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The Impact of the Urban Heat Island Effect on Mortality in the City of Bern

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Abstract

Heat is listed as one of the most critical environmental hazards. With current climate change levels, 37% of all deaths related to warm-season heat can be linked to anthropogenic climate change. Due to rising temperatures, the frequency, duration, and magnitude of hot extremes, particularly heatwaves, are predicted to increase. These hot extremes are further amplified in cities due to the urban heat island (UHI), which reduces the cooling of the urban area compared to its rural surroundings. It is, therefore, crucial to have an accurate and detailed understanding of the UHI within a city and to know which population groups are particularly vulnerable to it. This will enable us to better protect them from the harmful effects of heat in the future. We aim to (1) comprehensively explore the effect of the UHI on all-cause mortality in the city of Bern and (2) identify population groups that are particularly vulnerable to the UHI.

We combine high-resolution temperature and mortality data and implement a case-crossover study design. Using conditional logistic regression and distributed lag non-linear models (DLNM), we account for non-linear and lagged effects of temperature on mortality. From this, we obtain exposure-response relationships quantifying the relative risk (RR) of mean night-time temperature (T_{Night}), mean day-time temperature (T_{Day}), and the urban heat island intensity (UHII) on mortality.

From 2007 to 2018 and across 6273 cases, we found that for extreme nights with T_{Night} as high as 23.3 °C (99^{th} percentile temperature), the RR increases by 45% [95% CI: 1.17–1.79] versus the minimum mortality temperature (MMT) of 18%. For a UHII of 2.4 °C versus 2 °C, the risk increases by 25% [95% CI: 1.0–1.62]. To address the question of vulnerability, we ran analyses stratified by sex, age, and socioeconomic status. We found a similar RR for women [RR: 1.40, 95% CI: 1.06–1.86] and men [RR: 1.51, 95% CI: 1.10–2.08]. However, the RR increases with age (RR of 1.84 for people of 85 years and older, [95% CI: 1.37–2.47]) and deprivation (RR of 1.76 for SSEP 1, [95% CI: 1.20–2.59]).

Our findings suggest that, already today, the UHI has an effect on all-cause mortality in the city of Bern and that we need to include elderly and more deprived people as vulnerable groups when planning for a hotter future in cities.

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Abbreviations

DLNM Distributed Lag Non-Linear Model

MMT Minimum Mortality Temperature

RR Relative Risk

SNC Swiss National Cohort

SSEP The Swiss Neighbourhood Index of Socioeconomic Position or Swiss-SEP

T_{Day} Daily Mean Temperature

T_{Night} Mean Night-Time Temperature

UCB Urban Climate Bern

UHI Urban Heat Island

UHII Urban Heat Island Intensity

°C Degrees Celsius

1 Introduction

Due to anthropogenic climate change, temperatures are rising, and they will continue to do so in the future. Consequently, the frequency, duration, and magnitude of hot extremes, particularly heatwaves, are predicted to increase [1]. This shift towards a hotter climate comes at a high price for humanity because exposure to non-optimal temperatures is one of the most critical environmental hazards [2]. A study including 384 locations in 13 countries found that heat-related mortality on an annual basis lies at 0.42% [0.39–0.44%] and is still much smaller than the one related to cold (7.29% [7.02–7.49]) [3]. The value increases to 1.6–2.0% when only the summer period is considered [4, 5]. However, 37% [20.5–76.3%] of deaths related to warm-season heat can be linked to anthropogenic climate change [6], and it is estimated that globally, more than 490,000 people die due to heat per year [7]. For Switzerland, a recent study found 9.19% of excess mortality associated with non-optimal temperatures from 1969 to 2017. 0.28% [95% CI[1]: 0.18, 0.37] of this excess mortality were related to heat, translating into an additional 181 deaths per year [8]. During the exceptionally hot summer of 2003, 1000 excess deaths may be attributed to heatwaves [9, 10]. For the hot summers of 2015 and 2018, there was an additional death toll of 800 and 200 people, respectively [9, 11, 12], and a recent study on the extreme summer of 2022 found 600 excess deaths. 60% of these deaths could be attributed to climate change, with the largest impacts on elderly women [6].

The impact of heat on human health depends on the intensity and the duration of the event, the acclimatisation, the infrastructure, and the preparedness of a community, but also on each individual's ability to adapt to and cope with high temperatures. Other environmental stressors (e.g., air pollution, pollen, and noise) further aggravate the effects of heat on health. Among the symptoms of heat exposure are heat exhaustion and heat stroke [13]. However, extended periods of exceptionally high nocturnal and diurnal temperatures also introduce cumulative physiological stress on the human body. This stress aggravates respiratory and cardiovascular diseases (among others) [14, 15] and makes heatwaves one of the most dangerous natural hazards, resulting in significant excess mortality [13, 14].

There have been many studies on the effect of heat on human health and on who is affected most [16, 17, 18, 19]. Vulnerable groups include elderly people, pregnant women, and people with pre-existing conditions like cardiovascular diseases [6, 15, 16, 20, 21]. People with a migration background are affected more strongly because they are often exposed to several risk factors (e.g. lower socioeconomic status, less access to healthy food, higher exposure to noise or air pollution at their place of residence) simultaneously [22, 23]. High heat stress can also affect productivity and, consequently, our economy by reducing physical work capacity and motor-cognitive performance. There are estimates that over 1 billion people are exposed to high heat episodes at their workplace, and about one-third of those exposed workers experience adverse health effects [19]. Another important factor is the level of urbanisation of the direct environment. The IPCC (2021) states with very high

[1]A confidence interval (CI) is expected to typically contain the parameter we estimate. A 95% CI contains the parameter being estimated 95% of the time. The degree of confidence describes the long-run proportion of CIs which contain the true value. For example, out of all CIs we compute at the 95% level, 95% of them should contain the parameter's true value.

confidence that cities aggravate human-induced warming locally. Today, a large share of the human population lives in cities. With continuous world population growth and ageing, this proportion is set to increase up to 68% by the year 2050 [1, 24]. The combination of further urbanisation and an increased frequency of hot extremes will result in more severe heatwaves and a larger number of people at risk.

During heatwaves, air temperatures usually reach considerably higher values within a city than in the surrounding rural areas. This effect can be explained by the urban heat island (UHI), which results from differences in urban and rural meteorology [25]. In the context of human health, the canopy layer UHI, which describes the difference in near-surface air temperatures between street level and the highest buildings (where people move) and rural areas [26], is most relevant [27]. Due to its higher heat capacity, the built environment (e.g. streets, houses and sealed surfaces) influences the radiation and energy balance, i.e. how radiation and energy are distributed within the city. Since most of the city's surfaces are dry and there is less vegetation and ventilation than in rural areas, a larger proportion of the incident short-wave radiation is stored in building materials as sensible heat. The absorbed energy is released into the environment through long-wave radiation by humans felt as heat. Unlike in rural areas, however, the long-wave radiation cannot escape directly into space. It is emitted and re-absorbed between the various buildings and ultimately remains to a large extent in the urban canopy layer, thus increasing the heat emission to which the urban population is exposed. The latent heat flux (evaporation), which would have a cooling effect, is reduced because there is less water and vegetation available [27, 28, 29]. This results in a UHI following a diurnal pattern [26], which varies depending on weather conditions and season and is pronounced most strongly on days with clear skies and no winds during summertime [30]. UHI minima are observed during the day. After reaching its maximum in the evening after sunset, the UHI remains pronounced during the night [26]. While rural areas cool down as a result of outgoing long-wave emissions, the built environment releases the energy stored during the day and traps it within the city, and thus, the additional heat suppresses night-time cooling. Dense urban development with insufficient air corridors and few green spaces and water areas that provide evaporative cooling further intensify the effect [28]. The reduction of night-time cooling has a major influence on human health because it reduces the body's ability to recover from the heat stress of the previous day. Consequently, people's well-being and health are compromised, and the impacts of day-time heat exposure on human health mentioned above are aggravated [31, 32].

Over the last few years, the number of studies on the influence of the UHI (and, in general, heat in cities) on human health has increased a lot. Many of these studies were conducted in major cities of Europe, e.g. Madrid, Barcelona or London [15, 31, 32], which have a large spatial extent and are home to several million people. In Switzerland, cities are much smaller and show different structural and topographic characteristics. The smaller geographical extent and the lower population numbers and densities add an extra complexity. The complexity lies, on the one hand, in adequately representing such small-scale temperature variability and, on the other hand, in extracting clear and robust signals regarding mortality risk for small study populations. Still, there is a considerable amount of studies on the influence of heat and the UHI on health in Swiss cities (e.g. [9, 10, 16, 33]). For these kinds of studies, detailed knowledge about the temperature distribution within a city is essential, especially when combined with information about the distribution of (vulnerable) people across the city. By identifying and considering the effects of non-ideal temperature exposure and their patterns, we can help create adequate urban planning measures. The more detailed (spatially and socio-demographically) we understand the development and the effects of heat, the more specific and, correspondingly, more effective measures can be developed. Such locally specific climate adaptations enable the most ideal use of resources and a pleasant and healthy life in cities in the future.

One of the largest difficulties in this context is that high-resolution temperature measurement networks in cities are rare. Luckily, in the city of Bern, the Urban Climate Bern (UCB) project set up and maintains a dense temperature measurement network which spans the whole city and its surroundings. Hence, the main aim of this study is to (1) comprehensively explore the effect of the UHI on all-cause mortality in the city of Bern and (2) identify population groups that are particularly vulnerable to the UHI. The main novelty of this study is that we combine high-resolution (50 m x 50 m) temperature data with high-resolution mortality data from the Swiss National Cohort (SNC). We apply state-of-the-art statistical analysis by implementing a case-crossover study design and by using conditional logistic regression and distributed lag non-linear models (DLNM) for our analysis. We are currently unaware of other studies that assess the impact of the UHI on all-cause mortality with such highly resolved data for Switzerland. Below, we provide an overview of the study site and a detailed description of the data sets and the methodology used in our analyses (Section 2). The results are summarised in Section 3, followed by a discussion and an outlook on future study possibilities in Section 4. We draw a conclusion in Section 5.

