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Vulnerability to heat-related mortality and the effect of prevention measures: a time-stratified case-crossover study in Switzerland

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Summary

BACKGROUND: Swiss climate scenarios predict increases in the frequency and intensity of extreme heat episodes in the future. For the effective prevention of heat-related mortality, several aspects of the population's vulnerability to heat must be understood on a local level.

METHODS: A nationwide analysis of individual death records was conducted, enabling a more comprehensive understanding than typical heat studies based on aggregated data. A total of 320,306 individual death records from the Swiss National Cohort with precise address information during the warm season (May to September) from 2003–2016 were linked to indoor and outdoor high-resolution daily temperature estimates. A time-stratified case-crossover study combined with distributed lag non-linear models was then performed to assess the temperature-mortality associations for various causes of death and to estimate the potential effect modification of individual characteristics. Additionally, it was explored whether the effect of extreme heat changed over time in regions with and without cantonal heat-health action plans (HHAPs).

RESULTS: Using the temperature with the lowest cause-specific mortality risk (minimum mortality temperature) as the reference temperature, extreme heat (defined as ambient daily maximum temperature reaching 33 °C) was associated with a strong increase in all-cause mortality (odds ratio (OR): 1.21, 95% CI: 1.17–1.25) and disease-specific mortality from Alzheimer's disease and dementia (OR: 1.67, 95% CI: 1.48–1.88), COPD (OR: 1.37, 95% CI: 1.12–1.67), diabetes (OR: 1.34, 95% CI: 1.06–1.70), and myocardial infarction (OR: 1.26, 95% CI: 1.10–1.44). Indoor temperatures above 24 °C were found to be critical for mortality. The population most vulnerable to heat included older adults (≥75 years), unmarried individuals, people with a low education level, older women with low neighbourhood socioeconomic position, and men under 75 years old with low socioeconomic position. Overall, the risk of heat-related all-cause mortality in 2009–2016 was lower than that in 2003–2008. The decrease was significantly stronger in the region where cantonal HHAPs were implemented.

CONCLUSIONS: This study provides important information for planning targeted and effective measures to reduce heat-related health risks in Switzerland. It demonstrates that HHAPs contribute to reducing heat-related mortality, although they may not reach the high-risk population of individuals with low socioeconomic position. Future prevention efforts should also target the less privileged population, including people younger than 75 years.

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Introduction

Increasing heat stress is one of Switzerland's most critical climate-related risks [1]. Currently, Switzerland is experiencing long-term warming that is approximately twice that of the global average. According to the CH2018 Swiss Climate Scenarios, the frequency and intensity of heatwaves are expected to increase, presenting a substantial public health risk [2]. Exposure to high ambient temperatures is associated with various morbidity outcomes and an increased risk of premature death [3–7]. In Switzerland, recent heatwaves have caused substantial excess mortality of several hundred deaths [8–11]. Although heatwaves are part of naturally varying weather conditions, estimates indicate that approximately one-third of the heat-related deaths from 1991 to 2018 were attributable to human-induced climate change [12]. Given the continuing warming trend, preventative measures to reduce the heat-related mortality burden are crucial.

To protect the health of the population from heat, European public health authorities have introduced intervention measures. Many of these were implemented after the heatwave of 2003, which contributed to 70,000 excess deaths across the region [13], including nearly 1000 in Switzerland [14]. Health authorities in some cantons of Switzerland have implemented heat-health action plans (HHAPs). Such plans are recommended by the Word Health Organization (WHO) Europe and support a systematic and comprehensive public health response that consists of a portfolio of measures at different levels [15]. The canton of Ticino in the south of Switzerland and cantons in the Lake Geneva region implemented HHAPs between 2004 and 2008. These cantons followed the example of neighbouring countries France and Italy, which were among the first to

adopt national HHAPs [10, 16]. Cantonal HHAPs are coordinated by the cantonal health departments and include various public health measures involving different partners from the health and social care system. Measures are targeted to inform the population and health professionals about heat-related health risks, protect the most vulnerable groups during heat events, and support long-term adaptation to increasing heat stress. In cantons without HHAPs, public health measures are lacking or have only been partly implemented; partial implementations are mostly limited to single actions to raise awareness about heat-related health risks during heat episodes [8, 17, 18].

To effectively prevent heat-related health effects, several questions must be answered at the local level. The identification of the most vulnerable population groups is essential for planning effective interventions. A better understanding of the causes of death that are associated with heat might elucidate possible underlying vulnerabilities. Although it is important to determine the critical outdoor temperatures for heat-related mortality, an understanding of the role of indoor temperatures in buildings is also needed [19–21]. People spend most of their time indoors [22, 23]. However, to date, most studies have only reported the exposure-response relationships for outdoor temperature, and thus critical indoor temperatures remain unclear.

To better understand these important aspects of the prevention of heat-related mortality in Switzerland, a large, nationwide analysis of individual death records was carried out, providing a deeper understanding than typical heat studies that rely on aggregated mortality data. Using a case-crossover study design and a high spatial resolution model of daily temperature exposure, we aimed to systematically identify heat-related causes of death, investigate critical indoor temperatures for heat-related mortality, and define the most vulnerable populations by assessing various individual risk factors. In addition, we aimed to determine whether the prevention measures implemented in Switzerland changed the effect of extreme temperatures on mortality between 2003 and 2016.

Materials and methods

Study population

Individual death records from the Swiss National Cohort (SNC) from 2003 to 2016 were used [24]. The SNC is a long-term cohort based on the linkage of mortality and national census records for all people residing in Switzerland. It encompasses individual data on sex, age, marital status, education, accommodation, and other factors. The SNC also contains a Swiss-specific indicator for neighbourhood-based socioeconomic position, which allows the assessment of health effects by socioeconomic profiles [25, 26]. For the present 14-year analysis, only deaths in the permanent resident population that occurred during the warm season (May to September) were included. Observations with missing information on the residential building were excluded (n = 309), which left 320,306 deaths during the study period.

The main outcome was all-cause mortality (International Classification of Diseases, 10th version: A00–Z99). In addition, specific primary causes of death indicated by previous studies [6, 27] to have a plausible association with heat exposure were investigated. These included neoplasms (C00-D48), endocrine diseases (E00-E90), mental and behavioural disorders (F00-F99), diseases of the nervous system (G00-G99), cardiovascular diseases (CVDs; I00-I99), respiratory diseases (J00-J99), digestive diseases (K00-K93), renal diseases (N00-N39), and external-cause mortality (V01-Y98). CVDs were divided into cerebrovascular diseases (I60-I69), stroke (I60-I64), ischaemic heart diseases (I20-I25), myocardial infarction (I21-I22), and hypertensive diseases (I10-I15). Additionally, we considered the following primary death causes: diabetes (E10-E14), Alzheimer's disease and dementia (F00-F03, G30-G31.1, G31.8-G31.9), chronic obstructive pulmonary disease (COPD; J41-J44), suicide (X60-X84), and accidents (V01-X59).

Outdoor and indoor temperature exposure

The exposure to ambient temperature at the residential address of each deceased person was assessed using the temperature model by Flückiger et al. [28]. The model predicts the daily maximum temperature (Tmax), daily mean temperature (Tmean), and daily minimum temperature (Tmin) 2 m above ground level with a fine spatial resolution of 100 × 100 m across Switzerland. It was developed to capture small-scale temperature variability within cities and in complex topographic terrains using satellite data, station-based temperature measurements, atmospheric re-analysis data, and land-use information. Tmax was used for the analysis of the effect of heat on mortality to assess the effect of the most extreme warm season temperatures. Previous studies in Switzerland have shown that Tmean, Tmax, and Tmin are highly correlated and result in similar exposure-response relationships with mortality [10, 29]. However, to assess whether warm nights affected cause-specific mortality differently, the cause-specific exposure-response curves for outdoor Tmin are presented in the appendix.

Exposure to daily maximum indoor temperature (indoor Tmax) was estimated for each death using a simplified thermal building model for three typical Swiss building types [30]. Indoor temperature levels were simulated using predefined physical building parameters for single-family houses, apartment houses built in or before 1990, and apartment houses built after 1990 (table S1 in the appendix). The individual-level information on building type and building period was provided by the SNC. It was assumed that the windows were open (not tilted) during the night for natural cooling. The indoor temperature model considered individual outdoor Tmax levels and daily mean global radiation on the day of death and in the 14 days prior to account for the influence of the weather conditions on the thermal mass of the building. Outdoor temperature at the residential address was estimated with the fine-grained temperature model by Flückiger et al. [28]. The data on global radiation was collected from the MeteoSwiss monitoring network from the station closest to the building. A detailed description of the indoor temperature simulation and its comparison to a more complex thermal building simulation program is provided in the appendix A.

Statistical analysis

A time-stratified case-crossover design was used to investigate the acute effects of short-term temperature increas-

es on mortality. In this approach, the temperature exposure on and before the day of death (at the address of the deceased person) was compared with exposure during non-event (control) days [31]. Because each participant served as his or her own control, potentially confounding effects of individual time-invariant characteristics, such as age or sex, were controlled for. Control days were matched to the same day of the week within the month that the death occurred to avoid overlap bias [32]. Thus, a maximum of four control days per death was possible. In the time-stratified case-crossover design, acute heat-related health effects were assessed on the basis of individual temperature exposures. In contrast to classical time series studies relying on central monitoring stations, small-scale spatial contrasts in temperature exposure were explicitly considered in this study design.

Conditional logistic regression models with distributed lag non-linear models (DLNMs) were run to estimate associations between cause-specific mortality risks and outdoor and indoor temperatures, accounting for the nonlinear form of exposure-response functions [33]. The DLNM method relies on the definition of a cross-basis function. For outdoor temperature, the exposure dimension of the cross-basis term was modelled with a quadratic B-spline with two internal knots placed at the 50th and 90th percentile (P) of the warm season temperature distribution. The lag dimension was specified as a natural cubic spline with two internal knots placed at equally spaced values on the log scale, similar to the methods of previous studies investigating temperature-mortality associations during the warm season [29, 34, 35]. We considered lagged effects up to a week before death to capture potential short-term harvesting. An alternative number of lags (10) and the positions of the knots at P75 and P90, as well as two knots (P10/P90 and P75/P95), were tested for all-cause mortality, and the best model was selected according to the lowest Akaike information criterion (AIC).

Cumulative temperature-mortality associations were evaluated across the whole lag period for each death cause. These associations were centred at the cause-specific minimum mortality temperature (MMT), following a common approach of studies applying DLNM. This defines the temperature with the least mortality risk, corresponding to an odds ratio (OR) of 1. Similar to previous work [11, 36], the MMT was limited to values between P25 and P90 of warm season temperature distributions in this study.

To characterise the effect of extreme heat exposure on cause-specific mortality, cumulative (over lags 0–7) odds ratios (ORs) of mortality are presented as the change in mortality risk from the cause-specific MMT to the P98 of the warm season Tmax (33 °C).

