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# Mortality during Heat Episodes in Switzerland: A Story of Vulnerability

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**PAUL PUSCHMANN & TIM RISWICK [Eds.]**

# BUILDING BRIDGES

## *Scholars, History and Historical Demography*

### A Festschrift in Honor of Professor Theo Engelen

Valkhof Pers

## [16]

### MATHIAS LERCH & MICHEL ORIS

# Mortality during heat episodes in Switzerland: a story of vulnerability[1]

## INTRODUCTION

In recent years, Theo Engelen's research interest has moved to seasonal fluctuations in demographic behaviors. This contribution to his Festschrift is connected to this topic, although we consider a recent period and a specific issue, i.e. the mortality response to heatwaves. Although heatwaves have a long history, temperature peaks emerged as 'new social risks' on the political agenda in 1995. In July of that year, approximately 750 heath-related deaths occurred in Chicago over a period of just five days. Eric Klinenberg's (2002) book *Heat wave: A social autopsy of disaster in Chicago* became a bestseller, since in 2003 Europe was also hit by a similarly brutal episode. A so-called Omega block had led to a stagnation of the weather pattern, creating a high-pressure ridge that lasted for several days, mainly in France, Italy and Switzerland. The resulting record temperatures caused an excess of deaths which has been estimated to range from 35,000 to 55,000[2]. The large majority of the victims were older people living in urban agglomerations (Kovats & Jendritzky, 2005; Sardon 2006, p. 292). This led to the implementation of new heat warning systems. However, a second heat wave hit Europe in 2006, covering a larger area of the Northern Hemisphere and at its most intense in July. The anomalies in temperature maxima were also higher, resulting in the hottest summer ever recorded in Switzerland (Rebetez, Dupont & Giroud, 2008).

Heatwaves have since become an issue of concern for the future of our societies, with the emergence of global warming as a major challenge to human settlement. In Switzerland, the trend in warming during the 20th century was twice as pronounced as the worldwide trend, particularly in the last 40 years, which have seen an average increase in temperature of

0.6 degrees Celsius per decade, against 0.1 over the whole century. The challenges for human health are particularly exacerbated by the changing pattern of warming, which is more and more driven by an increase in maximum rather than minimum temperature and therefore mainly concerns summer rather than winter periods when compared to the past (Rebetez, et al., 2008). The Swiss population is thus increasingly exposed to extreme heat events, and is expected to be so in the future. Indeed, not only do predictions of an intensification of heat waves (in terms of frequency, intensity and duration) appear to be robust (Beniston, 2004), but all demographic scenarios also consistently predict a continuous process of population ageing and urbanization. As a result, a growing number of older (and consequently frailer) people living in dense human settlements will be particularly vulnerable to heat.

Although the adverse effect of heat on mortality has been confirmed in different countries, at different latitudes and on different continents (Basu, 2009; Basu & Samet, 2002), the literature shows considerable geographic heterogeneity in the phenomenon. The mortality response to temperature increases above optimal levels for survival of local populations was stronger in the Southern cities of Europe when compared with the Northern ones (Baccini, et al., 2008), whereas the inverse was observed in the United States (Curriero et al., 2002). The mortality response also differed greatly between US cities with identical weather patterns (Curriero et al., 2002). Moreover, there is considerable intra-city variability of heat-related mortality across neighborhoods and census tracts, pointing to the relevance of social and community level risk factors (Yardley, Sigal & Kenny, 2011).

This geographic heterogeneity mirrors the complexity of the phenomenon. Heat-related mortality is determined by the vulnerability of a complex socio-ecological system which is composed of 1) physical exposure to high temperature (i.e. heat), 2) the population's sensibility or its capacity to absorb the heat impact, and 3) the population's adaptation to extreme heat events at the societal and individual level (Wilhelmi & Hayden, 2010). Physical exposure is probably the best documented factor. Not only temperature per se, but also the duration and accumulation of heat lead to an increase in mortality. Moreover, heatwaves occurring earlier in the summer period are associated with more excess-deaths, since the populations so exposed are not yet acclimatized to high temperatures (Anderson & Bell, 2011; Basu & Samet, 2002; Rey et al., 2007; Tan et al., 2007). Well-functioning warning, awareness and prevention systems help to ensure the population's adaptation, and have been shown in France to mediate the negative effects of heat on mortality (Fouillet et al., 2008).

However, the second dimension of the vulnerability system, determined by the exposed populations' social and environmental susceptibility to the impact of heat, is understudied (Aström, Forsberg & Rocklöv, 2011). In this contribution, a particular effort is made to integrate this dimension into a comprehensive analysis of heat-related mortality. Our research strategy not only ascertains an accurate and differentiated measurement of physical exposure, but also investigates interactions with a complex set of other risk factors in a multilevel perspective. We account for the spatial and socioeconomic heterogeneity of exposed populations to test whether this confounds observed mortality responses to heat, or whether specific socioeconomic and environmental factors exacerbate heat-related mortality. In doing so, we aim to identify multidimensional vulnerability profiles, which are crucial for focusing preventive actions. Relying on daily meteorological information, exhaustive cohort-follow up mortality data and land use statistics, we apply the approach to the exhaustive older population of urban agglomerations in Switzerland.

