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Trends in Tropical Nights and their Effects on Mortality in Switzerland across 50 years

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Abstract

Due to climate change, the temperature is increasing, and hot weather extremes have become more frequent and severe. This can lead to heat-related health issues in the human population. Especially high nocturnal temperature leads to reduced well-being of the society. In this master thesis, I aimed to assess the change in frequency of Tropical Nights (TN) and their independent effect on the daily mortality in Switzerland across 50 years.

I derived the number of TNs ($nighttemperature \geq 20°C$) from the high-resolution hourly mean temperature (ERA5-Land reanalysis data set) between 1970-2019. I assessed the change in the frequency of TNs and the number of people exposed to TNs per district and decade by a spatiotemporal analysis. I then estimated the TN-mortality association by canton and cities using district-specific all-cause mortality data from 1980-2018 with conditional quasi-Poisson regression analysis.

I found an overall increase in the annual and decadal frequency of TNs and the population exposed to TNs in Switzerland between 1970-2019. This was mainly the case in the cities of Lausanne, Geneva, Basel, Lugano, Zurich, and around Lake Geneva, Lake Constance, and Ticino during the last two decades. The TN-mortality association was highly heterogeneous across cantons and cities. In particular, TNs were associated with an increased mortality risk of 37-22% in the cantons of Vaud, Zurich, Lucerne, and Solothurn. In contrast, a negative association was observed in Ticino, Basel-Land, and Thurgau, and a null association in the remaining cantons. Further, I found a trend of TNs representing a smaller risk in urban than in rural areas.

The findings indicate that TN is a relevant health hazard in some parts of Switzerland with potential larger impacts in the future. Because the frequency of TNs will further increase in the future due to climate change and increasing urbanization.

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Abbreviations

°C	Degree Celcius
BFS	Federal Statistical Office
C3S	Copernicus Climate Change Service
CI	Confidence Interval
DLM	Distributed Lag Linear Model
DLNM	Distributed lag Non-Linear Model
HW	Heatwave
IQR	Interquartile Range
MMT	Minimum Mortality Temperature
RR	Relative Risk
Tmean	Mean Temperature
TN	Tropical Nights

1 Introduction

Due to climate change, the temperature is increasing, and heat waves are becoming more frequent and severe [1]. This puts a burden on people's health and can lead to heat-related health issues and even to deaths [2, 3, 4]. The sixth assessment report of the IPCC [5] indicates with very high confidence that climate change has affected the physical health of people globally. Extreme heatwaves have resulted in human morbidity and mortality in all regions [5]. Also, the most recent Lancet report stated an increased vulnerability to heat extremes, especially for the vulnerable population (elderly people, babies, small children, pregnant women, and adults with chronic disease) [2, 6].

The last four heatwave summers in Switzerland (2003, 2015, 2018, and 2019) have resulted in increased mortality [4, 7]. Several studies showed the effect of heatwaves on human health by increasing mortality [4, 8, 9]. Due to this significant association between temperature and mortality, increasing temperatures represent a considerable risk for human health in Switzerland [8]. While a healthy body has mechanisms to regulate the heat to prevent heat-related health issues, this thermoregulatory system is limited in the vulnerable population. Therefore, they are more prone to heat-related health issues. Further, social vulnerability is also an important factor. Social vulnerability arises, for example, from culture and infrastructure [8, 9, 10, 11, 12].

There is evidence that high nighttime temperatures can increase the probability of mortality during heatwaves [13]. The minimum nighttime temperature is important for the body to recover during the night from the day's (heat) stress, especially during heatwaves. If not, this results in prolonged thermal stress and negatively impacts human health, comfort, and performance [14]. Several studies [14, 15, 16] investigated such effects of hot nights on human health in several cities across southern Europe and London. They provided evidence that the duration and excess of hot nights are strongly associated with mortality. Such findings are essential to help improving public health.

To the best of our knowledge, no comparative studies on hot nights associated with mortality have been made in Switzerland. Only heatwaves associated with deaths have been analyzed as a whole [4, 8, 9]. In Switzerland, hot nights are defined as Tropical Nights (TNs) when the minimum night temperature does not drop below 20°C [17, 18]. Thus, in order to better understand the effects of TNs on human health in Switzerland and consequently to develop and provide national and cantonal intervention plans and prevention actions, Swiss TNs need to better understood.

In the following, we will provide deeper insights into climate science and environmental epidemiology. The second chapter is the research article "Trends in Tropical Nights and their Effects on Mortality in Switzerland across 50 years" submitted to PLOS Climate journal. Followed by the article "Short Communication - Spatially Resolved Temperature Data, Daily All Cause-Mortality and Absolute Thresholds" submitted to Environmental Epidemiology. In the short communication article, we discuss the difference between using reanalysis and met-station data and using absolute or relative threshold definitions for TN.

1.1 Climate Science

The frequency and intensity of hot temperature extremes increased in the past years due to human-induced greenhouse gas emissions [5, 19, 20]. At the same time, the frequency and intensity of cold temperature extremes decreased on a global scale [5]. Today 75% of the heat extremes can be attributed to global warming [21]. It is projected that the frequency and intensity of hot extremes will increase nonlinearly with global warming in almost all inhabited regions of the world [5, 19, 20, 22]. Based on the sixth assessment report of the IPCC [5], an increase is also expected if global warming stabilizes at 1.5°C. The intensity of hot extremes will double at 2°C and quadruple at 3°C compared to 1.5°C global warming. Heatwaves will increase in their intensity, length, and frequency [5]. For the rarest and most extreme events, the anthropogenic influence is the biggest fraction, which will increase with global warming [23].

Further, central Europe and Switzerland are in a hotspot position for intensifying of such hot weather extremes [1, 24, 25]. The current climatic zone is shifting northward within the European continent with increasing greenhouse gas concentration. This leads to a new transitional zone between dry and wet climates in central Europe [26]. The new transitional zone is similar to the present-day Mediterranean region and brings the effect of land-atmosphere coupling to central Europe [24, 26]. The interaction between the land surface and atmosphere increases climate variability and is a major factor in exacerbating extremes such as heatwaves across Europe [1, 24, 25, 26]. The land-atmosphere coupling starts with low soil water in wide areas leading to reduced evaporation in vegetation. That causes limited cloud cover and rain, leading to increasing surface net radiation and higher temperatures up to extreme heat over days and weeks [24]. The land-atmosphere coupling is affected by global warming and has an important role in future climate change [26].

1.1.1 Heatwaves

Many record-breaking and destructive heatwaves have occurred in recent years around the world [19]. The heatwave summer of 2003 was the hottest in Europe in the last 500 years [19]. In Switzerland, the previous all-time record of the measured maximum temperature was topped with 2.4°C [19]. The next heatwave rolled over Europe in the summer of 2015, with new heat records [22]. The 2015 heatwave was recorded as the second hottest summer in Switzerland after 2003 since the beginning of registration [4]. Europe and Switzerland experienced the next heatwave summer in 2018. So far, this was registered as the third hottest summer in Switzerland [27]. The temperatures in summer 2019 were comparable with the summer of 2018. But the heatwave of 2019 replaced the one from 2018 as the third hottest summer behind 2003 and 2015 [9, 28]. In Ticino, the met-station Lugano recorded the longest heatwave (14 days) in July 2022 since the beginning of registration. Although the maximum temperatures were not record-breaking, the duration of this heatwave was extraordinary [29].

Studies projected that the number of heatwaves and the maximum heatwave temperature would increase in all European cities under all emission scenarios [1, 19, 20, 30]. The number of heatwaves will increase more in southern Europe (as much as 69%), while the maximum heatwave temperature will increase more in central Europe (up to 14°C) [30].

1.1.2 Tropical Nights

Next to the number of hot days, the number of hot nights has become more frequent in recent years around the world and Switzerland [1, 5, 31, 32, 33]. In Switzerland, the definition of TNs are nights with a minimum temperature over or equal to 20°C [2, 17, 18]. TNs mainly occur in low-lying areas with high population density, for example, on the Swiss Plateau, Ticino, and in lower Alpine Föhn valleys. The urban heat island effect may further amplify the heat stress and the number of TNs [1, 13]. The urban heat island effect describes the effect of slowly releasing the absorbed heat of the day during the night [13]. This prevents cooling in urbanized areas during the night, which can lead to TNs. Under the present-day conditions, the frequency of TNs increased in recent years, especially during heatwaves [5]. Projections showed an increase in the frequency of TNs under all the emission scenarios. Under RCP8.5, TNs will occur in almost all regions in Switzerland until 2085, even if they don't record TNs under the present-day conditions [1]. For example, today, Ticino experiences around 10 TNs per year, increasing to 60-90 TNs per year by the end of the century (RCP8.5) [1].

1.2 Human Sleep and Heat

Sleep is essential for human health and well-being [34]. Extreme environmental conditions during night may lead to sleep disturbances and sleep loss [35, 36]. Insufficient sleep quality and short sleep duration can increase morbidity and mortality [34, 37]. In fact, short sleep duration (< 7 hours) is proven to be associated with an increased risk of mortality with 26% in men and 21% in women [37]. The most important impact of hot nights on human health is the impairment on sleep and rest [14]. During a hot night, the body cannot rest from the day's heat stress, which may result in prolonged thermal heat stress [1, 14]. Studies showed that increased nighttime temperatures significantly influence sleep patterns [34, 38] and lead to sleep loss and insufficient sleep globally [39]. Especially, the combination of high nighttime temperatures and high diurnal temperatures can lead to failure in thermoregulation and result in a greater effect in heat-related mortality [14, 40]. Due to the urban heat island effect, the difference between nighttime and diurnal temperature may further decrease and increase the nighttime exposure [14, 40]. Due to climate change, nighttime warming will further increase, resulting in an increased incidence of insufficient sleep which will affect the most vulnerable first [34]. The most vulnerable people are elderly, women, and residents of lower-income countries [34, 39].

1.3 Environmental Epidemiology

Several studies [4, 7, 41, 42, 43, 44, 45] already looked at the association between extreme heat and human health and found a positive association with increasing mortality. These studies are part of environmental epidemiology, combining the research from environmental and climate science and epidemiology. Epidemiologists study health and diseases in populations [46], while environmental epidemiologists want to understand the effect of climate-related and other environmental exposures on human health [47]. Most studies evaluate health problems at the population level, especially because the entire population is involuntarily exposed to the environment [48]. Combining climate projections with epidemiological models can predict changing risks for climate-related health problems [47]. Environmental epidemiology research can help to provide prevention plans and warning systems and support policy choices and decision-makers [49].

Some studies have already looked at the association between hot nights and mortality with a focus on Southern Europe, Barcelona and London [14, 15, 16]. All studies found a positive association between hot nights and mortality, with an increased risk during hot nights compared to non-hot nights.

1.4 Risk Assessment

To assess the risk of TN in Switzerland, we looked at three components of the risk assessment scheme. The three components are hazard, exposure, and vulnerability. The interaction of these three components can represent a risk to the human population [50].

1.4.1 Hazard and Exposure

A hazard is a potential natural- or human-induced physical event that can lead to health issues or deaths [50]. The change in the frequency of a hazard represents the impact of this hazard in a defined region. The hazard can be region-specific and depends on the local conditions. For example, in present-day conditions, in Switzerland, most TNs occur in the region of lake Geneva and Ticino [1].

Exposure is the number of people exposed to the hazard [50, 51]. With an exposure assessment, we can look at the number of people-day exposed to TNs per year. This means the number of days experienced TNs multiplied by the total population exposed [51].

1.4.2 Vulnerability

Vulnerability is the probability of being affected by a hazard. The vulnerability can differ within a population, i.e., elderly people and women are more affected by high nighttime temperatures related to sleep loss [34, 39]. Further, the vulnerability can differ within regions. For example, vulnerability may be different for urban and rural residents and their respective sensitivity to heat [52].

1.5 Study Aims

I aimed for this thesis to investigate the spatiotemporal frequency and potential increase of TNs since 1970 in Switzerland and to understand whether this impacts human mortality. I assessed the change in TN frequency and the exposed population per district and decade through a spatiotemporal analysis as well as an exposure assessment. I then estimated the independent TN-mortality association by canton and city by doing a nationwide and city-specific analysis. I used quasi-Poisson regression analysis with data on all-cause mortality at the district level from 1980-2019.