The indoor temperature-mortality associations on the day of death were modelled on the basis of the exposure dimension of the DLNM method only (one-basis function; quadratic B-spline, 2 degrees of freedom) because indoor temperature levels were simulated using the temperature levels up to 14 days before death. Preliminary analyses, which also considered potential lagged effects of indoor temperature, revealed that these effects were negligible. The model parameters (degrees of freedom and alternative spline functions) were selected during preliminary analyses and validated using AIC. To evaluate the robustness of the method of defining the MMT of the temperature-mortality association for indoor Tmax, a sensitivity analysis was performed by widening the range from P25-P90 to P2-P90 of the warm season temperature distribution. All outdoor and indoor temperature-mortality models included an indicator variable for national public holidays.

To study effect modification by individual characteristics, stratified analyses for outdoor Tmax and all-cause mortality were conducted by age (<75 years, 75–84 years, >85 years), sex, marital status (married, single, divorced, and widowed adults), nationality (Swiss, European, and other nationalities), education (compulsory or less, upper secondary, and tertiary), neighbuorhood-based socioeconomic position (low, medium, and high), building period (before 1970, 1970–1990, and after 1990), and floor of residence (ground floor to 2nd floor, which includes single-family homes, 3rd to 5th floor, and >5th floor).

To assess whether public health interventions and public awareness contributed to a reduction in heat-related mortality in Switzerland, we compared the ORs of all-cause mortality during two time periods (2003–2008 versus 2009–2016) in three regions (all of Switzerland, cantons that had implemented HHAPs, and cantons without HHAPs). The cantonal HHAPs had all been implemented between 2004 and 2008. Thus, the more recent period marks the time when HHAPs were in place [10]. The models were run separately for each period and region to estimate the effect of extreme temperatures (the P98 of period- and region-specific warm season Tmax values) using the period and region-specific MMT as a reference.

All analyses were conducted with R software (version 4.1.3). The DLNM models were fitted in R using the dlnm package [33] following the exposure history approach described by Gasparrini [37].

Protocol and registration

No protocol has been registered for this observational study.

Ethical consent

The SNC was approved by the ethics committees of the canton of Bern (No KeK 153/2014, PB_2020-00050).

Results

Table 1 describes the characteristics of the study population and daily temperature levels for Switzerland and two regions of cantons (defined according to whether they had implemented HHAPs before 2009). Most of the participants (68%) were aged 75 or older. The age and sex distributions were similar in the two regions. However, the percentage of people with low socioeconomic position was higher in the region with HHAPs (32%) than in the region without HHAPs (18%). Outdoor Tmax was highly correlated with Tmin (0.80, Pearson correlation coefficient) and indoor Tmax (0.88). In both periods (2003–2008 and 2009–2016), the median exposure to outdoor Tmax was higher in cantons that had implemented HHAPs compared to those without such prevention measures. Annual means of outdoor Tmax on the day of death increased in both regions during the warm summers of 2003 and 2015 when major heatwaves occurred [9, 14] (figure S2 in the appen-

dix). Mortality from CVD (34.3%) and neoplasms (29%) accounted for the largest fraction of deaths (table S2 in the appendix). Alzheimer's disease and dementia, external-cause mortality, mental disorders, respiratory diseases, digestive diseases, diabetes, and renal diseases accounted for 6.8%, 6.3%, 5.7%, 5.4%, 4.1%, 2.1%, and 1.3% of mortality, respectively.

Figure 1 shows the cause-specific cumulative temperature-mortality associations for outdoor Tmax with the corresponding MMT. The risk of mortality generally increased with temperature, except for the risk of mortality from digestive diseases, which was not significantly associated with warm season temperature. For most diseases, temperature had a significant effect even at moderately warm temperatures. However, for various cardiovascular diseases and neoplasms, the risk increased most markedly above 30 °C. Using the MMT as a reference, extreme heat (33 °C) was associated with a significant increase in all-cause mortality across the lag period of 0–7 days (OR: 1.21, 95% CI: 1.17–1.25), and the mortality of multiple disease groups, including mental disorders (OR: 1.64, 95% CI: 1.44–1.86), respiratory diseases (OR: 1.62, 95% CI: 1.42–1.86), nervous disorders (OR: 1.43, 95% CI: 1.42–1.86), endocrine diseases (OR: 1.33, 95% CI: 1.10–1.62), CVD (OR: 1.21, 95% CI: 1.14–1.29), external causes (OR: 1.21, 95% CI: 1.07–1.38), and digestive diseases (OR: 1.11, 95% CI: 1.01–1.22) (table S2). Strong associations were found for the specific diseases Alzheimer's and dementia (OR: 1.67, 95% CI: 1.48–1.88), COPD (OR: 1.37, 95% CI: 1.12–1.67), diabetes (OR: 1.34, 95% CI: 1.06–1.70), and myocardial infarction (OR: 1.26, 95% CI: 1.10–1.44). Exposure-response curves for outdoor Tmin were similar (figure S3, table S2 in the appendix).

Figure 2 compares the risk of all-cause mortality and cause-specific mortality as a function of indoor and outdoor Tmax. The curves for indoor Tmax follow a similar pattern as those for outdoor Tmax. As indicated by the dotted vertical lines in figure 2, the ORs of mortality at the P98 of the warm season temperature distribution, which was 28 °C for indoor Tmax and 33 °C for outdoor Tmax, were comparable. Slightly higher ORs at the P98 were found for outdoor Tmax than for indoor Tmax for Alzheimer's disease and respiratory diseases (table S2). A statistically significant effect of indoor Tmax on all-cause mortality with the 95% confidence interval of the OR >1.0 was observed when indoor Tmax reached 23–24 °C. The indoor temperature-mortality associations for all investigated death causes are provided in the appendix (figure S4 in the appendix). Sensitivity analysis revealed that the exposure-response associations for indoor Tmax did not differ with alternative search strategies to define the MMT (figure S5 in the appendix).

In addition, we observed significant effect modification by neighbuorhood-based socioeconomic position and education. The heat-related effects were significantly stronger in people with low education levels than in those with high education levels (Chi-squared test p = 0.035). The effects of extreme heat on all-cause mortality were stronger in older women and men aged under 75 years with low socioeconomic position than in participants of the same age and sex with an intermediate or high socioeconomic position (figure S6 in the appendix). However, in men aged

Table 1:
Descriptive statistics of individual mortality and temperature data in Switzerland by time period (2003–2008; 2009–2016) and region (with and without heat-health action plans, HHAPs between 2003 and 2016).

		Time period and region									
		2003–2016		2003–2008				2009–2016			
		Switzerland		With HHAPs		Without HHAPs		With HHAPs		Without HHAPs	
Population, count (%)		320,306	100.0%	37,908	100.0%	99,637	100.0%	50,929	100.0%	131,832	100.0%
Number of cantons		26		6[a]		20		6[a]		20	
Age (years)	<75	101,763	31.8%	12,784	33.7%	31,806	31.9%	16,532	32.5%	40,641	30.8%
	75–84	94,049	29.4%	11,292	29.8%	30,567	30.7%	14,075	27.6%	38,115	28.9%
	85+	124,494	38.9%	13,832	36.5%	37,264	37.4%	20,322	39.9%	53,076	40.3%
Sex	Female	161,850	50.5%	19,142	50.5%	50,930	51.1%	25,465	50.0%	66,313	50.3%
	Male	158,456	49.5%	18,766	49.5%	48,707	48.9%	25,464	50.0%	65,519	49.7%
Socioeconomic position[b]	Low 1st quintile	70,797	22.1%	12,143	32.0%	18,644	18.7%	15,995	31.4%	24,015	18.2%
	Medium 2nd–4th quintile	179,534	56.1%	19,460	51.3%	57,473	57.7%	26,383	51.8%	76,218	57.8%
	High 5th quintile	49,214	15.4%	3,438	9.1%	16,785	16.8%	4,968	9.8%	24,023	18.2%
	Unknown	20,761	6.5%	2,867	7.6%	6,735	6.8%	3,583	7.0%	7,576	5.7%
Education	School-age or younger	1,733	0.5%	187	0.5%	451	0.5%	298	0.6%	797	0.6%
	Compulsory or less	119,845	37.4%	17,519	46.2%	39,672	39.8%	19,593	38.5%	43,061	32.7%
	Upper secondary	144,958	45.3%	14,504	38.3%	45,978	46.1%	20,544	40.3%	63,932	48.5%
	Tertiary level	43,078	13.4%	4,932	13.0%	11,746	11.8%	7,788	15.3%	18,612	14.1%
	Unknown	10,692	3.3%	766	2.0%	1,790	1.8%	2,706	5.3%	5,430	4.1%
Urbanisation	Urban	211,763	66.1%	25,223	66.5%	65,546	65.8%	33,784	66.3%	87,210	66.2%
	Peri-urban	59,510	18.6%	7,072	18.7%	18,143	18.2%	9,754	19.2%	24,541	18.6%
	Rural	49,033	15.3%	5,613	14.8%	15,948	16.0%	7,391	14.5%	20,081	15.2%
Outdoor Tmax, median (P5, P98)		22.4	13.8, 32.5	23.2	14.8, 32.6	22.2	13.5, 32.6	23.1	14.6, 32.4	22.0	13.6, 32.5
Outdoor Tmin, median (P5, P98)		12.3	6.0, 18.4	12.8	6.3, 19.1	12.3	5.6, 18.0	12.7	6.5, 19.1	12.1	6.1, 18.2
Indoor Tmax, median (P5, P98)		23.0	20.0, 28.0	23.0	20.1, 28.0	22.7	20.0, 28.0	23.4	20.3, 29.0	23.0	20.1, 28.0

[a] Cantons with heat-health action plans (HHAPs) include Ticino, Geneva, Vaud, Freiburg, Neuchâtel, and Valais, which introduced HHAPs between 2003 and 2008.