2 Methods and Material

2.1 Study Setting

The city of Bern is a medium-sized city in Switzerland with a geographical extension of 52 km^2 situated at a mean elevation of 550 meters above sea level. The city is located in the central-western part of the Swiss midland, nestled between the Alps to the south and the Jura mountains to the north. Its complex topography characterises Bern: Several hills (Könizberg, Bantiger, and Gurten) and valleys (Aaretal, Köniztal, Wangental, and Worblental) shape the topography of the city and its surroundings. In addition, the river Aare flows through the city and divides it into a western and an eastern part. Air temperature inversions, cold air drainage, and predominant south-westerly and north-easterly winds are some local effects that emerge from the city's natural topography [34]. Summers in Bern are warm and humid, with a mean temperature of 18.0 °C and a mean precipitation amount of 322 mm throughout the climatological reference period of 1991 - 2020 [35]. The city of Bern is currently divided into six administrative city districts [36] and is home to a population of approximately 134,500 people. The greater metropolitan area includes 425,800 people [37]. According to the statistical division of the canton, the city's population consists of 65,215 male and 69,291 female persons, 101,530 of whom are Swiss, and 32,976 belong to another nationality [38].

2.2 Temperature Data

We gathered two temperature data sets for the summer months of June, July, and August of the years 2007 until 2018 for the city of Bern: (1) Modelled mean night-time temperature (T_{Night}) from the Urban Climate Bern (UCB) project of the Geographical Institute of the University of Bern, and (2) daily mean temperature (T_{Day}) from the official MeteoSchweiz weather station at Bern-Zollikofen [39]. From the T_{Night} data set, we derived the urban heat island intensity (UHII) across the city of Bern (Section 2.2.1).

T_{Night} data from 2007 onward was provided as daily raster files. The grid resolution is 50 m x 50 m, covering an 11.45 km x 10.7 km area. For each night (10 pm until 6 am) of the summer months of June, July, and August, T_{Night} was modelled and mapped across the city of Bern [40]. The input data for the modelling was collected through a dense urban air temperature measurement network (Figure 1). This network consists of 70 to 90 low-cost devices that recorded air temperature every ten minutes from mid-May to mid-September 2018 until 2021. For more information concerning the measuring network, see Gubler et al. (2021) [41]. Based on high-resolution land cover data, a land use regression model was run and calibrated against the station data. The data we used in this study is the T_{Night} output of this modelling. The exact modelling process and the output data set are described in Burger et al. [40, 42]. All T_{Night} raster files were combined in one large stack holding the full T_{Night} information over the whole study period. The T_{Day} data consists of a single point measurement per day. Two days containing NAs were removed and not included in the study period.

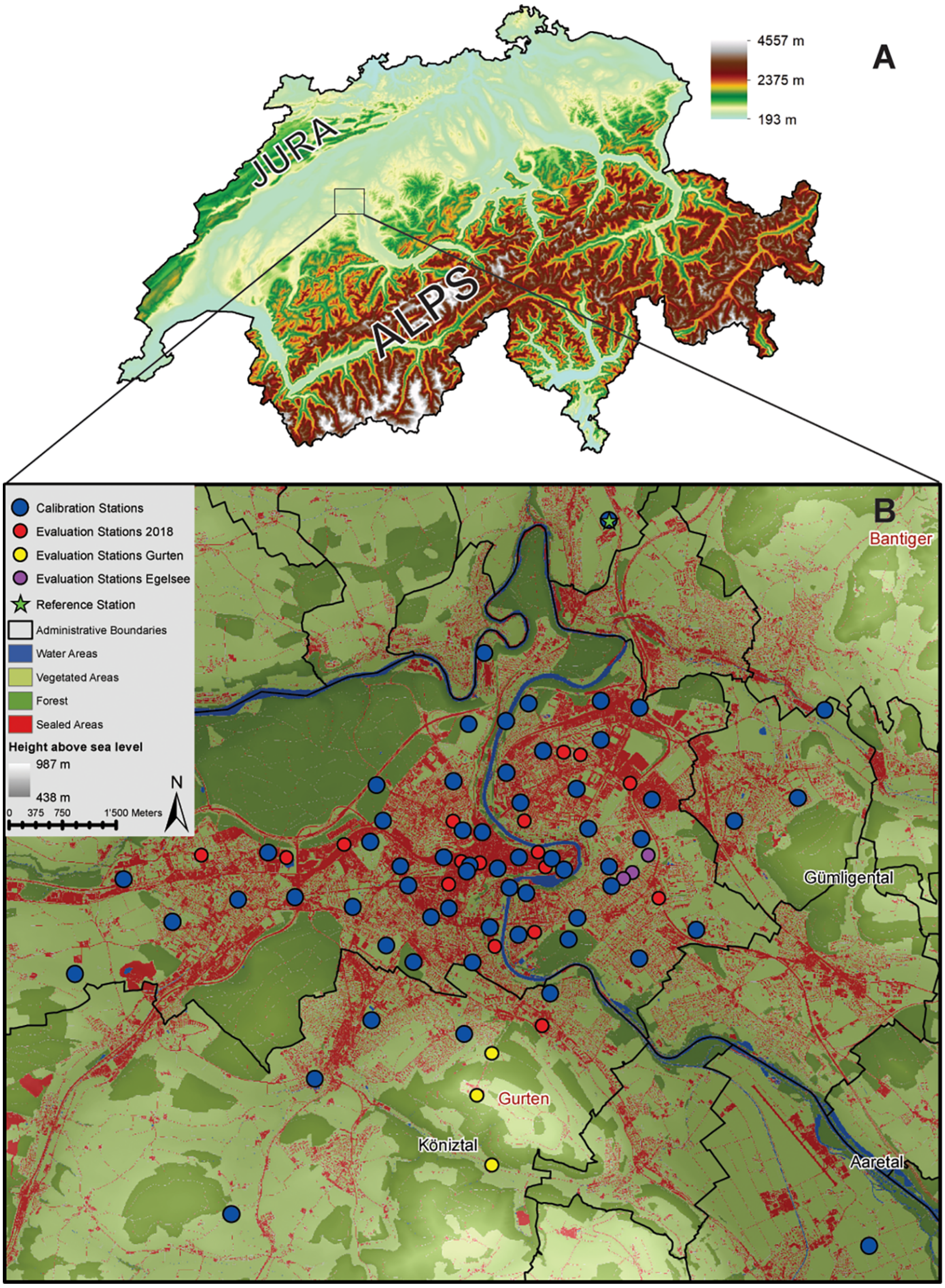

Figure 1: Location of the study site in the context of Switzerland including the main topographical features of the country (A). Detailed topography, land cover, and location of the air temperature measurement stations for the city of Bern and its surroundings (B). Source: Burger et al. (2022) [40].

2.2.1 Derivation of the Urban Heat Island Intensity

According to Gubler et al. (2021) and Burger et al. (2021), we used the temperature at the location of the official MeteoSwiss station in Bern-Zollikofen (46.99° N / 7.46° E) as a rural reference to determine urban-rural temperature differences. Following the traditional definition, we define the urban heat island intensity (UHII) as the difference in air temperature between any grid cell and the grid cell of Bern-Zollikofen. We extracted T_{Night} at Bern-Zollikofen for each day of the study period, subtracted this rural reference value from any other raster grid cell, and obtained the mean UHII (Equation 1). Each positive UHII value is assumed to be higher than the rural reference temperature due to the UHI.

$$UHII = T_{Station} - T_{Zollikofen} \tag{1}$$

2.3 All-Cause Mortality Data

The mortality data used in this study was collected in the context of the Swiss National Cohort (SNC). The SNC is a "long-term, population-based multipurpose cohort and research platform" that emerged from a collaboration between several Swiss public health institutes. In the current version of the SNC data set, census data from 1990 and 2000 were linked to mortality, life birth, and emigration records until 2019, to the register-based census and to annual structural surveys from 2010 onward [43].

For this study, we extracted the SNC data of people who lived in the city of Bern and died there during one of the summer months between 2007 and 2018. The start of the study period is defined by the availability of the T_{Night} data. Temperature data would be available for the years after 2018. However, SNC data was not. To run our main analysis, we extracted the unique SNCID, the date of death, and the geocode of the individual's place of residence one year before they died for each individual. For different stratified analyses, we included the variables sex, date of birth, and socioeconomic status. The variable socioeconomic status was incorporated into the analyses because there is a clear relation between individuals' socioeconomic status and their health or mortality, respectively [44, 45]. This relation is also observable across Switzerland when considering the Swiss Neighbourhood Index of Socioeconomic Position (SSEP) [46, 47]. The SSEP is a measure of socioeconomic position, which examines the impacts of socioeconomic characteristics of a neighbourhood that do not depend on an individual's characteristics or behaviour. The first version of this index (SSEP 1) is based on four variables of the census of the year 2000: rent per square meter, education level, occupation, and overcrowding. The SSEP 1 includes 1.27 million overlapping neighbourhoods consisting of approximately 50 households. It has become an important tool for epidemiological studies [48]. A more in-depth explanation of the SSEP data is provided in Appendix A.

