated to daily resolution for the age-group above 65 years and the period

1 January 2001 to 31 December 2010 (SOBB, 2013). The system group is assumed to be fully exposed to the indoor climate ($e = 0$) without air conditioning ($a = 0$).

3 Results

3.1 Building model parameterization

Parameterization of the simplified building models yields $k_1 = 0.65$ and $k_2 = 10.8\,K$ for the linear model, $\tau = 100\,h$ and $\lambda = 0.022\,m^2\,K\,W^{-1}$ for the physical model, and $b_1 = 1.1$, $b_2 = 3.8\,K$, and $\alpha = 0.25$ for the recursive model.

The resulting indoor temperatures are plotted exemplary for July 2007 in Fig. 2 together with the outdoor air temperatures which fluctuate with an amplitude of about 10 K. The numerical model also generates pronounced diurnal temperature variations of 2...3 K and the general trend follows the outdoor air temperatures with a retardation of several days. Of course, indoor night-time temperatures do not fall below 19 °C. All simplified models can reproduce the general trend, albeit the retardation is not reproduced with the linear model. The physical model is able to generate diurnal variations, albeit with lower amplitude. The recursive model and linear model are based on daily mean temperatures and therefore cannot reproduce diurnal variations.

The daily mean indoor temperature from the numerical model and the results of the linear model are plotted against the outdoor air temperature in Fig. 3, left. Obviously, the linear building model can reproduce the general trend of the detailed simulation data. However, maximum deviations may be almost 5 K as can be seen in a scatter-plot of the indoor temperatures from the linear model against the ones calculated with the numerical building model (Fig. 3, right). The root mean square deviation (RMSD) is 1.7 K. Normalization with the overall temperature span yields a normalized RMSD (nRMSD) of 13.5 %. The physical approach reproduces the data with a RMSD of 0.3 K and a nRMSD of 2.3 %. The recursive building approach yields a RMSD of 0.8 K and a nRMSD of 6.5 %.

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We can conclude that the simple physical building model is suited best to calculate daily mean indoor temperatures. If no data on solar irradiance is available the recursive model is suitable to recalculate the indoor temperatures also. A linear relation as in the linear model should be avoided because it would incorporate high deviations as thermal inertia and solar gains are not covered.

The parameters which have been derived for the exemplary residential building will be used in the following risk analysis section for all building models.

3.2 Risk analysis

3.2.1 Qualitative risk analysis

For qualitative evaluation the risk data are plotted against the different hazard signals, namely outdoor air-temperature and indoor temperatures calculated from the three simplified building models (Fig. 4). Additionally, arithmetic mean values of the mortality rates are given for a 1 K interval.

A correlation with the outdoor air temperature (Fig. 4, top) predicts unchanged mortality rates in a temperature range from 16 to 24 °C. At high outdoor air temperatures (> 27 °C) the signal for rising mortality rates is less accurate due to a low number of measurements, arithmetic mean mortality rates within a 1 K interval are fluctuating. Highest mortality rates can be observed in the temperature region around 29 °C and therefore do not correspond to the highest values of the hazard signal. Elevated mortality rates of the winter season are not relevant for this study and influence mortality rates at outdoor air temperatures lower than 15 °C only.

Evaluating the same risk data with indoor temperatures from the linear building model due to the linear transformation no qualitative change in the data compared to the outdoor climate approach is observed. Note that elevated mortality rates occur at 19 °C as the winter season data with elevated mortality rates is influencing this mean value.

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Using indoor temperatures from the physical building model for analysis it can be observed that mortality rates are increasing at indoor temperatures higher than 26 °C. A further sharp increase can be detected above 31 °C. A similar structure of the data is obtained with the recursive building model. The arithmetic mean mortality rates within 1 K intervals are not as steady in the physical approach as in the recursive approach. Highest mortality rates can be observed at highest hazard signals for both nonlinear models.