Previous studies in Switzerland have estimated an excess of 975 deaths (7%) during the 2003 heatwave, defined by a temperature threshold of 34 degree Celsius, which was limited in comparison with other thresholds in Europe (Grize et al., 2005). In the hottest and most Southerly canton of Ticino, death rates were not significantly higher during the heat wave, except to a limited extent among older people (Cerutti et al., 2006). However, physical exposure was only roughly measured in this latter study, and socioeconomic differentials in mortality were not addressed. Intra-urban differences in the number of excess deaths during the 2003 heat wave have been noted, with higher levels in central and suburban communes (Grize et al., 2005), pointing to the potential importance of environmental factors. In this study we will test whether this intra-urban gradient arose from the concentration of vulnerable people, living contexts and environments in central areas (when compared to the agglomeration belt) or from the differential sensitivity of inhabitants to the heat effect.

We will first review the empirical evidence on the determinants of heat-related mortality in relation to anticipated socioeconomic, contextual and environmental differentials, and then introduce the analytical strategy. Results from the multilevel models applied to the exhaustive older population of Swiss agglomerations during the summer periods 2001-2007 confirm a weak independent effect of heat on mortality, which was mainly concentrated during long and intense heat episodes. The mortality response was also relatively undifferentiated across socioeconomic groups, living contexts and environments. The bulk of the heat effect was actually accounted for by the spatial clustering of populations, which are more at risk of death in general, especially among men. Heat specifically exacerbated the risk of mortality only for institutionalized and, to a lesser extent, unmarried women. The analysis thus confirms the determinant role played by frailty and by the accumulation and spatial concentration of risk factors, rather than their specific effects during heatwaves.

## DIVERSITY IN POPULATION SUSCEPTIBILITY TO HEAT-RELATED MORTALITY

Despite identical physical exposure to heat, the population risks of mortality may differ from one place to another for at least three reasons. Firstly, individual determinants of susceptibility and adaptation to heat are not distributed uniformly in space. Differences in population structure (or composition) may therefore confound the comparison of heat-related mortality between neighborhoods, cities or countries. Secondly, the spatial aggregation of individuals and their interactions, as well as exogenous influences, determine place-specific group properties, which affect the health of all inhabitants (Macintyre, Ellaway & Cummins, 2002) and may influence their capacity to cope with heat stress. These so-called contextual effects have been shown to influence mortality independently from individual risk factors (Pickett & Pearl, 2001). Thirdly, environmental characteristics can be considered to be specific factors of mortality during heat (Smoyer, 1998). We will review here the evidence for these three groups of vulnerability factors, with a focus on confounding and interaction effects.

The populations most vulnerable to heat-related mortality are older people and those with pre-existing diseases (Basu, 2009; Basu & Samet, 2002). The body's ability to cope with heat stress (through evaporative skin cooling, increased blood flow to the head, etc.) declines with age, illness and medicine intake. Older and sick people may also perceive heat to a lesser extent and may be constrained in the adoption of adaptive behaviors (Hansen, Bis, Nitschke et al., 2011), such as extensive hydration, which have a strongly protective effect (Vandentorren, Bretin, Zeghnoun et al., 2006). Women are often found to be affected to a greater extent, but we believe this reflects gender differences in socioeconomic at-risk configurations, as well as in the cause of death patterns related to increased longevity, rather than biological factors.

Apart from these biological and medical factors, there is little agreement on social vulnerability profiles. Social isolation is certainly a risk factor, especially among the older population, because it acts as a barrier for people in need of assistance during heat stress (Klinenberg, 2002). Low socioeconomic status is also presumed to increase risk, because of lower capacity to afford technological adaptations to heat (such as air conditioning), and more vulnerable housing and location.

However, the control of socioeconomic factors at the individual level is a challenge, and can often be done only for a small sample of a population or of deaths. Because of data constraints, the socioeconomic characteristics of the whole population living in a specific place are often used as a proxy for the status of all its inhabitants. Such an approach implies an ecological bias, and reduces the concept of contextual effects to the aggregation of individual effects. This may be one reason for the heterogeneity in the conclusions of studies that have investigated the effect of socioeconomic status at the aggregate level using local percentages of unemployed or low-skilled people, median incomes, or other composite indexes. Indeed, no effect of these variables on heat-related mortality was observed in Rome (Schifano et al., 2009), Brisbane (Yu et al., 2010), Budapest and London (Ishigami et al., 2008). However, poorer neighborhoods had a higher excess mortality relative to affluent ones during heat-waves in St. Louis (Smoyer, 1998) and in the suburbs of Paris (Rey et al., 2009) as well as in US cities (Curriero et al., 2002). In Milan, higher median neighborhood income was, surprisingly, slightly associated with higher heat-related mortality among younger people (Ishigami et al., 2008).