2.4 Data Linkage

We linked the temperature and mortality data to determine each individual's temperature exposure. The T_{Day} measurements, which were all measured at Bern-Zollikofen, could be linked directly to the mortality data based on the individual's date of death. In the case of the higher resolved T_{Night} and UHII data, we assigned a unique ID to each grid cell of the raster. Based on the location of the individual's place of residence one year before their death and this ID, we linked the mortality case to the corresponding temperature grid cell. This linkage enabled us to extract a temperature time series for each individual over the whole study period (Figure 2). As a consequence of the SNC data set structure (Section 2.3), this could be done on an annual basis for all individuals who died after the year 2010. For individuals who died before or during 2010, the location of their residence is based on census data from the year 2000. For the y-coordinates of the year 2000, additional data pre-processing was needed. These coordinates were missing the leading digits 1 or, in some cases, 10. They were reset based on the digit length of the whole coordinate (e.g., the y-coordinate "1230401" was stored as "230401" and the y-coordinate "1076892" as "76892" in this column of the original data set. To obtain the correct coordinates, we reset them to "1230401" and "1076892"). A total of 6,440 mortality cases were distributed across 3,371 unique temperature cells. However, the grid cells along the border of the temperature raster contained NAs, which led us to exclude 167 mortality cases (2.59%) that were located within these grid cells.

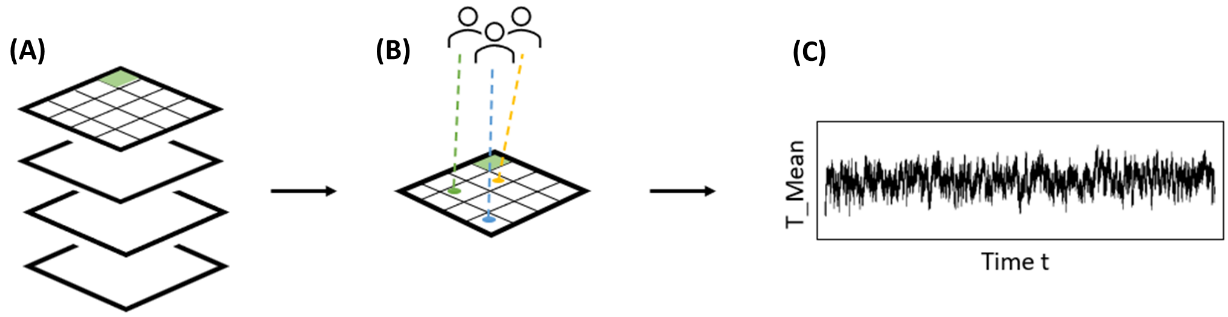

Figure 2: Schematic of the temperature-mortality data linkage: (A) All temperature raster files were combined in one large raster stack, each holding all the T_{Night} and UHII information, respectively. Each grid cell was assigned a unique ID (green). (B) The temperature and mortality data were linked based on the location of each individual's place of residence and the corresponding raster cell ID. (C) From this, we extracted the temperature time series for each individual over the whole study period.

2.5 Statistical Analysis

Since individual-level information on our study population is available, a suitable study design for this work is the case-crossover design [49]. It enables us to investigate transient effects of intermittent exposure, namely the impact of varying heat exposure on an individual's mortality risk. The fact that the study is conducted on the individual level comes with the advantage that we can study individual risk factors and, therefore, analyse the effect of the UHI more accurately. In a case-crossover study design, each subject serves as its own control, preventing the splitting of study populations into an exposure and control group and ensuring that the controls are representative of the study population. Additionally, characteristics of the study subject that are constant over time are accounted for. For example, without individual-level data, we assume the number of smokers on a given day in a city to be the same across time. However, when using individuals as their own control, we account for characteristics like smoking in a more precise way. With the case-crossover study design, we only have to consider changing characteristics and external factors as confounders. However, we must remember that the analysis stays on an individual level, and we cannot infer information on a neighbourhood level. We created the controls mentioned above by using the function `CXover.data` in `R` [50]. With this function, an individual's day of death is defined as case day. All the same weekdays (as the weekday of the day of death) of the month are extracted as control days for this individual. For example, if someone died on July 27th, 2017 (Thursday), this day is set as case day. All other Thursdays of July 2017 serve as control days for this individual.

Besides the availability of individual-level mortality data, we must also consider typical characteristics of the temperature-mortality association to create a suitable study design. Temperature shows non-linear and delayed effects on several health outcomes, including mortality (e.g. [33, 51]). For both high and low temperatures, the risk of mortality increases at extremes above and below optimal values, where the risk is minimal. Furthermore, many studies report short-term effects of high temperatures on the exposure day and within the three following days [52, 53, 54]. Because of this exposure-response relationship between temperature and mortality, we investigate the lag days 0 to 1. Consequently, we only keep the temperature values of the day of death and the previous day and the corresponding values of the control days for each individual. We run our main analysis with a data set containing the following variables: Date of death, SNCID, status (case or control day), T_{Night}, T_{Day}, and UHII for the case and control days at lag 0 and lag 1. An overview of the different model runs and which data sets were used for each run are given in Section 2.6 and in the Appendix.

We implement a conditional logistic regression to investigate the risk and control for several confounders simultaneously. We use generalised negative models (GNM) with a binomial family that links the mortality status with a series of predictors [55, 56]. The non-linear and lagged effects of temperature are modelled using distributed lag non-linear models (DLNM) [55, 57]. DLNMs extend the simpler distributed lag models (DLM) by relaxing the strong assumption of linearity of the exposure-response relationship. This extension enables us to model complex exposure-response relationships, where the risk varies depending on the intensity of exposure and the lag [58, 59]. We define an exposure-response function and a lag-response function and combine them to represent the exposure-lag association. We use a quadratic B-spline function with internal knots at the 50th and 90th percentile of the temperature range to include the specific temperature-mortality association. This function is applied directly in the model formula and combined with functions of time to account for long-term, seasonal, and weekly trends. To account for both the predictor and the lagged effects, we specify two parametrisations of the exposure series to model the relationship in the dimensions of the predictor and the lag. The transformation is carried out by the `crossbasis()` function of the `dlnm` package in `R`. We applied the transformations to the temperature series, using a natural spline function for the response. From this, we obtain bi-dimensional exposure-lag-response associations between temperature and all-cause mortality. Finally, we computed the relative risk (RR) with 95% confidence intervals (CI). The RR values in this study represent the risk of a temperature increase versus the temperature where the mortality risk is at its minimum, the minimum mortality temperature (MMT). The MMT that is representative of this study is at 18 °C. To obtain the best representation of the risk associated with the UHII, we first tested three different crossbases. One is linear, one is non-linear using a natural spline, and one uses a threshold function (i.e., no effect until a level of UHII above which the risk increases linearly). According to the Akaike information criterion (AIC), the one using a threshold results in the best model, so we ran all analyses including UHII data using a crossbasis with a threshold at a UHII of 2 °C.

For analyses stratified by sex, age, and socioeconomic status, we also included sex, date of birth, and socioeconomic status (Section 2.3). Based on the variable sex, we could directly divide the study population into male and female cases. The age had to be calculated based on the variables date of birth and date of death. Afterwards, we split the study population into the following age categories: < 65, 65 - 84, and ≥ 85 years. To study the influence of socioeconomic status on the temperature-mortality relationship, we used SSEP tertiles. Due to missing data, 324 cases (5.16%) had to be removed for this analysis. The SSEP is used to compare cities across the whole of Switzerland. However, if we only look at the city of Bern, there are relatively few people who, compared to Switzerland, fall into the lowest SSEP category (Cat. 1: 1142, Cat. 2: 1725, Cat. 3: 3082). Thus, we re-calculated the SSEP tertiles relative to the city of Bern. This re-calculation gave us three new categories containing 1938 cases for the stratified analysis. All analyses were performed in `R, version 4.2.0 (2022-04-22)`, using the `gnm` and `dlnm` packages.

2.6 Model Overview

Table 1 gives an overview of the different models we ran in the context of this study. First, we ran all main analyses for the whole study population and the whole study period. We used the T_{Night}, T_{Day}, UHII data, and the corresponding data combinations (Models 1 - 6). In the second step, we investigated the mortality risk associated with temperature for several subgroups. We divided the study population by sex, age, and socioeconomic status (Section 2.5). We ran the stratified analyses (S1) for the T_{Night} data only (Models 7 - 17), for T_{Night} accounted for UHII (Models 18 - 25), and for T_{Day} accounted for UHII (Models 26 - 33).

For a second stratified analysis (S2), we divided the study population into two groups: one with high UHII exposure and one with low UHII exposure. Each individual was assigned to one of the two subgroups based on the mean UHII at their place of residence. We used a threshold of a mean UHII of 1 °C to separate the study population, which resulted in 4,857 cases in the low and 1416 cases in the high UHII category. A higher threshold would not have been possible since this would have resulted in fewer cases in the high UHII group. In the next step, we used these subgroups to extract the RR of increased T_{Day} and T_{Night} (Models 34 - 35).

In the last step, we ran a time-stratified analysis (S3). We created two subsets, one containing the cases of June and one containing the cases of August. The analysis aimed to identify the possible effects of acclimatisation and adaptation on mortality risk. Again, we ran the analyses for the T_{Night}, the T_{Day}, the UHII data, and the corresponding combinations (Models 36 - 40).

Table 1: Overview on the models that were run in the course of this study. The first six models were run as main models without any stratification (Main). Models 7 to 40 were used to run stratified analyses. S1 models are stratified by sex, age, and socioeconomic status. S2 models by high vs. low UHII and S3 by June and August. Models labelled with an asterisk (*) were not considered for the final results but can be found in the Appendix.

Nr.	**Analysis**	**Temperature Data**
1	Main	T_{Night}
2	Main	T_{Day}
3*	Main	T_{Night} + T_{Day}
4	Main	UHII
5	Main	T_{Night} + UHII
6	Main	T_{Day} + UHII
7 - 17	S1	T_{Night}
18 - 25	S1	T_{Night} + UHII
26 - 33	S1	T_{Day} + UHII
34	S2	T_{Day}
35	S2	T_{Night}
36*	S3	T_{Night}
37*	S3	T_{Day}
38*	S3	UHII
39*	S3	T_{Night} + UHII
40*	S3	T_{Day} + UHII

3 Results

Below, we present the results of this thesis. The analysis stratified by sex, age, and socioeconomic status is shown for T_{Night} accounted for UHII. For the matter of transparency, the analysis for T_{Night} only and for T_{Day} accounted for UHII can be found in the Appendix.