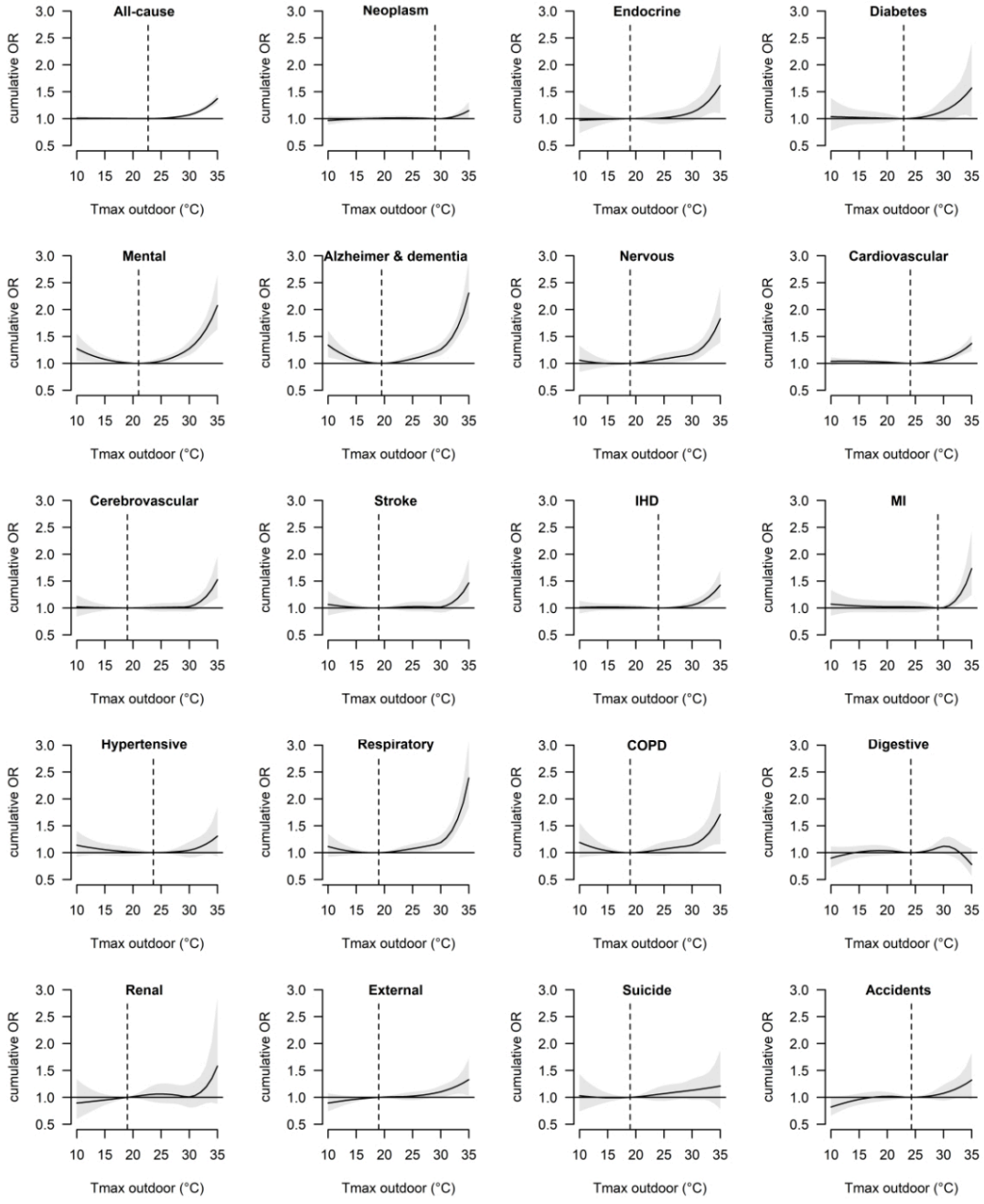
[b] The neighbourhood-based socioeconomic position index ranging from the lowest (0) to highest (5) quintiles [26].

Tmax: Daily maximum temperature; P5: 5th percentile of warm season temperature distribution; P98: 98th percentile of warm season temperature distribution.

≥75 years, the heat-related effects tended to be stronger among those with a high socioeconomic position. Overall, building characteristics and floor were not effect modifiers; however, in the population with a low socioeconomic position, risks increased in persons who lived in a building constructed from 1970 to 1990, lived on the 3rd to 5th floor, or experienced high indoor temperatures (≥24 °C) (figure S6 in the appendix). By contrast, for the population with a high socioeconomic position, living in an apartment building on the 3rd floor or higher was not a risk factor for heat-related mortality.

In Switzerland, the risk for heat-related all-cause mortality was significantly lower in 2009–2016 than in 2003–2008 (figure 3, figure S7 in the appendix). Although the decrease in mortality risk for outdoor temperatures reaching the P98 of period- and region-specific warm season Tmax values was statistically significant in the region of cantons that have implemented HHAPs, a smaller and nonsignificant difference was found across cantons where no such measures had been taken (table S3 in the appendix). When comparing the period-specific ORs of vulnerable population groups in the region that had introduced HHAPs, we observed a stronger reduction in risk in those aged 75 and

Figure 1: Overall cumulative exposure-response associations (with 95% confidence intervals) between outdoor daily maximum temperature (Tmax) and cause-specific mortality along 7 days of lag in Switzerland during the warm seasons (May to September) of 2003–2016. The dashed vertical lines indicate the cause-specific minimum mortality temperature. OR: odds ratio; IHD: ischaemic heart disease; MI: myocardial infarction; COPD: chronic obstructive pulmonary disease.



older than in those with low socioeconomic position (table S3). For the latter, no statistically significant difference in effect was found between the two time periods.

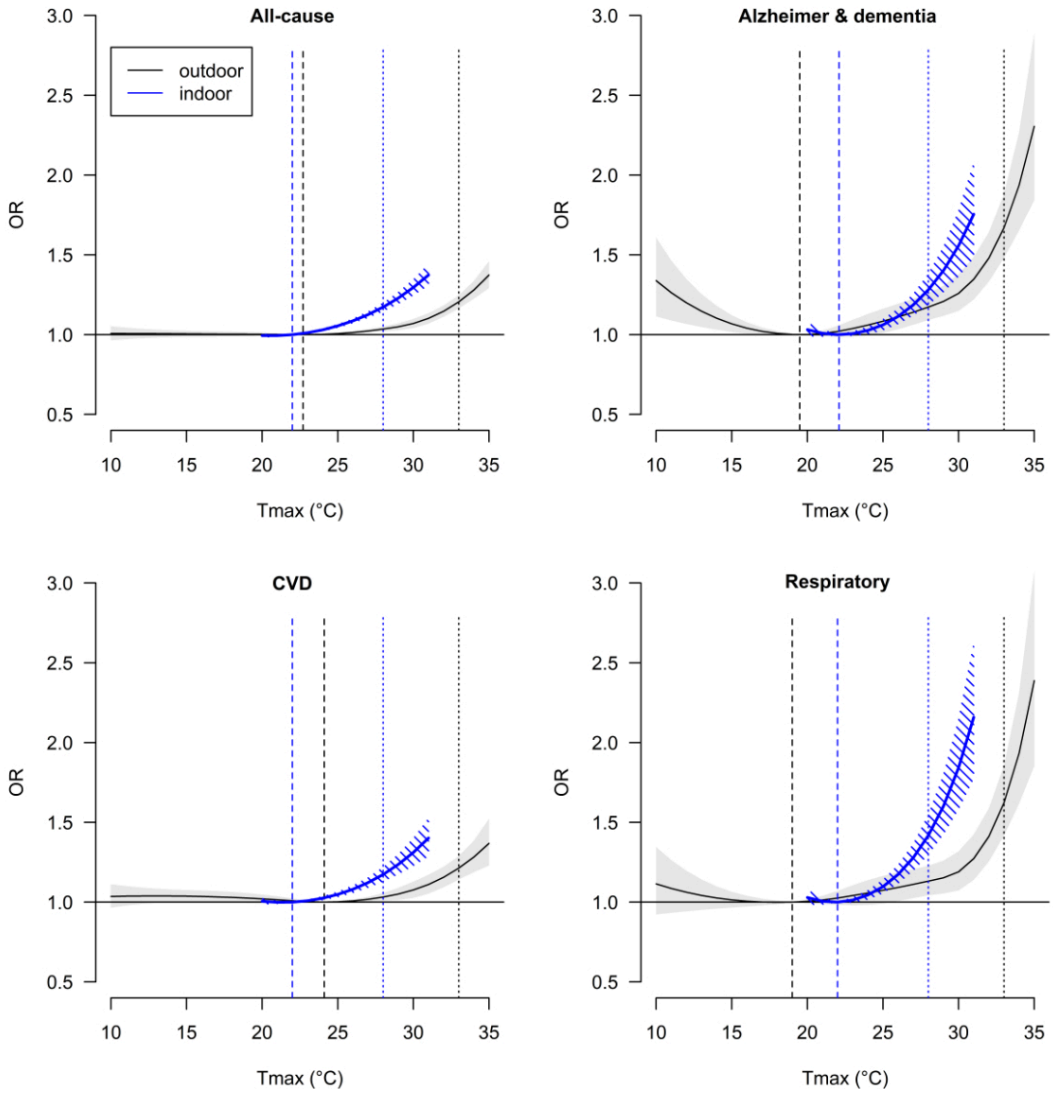
However, when 2003 was excluded from the analysis, the observed decrease in risk associated with extreme heat between the two periods became smaller (and nonsignificant) in the region that had introduced HHAPs (figure S8 in the appendix). In the region without HHAPs, no risk reduction was observed.

Discussion

Using individual mortality data from all of Switzerland, we assessed various crucial aspects of the prevention of heat-related mortality. In addition to all-cause mortality, extreme heat, defined as a Tmax of 33 °C, was strongly associated with specific diseases, including Alzheimer's disease and dementia, COPD, diabetes, and myocardial infarction. Our analysis also suggests that maximum indoor temperatures above 24 °C have a significant effect on mortality. Older adults (≥75 years old) were at an increased risk of heat-related mortality, along with individuals who were not married and those with a low education level. In addition, a low socioeconomic position increased the risk for heat-related mortality in older women and men under 75 years old.

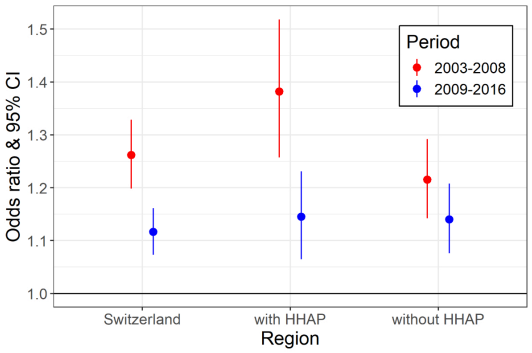
Our study provides further evidence that HHAPs help reduce heat-related mortality risk in regions with heat stress. In the cantons that implemented HHAPs between 2004 and 2008, the ORs of mortality associated with extreme heat were significantly lower in the more recent period (2009–2016). In the region without HHAPs, the risk reduction was considerably smaller and not statistically significant. In this region, public health measures to protect the population from the dangers of hot weather are lacking at the cantonal or city level or have been only partially introduced. Assessments of HHAPs at the city or country level in Europe and North America have also found that HHAPs

Figure 2: Comparison of outdoor (black curve) and indoor (blue curve) temperature-mortality associations (with 95% confidence intervals) for specific mortality causes in Switzerland during the warm seasons of 2003–2016. Odds ratios (ORs) represent the change in mortality risk associated with outdoor and indoor daily maximum temperature (Tmax) versus the cause-specific minimum mortality temperature (dashed vertical lines). Dotted vertical lines mark the 98th percentile of the warm season Tmax.



lower the health burden of heatwaves, although a causal effect remains to be clearly established [38, 39]. Overall, the region without HHAPs was less affected by heat exposure than the Lake Geneva region and the canton of Ticino in the south of Switzerland. Therefore, Switzerland provides an example that in regions particularly affected by heat exposure and its associated mortality risks, joint action from different stakeholders helps protect the population from heat. Nevertheless, this ecological comparison of regions is limited in terms of causal inference. Our sensitivity analysis excluded the year 2003 and showed a less pronounced risk reduction between the two periods in the region where cantonal HHAPs were introduced. However, the analysis revealed no risk reduction in the region without HHAPs when the year 2003 was excluded. Therefore, it is likely that HHAPs have contributed to reducing heat-related mortality in the region with such measures in the more recent period.