3.2.2 Quantitative risk analysis

In a quantitative regression analysis the coefficient of determination R^2 for a linear relation between hazard and risk is evaluated for all four approaches with Eq. (4). The hazard is determined according to Eq. (3) with threshold temperatures in the range of 16 to 30 °C for outdoor air temperatures and 21 to 30 °C for indoor temperatures. Furthermore the relative SD of the estimated vulnerability is calculated. The risk data for temperatures below the threshold temperature are used to calculate a constant base rate of the risk r_0. With this segmented approach it is possible to obtain a consistent structuring of the risk data into heat-effected and heat-uneffected risks. Excess rates in this way are consistent with the preceding data at lower temperatures. The total risk is:

$$r_{\mathrm{tot}} = \begin{cases} \left((1-a)(1-e)h_{\mathrm{in}} + eh_{\mathrm{out}}\right)v + r_0, & \text{if} \quad (1-a)(1-e)h_{\mathrm{in}} + eh_{\mathrm{out}} > 0 \\ r_0, & \text{otherwise.} \end{cases} \tag{14}$$

Risk data for outdoor air temperatures exceeding 15 °C and for indoor temperatures exceeding 20 °C are used, as data points at lower temperatures might be influenced by cold related risk effects. An exemplary regression result with indoor temperatures from the recursive building model and a threshold temperature of 29 °C is shown in Fig. 5.

Only combinations of base rate and heat-effected risk data are used which can be separated according to their median values with high statistical significance. The null hypothesis that data below and above the threshold temperature are independent sam-

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ples from identical continuous distributions with equal medians had to be rejected with a Wilcoxon rank sum test at a 1 % significance level.

Furthermore, only results of the regression analysis with high statistical significance are used for the evaluation, meaning that *p* values obtained from a two-sided *t* test are lower than a significance level of 0.1 %. We compare R^2 calculated for the heat-influenced region of positive hazard values and the relative SD of the estimated vulnerability. All results are plotted in Fig. 6 (top and middle). Furthermore results of an event based regression analysis as described by Scherer et al. (2014) are given for comparison. The mean number of excess deaths per year is calculated with the different approaches. Note that the uncertainty of the number of excess deaths is calculated for a 95 % confidence interval from the relative SD and an assumed normal distribution of the mortality rate.

The outdoor temperature approach and the indoor temperature approach based on the linear model can explain less than 17 % ($R^2 < 0.17$) of the variability in the mortality rates with most threshold values. The outdoor temperature approach delivers relative SDs of the estimated vulnerability higher than 0.15 for threshold temperatures exceeding 23 °C. The approach with temperatures calculated from the linear building model yields an elevated relative SD of the estimated vulnerability exceeding 0.15 at threshold temperatures higher than 26 °C. The physical and recursive building models give higher R^2 than the other two models for threshold temperatures higher than 27 °C. The relative SD of the estimated vulnerability does not exceed 0.13 for threshold temperatures up to 30 °C. Obviously, excess numbers are decreasing with higher threshold temperatures for all hazard signals. Excess numbers are comparable for all approaches ranging from approximately 250 to 40 deaths a^{-1}, albeit in a shifted range of threshold temperatures.

Considering the regression results we see that the choice of the threshold temperature has to balance between low uncertainty and high explained variance. From the given results we can extract estimates with the target that R^2 is maximum and the uncertainty of explained mortality is below 15 % (see Table 2).

4 Discussion

The analysis of the exemplary data set with indoor temperatures calculated with a simple physical and recursive building model has shown a better regression performance at comparable uncertainty than a correlation with outdoor temperatures or temperatures calculated with a linear building model. Especially data with high excess mortality could be assigned to high indoor temperatures. Obviously, appropriate threshold temperatures for indoor and outdoor hazard have to be chosen differently with the indoor threshold temperature being higher than the outdoor threshold temperature. The shifting in threshold temperatures can be understood with the linear building model and the linear hazard approach, $h_{in} = ch_{out}$, as defined in the simplified indoor/outdoor risk concept. If the hazard is based on the hazard definition function as in Eq. (3) it can be stated:

$$\begin{aligned} h_{in} = ch_{out} &= c(T_{out} - T_{out,Th}) \\ &= T_{in} - T_{in,Th} = k_1 T_{out} + k_2 - k_1 T_{out,Th} - k_2 \\ &= k_1 (T_{out} - T_{out,Th}) = k_1 h_{out}. \end{aligned}$$