3.1 Data Description

A general overview of the temperature and mortality data for each year of the study period is given in Table 2. We included 6,273 mortality cases between 2007 and 2018 in the city of Bern. Overall, the cases are distributed relatively evenly across all years of the study period. The largest number of cases was registered in 2013, with 578 cases (9.21% of all cases). The fewest people died in 2016 (489 cases, 7.80%). T_{Night} values averaged over the whole summer period of each year range from 14.3 °C in 2007 and 2014 to 16.6 °C in 2016. The overall mean is at 15.3 °C. As expected, mean T_{Day} values are higher than T_{Night}. They range from 17.1 °C in 2007 and 2014 to 19.8 °C in 2015, with an overall mean of 18.3 °C. For T_{Night} and T_{Day}, most of the higher values were registered during the second part of the study period. For the UHII, no clear patterns can be observed. All values lie between -0.30 °C (2018) and -0.36 °C (2007), resulting in an overall mean of -0.33 °C.

Table 2: Descriptive statistics of the temperature and mortality data used in this study. Included for each summer of the study period are the number of deaths, T_{Night}, T_{Day}, and UHII.

Year	**Number of Deaths (%)**	**T_{Night} [°C]**	**T_{Day} [°C]**	**UHII [°C]**
2007	499 (7.96)	14.3	17.1	-0.36
2008	496 (7.91)	14.7	17.6	-0.34
2009	510 (8.13)	15.4	18.3	-0.33
2010	508 (8.10)	15.3	18.1	-0.34
2011	541 (8.62)	14.9	17.6	-0.34
2012	555 (8.85)	15.4	18.2	-0.33
2013	578 (9.21)	15.3	18.3	-0.31
2014	513 (8.18)	14.3	17.1	-0.34
2015	550 (8.77)	16.6	19.8	-0.31
2016	489 (7.80)	15.4	18.2	-0.34
2017	495 (7.89)	16.1	19.3	-0.33
2018	539 (8.59)	16.3	19.6	-0.30
Total	6273 (100)	15.3	18.3	-0.33

The T_{Night} distribution and the corresponding UHII across the study site are shown for two example nights in Figure 3. We can see that the study area consists of regions with a high proportion of built environments in contrast to neighbourhoods with lots of green spaces, which represent areas with different levels of heat exposure for the study population.

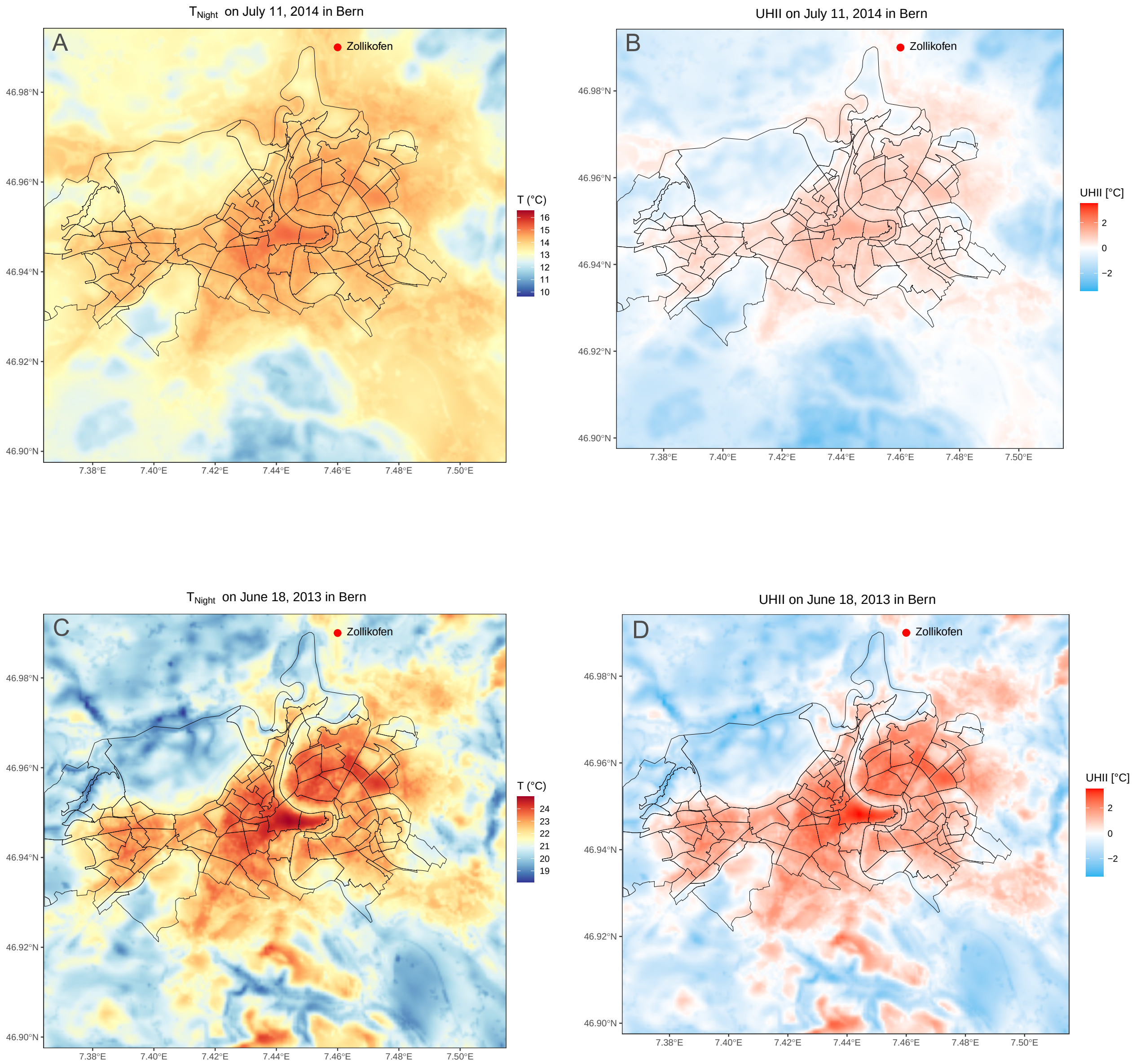

Figure 3: Comparison of T_{Night} across the city of Bern and its surroundings including the rural reference station at Zollikofen (red dot) during the nights of (A) July 11th, 2014 and (C) June 18th, 2013. (B) and (D) show the corresponding UHIIs during the two nights.

On July 11th, 2014 (Figure 3A), T_{Night} values range from 11 °C to 15 °C. The temperature distribution across the city and its surroundings is relatively flat. The main exception is the Gurten hill, where temperatures are around 2 to 5 °C lower than in the city. Even at these low T_{Night} values, the inner city is warmer than the surrounding areas. If we look at the UHII in Figure 3B, we see that the maximum UHII is 1.49 °C. The strongest negative deviation is -2.77 °C on the Gurten hill.

On June 18th, 2013 (Figure 3C), we see one of the hottest nights of the study period. T_{Night} values range from 18 °C to almost 25 °C, meaning that in parts of the city, people experienced a tropical night (T_{Night} > 20 °C) [60]. This night followed a day with a T_{Day} of 25.5 °C, and the two days before were hot with T_{Day} > 20 °C. We can observe an apparent distinction between the city's built environment and its surroundings, like forests and agricultural areas. Again, we observe the highest T_{Night} values in the inner city, followed by the industrial area in the Northeast (BernArena). Just next to the inner city, we can detect the river Aare, which flows through the city and has a strong cooling effect. The same patterns are observable when looking at the UHII during this night (Figure 3D). Maximum UHII values reach 3.49 °C in the inner city, while the surroundings do not heat up so strongly. In the surrounding areas, the lowest UHII values are at -3.39 °C. The Aare reduces the UHII within the city to values around 0 °C.

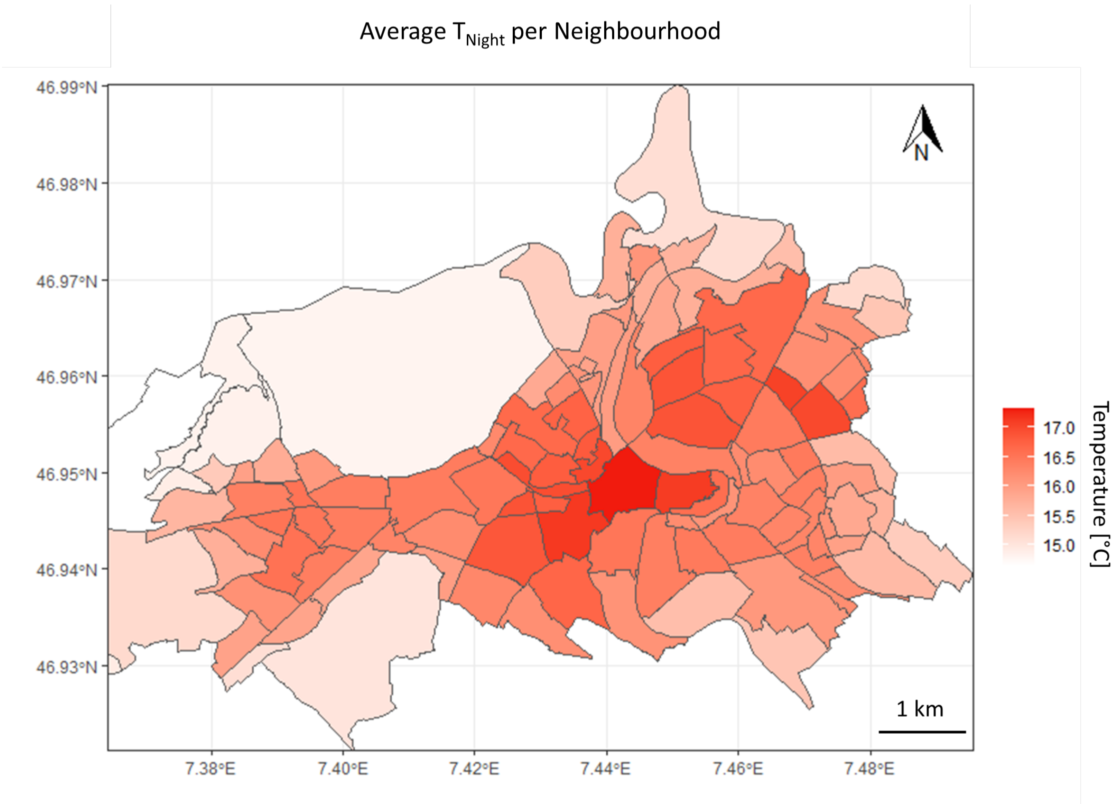

Figure 4: Average T_{Night} during the summer months June, July, and August of the years 2007 until 2018 per neighbourhood of the city of Bern.