Figure 3: Cumulative odds ratios (ORs) with 95% confidence intervals (CIs) of heat-related all-cause mortality at region- and period-specific (2003–2008 versus 2009–2016) extreme outdoor daily maximum temperatures (Tmax) in Switzerland. Extreme temperatures are defined as the 98th percentile of the region- and period-specific Tmax. The region with heat-health action plans (HHAPs) covers cantons that implemented HHAPs between 2003 and 2008.



In addition, we found that the less socioeconomically privileged population is at a high risk of heat-related mortality. Our effect modification analysis revealed that a low education level and a low neighbuorhood-based socioeconomic position are risk factors for heat-related mortality. The latter risk factor was most evident among older women and young men. Older women are generally considered more adversely affected by hot weather than men in the same age group. The reasons for the higher heat-related mortality risk among women are multifaceted; potential explanations include women's higher life expectancy, their lower thermoregulation capacity, the increased risk of cardiovascular events in postmenopausal women, and other gender-related sociocultural factors [40]. Our results indicate that a low socioeconomic position can further increase the vulnerability of older women. Reducing the physical and social isolation of older women during heat events may minimise their susceptibility to high temperatures. In

Table 2:
Cumulative odds ratios (ORs) with 95% confidence intervals of heat-related all-cause mortality at outdoor daily maximum temperatures of 33 °C in relation to the minimum mortality temperature of 22.7 °C, stratified by individual characteristics. Significant differences (p <0.05, assessed by Chi-squared tests) across categories in the total population (P_{total}) and between males and females (P_{male}/P_{female}) are marked in bold.

		Total				Male			Female			
Population		**Deaths**	**OR**	**95% CI**	**P total**	**Deaths**	**OR**	**95% CI**	**Deaths**	**OR**	**95% CI**	**P male /P female**
Total		320,306	1.21	1.17–1.25		158,456	1.17	1.11–1.23	161,850	1.24	1.18–1.30	0.074
Age (3 groups)	Under 75	101,763	1.11	1.05–1.18	**0.006**	64,001	1.14	1.06–1.23	37,762	1.07	0.97–1.18	0.291
	75–84	94,049	1.24	1.16–1.32		49,711	1.21	1.11–1.32	44,338	1.27	1.16–1.38	0.469
	85+	124,494	1.26	1.19–1.33		44,744	1.16	1.06–1.27	79,750	1.31	1.23–1.40	**0.033**
Age (2 groups)	Under 75	101,763	1.11	1.05–1.18	**0.002***	64,001	1.14	1.06–1.23	37,762	1.07	0.97–1.18	0.291
	75+	218,543	1.25	1.20–1.30		94,455	1.19	1.11–1.26	124,088	1.30	1.23–1.37	**0.033**
Marital status	Married	129,561	1.12	1.06–1.18	**0.002**	91,853	1.13	1.06–1.20	37,708	1.10	1.00–1.22	0.728
	Single	37,211	1.38	1.25–1.52		18,309	1.39	1.21–1.60	18,902	1.37	1.19–1.57	0.878
	Widowed	116,291	1.23	1.16–1.30		29,514	1.14	1.02–1.27	86,777	1.26	1.18–1.34	0.134
	Divorced	30,488	1.22	1.10–1.35		15,280	1.16	0.99–1.35	15,208	1.28	1.10–1.48	0.371
Education	Compulsory or less	119,845	1.26	1.19–1.33	0.084	39,036	1.21	1.09–1.34	80,809	1.28	1.19–1.36	0.376
	Upper secondary	144,958	1.19	1.13–1.25		79,519	1.17	1.09–1.25	65,439	1.21	1.12–1.30	0.540
	Tertiary	43,078	1.12	1.02–1.23		33,485	1.11	1.00–1.23	9,593	1.16	0.96–1.40	0.671
Socioeconomic position[b]	Low	70,797	1.25	1.16–1.35	0.465*	36,546	1.20	1.08–1.33	34,251	1.31	1.17–1.46	0.266
	Medium	179,534	1.19	1.13–1.24		88,629	1.13	1.06–1.20	90,905	1.24	1.17–1.32	**0.033**
	High	49,214	1.18	1.08–1.28		24,555	1.28	1.14–1.44	24,659	1.08	0.96–1.21	**0.036**
Nationality	Swiss	246,820	1.20	1.16–1.25	0.493	118,864	1.15	1.09–1.22	127,956	1.25	1.19–1.32	**0.032**
	European	18,757	1.30	1.14–1.49		11,768	1.28	1.08–1.52	6,989	1.34	1.08–1.67	0.716
	Other nationality	54,729	1.19	1.10–1.28		27,824	1.19	1.07–1.33	26,905	1.19	1.07–1.32	0.951
Building construction period	Before 1970	217,172	1.18	1.14–1.23	0.253	107,614	1.16	1.09–1.23	109,558	1.21	1.14–1.28	0.329
	1970–1990	98,781	1.26	1.18–1.34		48,691	1.19	1.09–1.30	50,090	1.32	1.21–1.44	0.102
	After 1990	1,320	1.26	0.76–2.12		615	1.18	0.56–2.51	705	1.17	0.57–2.43	0.990
Floor	Floor 0–2	151,282	1.16	1.10–1.22	0.872	73,198	1.17	1.08–1.26	78,084	1.15	1.07–1.23	0.727
	Floor 3–5	45,420	1.19	1.07–1.32		20,181	1.19	1.02–1.39	25,239	1.19	1.03–1.37	0.979
	Floor 6+	23,047	1.13	0.91–1.40		9,582	1.01	0.75–1.38	13,465	1.26	0.93–1.72	0.322

[a] Differences across categories within the total population (P_{total}) and in category-specific odds ratios between males and females (P_{male}/P_{female}) were assessed using the Chi-squared test. Significant p-values of <0.05 are marked in bold.

[b] Socioeconomic position: low: 1st quintile, medium: 2nd–4th quintile, high: 5th quintile

*significant interaction with sex

men under 75 years old, a lower socioeconomic position might increase the heat-related mortality risk for several reasons, including increased heat exposure at work and at home, more comorbidities, and personal behavioural factors, such as underestimating the health risks of extreme heat and not adhering to recommendations on how to behave during heat episodes [34]. Prevention strategies in recent years have targeted older adults. However, the prevention measures did not seem to effectively reach people with low socioeconomic positions. We found no significant difference in effect among the population with low socioeconomic position when comparing the two periods in the region with cantonal HHAPs. Therefore, our results suggest that future prevention efforts are needed to specifically target the less socioeconomically privileged population, including men under 75 years old. To reach this group, participatory approaches to developing targeted information and alert systems are recommended [15].

Surprisingly, similar to a recent study on heat-related cardiovascular mortality in the Zurich region, the odds of heat-related all-cause mortality were elevated among older men with a high neighbourhood-based socioeconomic position [34]. Although we cannot fully explain this finding, the potentially longer life expectancy of more socioeconomically privileged men could play a role. In our study population, however, the mean age among men aged 75 and older with low (85 years) and high socioeconomic position (86 years) was similar.

Our results illustrate that several disease systems are sensitive to heat. These findings show that it is crucial to intensify the care of patients with chronic respiratory diseases such as COPD, Alzheimer's disease and dementia, diabetes and certain cardiovascular health problems during heat episodes. Different mechanisms may be at play. For cardiovascular diseases, we found significant associations with stroke, ischaemic heart disease, and myocardial infarction, similar to previous investigations on heat-related cardiovascular mortality [27, 34, 41, 42]. Biological mechanisms to regulate the body temperature cause a redistribution of the blood flow away from core organs, an increased heart rate, and organ oxygen demand. This elevates cardiovascular strain and may explain the elevated likelihood of acute coronary events during heat episodes [6]. The increased mortality risk for hypertensive diseases during hot weather seems counterintuitive, as exposure to heat leads to reduced blood pressure and peripheral vasodilatation. It is plausible that the elevated heat-related mortality risk in patients with chronic hypertension is attributable to an inadequate dose reduction of anti-hypertensive medication [43].

We found a particularly strong association between high temperatures and mortality from Alzheimer's disease and dementia, especially at ambient temperatures above 30 °C. People with dementia, specifically Alzheimer's disease, should thus be considered a high-risk group during hot weather. Patients with Alzheimer's disease and dementia may have a higher risk of heat-related mortality because of their limited ability to recognise and alleviate heat stress. In addition, some of their medications reduce thermoregulation capacity (e.g. neuroleptics). The high heat-related mortality risk associated with Alzheimer's disease and dementia may also be related to the age of the patients. In our study population, the average age of individuals with this main death cause was 87 years. In addition, previous studies reported that a low income is an additional risk factor for heat-related mortality in patients with Alzheimer's disease and dementia [44, 45].

A growing number of national and international studies have reported that heat can affect external causes of death, such as accidents and suicides [27, 46, 47]. It remains unclear whether these causes of death are causally related to heat or rather to good weather conditions favouring risky activities. Strikingly, heat-mortality associations tend to be more linear for external death causes compared with other outcomes, which suggests that causal explanations other than heat may be involved.

Ensuring comfortable indoor temperatures is essential for preventing the exacerbation of symptoms of at-risk groups, which often spend most of their time indoors. The associations found between indoor temperature and mortality in our study reflected the association with outdoor temperature. The high correlation between indoor Tmax and outdoor Tmax and the rarity of air conditioning in residential buildings in Switzerland likely explain this finding. Nonetheless, periods of prolonged heat and certain building characteristics can considerably reduce thermal comfort in indoor environments [19, 20]. For Alzheimer's disease and dementia as well as respiratory diseases, we found a strong increase in mortality risk at high indoor temperatures. The exacerbation of respiratory symptoms with increasing indoor temperatures has been reported in case studies; one study reported increased respiratory emergency distress calls at indoor temperatures above 26 °C in New York during summer 2013 [21]. Others described adverse effects of high indoor temperatures on diabetes management, schizophrenia, and dementia symptoms without reporting exposure-response functions [20]. Considering climate change, the public health sector must work with other relevant stakeholders (e.g. architects and city planners) to prevent indoor overheating. Our analysis of heat-related mortality suggests that indoor temperatures above 24 °C are associated with a significantly increased mortality risk. The temperature threshold for health-supporting indoor environments may be higher for the young and healthy population. Further studies assessing the indoor temperature threshold above which adverse effects become stronger and more frequent are warranted.

This is the first case-crossover study assessing cause-specific heat-related mortality risk and individual effect modifiers of extreme heat using individual death records from all of Switzerland. The strength of this study is that we assigned the temperature exposure at the address of each deceased person using daily temperature data with a high spatial resolution. Therefore, our study likely provides less biased and more precise effect estimates than most time-series studies using aggregated numbers of daily deaths and exposure data from central monitoring stations or temperature models with coarser spatial resolutions. Moreover, to our knowledge, this is the first study to examine both outdoor and indoor temperature relationships with various causes of mortality.