Canoui-Poitrine et al. (2006) observed a change in both the geography and the socioeconomic composition of deaths during the heat wave in Paris when compared to reference years, and concluded that both contextual and individual factors affect heat-related mortality. After controlling for various confounding effects at the local and individual level, manual workers in France were found to have higher mortality during heatwaves than managers who were older (Vandentorren et al., 2006). This contrasted with Mexico and Chile, where individual educational attainment did not have an effect (Bell et al., 2008). Even when the effect of socioeconomic status is estimated simultaneously at the individual and contextual level, results diverge. Local levels of unemployment did not affect heat-related mortality in Barcelona and Sao Paulo, but the lowest skilled among older women were characterized by the highest excess mortality (Borell et al., 2006; Gouveia, Hajat & Armstrong, 2003). Browning, Wallace, Feinberg, et al. (2006), by contrast, showed that individual socioeconomic characteristics had the same effect on mortality during the 1995 heat wave in Chicago when compared to previous summers. But neighborhood affluence and commercial vitality protected individuals only during the heat wave. A more dynamic social ecology, it was argued, is protective against heat-related mortality, because it maintains more healthy social institutions and limits neighborhood infrastructural decay.

Conclusions regarding social risk factors are also heterogeneous. Social isolation at the individual level is often inferred from marital status, on the assumption that the single, divorced and widowed are more at risk of isolation. Unmarried older people did in fact show higher mortality in Rome (Schifano et al., 2009) and in Paris (Canoui-Poitrine et al., 2006). However, in the latter city, this may have resulted from a selection effect, as marital status did not play a role when controlling for several individual and household-level variables indicating social status (Vandentorren et al., 2006). Living arrangements may be of more importance than marital status. In Modena, unmarried women did not have higher mortality when controlling for negative effects associated with living in either a single-person household or a care institution, where people may respectively feel themselves more isolated and be frailer (Foroni et al., 2007).

At the local level, denser patterns of social interaction are usually expected to increase assistance to those people most sensitive to heat. Assuming that demographically more stable neighborhoods are characterized by a higher degree of social interaction, Smoyer (1998) and Uejio et al. (2011) did indeed observe a negative relationship with heat-related mortality in St. Louis and in Philadelphia. The empirical sociological investigation by Klinenberg (2002) of the 1995 episode in Chicago showed higher vulnerability among African-Americans compared to Hispanics. The author related this differential to the fact that many African-Americans lived in areas of sub-standard housing and less cohesive neighborhoods, while Hispanics lived in areas of higher density, but more social cohesion. However, Browning et al. (2006) did not find an effect of the neighborhood's demographic stability.

In contrast to these competing conclusions on socioeconomic differentials in heat-related mortality at the individual and contextual level, there is more convergence in results regarding the impact of the environment. Population density and the scarcity of green areas are major determinants (Medina-Ramon & Schwartz, 2007; Uejio et al., 2011; Vandentorren et al., 2006). Dark-colored built environments absorb more heat than green areas and cool down to a lesser extent at night, while nearby high-rise buildings lower the speed of winds that refresh urban air. The concentration of human activity exacerbates meteorological phenomena through the effects of air pollution and the wastage of heat associated with high energy use. The combinations of these factors have been explored by epidemiologists and environmentalists, who coined the term *urban heat island effect* (UHI) about half a century ago. Moreover, urban sprawl exacerbates the heat island effect. More sprawling US metropolitan regions did indeed experience a more marked increase in heat events during the second half of the 20th century (Stone, Hess & Frumkin, 2010), and heat island effects were associated with more numerous and more intense heatwaves in Chinese cities, leading to higher excess mortality in central and suburban communes (Tan et al., 2010).

This review of the literature shows up many apparent contradictions, and highlights the fact that living environments are made up of a combination of many factors, which create 'sub-environments'. Their specific exposure to the risk of heat-related mortality has to be assessed in order to better target prevention. Moreover, data constraints often motivate a focus on one single aspect of the vulnerability profile in isolation from the others. Yet the accumulation of disadvantages has to be taken into account, particularly in urban environments, since individual, contextual and environmental factors in heat-related mortality tend to overlap in highly differentiated settings. The more densely populated neighborhoods may be inhabited by poorer populations, and this fiscal disadvantage may in turn alter the development and maintenance of local infrastructure and environment. In the US, city-centers clearly accumulate factors of vulnerability to heat-related mortality (Reid et al., 2009). Confounding effects must also be assessed to determine the expected efficiency of different alternative interventions. The independent impact of population density on heat-related mortality, for example, was small or in the opposite direction, after controlling for socioeconomic characteristics of local populations in St. Louis, Massachusetts and Paris (Hattis, Ogneva-Himmelberger & Ratick, 2012; Rey et al., 2009; Smoyer, 1998).