Similar patterns can be observed when we consider T_{Night} averaged over the whole study period (Figure 4). The neighbourhood with the highest average T_{Night} is the Upper Old Town (17.32 °C), followed by Monbijou (17.13 °C), the Lower Old Town (17.11 °C), and the BernArena (17.06 °C). In these neighbourhoods, T_{Night} values range from 6.45 °C to 26.57 °C over the whole study period. On the opposite end, the lowest T_{Night} averages are observed in Riedern (14.65 °C), Grosser Bremgartenwald (14.81 °C), and Eichholz (14.85 °C). T_{Night} over the whole study period ranges from 5.46 °C to 24.16 °C in these neighbourhoods.

3.2 Temperature-Mortality Associations

Figure 5 shows the exposure-response associations we modelled for (A) T_{Night}, (B) T_{Day}, and (C) UHII. The curves represent the cumulative RR of mortality (with 95% CI) over a 1-d lag period for each temperature value in the observed range. The RR represents the change in mortality risk at any given temperature compared to a reference temperature. For T_{Night} and T_{Day}, the reference temperature is the MMT, set at 18 °C, where the mortality risk is lowest. For the UHII, the reference intensity is set at 2 °C. A total of 6,273 mortality cases were considered for these analyses.

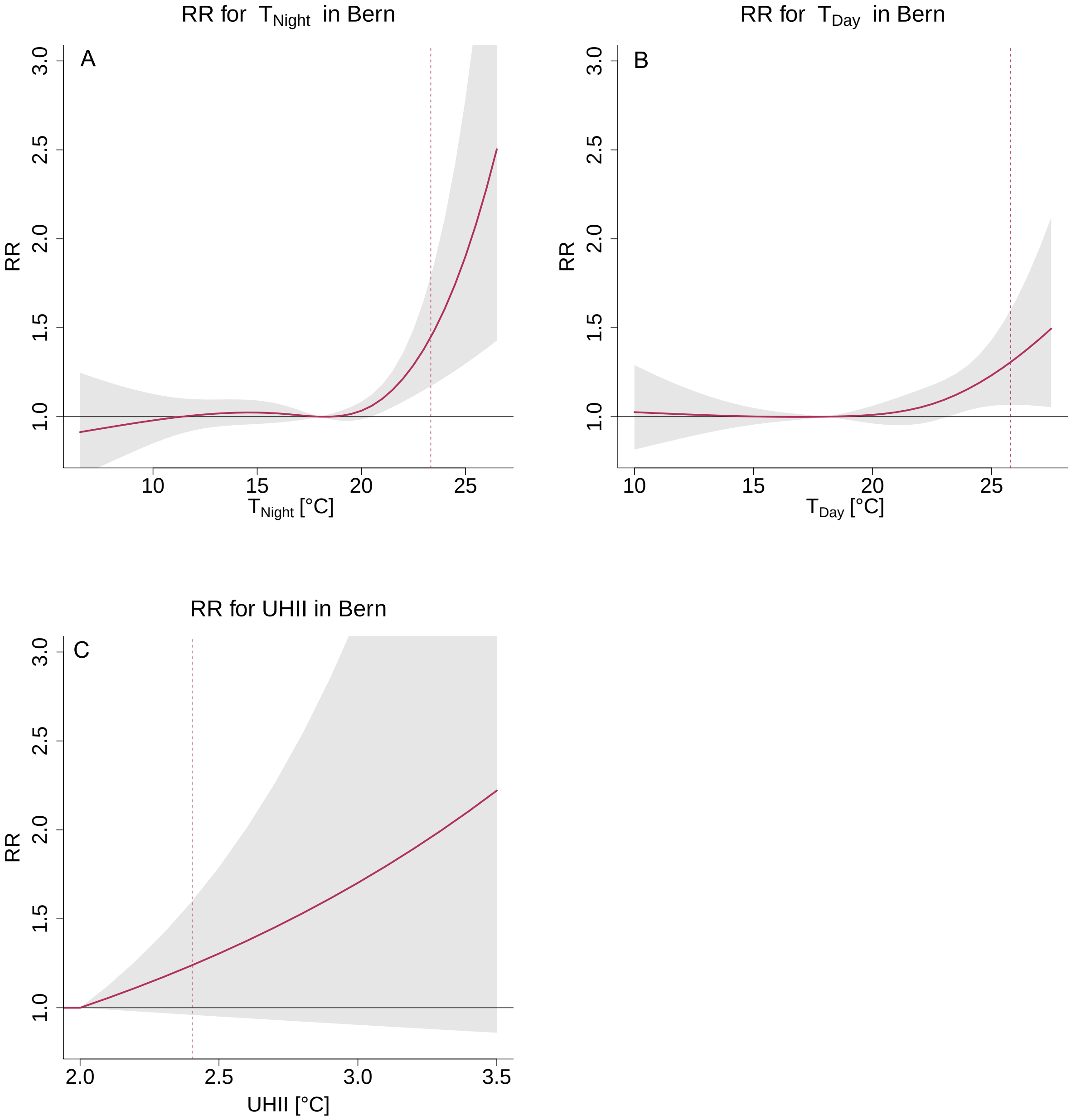

Figure 5: ERFs representing the temperature-mortality association in terms of RR (with 95% CI, shaded grey) for a 1-day lag of (A) T_{Night}, (B) T_{Day}, and (C) UHII versus a MMT of 18 °C for (A) and (B) and versus a UHII of 2 °C for (C) in the city of Bern. For comparison, the vertical dashed lines represent the 99^{th} percentile temperatures.

Extreme-heat nights with T_{Night} of 23.3 °C (corresponding to the 99^{th} percentile temperature of T_{Night}) were associated with an increase in mortality risk of 45% [95% CI: 1.17–1.79] versus the MMT (Figure 5a). Extremely hot days, defined as days with T_{Day} above the 99^{th} percentile of the temperature distribution (25.8 °C), were associated with an increase in mortality risk of 31% [95% CI: 1.07–1.60] versus the MMT (Figure 5b). For a UHII of 2.4 °C (99^{th} percentile temperature of UHII), the RR increases by 24% [95% CI: 0.96–1.60]. Table 3 indicates the RR for the 99^{th} percentile for T_{Night}, T_{Day}, and UHII (with 95% CI). For T_{Day} accounted for T_{Night}, the effect of T_{Day} disappears (RR: 0.90 [95% CI: 0.55–1.45]). It seems that it is taken by T_{Night} because the two are highly correlated (corr = 0.92). Consequently, we did not consider the models, including both T_{Night} and T_{Day}, in further analyses. The RR of 1.57 [95% CI: 1.01–2.45] for T_{Night} accounted for T_{Day} is to be considered with caution. The RR for T_{Night} and T_{Day} accounting for UHII are very similar to the RR values without accounting for UHII (rounded values, not exactly the same). In the case of the UHII data, all models showed very similar results.

Table 3: Citywide analysis from 2007 to 2018 with the RR of T_{Night}, T_{Day}, and UHII on mortality. The second column summarises the independent RR of the different temperature variables on mortality. The third column shows the RR of T_{Day} and UHII accounted for T_{Night}. The fourth column contains the RR of T_{Night} and UHII accounted for T_{Day}. In the fifth column, the RR of T_{Night} and T_{Day} accounted for UHII are summarised. The corresponding MMT is at 18 °C for T_{Night} and T_{Day} and at 2 °C for the UHII. A total of 6,273 mortality cases were included in each of the analyses. Since T_{Night} and T_{Day} are highly correlated, the model containing both data sets was not considered for further analyses (*).

Temperature Data	**RR Main Analysis [95% CI]**	**RR acc. T_{Night} [95% CI]**	**RR acc. T_{Day} [95% CI]**	**RR acc. UHII [95% CI]**
T_{Night}	1.45 [1.17 – 1.79]	..	1.57 [1.01 – 2.45]*	1.45 [1.17 – 1.79]
T_{Day}	1.31 [1.07 – 1.60]	0.90 [0.55 – 1.45]*	..	1.31 [1.07 – 1.60]
UHII	1.24 [0.96 – 1.60]	1.25 [1.0 – 1.62]	1.27 [0.98 – 1.64]	..

3.3 Stratified Analysis - Sex, Age, and Socioeconomic Status

In Figure 6, the results of the analysis stratified by the subgroups sex, age, and socioeconomic status are shown for T_{Night} accounted for UHII. The exact RR values for T_{Night} accounted for UHII and for UHII accounted for T_{Night} can be found in the Appendix. 6,273 mortality cases were included for the analysis by sex and age. For the analysis by socioeconomic status, 5,949 cases could be considered. After a night with T_{Night} of 23.3 °C, the RR for women and men increased by 40% [95% CI: 1.06–1.86] and by 51% [95% CI: 1.10–2.08], respectively, versus after a night with T_{Night} of 18 °C. In the case of a UHII of 2.4 °C versus a UHII of 2 °C, the RR for women increased by 57% [95% CI: 1.09–2.26]. The effect is unclear for men [RR: 0.97, 95% CI: 0.76–1.39].