Several limitations must be acknowledged. Some exposure misclassification of outdoor and indoor temperature exposure is expected, as we only assigned daily temperature

levels at the residential address and ignored exposure away from home. Given that most of the study population was ≥75 years old and we considered 7 days of exposure before death, it is likely that the study population spent most of their time at home. Additionally, indoor temperature estimates have some uncertainty because of assumptions about the input variables and the simplified thermal building model used. Further analyses exploring the association between mortality and indoor temperature with more detailed information on the residential building, occupancy/ventilation behaviour, and time spent indoors are warranted. Another limitation is that we did not consider other potential environmental risk factors, such as air pollution. During periods of hot weather, ozone levels tend to be high and may increase the health risks of heat. However, previous studies have found that the acute effect of ozone on mortality is relatively small [48, 49]. Moreover, because temperature is a contributory cause of the formation of ozone with no reverse causal effect, we consider it legitimate to ignore the effects of temperature on mortality mediated by ozone.

Conclusions

This study provides important information for planning targeted and effective measures to reduce the health risks of heat in Switzerland. It adds to the growing literature showing a positive effect of coordinated measures such as HHAPs in reducing the health burden of heat, especially in regions with heat stress. However, our results suggest that HHAPs must better address the less socioeconomically privileged population, particularly men under 75 years old. Additionally, future prevention efforts should focus specifically on patients with Alzheimer's and dementia, diabetes, and COPD. Due to rising temperatures, coordinated measures between stakeholders to reduce vulnerability to heat are becoming increasingly important, and such measures should be extended to other regions in Switzerland.

Data sharing statement

The SNC data cannot be shared by the authors. The data are the responsibility of the Federal Statistical Office, and may be ordered here: https://www.bfs.admin.ch/bfs/en/home/statistics/population/surveys/snc.html. The R code is available upon request from the corresponding author.

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Potential competing interests

All authors have completed and submitted the International Committee of Medical Journal Editors form for disclosure of potential conflicts of interest. No potential conflict of interest related to the content of this manuscript was disclosed.

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Appendix

A. Indoor temperature model

A.1. Description of simplified thermal building model for the simulation of indoor temperatures

For this case-crossover study, daily maximum indoor temperature levels were estimated for each person on the day of death (n=320'306) and corresponding control days (n=1'097'303). To simulate indoor temperature levels, we used individual-level information on the residential buildings provided by the Swiss National Cohort. For each death, information on the building type (single family-house or apartment building), building period (before or after 1990) and the address location was available. Given the large number of simulations required and the limited information on building characteristics, we decided to use a simplified model [1] to estimate the daily indoor temperature instead of a complex thermal building simulation program (e.g., IDA ICE, TRNSYS, or EnergyPlus). To account for the transient effect of the weather conditions on the thermal mass of the building, we included the 14 days prior the day of death and control days in the simulations.

The simplified model is a two-node room model that considers thermal mass, a window ventilation model, outdoor surfaces and an internal heat source. The model assumed that the windows were open (not tilted) during the night for natural cooling. The building parameters used in the study are shown in **Table S1**. The relationship between the external global radiation and the solar radiation entering the room through shading devices and windows was represented in the simplified model using quadratic regression. The coefficients were pre-calculated for the three building types considered in the thermal simulations using IDA ICE (EQUA Simulation AB). Data on daily mean global radiation from the nearest monitoring site was collected from the IDAweb database, a service provided by MeteoSwiss, the Federal Office of Meteorology and Climatology.

Outdoor daily maximum temperature at the residential addresses on the day of death and control days, as well as 14 days before, were estimated with the fine-grained temperature model developed by Flückiger et al. 2022 [2]. Since hourly data were required for the indoor temperature simulations, the daily values were determined by applying the procedure described by Chow and Levermore [3] .

The simplified two-node room model estimates indoor temperature as follows:

The conservation of energy at node ϑ is described by:

$$U_{fw}\, A_{fw}\, (\vartheta_o - \vartheta) + U_f\, A_f\, \left(\vartheta_f - \vartheta\right) + \dot{m}_a\, c_a\, (\vartheta_o - \vartheta) + \dot{Q}_v = 0 \qquad (1)$$

and at node ϑ_f

$$U_f\, A_f\, \left(\vartheta - \vartheta_f\right) + \dot{Q}_s = d_f\, \rho_f\, c_f\, A_f\, \frac{d\vartheta_f}{dt} \qquad (2)$$

Describing the differential term

$$\frac{d\vartheta_f}{dt} \text{ as } \frac{\vartheta_f - \vartheta_{f-1}}{\Delta t} \qquad (3)$$

and inserting the abbreviations

$$\mathrm{A} = U_{fw}\, A_{fw};\ \mathrm{B} = U_f\, A_f;\ C = \dot{m}_a\, c_a;\ D = \frac{d_f\, \rho_f\, c_f\, A_f}{\Delta t} \qquad (4)$$

we obtain the system of equations

$$A\, (\vartheta_o - \vartheta) + B\, \left(\vartheta_f - \vartheta\right) + C\, (\vartheta_o - \vartheta) + \dot{Q}_v = 0 \qquad (5)$$

$$B\, \left(\vartheta - \vartheta_f\right) + \dot{Q}_s = D\, \left(\vartheta_f - \vartheta_{f-1}\right) \qquad (6)$$

Indoor temperature is calculated according to

$$\frac{B\,(B+D)}{(A+B+C)\,(B+D)-B^2}\left[\frac{1}{(B+D)}\dot{Q}_s+\frac{D}{(B+D)}\vartheta_{f-1}+\frac{(A+C)}{B}\vartheta_o+\frac{1}{B}\dot{Q}_v\right]=\vartheta \quad (7)$$

and the floor temperature at the actual time step

$$\frac{1}{(B+D)}\left[\dot{Q}_s+B\,\vartheta+D\,\vartheta_{f-1}\right]=\vartheta_f \quad (8)$$

The air mass flow through the open window is given by the equation

$$\dot{m}_a=C_d\,H\,W\,\rho_a\frac{1}{3}\sqrt{g\,H\,\frac{\vartheta-\vartheta_o}{\vartheta_o+273.15}} \quad (9)$$

The area of the window opening can be represented as

$H\,W=A_{fw}\,a_{fo}$ (where mean window height $H=\overline{H}=1.2\,m$).

Substituted into equation (9), the mass flow for the fully open single sided ventilation window (no cross flow) is calculated as

$$\dot{m}_a=C_d\,A_{fw}\,a_{fo}\,\rho_a\frac{1}{3}\sqrt{g\,\overline{H}\,\frac{\vartheta-\vartheta_o}{\vartheta_o+273.15}} \quad (10)$$

The empirical value of the discharge coefficient can be assumed to be approximately 0.6 [4]. To avoid an iteration at every time step to calculate ϑ from equation (7) based on equation (10), the previous indoor temperature ϑ_{-1} is used in (10) instead of the actual indoor temperature ϑ.

Table S1: Building parameters used for the indoor temperature simulations for three building types.

Description	Parameter in simplified model	Apartment house (built until 1990)	Apartment house (built after 1990)	Single-family house
Thermal transmittance (U-value) window (including frame)	-	2.70 W/(m^2 K)	0.76 W/(m^2 K)	2.80 W/(m^2 K)
Thermal transmittance (U-value) façade (without window)	-	1.40 W/(m^2 K)	0.15 W/(m^2 K)	1.40 W/(m^2 K)
Thermal transmittance (U-value) façade (including windows)	U_{fw}	1.72 W/(m^2 K)	0.46 W/(m^2 K)	1.62 W/(m^2 K)
Solar transmittance (g-value) (including solar protection)	-	0.39	0.22	0.39
Façade area (including windows)	A_{fw}	229 m^2	231 m^2	86 m^2
Opening proportion of the window in relation to the façade area	a_{fo}	0.117	0.103	0.084
Heat transfer coefficient between air node and floor	U_f	8.3 W/(m^2 K)	9.1 W/(m^2 K)	10.0 W/(m^2 K)
Floor area	A_f	265 m^2	325 m^2	75 m^2
Storage active thickness of the floor	d_f	0.15 m	0.15 m	0.15 m
Indoor temperature at which the window is opened	ϑ	20°C	20°C	20°C
Possible window opening time	-	20:00-05:00	20:00–05:00	20:00–05:00

A_f	Floor area	m^2
A_{fw}	Façade area (including windows)	m^2
a_{fo}	Opening proportion of the window in relation to the façade area	-
C_d	Discharge coefficient	-
c_a	Specific heat capacity of air	J/(kg K)
c_f	Specific heat capacity of the storage active floor material	J/(kg K)
d_f	Storage active thickness of the floor	m
g	Earth gravity	m/s^2
H	Height of the window	m
$\dot{m}_a$	Air mass flow	kg/s
U_f	U-value between air node and floor node	W/(m^2 K)
U_{fw}	U-value façade (including windows)	W/(m^2 K)
ϑ_o	Outdoor temperature	°C

ϑ	Indoor temperature	°C
Δt	Time interval	s
ϑ_f	Temperature at floor node	°C
ϑ_{f-1}	Temperature of previous time step at floor node	°C
ρ_f	Density of the storage active floor material	kg/m^3
ρ_a	Air density	kg/m^3
$\dot{Q}_v$	Convective heat at the air node	W
$\dot{Q}_s$	Radiation heat at the thermal mass node (floor)	W
W	Width of the window	m

Figure S1 presents a comparison between the indoor temperatures calculated for apartment houses (building period until 1990) by the simplified model and those calculated by a detailed IDA ICE simulation with a deviation of +/- 1 K. The building parameters used are described in **Table S1**.

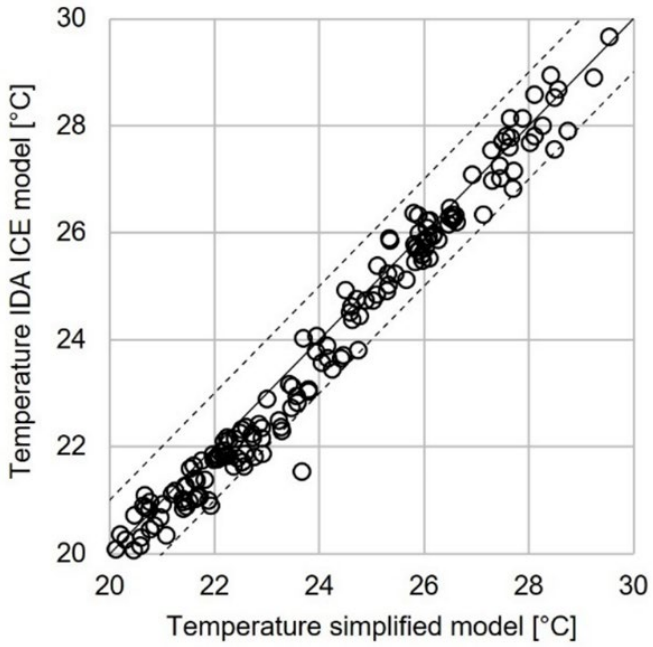


Figure S1: *Comparison between the indoor temperatures calculated by the simplified model (x-axis) and those calculated by a detailed IDA ICE simulation (y-axis) for apartment buildings (built until 1990).*

References

1. Koschenz M, Domingo-Irigoyen S, Niffeler M, Ragettli MS, Flückiger B, Kafadar M, et al. ResCool: Klimaanpassung von Neu-, Um- und bestehenden Wohnbauten – effiziente Kühlkonzepte. 2021 https://www.aramis.admin.ch/Default?DocumentID=68310&Load=true.
2. Flückiger B, Kloog I, Ragettli MS, Eeftens M, Röösli M, de Hoogh K. Modelling daily air temperature at a fine spatial resolution dealing with challenging meteorological phenomena and topography in Switzerland. International Journal of Climatology. 2022:1-16. doi: 10.1002/joc.7597.
3. Chow DHC, Levermore GJ. New algorithm for generating hourly temperature values using daily maximum, minimum and average values from climate models. Building Services Engineering Research and Technology. 2007;28(3):237-48. doi: 10.1177/0143624407078642.
4. Favarolo PA, Manz H. Temperature-driven single-sided ventilation through a large rectangular opening. Building and Environment. 2005;40(5):689-99. doi: https://doi.org/10.1016/j.buildenv.2004.08.003.