So we learn three important things from the linear building model: firstly, the parameter c in the simplified risk concept equals the parameter k_1 of the linear building model. Thus, c can be derived from measurement data. Secondly, we can state that the simplified indoor/outdoor risk concept inherits the uncertainty of the linear building model as does the traditional risk concept. Thirdly, comparing different approaches, threshold temperatures have to be transformed according to the building model. This building influence might explain the fact that traditional risk based studies often encounter low outdoor threshold temperatures. For instance, Scherer et al. (2014) derived a threshold temperature of 21 °C from a regression analysis with daily mean outdoor air temperatures to describe heat-related mortality in Berlin, Germany. Huynen et al. (2001) and Kunst et al. (1993) derived a threshold temperature of 16.5 °C for the impact of averaged daily outdoor air temperatures on heat-related mortality among the

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population > 65 years of age in the Netherlands. A threshold temperature of 19 °C was reported by Hajat et al. (2002) for London, UK. Despite the argumentation that weather stations are very often situated at airports or in rural areas and therefore do not represent the UHI effect (Hajat and Kosatky, 2010), the elevated indoor temperatures within buildings is a further valid explanation for low threshold temperatures in an outdoor temperature based risk analysis.

Many studies make use of lag parameters as increasing risk is following a heat wave with a retardation of several days. Typical lag length is documented in the order of 1–2 days (Gosling et al., 2009; Hajat and Kosatky, 2010). Huynen et al. (2001) uses lag periods in a statistical analysis and derived elevated mortality especially for short term lags of 1–2 days. Human physiology is an often used explanation for the lag, but part of this lag can be attributed to building inertia also. However, this effect cannot be covered with the linear building model approach and is only reproduced by the physical and recursive models, which explains the better regression results of these approaches.

Some studies use smoothing techniques to evaluate time-series data (e.g. non-parametric locally weighted scatter-plot smoothing (Hajat et al., 2002) or moving average smoothing (Davis et al., 2003), to differentiate between heat wave events and short-term events of elevated temperature. The thermal capacitance of buildings has the same effect, but is part of the causal chain from the adverse outdoor heat to the effective health impact. Therefore smoothing techniques in heat risk analysis have to be interpreted concerning their description of thermal inertia.

In contrast to other studies such as from Scherer et al. (2014) or Huynen et al. (2001) a separate calculation of excess deaths attributed to additional lag days is not part of this study, which might explain the low absolute number of excess deaths. It is therefore very important to always explain the underlying modeling procedure when comparing calculated risks such as excess number of deaths.

Comparing the recursive model which is based on outdoor air temperatures only and the physical model which includes also solar gains there is not much difference. This proves again that it is most important to cover the general trend of temperature retardation within the building. As the models were calibrated with simulation results from a complex numerical building model, the recursive model includes solar gains also, albeit indirectly. As this model can only cover a mean value of internal gains but has a similar regression performance as the physical model it might be preferable to be used in risk analysis studies due to its simplicity.

The general approach of using indoor conditions can also be interpreted as an alternative hazard definition function. Exemplary for the physical building model we can formulate:

$$h = \mathrm{HDF}(T_{\mathrm{in}}, T_{\mathrm{in,Th}}) = \mathrm{HDF}(T_{\mathrm{out}}, \dot{I}, \tau, \lambda, T_{\mathrm{heat}}, T_{\mathrm{out,Th}}).$$

Following this interpretation the better regression of the physical model in comparison to the outdoor climate can also be explained with the additional input of the radiation data and retardation parameters. The risk approach therefore should also be compared to hazard signals that are already based on temperature and radiation, e.g. mean radiant temperature, PMV or UTCI.

Scherer et al. (2014) proposed an exponential increase in mortality at elevated heat strain quantified in an event based approach in degree days. This exponential approach might also be applied to further indoor/outdoor risk studies. Vice versa, event detection can be refined by including the indoor climate conditions.