The mortality risk increases with age, resulting in the highest RR for people aged 85 and older. For T_{Night} and UHII, the RR increased by 84% [95% CI: 1.37–2.47] and by 45% [95% CI: 1.00–2.10], respectively. In the intermediate age category, the RR increases by 27% [95% CI: 0.90–1.80] for T_{Night} (21% [95% CI: 0.80–1.82] for UHII). In the lowest age category, there was no strong evidence for an effect (RR 0.76 [95% CI: 0.40–1.45] for T_{Night}, RR 0.93 [95% CI: 0.44–1.93] for UHII).

When looking at socioeconomic status, the highest RR is observed in the lowest category, meaning the mortality risk increases substantially for the most deprived group. For T_{Night}, the RR increases by 76% [95% CI: 1.20–2.59], followed by 35% [95% CI: 0.93–1.94] in the SSEP 3 category and 26% [95% CI: 0.93–1.94] in the SSEP 2 category.

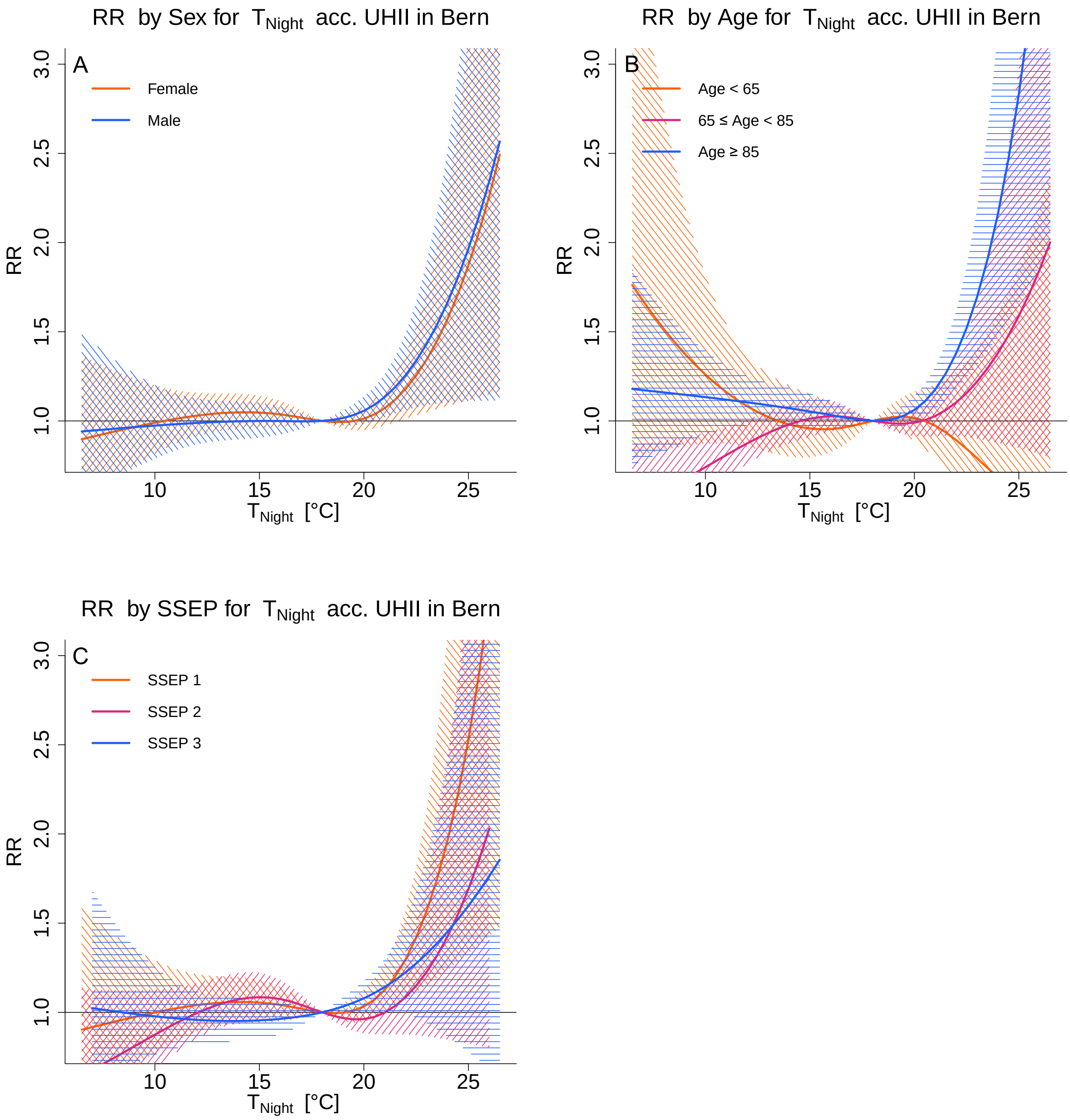

Figure 6: ERFs representing the temperature-mortality association in terms of RR (with 95% CI, dashed areas) for a 1-day lag of T_{Night} accounted for UHII versus an MMT of 18 °C in Bern for (A) sex, (B) age, and (C) socioeconomic status. A total of 6,273 mortality cases were included for (A) and (B) and 5,949 mortality cases for (C).

3.4 Stratified Analysis - Urban Heat Island Intensity

Our findings for the analysis stratified by UHII intensity are shown in Table 4 for T_{Night} and for T_{Day}. Mortality cases were assigned to one of the two subgroups based on the mean UHII at their place of residency over the whole study period. 1,416 cases were part of the high UHII group with a mean UHII larger or equal to 1 °C; the low UHII category (mean UHII $<$ 1 °C) contained 4,857 cases. For individuals living in an area of high UHII, the RR of mortality increased by 77% [95% CI: 1.15–2.73] after a night with a T_{Night} of 23.3 °C compared to a night with a T_{Night} of 18 °C. The RR also increased in the low UHII group, but only by 31% [95% CI: 1.02–1.69]. Similar patterns could be observed for T_{Day}, but with a lower magnitude. The RR in the high UHII category increased by 64% [95% CI: 1.06–2.52]. In the low UHII category, it rose by 23% [95% CI: 0.98–1.55].

Table 4: Citywide analysis from 2007 to 2018 with the RR of T_{Night} and T_{Day} on mortality for high (mean UHII $\geq$ 1 °C) versus low (mean UHII $<$ 1 °C) UHII exposure. The corresponding minimum mortality temperature (MMT) is at 18 °C. A total of 6,273 mortality cases were included in the analysis.

UHII Group	**RR T_{Night} [95% CI]**	**RR T_{Day} [95% CI]**	**Deaths**
High UHII	1.77 [1.15 – 2.73]	1.64 [1.06 – 2.52]	1416
Low UHII	1.31 [1.02 – 1.69]	1.23 [0.98 – 1.55]	4857

Remark: The results of the time-stratified analysis (June vs August) are somewhat unclear and, therefore, included in the Appendix rather than the Results Section.

4 Discussion

During our study period from 2007 until 2018, we could observe an effect of increased temperatures on the risk of mortality in the city of Bern. Specifically, for a UHII of 2.4 °C (corresponding to the 99^{th} percentile temperature) versus a UHII of 2 °C, the mortality risk increased by 25% when accounting for T_{Night}. The most substantial effect on the risk of mortality was observed for T_{Night} (23.3 °C, 99^{th} percentile temperature) versus the MMT of 18 °C, followed by T_{Day} (25.8 °C versus 18 °C), with an increase in mortality risk of 45% and 31%, respectively. In both cases, we accounted for UHII in the analysis. Therefore, we observed that the heat stress from increased daytime temperatures negatively affects human health. However, increased night-time temperatures, which can result from the UHI, have an even stronger impact on mortality risk. This could also be observed in a study investigating the effect of night-time temperatures on mortality in London [31], which found mortality risks for day- and night-time temperatures similar to our study. A different study investigating the mortality risk associated with the UHI for 85 cities across Europe found an overall protective effect. However, during extreme heat, mortality risks increased substantially [61]. When considering the vulnerability factors sex, age, and socioeconomic status, we observed a similar effect for women and men. The mortality risk increased with age, resulting in people aged 85 and older at the highest mortality risk. Furthermore, the most deprived population group was most vulnerable to increased heat stress, while the intermediate SSEP category was the least affected.

In our analysis stratified by age, sex, and socioeconomic status, we found a similar mortality risk for women (RR: 1.40) and men (RR: 1.51). When comparing these findings to other studies, the values vary depending on the study site and design. Several European studies reported higher susceptibility for females to heat [62, 63, 64]. However, several studies suggest that the risk varies not only depending on sex but also on an individual's age. For example, Vicedo-Cabrera et al. (2023) found that females aged 65 or older are, on average, more affected than men. The risk of mortality associated with heat increased by 36% for women compared to 23% for men. Such findings can be attributed to physiological reasons, such as a reduced sweating capacity, which, in the next step, reduces the ability to cope with heat stress. Social factors also play an essential role, i.e., many elderly women live alone, which negatively impacts their health [16, 62].

This study did not investigate possible vulnerability factors like age and sex in combination. However, we also observed the largest mortality risk in the highest age category. For people aged 85 years or older, the RR was 1.84. There was also an observable effect for the intermediate age category ($65 \leq \text{age} < 84$, RR: 1.27). However, there is no clear signal for people aged 65 or younger. Our findings are in accordance with international literature, where many studies conclude that the highest mortality risk is found in the highest age category [16, 65]. Due to the high prevalence of chronic diseases, declining physiological protective mechanisms, and social isolation, older people are especially susceptible to environmental hazards, in general, [66, 67, 68, 69]. In the context of heat, this results from decreased abilities concerning thermoregulation and as a consequence of comorbidities and social isolation [67, 68, 70]. Considering that age modifies the effects of heat exposure, we need to reflect on current trends of progressive population ageing. Globally, the population share aged 65 and older is expected to rise from the current 9% to 16% by the year 2050 [71]. In Switzerland already today, almost 20% of the people are older than 65. By 2060, this population share is set to increase to 30% [72]. The combination of increasing temperatures due to climate change and an increasing number of older people will result in a larger pool of susceptible people [73, 74, 75, 76] and pose additional challenges to society and especially public health.