The importance of considering simultaneously the various risk factors for heat-related mortality that operate at different levels of social organization has often been underlined (Basu & Samet, 2002; Canoui-Poitrine et al., 2006; Smoyer, 1998; Yardley et al., 2011), but rarely operationalized (see Browning et al., 2006 for one of the exceptions). While relying on cohort-follow-up data on the exhaustive older population in urban agglomerations of Switzerland, we contribute to this line of multilevel research. We anticipate that older people, and also those who are frailer because of pre-existing diseases, will be more vulnerable to heat stress. Educational attainment and marital status are good proxies for socioeconomic status and social isolation respectively at the individual level, because in Switzerland these variables are most clearly related to health status (Burton-Jeangros, 2009) and strongly affect survival. At age 30, men and women holding a tertiary school diploma can expect to live respectively up to 7.1 and 3.6 years longer than the lowest skilled, and married people benefit from a similar advantage compared to singles (Schumacher & Vilpert, 2011; Spoerri, et al., 2006). We may expect heatwaves to exacerbate these socioeconomic inequalities in mortality, because of differences in available resources and access to social support.

Similarly, a poor living context may increase mortality through its physiological effects on health, particularly in extreme meteorological conditions, because of poor material resources and infrastructural endowment (Pickett & Pearl, 2001). The local distribution of wealth may play a role as well. On the one hand, it is argued that a high degree of stratification of local populations corrodes social capital, and so decreases social support for remaining in good health (Kawachi, et al., 1997; Wilkinson, 1996). This is particularly relevant during heatwaves, when social capital is a determinant for the promotion of adaptive behavior among older people. On the other hand, collective resources (such as recreational areas, higher quality infrastructure, etc.) which benefit all residents are more developed in these settings, thanks to important fiscal contributions by a small minority of very affluent inhabitants (Stafford, & Marmot, 2003).

At the environmental level, we may expect that where a larger proportion of the residential context is occupied by green areas, and population density of the built-up environment is lower, the heat island effect, and hence the mortality response to heat, will be diminished. We also anticipate that individuals living on the top floors of (apartment-)buildings will be particularly exposed to heat stress and the related risk of dying, as occurred in Paris (Vandentorren, et al., 2006). Moreover, urban sprawl is likely to exacerbate these effects, leading to higher mortality during heatwaves.

The strength of our analytical strategy lies not only in the simultaneous appreciation of different factors of the population's susceptibility to heat-related mortality, but also in the accurate measurement of physical exposure to heat. This is made possible by a combination of time-series analysis and the study of differential mortality in a multilevel modeling framework.

Physical exposure to heat is measured using time-series data of daily temperature maxima during the main summer months (June, July and August) for the years 2001 to 2007. These meteorological data were obtained from 26 stations of MeteoSuisse located in urban agglomerations of Switzerland.[3] For each municipality under study, we identified temporal sequences of heat and non-heat episodes over the summer periods. Heat episodes start with at least three consecutive days of temperature maxima of at least 30 degree Celsius (i.e. the official threshold established by MeteoSuisse to launch heat warning systems) and end with the second consecutive day during which the temperature is below this threshold. Thus, we define heat to include at least two consecutive nights during which there are few opportunities to recover from the heat stress; this is also so as to capture lagged mortality effects. This time-varying information on heat in the communes under study is imputed to the daily exposure population of all municipalities of the same urban agglomeration. Using the criteria of duration (at least one week versus longer periods) and temperature maxima (less than or at least 33.5 degrees Celsius), we defined four types of heat exposure: short and weak, short and intense, long and weak and long and intense episodes.

The exposure population aged 65 to 89 is estimated for the summer periods 2001 to 2007 from the *Swiss National Cohort* (SNC) follow-up mortality database: 94% of registered deaths for the years 2001-2007 have been linked to the individuals enumerated at the 2000 Census using a mix of deterministic and probabilistic methods (Bopp et al., 2008). Unlinked deaths were imputed according to a stratified random technique in a later version of the SNC database, and are included in our analysis. Exposure to mortality starts in June of each year and ends either with death or with truncation due to emigration (which is known only for foreigners) or the end of the summer period (end of August). The dependent variable is mortality from all causes. We estimated 408,360,190 person-days of exposure (experiencing 34,155 deaths) and matched these with place-specific daily information on heat-episodes.

Multilevel models are specified to test the independent effect of heat on mortality, as well as its interaction effects with individual, contextual and environmental risk factors. Standard errors of the mortality effects are adjusted for the clustering of individual observations at three hierarchical levels of analysis: individuals constitute the first level and are nested in municipalities defined as the second level, which determine the socioeconomic living context and environment, as well as exposure to heat. Municipality populations are further nested in agglomerations, which constitute the third and last level of analysis.