The modeling procedure assumes constant building parameters. Nonetheless, during the evaluation period a substantial part of the building structure possibly was refurbished (at 1 % refurbishment rate a^{-1} 10 % of the buildings were altered during the time span) and the representative indoor climate for the group under consideration might have changed. Therefore, a more detailed risk evaluation has to take these changing building conditions for the group under evaluation into account and has to evaluate specific refurbishment measures and their influence on indoor summer climate.

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5 Conclusions

For the evaluation of heat-related risks it is necessary to also consider the indoor effects. Building models are essential in the understanding and evaluation of the indoor climate and allow for a recalculation also of historic indoor conditions. In this way, a risk analysis based on historic outdoor climate data can be also interpreted from the indoor context. Model parameterization can be based on measurement data or on complex building models as shown in this study.

As can be seen in the exemplary regression analysis mortality rates are highly elevated for extreme indoor temperatures. Such high temperatures can be expected during extreme heat waves. So, on the one hand mitigation strategies such as countermeasures to urban heat island have to be evaluated concerning their general impact on the heat-related risk within a city. On the other hand, especially their influence on risk reduction during excessive heat has to be evaluated concerning indoor and outdoor climate.

The developed indoor/outdoor risk concept differentiates between indoor and outdoor hazard. Using this risk concept, the effect of countermeasures to urban heat island, building design and air conditioning on risk reduction can be quantified separately.

We have shown that assuming linearity between indoor and outdoor hazard is not very accurate, but allows for an interpretation of exposition, air-conditioning ratio, and building standard within a traditional risk approach. It was shown that the definition of vulnerability in a traditional risk approach based on the outdoor hazard does not contradict exposition towards the indoor hazard. The inaccuracy of the linear assumption can be prevented by application of a physical or recursive building model. These simplified modeling approaches are considered to be sufficient to calculate the indoor hazard. The significant higher accuracy of the regression results between hazard and mortality rates shows that essential causalities are included in the concept. Especially retardation effects and temperature elevation due to solar gains are covered.

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Smoothing techniques applied to identify hazardous events and lag-identification techniques in former studies have to be discussed in accordance with the building structure. We suggest that these techniques indirectly include the thermal capacitance of the building stock.

The indoor/outdoor risk concept has to be validated with further data. Especially risk data of populations at similar socioeconomic conditions but within different building structures have to be analysed to evaluate the specific influence of the building typology on adverse health effects. Furthermore, groups with different access to air conditioning have to be evaluated for further validation of the attribution of air conditioning on risk prevention. The sensitivity of the findings on the specific building parameters has to be evaluated to define the required quality of the building model parameterization. A spatial refinement of the risk evaluation would also include refinement of the building models to reflect the spatial building diversity of the region of interest.

The findings allow for a better assessment of mitigation strategies, such as greening actions, on the outdoor climate level to reduce heat-related risks. Predictive studies are much more reliable if trends concerning climate change, urban heat island development, building design, and market penetration of air-conditioning equipment can be considered separately, which could be done with the indoor/outdoor risk approach in a plausible manner.

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Table 1. Basic assumptions for the implementation of a Berlin residential building from construction period 1860 to 1918 in the numerical model (in accordance with IWU, 2011, code DE.N.AB.02.Gen).