We also observed an effect for the last vulnerability factor included in this study, namely socioeconomic status. Individuals belonging to the lowest SSEP category 1, the most deprived, were at the highest risk (RR: 1.76). The lowest risk was found in the intermediate SSEP category 2 (RR: 1.26). The finding that socioeconomically disadvantaged people are at higher risk aligns well with many other studies [33, 77, 78]. It can be explained, amongst others, by small-scale factors such as access to greenness or air conditioning [33] or the prevalence of other stressors like noise pollution [79]. For the city of Bern, we found that the people who are at the highest risk are not the most exposed. For example, in the city centre's upper and lower old town, T_{Night} were highest. Concerning UHII, we found a higher risk of mortality for people living in an area with high UHII (RR 1.77 for a mean UHII ≥ 1 °C) in comparison to people who live in areas with low UHII (RR of 1.31 for mean UHII < 1 °C). However, the city centre is also where rents are high and, therefore, where wealthier people live. Consequently, the increased risk of mortality amongst the most deprived population group is not only due to high heat exposure but can also be explained by factors such as lifestyle (e.g. high-intensity labour and outdoor work, less healthy or balanced diet, exposure to other stressors) and restricted means to protect themselves from high heat exposure (e.g. well-insulated housing, cooling system). We found few studies concerning the spatial distribution of heat-related mortality risks. However, one study investigating the 2003 heatwave in Paris observed substantially higher mortality risks for socioeconomically more deprived people compared to wealthier people at the same temperature exposure level [80].

Lastly, the findings of our time-stratified analysis (June vs. August) are somewhat uncertain. However, we could observe an interesting tendency of an increased mortality risk in June (RR: 1.33 for the 99^{th} percentile temperature of T_{Night}) versus August (RR: 1.05 for the 99^{th} percentile temperature of T_{Night}). Ragettli et al. (2017) and Gasparrini et al. (2016) also found similar trends. Given the availability of a larger study population, this could be an interesting starting point for future studies.

Heat-related mortality risks are highly variable in space and across different study settings, which makes the comparison difficult [3, 16, 33, 62]. Some studies conclude that adaptation measures such as heat action plans positively impact and reduce vulnerability to high temperature exposure [16, 77]. Other studies found a decline in heat-related vulnerability, which suggests that the population partially adapted to increased temperatures [81, 82, 83]. A decrease in heat-related excess mortality could also be observed in Switzerland [84]. However, a large body of literature concludes that climate change will result in an additional heat-mortality burden, which is expected to increase in the future [6, 9, 16]. A decrease in cold-related mortality will not compensate for this trend. Mortality related to low temperatures is expected to increase because of population ageing [33].

The findings discussed above inevitably raise the question of how to adapt to rising temperatures in cities and how to reduce people's vulnerability to extreme heat. Two of the most prominent measures in this context are increasing green and blue spaces. Incorporating more green space instead of sealed surfaces is well-studied and welcomed by the urban population because it often reduces thermal stress. More greenness can lead to several health co-benefits, especially in combination with a reduction in traffic [85]. These benefits include reduced air and noise pollution, lower stress levels, and increased physical activity. Therefore, they are beneficial not only in the context of heat but also for human health in general. A prominent example of where such measures were implemented is the Barcelona superblock model [86], which "provides a paradigm shift towards people-centred city planning" and "aims to reclaim public space for people, reduce motorised transport, promote sustainable mobility and active lifestyles, provide urban greening and mitigate effects of climate change". However, all these measures must always be well-designed and adapted to the local situation. Otherwise, they can intensify the thermal discomfort of people living in cities [21]. A last point to consider, especially when new city districts are being built, is the local meteorology. We need to be aware of beneficial characteristics like cold air flows or predominant wind directions, which ensure the city's ventilation to incorporate them in future city planning and benefit from them.

This study has several strengths. The SNC provides high-resolution mortality data for the city of Bern, which can be linked to temperature data based on geolocation. Thanks to the UCB, a dense temperature measuring network spans the city and its greater metropolitan area and provides high temporal and spatial resolution temperature measurements. In combination, these two high-resolution data sets gave us refined information on the temperature exposure of our study population, and we could conduct the analyses on an individual level. This allows us to unravel the additional effect of the UHI from the temperature impacts on mortality in the city of Bern.

Some limitations should be acknowledged. First, with 134,500 inhabitants, the city of Bern is still relatively small. In combination with the study period of 12 years, this resulted in 6,372 cases that could be investigated, which sometimes made it difficult to obtain a clear or robust result. Second, in our study period from 2007 until 2018, we include the hot summers of 2015, 2017, and 2018. However, this study does not include the even hotter summers of 2019, 2022, and 2023 [87] because the COVID-19 pandemic influences epidemiological studies. Further analyses including those summers might lead to a more explicit determination of the effect of heat on mortality. As a third point, we need to remember that the locations of the places of residence of the people who died before 2010 are based on census data from the year 2000. This comes with the possibility that people might have moved during this time without our knowledge and, therefore, imprecise estimation of the heat stress these individuals were exposed to. Additionally, the place of residence might not accurately represent an individual's temperature exposure. People move and might spend a lot of time elsewhere. For example, someone living in a green neighbourhood that cools down nicely at night might be exposed to heat all day while working in the inner city or on a construction site in the sun or vice versa. Nevertheless, if we assume that most people return to their place of residency at the end of the day and since night-time temperature exposure has a significant impact on our body's ability to regenerate from day-time heat exposure, the place of residency should still give us a good measure of an individuals heat exposure. Lastly, we did not account for confounders such as air pollution or humidity, which also influence human health. However, some studies state that the optimal metric to model heat-related mortality varies from country to country and that heat-related mortality in current climate conditions can be estimated well with dry-bulb temperatures [88].

Bearing in mind the points discussed above, it would be interesting to run future studies on the impact of the UHI on mortality over a more extended period of time. SNC data on mortality is available for all of Switzerland, so we could extrapolate the method to other Swiss cities. They would, however, also need to provide detailed information on temperature, either from a dense measurement network or modellings. Considering population size, four cities could be of interest: Zürich, Geneva, Basel, and Lausanne. Otherwise, it would make more sense to investigate the temperature-mortality association on an individual level in larger cities outside Switzerland. Since an individual's mortality risk is composed of vulnerability, exposure, and hazard, any improvement concerning one of these factors comes as an improvement of the study. By including more variables in the stratified analysis, we could improve the exposure assessment or an individual's vulnerability. Such variables could, for example, be the type of housing or the age of a building. Including more variables concerning vulnerability would enable us to understand better how well someone can mitigate high temperatures, for example, through good insulation or cooling systems. Last but not least, we could consider different ways to determine an individual's exposure to heat. By evaluating the geolocations of mobile phones, we could get a better representation of where people spend most of their time and what consequences this has on their heat exposure. The use of mobile phone data would impose new difficulties concerning data security; however, if appropriately addressed, such information bears considerable potential.

5 Conclusion

We aimed to (1) comprehensively explore the effect of the UHI on all-cause mortality in the city of Bern and (2) identify population groups that are particularly vulnerable to the UHI. By linking high-resolution temperature and mortality data and analysing them in a case-crossover study design using conditional logistic regression and DLNMs, we found an effect of UHII and other temperature variables on mortality in the city of Bern. In our stratified analysis, we observed a similar risk for women and men, and we identified older people (85 years and older) and people of low socioeconomic status (SSEP 1) as population groups most vulnerable to increased temperature exposure. Our findings show that the UHI must be considered for future city planning strategies and that adaptation and mitigation measures must be tailored to the city's population, particularly those most at risk.

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A Appendix

Methods and Material

Swiss Neighbourhood Index of Socioeconomic Position (SSEP)

Since the SSEP data collection has changed (Section 2.3), automatic updating of the index is not possible, and a new version as well as a hybrid version of the two has been constructed. The changes within these different indices are tolerably small, and we therefore stick to the SSEP 1 data, which is already included in the SNC data set. Details on the construction of the SSEP indices and the differences between them can be found in Panczak et al. (2023) [48].

Model Overview corresponding to the R Code used in this Analysis

Table 5: Overview on the models that were run in the course of this study corresponding to the R code used in this analysis. The first six models were run as main models without any stratification. For models 7 to 40 the investigated subgroups are summarised in the second and fifth column. Temperature data that was included in each model are summarised in columns three and six. Models labeled with an asterisk (*) were not considered for the final results.

