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CLIMATE CHANGE RESEARCH

The effect of humidity in association with high temperatures on health outcomes

Master Thesis

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handed in by

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Abstract

Anthropogenic climate change is arguably the biggest health threat for the global population in the 21st century. Excess deaths observed during the summer 2003 heatwave in Europe have contributed to an increased public awareness on risks of heat stress exposure. Previous studies have associated the exposure to ambient temperature with mortality. There is good evidence that physiological stress from high temperatures is greater if humidity is higher. However, there is still no robust evidence on the role of humidity in epidemiological studies. We aimed to further clarify the effect of humidity in association with temperature on daily mortality in summer by using a Swiss cantonal dataset. Here, we show that extreme compound hot and humid conditions coincided with higher excess deaths across Switzerland, compared to merely hot conditions. We found that this effect is most visible for the summers of 2003, 2015 and 2018 in Zurich canton *(compound hot-humid day average: 16.7%, hot day average: 8.9% excess mortality)*. However, our results on the exposure-response association do not support this finding. We demonstrate that the associated increase in relative risk is negligible for extreme humid conditions *(Zurich canton, partial pressure humidity: RR: 1.005 [95% confidence interval (CI): 1.002, 1.008] per 10 percentiles)*. We confirm the slight protective effect of humidity as expressed by relative humidity *(Zurich canton, relative humidity: RR: 0.988 [95% confidence interval (CI): 0.984, 0.991] per 10 percentiles)* as shown in previous studies. But we highlight the importance of choosing an adequate variable of humidity and advice future epidemiological studies to use a humidity variable with smaller temperature-dependence than relative humidity. Our findings support recent decisions to not include humidity in Swiss heat warning systems.

Keywords— climate change, heat stress, health, temperature, humidity, mortality

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Contents

1 Introduction

Climate change research has become an increasingly popular topic of study and public interest for scholars and the people in the last decades. Global surface temperature has risen by 1.1°C since 1850 and each of the last four decades has been successively warmer than any decade that preceded it since pre-industrial times. It is *very likely* that heatwaves increase in intensity and frequency with every additional 0.5°C of global warming [IPC21]. That is why researching impacts related with a changing climate has become increasingly demanded. We want to answer questions on what that actually implies in different parts of the world and on different timescales. Recently, the impact of climate change on human health has increasingly become a subject of scholarly attention [Vic+21]. As the distribution of meteorological variables shifts, this results in a change in risks and in the occurrence of adverse weather conditions [Le +06; Pou+05; Sem+96]. For instance, people exposed to extreme weather in the form of heat stress will show health effects depending on their vulnerability. Their vulnerability could either be explained by demographic aspects [Sco+18], or by their socio-economic status [Ser+19].

Until now in environmental epidemiology, the heat stress hazard on humans is commonly expressed simply by the driver of ambient temperature [Gas+15]. To further advance the current state of knowledge, we need to include in the model not only ambient temperature, but also radiation, wind speed, and humidity [BH20]. The hazard of heat stress can cause a range of adverse health outcomes. During periods of sustained high heat stress, hyperthermia or heat stroke become common among the groups most vulnerable (elderly, very young children, people with underlying health conditions) [BH20]. But it is unclear if humidity confounds or moderates the association between ambient temperature and mortality. Therefore, knowing this would be extremely valuable to support evidence-based risk management and to protect the population groups at risk.

This adverse effect in humans is commonly expressed as *heat stress*. We do this in an epidemiological setting. Epidemiological evidence used in research focuses on detecting the main drivers and risk factors for adverse health outcomes. In this study setting, the major challenge is to attribute exposure to an outcome and link them by causality [PM18]. This link always risks being biased by confounding or moderating factors, and therefore a well-founded research concept is essential. Our study is set in the environmental context of epidemiological studies. We explore human exposure to meteorological variables and the short-term adverse health outcomes they are associated with.

The next three chapters introduce the research fields of physiology, climate sciences and environmental epidemiology. Each field has its own way to approach the topic of heat stress. We aim to provide an overview thereof and summarize the literature and most important findings. We start by looking at the physiological response to heat stress.

1.1 The human heat engine

Physiologically, we can think of the human body as a heat engine that burns food to do work. This metabolic process is exothermic, and it requires the consumption of food and water to feed the heat engine. Simultaneously, the engine loses resulting metabolic heat. The metabolic heat that is generated within the body's core depends on the level of activity. From a baseline metabolic rate, this could go up to around ten times the minimum rate due to physical activity [BH20]. The metabolic heat equation [HF11] links the different inputs and outputs:

$$\Delta S = (M - W_{ex}) \pm (R + C) - E \tag{1}$$

ΔS: change in body heat content
M: metabolic heat production
W_{ex}: mechanical work
R: radiative heat exchange
C: convective heat exchange
E: evaporative heat loss
all in units of J/s

The process of homeostasis ($\Delta S = 0$) describes an equilibrium between the consumption input and the metabolic heat output. The human body goes through a series of complex processes in order to maintain the core temperature within a narrow range, close to 37°C [BH20]. Any sustained deviation from the state of homeostasis results in risks for human health and well-being. Humidity may play an important role by limiting the evaporative heat loss rate (E) during humid conditions [MV18].

1.2 Climate sciences

Climate scientists have only recently started to cover heat stress in their research. For example, Sherwood and Huber [SH10] found a threshold of adaptability to climate change for humans. Their study acknowledged that wet-bulb temperature (T_w) exceeding skin surface temperature for a sufficient long duration will lead to fatal consequences. T_w is defined as the lowest temperature achieved by adiabatic evaporation of water in the air until the air is saturated [BOH15]. Dunne et al. [DSJ13] investigated the labour capacity in a hotter climate and found a significant reduction in labour capacity especially in the hot months of the year. Mora et al. [Mor+17] explored patterns of deadly heat, and identified the increasing importance of (relative) humidity with extreme high temperatures. Most recently, an extensive study by Buzan and Huber [BH20] on moist heat stress summarized the physiological aspects, the impact on labour capacity and the change in heat indices with global warming. Their 2020 study concluded that the tropics will become permanently heat stressful for humans year around, already with small changes in global mean temperature. In summary, while climate scientists clearly differentiate between dry and moist heat stress, the latter has a more severe adverse impact on human health [BH20].

1.3 Environmental epidemiology

There is scientific consensus that high temperature drives heat stress and mortality related to it. Gasparrini et al. [Gas+15] systematically assessed heat stress across the whole temperature range and for population samples exposed to different climates. They run a time series regression that looks into the short-term association between temperature and mortality. They defined a reference point of optimal temperature per population sample as the minimum mortality temperature (MMT). Exposures higher than the MMT was defined as heat exposure. They concluded that non-optimal ambient temperature (heat exposure) increases relative risk with respect to the optimal temperature. The attributable deaths to heat exposure were reported (0.42 %, CI: 0.39–0.44). The same methodology has been tested and applied from 2015 onward by the Multi Country Multi City (MCC) Collaborative Research Network [Gas]. This time series method is considered the most often used technique by independent researchers by now [Bao+16; Sco+18; Haj+16]. A more recent study by Armstrong et al. 2019 [Arm+19] analysed humidity associated with high temperatures and their impact using a time series method on all-cause mortality. Their study explored various expressions of humidity (relative humidity, specific humidity), and they found a weak protective effect with increased humidity (decrease of 1.1% in mortality with an increase of 23% in relative humidity). This contradicts current and hypotheses in other fields [BH20]. Therefore, the authors remain critical of their findings and say more in depth analyses need to be done on humidity. Armstrong et al. argue that public health policy cannot assume humidity has an impact based on the physiologic evidence alone. They finally suggest, that heat warning systems should be careful when including humidity in their heat stress metrics.

To summarize, humidity is rarely at the focus in health impact studies. Although environmental epidemiological studies acknowledge that humidity is important to quantify health outcomes, it is rare that a humidity variable is included in the research. Often, humidity is treated as a confounding variable only [BTC10; ZLS+14]. The studies that incorporate humidity express it differently, which makes it difficult to compare results. While some studies find and increased health risk with higher humidity [Lin+09; Bar12], other studies find no effect on health [Van+11; BTC10]. Furthermore, biometeorological indices that associate a mix of temperature and humidity with health outcomes make it hard to conclude on the unique influence of humidity on health [DME16].

1.4 Health risk terminology

The definition of any risk presupposes that we are aware it exists. To define a risk, we have to build up on this awareness and create a shared mental model, which helps us finding a consensus of the qualitative and quantitative aspects of that risk. Death rate spikes during the European heatwave 2003 [Mit+16] created a widespread awareness of the risk of heat stress on the human body. In French cities alone, 14'800 excess deaths were estimated for the period between August 1 and August 20 of 2003 [Gri+05]. After identifying the risk, one looks for a qualitative or quantitative model to express the risk. The health risk induced by heat stress is a qualitative relationship of the following terms:

$$risk = hazard \times exposure \times vulnerability \; [Lei + 10] \tag{2}$$

This is a very general definition and it is worth discussing the different terms and the state of research thereof.

1.4.1 Hazard and exposure

Climate change impacts on the population are increasing, as recently reported by Mukherjee et al 2021 [Muk+21]. This is resulted by more severity and variability in the local climate, as well as by the population growth. Depending on the region, it can be the change in weather hazard or in the exposed population that has a larger impact on the change in heat stress risk. But the heat stress risk is not completely explained without expressing the local population vulnerability.

1.4.2 Vulnerability

The same level of impact can result in a different risk due to a different heat stress vulnerability of the population. Heat stress vulnerability within a city can already be heterogeneous as the access to air conditioning and the housing conditions differ [Mad+15]. Furthermore, elderly are particularly susceptible to heat stress risks [Sco+18]. Investigating heat vulnerability based on determinants such as the demographic structure of population and the socio-economic status is therefore an important challenge.

Another research question is whether the outdoor ambient exposure is a good indicator of the health risks for the population. This hints to the fact, that people in industrialized countries spend a lot of time indoors. There is evidence, that outdoor temperature correlates well with indoor temperatures in the summer time [NSD14]. On the contrary, outdoor humidity does not correlate well with indoor humidity the summer time [NSD14], and where heat stress is potentially important. The correlation is not given for the winter time either, which is less important for our study purpose.

1.5 Compound events

We simplified the complex drivers of heat stress hazard by applying the framework of compound events [Zsc+20]. The two main drivers *hot temperatures* and *humidity* contribute to an increase in heat stress hazard, which could eventually lead to mortality impact. The scheme is summarized in Figure 1.

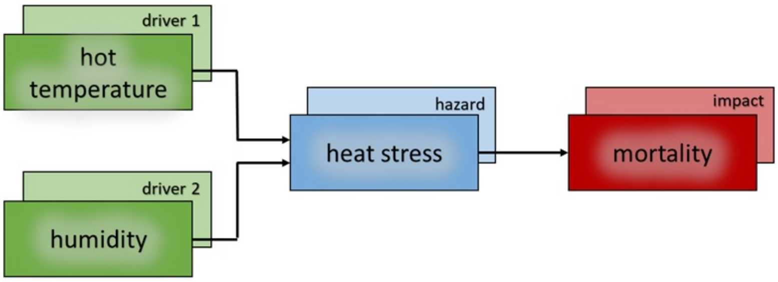


Figure 1: A multivariate compound event, following the framework by Zscheischler et al. 2020 [Zsc+20]

1.6 Study aim

The aim of the master thesis is to investigate the effect of humidity in association with high temperatures on all-cause mortality. The effect is assessed from 1989 to 2018 in Switzerland.

Objectives

- To collect and summarize the research and evidence from different disciplines of research
- To compare temperature and humidity observations from 34 point-based weather stations across Switzerland
- To assess the excess mortality during selected summer seasons in Switzerland and compare them with the environmental exposure
- To estimate exposure-response functions that represent the humidity-mortality and humidity and temperature-mortality association in Switzerland.

1.7 Hypothesis

We acknowledge that the effect of humidity is controversially discussed in the scientific community. We hypothesize that humidity in combination with high temperatures has an adverse effect on all-cause mortality and that heat stress from high temperature is greater if humidity is higher and thus, that humidity should be included in Swiss heat warning systems.

2 Materials and Methods

2.1 Materials

Data on all-cause daily mortality was provided by the Swiss Federal Statistical Office (SFSO) and it covers the years 1989 to 2018. The data includes all-cause mortality on a municipality level that occurred in Switzerland. Death counts were aggregated on a cantonal level.

The meteorological data includes overall 34 weather stations spread across Switzerland. Daily observations on meteorological variables were collected from the meteoswiss IDAweb database [Metb], for the years of 1989 to 2018. The meteorological variables cover humidity as partial pressure in [hPa] as well as temperature as daily maximum, daily minimum and daily mean temperature in [°C]. Relative humidity values in [%] were derived by calculating saturation pressure, and by using partial pressure according to the method in Davis et al. 2016 [DME16]. Figure 2 depicts the 34 weather stations, from which the observations were retrieved.

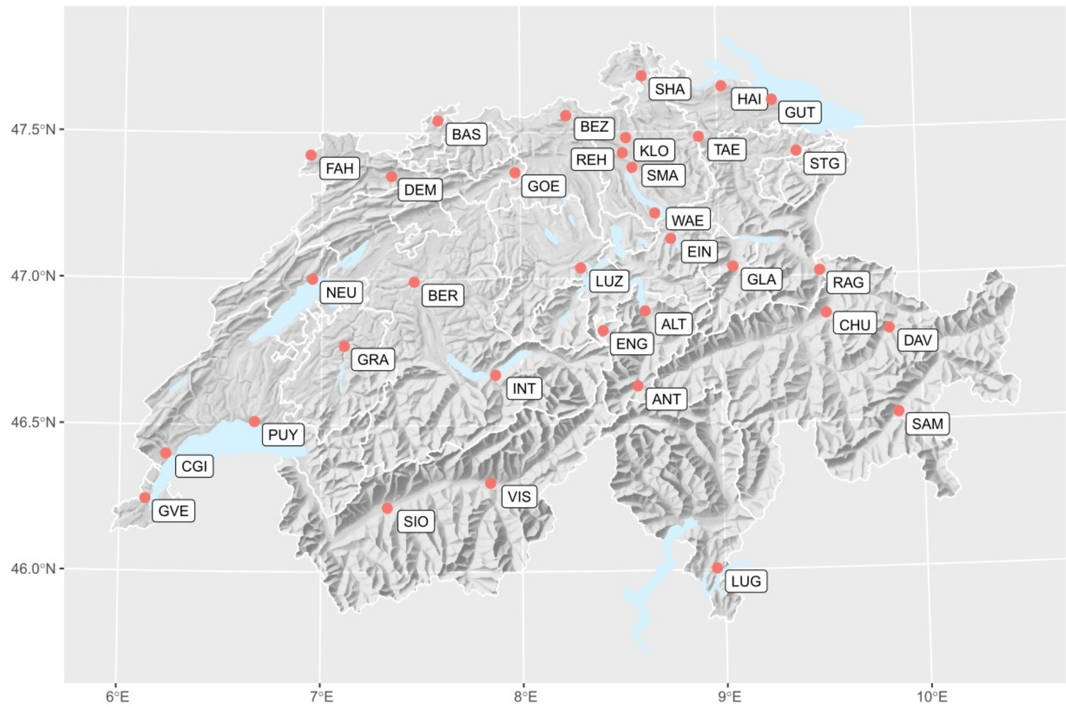


Figure 2: Swiss map with all monitor stations

2.1.1 Weather station weighting method

The weather station observations were evaluated to get a weighted daily average observation for every meteorological variable and for each canton as was previously done by de Schrijver et al. 2021 [Sch+21]. To define how significant a single station in a specific canton is, we applied a 5-km buffer around the station as depicted in Figure 3. By overlying raster data about population densities from the Socioeconomic Data and

Applications Center (sedac) [UN], we utilized the software ArcGis to calculate the mean population density inside each buffer. The selected data from sedac was for the year 2010 and on a resolution of 1 km. We weighted the stations per population density. A station in a scarcely populated area gets a smaller significance value (significance value between 0 and 1) than a station in a city. The significance values for all stations in a canton add up to 1. The significance values per station were now applied to the station data set. Therefore, the temperature and humidity variables reflect a mix of the monitor stations in the same canton, weighted with their respective significance values. This accounts for the population exposure, which is what is ultimately relevant for our study purpose.

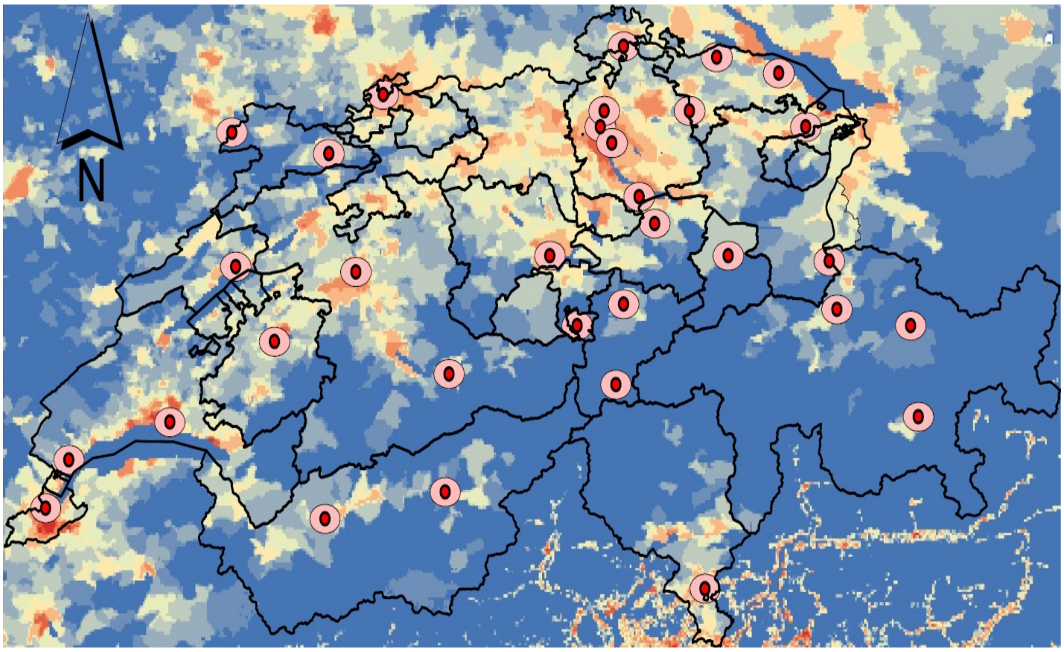


Figure 3: Swiss cantonal map with all monitor stations (meteoswiss) and population densities for 2010 (sedac). The color gradient *blue* to *red* describes the increase in population density from low (rural) to high (urban areas) population density.

2.1.2 Dealing with missing values

A common task in statistical analyses is to deal with information gaps in the data. In the Swiss cantonal data from 1989 to 2018, there are missing values for both the temperature and humidity variables in the time series.

For the stations in the cantons Solothurn (Gösgen) and Aargau (Beznau) there are missing values for partial pressure from 1989-01-01 to 2008-06-03. Those values were imputed by the observations of the closest monitor (Zollikofen). There are 7873 missing values for maximum temperature in the canton of Uri (Andermatt). We abstained from imputing values here. We listed the missing values of our meteorological values in the supporting information A.2.1. We presuppose a complete track of death counts, since there was only an entry in death counts whenever at least one death occurred. We did abstain from further imputing any missing values in the data.

2.1.3 Data description

For Zurich canton, the daily mean summer temperature was between 3.6-27.8°C and the daily maximum temperature was in the range of 6.0-36.4°C. For humidity, daily mean partial pressure was in the range of 5.4-21.7 hPa, while daily mean RH was between 37.5-97.7%.

				Summer distribution of temperature and humidity: mean (mininum, maximum)			
Canton	**N**	**Period**	**Deaths**	**Tmax**	**Tmean**	**ParPres mean**	**RelHum mean**
Zuerich	3	1989-2018	124326	22.0 (6.0, 36.4)	16.6 (3.6, 27.8)	13.7 (5.4, 21.7)	71.8 (37.5, 97.1)
Geneva	1	1989-2018	37433	23.7 (8.2, 39.7)	18.0 (5.4, 29.5)	13.6 (5.4, 21.3)	65.8 (28.5, 94.5)
Valais	2	1989-2018	26843	24.5 (5.4, 37.5)	17.9 (4.2, 28.4)	13.1 (5.4, 20.3)	63.1 (36.0, 97.2)
Ticino	1	1989-2018	32595	24.3 (9.7, 35.9)	19.8 (7.2, 28.5)	15.8 (3.8, 27.5)	68.0 (22.0, 98.4)
Basel-Stadt	1	1989-2018	27268	23.1 (7.6, 38.6)	17.6 (5.5, 29.2)	14.2 (6.0, 22.7)	70.0 (36.2, 98.9)

Table 1: Distribution of key variables by selected cantons. N is the number of monitor stations per canton. The minimum and maximum temperature and humidity values are those for the canton, and not the individual monitor station values.