Component	Specification
General	apartment block, 5 storey, gable roof, wooden beam ceiling, solid brick masonry, heated area $754\,\mathrm{m}^2$, adiabatic south-oriented and north-oriented walls, partial shading by other buildings
Floor	U value = $0.9\,\mathrm{W\,m^{-2}\,K^{-1}}$, $\lambda_{th} = 1.55\,\mathrm{W\,m^{-1}\,K^{-1}}$, $\rho = 1800\,\mathrm{kg\,m^{-3}}$, $c_p = 840\,\mathrm{J\,kg^{-1}\,K^{-1}}$
Windows	U value = $3.5\,\mathrm{W\,m^{-2}\,K^{-1}}$, g value = 0.8
Outer masonry	U value = $1.7\,\mathrm{W\,m^{-2}\,K^{-1}}$, $\lambda_{th} = 0.96\,\mathrm{W\,m^{-1}\,K^{-1}}$, $\rho = 2000\,\mathrm{kg\,m^{-3}}$, $c_p = 840\,\mathrm{J\,kg^{-1}\,K^{-1}}$
Inner masonry	$d = 0.3\,\mathrm{m}$, $\lambda_{th} = 0.96\,\mathrm{W\,m^{-1}\,K^{-1}}$, $\rho = 2000\,\mathrm{kg\,m^{-3}}$, $c_p = 840\,\mathrm{J\,kg^{-1}\,K^{-1}}$
Roof	U value = $1.3\,\mathrm{W\,m^{-2}\,K^{-1}}$, $\lambda_{th} = 1.55\,\mathrm{W\,m^{-1}\,K^{-1}}$, $\rho = 1800\,\mathrm{kg\,m^{-3}}$, $c_p = 840\,\mathrm{J\,kg^{-1}\,K^{-1}}$

d = thickness, λ_{th} = thermal conductivity, ρ = density, c_p = specific heat.

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Table 2. Selected regression results.

Model	T_{Th}	NrD	R^2	rSD	excD a^{-1}
Outdoor	23	160	0.12	0.142	89 ± 25
Linear	26	141	0.12	0.150	81 ± 24
Physical	30	28	0.40	0.130	46 ± 12
Recursive	30	20	0.44	0.125	40 ± 10

T_{Th} threshold temperature [°C], NrD = number of days, R^2 = coefficient of determination, rSD = relative SD of the estimate, excD a^{-1} = number of excess deaths per year (uncertainty calculated with 95 % confidence interval).

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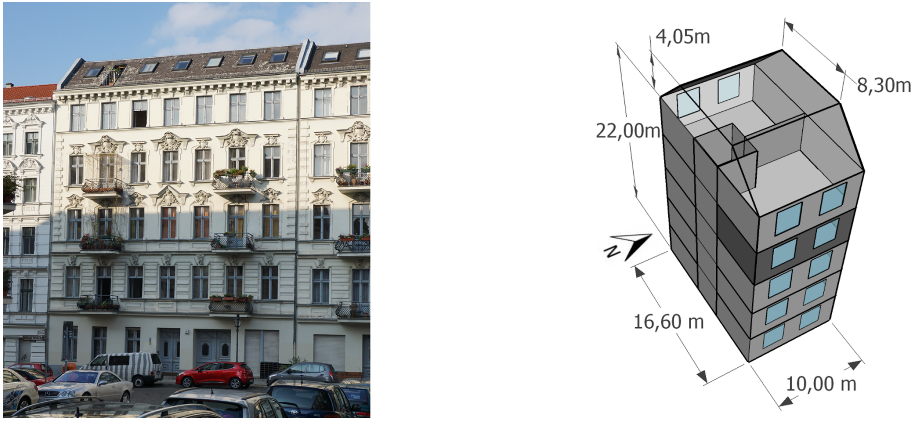

Figure 1. Typical residential building in Berlin (left) and graphical representation of a simplified building for numerical modeling (right). The analysis zone is marked in dark-grey color.

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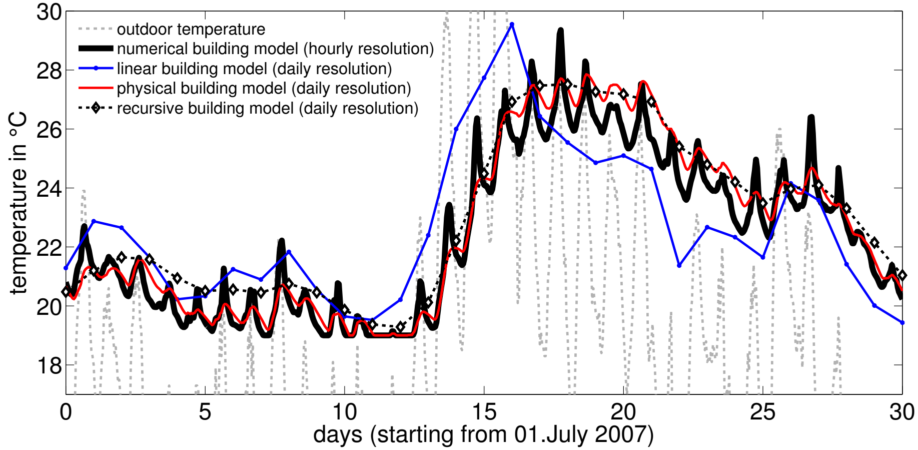