1.6 Hypothesis

I hypothesize that the frequency of TNs and the population exposed to TNs increased in the last decades in Switzerland. Further, I hypothesize that there exists an independent effect of TNs on mortality so that TN represents a relevant health hazard in Switzerland.

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2 Trends in Tropical Nights and their Effects on Mortality in Switzerland across 50 years

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Abstract

Increasing temperature and more frequent and severe heat waves in Switzerland are leading to a larger heat-related health burden. Especially, high nocturnal temperature which is usually associated with the urban heat island effect, reduces the well-being of society. We aimed to assess the spatiotemporal patterns in the frequency, the exposed population to Tropical Nights (TNs), and its independent effect of TNs on daily mortality in Switzerland.

We derived the number of TNs ($nighttemperature \geq 20$°C) per district using the corresponding population-weighted temperature series based on high resolution hourly mean temperature (ERA5-Land reanalysis data set) between 1969-2020. We assessed the change in TN frequency and the exposed population per district and decade through a spatiotemporal analysis. We then estimated the TN-mortality association by canton using data on all-cause mortality at the district level from 1980-2018 with conditional quasi-Poisson regression analysis.

We found an overall increase in the annual frequency of TN (from 90 to 2113 TNs per decade) and population exposed (from 3.7 million to over 157 million people-TN per decade) in Switzerland between 1970-2019, mainly in the cities of Lausanne, Geneva, Basel, Lugano, and Zurich and during the last two decades. Once controlled for the daily mean temperature, the TN-mortality association was highly heterogeneous across cantons. In particular, TNs were associated with an increase of 37-22% in the risk of mortality in the cantons of Vaud (Relative risk:1.37 [95% CI:1.19-1.59]), Zurich (1.33 [0.99-1.79]), Lucerne (1.33 [0.95-1.87]) and Solothurn (1.22 [0.88-1.69]), while a negative association was observed in Ticino (0.51 [0.37-0.7]), Basel-Land (0.4 [0.24-0.65]) and Thurgau (0.65 [0.5-0.85]), and a null association in the remaining cantons.

Our findings indicate that TN is a relevant health hazard for a large part of the Swiss population with potentially larger impacts in the future due to climate change and increasing urbanization.

2.1 Introduction

Due to climate change, the frequency and intensity of hot temperature extremes have increased in recent years [1]. These extreme heat episodes, such as heatwaves, are frequent events in the summer months in a temperate climate, especially in Southern Europe [1, 2, 3, 4]. Next to the increasing number of hot days, also the frequency of hot nights increased in the last years in most regions. These extreme heat events as hot days and hot nights are projected to further increase in almost every region in the world [1]. On top of the progressive warming of the climate, the accelerated growth of the cities and increasing urbanization of the land surface is expected to further amplify the increased frequency of hot nights due to the urban heat island effect [5]. The urban heat island effect describes the release of the absorbed heat during the night in urban areas [5]. This heat release prevents the urban area from cooling down and can lead to a hot night.

Numerous studies showed that extreme heat impacts the human health by increasing human mortality and morbidity [6, 7, 8, 9, 10]. This association is usually J-shaped for the summer months with increasing mortality risk with increasing temperatures [11, 12]. Due to this significant association between temperature and mortality, increasing temperatures represent a considerable risk for human health [13]. Globally, 37% of heat-related deaths can be attributed to anthropogenic Climate Change [8]. Most studies so far have used the daily mean temperature to analyze the association between heat extremes and mortality, as a representation of the average heat exposure during the day [13, 14]. However, there is some evidence that high night temperatures may additionally increase the mortality risk during heatwaves [5]. Increased minimum night temperature leads to insufficient sleep and disturbs the nocturnal rest of the human body [15, 16, 17]. Several studies found independent effect of hot nights on mortality in several cities in Europe [18, 19, 20]. One study found a risk of hot-night excess from 1.12 (95% CI: 1.05-1.20) in France to 1.37 (95% CI: 1.26-1.48) in Portugal [19]. This results in prolonged thermal stress, negatively impacting human health, comfort, and performance, especially among the older populations [15, 19, 21, 22, 23]. Evidence shows that short sleep duration and poor sleep quality are associated with increased mortality [24, 25, 26].

In Switzerland, hot nights are defined as Tropical Nights (TNs) when the nighttime temperature does not drop below 20°C [27, 28, 29]. While some studies have used a 20°C threshold to define a TN [19], others have used relative thresholds (i.e., 95% or 99% of the temperature distribution) [18, 20]. Under the present-day conditions, TNs mostly occur in Switzerland in low-lying urban areas and in Ticino, although it is expected that its frequency and intensity will increase throughout Switzerland under all emission scenario projections [22]. Several studies analyzed the association between heat and mortality in Switzerland and found an effect of extreme heat on human health by increasing mortality [13, 14, 28, 30]. However, to the best of our knowledge, no comparative studies on TNs associated with mortality have been conducted for Switzerland so far. Advancing knowledge on the impact of TNs on health is needed to design more efficient public health plans, especially for the future increase in hot nights.

In this study we therefore aimed at comprehensively assessing TNs and its impact on mortality in Switzerland in a spatially explicit, nationwide study using high-resolution data. In particular, we investigated the spatiotemporal patterns in frequency and exposed population to TNs since 1970 across districts and estimated the TN-mortality association in each canton and the eight largest cities in Switzerland between 1980-2019.

2.2 Data and Methods

2.2.1 Data

2.2.1.1 Temperature Data

We obtained gridded hourly mean temperature data for the period 1970 to 2019 with a 9-km resolution across Switzerland from the ERA5-Land reanalysis data set provided by Copernicus Climate Change Service (C3S) [31, 32]. We derived hourly series in each of the 143 districts using the grid cells that intersect their boundaries [33]. We chose the 2018 district boundaries of the Federal Statistical Office (BFS). We obtained population weighted-hourly district-specific temperature series using the spatially-resolved total population in 2010 at 1-km resolution [34] to account for the heterogeneous distribution of the population due to the irregular orography, as explained elsewhere [35]. According to the official definition of MeteoSwiss, a TN was defined as a night where the minimum temperature between 9 PM and 6 AM was above 20°Celsius [27].

2.2.1.2 Mortality Data

We collected data on all-cause mortality at the municipality level in Switzerland from 1980 to 2019 from the BFS. We aggregated the data into daily counts of all-cause deaths in each district for the total and by age categories (under 75 and over 75) and sex (male and female).

2.2.2 Methods

2.2.2.1 Hazard and Exposure Assessment

We computed the average annual frequency of TNs for each year, decade, and districts, and analyzed and mapped their respective spatiotemporal frequency patterns. Similarly, we performed an assessment of the exposure by quantifying the population at risk of TN by district and decade. We multiplied the total number of TNs per district and decade by the population size at the midpoint year of each decade. The resulting estimates were again illustrated in maps [36].

2.2.2.2 Vulnerability Analysis

We applied a case time-series design to determine the association between TNs and mortality in Switzerland [37]. This study design allowed us to model the TN-mortality association in each Canton using the district-specific high-resolution exposure and mortality data defined at lower spatial unit (i.e., district) [38]. Specifically, we performed a conditional quasi-Poisson regression and included a matching stratum by year, month, and day of the week at the district level to control for long-term trends and seasonal patterns. The analysis was restricted to the months from May to September and covered the period between 1980 and 2018 due to low TN frequencies before 1980 and a limited availability of mortality data (i.e., until 2018). We modelled the TN-mortality association with unconstraint-distributed lag linear model (DLM) with three days of lag to account for delayed effects and harvesting [39]. To estimate the independent TN-mortality association, we controlled for daily mean temperature using unconstraint-distributed lag non-linear model (DLNM) with three days of lag and a quadratic B-spline with two internal knots placed at the 50th and 90th percentile of the district-specific temperature distribution. In an additional analysis, we performed a city-specific analysis with the eight largest cities in Switzerland by using the data of the specific district. We also stratified the analysis by sex (male/female) and age (under 75/over 75). All analyses were performed in R, version 4.1.1 (2021-08-10), using the gnm, and dlnm packages.

2.3 Results

2.3.1 Hazard

Table 2.1: Average number of TNs per canton and decade from 1970-2019. Sum of TNs of all districts per canton divided by the number of districts.

	1970-1979	**1980-1989**	**1990-1999**	**2000-2009**	**2010-2019**
Zürich	0	2	5	12	16
Bern	0	1	4	14	20
Luzern	0	1	6	11	14
Schwyz	0	0	2	6	6
Nidwalden	0	0	0	1	0
Zug	0	1	0	4	5
Fribourg	0	1	2	6	14
Solothurn	0	2	3	16	21
Basel-Stadt	0	8	3	19	30
Basel-Landschaft	0	1	1	13	13
Schaffhausen	3	8	22	23	35
St.Gallen	0	0	1	2	6
Aargau	1	3	9	21	29
Thurgau	4	7	15	26	39
Ticino	0	8	14	23	47
Vaud	4	7	21	29	50
Neuchâtel	0	0	1	7	7
Genève	1	5	10	29	51
Jura	0	0	0	12	11

*table contains only cantons with at least one TN

Table 2.1 shows the average number of TNs per decade from 1970-2019 in each canton. Out of the 26 Swiss cantons, 7 were not included since no TNs were registered. For the reported canton-specific summaries, only the districts with at least one TN are considered. The total number of TNs is added for each canton and then divided by the number of considered districts in the canton. The table with the number of TNs per districts is in the supplement file (Table S1).

Over the last five decades the frequency of TNs has increased in Switzerland (from 90 TNs in all districts in 1970-1979 to 2113 TNs in all districts in 2010-2019) (Table 2.1 and Fig 2.1 and 2.2). The heatmap in Fig 2.1 illustrates the number of TNs per district and by year, listing all districts having experienced at least one TN within the analyzed time period. In Fig 2.2 the number of TNs per district and by decade are illustrated. Our results suggest that TNs are not only increasing in frequency but also across space (i.e., districts) affecting more and more districts until 2019. In the first decade (1970-1979), TNs occurred in 20 districts, while by 2000, this increased to 68 districts; by the end of 2019, we observed TNs in 85 districts. TNs mainly happen on the Swiss Plateau and in Ticino, mainly in the areas of larger cities, i.e., Lausanne (77 TNs in the last decade), Geneva (51), Basel (30), Lugano (21), and the region of Zurich (190 in 12 districts). We observe the largest increase in number of TNs around Lake Geneva and Lake Constance, as well as in Ticino (Fig 2.2). Fig 2.1 also shows this increasing temporal trend with the largest number of TNs in 2003 when the famous 2003 European heatwave happened followed by the more recent summers (e.g., 2015) characterized as well as particularly hot.

Figure 2.1: Heatmap of number of TNs per year for each district in Switzerland sorted by canton from 1970-2019.

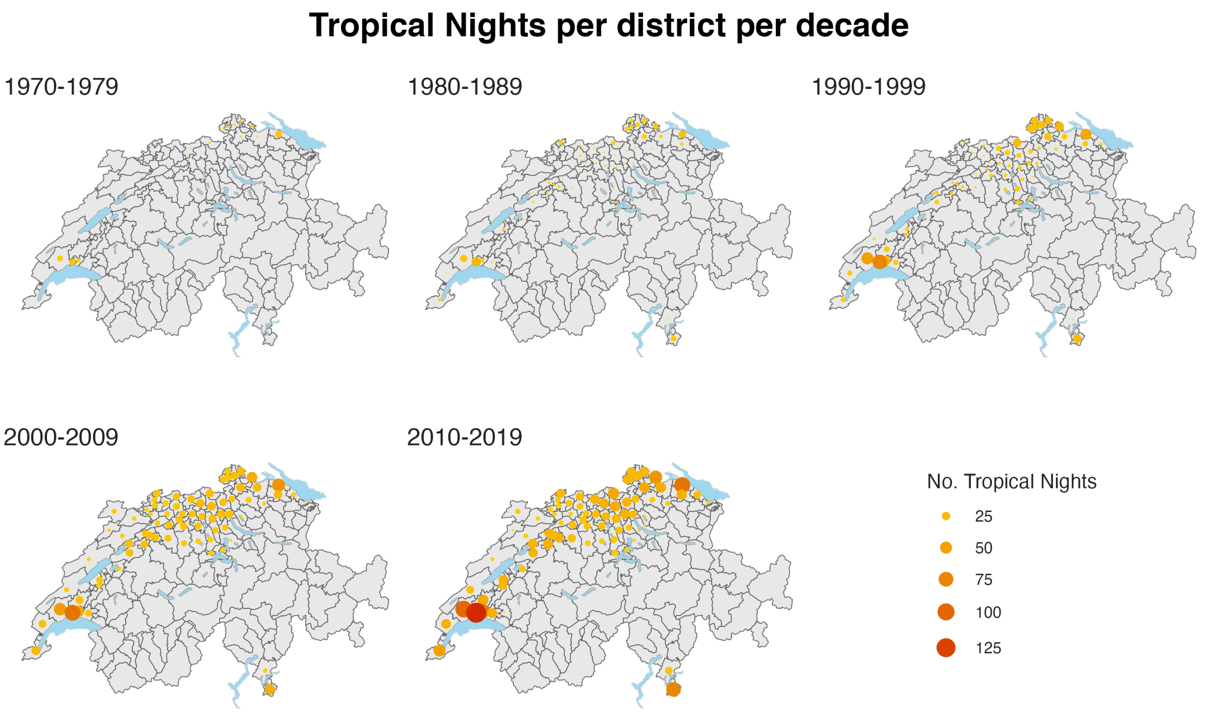

Figure 2.2: Number of TNs per district and decade in Switzerland from 1970-2019 with a continuous scale. The number of TNs are indicated with a circle, where the size and colour correspond to the number of TNs.