B. Additional results

Figure S2: Average annual daily maximum temperature at day of death in Switzerland by region. The region with heat-health action plans (HHAPs) covers cantons that implemented HHAPs between 2003 and 2008.

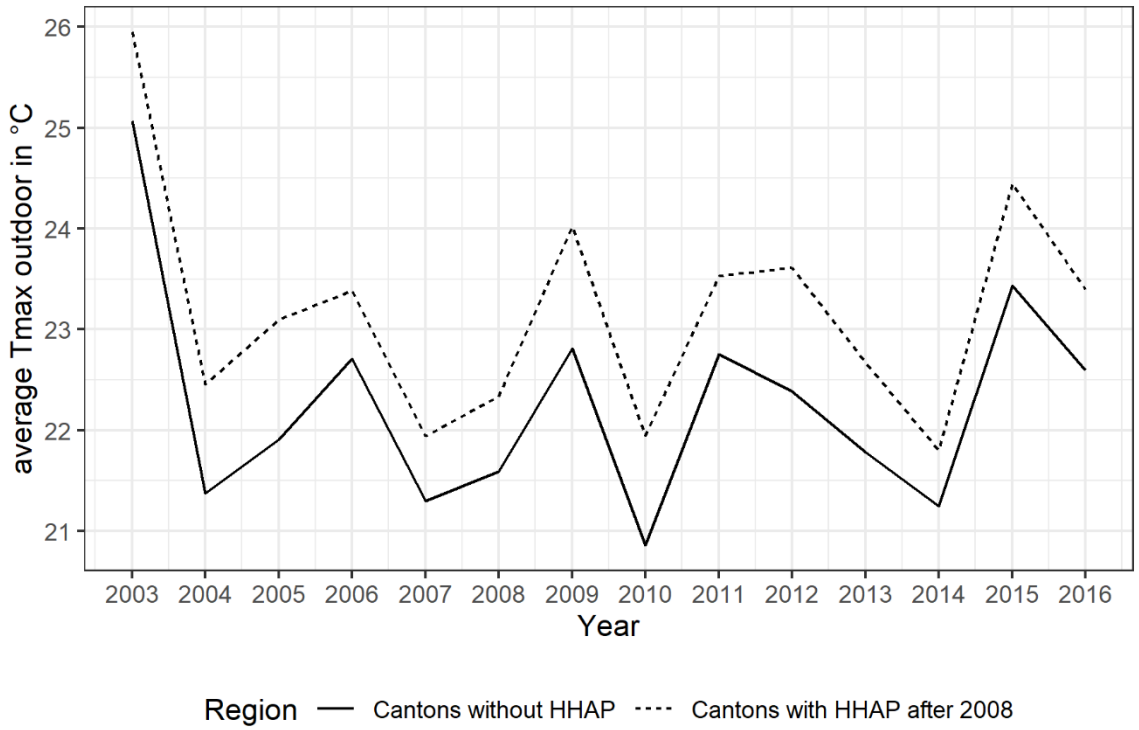


Figure S3: Overall cumulative exposure-response associations (with 95% confidence intervals) between outdoor daily minimum temperature (Tmin) and cause-specific mortality along 7 days of lag in Switzerland during the warm season (May to September) 2003-2016. The dashed vertical lines indicate the cause-specific minimum mortality temperature. OR: odds ratio; IHD: ischemic heart disease; MI: myocardial infarction; COPD: chronic obstructive pulmonary disease.

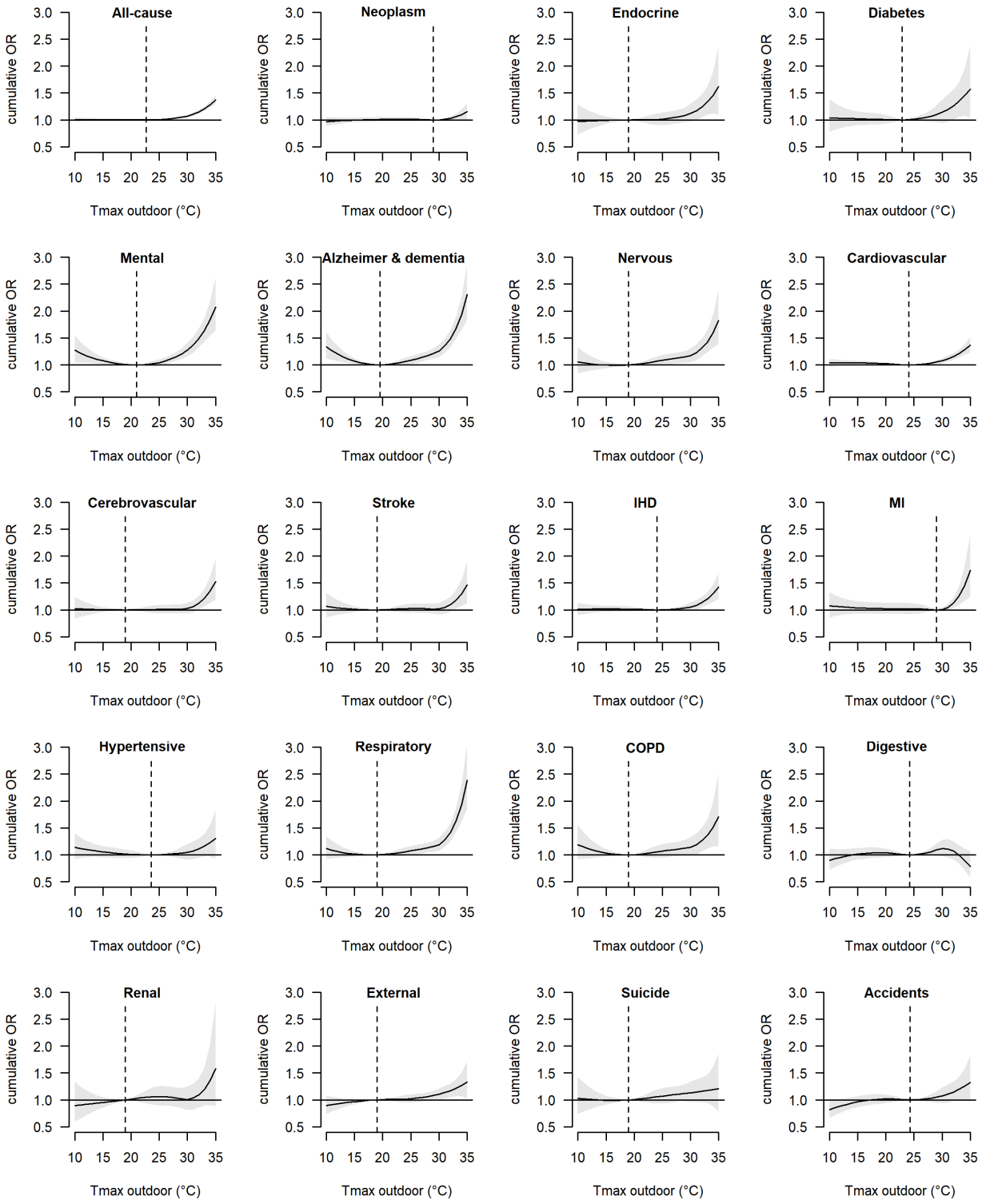


Figure S4: Exposure-response associations (with 95% confidence intervals) between indoor daily maximum temperature (Tmax indoor) and cause-specific mortality in Switzerland during the warm season (May to September) 2003-2016. The dashed vertical lines indicate the cause-specific minimum mortality temperature. OR: odds ratio; IHD: ischemic heart disease; MI: myocardial infarction; COPD: chronic obstructive pulmonary disease.