Figure 2. Outdoor air temperature and indoor temperatures calculated from building models for July 2007.

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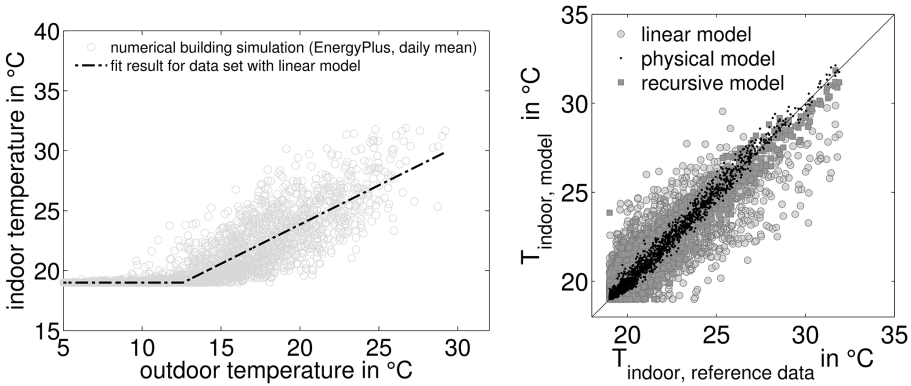

Figure 3. Linear building model fitted to simulation results (mean daily indoor temperature) of a typical residential building of Berlin (left), parameterization results of linear, physical, and recursive building model for the residential building data (right).

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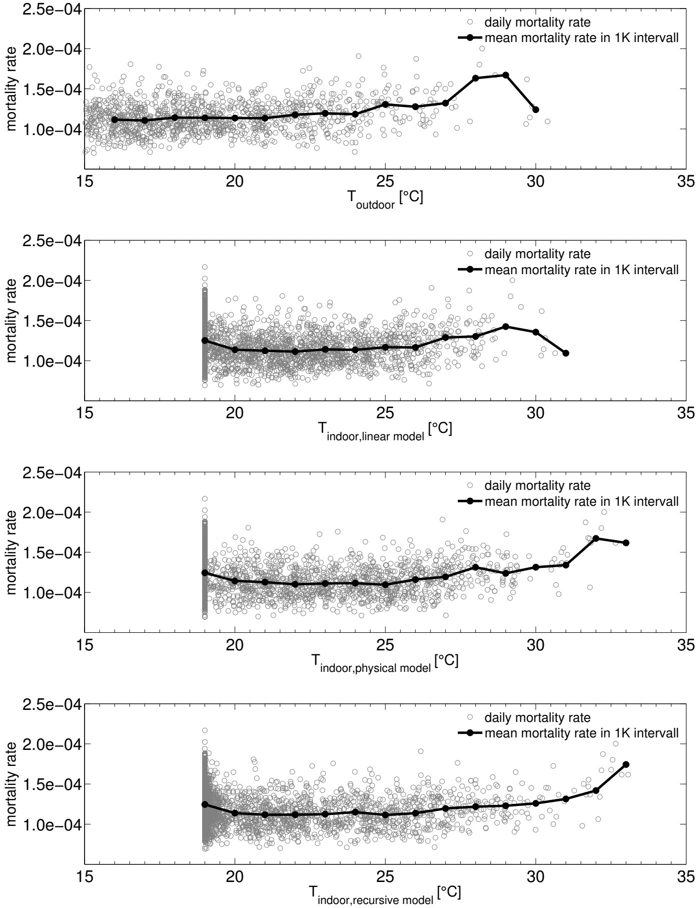

Figure 4. Mortality rate of Berlin citizens aged 65 and older in relation to measured outdoor air temperature, indoor air temperature simulated with linear building model, physical building model and recursive building model (from top to bottom).