2.3.2 Exposure

Fig 2.3 illustrates the population exposed to TNs per district and decade. It shows that the population exposed to TNs strongly increased between 1970 and 2019. The most substantial increase happened mainly in the cities of Zurich, Basel, Lausanne, Geneva, and south Ticino (i.e., Lugano and Mendrisio). But the most significant increase was observed in Geneva. In the first decade (1970-1979), Geneva had around 33’733 people-TN per year exposed to TN, whereas in the last decade (2010-2019), in average almost 2.5 million people-TN per year were exposed (Table S2).

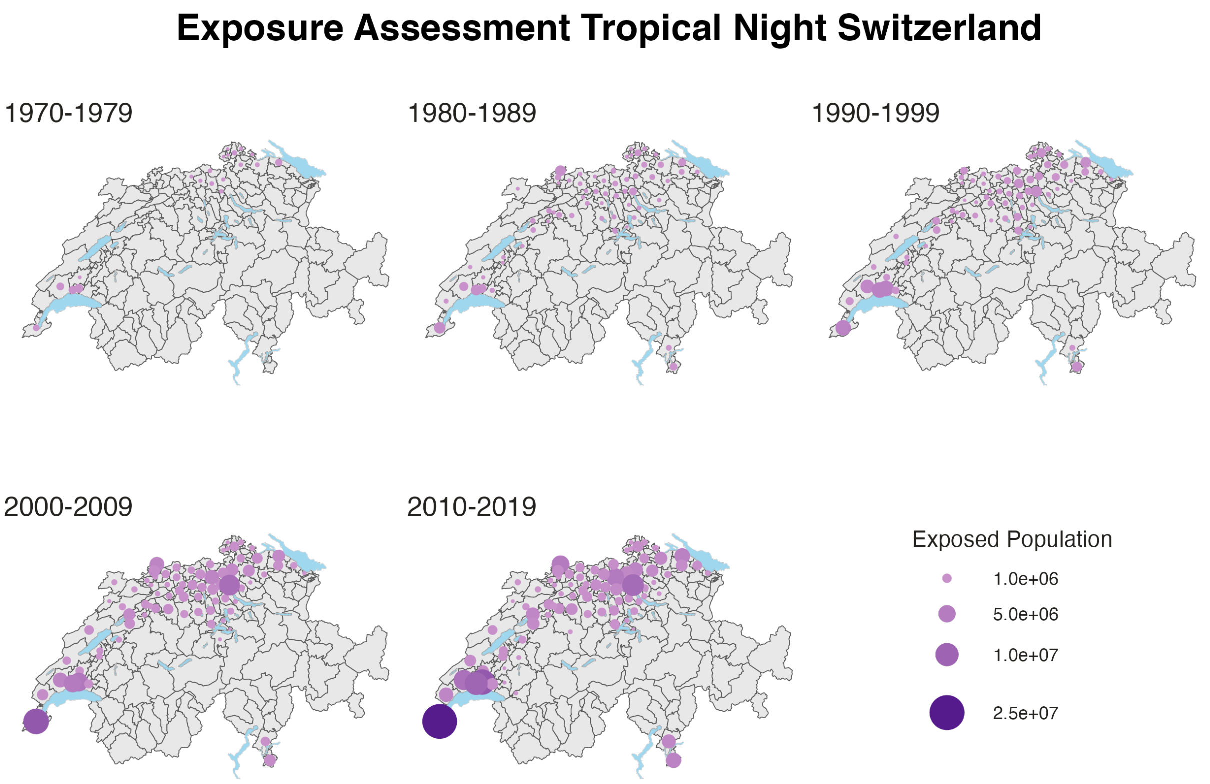

Figure 2.3: Exposure assessment of population exposed to TNs per district and decade in Switzerland from 1970-2019 with a continuous scale. The number of people-TN exposed is indicated with a circle, where the size and colour correspond to high exposure.

2.3.3 Vulnerability

2.3.3.1 Description of the Temperature and Mortality Data between 1980-2018

Overall, we analyzed 646’983 death records in 14 cantons and 230’627 death records in eight cities throughout Switzerland (Table 2.2). The Canton of Vaud reported the highest average number of TNs per district with 113 TNs between 1980-2018. While Lausanne (167) reported the highest number of TNs of the cities. In addition, most of the cities reported more TNs than the average number of TNs of their corresponding canton (i.e., Lausanne 167 vs. Vaud 113). The highest mean temperature is measured in the Canton of Ticino (17.38°C) and the City of Basel (16.91°C), respectively.

Table 2.2: Descriptive statistics by canton and city for the number of TNs, number of deaths, daily mean temperature and IQR from May-September 1980-2019.

Category	Name	TN	Deaths	Tmean (May-Sept)	IQR (May-Sept)
Canton	Zürich	37*	161368	15.86	5.54
	Bern	41*	54172	15.43	5.58
	Luzern	35*	39077	15.46	5.56
	Fribourg	25*	23145	15.33	5.57
	Solothurn	43*	41030	15.78	5.52
	Basel-Stadt	64*	36639	16.91	5.61
	Basel-Landschaft	30*	30513	15.93	5.52
	Schaffhausen	92*	10909	16.09	5.59
	Aargau	66*	62135	16.17	5.53
	Thurgau	91*	27735	16.16	5.57
	Ticino	96*	22607	17.38	5.19
	Vaud	113*	79376	15.80	5.69
	Genève	99*	48489	16.47	5.72
	Jura	16*	9788	14.76	5.56
City	Zürich	57	64518	16.05	5.59
	Genève	99	48489	16.47	5.72
	Basel	64	36639	16.91	5.61
	Lausanne	167	19851	16.36	5.67
	Winterthur	36	18094	15.64	5.57
	Luzern	43	12613	15.49	5.55
	Lugano	36	16397	16.86	5.14
	Biel/Bienne	65	14026	15.69	5.57

*Total number of TNs per Canton divided by the number of districts

2.3.3.2 Nationwide Analysis

Fig 2.4 shows the relative risk (RR) of mortality associated with TN per canton. TNs were positively associated with an increased mortality risk between 37-22% in the canton of Vaud (1.37 (95% CI: 1.19-1.59), Zurich (1.33 (95% CI: 0.99-1.79)), Lucerne (1.33 (95% CI: 0.95-1.87)), and Solothurn (1.22 (95% CI: 0.88-1.69)). Meanwhile, a negative association is observed in the canton of Ticino with a RR of 0.51 (95% CI: 0.37-0.7), Basel-Land (0.40 (95% CI: 0.24-0.65)) and Thurgau (0.65 (95% CI: 0.50-0.85)). The cantons of Basel-Stadt and Geneva also showed a risk below 0.85. Null estimates were found in the remaining cantons, (e.g., Bern, with a risk of 1.03 (95% CI: 0.79-1.35)). The subgroup analysis results show no consistent patterns, with varying risks across sex and age groups (Fig S3 and S4).

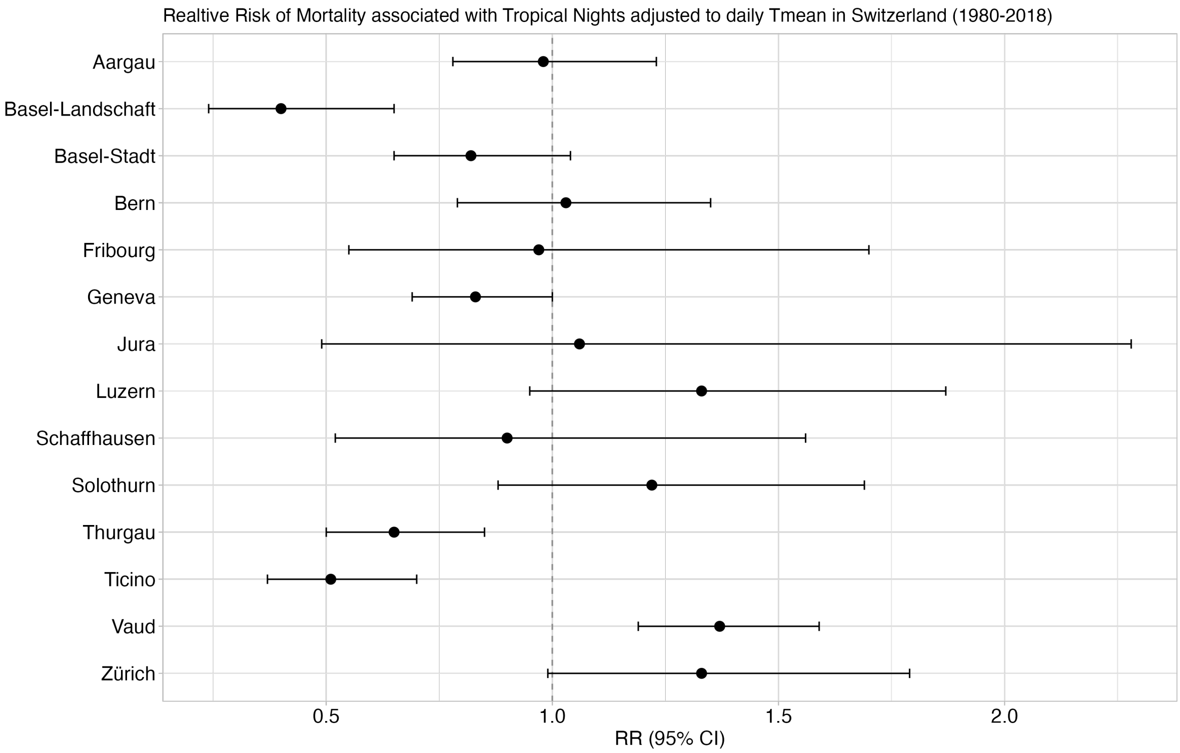

Figure 2.4: Nationwide analysis. Relative risk (RR) and 95% confidence interval (CI) of mortality with TNs in the cantons of Switzerland (1980-2018).

2.3.3.3 City-specific Analysis

Fig 2.5 illustrates the RR of mortality associated with TNs across the largest cities of Switzerland. TNs are associated with an increased risk, although highly imprecise, in Lugano (1.19 (95%CI: 0.78-1.8)), Lucerne (1.46 (95% CI: 0.85-2.49)), and Winterthur (1.34 (95% CI: 0.78-2.31)). Whereas the other cities show some evidence for a protective association, such as in Geneva (0.83 (95% CI: 0.69-1)) and Basel (0.82 (95% CI: 0.65-1.04)).