2.2 Excess mortality method

We selected three extended summers (May-September) within the observational period from 2000 to 2018. We wanted to select three particularly hot summers that were: 2003, 2015 and 2018. The number of daily deaths expected in a specific summer was estimated by extrapolating a quasi-Poisson regression model that was fitted to the (observed) daily deaths for the observation period of 2000 to 2018. Equation 3 explains this relationship.

$$log[E(Y_t)] = \alpha + s(t; \boldsymbol{\beta}) \tag{3}$$

Y_t: outcome
α: y-intercept
$s(t; \boldsymbol{\beta})$: linear term (long term), sine and cosine term (seasonality)

The trends in the fit were controlled by a linear function of time for the long-term trend, and controlled by a trigonometric polynomial function of sine and cosine terms for the seasonal trend. The trigonometric polynomial terms were chosen for a one-year period, according to the method Vicedo et al. 2016 [Vic+16] and the Akaike's information criterion [Aka74] called the best choice.

2.2.1 Percentage of excess mortality

We calculated the number of excess deaths per day by subtracting the expected deaths from the observed number of deaths. The percentage of excess mortality (Equation 4) is the excess deaths divided by the number of expected deaths.

$$excess\ mortality \ = \ \frac{observed\ deaths \ - \ expected\ deaths}{expected\ deaths} \cdot 100\% \qquad (4)$$

We illustrated the percentage of excess mortality for each day in the specific summer.

2.2.2 Extreme value statistics: 90$^{\text{th}}$ percentile exceedances

We defined a threshold of extreme hot and humid conditions as the 90$^{\text{th}}$ percentile of respective summer distributions of 2000 to 2018 as suggested by Buzan et al. 2015 [BOH15]. A threshold-exceedance of temperature was defined as a *hot day*, of humidity as a *humid day*, and for both variables at the same time as a *compound day*. We accounted for lagged effects in mortality as suggested in Gasparrini et al. 2015 [Gas+15] by defining the three consecutive days of a threshold exceedance as a hot/humid/compound day as well. For Zurich canton, this threshold is 29.1°C for maximum temperature and 17.8 hPa for mean partial pressure. We depict in Figure 4 the counts of threshold exceedances for daily maximum temperature and daily mean partial pressure of humidity respectively.

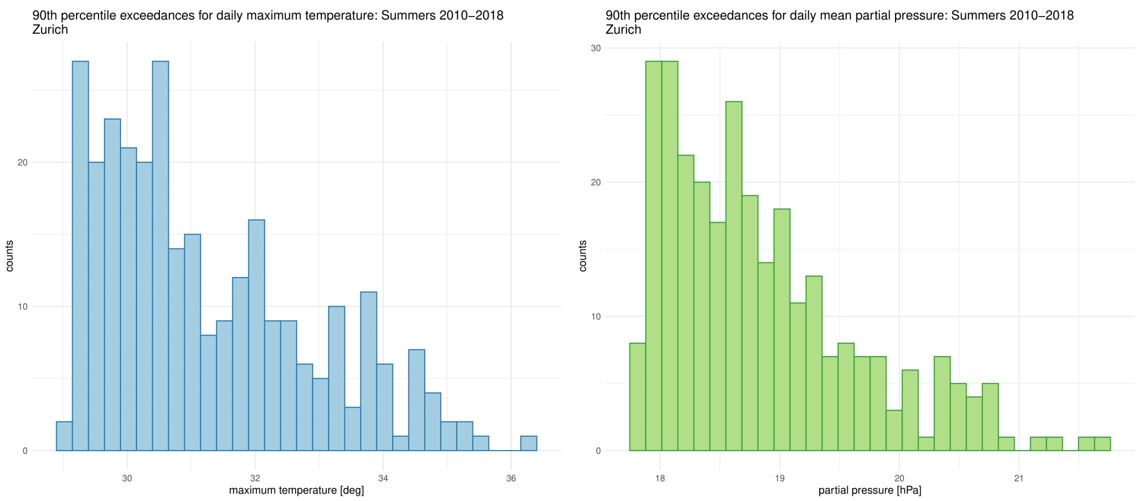


Figure 4: Threshold exceedances in daily maximum temperature *(left)* and mean partial pressure of humidity *(right)* for Zurich canton

2.2.3 Time series of environmental exposure

The illustration was complemented by a time series of daily maximum temperature and daily mean partial pressure humidity.

2.3 Exposure-response curves method

The method aims to quantify the health burden of all-cause mortality, attributable to high temperature and humidity exposure.

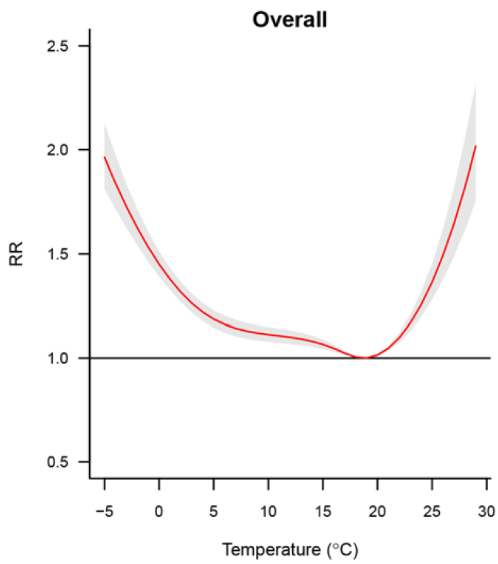


Figure 5: Overall cumulative mortality risk relative risk (RR) (*red*) and 95% confidence interval (*shaded area*) [VSG19]

$$log[E(Y_t)] = \alpha + f(x_t;\boldsymbol{\theta}) + s(t;\boldsymbol{\beta}) + \sum_{p=1}^{P} h_p(z_{pt};\boldsymbol{\gamma_t}) \quad [VSG19] \tag{5}$$

Y_t: outcome
α: y-intercept
$f(x_t;\boldsymbol{\theta})$: association with environmental exposure of interest x at time t
$s(t;\boldsymbol{\beta})$: baseline trend, capturing the confounders that change slowly over time
$h_p(z_{pt};\boldsymbol{\gamma_t})$: other confounders varying on a daily basis (e.g. day of the week)

We conducted a time series analysis to assess the temporal pattern in the all-cause mortality outcome and the environmental exposure. We explained the all-cause mortality outcome by the short-term variation in temperature and humidity exposures [Bha+13]. The distribution of all-cause mortality counts is discrete, and can be explained by a Poisson distribution. A Poisson distribution model trying to capture the distribution will not catch the variance independently of the mean of the distribution. Here, a model with additional parameters can better mach the overdispersed shape of the distribution. Therefore we applied a quasi-Poisson regression to the Swiss cantons, according to Equation 5, to estimate cantonal specific exposure response ratios, expressed as a risk ratio. The raw all-cause mortality is likely to be dominated by seasonality and by long-term trends [Bha+13]. We therefore wanted to remove those trends and applied a flexible spline function. This makes sure that the long term trend is captured and it allows for variations from one year to the next. We further adjusted for lagged effects in the regression. The day of the exposure, there are usually elevated mortality rates observed that overestimate the exposure effects because the incidence of deaths was brought forward in time. The delayed days usually show a protective effect, because vulnerable people already died. This phenomena is called harvesting [Gas+15]. Harvesting shifts the incidence of deaths forward in time. Taking this into account, the exposure series had to be shifted forward in time. This was done by using a *distributed lag non-linear model* (DLNM) [Gas11; GAK10]. The DLNM applies all lag models simultaneously and thus allows for adjustments to be made between the different lag effects on the (non-)linear model.

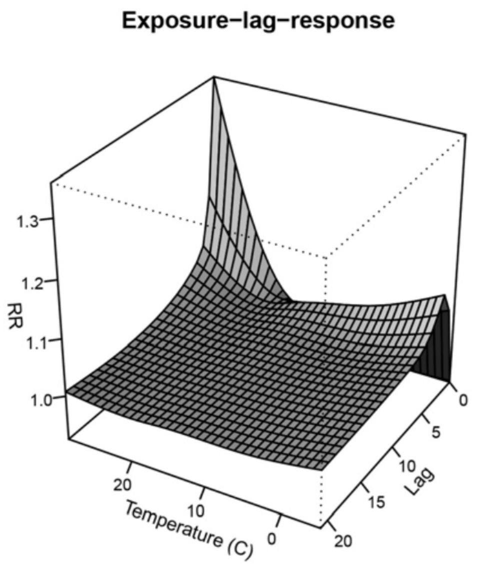


Figure 6: The exposure-lag-response, showing a sharp decrease in relative risk after 3 days. [VSG19]

The DLNM is defined by a cross-basis, which is a bi-dimensional functional space of the exposure-response space and lag-response space. Those are characterised by two sets of functions. The two sets of functions are potentially linear, polynomial, threshold, or spline functions. Using two sets of functions independently allows us to express the relationships of the outcome (all-cause mortality) with both the lag (days) an the exposure (temperature and humidity). These functions are combined via a special tensor product defined by a bi-dimensional cross-basis [GAK10]. A cross-basis was build for the crude maximum temperature and all-cause mortality association, and another two were build for the mean partial pressure humidity and all-cause mortality and the relative humidity and all-cause mortality association. The exposure effect was now estimated by using five different formula for the regression Equation 5. They all regress mortality as a function of some cross-basis, the day of the week and the seasonality. Formula 1 includes the maximum temperature cross-basis, formula 2 the mean partial pressure humidity cross-basis. Formula 3 includes both the maximum temperature and the mean partial pressure humidity cross-basis. Formula 4 includes the relative humidity cross-basis and formula 5 includes both the maximum temperature and the relative humidity cross-basis.

A chosen formula for the regression equation served to get a general linear model (glm), which was used for the cross-prediction. This contains the cantonal specific regression coefficients, and they explain the regional specific exposure-response association of temperature, humidity and mortality. The relative risk for temperature is expressed with respect to the *minimum mortality temperature* (MMT). The MMT is a canton specific parameter, corresponding to the temperature with the lowest relative risk (RR) or also known as the optimal temperature. Temperatures higher than the MMT are identified as heat exposure.

2.3.1 Best cross-basis model selection

As a preliminary step, we compared the quasi-Akaike information criterion (qAIC) [Aka74], summed over the previously selected cantons. The qAIC indicates goodness of fit and penalizes models with too much complexity at the same time. A lower value of qAIC indicates a better predictive ability of a model. We modelled the exposure-response association by different representation forms of a cross-basis for humidity alone and evaluated the model by qAIC. We next evaluated the qAIC for a fixed cross-basis for daily maximum temperature in combination with different forms of cross-bases of humidity in Figure 10.

We tested four functions for the humidity-response dimension:

- A linear function
- A natural-spline function with two internal knots (knots at the 50th and 90th percentile)
- A natural-spline function with one internal knot (knot at the 75th percentile)
- A threshold-function with a linear increase in effect after the 90th percentile

We applied five different functions to model the lag-response dimension:

- A B-spline function with one internal knot
- A strata function with the break at lag=1
- An integer function
- A natural-spline with one internal knot
- A strata function with two breaks at lag=1, and lag=3

In summary, the combination of the cross-basis for maximum daily temperature and the humidity cross-bases resulted in 20 models. An overview of the models can be inspected in the supporting information A.2.1.

We selected the model by the lowest value in qAIC for the combinations of temperature and humidity cross-bases as depicted in Figure 10 to run the analysis .

2.3.2 Time-response effect for humidity

Studies have shown that the temperature effect is relevant in the time-response space up to around 3 days [Gas+15; Arm+19].

2.3.3 Model with interaction term cross-basis

As a supplementary step, we looked into a model for temperature and humidity with an interaction term. With the interaction term models, we were interested in testing an observed effect on health by conditioning on either temperature or humidity. The method of regression is similar as previously explained in the previous chapters on the exposure-response curves. The novel element is how we represent the cross-bases for temperature and humidity. We created a *dummy-variable* a=[0,1] for humidity first. This dummy variable would have the value 1 if the conditions were very wet (>90^{th} percentile of humidity distribution), and 0 otherwise. The dummy variable was now multiplied with the cross-basis, and made sure to evaluate the days with wet conditions and the respective temperature effect only.

Second, we conditioned on temperature and and created a dummy variable with the value 1 for very hot conditions (>90^{th} percentile of temperature distribution), and 0 otherwise. The dummy variable was multiplied with the cross-basis, and thus only the humidity effect during hot days was evaluated.

3 Results

Here, we report the results on excess mortality, and on the the exposure-response curves. The cantonal specific results reported here are for Zurich canton. Further results for the cantons of Basel-Stadt, Ticino, Valais and Geneva can be inspected in the supporting information A.2.2.

3.1 Excess mortality

The observed weekly deaths for Zurich canton from 2000 to 2018 in Figure 7 are between 69 and 319 counts, while the average weekly death counts for Zurich canton are 201.

Figure 8 compares observed weekly mortality for the summers 2003, 2015 and 2018. Weekly mortality in the extended summer varies from 182 to 202 counts on average for 2000 to 2018. For the summers 2003, 2015 and 2018 the total number of deaths is 12'813. The weekly mortality has some spikes in the time series. The maximum observed weekly mortality for summer 2003 is in mid-August with 234 death counts, for summer 2015 in mid-July with 225 death counts, and for 2018 in early August with 233 death counts. The average weekly mortality for summers 2003, 2015 and 2018 is with 195, 198 and 196 death counts equivalently high in comparison to the average weekly mortality of all years from 2000 to 2018 with 190 death counts.

3.1.1 Seasonal excess mortality

Figure 9 depicts the seasonal excess mortality for 2018. We investigated the summers of years 2003, 2015 and 2018. The red bars in Figure 9 illustrate the relationship of observed and expected deaths. This is represented by the percentage of daily excess mortality. The plot is restricted to the extended summer months of May, June, July, August and September. For descriptive and comparative purposes, we added the temperature series of daily maximum temperature in orange, and the daily series of mean partial pressure in blue. Orange shades correspond with an exceedance of the 90^{th} percentile in maximum temperature and thus a hot day. Blue shades indicate the exceedance of the 90^{th} percentile in mean partial pressure and thus correspond with a humid day. The temporal co-occurrence corresponds to a compound hot-humid day, indicated by a grey shade. We also expanded the shades of extreme exposure up to three days after the last exeedance of the threshold to account for lagged effects [Gas+15; Arm+19; Vic+16].

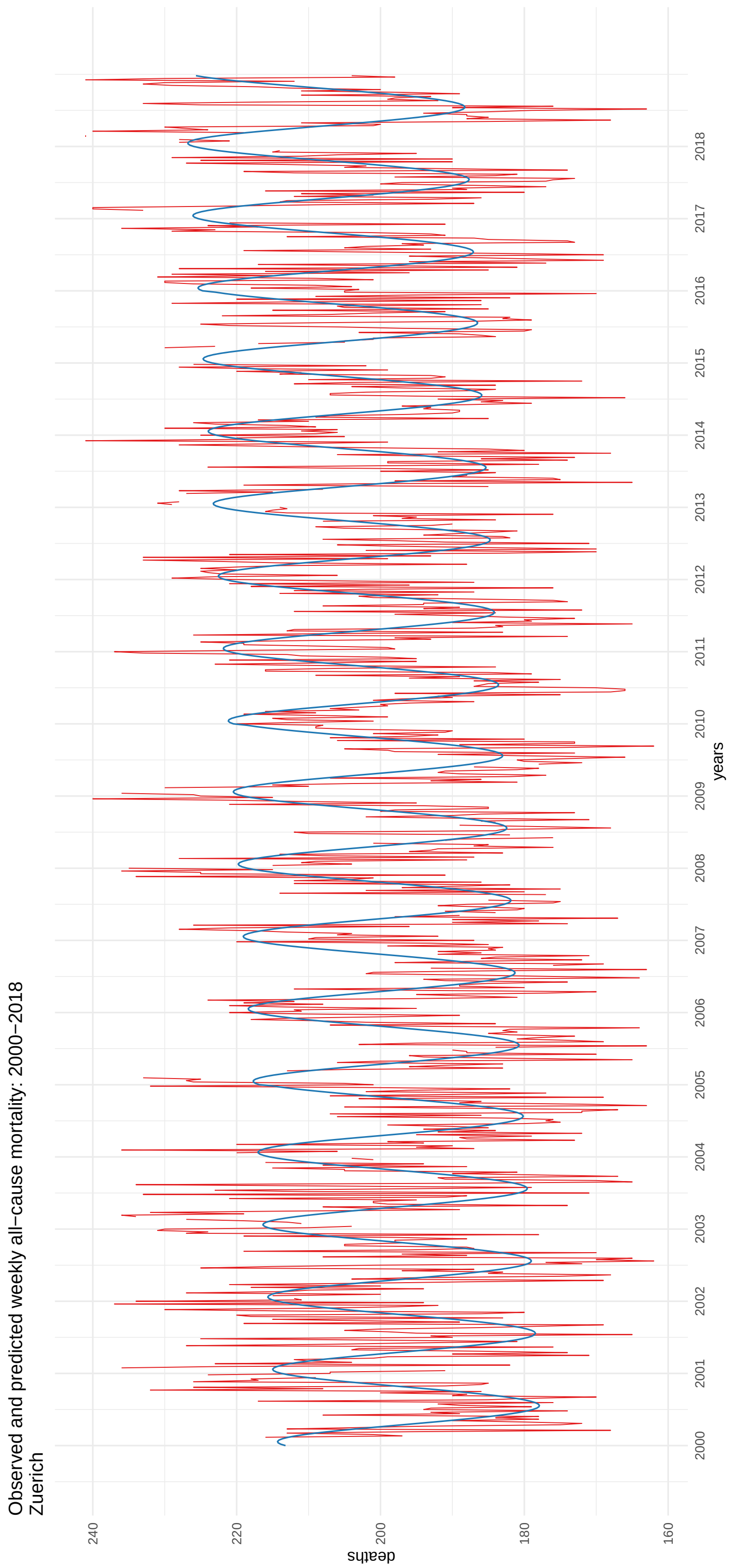


Figure 7: The observed weekly mortality counts in *red* and the predicted weekly mortality counts in *blue* for Zurich canton restricted to the period from 2000 to 2018

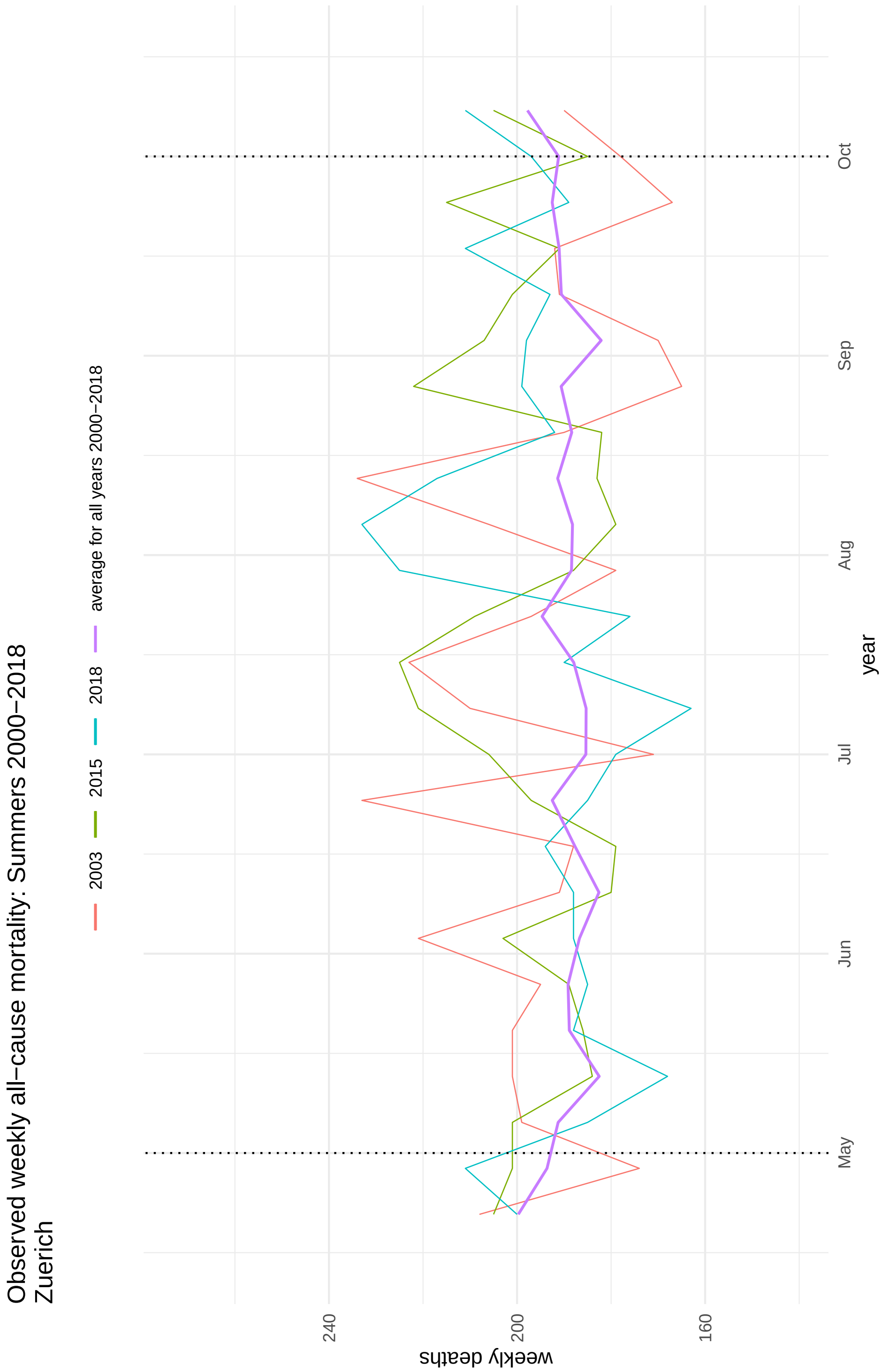


Figure 8: The observed weekly mortality for Zurich canton. A dashed black vertical line marks the period of the extended summer, which includes the months of May, June, July, August and September. The weekly time series of observed mortality counts depicts the years 2003, 2015, 2018 and the average for all years 2000-2018.