Discrete-time random-intercept logistic regression models are specified, allowing the intercept to vary across agglomerations and municipalities (Rasbash et al., 2005). The logged-odds of dying are estimated from the model intercept, which constitutes the baseline hazard function of mortality all over urban Switzerland according to time-varying age ($\beta_0(t)$), and the additive effects of individual, contextual and environmental variables, as well as the effect of time-varying heat episodes (respectively $x_{1ijk}$, $W_{1jk}$, and $Heat_{1k}$):

$$\log\left(\frac{h_{ijk}(t)}{1-h_{ijk}(t)}\right)=\beta_0(t)+\beta_1 x_{1ijk}+\alpha_1 W_{1jk}+\alpha_2 Heat_{2k}+(v_{0k}+u_{0jk}+e_{0ij})$$

with individuals *i* nested in 737 municipalities *j* composing 26 agglomerations *k*.

The variance in mortality is partitioned into variation between individuals within each cluster (corresponding to $e_{oij}$) and variation in average mortality between clusters ($u_{ojk}$, $v_{ok}$). Thus, the standard errors of the heat effect are adjusted for the local clustering of individual exposures. We also focus on the extent to which local heat-related mortality arose from the spatial concentration of more vulnerable subpopulations, in terms of individual, contextual and environmental characteristics which are controlled for in a second model. Socioeconomic differentials in the mortality response to heat are also investigated through interaction effects in a third model. Models are estimated in MLWIN version 2.2 through the Markov chain Monte Carlo method (MCMC; [Browne, 2003; Rasbash et al., 2005]).

The models are specified for each sex separately, as exploratory tests showed that there was no significant gender difference in heat effects (not shown). We control the heat effect for the differences in population composition in terms of *age, marital status* (married versus unmarried) and the level of *educational attainment* (using broad ISCED categories; none to compulsory Secondary School I, Secondary School II which is either on-the-job training or general school, and Tertiary). *Frailty and the presence of co-morbidities* are proxied by residence in an elderly or health care institution. Specific risk factors for heat-related mortality are assessed through the interaction effects of these confounders with the four types of heat exposure.

Contextual variables are derived from the 2000 Census. Relative differences in *material deprivation between living contexts* are estimated using the Townsend index (Townsend, Phillimore & Beattie, 1988); an unweighted sum of standardized percentages of overcrowded private households (i.e. more than one person per room), non-owned private dwellings, unemployment rates and the share of population aged 25 and higher having at best a Secondary School I diploma. Based on the relative importance of deprived subpopulations in each cluster, relative to the Swiss average, area-level deprivation is inferred: a high value of the index means a higher than average level of deprivation. *Material inequality within the living context* is estimated using an unconventional Gini-index based on the distribution of wealth, approximated here for each individual by an un-weighted sum of the inverse attributes used for the Townsend index (i.e. not living in an overcrowded household, ownership of the dwelling, not being unemployed and having an educational attainment above the compulsory Secondary I level). The higher the Gini-index, the more unequal is the wealth distribution among inhabitants of a living context.

The Swiss land use statistics of the Federal Office of Statistics (OFS) are used to characterize urban environments. In this analysis, we rely on the 1992/97 version because the latest version has not yet been updated for all Swiss communes. Green and recreational areas, as well as the surroundings of houses and blocks (which are assumed to be mainly green areas), are distinguished from the built-up environment (including the urban transport infrastructure such as roads, parking lots, etc.). Population density refers exclusively to the municipality built-up area. To differentiate direct physical exposure to heat, we also distinguished residents of apartments located on the top floor of buildings from other urban inhabitants. Since information on air pollution is not available for all urban communes, this exacerbating effect of heat could not be controlled for. However, our results should not be significantly biased, as air pollution usually accounts only slightly for heat-related excess mortality (Basu, 2009).

Urban sprawl is measured at the level of agglomerations using the average difference in intercensal demographic growth of the agglomeration belt compared to the city center between 1970 and 2000.

Model 1 adjusts the likelihood of mortality only for the effects of the four types of heat-episode, which all significantly increase mortality among men and women (see Table 1 and 2, respectively). As seen in Model 2, further adjustments for local population composition, context and environments strongly reduce the spatial variance of mortality at the municipality level and increase the fit of the models to the data (as evinced by the decline in the Bayesian Information Criterion (DIC)).

The likelihood of dying increases sharply with age for both sexes. Results also confirm the protective effects of marriage and higher-level education. Mortality in penthouse-apartments did not significantly differ when compared to residents of other private dwellings. However, the strongly increased likelihood of dying for residents in old age or health care institutions confirms their high level of frailty (Lalive-d'Epinay & Spini, 2008). The fact that the excess-risk is more marked for women than for men may be explained by the fact that they are in worse health on moving into institutions. Husbands not only tend to die earlier than their wives, but also more frequently die at home, so that women are more at risk of being institutionalized when experiencing health problems, leading to a higher concentration of frailty.