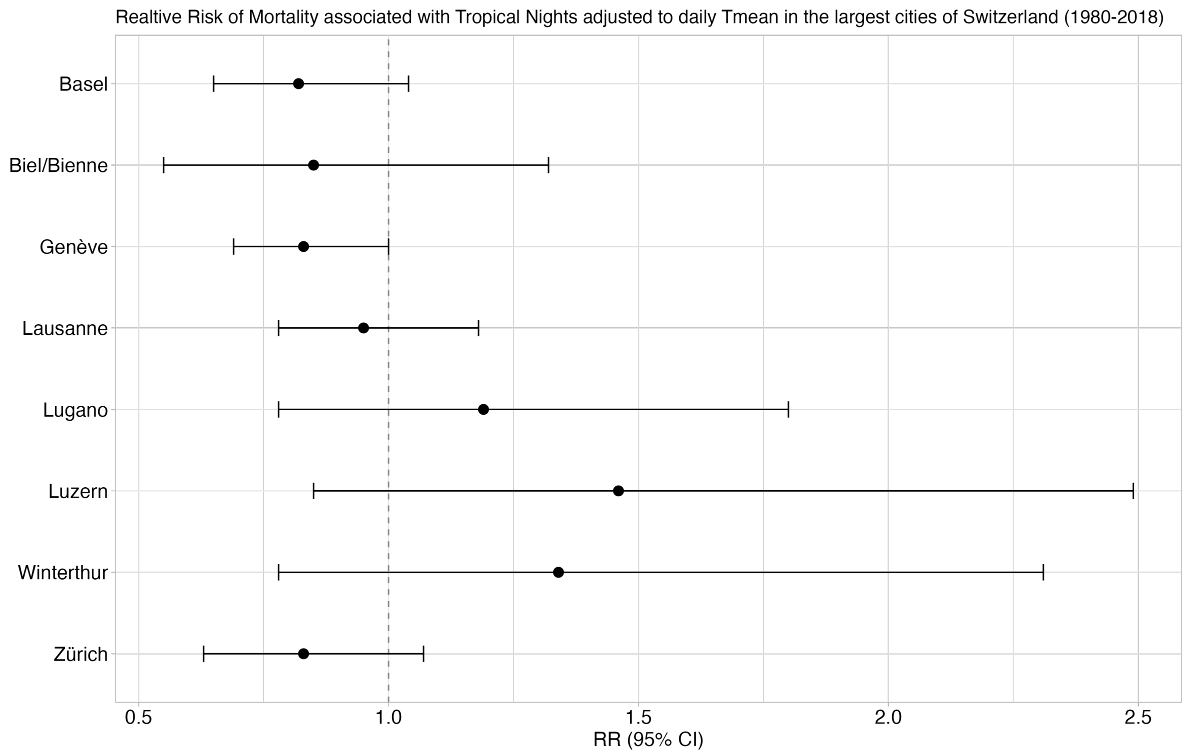

Figure 2.5: City-specific analysis. Relative risk (RR) and 95% confidence interval (CI) of mortality with TNs in the largest cities of Switzerland (1980-2018). The districts of the cities of Basel and Genève correspond to the canton.

Comparing Fig 2.4 and 2.5, different trends can be seen between some cities and their Canton. For example, a negative association is found in the city of Zurich (0.83 (95% CI: 0.63-1.07)), while there is a positive association within the canton of Zurich (1.33 (95% CI: 0.99-1.79)). The same difference is found in Lausanne and Vaud, and the opposite trend is in Lugano and Ticino.

We also provided results derived from the model not adjusted by the daily mean temperature and they can be found in the supplementary materials. Fig S1 and S2 are showing the RR of the association between TNs and mortality per cantons and cities, respectively.

2.4 Discussion

Our findings indicate that the frequency of TNs in Switzerland has increased overall between 1970 and 2019, mainly in urban areas and their greater agglomerations (Lausanne, Geneva, Basel, Lugano, and Zurich). The population exposed to TNs in Switzerland also increased, with the most substantial increases in the largest cities. However, the vulnerability to TNs in terms of associated mortality risk seems to be highly variable across cantons and cities.

2.4.1 Hazard

Due to climate change, the average temperature has increased during the last decades and is projected to further increase in all regions in Switzerland in the future [22]. The CH2018 report [22] states that Switzerland represents a hotspot for changes in hot temperature extremes, such as heatwaves and TNs. Our results confirm these observations with an increasing trend in the frequency of TNs. In addition, these changes occur in low-lying areas with high population density, where the urban heat island effect may further amplify these extremes [22, 40], as we observed in this study with larger increases in urban regions. Other studies from Georgian Territory, Spanish Mediterranean coast, and Seoul, also showed a significant increase in TNs within the last decades [41, 42, 43].

2.4.2 Exposure

The population exposed to TNs increased overall in Switzerland between 1970 and 2019, due to both an exponential increase in the frequency of TNs, as indicated before, and in population, which occurred mainly around the largest cities and urban agglomerations. Between 1990 and 2020, the population in Switzerland increased by 28% [44]. Our findings are similar to a previous study by Tuholske et al. [36] who explored whether the population growth or the increasing temperature is the main driver of the increasing exposure to extreme heat. They estimated the population exposed to extreme heat in 13'115 urban settlements over 33 years and found a spatially heterogenous result about what mainly drove the exposure (population growth or climate change).

2.4.3 Vulnerability

We did not observe a clear spatial pattern in vulnerability to TNs across the cantons or across the largest cities of Switzerland (Fig 2.4 and 2.5). While a TN may represent a health risk in Vaud, Zurich, Lucerne, and Solothurn with increased mortality around 40%, these are associated with a protective effect in Ticino, Basel-Land, and Thurgau. This disparity across Cantons can possibly be attributed to differences in public health strategies, infrastructure (i.e. greenness), socioeconomic status, social equity, and cultural characteristics [45, 46, 47, 48]. For example, in addition to the national public health strategy during heatwaves, some cantons such as those in the French-speaking part of Switzerland (i.e., Geneva, Vaud, Fribourg, Neuchâtel and Valais) and Ticino have additional procedures such as heat plans [49]. Heat plans could possibly explain the protective effect of TNs in some cantons, such as in Geneva and Ticino, in some part. However, other cantons still have a greater risk during TNs despite heat warning plans (i.e., Vaud). In fact, recent studies exploring the heat warning systems' effectiveness and health prevention plans on heat-related mortality show heterogenous results [28, 50, 51, 52, 53]. Additionally, we found a contrasting pattern comparing the risk in canton and city. While TNs have a protective effect in the city, they represent a risk at the canton level (i.e., Lausanne and Vaud). We hypothesize that there could be a gap between rural and urban residents' sensitivity to heat. With urban residents more aware and used to heat compared to the rural population and therefore better prepared in case of a heat wave and increased occurrence of TNs [54, 55].

Our results of the association of TNs with mortality on the canton level fall in a similar range as the RR from other studies [19, 20]. This suggest that TNs should be still considered as a relevant health hazard in Switzerland. This has a sense of urgency since it has been suggested that due to climate change and the hotspot position of Switzerland, the frequency of TNs will increase in the future [4, 22]. Particularly, as we consider our results as a conservative estimate. An indication for this is the much higher frequency of TNs registered in areas with complex orography (i.e., Ticino) when met-station data is used compared to ERA5-Land. We tested this for a selected number of cities (i.e., Zurich, Lugano) as part of our study (Fig S5). In fact, other similar studies looking into TNs alternatively used temperature data from meteorological monitoring stations [18, 19, 20]. While gridded temperature data has shown the be a good proxy of temperature exposure on a relative temperature distribution having the advantage of assigning high-resolution exposure to all districts and rural areas even those lacking met-stations [35, 56], a key disadvantage of ERA-5 reanalysis data might be its bias towards cooler temperatures, smoothing out peak temperatures. Consequently, we might observe less TNs with the gridded dataset, compared to met-station data, which could affect our estimates, particularly as TNs are defined on an absolute temperature basis. Other studies used a percentile (95%, 99%) to define a TN or hot nights [18, 20]. This has the advantage of catching the local climate characteristics [18]. However, the fixed 20°C threshold is the official definition of TNs used by the Swiss government was also applied by several other studies focusing on Switzerland [27]. Future studies will therefore aim to explore how the choice of data set and the definition of TNs influence the TN-mortality association.

We acknowledge several limitations of this study. We did not control for potential confounders such as air pollution and humidity since data on these variables was not available for the study period. However, other studies showed no significant influence of air pollution and humidity on temperature association analysis [57, 58]. Further, we did not assess the role of contextual variables explaining the differences across cantons and cities. There are factors reducing the heat-related mortality and act as an effective heat adaption strategy [59]. Based on our study design, we account for these factors within a given district [38], but we cannot determine the reason for the increase or decrease between cantons and cities; we lack a spatial component for that.

2.5 Conclusion

Our findings indicate that the number of TNs have increased in the last five decades in Switzerland. Together with the population growth, the population exposed to TNs has strongly increased since 1970. Although TNs still remains an important health hazard in some cantons, in others TNs are associated with lower mortality risk, compared to non-TNs. This can possibly be due to the implementation of heat plans and other public health measures. Further research is needed to better understand the nighttime temperature's importance on health and improve current national and cantonal public health strategies. First steps, such as changing the national warning system, have already been taken to protect the population's health during the summer months in Switzerland.

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3 Short Communication - Spatially Resolved Temperature Data, Daily All Cause-Mortality and Absolute Thresholds

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Abstract

An increasing number of epidemiological studies are applying spatially resolved weather data to study the temperature-mortality association and corresponding impacts around the world. Spatially resolved weather data has shown to be a good proxy on a relative scale, the absolute temperature distribution between the two exposure dataset do largely differ, which could introduce challenges when analysing tropical nights (TNs) and heat warning systems which are defined on an absolute threshold. Therefore, we aim to explore the association between TNs, defined on an absolute scale versus relative scale, and mortality using a comparative assessment between insitu-stations and spatially-resolved temperature data in two districts of Switzerland.

We determined the number of TNs ($nighttemperature \geq 20$°C resp. 99%) using the population-weighted temperature series based on high resolution hourly mean temperature (ERA5-Land) and by the minimum night temperature from the met-station data. We then estimated the independent TN-mortality association at district level using the corresponding all-cause mortality data from 1980-2018 with conditional quasi-Poisson regression analysis.

We found a similar number of TNs in Zurich (61 vs. 53) for the met-station and ERA5-Land, respectively, while in Lugano the ERA5-Land observed substantially less TNs than the met-station data (33 vs. 687). The RR for TNs using 20°C, yielded larger risks in Zurich for monitors compared to ERA5-Land (RR=1.05 (95%CI:0.85;1.26) vs. RR=0.83 (95%CI:0.63;1.07)) but is reversed in Lugano (RR=0.99 (95%CI:0.85;1.14) vs. RR=1.19 (95%CI:0.78;1.80)). Using the 99th percentile compared to the 20°C threshold yielded a very similar RR in Zurich, while in Lugano a substantial difference exists in met-station data (99%: 0.88 vs. 20°C: 0.99) as well for the ERA5-Land (99%:1.06 vs. 20°C: 1.19).

In conclusion, spatially resolved weather data and monitor station data observed different frequencies of threshold-based definitions, particularly in regions with complex orography, leading to heterogeneous results. Future studies should carefully consider

the chosen exposure dataset as well as the application of absolute or relative-threshold definitions.

3.1 Background

In recent years, an increasing number of epidemiological studies apply spatially resolved weather data to assess the temperature-mortality association and corresponding impacts around the world [1, 2, 3, 4]. Resolved weather data are defined as products that are based on global and regional weather forecasts which are corrected and constrained by temperature observations [5]. These have shown to be an excellent proxy for temperature exposure of populations to identify areas of high risk the temperature-mortality association and impacts globally [6, 7, 8, 9]. Moreover, these products are largely valued due to their complete spatial and temporal coverage at a high resolution, making it possible to also study impacts in remote regions without adequate exposure data [8].

However, even though the estimated temperature-mortality association, and the corresponding heat- and cold-related mortality impacts are similar between climate reanalysis products and monitor stations on a relative temperature scale (percentile basis), the absolute temperature distributions between the two exposure datasets do largely differ, particularly in regions with a complex orography [6, 9]. While this is not problematic for most epidemiological studies that aim to quantify the temperature-mortality impacts, more studies have started to take the additional step of analyzing and studying the impacts of tropical nights (TNs) [10, 11, 12] or climate adaptation strategies such as heat warning systems [2, 13, 14]. As the definition of TNs, as well as heat warning alerts, is based on when and how often an absolute threshold is exceeded, the observed frequency is dependent on the exposure source. The exposure source can vary between the reanalysis data and monitor stations data because the temperature distribution is shifted. Moreover, a difference in the observed frequency might yield heterogeneous measures of association and impacts when studying the impacts of TNs using an absolute scale versus on a percentile basis.