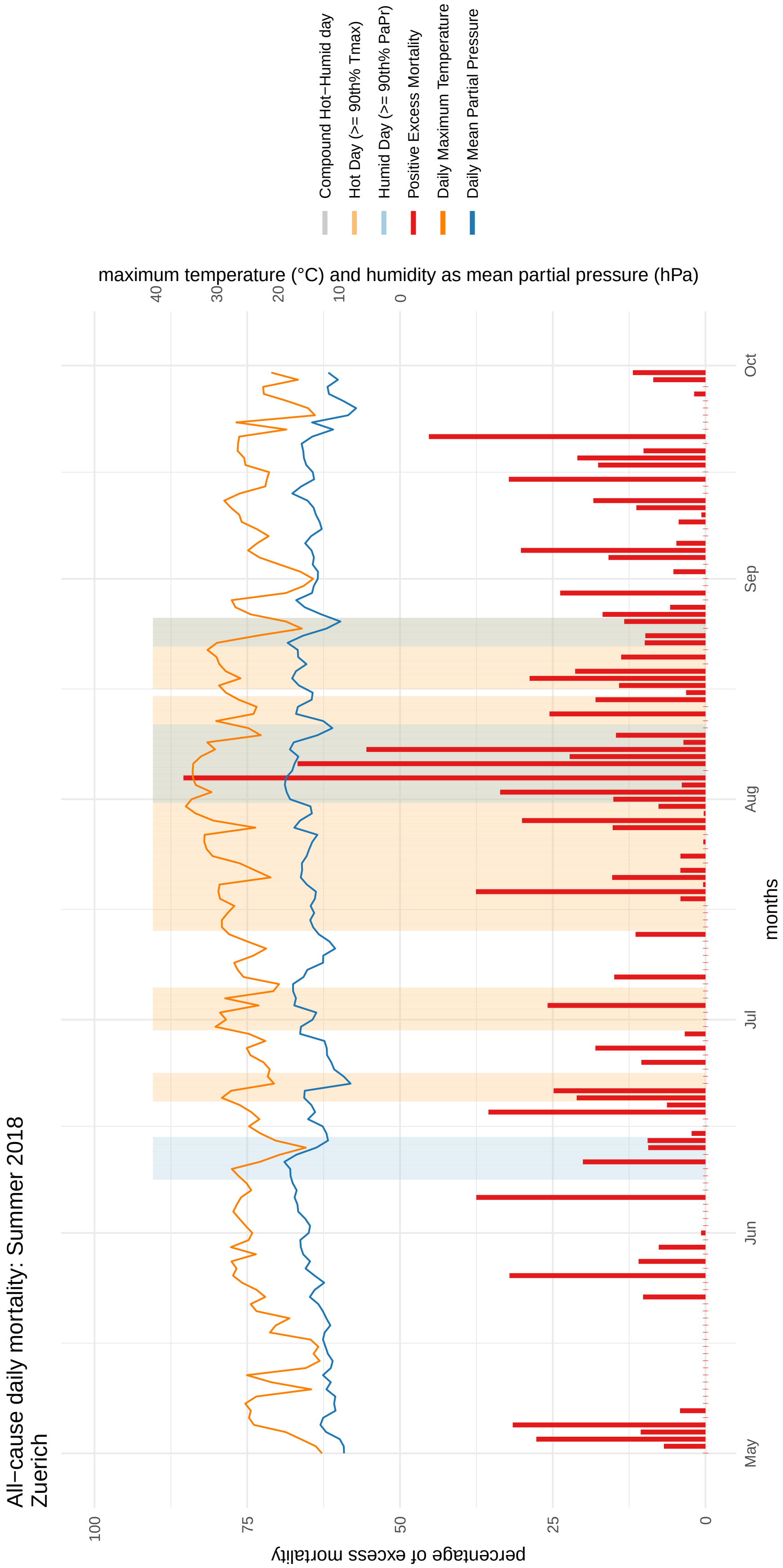


Figure 9: The excess mortality plot for the summer of 2018 for Zurich canton

3.1.2 Percentage of excess mortality

We report our findings for the excess mortality in Table 2. We therefore compare averaged percentages of excess mortality for different exposures (compound hot-humid day, hot day, humid day, average summer day).

Canton and Year	**Compound Day**	**Hot Day**	**Humid Day**	**Average Summer Day**
Zurich-2003	12.9	12.4	11.1	6
Zurich-2015	16.1	9	13.5	3.2
Zurich-2018	20.9	5.2	15.9	0.4
Geneva-2003	11.4	24	14.5	14.6
Geneva-2015	25.1	14.6	20.5	4.5
Geneva-2018	8	0.7	0.6	1.3
Valais-2003	14.6	14.8	5.8	1.4
Valais-2015	7.5	5.9	6.3	3.1
Valais-2018	7.4	9.2	5.4	1.8
Ticino-2003	12.4	8.9	7.5	3
Ticino-2015	32.7	23.4	29.4	6.2
Ticino-2018	3.8	0.6	-1.6	-1.9
Basel-Stadt-2003	33.1	29.1	31.5	13.4
Basel-Stadt-2015	18.9	18.3	22.7	8.8
Basel-Stadt-2018	32.6	10.7	11.4	-0.8

Table 2: Table with the exposure-specific percentage [%] of excess mortality

Our results suggest that for Zurich canton, the exposure to a compound day in the years 2003, 2015 and 2018 altogether results in 16.7% excess mortality. The exposure to a hot day results in 8.9% excess mortality in comparison to 3.2% for an average summer day.

Summarizing the results over the five cantons (Zurich, Geneva, Valais, Ticino and Basel-Stadt) and three years (2003, 2015 and 2018) investigated, the percentage of excess mortality was:

- Compound day: 17.2%
- Hot day: 12.5%
- Average summer day: 4.3%

3.2 Exposure-response curves

The exposure-response curves are reported for the summers from 1989 to 2018.

3.2.1 Best cross-basis model selection

The result in Figure 10 indicates that *model 5* is the best representation of a humidity cross-basis. It has a linear variable-response function and a strata function with break at lag=1 for the time response.

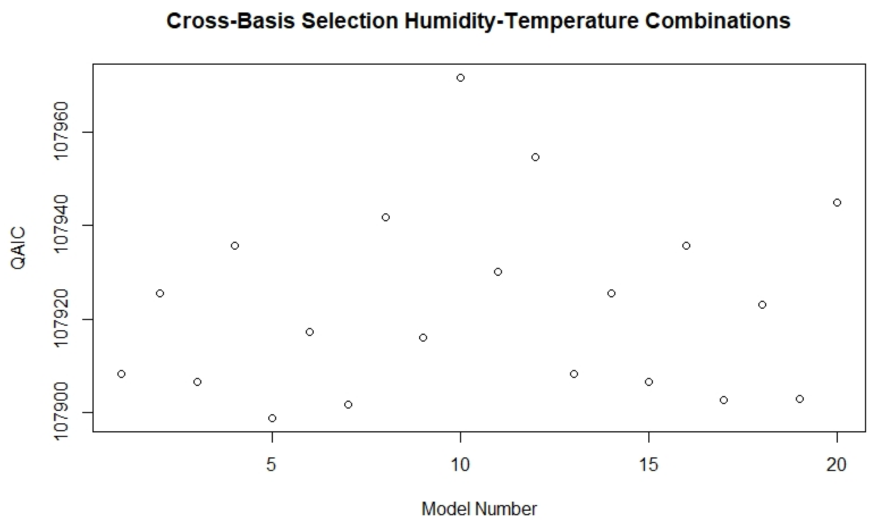


Figure 10: The qAIC score for the models with a fixed cross-basis for temperature with different forms of cross-bases for humidity

3.2.2 Time-response effect for humidity

We investigated the time-response effect for humidity and looked at the delayed effects up to 10 days in Figure 11. The immediate effect of an increase above the 1.0 relative risk line is followed by a drop in relative risk for the following 4 days. The relative risk reaches the 1.0 relative risk line again at about 5 days of lag.

We set the maximum lag-days investigated to 5, depicted in Figure 12. This covers the main immediate effect that is suspected to be amplified by the effect of harvesting and the protective effect during the upcoming days that moderate the overall relative risk effect of humidity exposure.

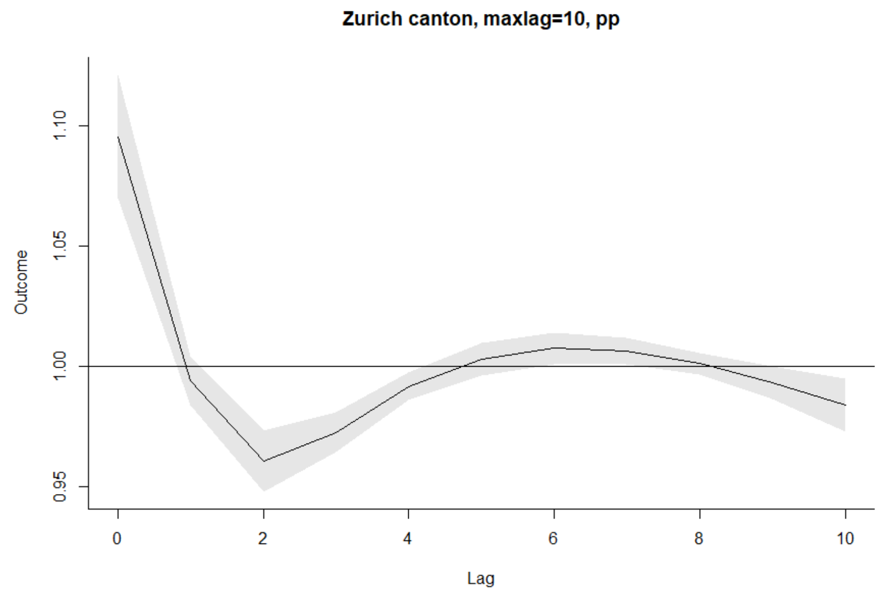


Figure 11: The lag-response association in terms of relative risk and 95% confidence interval (*shaded area*), with an integer model within 10 days after exposure for a humidity cross-basis for Zurich canton

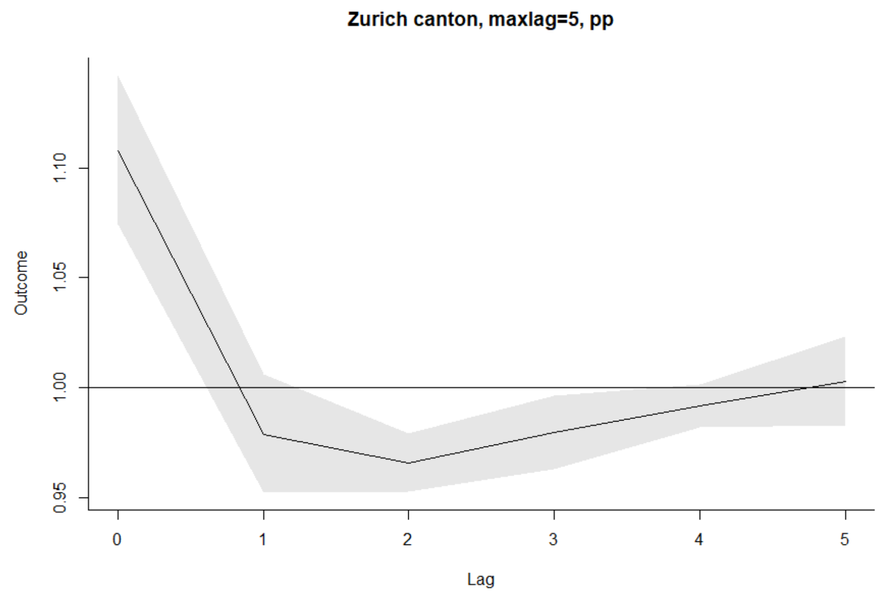
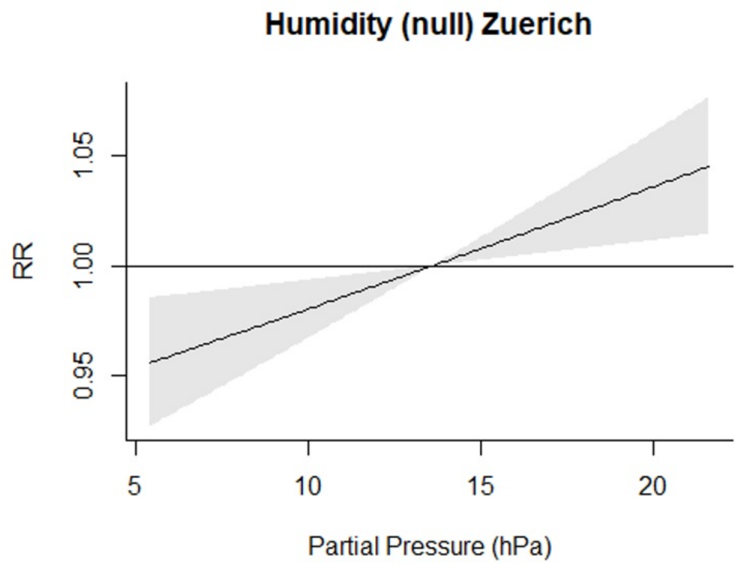


Figure 12: The lag-response association in terms of relative risk and 95% confidence interval (*shaded area*), with an integer model within 5 days after exposure for a humidity cross-basis for Zurich canton

3.2.3 Exposure-response curves for humidity without temperature

In Figure 13, we plot a cumulative relative risk (RR) exposure-response and lag-response over the lags 0-5 for mean partial pressure humidity.

a)



b)

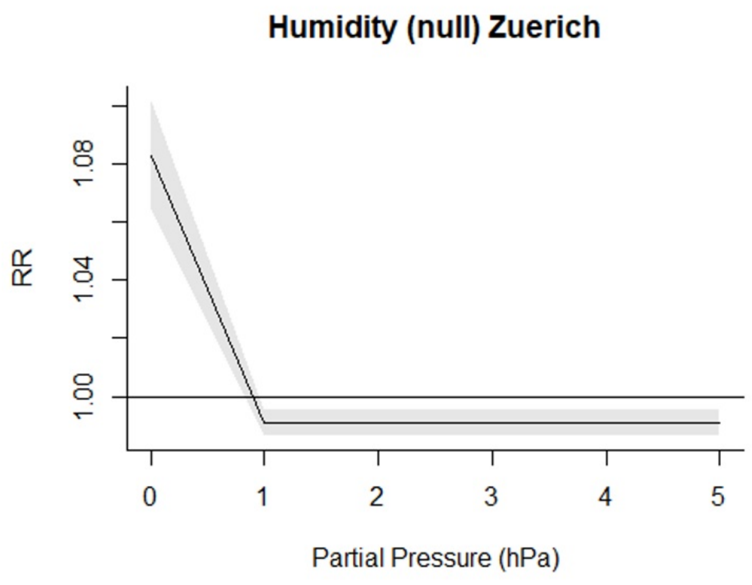
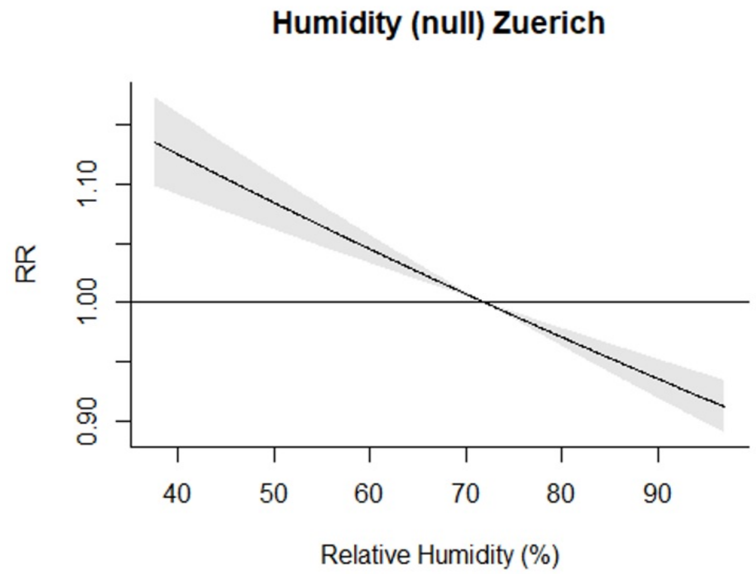


Figure 13: **a)** Exposure-response and **b)** time-response in terms of relative risk and 95% confidence interval (*shaded area*), for mean partial pressure of humidity for Zurich canton with model 5

The results for the overall relative risk (RR) in the selected cantons are reported in Table 3 in Chapter 3.2.5 .

We investigated in Figure 14 the effect with the other variable: relative humidity.

a)



b)

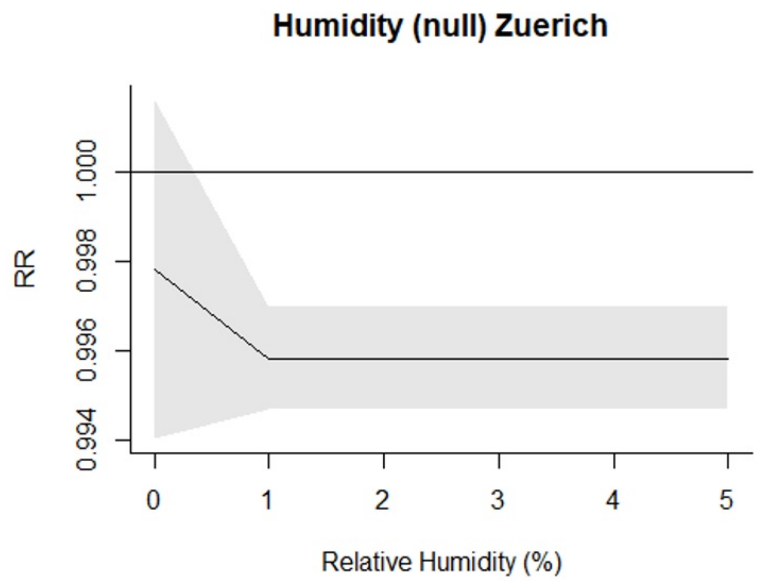


Figure 14: **a)** Exposure-response and **b)** time-response in terms of relative risk and 95% confidence interval (*shaded area*), for mean relative humidity for Zurich canton with model 5

The results for the overall relative risk (RR) in the selected cantons are reported in Table 4 in Chapter 3.2.5 .

The selected cantons showed an increased relative risk with increasing partial pressure humidity, while the relative risk was decreasing for increased values in relative humidity. For relative humidity, the confidence intervals for the exposure-response curves cross the 1.0 effect-line. This moderates the protective effect of increased relative humidity on all-cause mortality. For partial pressure humidity, the relative risk ratios increased with increasing humidity throughout all selected cantons. Only for Valais canton, we did not observe evidence for an increased effect of partial pressure humidity on all-cause mortality. The magnitude of increase in relative risk is rather moderate with an increase of all-cause mortality of 0.5-0.9% per 10 percentiles increase humidity.