As expected, a higher level of local material deprivation was associated with a higher mortality. Local inequality, by contrast, is interestingly associated with a slightly lower likelihood of dying (although only significantly for women). This tends to support the hypothesis related to the greater availability of collective resources in highly stratified living contexts. The population density of the built environment and the proportion of green areas do not have a statistically significant and independent effect.

However, the most important result of Model 2 is that the mortality effect associated with short heat episodes, as well as that with long but weak episodes, decreased after standardization of the local exposure population and living context for the aforementioned characteristics. Thus, subpopulations which are more vulnerable to the risk of death in general are concentrated in places most affected by heat, explaining much of heat-related mortality. This spatial clustering of vulnerabilities indeed entirely accounts for the mortality response among men, except during long and intense heat episodes. Among women, it only slightly mediates the mortality effect of all heat episodes, which however remain statistically significant.

*Table 1: The effect of heat episodes and individual, contextual and environmental factors on male mortality at age 65-89, Switzerland, June-August 2001-2007*

| **Explanatory variables** | | Model 1 | | Model 2 | | Model 3 (with Interaction effects) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | O.R. | S. | O.R. | S. | O.R. | S. | O.R. | S. | O.R. | S. | O.R. | S. | O.R. | S. |
| Constant | | 0.00 | *** | 0.00 | *** | 0.00 | *** | | | | | | | | |
| Heat exposure | Non-heat | 1 | | 1 | | 1 | | | | | | | | | |
| | Short-weak heat | 1.11 | ** | 1.06 | ns | 0.95 | ns | | | | | | | | |
| | Short-intense heat | 1.13 | * | 1.06 | ns | 1.04 | ns | | | | | | | | |
| | Long-weak heat | 1.13 | ** | 1.09 | ns | 1.31 | ns | | | | | | | | |
| | Long-intense | 1.18 | *** | 1.16 | *** | 1.20 | *** | | | | | | | | |
| **Individual and municipality characteristics** | | | | | | Non-heat | | Short-weak | | Short-intense | | Long-weak | | Long-intense | |
| Age group | Less than 75 years | | | 0.32 | *** | 0.32 | *** | 1.11 | ns | 1.03 | ns | 1.03 | ns | 0.96 | ns |
| | 75 years and more | | | 1 | | 1 | | 1 | | 1 | | 1 | | 1 | |
| Marital status | Not married | | | 1 | | 1 | | 1 | | 1 | | 1 | | 1 | |
| | Married | | | 0.73 | *** | 0.73 | *** | 0.99 | ns | 1.12 | ns | 0.86 | ns | 0.94 | ns |
| Educational attainment | Secondary I (and lower) | | | 1.15 | *** | 1.14 | *** | 1.07 | ns | 0.94 | ns | 1.15 | ns | 1.03 | ns |
| | Secondary **ii** | | | 1 | | 1 | | 1 | | 1 | | 1 | | 1 | |
| | Tertiary | | | 0.79 | *** | 0.80 | *** | 1.04 | ns | 0.77 | ns | 0.75 | ns | 1.02 | ns |
| Household | Penthouse apartment | | | 0.99 | ns | 1.00 | ns | 1.01 | ns | 0.94 | ns | 0.91 | ns | 0.91 | ns |
| | Other private household | | | 1 | | | | 1 | | 1 | | 1 | | 1 | |
| | Institution | | | 2.72 | *** | 2.69 | *** | 1.20 | ns | 0.67 | ns | 0.52 | ns | 1.18 | ns |
| Municipality char. | Inter-municipality deprivation | | | 1.02 | *** | 1.02 | *** | 1.02 | ns | 0.93 | ns | 0.98 | ns | 0.96 | ns |
| | Intra-municipality inequality | | | 0.99 | ns | 0.985 | ** | 1.00 | ns | 1.11 | ns | 0.97 | ns | 1.02 | ns |
| | Density of built-up area | | | 1.000 | ns | 1.000 | ns | 1.000 | ns | 1.003 | ns | 1.000 | ns | 1.001 | ns |
| | Share of green areas | | | 0.999 | ns | 0.999 | ns | 1.002 | ns | 0.997 | ns | 0.995 | ns | 0.996 | ns |
| Agglo char. | Urban sprawl | | | | | 1.002 | ns | 1.010 | ns | 1.000 | ns | 1.027 | ns | 0.999 | ns |
| Model statistics | Person-days | 170'491'473 | | 170'491'473 | | 170'491'473 | | | | | | | | | |
| | Events | 17073 | | 17073 | | 17073 | | | | | | | | | |
| | DIC | 90768 | | 83543 | | 83598 | | | | | | | | | |
| Geographic Variance | Agglomeration level | 0.004 | ns | 0.002 | * | 0.003 | ns | | | | | | | | |
| | Municipality level | 0.014 | *** | 0.002 | *** | 0.000 | *** | | | | | | | | |

Source: MeteoSuisse, Swiss land use statistics and Swiss National Cohort database (Census 2000 & Vital statistics 2001-07). Notes: O.R = Odds Ratio, S = Statistical significance (*** = at 0.01 level, ** = at 0.05 level), DIC = Bayesian Information Criterion.