Nr.	Subgroup	Temperature Data	Nr.	Subgroup	Temperature Data
1	..	T_{Night}	21	$65 \leq$ Age < 85	T_{Night} + UHII
2	..	T_{Day}	22	Age ≥ 85	T_{Night} + UHII
3*	..	T_{Night} + T_{Day}	23	SSEP 1 - BE	T_{Night} + UHII
4	..	UHII	24	SSEP 2 - BE	T_{Night} + UHII
5	..	T_{Night} + UHII	25	SSEP 3 - BE	T_{Night} + UHII
6	..	T_{Day} + UHII	26	Female	T_{Day} + UHII
7	Female	T_{Night}	27	Male	T_{Day} + UHII
8	Male	T_{Night}	28	Age < 65	T_{Day} + UHII
9	Age < 65	T_{Night}	29	$65 \leq$ Age < 85	T_{Day} + UHII
10	$65 \leq$ Age < 85	T_{Night}	30	Age ≥ 85	T_{Day} + UHII
11	Age ≥ 85	T_{Night}	31	SSEP 1 - BE	T_{Day} + UHII
12*	SSEP 1 - CH	T_{Night}	32	SSEP 2 - BE	T_{Day} + UHII
13*	SSEP 2 - CH	T_{Night}	33	SSEP 3 - BE	T_{Day} + UHII
14*	SSEP 3 - CH	T_{Night}	34	UHII High vs. Low	T_{Day}
15	SSEP 1 - BE	T_{Night}	35	UHII High vs. Low	T_{Night}
16	SSEP 2 - BE	T_{Night}	36*	June vs. August	T_{Night}
17	SSEP 3 - BE	T_{Night}	37*	June vs. August	T_{Day}
18	Female	T_{Night} + UHII	38*	June vs. August	UHII
19	Male	T_{Night} + UHII	39*	June vs. August	T_{Night} + UHII
20	Age < 65	T_{Night} + UHII	40*	June vs. August	T_{Day} + UHII

Results

Table 6: Citywide analysis from 2007 to 2018 with the RR of T_{Night} on mortality for the subgroups sex, age, and socioeconomic status. The corresponding MMT is at 18°C. The total number of deaths per subgroup is summarised in the third column.

Subgroup	**RR T_{Night} [95% CI]**	**Deaths**
Female	1.39 [1.05 – 1.84]	3435
Male	1.52 [1.10 – 2.09]	2838
Age < 65	0.75 [0.39 – 1.41]	809
65 ≤ Age < 85	1.29 [0.91 – 1.82]	2456
Age ≥ 85	1.82 [1.35 – 2.44]	3008
SSEP1 – BE	1.78 [1.21– 2.61]	1983
SSEP 2 – BE	1.26 [0.86 – 1.83]	1983
SSEP 3 – BE	1.34 [0.93 – 1.93]	1983

Table 7: Citywide analysis from 2007 to 2018 with the RR of T_{Night} and UHII for the subgroups sex, age, and socioeconomic status. The second column shows the independent RR of T_{Night} on mortality accounted for UHII. The third column contains the RR of UHII accounted for T_{Night}. The corresponding MMT is at 18 °C. The total number of deaths per subgroup is summarised in the last column.

Subgroup	**RR T_{Night} acc. UHII [95% CI]**	**RR UHII acc. T_{Night} [95% CI]**	**Deaths**
Female	1.40 [1.06 – 1.86]	1.57 [1.09 – 2.26]	3435
Male	1.51 [1.10 – 2.08]	0.97 [0.76 – 1.39]	2838
Age < 65	0.76 [0.40 – 1.45]	0.93 [0.44 – 1.93]	809
65 ≤ Age < 85	1.27 [0.90 – 1.80]	1.21 [0.80 – 1.82]	2456
Age ≥ 85	1.84 [1.37 – 2.47]	1.45 [1.00 – 2.10]	3008
SSEP1 – BE	1.76 [1.20 – 2.59]	1.14 [0.76 – 1.76]	1983
SSEP 2 – BE	1.26 [0.86 – 1.84]	1.04 [0.66 – 1.64]	1983
SSEP 3 – BE	1.35 [0.93 – 1.94]	1.46 [0.94 – 2.26]	1983

Table 8: Citywide analysis from 2007 to 2018 with the RR of T_{Day} and UHII for the subgroups sex, age, and socioeconomic status. The second column shows the independent RR of T_{Day} on mortality accounted for UHII. The third column contains the RR of UHII accounted for T_{Day}. The corresponding MMT is at 18°C. The total number of deaths per subgroup is summarised in the last column.

Subgroup	**RR T_{Day} acc. UHII [95% CI]**	**RR UHII acc. T_{Day} [95% CI]**	**Deaths**
Female	1.24 [0.94 – 1.63]	1.59 [1.11 – 2.28]	3435
Male	1.41 [1.04 – 1.90]	0.97 [0.68 – 1.40]	2838
Age < 65	0.65 [0.35 – 1.23]	0.94 [0.45 – 1.97]	809
65 ≤ Age < 85	1.25 [0.91 – 1.72]	1.20 [0.80 – 1.82]	2456
Age ≥ 85	1.57 [1.18 – 2.10]	1.47 [1.02 – 2.13]	3008
SSEP1 – BE	1.52 [1.06 – 2.16]	1.14 [0.74 – 1.76]	1983
SSEP 2 – BE	1.00 [0.68 – 1.46]	1.07 [0.67 – 1.68]	1983
SSEP 3 – BE	1.58 [1.10 – 2.27]	1.43 [0.92 – 2.20]	1983

Table 9: Citywide analysis from 2007 to 2018 with the RR of T_{Night} on mortality for the summer months June and August. The second column shows the independent RR of T_{Night} on mortality. The third column contains the RR of T_{Night} accounted for UHII. In the last column, the number of deaths for each subgroup is summarised. The corresponding MMT is at 18°C.

Month	**RR Main Analysis [95% CI]**	**RR acc. UHII [95% CI]**	**Deaths**
June	1.33 [0.90 – 1.98]	1.32 [0.89 – 1.95]	1978
August	1.05 [0.74 – 1.49]	1.05 [0.74 – 1.49]	2083

Table 10: Citywide analysis from 2007 to 2018 with the RR of T_{Day} on mortality for the summer months June and August. The second column shows the independent RR of T_{Day} on mortality. The third column contains the RR of T_{Day} accounted for UHII. In the last column, the number of deaths for each subgroup is summarised. The corresponding MMT is at 18°C.

Month	**RR Main Analysis [95% CI]**	**RR acc. UHII [95% CI]**	**Deaths**
June	1.09 [0.76 – 1.56]	1.09 [0.76 – 1.55]	1978
August	0.93 [0.69 – 1.25]	0.93 [0.69 – 1.25]	2083

Table 11: Citywide analysis from 2007 to 2018 with the RR of UHII on mortality for the summer months June and August. The second column shows the independent RR of the UHII on mortality. The third column contains the RR of UHII accounted for T_{Night}. The fourth column contains the RR of UHII accounted for T_{Day}. In the last column, the number of deaths for each subgroup is summarised. The corresponding MMT is at 18°C.

Month	**RR Main Analysis [95% CI]**	**RR acc. T_{Night} [95% CI]**	**RR acc. T_{Day} [95% CI]**	**Deaths**
June	1.58 [0.96 – 2.59]	1.65 [1.00 – 2.72]	1.66 [1.01 – 2.73]	1978
August	0.97 [0.84 – 1.13]	1.10 [0.79 – 1.53]	1.01 [0.79 – 1.52]	2083

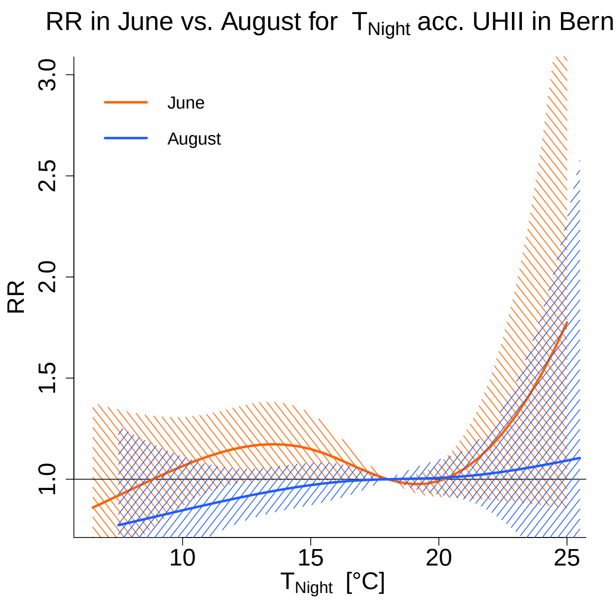

Figure 7: ERFs representing the temperature-mortality association in terms of RR (with 95% CI, dashed areas) for a 1-day lag of T_{Night} accounted for UHII versus a MMT of 18 °C in Bern for June and August.

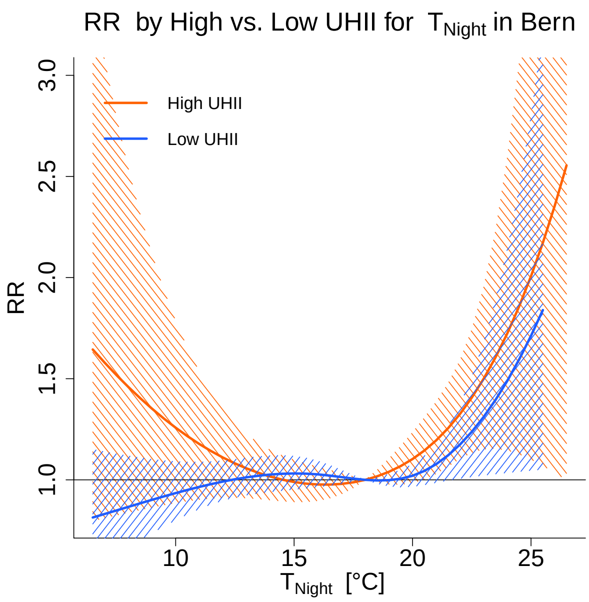

Figure 8: ERFs representing the temperature-mortality association in terms of RR (with 95% CI, dashed areas) for a 1-day lag of T_{Night} versus a MMT of 18 °C in Bern for high (mean UHII $\geq$ 1 °C) versus low (mean UHII $<$ 1 °C) UHII exposure.

Declaration of consent

on the basis of Article 30 of the RSL Phil.-nat. 18

Name/First Name: Wehrli/Adrienne

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Study program: Climate Sciences

Bachelor ☐ Master ☑ Dissertation ☐

Title of the thesis: The Impact of the Urban Heat Island Effect on Mortality in the City of Bern

Supervisor: Prof. Ana M. Vicedo-Cabrera
Prof. Stefan Brönnimann

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