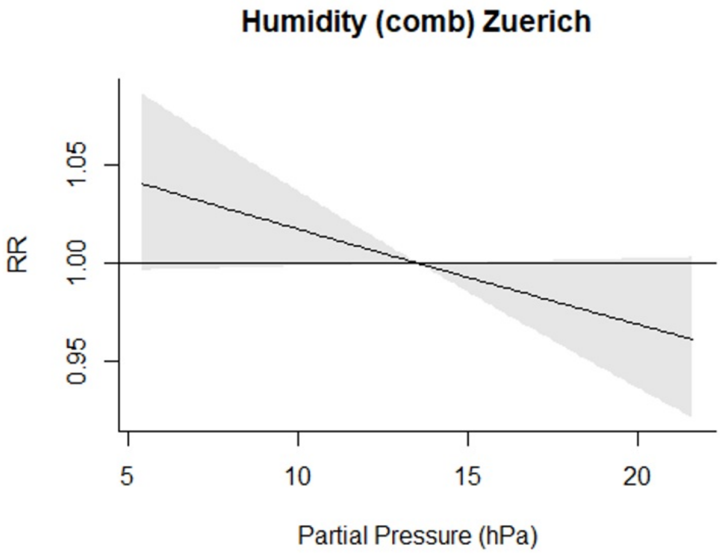
The different sign in the relative risk ratios for partial pressure and relative humidity demanded further examination. We therefore investigated the co-occurence of hot-humid conditions by summer-seasonal scatterplots that can be inspected in the supporting information A.2.2. We observed, that the days with highest temperatures did not correspond to high values in relative humidity. However, partial pressure humidity was higher during the warmest days.

3.2.4 Exposure-response curves for humidity with temperature

Temperature plays an important role in the heat stress and mortality exposure-response association. Therefore we now investigated the effect of humidity with having a cross-basis representation for humidity and temperature in the regression Equation 5.

The results for daily mean partial pressure humidity in combination with daily maximum temperature are depicted in Figure 15.

a)



b)

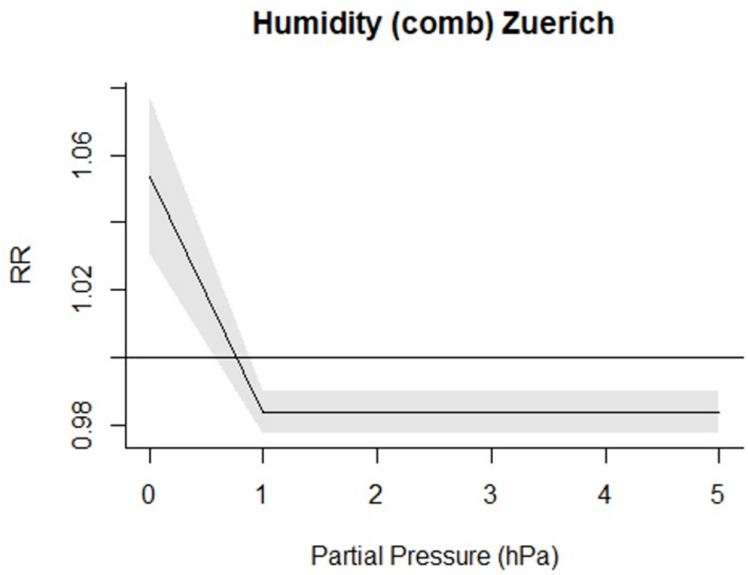
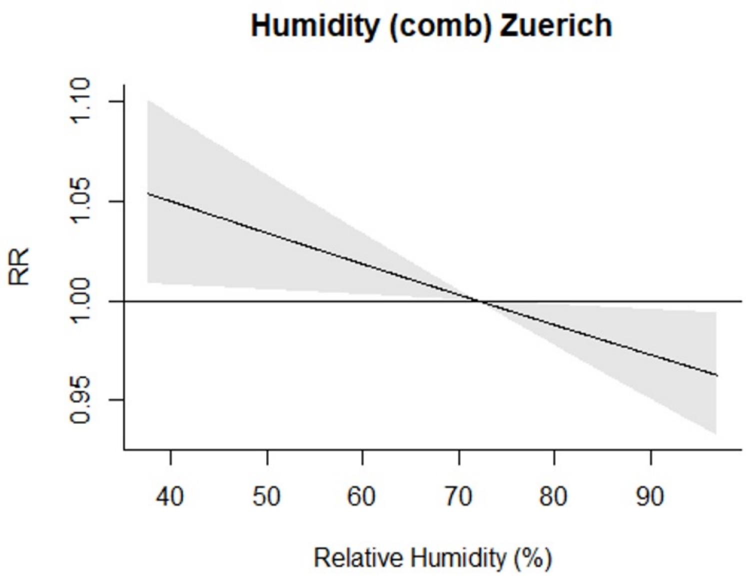


Figure 15: **a)** Exposure-response and **b)** time-response in terms of relative risk and 95% confidence interval (*shaded area*), for mean partial pressure humidity in combination with daily maximum temperature for Zurich canton

The results for daily mean relative humidity in combination with daily maximum temperature are depicted in Figure 16.

a)



b)

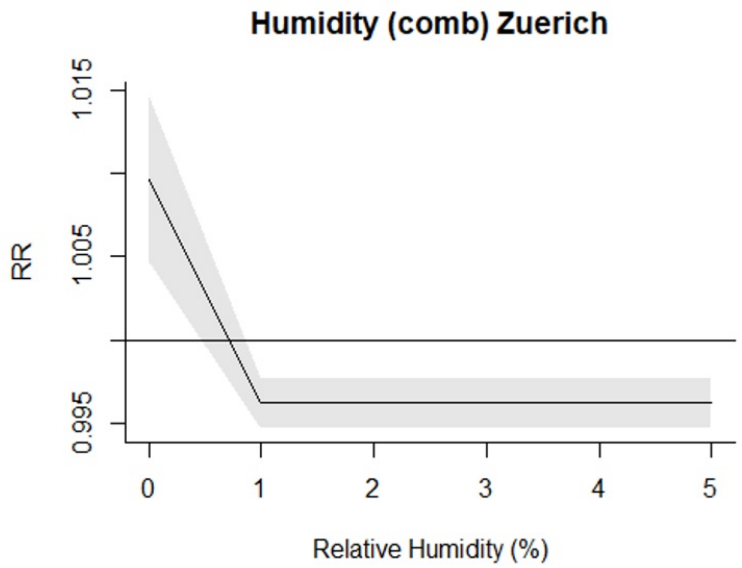


Figure 16: **a)** Exposure-response and **b)** time-response in terms of relative risk and 95% confidence interval (*shaded area*), for mean relative humidity in combination with daily maximum temperature for Zurich canton

The results for the overall relative risk (RR) in the selected cantons are reported in Table 5 in Chapter 3.2.5 .

3.2.5 Relative risk ratios summary

Here we report the summary of the relative risk ratios. For humidity, it is reported as the increase of RR within 10 percentile units of increase in the respective humidity unit (e.g. between the 50-60th percentile of the partial pressure humidity distribution). For temperature it is the relative risk at the 99th percentile of the maximum temperature distribution.

Canton	**CB Partial Pressure (null)**	**CB Partial Pressure (combination)**
Zuerich	1.00502 [1.00163 - 1.00843]	0.99556 [0.99078 - 1.00037]
Basel-Stadt	1.01135 [1.00466 - 1.01810]	1.00540 [0.99620 - 1.01468]
Ticino	1.00879 [1.00276 - 1.01484]	1.00199 [0.99482 - 1.00922]
Valais	1.00614 [0.99919 - 1.01313]	1.00302 [0.99384 - 1.01230]
Geneva	1.00786 [1.00255 - 1.01320]	0.99965 [0.99227 - 1.00708]

Table 3: The relative risks and 95% confidence interval per canton for a crude mean partial pressure humidity model, and in combination with maximum temperature

Canton	**CB Relative Humidity (null)**	**CB Relative Humidity (combination)**
Zuerich	0.98757 [0.98434 - 0.99081]	0.99486 [0.99058 - 0.99916]
Basel-Stadt	0.99538 [0.98916 - 1.00164]	1.00439 [0.99613 - 1.01271]
Ticino	0.99888 [0.99437 - 1.00341]	1.00157 [0.99655 - 1.00662]
Valais	0.99475 [0.98788 - 1.00168]	1.00118 [0.99228 - 1.01015]
Geneva	0.99020 [0.98477 - 0.99565]	1.00154 [0.99509 - 1.00803]

Table 4: The relative risks and 95% confidence interval per canton for a crude mean relative humidity model, and in combination with maximum temperature

Canton	**CB Maximum Temperature (null)**	**CB Maximum Temperature and Partial Pressure (combination)**	**CB Maximum Temperature and Relative Humidity (combination)**
Zuerich	1.32 [1.23 - 1.41]	1.35 [1.25 - 1.45]	1.29 [1.2 - 1.38]
Basel-Stadt	1.36 [1.18 - 1.57]	1.33 [1.14 - 1.54]	1.39 [1.19 - 1.62]
Ticino	1.21 [1.07 - 1.37]	1.21 [1.06 - 1.37]	1.22 [1.08 - 1.38]
Valais	1.19 [1.03 - 1.37]	1.17 [1.01 - 1.36]	1.19 [1.03 - 1.39]
Geneva	1.29 [1.14 - 1.46]	1.29 [1.13 - 1.46]	1.30 [1.14 - 1.47]

Table 5: The relative risks and 95% confidence interval per canton for a crude maximum temperature model, and in combination with mean partial pressure humidity and mean relative humidity

The effect of humidity on all-cause mortality alone suggest some evidence for an increased relative risk. Including temperature in the model moderated the effect of humidity by such that there was now no evidence of an increase in relative risk of all-cause mortality. This result is uniform for all cantons and for the variables partial pressure and relative humidity.

The effect of temperature on all-cause mortality shows the expected pattern of a non-linear increase for highest temperatures as reported previously by several studies [Gas+15; Ser+19; Sco+18; Bao+16].

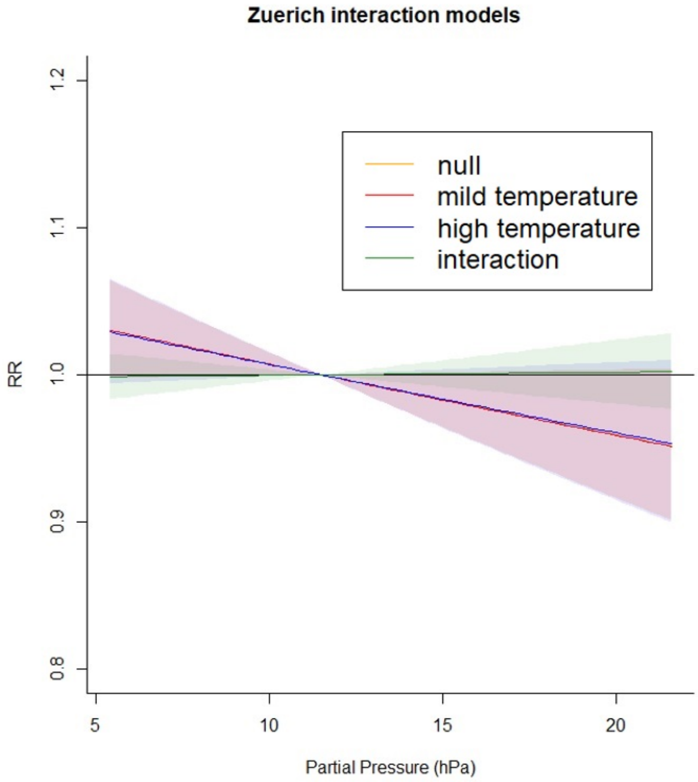
Now, we compared the effect of temperature with, and without having humidity in the regression model. The effect of temperature changed very little if humidity was in the model or not. The change in best estimate relative risk at the 99$^{\text{th}}$ percentile was as little as 0-3% for the selected cantons.

3.2.6 Exposure-response curves for model with interaction term

We first conditioned on temperature by evaluating the effect of humidity only for days where temperature exceeded the 90$^{\text{th}}$ percentile. The result depicted in Figure 17 a) shows no change in effect after conditioning. Therefore, we can assume the effect of humidity to be equally informative across the whole summer than on the hot days only.

At last, we conditioned on humidity to assess the temperature effect. We evaluated the effect of temperature only on days that were very humid. The results show potentially increased risks in the temperature range of 26-33°C. The broadness of the confidence interval makes it hard to draw a conclusion from those results though.

a)



b)

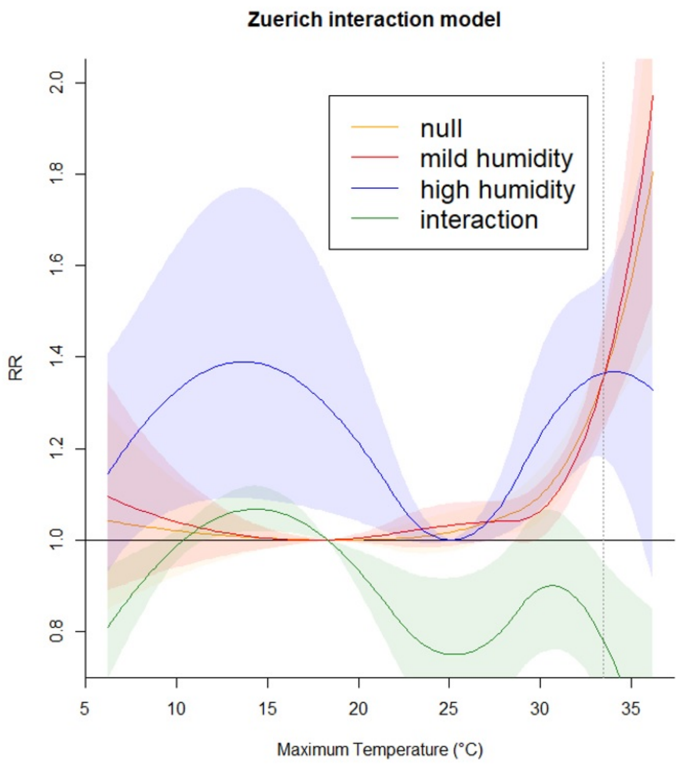


Figure 17: **a)** Mean partial pressure humidity and **b)** maximum temperature interaction model exposure-association in terms of relative risk and 95% confidence interval (*shaded area*), for Zurich canton

4 Discussion

We showed that extreme compound hot- and humid conditions with respect to hot conditions coincided with higher excess deaths across Switzerland. We found that this effect is most visible for the evaluated summers of 2003, 2015 and 2018 in Zurich canton. Although, our results on the exposure-response association show that the associated increase in relative risk is negligible for extreme humid conditions. We confirm the slight protective effect of humidity as expressed by relative humidity as shown in Armstrong et al. 2019 [Arm+19]. But we highlight the importance of choosing an adequate representation of humidity and advice future epidemiological studies to use a humidity expression with smaller temperature-dependence than relative humidity. Our results imply that temperature is a sufficiently strong indicator for the quantification of heat-related health risks in Switzerland. Accordingly, the Swiss heat warning system is now based up on the daily mean temperature. We further discuss and compare our findings with previous studies in the following sub chapters.

Excess mortality

The extended summer days (May-September) of 2003, 2015 and 2018 in Zurich canton were associated with an estimated increase in all-cause excess mortality of 3.2% on average. The increase in excess mortality followed a pattern of extreme warm days, with 8.9% as the average excess mortality percentage for hot days. Adding the exposure to humid conditions on top, the average excess mortality for a compound hot-humid days was 16.7%. A previous study by Grize et al. 2005 [Gri+05] investigated the excess-mortality percentage during summer 2003 (June - August) in Switzerland. They reported an overall 6.9% (95% CI: 4.9-8.8%) of excess mortality for Switzerland. Our result for Zurich canton in 2003 (May - September) with an average excess mortality is 6.0% and within that confidence interval. Higher excess mortality were found in our result in accordance with Grize et al. 2005 for Basel-Stadt and Geneva. Another previous study by Vicedo et al. 2016 [Vic+16] investigated the excess-mortality percentage during summer 2015 (June – August) in Switzerland. They found and overall 5.4% (95% CI: 3.0-7.9%) of excess mortality for Switzerland. Our result for Zurich canton in 2015 (May – September) with an average excess mortality is with 3.2% within that confidence interval. The other selected cantons in our study confirm the magnitude in excess-mortality percentage found by Vicedo et al. 2016. Although the lengths of the summer periods investigated differ, we confirm the finding that excess mortality was a only a little lower for 2015 in comparison to 2003 in Switzerland. Compound hot-humid conditions coincide with higher excess mortality percentages than just hot days in Zurich canton, and this is supported by the results in the cantons of Basel-stadt, Valais, Ticino and Geneva in Table 2.

Strong positive excess mortality periods occured at different times of the summer season across the Swiss cantons. Some cantons already experienced a first peak in excess mortality in July, others had their peaks in the second half of the summer month. We could observe for the summers, that a sequence of extreme heat resulted in a more pronounced peak for the first period with respect to the following periods. A study by Spangler et al. 2021 [SW21] investigated summer temporal and intraseasonal heat mortality risks in the US. They reported a decrease in late-season mortality between two decades, 1973-1982 and 1997-2006. But the early-season heat mortality risk has persisted and not changed by much, as they report. We agree with our results with those findings.

We compared the excess mortality of summer 2015 with the summer 2003, and we found an overall decrease of excess mortality for the summer 2015 across all cantons. While some cantons had still a high excess mortality in 2015, others showed a less pronounced excess mortality rate. A possible reason for that could be the adaptation to heat exposure by a higher resilience of the population and a lower overall vulnerability. Sera et al. 2020 [Ser+20] investigated the effect of air conditioning and heat-related mortality. They showed an independent association between increased prevalence of air conditioning and lower heat-related mortality risk. They conclude that other factors have equal or more important roles in increasing the resilience of populations.

Other reasons might include differences in the demographic structure or an overall decrease in heat vulnerability by an increase in socio-economic status. Grize et al. 2005 [Gri+05] reported that prior to the European heat wave of 2003, only Ticino and Geneva had some sort of heat warning system in place. This changed between 2003 and 2015 with the implementation of a national heat warning system in 2005 [Meta]. Until 2020, the Swiss heat warning system was based on the Heat Index (HI), a mixed temperature and humidity metric. Nowadays, the warning systems is based on the daily mean temperature. The implementation of a national heat warning system is another factor that could explain further the reduced heat-mortality risk between 2003 and 2015.

Exposure-response curves

Across the investigated Swiss cantons, little information on the exposure-response association could be added when including a variable of humidity. The direction of the association of humidity and mortality was inconsistent, with a small protective effect for the variable of relative humidity, and a negligible or small increased effect for the variable of partial pressure humidity. The study by Armstrong et al. 2019 [Arm+19] reports similar results for relative humidity (decrease of 1.1% in mortality with an increase of 23% in relative humidity). The protective effect was made up by a positive coefficient at lag day 0, and outweighted by negative coefficients at lag days 1 to 3. Our results for the cantons of Zurich, Basel-Stadt and Ticino are in accordance with those findings, while cantons of Valais and Geneva differ in the coefficients sign with still an overall protective effect. The confidence intervals provide little evidence to draw further conclusions on the importance of the lag structure. Our best suggestion now is, that the temperature variable might describe the most important part of the exposure-response association.

Adding complexity with a humidity variable does not necessarily result in a more comprehensive model [May04]. Therefore we take the position of model simplicity when considering the modelling of heat-mortality associations. We further investigated the inconsistent humidity effect on mortality. We observed that the hottest days did not coincide with days of high relative humidity. In comparison, the hottest days coincided with higher values in partial pressure humidity. If we assume temperature plays the major role in the heat-mortality association, it becomes evident why relative humidity shows a protective effect.

Regarding the interaction model, we see potential in evaluating the effect of temperature with a humidity interaction model in future studies and abstain from drawing a conclusion from our results in Figure 17 b).

Choice of humidity variable in health assessments

We observed more consistent results with the variable partial pressure than with relative humidity. The variable of relative humidity is strongly dependent on temperature [DME16]. In fact, the denominator as saturation vapor pressure varies exponentially with temperature. Adding relative humidity in a model thus adds little more information to a model that already contains some variable of temperature. We support the use of more absolute humidity variables such as partial pressure humidity, absolute humidity or specific humidity for health assessments.

Implications

In this study, we tested the hypothesis, that humidity in combination with high temperatures has higher adverse effects on all-cause mortality than high temperatures alone. We could not provide strong evidence to support this hypothesis for the observations in Switzerland. This contradicts the line of argumentation from physiology and climate sciences, that heat stress is greater if humidity is higher. Our results imply that for the current observed environmental conditions, humidity might not play an important role in Switzerland after all. Public health policy might focus on temperature to evaluate heat stress for the population at risk. Heat warning systems might perform as based on temperature alone. At the same time, this understanding is very likely to change the not so distant future. With climatic conditions becoming more hazardous for human health, critical thresholds of deadly heat will be approached [SH10]. It will be crucial to test the humidity effects again and to evaluate, if current results still hold in a world greater heat stress.

Limitations and strengths of this study

We want to acknowledge some limitations and point out the strengths of our study nevertheless. A first issue is, that the monitor stations of MeteoSwiss are typically at the outskirts of urban centres and therefore, micro-climatic conditions can hardly be assessed with the data we used here. The exposure of the population is another area where we see potential for improvement. A future study might account for the region specific association between ambient outdoor- and indoor conditions, estimate the time spent indoors and outdoors and eventually be more precise in assessing the actual exposure.