*Table 2: The effect of heat episodes and individual, contextual and environmental factors on female mortality at age 65-89, Switzerland, June-August 2001-2007*

| **Explanatory variables** | | Model 1 | | Model 2 | | Model 3 (with Interaction effects) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | O.R. | S. | O.R. | S. | O.R. | S. | O.R. | S. | O.R. | S. | O.R. | S. | O.R. | S. |
| Constant | | 0.00 | *** | 0.00 | *** | 0.00 | *** | | | | | | | | |
| Heat exposure | Non-heat | 1 | | 1 | | 1 | | | | | | | | | |
| | Short-weak heat | 1.15 | *** | 1.09 | ** | 1.03 | ns | | | | | | | | |
| | Short-intense heat | 1.27 | *** | 1.18 | *** | 1.03 | ns | | | | | | | | |
| | Long-weak heat | 1.16 | ** | 1.15 | ** | 0.96 | ns | | | | | | | | |
| | Long-intense | 1.22 | *** | 1.20 | *** | 1.16 | ** | | | | | | | | |
| **Individual and municipality characteristics** | | | | | | Non-heat | | Short-weak | | Short-intense | | Long-weak | | Long-intense | |
| Age group | Less than 75 years | | | 0.30 | *** | 0.31 | *** | 0.91 | ns | 1.01 | ns | 1.05 | ns | 0.91 | ns |
| | 75 years and more | | | 1 | | 1 | | 1 | | 1 | | 1 | | 1 | |
| Marital status | Not married | | | 1 | | 1 | | 1 | | 1 | | 1 | | 1 | |
| | Married | | | 0.63 | *** | 0.63 | *** | 0.79 | ** | 1.23 | ns | 1.09 | ns | 0.99 | ns |
| Educational attainment | Secondary **i** (and lower) | | | 1.16 | *** | 1.16 | *** | 1.13 | ns | 1.05 | ns | 1.02 | ns | 0.97 | ns |
| | Secondary II | | | 1 | | 1 | | 1 | | 1 | | 1 | | 1 | |
| | Tertiary | | | 0.82 | *** | 0.81 | *** | 0.90 | ns | 1.26 | ns | 0.86 | ns | 1.05 | ns |
| Household | Penthouse apartment | | | 1.01 | ns | 1.01 | ns | 1.06 | ns | 1.11 | ns | 0.85 | ns | 1.01 | ns |
| | Other private household | | | 1 | | 1 | | 1 | | 1 | | 1 | | 1 | |
| | Institution | | | 3.50 | *** | 3.39 | *** | 1.24 | ns | 1.15 | ns | 1.17 | ns | 1.22 | *** |
| Municipality char. | Inter-municipality deprivation | | | 1.02 | *** | 1.02 | *** | 1.03 | ns | 1.01 | ns | 1.09 | ns | 1.03 | ns |
| | Intra-municipality inequality | | | 0.98 | ** | 0.989 | ns | 0.96 | ns | 0.87 | ** | 0.97 | ns | 0.98 | ns |
| | Density of built-up area | | | 0.999 | *** | 0.999 | *** | 1.000 | ns | 0.998 | ns | 0.999 | ns | 1.000 | ns |
| | Share of green areas | | | 0.997 | *** | 0.997 | *** | 1.007 | ns | 0.993 | ns | 1.017 | ns | 1.002 | ns |
| Agglo char. | Urban sprawl | | | | | 0.995 | ns | 1.023 | ns | 0.967 | ** | 1.015 | ns | 0.998 | ns |
| Model statistics | Person-days | 237'868'717 | | 237'868'717 | | 237'868'717 | | | | | | | | | |
| | Events | 17083 | | 17083 | | 17083 | | | | | | | | | |
| | DIC | 87861 | | 77507 | | 77537 | | | | | | | | | |
| Geographic Variance | Agglomeration level | 0.006 | ns | 0.005 | * | 0.005 | ** | | | | | | | | |
| | Municipality level | 0.014 | *** | 0.001 | *** | 0.001 | *** | | | | | | | | |

Source: MeteoSuisse, Swiss land use statistics and Swiss National Cohort database (Census 2000 & Vital statistics 2001-07). Notes: O.R = Odds Ratio, S = Statistical significance (*** = at 0.01 level, ** = at 0.05 level), DIC = Bayesian Information Criterion.

To test whether heat affects the survival of specific populations to different extents, Model 3 includes interaction effects between the four types of heat-episodes and the socioeconomic and environmental variables. With few interaction terms being statistically significant, the general conclusion is that heat has a rather undifferentiated impact. Moreover, the independent effect of long and intense heat episodes remains statistically significant, highlighting a generalized mortality response to extreme heat events.