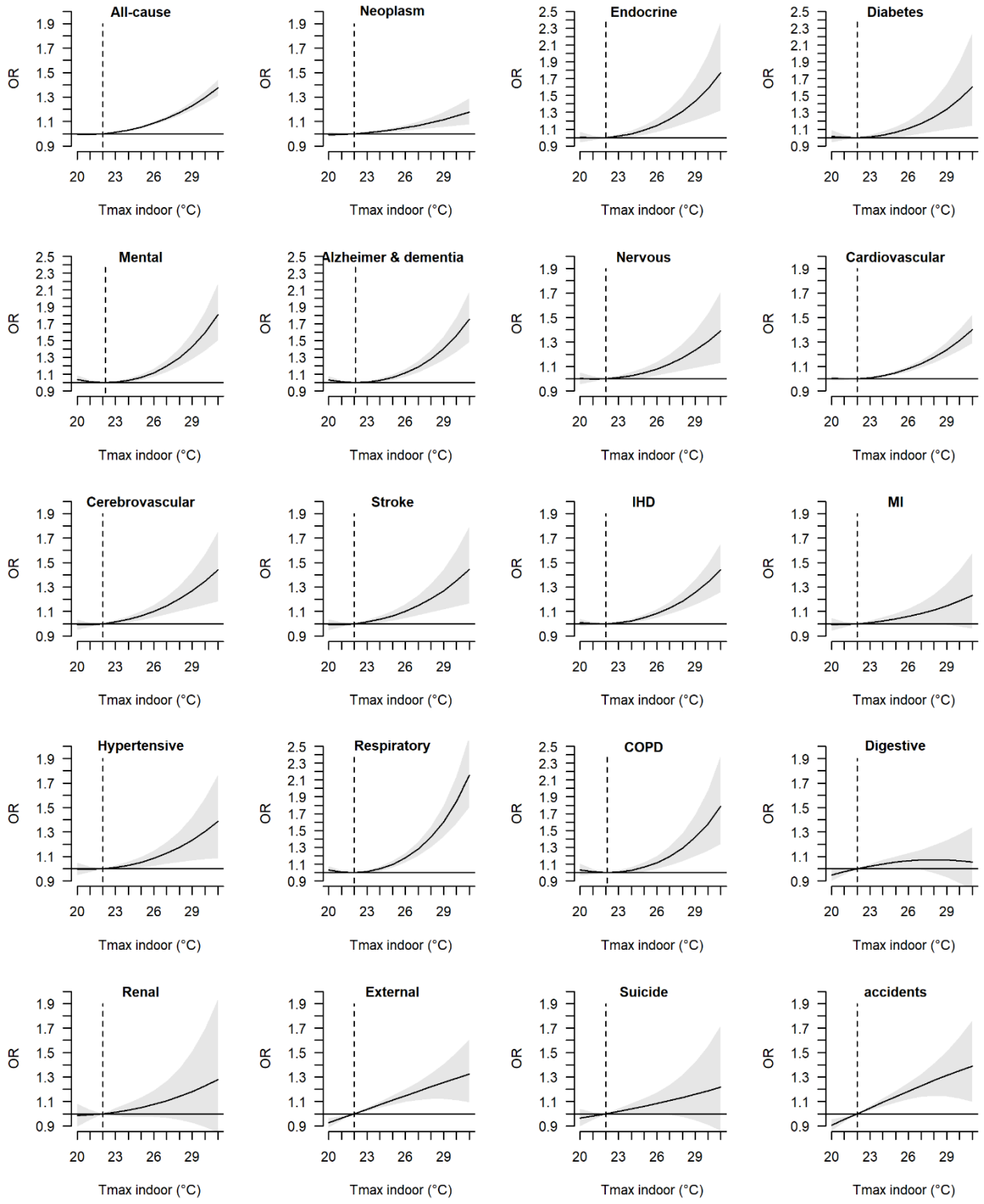


Figure S5: Sensitivity analysis for indoor daily maximum temperature (Tmax indoor): Comparison of cause-specific exposure-response functions with 95% confidence intervals limiting the minimum mortality temperature between the 25th and 90th percentile (P) of warm-season Tmax indoor (**grey curves, as presented in the manuscript**) and between P2 and P90 (**blue curves**). The dashed vertical lines indicate the cause-specific minimum mortality temperature. OR: odds ratio; IHD: ischemic heart disease; MI: myocardial infarction; COPD: chronic obstructive pulmonary disease.

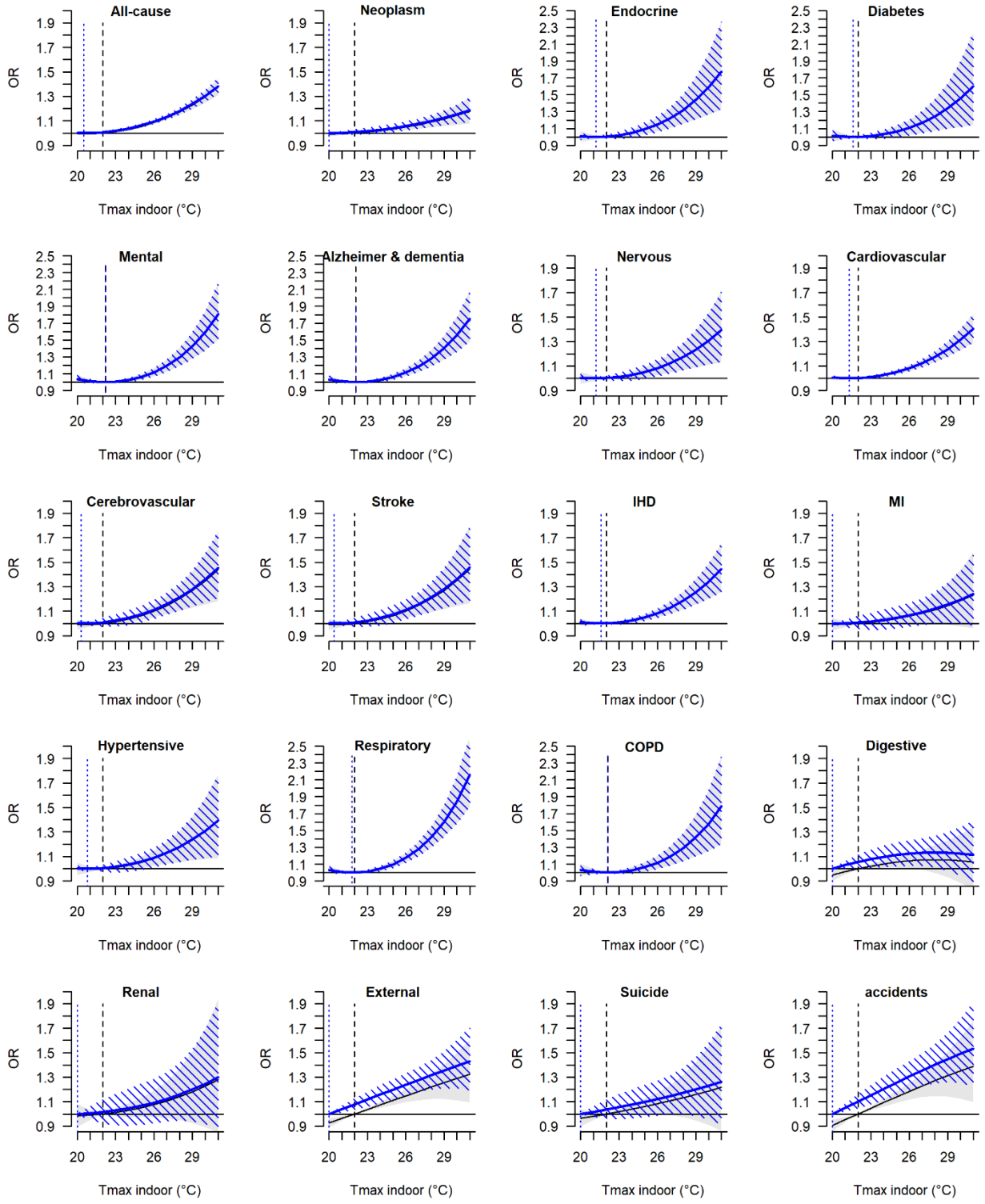
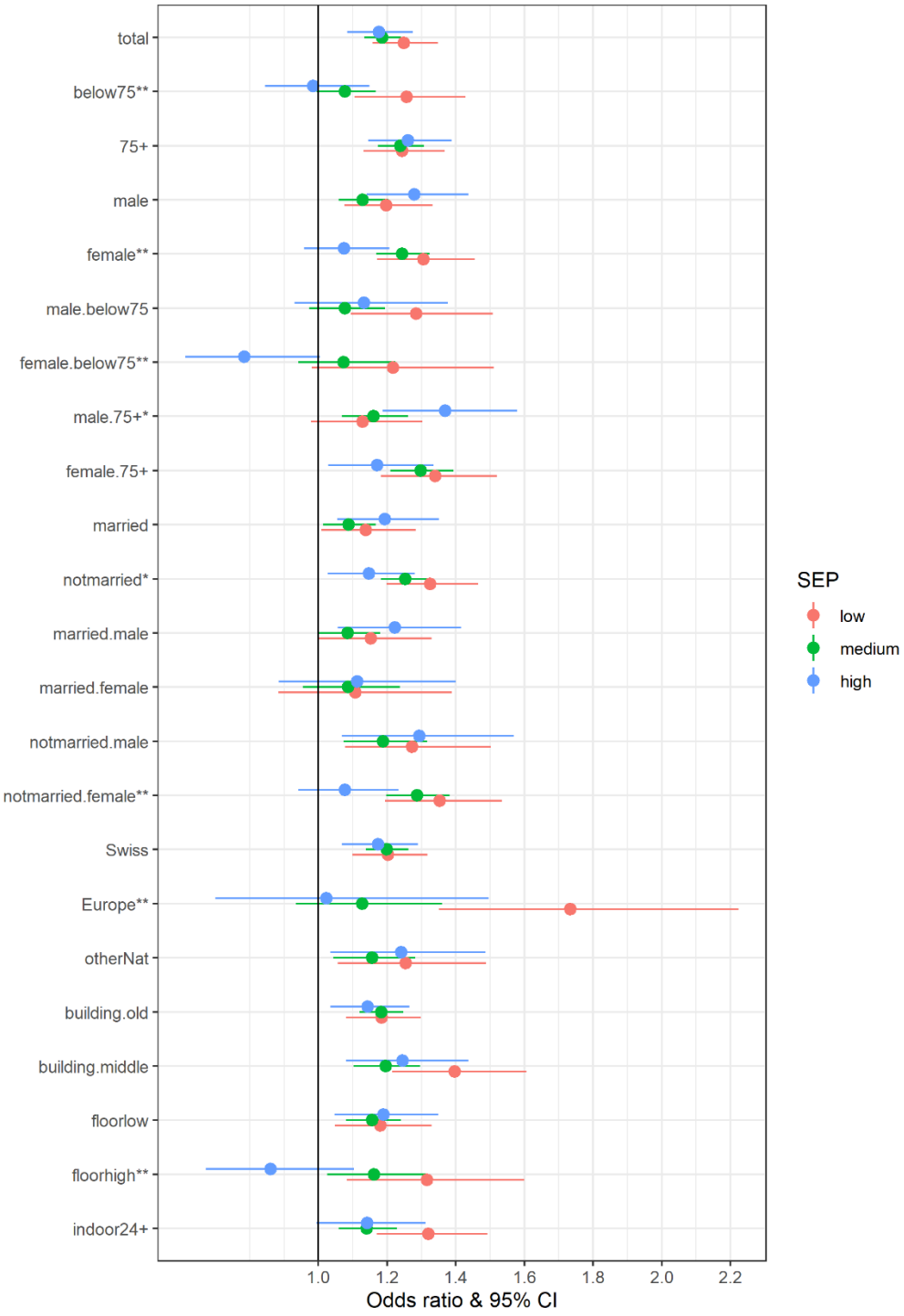


Figure S6: Cumulative Odds Ratios (OR) with 95% confidence intervals of all-cause mortality associated with an outdoor daily maximum temperature of 33°C compared to the minimum mortality temperature at 22.7°C, stratified over individual characteristics and neighborhood socio-economic position (SEP).



Stars mark statistically significant different OR between high and low SEP. Significant levels: **p-value<0.05, *p-value <0.1;
Below75: aged below 75; (fe)male.below75: (fe)males aged below 75; (fe)males.75+: (fe)males aged 75 and older; Swiss: Swiss nationality; Europe: nationality of an European country; otherNat: nationality of a non-European country; building.old: living in a building that was build before 1970; building.middle: living in a building that was built between 1970 and 1990; floorlow: living in an apartment building on ground to 2nd floor; floorhigh: living in an apartment building on floor 3+; indoor24+: indoor daily maximum temperature on the day of death was ≥24°C.

Figure S7: Comparison of temperature-mortality associations (with 95% confidence intervals) during the warm-season (May to September) for two periods (2004-2009 and 2010-2016) and by region (Switzerland, cantons with and without heat-health action plans HHAP). Odds Ratios (OR) represent the change in mortality risk associated with daily maximum temperature (Tmax) versus the period- and region-specific minimum mortality temperature (dashed blue and red vertical lines). The black dashed line marks the 98th percentile of warm-season Tmax (33°C). The region with heat health action plans (HHAPs) covers cantons in the Lake Geneva region and the canton of Ticino that implemented HHAPs between 2004 and 2008.