Another issue is that low power in data and the small difference in excess mortality percentage between hot-humid and hot conditions does not provide strong evidence to draw conclusions on whether humidity clearly adds on the heat exposure risk. A follow-up project here is to include Bayesian statistics in order to quantify the uncertainty in the excess mortality percentages. This method has been applied in previous studies investigating the excess mortality due to the covid-19 pandemic [Big+20].

There is another general point to make on the excess mortality study. It is important to note that the environmental exposure for the excess mortality method was not part of the regression equation. Therefore we abstain from taking any strong association between the environmental exposure and the all-cause mortality. We can merely describe, how well those two coincide without providing a causal relationship. Nevertheless, this study supports the idea that compound hot-humid conditions might be slightly deadlier in the Swiss cantons investigated.

A major strength of our study is that we synthesize knowledge from research fields to provide a more holistic view on heat stress risks related with climate change.

4.1 Outlook

More interdisciplinary research in collaboration with experts from physiology might lead to a clearer picture of the association. A PhD project will proceed the research on the effect of compound events on human health. The role of humidity within the topic of heat stress will be investigated by:

- Health impact assessment of past heatwaves in Europe, accounting for humidity contribution
- Test the combined effect of temperature and humidity on elderly, assessment on the individuals 2010 to 2019 (Bern)
- Assess if humidity is relevant for hospitalizations

A publication by Dr. Ana M. Vicedo-Cabrera (*in preparation*) will summarize the methods in the fields of climate sciences, physiology, and environmental epidemiology used to assess the effect of compound events on human health. The same study will also name the challenges of approaching the heat stress topic interdisciplinarily. Most importantly, the lack of an overall physical representation of the heat stress effect on human health limits the power of interpretation. We highlight that more advances in the process-based understanding of physiological responses to heat can lead to a clearer picture of the heat-mortality association.

4.2 Conclusion

This thesis provides an overview of heat related mortality in Switzerland in the years 1989 to 2018. We investigated the role of humidity in association with high temperatures on health outcomes. We introduced the research fields of physiology, climate sciences and environmental epidemiology. We show how all of these fields make important contributions to our understanding of heat stress and related health risks. Our results support the following conclusions: *First*, increased excess mortality was observed for hot-humid compared to hot conditions in Switzerland for the summers 2003, 2005 and 2018. *Second*, little evidence was found on the role of humidity variables in the exposure-response associations for the summers 1989-2018. *Finally*, temperature is a sufficiently strong indicator for quantifying the heat-related health risks in Switzerland.

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List of Figures

List of Tables

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A Appendix

A.1 Git-hub

Further results for the cantons of Basel-Stadt, Ticino, Valais and Geneva, as well as the R code can be inspected at:
https://github.com/ckestenholz/TempHumidity.

A.2 Supporting information

This contains supporting information for the main text as tables and figures .

A.2.1 Tables

Canton	Tmax	Tmean	Tmin	Par Pre	RH
Zurich	0	0	0	0	0
Bern	0	0	0	0	0
Luzern	0	0	0	0	0
Uri	3366 (7873)	0	0	0	0
Schwyz	0 (2)	0 (1)	0 (1)	0 (17)	18
Obwalden	0	0	0	0	0
Nidwalden	0	0	0	0	0
Glarus	0	0	0	0	0
Zug	0	0	0	0	0
Fribourg	65 (227)	67 (248)	66 (229)	66 (247)	67 (248)
Solothurn	12 (20)	12 (19)	12 (20)	0	12 (19)
Basel-Stadt	0	0	0	0	0
Basel-Landschaft	0	0	0	0	0
Schaffhausen	0	0	0	0	0
Appenzell Ausserhoden	0	0	0	0	0
Appenzell Innerhoden	0	0	0	0	0
St. Gallen	0 (17)	0 (15)	0 (15)	0 (17)	0 (17)
Graubuenden	0	0	0	0	0
Aargau	6 (10)	6 (8)	6 (10)	0	6 (8)
Thurgau	0	0	0	0 (12)	0 (12)
Ticino	0	0	0	0	0
Vaud	0	0	0	0	0
Valais	0 (1)	0	0 (1)	0	0
Neuchatel	0	0	0	0	0
Geneva	0	0	0	0	0
Jura	19 (19)	18 (18)	18 (18)	26 (26)	26 (26)

Missing values after imputting for the extended summer period (May-September) and year around (in brackets) for all Swiss cantons.

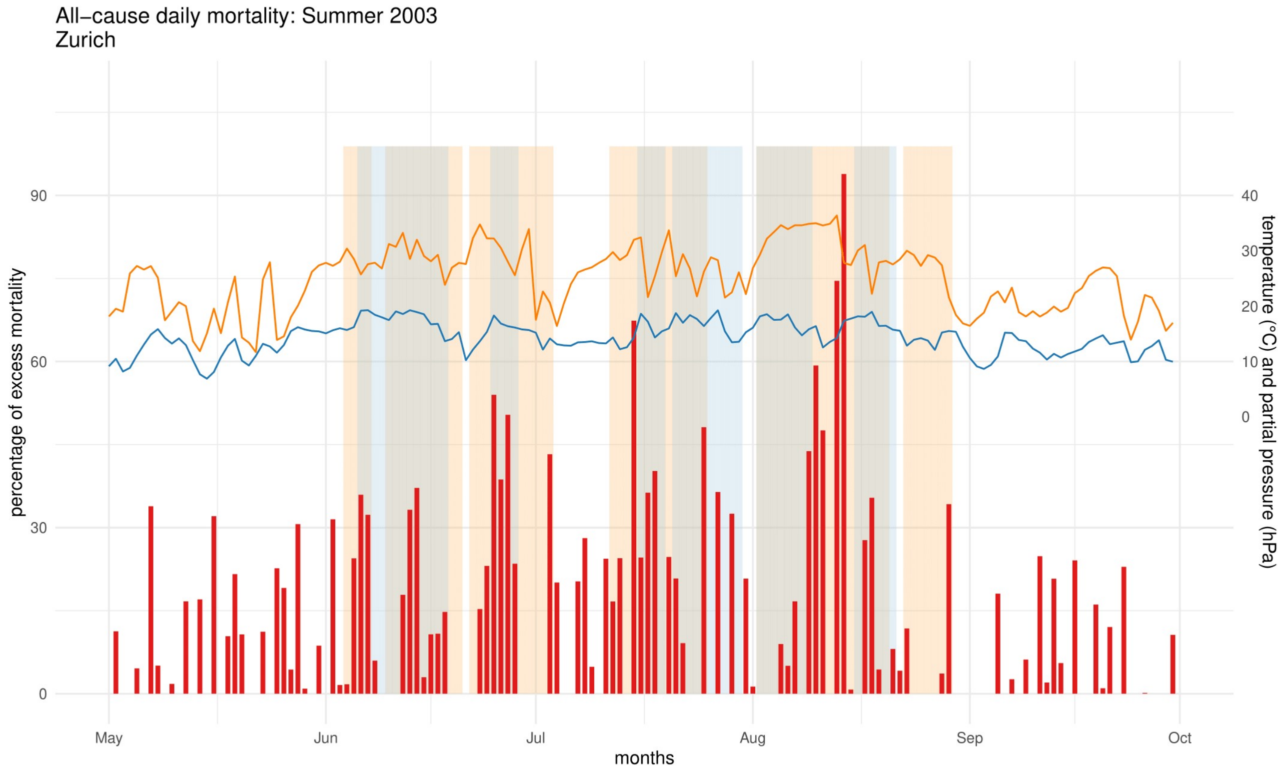
Model #	Variable-Response	Time-Response
1	lin	logknots
2	ns 2 knots	logknots
3	ns 1 knot	logknots
4	thr	logknots
5	lin	strata br 1
6	ns 2 knots	strata br 1
7	ns 1 knot	strata br 1
8	thr	strata br 1
9	lin	integer
10	ns 2 knots	integer
11	ns 1 knot	integer
12	thr	integer
13	lin	ns 1 knot
14	ns 2 knots	ns 1 knot
15	ns 1 knot	ns 1 knot
16	thr	ns 1 knot
17	lin	strata br 1,3
18	ns 2 knots	strata br 1,3
19	ns 1 knot	strata br 1,3
20	thr	strata br 1,3

The different models (index) of a humidity cross-basis with a fixed cross-basis for temperature

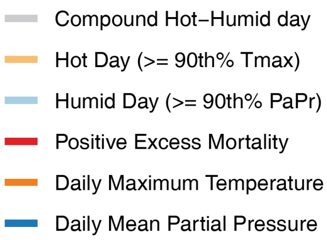
A.2.2 Figures

Excess mortality plots

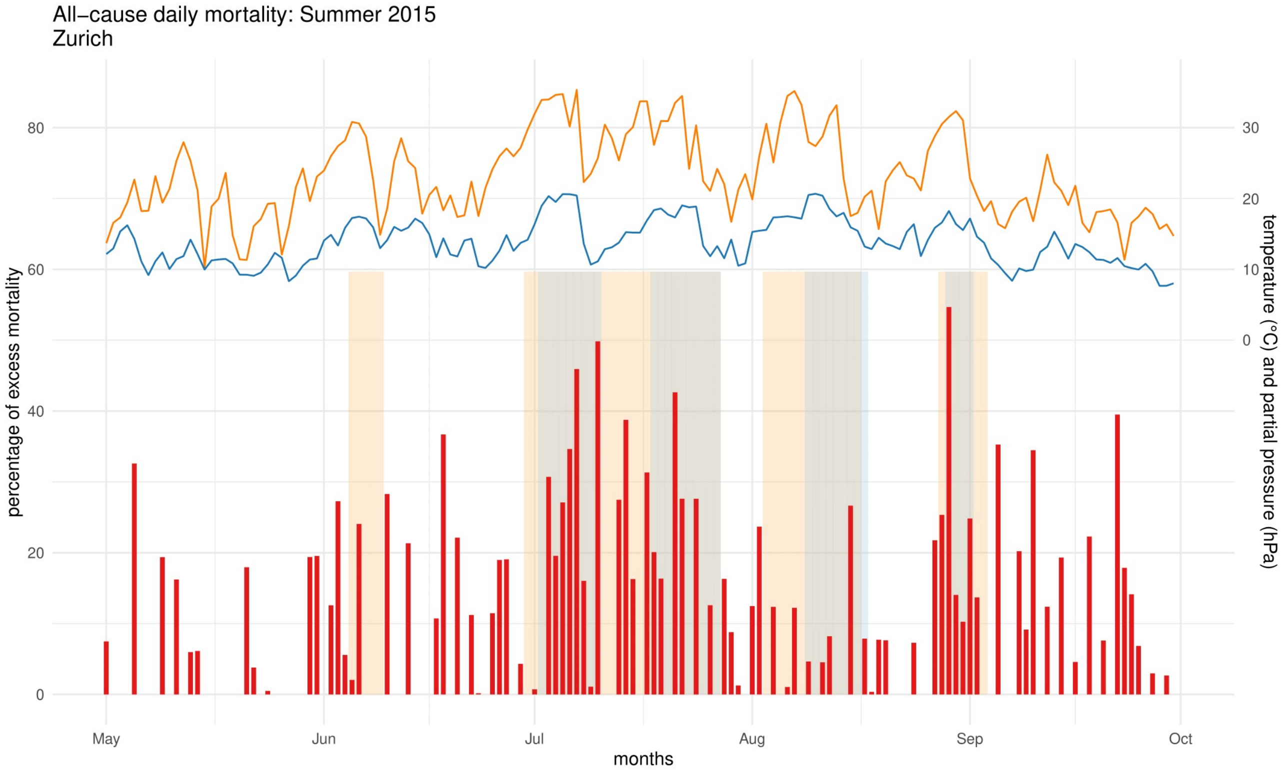
a)



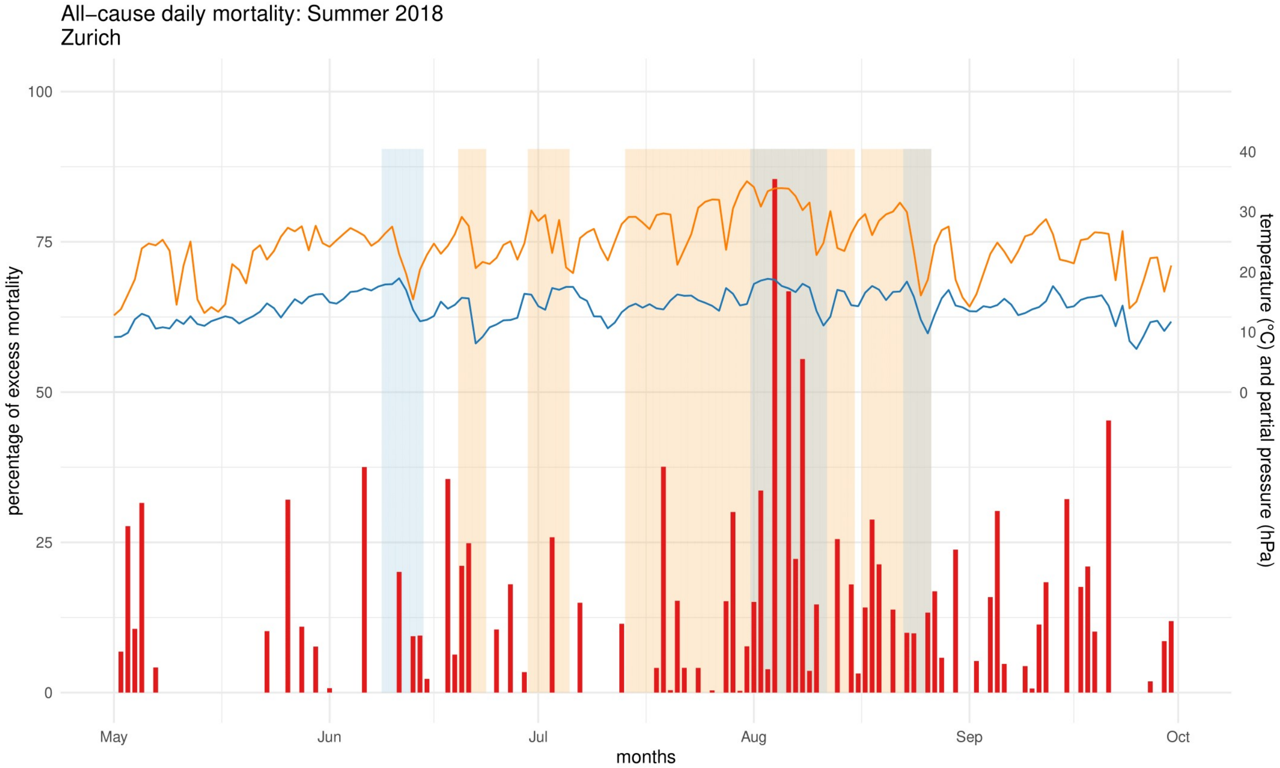
b)



c)

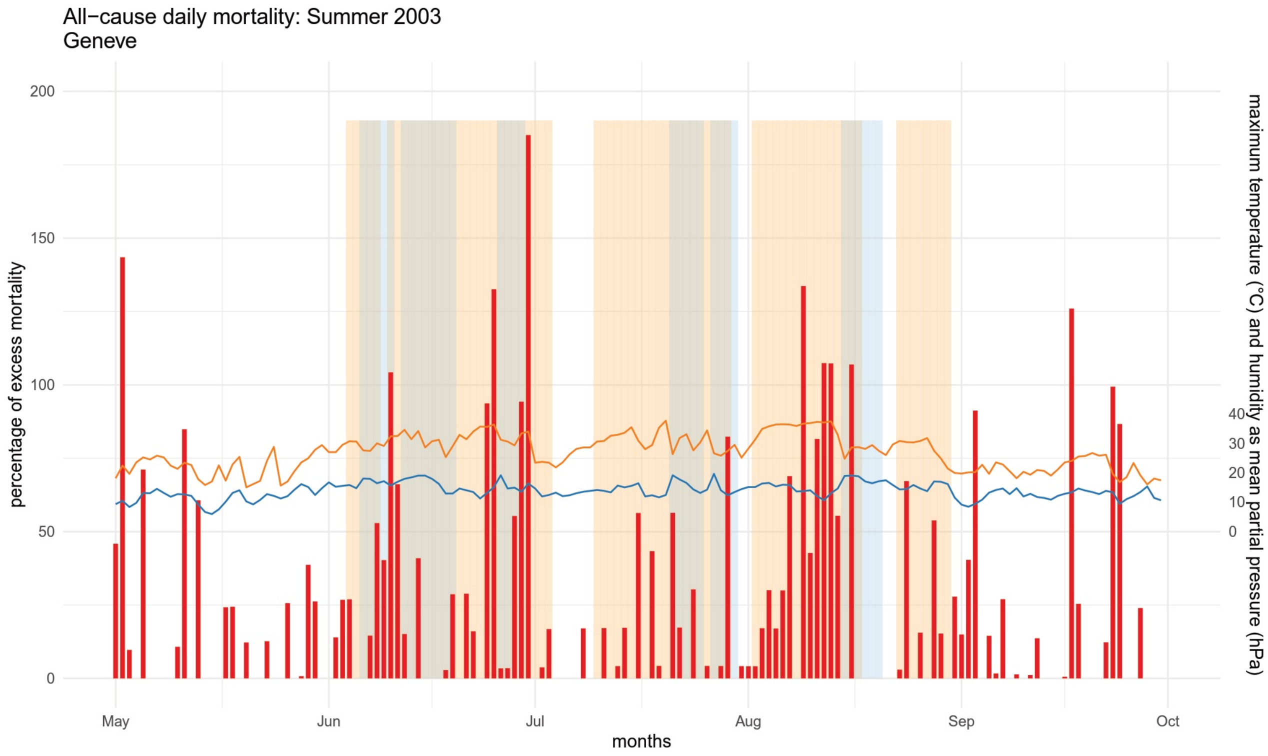


d)

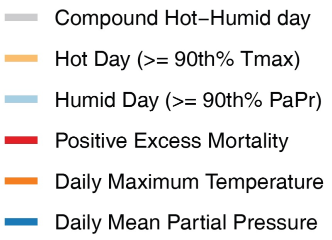


The excess mortality plots for summers **a)** 2003, **c)** 2015 and **d)** 2018 and the respective legend **b)** for Zurich canton

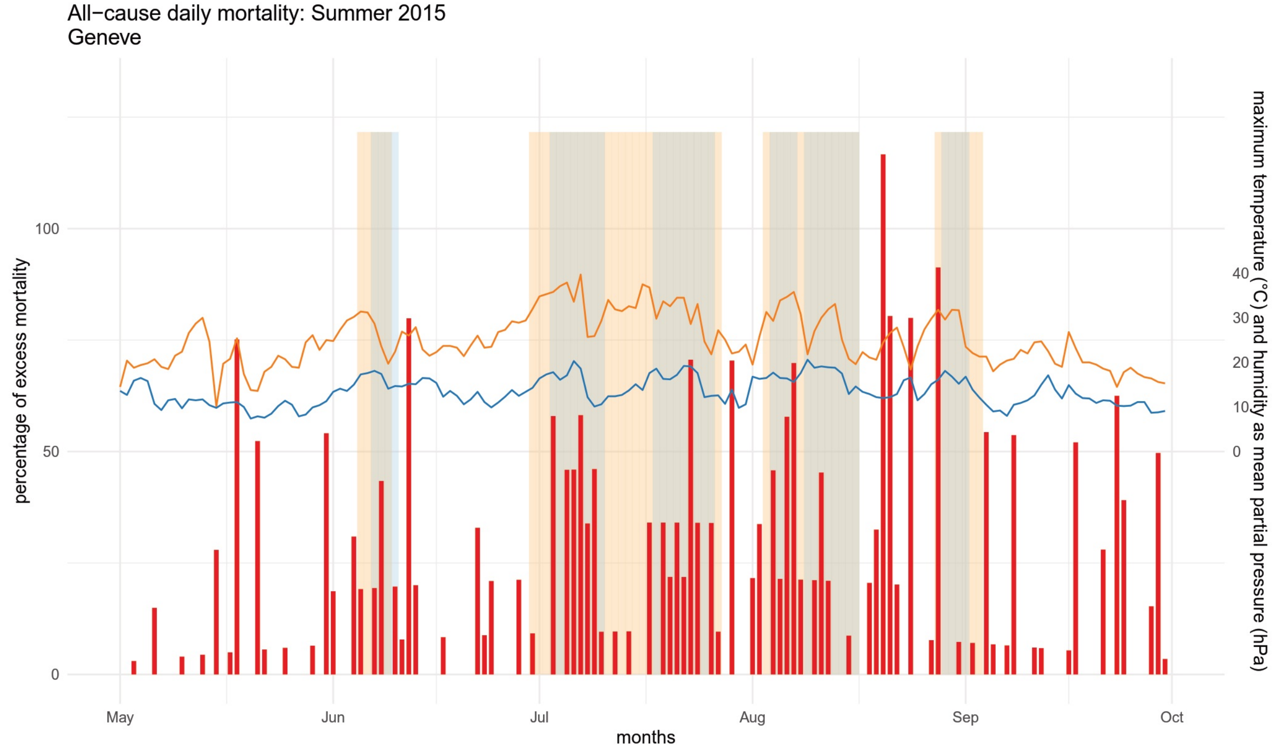
a)