Therefore, to illustrate the problem of using absolute threshold based cut-off points, we aim to explore the association between TNs, defined on an absolute scale versus relative scale, and mortality using a comparative assessment between ground-station monitors and spatially resolved weather data in the two Swiss cities Zurich and Lugano.

3.2 Methods

3.2.1 Temperature and Mortality Data

We obtained hourly gridded mean temperature data between 1980-2018 from the ERA5-Land reanalysis dataset provided by Copernicus Climate Change Service [15, 16] with a 9-km resolution across Switzerland. We derived the average time series for the two districts of the cities Zurich and Lugano by intersecting the district shapefile with the population-weighted temperature cells. Subsequently, we calculated the daily population-weighted minimum nighttime temperature between 9PM and 6AM for each district. As TNs only occur in warmer months in Switzerland, we included all days between May and September. For monitor stations, we retrieved the daily minimum nighttime temperature for the two stations Zürich-Fluntern (SMA) and Lugano from the IDAweb repository [17]. We defined a TN based on an absolute and a relative scale. A TN is a night with a minimum temperature above or equal to 20°C or the 99th percentile, respectively [12, 18, 19, 20].

We collected daily all-cause mortality data in Switzerland between the 1 January 1980 and 31 December 2018 from the Federal Statistical Office (BFS) at municipality level resolution and aggregated these to the corresponding 143 districts.

3.2.2 Statistical Analysis

To estimate the association between TNs and mortality in Lugano and Zurich, we performed a simple time series analysis with a conditional quasi-Poisson regression and distributed lag (non-)linear models (DLM/DLNM). The simple time series design allowed us to model the TN-mortality association per canton while using high resolution exposure and mortality data defined at a small scale (i.e., district). The design also allowed for control of long-term temporal trends since we defined matching strata by year, month, and day of the week at district level [21]. We modelled the TN-mortality association with unconstraint-distributed lag linear model (DLM) with a lag of 3 days to account for short-term harvesting and lagged effects of TNs. We also controlled for daily mean temperature to get the independent TN-mortality association. To model the daily mean temperature-mortality association, we applied an unconstraint-distributed lag non-linear model (DLNM). We modelled the temperature mortality association as a quadratic B-spline with two internal knots placed at the 50th and 90th percentile of the district-specific temperature distribution while we included 3 days of lag as an integer to account for short-term harvesting and the lagged effects.

We ran the analysis for the two sets of weather data (i.e. reanalysis and monitor data), with each dataset using their independent TN definition based on the 20°C threshold and the 99th percentile of their own temperature distribution.

3.3 Results

Figure 3.1 illustrates the districts of Zurich and Lugano, the two main cities in the Cantons of Zurich and Ticino with the corresponding elevation, the temperature grid cells (9-km) and the location of the monitor station. Zurich is an urban area in the north of Switzerland, while Lugano is located in a mountainous region (Figure 3.1). Between the month May-September from 1980-2019, there were 16397 and 64518 deaths in the districts of Lugano and Zurich, respectively.

Table 3.1 shows the number of observed TNs for Zurich and Lugano by exposure dataset (climate reanalysis or monitor station). While in Zurich a similar number of TNs were observed between the ERA5 and monitor stations (53 vs. 61), in Lugano the ERA5 observed substantially less TNs as opposed to monitor stations (33 vs. 687). Moreover, a higher daily mean temperature (Tmean) was observed by the monitors in Lugano (15.8°C) versus ERA5 (12.7°C), which is not evident in Zurich (monitor: 12.4°C vs. ERA5: 12.1°C),

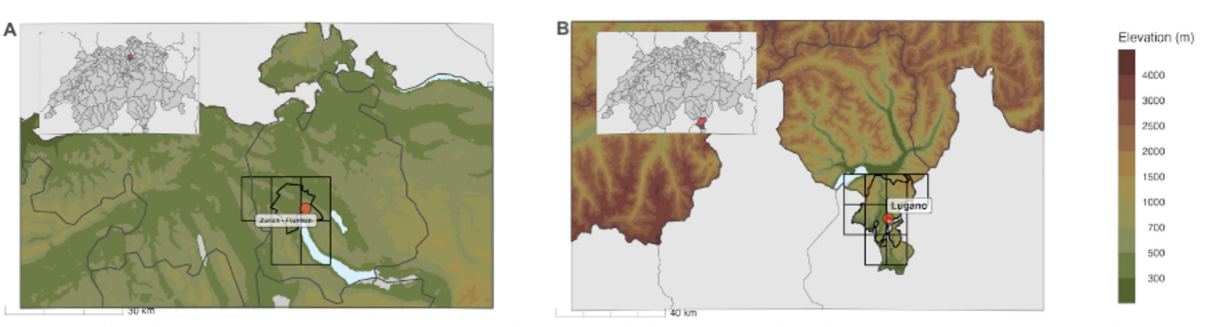

Figure 3.1: The selected districts of Zurich (A) and Lugano (B) with the elevation (in meters), the size of included temperature cells for the daily night temperature (in black) and the location of the monitor station in red.

while the standard deviation is similar between monitors and ERA5 in both locations (Table 3.1 and Figure 3.2). Figure 3.2 illustrates the temperature distribution for the ERA5 and monitors (A), as well as identification of the days which are considered TNs by the ERA5 (in red) and the monitor stations (in blue) in the summer of 2015 (B). In Zurich, the monitor station identifies all TNs, and the same nights are confirmed by the ERA5 TNs except for one night. In Lugano, ERA5 captured much more TNs than the monitoring stations, but all the TN from the monitoring stations are confirmed by the ERA5 TNs.

Table 3.1: Summary of the number of TNs, mean temperature and standard deviation for the monitor stations and ERA5. The measure of association for daily mean temperature, and TN adjusted by temperature at 20°C and 99th percentile are expressed as a RR with the corresponding 95%CI.

	#TN	**mean**	**sd**	**temp 99%**	**RR temp**	**RR TN (20°C)**	**RR TN (99%**
Zürich ERA5	53	12.02	3.67	19.78	1.27 [1.15-1.40]	0.83 [0.63-1.07]	0.88 [0.69-1.13]
Zürich station	61	12.41	3.61	19.90	1.21 [1.11-1.31]	1.05 [0.87-1.26]	1.05 [0.87-1.26]
Lugano ERA5	33	12.68	3.64	19.49	1.21 [1.06-1.38]	1.19 [0.78-1.80]	1.06 [0.74-1.52]
Lugano station	687	15.78	3.44	22.70	1.35 [1.11-1.63]	0.99 [0.85-1.14]	0.88 [0.69-1.13]

The temperature-mortality association is similar between monitors in Zurich (Relative Risk (RR)=1.21 (95%CI:1.11;1.31)) vs. ERA5 (1.27 (95%CI:1.15;1.40)) while larger difference is observed in Lugano (monitor: 1.35 (95%CI:1.11;1.63) vs. ERA5 1.21(95%CI:1.06;1.38)). However, for TN-mortality association, defined using 20°C as a threshold, we observe larger risks in Zurich for monitors (1.05 (95%CI:0.87;1.26) vs.

0.83 (95%CI:0.63;1.07)) but is reversed in Lugano (0.99 (95%CI:0.85;1.14) vs. 1.19 (95%CI:0.78;1.80)) for the monitor and ERA5 respectively. We found the same pattern using the 99th percentile for the TN definition, with a larger risk in Zurich for monitors (1.05 (95%CI:0.87;1.26) vs. 0.88 (95%CI:0.69;1.13)) but reserved in Lugano (0.88 (95%CI:0.69;1.13) vs. 1.06 (95%CI:0.74;1.52)) for monitor and ERA5 respectively. Comparing the 99th percentile with the 20°C threshold, we found a very similar risk in Zurich for monitor and ERA5 dataset. While in Lugano we found a substantial difference in the monitor data (0.99 (95%CI:0.85;1.14) vs. 0.88 (95%CI:0.69;1.13)) as well as in the ERA5 data (1.19 (95%CI:0.78;1.80) vs. 1.06 (95%CI:0.74;1.52)) for the 20°C and 99th percentile respectively.

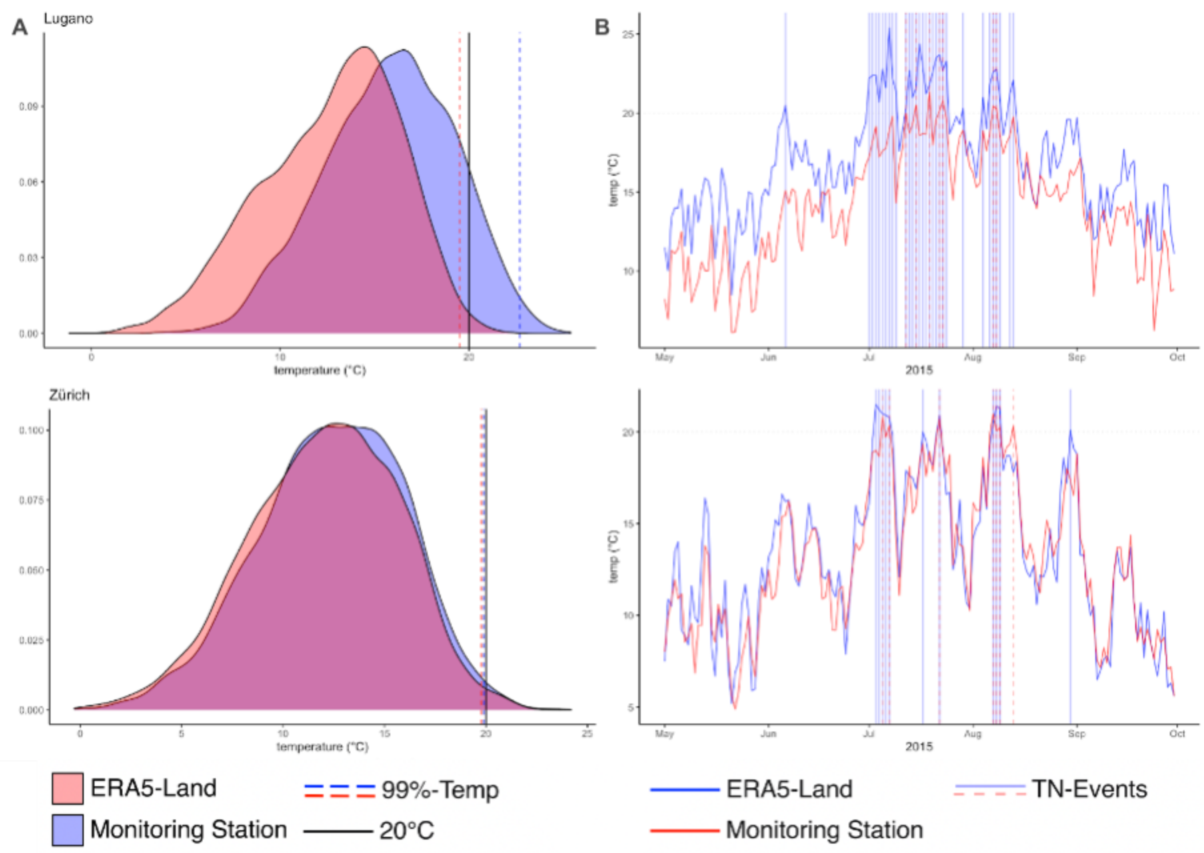

Figure 3.2: The nighttime temperature distribution for the ERA5 (in red) and the monitor station (in blue) (A), combined with the observed nighttime temperature series for 2015 by exposure dataset (B). The red and blue lines in A, represent the 99th percentile. In panel B, the observed TNs for the monitor stations are illustrated in blue, while for the ERA5 in red.

3.4 Discussion

Despite the many advantages of using spatially resolved weather data, this study found that using such data yielded heterogeneous measures of association between TNs (defined on an absolute scale) and mortality in Switzerland compared to monitor stations. Moreover, the number of TNs observed were more similar in homogenous regions such as Zurich. While larger differences in observed number of TNs were evident in regions with more complex orography such as Lugano. Lastly, we observed that using a percentile-based threshold or absolute cut-off point to estimate the TN-mortality association yielded further heterogeneous results.