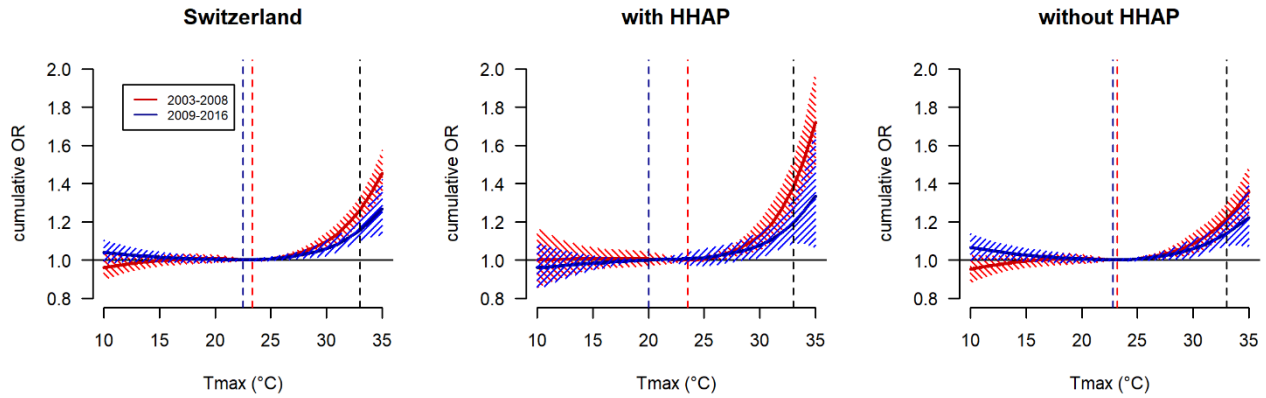


Figure S8. Cumulative Odds Ratios (ORs) with 95% confidence intervals (CI) of heat-related all-cause mortality at region- and period-specific (2004-2008 versus 2009-2016) extreme outdoor daily maximum temperatures (Tmax) without the year 2003 in Switzerland. Extreme temperatures are defined as the 98th percentile of region- and period-specific Tmax. The region with heat-health action plans (HHAPs) covers cantons that implemented HHAPs between 2003 and 2008.

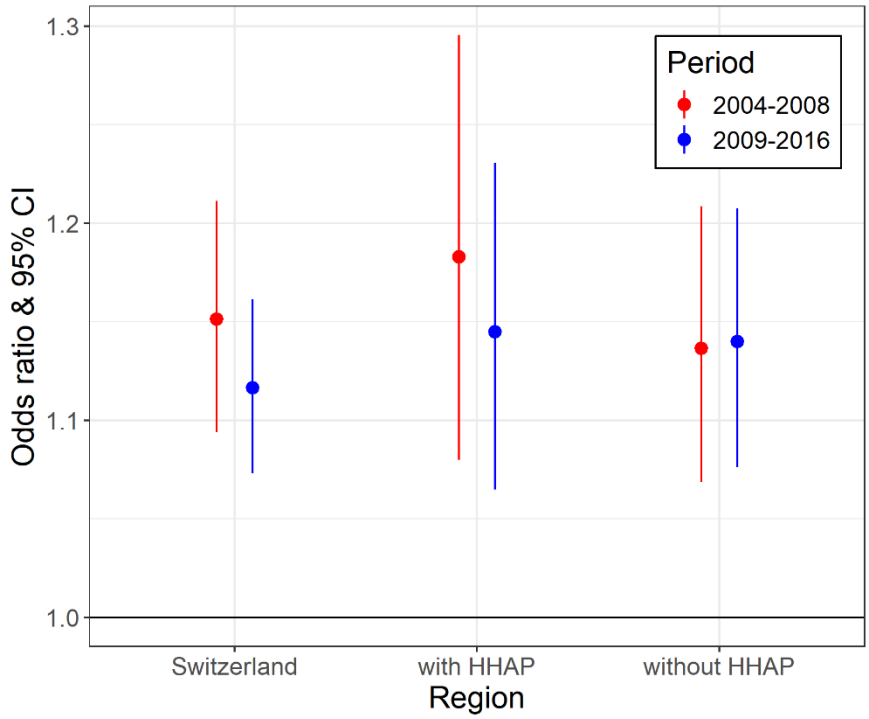


Table S2: Odds Ratios (ORs) with 95% confidence intervals (CI) of cause-specific mortality associated with an outdoor daily maximum temperature (Tmax) of 33°C, with an outdoor daily minimum temperature (Tmin) of 18°C and indoor Tmax at 28°C, as compared to the respective minimum mortality temperature (MMT). The thresholds correspond to the 98th percentile of the respective temperature distribution during the warm season in Switzerland between 2003 and 2016.

Cause of death	ICD-10-codes	Deaths (%)	Average age (years)	Tmax outdoor (at 33°C)		Tmin outdoor (at 18°C)		Tmax indoor (at 28°C)	
				MMT	OR (95% CI)	MMT	OR (95% CI)	MMT	OR (95% CI)
All causes	A00-Z99	320'306 (100.0)	78	22.7	1.21 (1.17; 1.25)	13.2	1.12 (1.09; 1.15)	22	1.17 (1.15 1.20)
Neoplasms	C00-D48	92'862 (29.0)	73	29.0	1.06 (1.00; 1.11)	14.1	1.03 (0.98; 1.09)	22	1.09 (1.05 1.13)
Endocrine diseases	E00-E90	8'531 (2.7)	79	19.0	1.33 (1.10; 1.62)	10.0	1.19 (1.01; 1.40)	22	1.31 (1.16 1.49)
Diabetes	E10-E14	6'790 (2.1)	81	22.9	1.34 (1.06; 1.70)	10.0	1.19 (0.99; 1.43)	22	1.24 (1.07 1.44)
Mental and behavioral disorders	F00-F99	18'258 (5.7)	84	21.0	1.64 (1.44; 1.86)	12.9	1.40 (1.25; 1.57)	22	1.29 (1.19 1.40)
Nervous system diseases	G00-G99	14'709 (4.6)	80	19.0	1.43 (1.24; 1.65)	10.0	1.28 (1.14; 1.44)	22	1.17 (1.07 1.28)
Alzheimer & dementia	F00-F03, G30-G31.1, G31.8-G31.9	21'758 (6.8)	87	19.5	1.67 (1.48; 1.88)	12.4	1.38 (1.25; 1.53)	22	1.28 (1.19 1.38)
Cardiovascular diseases	I00-I99	109'846 (34.3)	83	24.1	1.21 (1.14; 1.29)	13.7	1.09 (1.03; 1.14)	22	1.17 (1.13 1.22)
Cerebrovascular diseases	I60-I69	19'280 (6.0)	83	19.0	1.21 (1.07; 1.38)	16.6	1.07 (1.01; 1.13)	22	1.20 (1.10 1.31)
Stroke	I60-I64	16'053 (5.0)	82	19.0	1.18 (1.02; 1.36)	16.8	1.06 (1.00; 1.12)	22	1.20 (1.09 1.32)
IHD	I20-I25	42'047 (13.1)	82	24.0	1.21 (1.10; 1.33)	16.3	1.07 (1.02; 1.12)	22	1.18 (1.12 1.26)
MI	I21-I22	13'029 (4.1)	78	29.0	1.26 (1.10; 1.44)	16.8	1.06 (1.00; 1.13)	22	1.11 (1.00 1.24)
Hypertensive diseases	I10-I15	13'057 (4.1)	86	23.6	1.16 (0.97; 1.39)	10.1	1.04 (0.91; 1.18)	22	1.17 (1.06 1.31)
Respiratory diseases	J00-J99	17'274 (5.4)	81	19.0	1.62 (1.42; 1.86)	12.8	1.45 (1.29; 1.63)	22	1.42 (1.30 1.55)
COPD	J41-J44	8'249 (2.6)	79	19.0	1.37 (1.12; 1.67)	12.4	1.25 (1.05; 1.48)	22	1.29 (1.14 1.47)
Digestive diseases	K00-K93	13'113 (4.1)	77	24.2	0.99 (0.84; 1.18)	13.3	1.10 (0.96; 1.26)	22	1.07 (0.97 1.19)
Renal diseases	N00-N39	4'051 (1.3)	84	19.0	1.19 (0.89; 1.59)	10.0	1.00 (0.80; 1.26)	22	1.14 (0.95 1.37)
External causes	V01-Y98	20'305 (6.3)	65	19.0	1.21 (1.07; 1.38)	10.0	1.08 (0.97; 1.19)	22	1.22 (1.12 1.33)
Suicide	X60-X84	6'422 (2.0)	55	19.0	1.18 (0.94; 1.47)	10.0	1.11 (0.92; 1.33)	22	1.13 (0.97 1.32)
Accident	V01-X59	13'082 (4.1)	70	24.3	1.20 (1.01; 1.42)	16.8	1.04 (0.97; 1.10)	22	1.27 (1.15 1.41)

IHD: ischemic heart disease; MI: myocardial infarction; COPD: chronic obstructive pulmonary disease.

Table S3: Cumulative Odds Ratios (ORs) with 95% confidence intervals (CI) of heat-related all-cause mortality at extreme outdoor daily maximum temperatures (Tmax) of 33°C compared to region- and period-specific minimum mortality temperature (MMT) in the total population, for the elderly (aged 75+) and individuals with a low neighborhood socio-economic position (SEP). The region with heat-health action plans (HHAPs) covers cantons that implemented HHAPs between 2003 and 2008.

Population	Time period	Switzerland		Region with HHAPs		Region without HHAPs	
		OR (95% CI)		OR (95% CI)		OR (95% CI)	
total	2003-2016	1.21	(1.17; 1.25)	1.28	(1.21; 1.37)	1.17	(1.13; 1.22)
	2003-2008	1.26	(1.20; 1.33)	1.38	(1.26; 1.52)	1.21	(1.14; 1.29)
	2009-2016	1.12	(1.07; 1.16)**	1.14	(1.06; 1.23)**	1.14	(1.08; 1.21)
Age 75+	2003-2016	1.25	(1.20; 1.30)	1.37	(1.27; 1.48)	1.21	(1.15; 1.27)
	2003-2008	1.31	(1.23; 1.39)	1.48	(1.32; 1.66)	1.24	(1.15; 1.34)
	2009-2016	1.15	(1.10; 1.21)**	1.21	(1.11; 1.32)**	1.18	(1.10; 1.27)
Low SEP	2003-2016	1.25	(1.16; 1.35)	1.31	(1.17; 1.48)	1.20	(1.08; 1.32)
	2003-2008	1.32	(1.17; 1.48)	1.43	(1.19; 1.70)	1.24	(1.07; 1.44)
	2009-2016	1.16	(1.06; 1.27)	1.22	(1.07; 1.40)	1.17	(1.01; 1.36)

Significant difference between time period 2003-2008 and 2009-2016 (**p<0.05,*p<0.10; assessed by Chi-squared tests)