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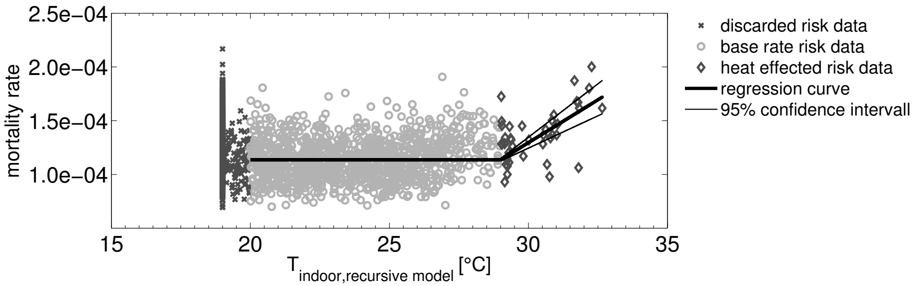

Figure 5. Mortality rate of Berlin citizens aged 65 and older in relation to measured outdoor air temperature and exemplary regression curve for threshold temperature of 29 °C.

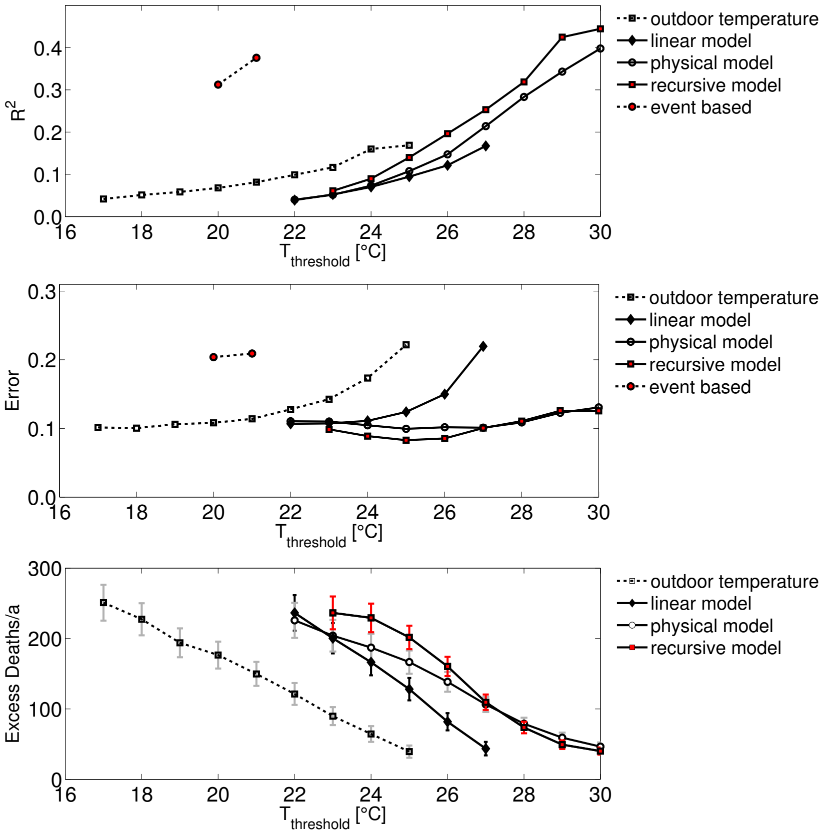

Figure 6. Coefficient of determination R^2 (top), relative SD of the estimated vulnerability (middle) for the time-series regression analysis and calculated excess deaths (bottom) in dependence of threshold temperature for outdoor hazard and indoor hazard calculated with linear, physical, and recursive building model. Results of the event based regression analysis with a significance level of 0.1 % are calculated according to Scherer et al. (2014).

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