Overall, we did not observe an independent effect of TNs on mortality, which is in contrast with some previous studies [10, 11, 12], and could be explained in three ways. First, the implementation of public health measures which are associated with TNs in Switzerland (i.e. heat warning alerts) might have reduced the risk [22]. Second, previous studies have only explored urban regions and used monitor stations as their exposure datasets, which in our study yielded larger risk as opposed to ERA5 data [8, 10, 11, 12]. Finally, some studies have used an absolute threshold [11], while others have used a percentile-based definition for a TN [10, 12]. Using a relative threshold has the advantage of capturing the local climate characteristics which is not the case with an absolute threshold definition, as is used by most federal governments (including CH) [19, 23] and could explain the difference between study results as well as between definition results within this study.

Previous studies exploring the temperature-mortality association found similar performance between climate reanalysis data and monitor stations, which unlike using threshold definitions, is based on their own relative temperature distribution [6, 7, 8, 9]. As the definition of a TN is defined on an absolute scale, the number of observed TNs varied largely between exposure dataset, resulting in heterogeneous measures of association. The concerns of TNs with heterogeneous definitions and exposure datasets, can be extended to studies exploring the effectiveness of heat action plans and heat alerts, which are often issued on an absolute threshold [2, 14, 24, 25]. Moreover, whether a heat warning alert definition is based on an absolute or relative scale can yield substantial heterogeneity in the observed number of alerts issued, which has possible implications for public health effectiveness as well as generalizability of studies.

In conclusion, spatially resolved weather data and monitor station data observe different frequencies of threshold-based definitions, particularly in regions with complex orography, leading to heterogeneous results. Therefore, future studies should carefully consider the chosen exposure dataset as well as the application of absolute or relative-threshold definitions. Future research should further explore why heterogenous risks can be observed between different exposure datasets and explore the discrepancy in risk between urban and rural regions.

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4 Conclusion

In this thesis, I analyzed at the change in frequency of TNs, the population exposed to TNs, and their effect on mortality in Switzerland across 50 years. I found that the frequency of TNs increased in the past decades, as well as the population exposed. In some cantons, the risk of dying during a TN is higher than in non-TN, while in other cantons, I found a protective effect during TNs. Compared with the city-specific analysis, I found the trend that TNs represent a smaller risk in urban areas than in rural areas. This difference between the cantons and the urban and rural areas can possibly be attributed to the differences in public health measures and heat plans and different sensitivity to heat. Nevertheless, further research is needed to better understand the nighttime temperature and its importance in health to improve current national and cantonal public health strategies.

In the commentary paper, I discussed the difference in using a reanalysis or met-station data set and the definition of TNs based on an absolute or relative threshold. I found heterogeneous results in regions with complex orography. Future studies should carefully choose the dataset and the application of absolute or relative-threshold definitions, considering their research question and study area.

In conclusion, TNs are a relevant health hazard in Switzerland. TNs should be considered in national and cantonal public health strategies, especially when considering the ongoing global warming as well as the hotspot position of Switzerland.

5 Appendix

Supporting Information for

Trends in Tropical Nights and their Effects on Mortality in Switzerland across 50 years

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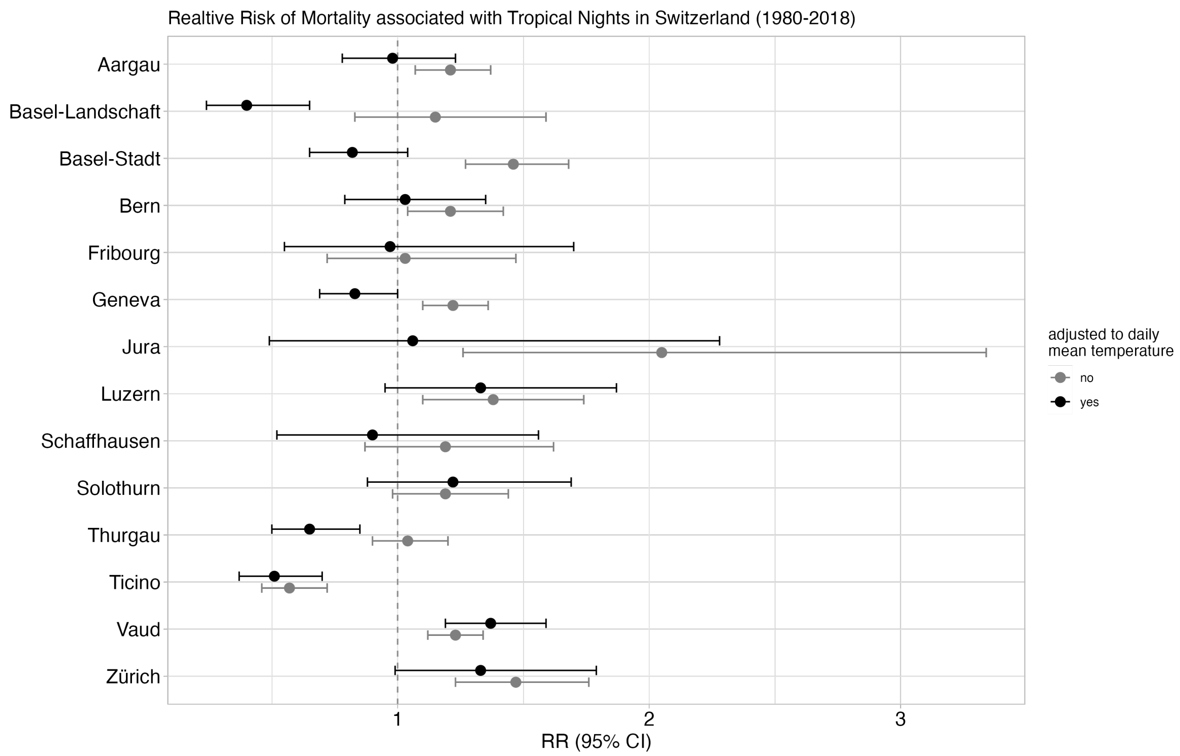

Figure S1: Relative risk (RR) of mortality associated with TNs across cantons in Switzerland from 1980-2018. Black: RR from model adjusted to daily mean temperature. Grey: RR from model not adjusted to daily mean temperature.

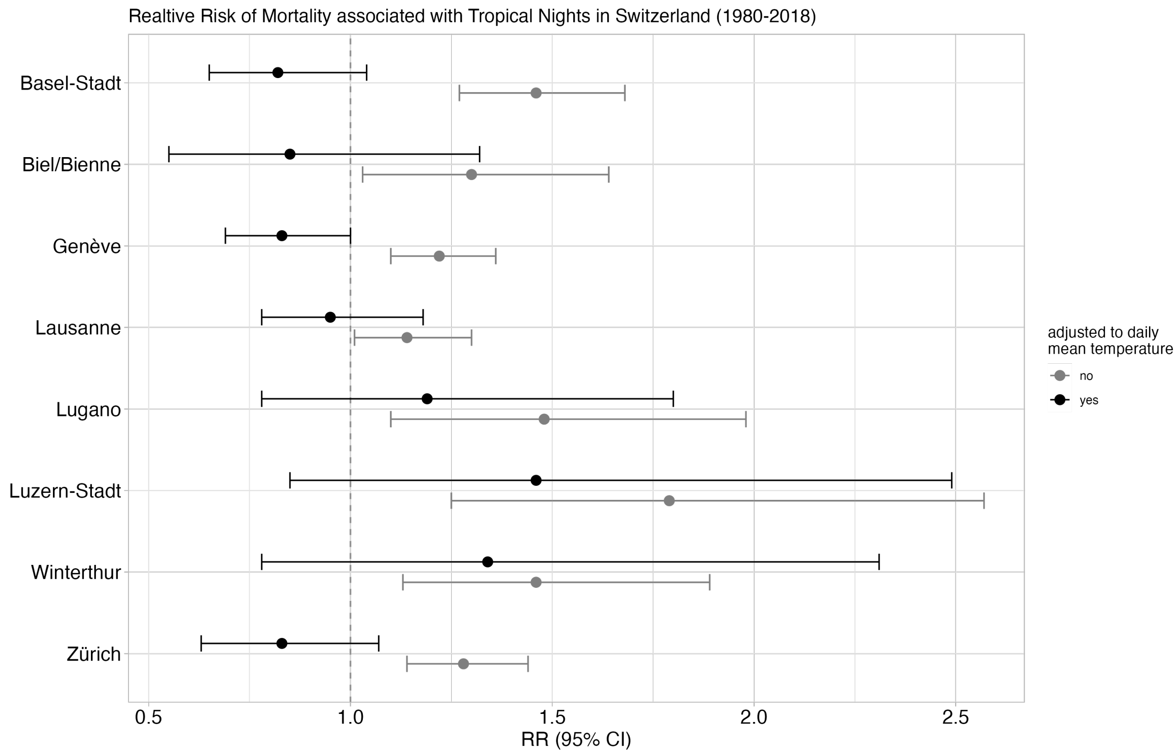

Figure S2: Relative risk (RR) of mortality associated with TNs across the largest cities in Switzerland from 1980-2018. Black: RR from model adjusted to daily mean temperature. Grey: RR from model not adjusted to daily mean temperature.

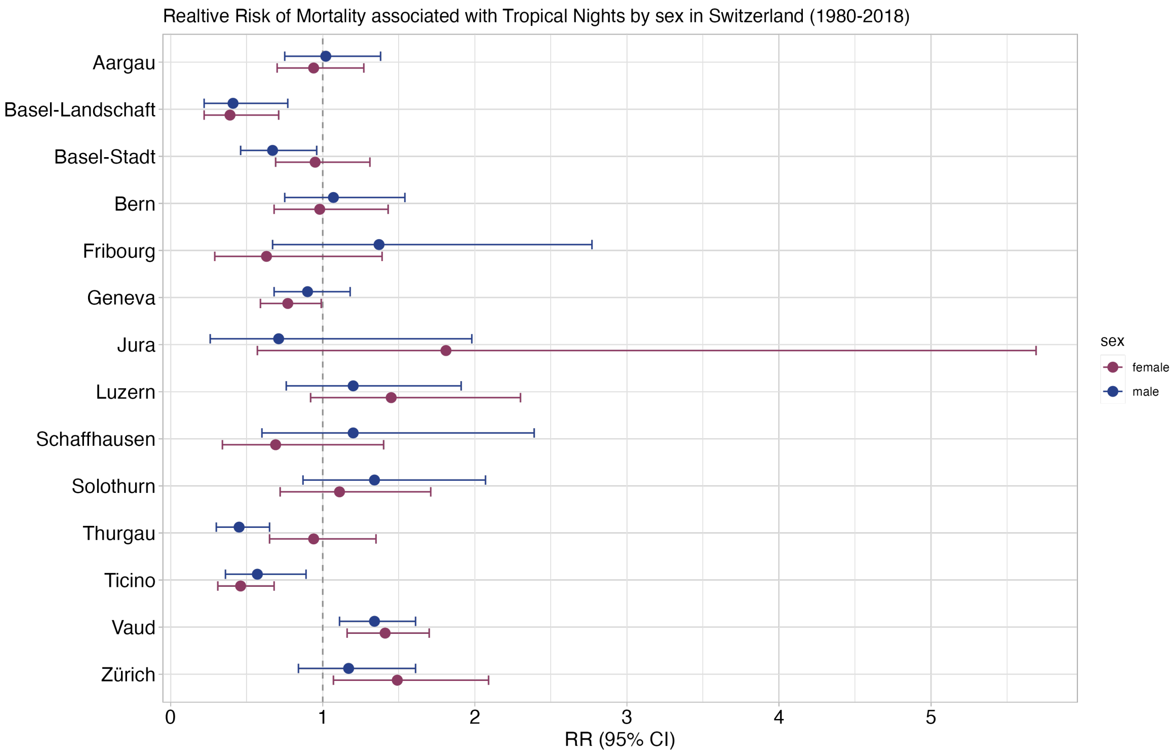

Figure S3: Subgroup analysis by sex, relative risk (RR) of mortality associated with TNs across cantons in Switzerland from 1980-2019. The RR of males is illustrated in blue while the RR of females is in purple.