All−cause daily mortality: Summer 2003
Geneve
percentage of excess mortality
200
150
100
50
0
May
Jun
Jul
Aug
Sep
Oct
months
maximum temperature (°C) and humidity as mean partial pressure (hPa)
40
30
20
10
0

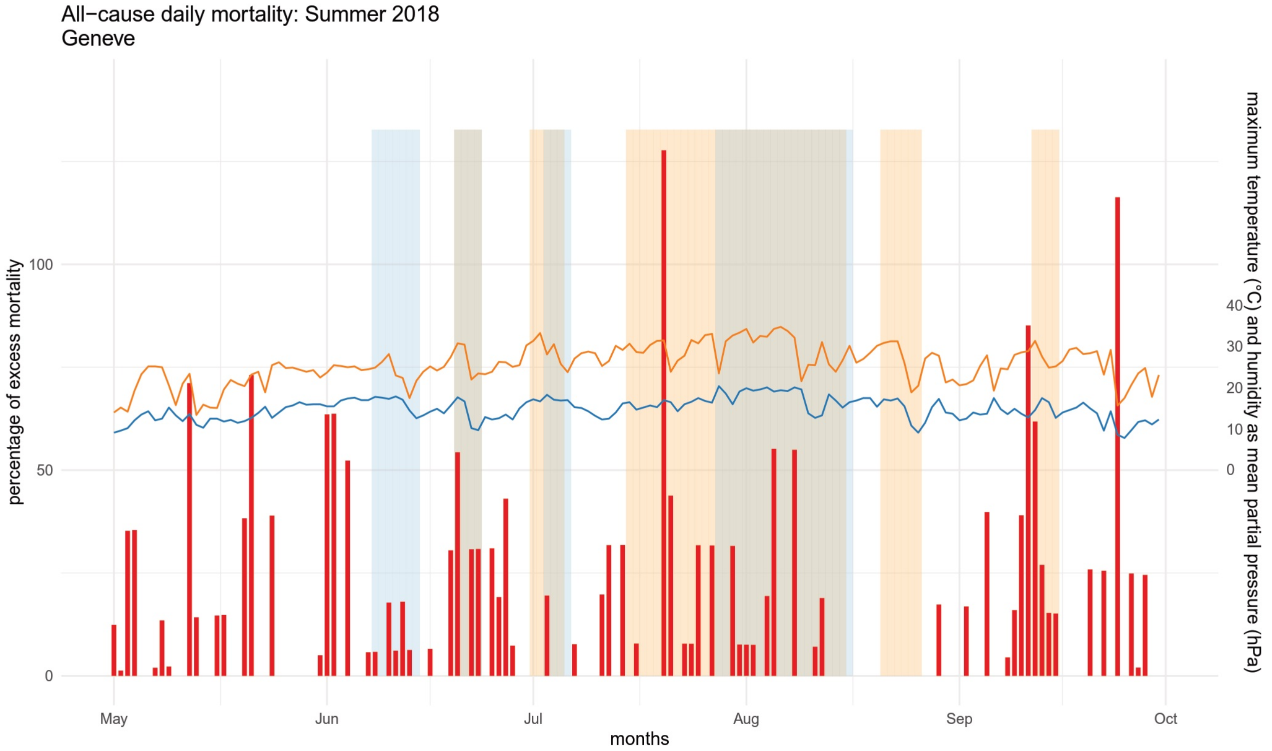
b)


Compound Hot−Humid day
Hot Day (>= 90th% Tmax)
Humid Day (>= 90th% PaPr)
Positive Excess Mortality
Daily Maximum Temperature
Daily Mean Partial Pressure

c)

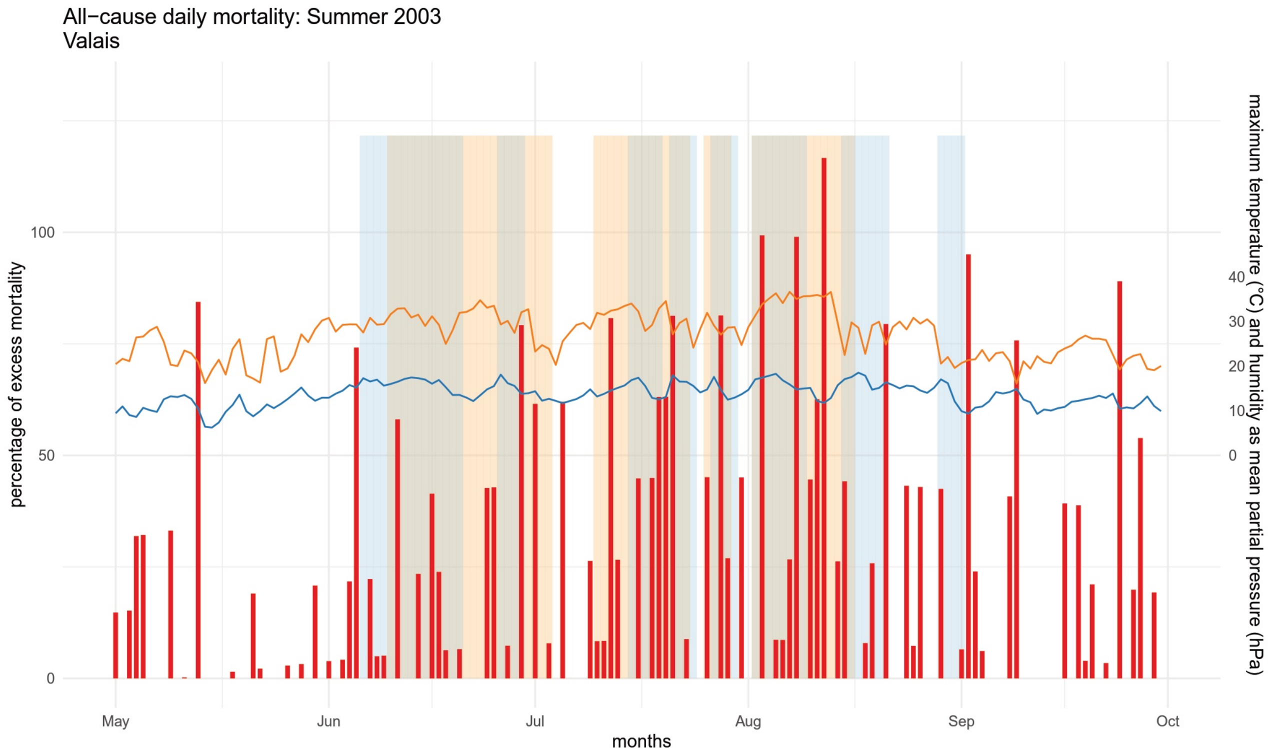


d)

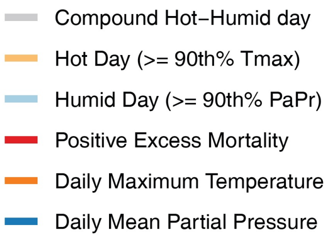


The excess mortality plots for summers **a)** 2003, **c)** 2015 and **d)** 2018 and the respective legend **b)** for Geneva canton

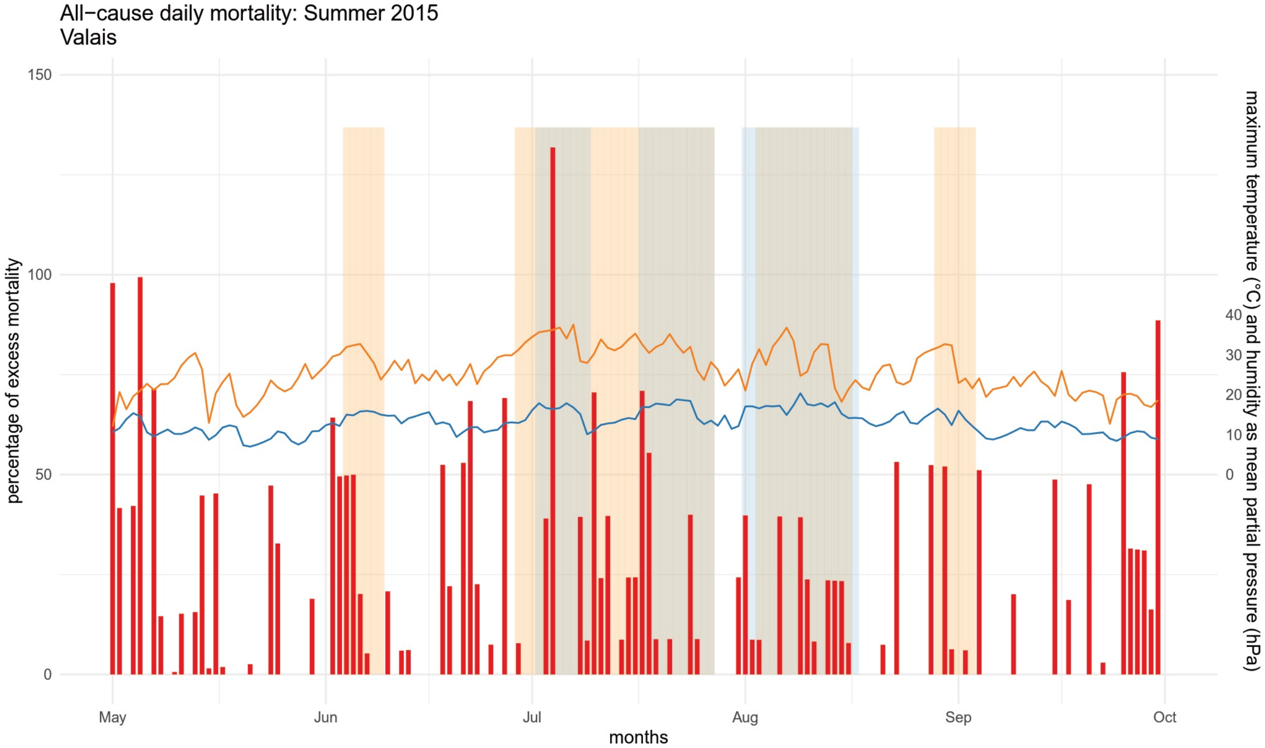
a)


All−cause daily mortality: Summer 2003
Valais
percentage of excess mortality
100
50
0
maximum temperature (°C) and humidity as mean partial pressure (hPa)
40
30
20
10
0
May
Jun
Jul
Aug
Sep
Oct
months

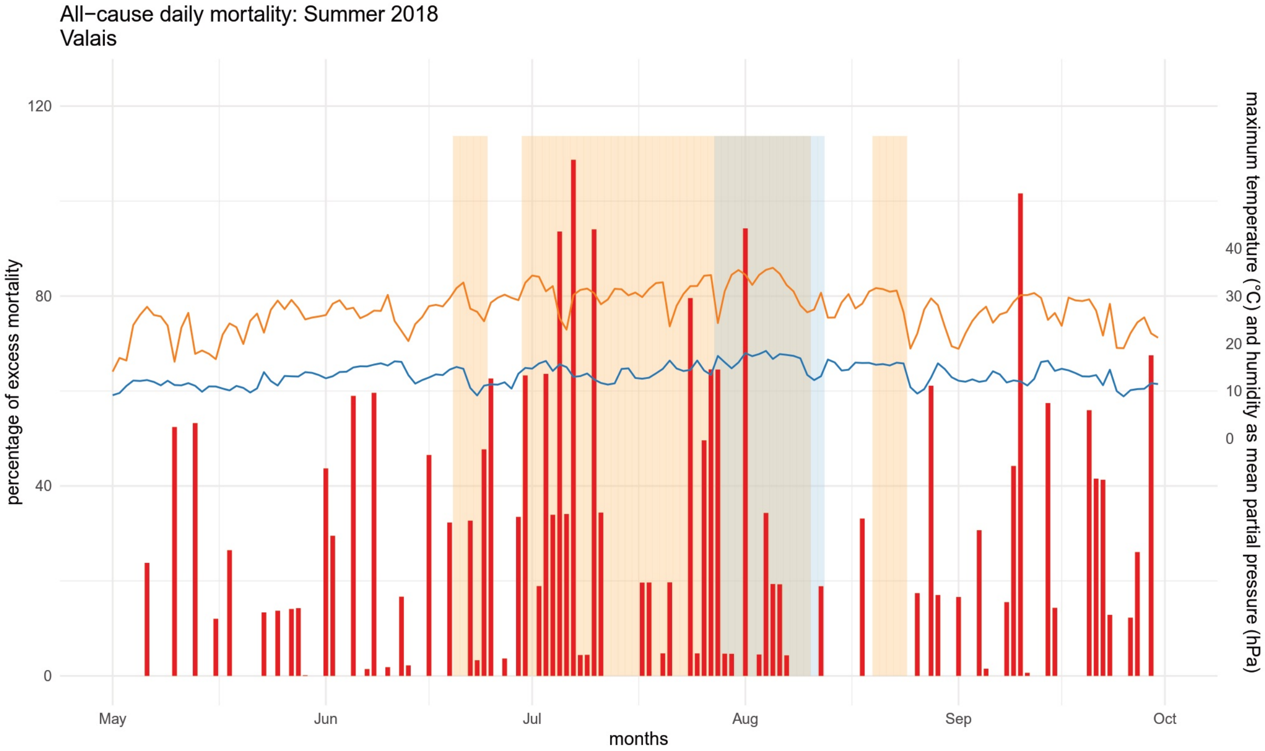
b)


Compound Hot−Humid day
Hot Day (>= 90th% Tmax)
Humid Day (>= 90th% PaPr)
Positive Excess Mortality
Daily Maximum Temperature
Daily Mean Partial Pressure

c)

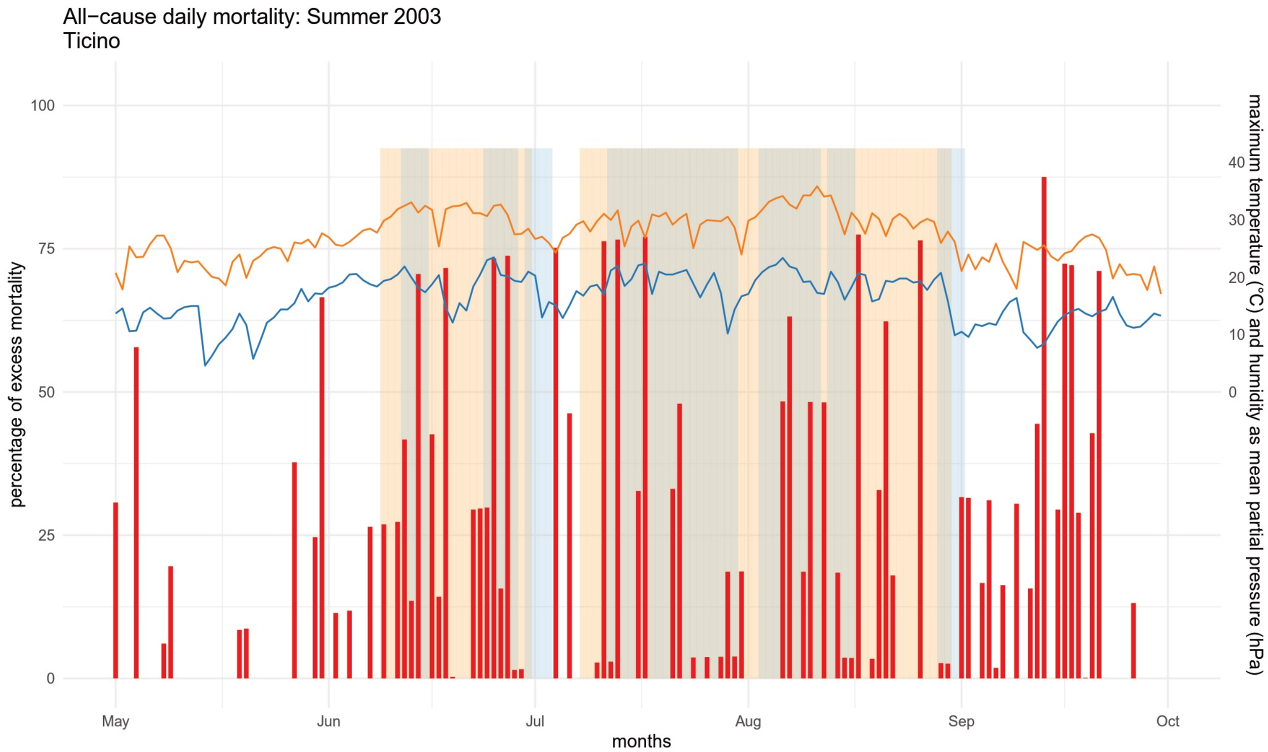


d)



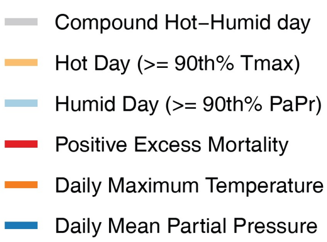
The excess mortality plots for summers **a)** 2003, **c)** 2015 and **d)** 2018 and the respective legend **b)** for Valais canton

a)



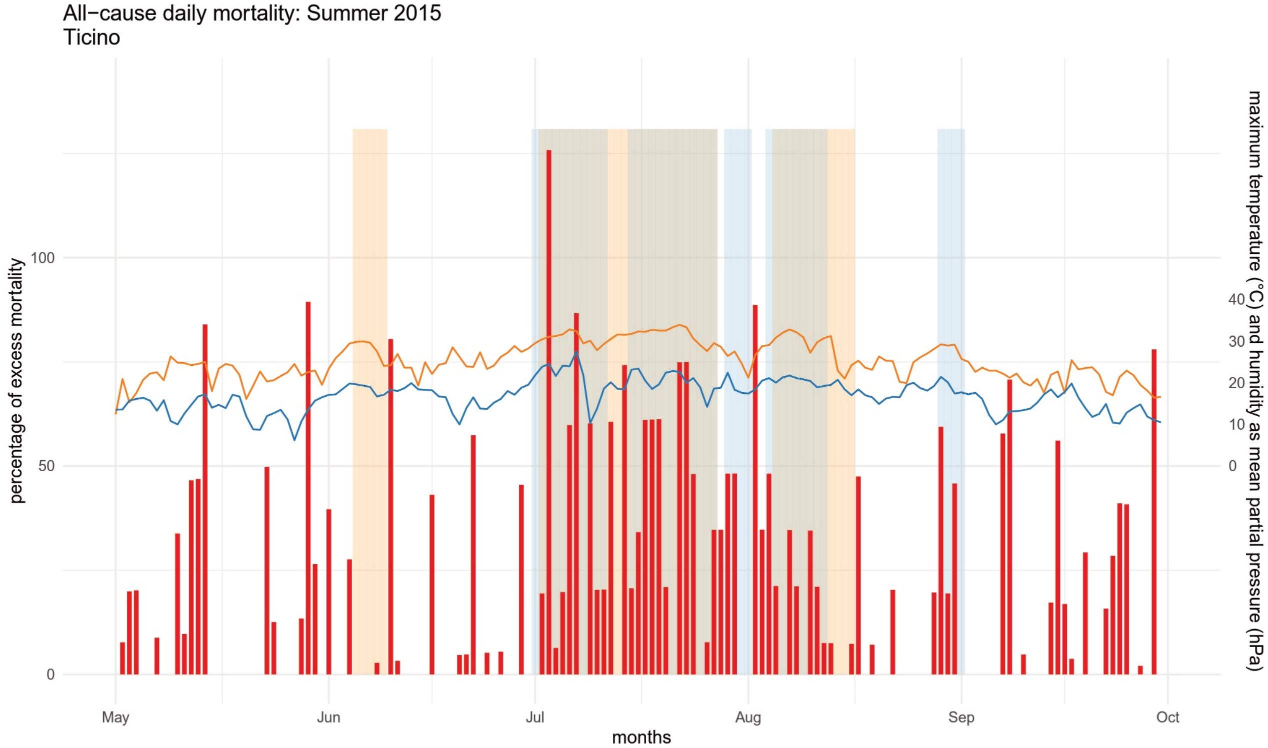
All−cause daily mortality: Summer 2003
Ticino
percentage of excess mortality
100
75
50
25
0
maximum temperature (°C) and humidity as mean partial pressure (hPa)
40
30
20
10
0
May
Jun
Jul
Aug
Sep
Oct
months

b)