Model 3 nevertheless shows one substantive result. The most vulnerable populations during heat episodes are clearly the residents of old age or health care institutions. The positive interaction effect of heat and residence in these institutions is stronger and statistically more significant for women than men. Gender differentials in the degree of frailty among institutionalized individuals may again help to explain these differences. Married women are also more protected than others during heat, although only when the episodes are short and weak. The independent mortality effect of short heat episodes, as well as that of long and weak ones, is completely accounted for by the excess female mortality among the non-married and those living in institutions during heatwaves. Moreover, excess-mortality in institutions is strongest in both the most intense heat episodes and the apparently less harmful one, i.e. the long and intense period, as well as the short and weak ones (although not significantly). Other interaction effects of heat, including those with environmental factors, are not statistically significant. Although local inequality and the extent of urban sprawl are significantly associated with lower female mortality during heat, these effects are not consistent across types of heat episode and gender.

## DISCUSSION AND CONCLUSION

The Swiss population is increasingly exposed to heat stress during summer periods and is expected to be even more so in the future. The mortality crises during the last European and American heatwaves have been traumatic from a political point of view, leading to a recent accumulation of empirical evidence about their determinants, which should help improve prevention systems in an expected future of global warming, population ageing and urbanization. Yet, there is a considerable geographical heterogeneity in heat-related mortality, which mirrors complex interactions between physical exposure to heat and different dimensions of a socio-ecological system of vulnerability; these include biological and medical characteristics, individual socioeconomic status, living contexts and the urban environment. The aim of this study was to develop a research strategy capable of integrating these principal lines of investigation to identify specific vulnerability profiles and to account for potential confounding or accumulation of risk factors. Heat exposure was accurately measured and differentiated, and the heterogeneity of the at-risk populations and living environments was accounted for. This was made possible by the linkage of meteorological time-series data and exhaustive cohort follow-up person-day mortality data, as well as land use statistics for Switzerland. The spatial clustering of heat exposure was controlled for in a multilevel model, and interactions with exacerbating or specific risk factors were tested.

We confirmed a small independent mortality effect of the (rare) prolonged episodes of very high temperatures (by Swiss standards). However, our results highlighted a rather undifferentiated impact on survival for the majority of the older population of Switzerland, particularly among men. We did not find marked socioeconomic and contextual differentials in the populations' capacity to cope with heat, nor did we confirm the importance of the environmental factors that are often considered as being specific to heat-related mortality.

Mortality during weak, as well as intense but short, heat episodes mainly occurred in places where risk factors of general mortality accumulate, leading to an increased exposure to the risk of death during heat – especially for men. Switzerland has in fact recently experienced a new intra-urban differentiation in both population composition and mortality. Life expectancy at birth has become lower in central municipalities when compared to agglomeration-belt ones, and this has been explained by the socioeconomic consequences of peri-urbanization: deprived and more vulnerable subpopulations have stayed in city centers, which have experienced not only a downgrading of the living context that may have promoted specific at-risk behavior, but also environmental congestion effects (Lerch, Oris, & Wanner, 2017). Based on our results, we explain the higher mortality during heat episodes by this accumulation and spatial concentration of general risk factors in inner cities, rather than by their specific effects related to heat. Heat did not significantly exacerbate differentials in individual risks of dying among men, but the combination of individual, contextual and environmental risk factors into a particularly vulnerable profile during heat lead to an increase in mortality. However, the mortality response among women was confounded to a lesser extent by such a compositional effect. Heat episodes did specifically exacerbate the risk of dying for those women who were isolated and frail, as was indicated by increased mortality among the unmarried and those in institutions. The limited effect of heat on mortality in Switzerland may be related to the small size of cities, to the high living standards providing the majority of population with the resources to cope with heat stress, as well as to a high minimum standard of housing. Similarly, the socially undifferentiated nature of the effect underlines the efficiency of the socio-sanitary system of prevention and intervention among the most vulnerable groups, including those in old age and health-care institutions. The higher risk of mortality in institutions was in fact shown to be concentrated in both the apparently harmless and the very intense heat episodes, which can be explained by the fact that these are respectively hard to predict and particularly difficult to cope with over a prolonged period. Moreover, Switzerland ranks among the world's top-five countries in terms of longevity; mortality is strongly compressed in older ages, with deaths mainly occurring between 72 and 88 for males and 78 and 92 for females. This leaves little room for mortality differentials during the relatively short exposure periods constituted by heat episodes. Since heat fatalities in Switzerland particularly involved people who are frailer or more vulnerable in many regards, harvesting may have played a non-negligible role in precipitating deaths that would have otherwise occurred only a few days or weeks later. However, these speculations require further research.

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2. In an article published in 2008, Jean-Marie Robine and his colleagues even estimated that « Death toll exceeded 70,000 in Europe during the summer of 2003 » (Robine, Cheung, Le Roy et al., 2008).
3. In the four agglomerations for which two measurement points are provided, we selected the most central one.