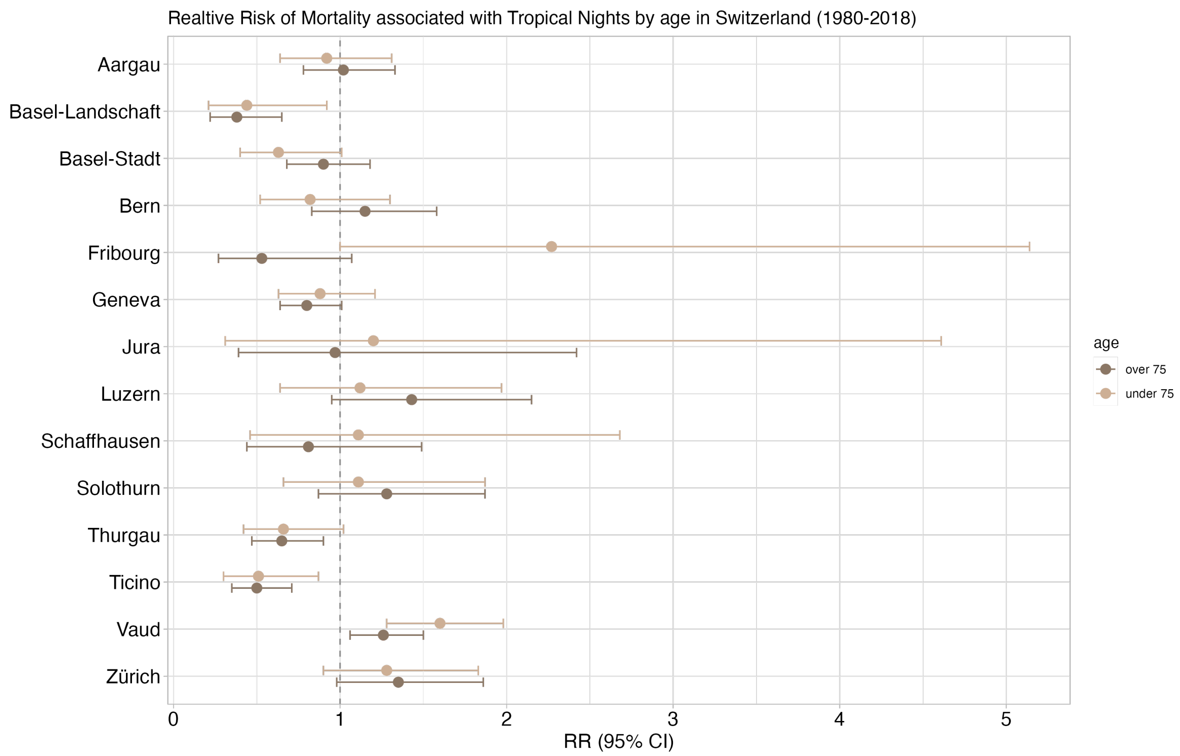

Figure S4: Subgroup analysis by age, relative risk (RR) of mortality associated with TNs across cantons in Switzerland from 1980-2018. In dark brown is the RR of the over 75-year-old and in bright brown the RR of the under 75-year-old.

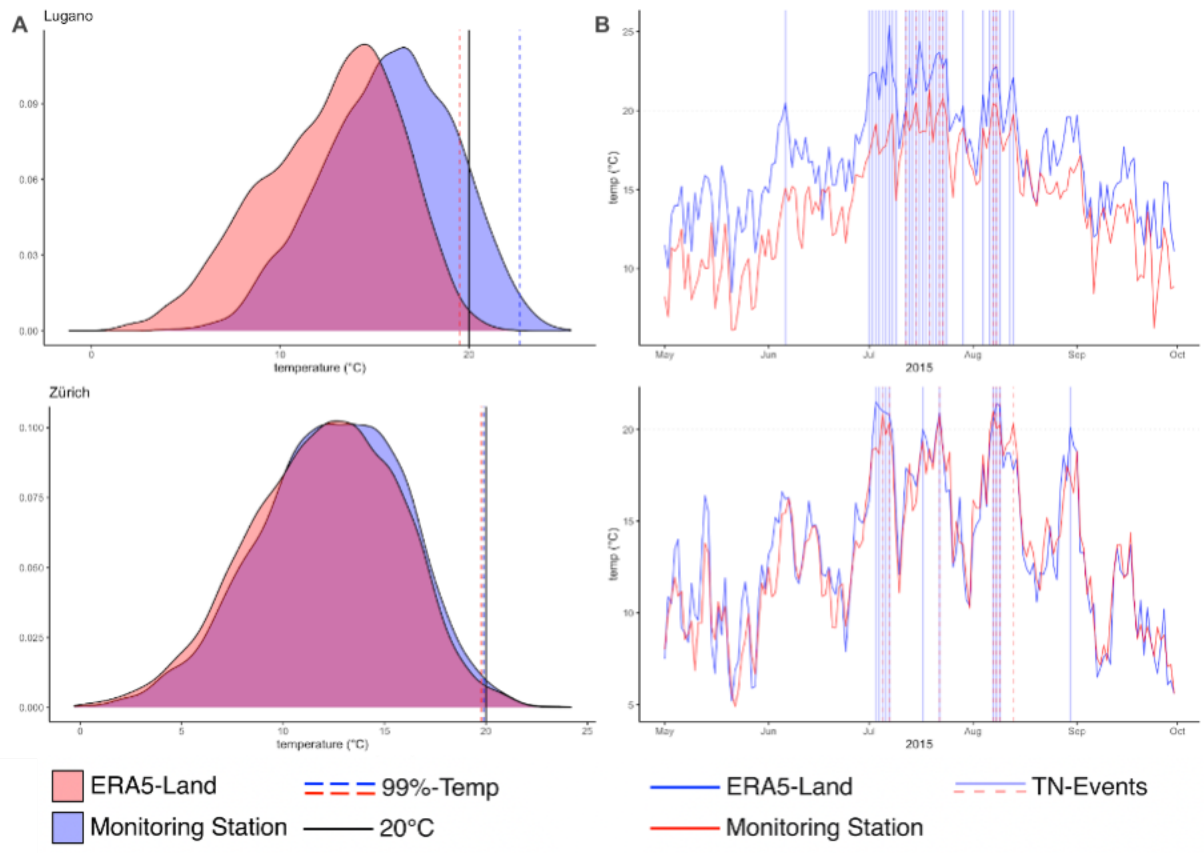

Figure S5: Comparing ERA5-Land (red) with monitoring station (blue). Left: overall nighttime temperature distribution (May-September) with ERA5-Land vs monitoring station in Lugano and Zurich. Additionally, the 99% percentile (dashed red and blue) and 20°C threshold (black) as lines. Right: observed nighttime temperature series from May – September 2015 with TN-Events (vertical lines) for ERA5-Land (blue) and monitoring station (red).

Table S1: Number of TNs per decade from 1970-2019 for each district in Switzerland.

	1970-1979	**1980-1989**	**1990-1999**	**2000-2009**	**2010-2019**
Affoltern	0	1	2	15	15
Andelfingen	3	10	20	27	39
Bülach	0	2	6	17	21
Dielsdorf	1	2	9	21	32
Hinwil	0	1	0	0	1
Horgen	0	1	0	1	4
Meilen	0	0	0	0	3
Pfäffikon	0	0	1	1	2
Uster	0	0	1	4	4
Winterthur	0	2	5	14	13
Dietikon	1	2	8	24	33
Zürich	0	2	5	23	23
Jura bernoise	0	0	0	9	9
Biel/Bienne	0	2	7	23	31
Seeland	0	3	9	22	32
Oberaargau	0	2	3	18	25
Emmental	0	0	0	0	1
Bern-Mittelland	0	0	0	0	0
Thun	0	0	0	0	0
Obersimmental-Saanen	0	0	0	0	0
Frutigen-Niedersimmental	0	0	0	0	0
Interlaken-Oberhasli	0	0	0	0	0
Luzern-Stadt	0	2	9	11	16
Luzern-Land	0	1	3	4	9
Hochdorf	0	2	11	13	18
Sursee	0	2	5	11	12
Willisau	0	0	1	14	13
Entlebuch	0	0	0	0	0
Kt. Uri	0	0	0	0	0

Einsiedeln	0	0	0	0	0
Gersau	0	0	0	1	1
Höfe	0	0	0	0	0
Küssnacht (SZ)	0	1	5	11	10
March	0	0	0	0	0
Schwyz	0	0	0	0	0
Kt. Obwalden	0	0	0	0	0
Kt. Nidwalden	0	0	0	1	0
Kt. Glarus	0	0	0	0	0
Kt. Zug	0	1	0	4	5
La Broye	0	4	7	18	33
La Glâne	0	0	0	0	1
La Gruyère	0	0	0	0	0
La Sarine	0	0	0	0	1
See/Lac	0	2	2	9	18
Sense	0	0	0	0	0
La Veveyse	0	0	0	0	2
Gäu	0	0	2	19	20
Thal	0	0	1	12	11
Bucheggberg	0	3	5	21	35
Dorneck	0	1	1	13	13
Gösgen	0	2	2	17	16
Wasseramt	0	5	5	20	33
Lebern	0	4	4	18	30
Olten	0	1	4	19	20
Solothurn	0	4	4	19	31
Thierstein	0	0	0	7	8
Kt. Basel-Stadt	0	8	3	19	30
Arlesheim	0	2	1	13	13
Laufen	0	0	0	8	10
Liestal	0	1	2	14	17

Sissach	0	3	2	18	17
Waldenburg	0	0	0	12	8
Oberklettgau	3	7	22	19	30
Reiat	4	9	21	25	32
Schaffhausen	3	8	21	22	30
Schleitheim	2	6	19	16	28
Stein	5	11	29	39	60
Unterklettgau	3	8	22	17	29
Hinterland	0	0	0	0	0
Mittelland	0	0	0	0	0
Vorderland	0	0	0	0	0
Kt. Appenzell i.Rh.	0	0	0	0	0
St. Gallen	0	0	0	0	0
Rorschach	0	0	1	2	6
Rheintal	0	0	0	0	0
Werdenberg	0	0	0	0	0
Sarganserland	0	0	0	0	0
See-Gaster	0	0	0	0	0
Toggenburg	0	0	0	0	0
Wil	0	0	0	0	0
Albula	0	0	0	0	0
Bernina	0	0	0	0	0
Engiadina Bassa/Val Müstair	0	0	0	0	0
Imboden	0	0	0	0	0
Landquart	0	0	0	0	0
Maloja	0	0	0	0	0
Moesa	0	0	0	0	0
Plessur	0	0	0	0	0
Prättigau/Davos	0	0	0	0	0
Surselva	0	0	0	0	0
Viamala	0	0	0	0	0

Aarau	0	3	4	18	22
Baden	1	2	10	27	39
Bremgarten	0	3	7	24	29
Brugg	1	2	11	27	36
Kulm	0	1	6	18	21
Laufenburg	2	2	11	22	33
Lenzburg	0	3	5	20	25
Muri	0	0	6	15	21
Rheinfelden	0	3	4	20	25
Zofingen	0	2	6	20	19
Zurzach	3	7	25	24	46
Arbon	0	2	4	9	22
Frauenfeld	2	6	13	26	39
Kreuzlingen	17	21	43	60	89
Münchwilen	0	2	1	7	10
Weinfelden	0	5	12	26	37
Bellinzona	0	0	0	0	0
Blenio	0	0	0	0	0
Leventina	0	0	0	0	0
Locarno	0	0	0	0	0
Lugano	0	2	2	8	21
Mendrisio	0	13	26	38	73
Riviera	0	0	0	0	0
Vallemaggia	0	0	0	0	0
Aigle	0	0	0	0	0
Broye-Vully	0	1	6	12	27
Gros-de-Vaud	1	2	14	23	41
Jura-Nord vaudois	0	1	3	10	22
Lausanne	8	7	32	43	77
Lavaux-Oron	0	3	12	18	34
Morges	13	19	51	54	97

Nyon	0	2	10	22	34
Ouest lausannois	16	30	74	87	139
Riviera-Pays-d'Enhaut	0	0	0	0	1
Brig	0	0	0	0	0
Conthey	0	0	0	0	0
Entremont	0	0	0	0	0
Goms	0	0	0	0	0
Hérens	0	0	0	0	0
Leuk	0	0	0	0	0
Martigny	0	0	0	0	0
Monthey	0	0	0	0	0
Raron	0	0	0	0	0
Saint-Maurice	0	0	0	0	0
Sierre	0	0	0	0	0
Sion	0	0	0	0	0
Visp	0	0	0	0	0
Cant. de Neuchâtel	0	0	1	7	7
Cant. de Genève	1	5	10	29	51
Delémont	0	0	0	8	8
Les Franches-Montagnes	0	0	0	5	3
Porrentruy	0	1	0	10	11

Table S2: Number of population exposed to TNs as people-TN per decade from 1970-2019 for each district in Switzerland.