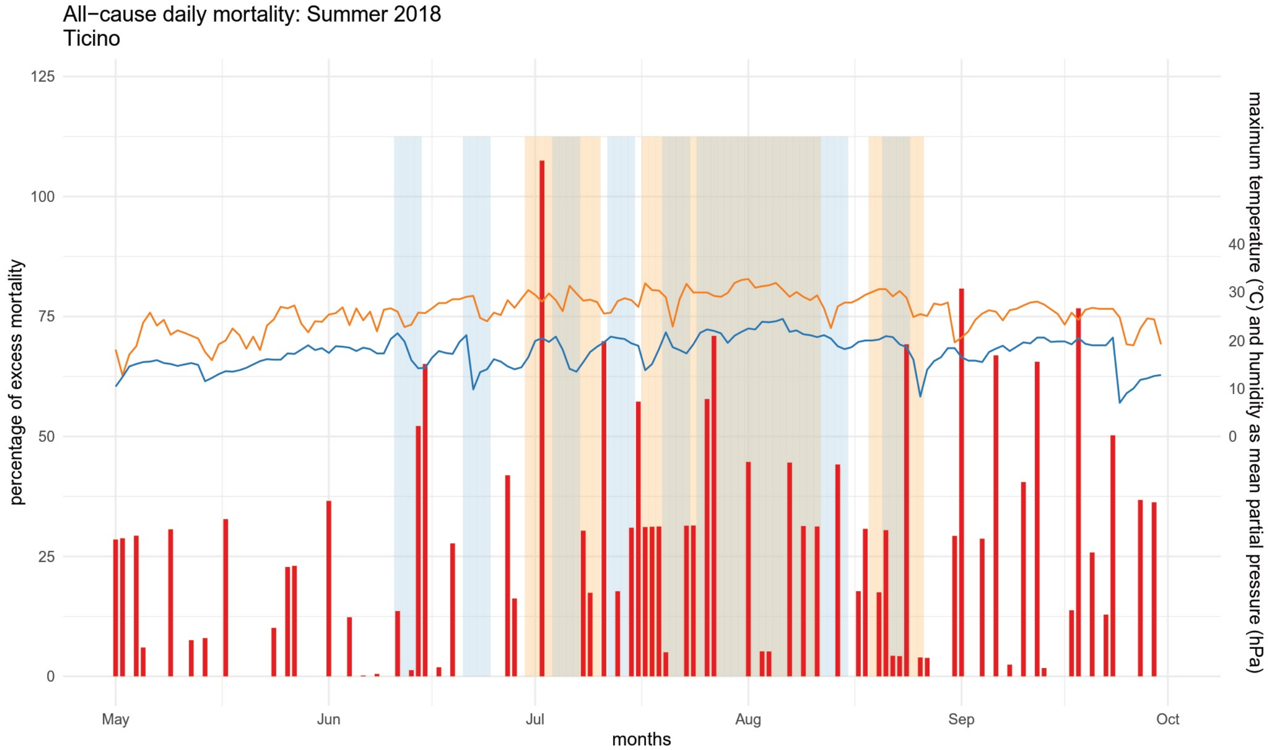


Compound Hot−Humid day
Hot Day (>= 90th% Tmax)
Humid Day (>= 90th% PaPr)
Positive Excess Mortality
Daily Maximum Temperature
Daily Mean Partial Pressure

c)

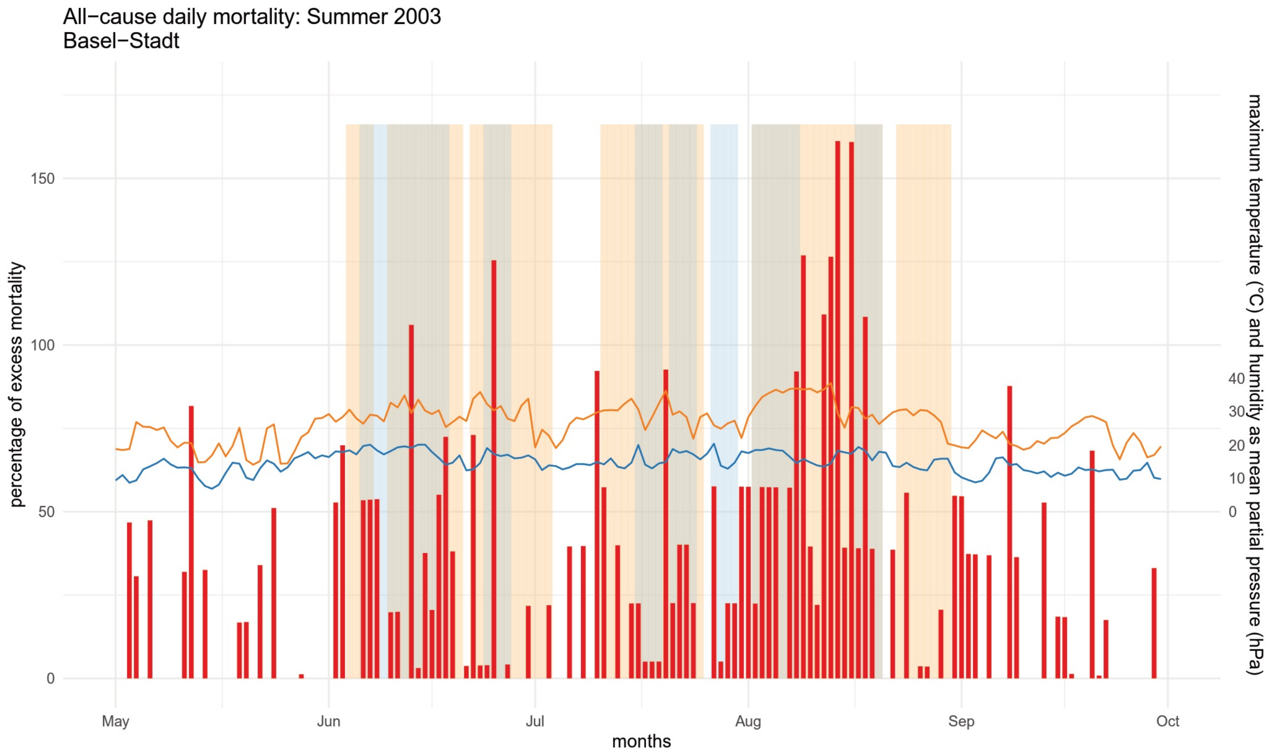


d)



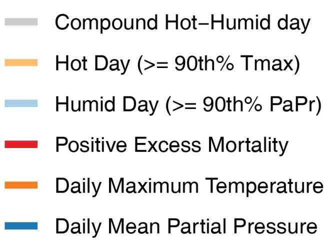
The excess mortality plots for summers **a)** 2003, **c)** 2015 and **d)** 2018 and the respective legend **b)** for Ticino canton

a)



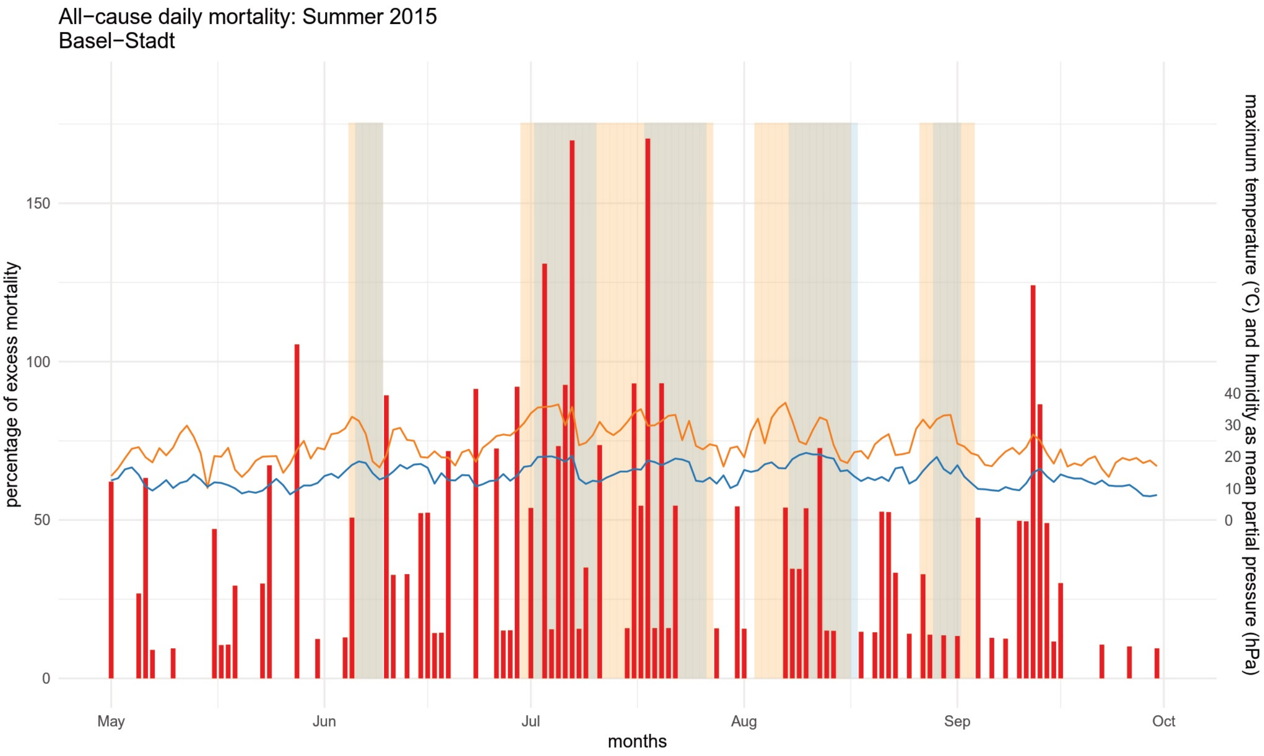
All−cause daily mortality: Summer 2003
Basel−Stadt
percentage of excess mortality
150
100
50
0
maximum temperature (°C) and humidity as mean partial pressure (hPa)
40
30
20
10
0
May
Jun
Jul
Aug
Sep
Oct
months

b)

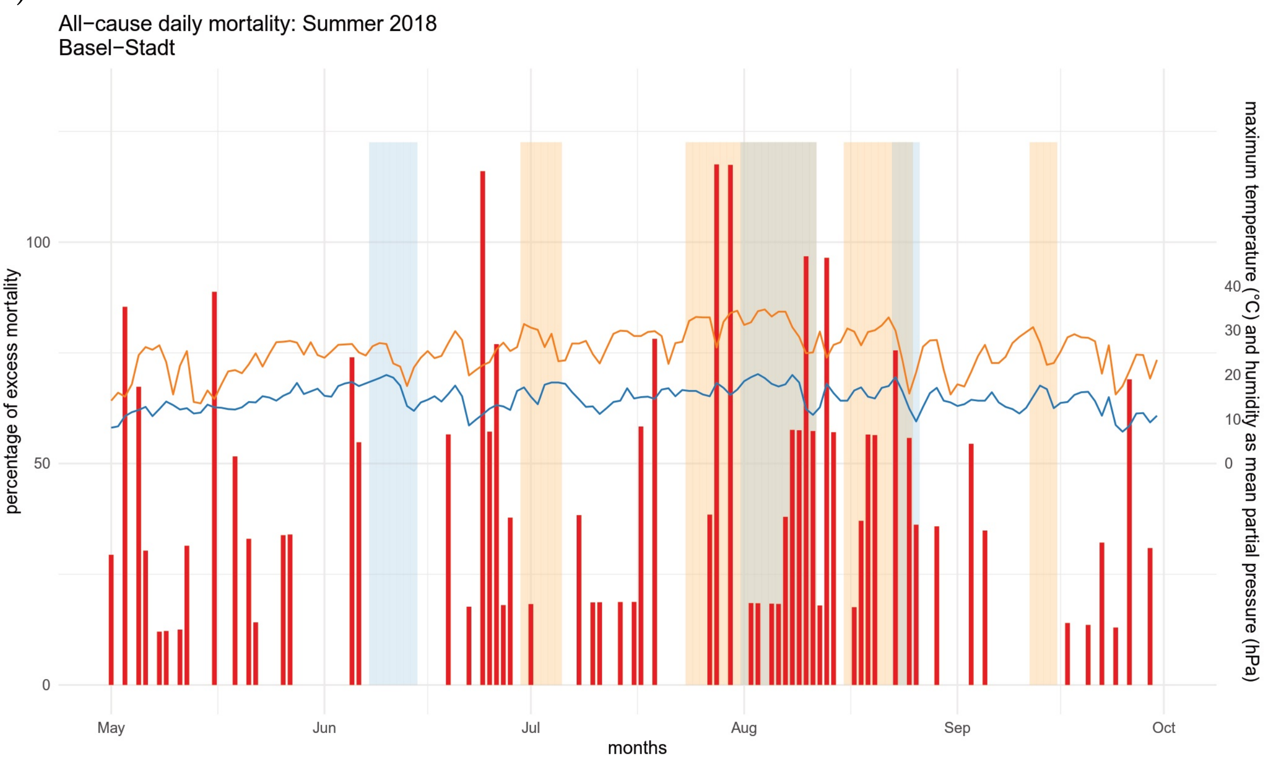


Compound Hot−Humid day
Hot Day (>= 90th% Tmax)
Humid Day (>= 90th% PaPr)
Positive Excess Mortality
Daily Maximum Temperature
Daily Mean Partial Pressure

c)

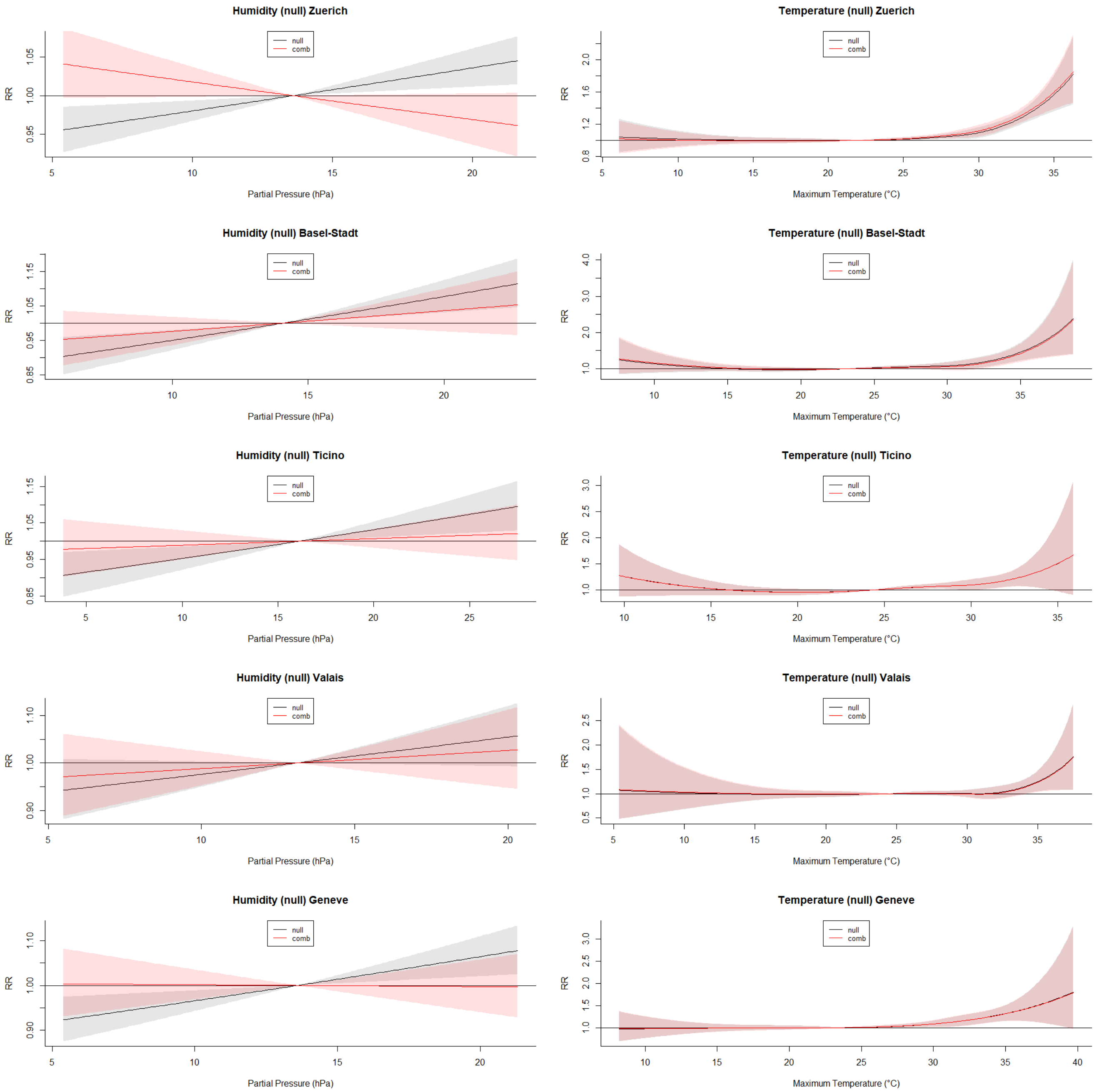


d)

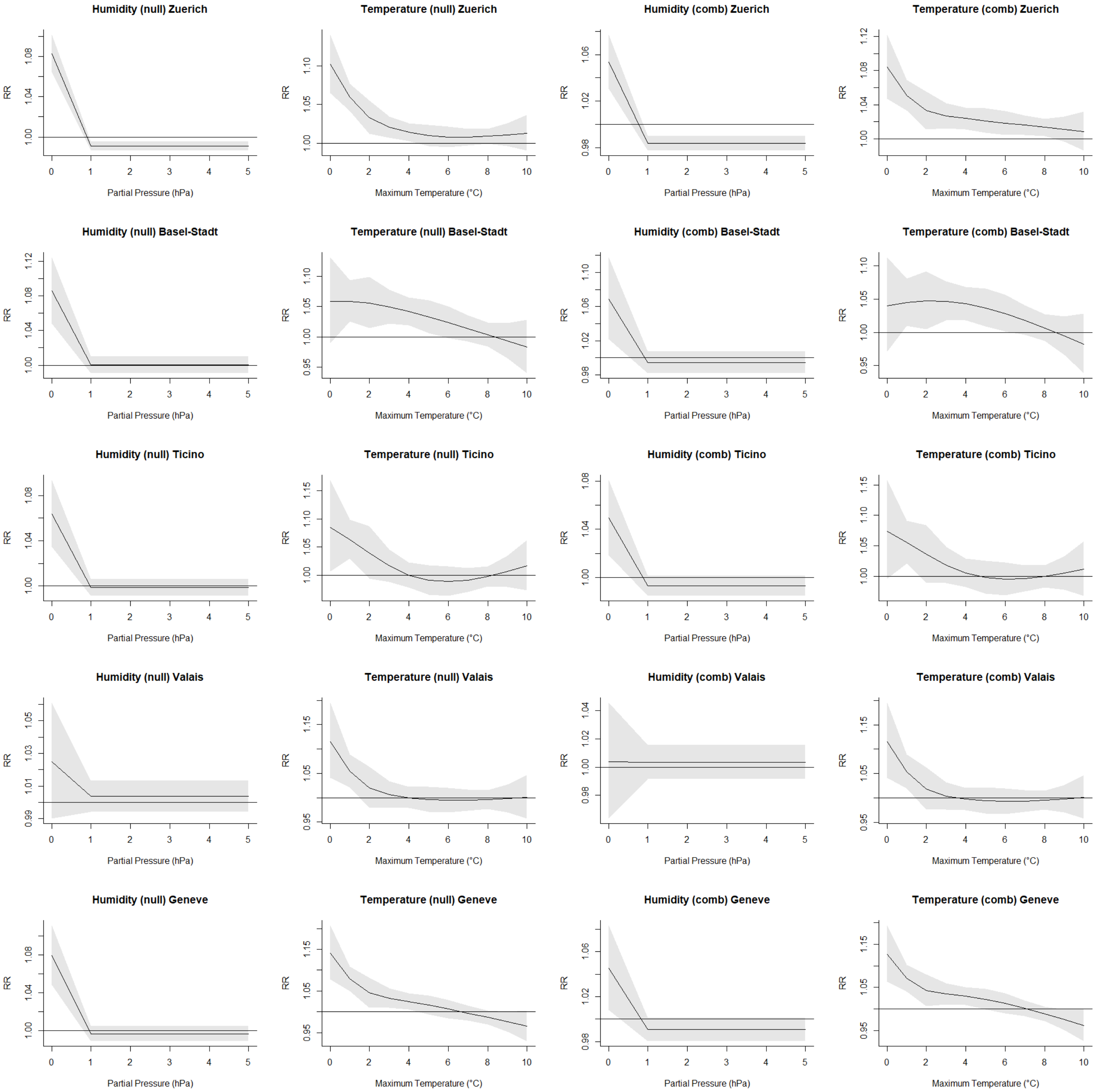


The excess mortality plots for summers **a)** 2003, **c)** 2015 and **d)** 2018 and the respective legend **b)** for canton Basel-Stadt

Exposure-response curves with partial pressure humidity

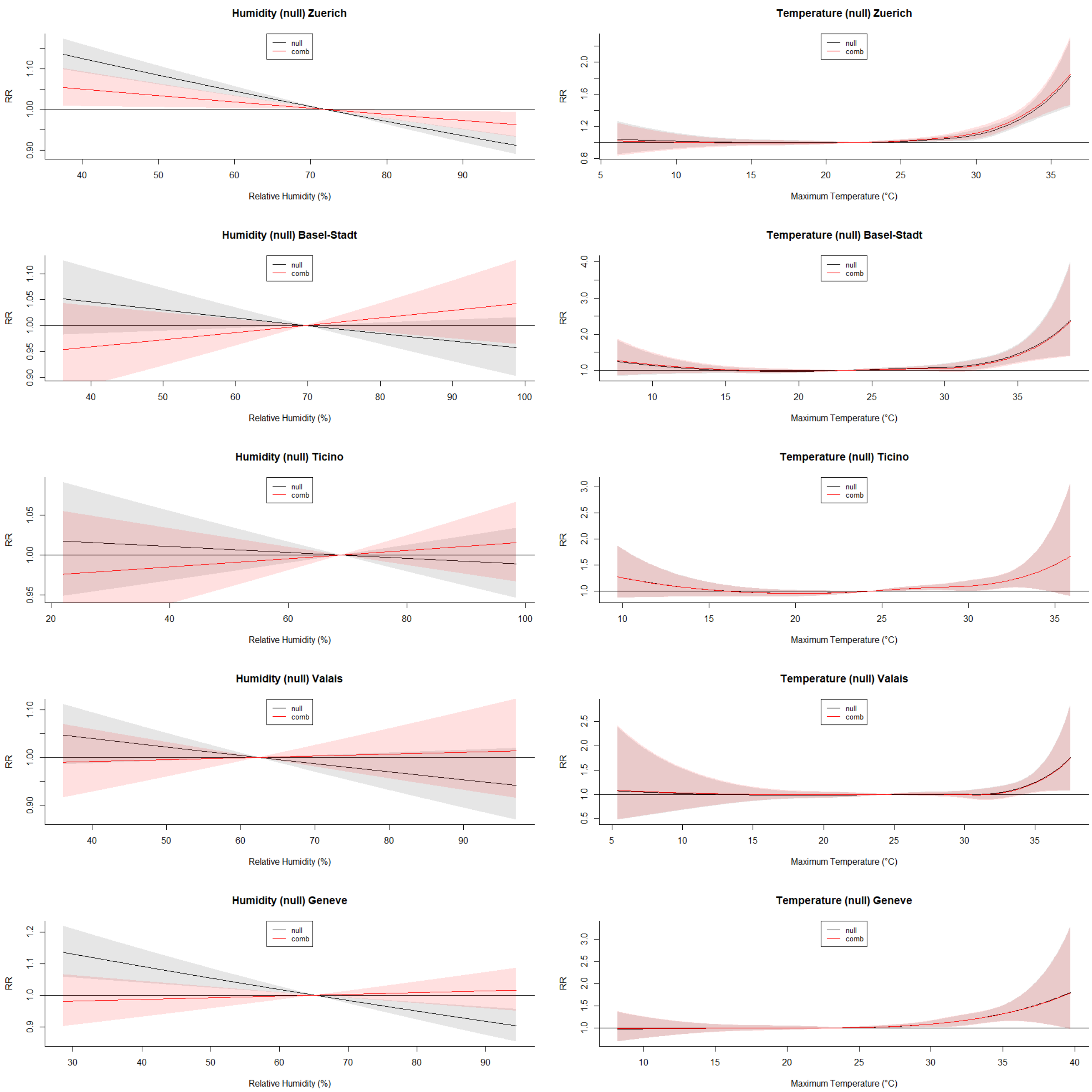


The exposure response curves for partial pressure humidity only *(black)* and for humidity with temperature *(red)* for the cantons Zurich, Geneva, Valais, Ticino and Basel-Stadt

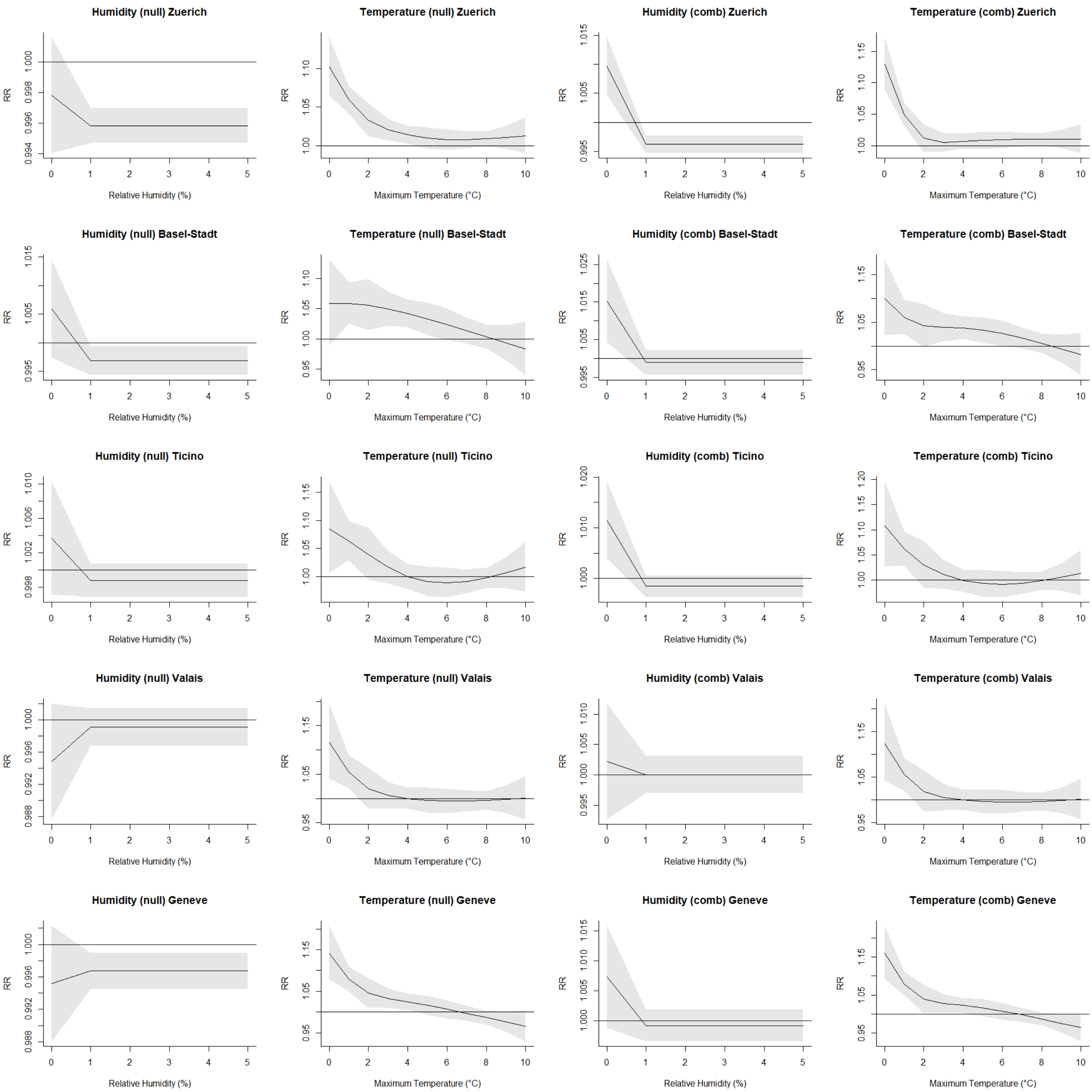


The time response curves for partial pressure humidity only *(black)* and for humidity with temperature *(red)* for the cantons Zurich, Geneva, Valais, Ticino and Basel-Stadt

Exposure-response curves with relative humidity

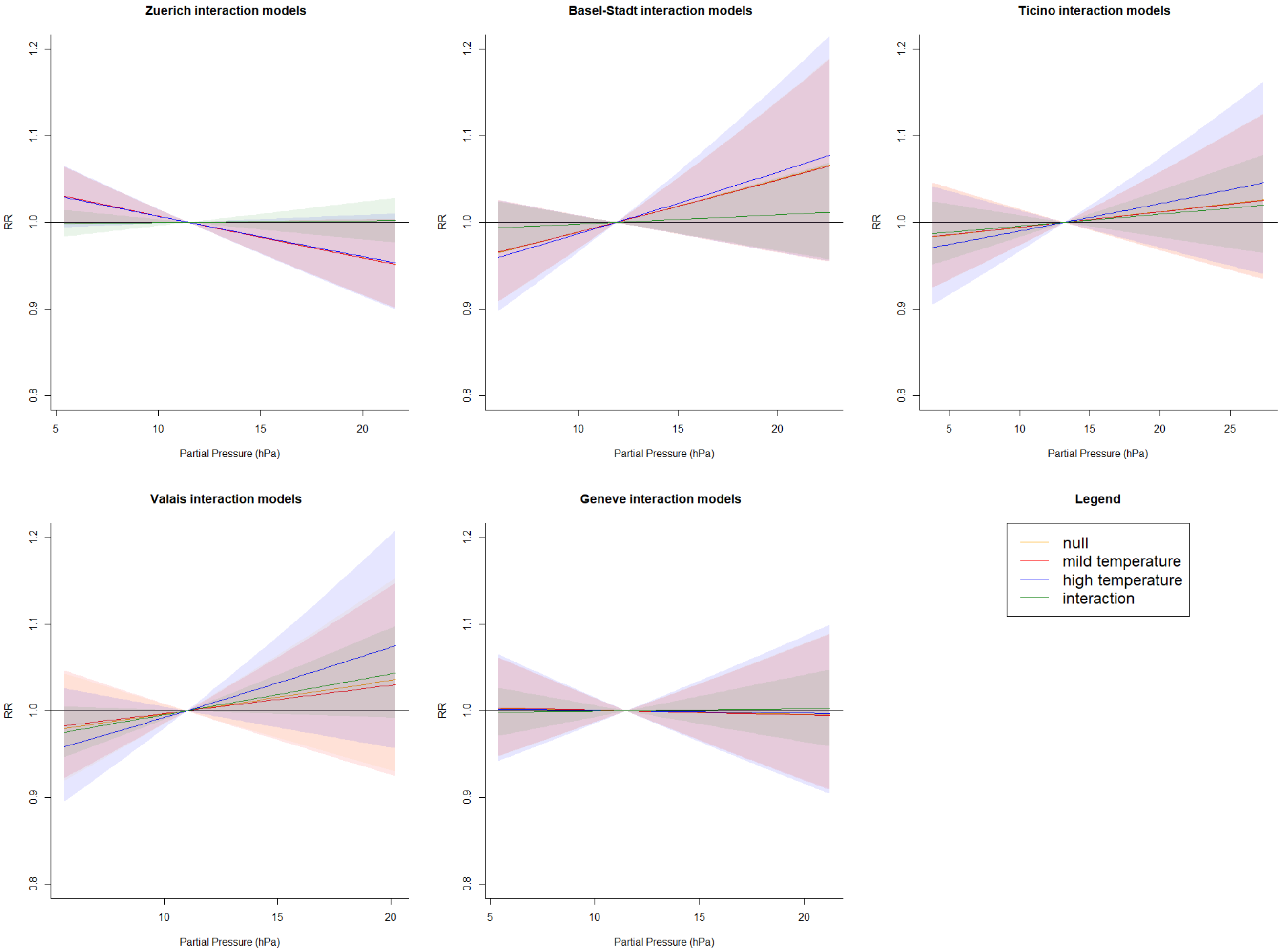


The exposure response curves for relative humidity only *(black)* and for humidity with temperature *(red)* for the cantons Zurich, Geneva, Valais, Ticino and Basel-Stadt

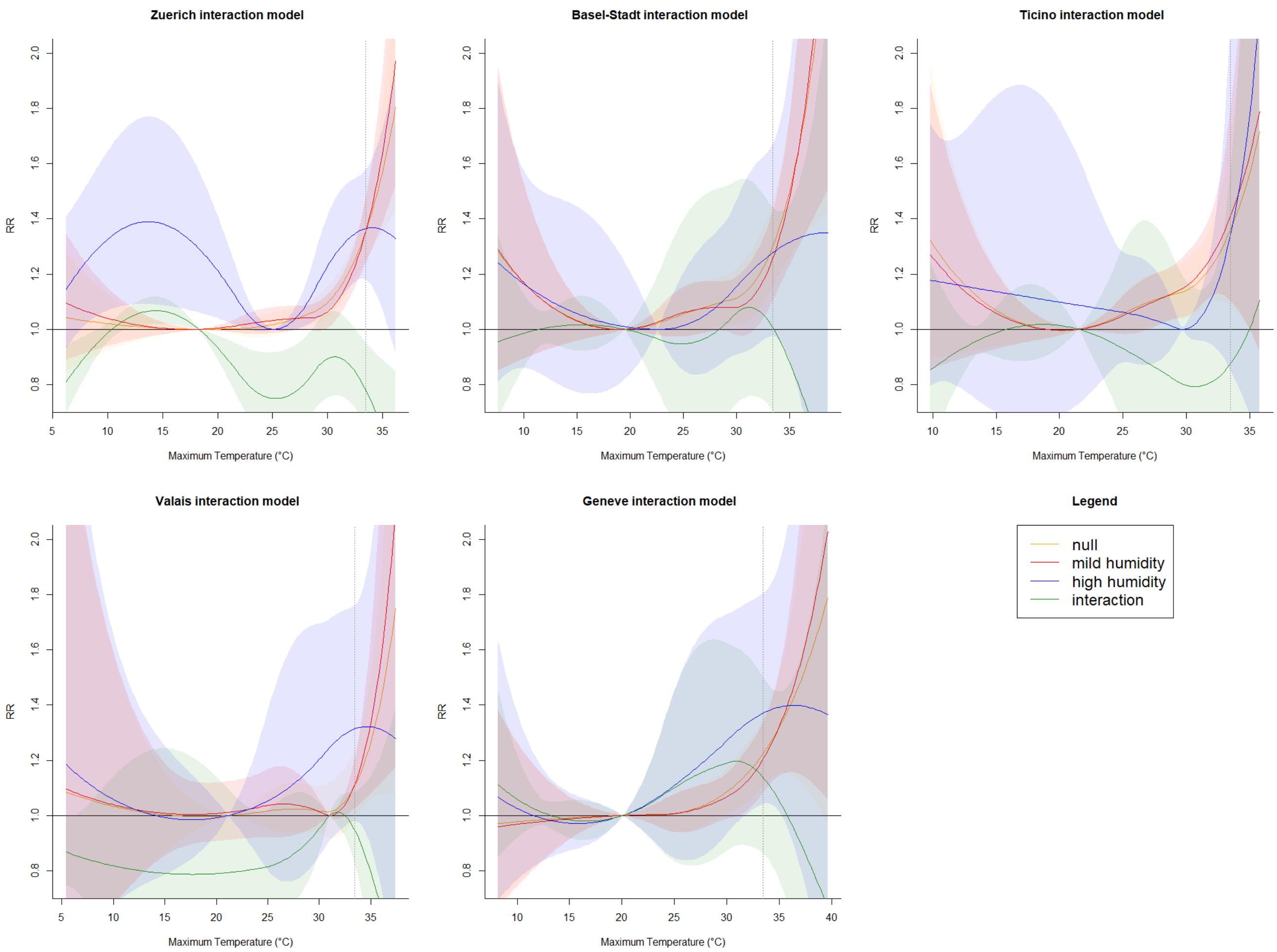


The time response curves for relative humidity only *(black)* and for humidity with temperature *(red)* for the cantons Zurich, Geneva, Valais, Ticino and Basel-Stadt

Interaction model humidity and temperature



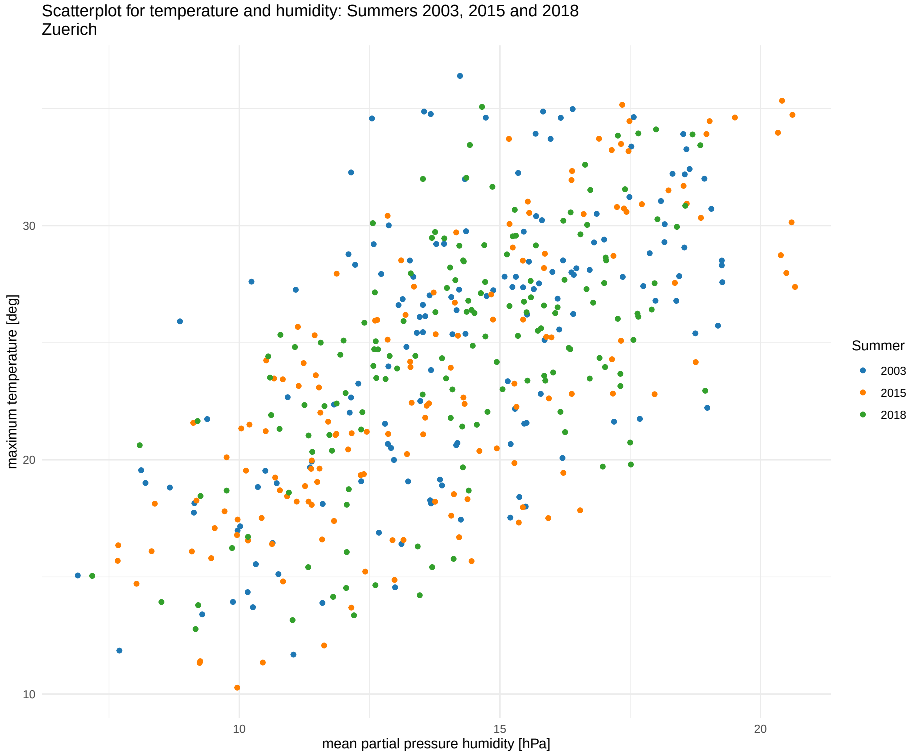
The interaction model curves for partial pressure humidity *(black)* *(red)* for the cantons Zurich, Geneva, Valais, Ticino and Basel-Stadt



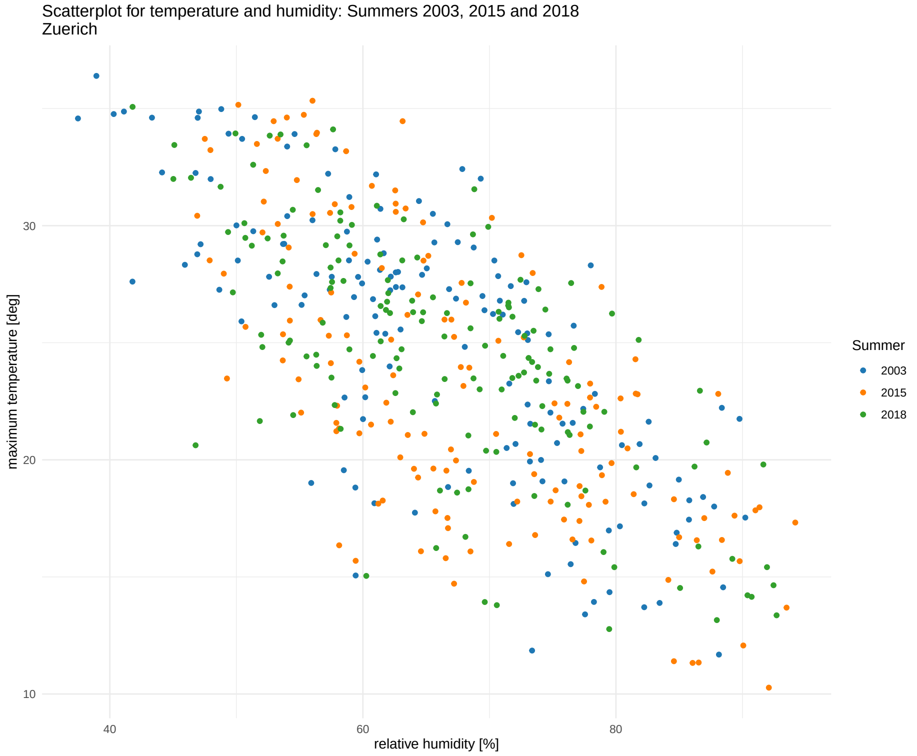
The interaction model curves for maximum temperature *(black)* *(red)* for the cantons Zurich, Geneva, Valais, Ticino and Basel-Stadt

Scatterplots humidity and temperature

a)



b)



The scatterplot for humidity as **a)** partial pressure and **b)** relative humidity and maximum temperature for Zurich canton

Declaration of consent

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

Name/First Name: Kestenholz Christoph

Registration Number: 19-103-548

Study program: MSc in Climate Sciences

Bachelor ☐ Master ☑ Dissertation ☐

Title of the thesis: The effect of humidity in association with high temperatures on health outcomes

Supervisor: Dr. Ana Maria Vicedo-Cabrera

I declare herewith that this thesis is my own work and that I have not used any sources other than those stated. I have indicated the adoption of quotations as well as thoughts taken from other authors as such in the thesis. I am aware that the Senate pursuant to Article 36 paragraph 1 litera r of the University Act of 5 September, 1996 is authorized to revoke the title awarded on the basis of this thesis.

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Date: 2021.11.05 08:58:47 +01'00'

Signature