	1970-1979	**1980-1989**	**1990-1999**	**2000-2009**	**2010-2019**
	1970-1979	1980-1989	1990-1999	2000-2009	2010-2019
Affoltern	0	35297	78777	680980	785100
Andelfingen	66206	230975	494101	740495	1196552
Bülach	0	201699	698465	2382814	3536155
Dielsdorf	50509	113366	579294	1591005	2859610
Hinwil	0	65793	0	0	95354
Horgen	0	90234	0	103373	451680
Meilen	0	0	0	0	262846
Pfäffikon	0	0	48234	53983	121535
Uster	0	0	97911	447238	512041
Winterthur	0	227495	630493	2017593	2145929
Dietikon	61168	127947	546800	1817980	2791779
Zürich	0	576067	1544600	7825565	8665373
Jura bernoise	0	0	0	460572	469923
Biel/Bienne	0	163976	590909	2057012	2965348
Seeland	0	175829	545565	1422986	2228980
Oberaargau	0	150333	222369	1354137	1929649
Emmental	0	0	0	0	95507
Bern-Mittelland	0	0	0	0	0
Thun	0	0	0	0	0
Obersimmental-Saanen	0	0	0	0	0
Frutigen-Niedersimmental	0	0	0	0	0
Interlaken-Oberhasli	0	0	0	0	0
Luzern-Stadt	0	122447	568053	735053	1141680
Luzern-Land	0	75887	243493	357298	890562
Hochdorf	0	113027	659490	853096	1301895
Sursee	0	103181	282639	705303	877840
Willisau	0	0	44930	660772	650531

Entlebuch	0	0	0	0	0
Kt. Uri	0	0	0	0	0
Einsiedeln	0	0	0	0	0
Gersau	0	0	0	1448	1618
Höfe	0	0	0	0	0
Küssnacht (SZ)	0	8015	43142	105026	106050
March	0	0	0	0	0
Schwyz	0	0	0	0	0
Kt. Obwalden	0	0	0	0	0
Kt. Nidwalden	0	0	0	35457	0
Kt. Glarus	0	0	0	0	0
Kt. Zug	0	82631	0	411598	586378
La Broye	0	61351	129242	418546	958536
La Glâne	0	0	0	0	22847
La Gruyère	0	0	0	0	0
La Sarine	0	0	0	0	102808
See/Lac	0	44703	50361	264423	617919
Sense	0	0	0	0	0
La Veveyse	0	0	0	0	36017
Gäu	0	0	32876	342981	400258
Thal	0	0	14239	170366	157058
Bucheggberg	0	19920	33721	148526	261532
Dorneck	0	16077	16713	232099	249744
Gösgen	0	49880	50303	443068	434541
Wasseramt	0	218933	218984	900015	1541182
Lebern	0	180258	180507	837472	1451845
Olten	0	45539	185617	925597	1033999
Solothurn	0	51855	53280	267310	465657
Thierstein	0	0	0	87209	103518
Kt. Basel-Stadt	0	1485042	537845	3377291	5332077
Arlesheim	0	274645	139971	1904175	2010322

Laufen	0	0	0	149761	202406
Liestal	0	49611	101148	741743	953082
Sissach	0	85771	59407	573680	587342
Waldenburg	0	0	0	180314	124170
Oberklettgau	9482	23167	77686	73736	128573
Reiat	30037	68981	168017	215524	299004
Schaffhausen	144595	385366	1026459	1120876	1609337
Schleitheim	6174	17483	53202	44395	77789
Stein	22421	49787	135118	192139	314227
Unterklettgau	17028	44988	124119	97980	171619
Hinterland	0	0	0	0	0
Mittelland	0	0	0	0	0
Vorderland	0	0	0	0	0
Kt. Appenzell i.Rh.	0	0	0	0	0
St. Gallen	0	0	0	0	0
Rorschach	0	0	32316	68382	218516
Rheintal	0	0	0	0	0
Werdenberg	0	0	0	0	0
Sarganserland	0	0	0	0	0
See-Gaster	0	0	0	0	0
Toggenburg	0	0	0	0	0
Wil	0	0	0	0	0
Albula	0	0	0	0	0
Bernina	0	0	0	0	0
Engiadina Bassa/Val Müstair	0	0	0	0	0
Imboden	0	0	0	0	0
Landquart	0	0	0	0	0
Maloja	0	0	0	0	0
Moesa	0	0	0	0	0
Plessur	0	0	0	0	0
Prättigau/Davos	0	0	0	0	0

Surselva	0	0	0	0	0
Viamala	0	0	0	0	0
Aarau	0	163461	239112	1216662	1688163
Baden	92932	200291	1096977	3348250	5488911
Bremgarten	0	156884	399295	1548025	2127413
Brugg	42161	85606	487078	1279074	1844969
Kulm	0	33170	204006	645816	802338
Laufenburg	36118	38542	231833	526209	897824
Lenzburg	0	113126	208119	954957	1376882
Muri	0	0	155597	450098	731424
Rheinfelden	0	73993	112315	662683	974076
Zofingen	0	97764	316846	1179913	1259806
Zurzach	78476	185908	686410	702363	1448356
Arbon	0	81661	172614	423165	1136005
Frauenfeld	96331	300834	689910	1501034	2463531
Kreuzlingen	459779	625765	1434243	2310341	3955899
Münchwilen	0	64275	34376	264801	418726
Weinfelden	0	222275	551735	1272757	1945504
Bellinzona	0	0	0	0	0
Blenio	0	0	0	0	0
Leventina	0	0	0	0	0
Locarno	0	0	0	0	0
Lugano	0	226107	239629	1046709	3023426
Mendrisio	0	600351	1215750	1851400	3743654
Riviera	0	0	0	0	0
Vallemaggia	0	0	0	0	0
Aigle	0	0	0	0	0
Broye-Vully	0	25063	167743	389721	1023614
Gros-de-Vaud	21559	49536	404284	806834	1741448
Jura-Nord vaudois	0	57673	193522	748807	1918321
Lausanne	864399	812443	4051224	6110057	12321551

Lavaux-Oron	0	125051	542438	910863	1938457
Morges	581303	935065	2816720	3484999	7334950
Nyon	0	110868	645526	1730773	3252309
Ouest lausannois	719542	1462717	3976349	5321484	9710818
Riviera-Pays-d'Enhaut	0	0	0	0	78165
Brig	0	0	0	0	0
Conthey	0	0	0	0	0
Entremont	0	0	0	0	0
Goms	0	0	0	0	0
Hérens	0	0	0	0	0
Leuk	0	0	0	0	0
Martigny	0	0	0	0	0
Monthey	0	0	0	0	0
Raron	0	0	0	0	0
Saint-Maurice	0	0	0	0	0
Sierre	0	0	0	0	0
Sion	0	0	0	0	0
Visp	0	0	0	0	0
Cant. de Neuchâtel	0	0	153695	1112359	1162946
Cant. de Genève	337328	1789677	3864375	12503931	24696141
Delémont	0	0	0	282177	291735
Les Franches-Montagnes	0	0	0	48579	30736
Porrentruy	0	26446	0	248324	271025

Table S3: Nationwide analysis from 1980-2018 with the relative risks (RR) of TNs on mortality for each canton. First column shows RR of TNs on morality, second the independent RR of TNs on mortality accounted for daily mean temperature. Third, RR of daily mean temperature accounted for TNs with the corresponding minimum mortality temperature (mmt). Fifths, RR of daily mean temperature and the corresponding mmt. Finally, the average number of TNs per canton and the number of deaths.

	RR TN [95% CI]	**RR TN acc. Tmean [95% CI]**	**RR Tmean acc. TN [95% CI]**	**mmt**	**RR Tmean [95% CI]**	**mmt**	**TN/district**	**deaths**
Zürich	1.47 [1.23 - 1.76]	1.33 [0.99 - 1.79]	1.12 [1.02 - 1.25]	16.5	1.21 [1.13 - 1.29]	16	37	161368
Bern	1.21 [1.04 - 1.42]	1.03 [0.79 - 1.35]	1.11 [1.01 - 1.22]	15	1.11 [1.05 - 1.18]	15	41	54172
Luzern	1.38 [1.1 - 1.74]	1.33 [0.95 - 1.87]	1.08 [0.97 - 1.2]	17	1.15 [1.06 - 1.24]	17.5	35	39077
Fribourg	1.03 [0.72 - 1.47]	0.97 [0.55 - 1.7]	1.05 [0.91 - 1.21]	18.5	1.05 [0.94 - 1.16]	18.5	25	23145
Solothurn	1.19 [0.98 - 1.44]	1.22 [0.88 - 1.69]	1.04 [0.92 - 1.17]	17.5	1.09 [1.01 - 1.18]	17.5	43	41030
Basel-Stadt	1.46 [1.27 - 1.68]	0.82 [0.65 - 1.04]	1.42 [1.29 - 1.56]	15.5	1.33 [1.25 - 1.41]	15.5	64	36639
Basel-Landschaft	1.15 [0.83 - 1.59]	0.4 [0.24 - 0.65]	1.71 [1.49 - 1.95]	13	1.42 [1.29 - 1.56]	13	30	30513
Schaffhausen	1.19 [0.87 - 1.62]	0.9 [0.52 - 1.56]	1.23 [0.91 - 1.67]	18	1.19 [0.99 - 1.43]	18	92	10909
Aargau	1.21 [1.07 - 1.37]	0.98 [0.78 - 1.23]	1.15 [1.03 - 1.28]	13	1.14 [1.07 - 1.21]	13	66	62135
Thurgau	1.04 [0.9 - 1.2]	0.65 [0.5 - 0.85]	1.42 [1.23 - 1.64]	17	1.17 [1.08 - 1.28]	17	91	27735
Ticino	0.57 [0.46 - 0.72]	0.51 [0.37 - 0.7]	1.12 [0.95 - 1.31]	22	0.88 [0.78 - 0.99]	22	96	22607
Vaud	1.23 [1.12 - 1.34]	1.37 [1.19 - 1.59]	0.95 [0.87 - 1.03]	21	1.09 [1.03 - 1.15]	19	113	79376
Genève	1.22 [1.1 - 1.36]	0.83 [0.69 - 1]	1.36 [1.23 - 1.5]	17.5	1.26 [1.18 - 1.34]	17.5	99	48489
Jura	2.05 [1.26 - 3.34]	1.06 [0.49 - 2.28]	1.41 [1.19 - 1.66]	11	1.42 [1.26 - 1.6]	11	16	9788

*contains only cantons with at least 1 TN/year

Table S4: City-specific analysis from 1980-2018 with the relative risks (RR) of TNs on mortality for the largest cities in Switzerland. First column shows the RR of TNs on mortality and the second the independent RR of TN on morality accounted for daily mean temperature. The table also shows the number of TNs and number of deaths for the districts of each city.

	RR TN [95% CI]	**RR TN acc. Tmean [95% CI]**	**TN**	**deaths**
Zürich	1.28 [1.14 - 1.44]	0.83 [0.63 - 1.07]	57	64518
Genève	1.22 [1.1 - 1.36]	0.83 [0.69 - 1]	99	48489
Basel	1.46 [1.27 - 1.68]	0.82 [0.65 - 1.04]	64	36639
Lausanne	1.14 [1.01 - 1.3]	0.95 [0.78 - 1.18]	167	19851
Winterthur	1.46 [1.13 - 1.89]	1.34 [0.78 - 2.31]	36	18094
Luzern	1.79 [1.25 - 2.57]	1.46 [0.85 - 2.49]	43	12613
Lugano	1.48 [1.1 - 1.98]	1.19 [0.78 - 1.8]	36	16397
Biel/Bienne	1.3 [1.03 - 1.64]	0.85 [0.55 - 1.32]	65	14026

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Declaration of consent

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

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Supervisor: Dr. Ana Maria Vicedo-Cabrera
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