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Social inequalities in heat-related mortality in the Czech Republic

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Prague, March 31st, 2022 Chloé Vésier

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Social inequalities in heat-related mortality in the Czech Republic

ABSTRACT

Because of climate change, summer temperatures are predicted to rise and heat waves to be more recurrent, including in Central Europe. It is important to understand heat-related risks on human mortality and to identify inequalities in vulnerability among the population, such as sex and gender inequalities. In this study, the associations between daily temperature and mortality during the five warmest months of the year (from May to September) have been analysed in the Czech Republic for the period 1995–2019. The primary focus of the analysis was on the differences in the associations by sex, i.e., between men and women. These two categories were further divided by age, marital status, residence's location and cause of death. Mortality time series have been modelled by a quasi-Poisson regression model with a distributed lag non-linear model (DLNM) to account for the delayed and non-linear effects of temperature on mortality. The heat-related mortality risks obtained in each population group were expressed in terms of risk at the 99th percentile of summer temperature relative to the minimum mortality temperature.

The results showed that women were more at risk to die because of heat than men. With regard to age, the highest risk for men was observed between 75 to 84 years old, while risk for women was higher for women above 85 years old. Risks among married people were lower than risks among single, divorced and widowed people, and risks in divorced women were significantly higher than in divorced men. Results on residence's location revealed a significantly higher risk for women living in the capital city Prague than in the regions, while among men, the mortality risk was slightly higher for those living in the regions. Ultimately, deaths by cardiovascular or respiratory diseases were found more sensitive to heat than other causes of death.

Thus, this study showed that social and demographic criteria impacted the heat vulnerability and in particular, results highlighted the important role of sex and gender inequalities in heat-related mortality. Deeper studies on these social drivers would be relevant to design efficient and fair mitigation and adaptation strategies.

Keywords: DLNM, sex and gender inequalities, heat-stress

Vliv sociálních nerovností na úmrtí v důsledku horkého počasí v ČR

SHRNUTÍ

V důsledku klimatických změn se předpokládá růst průměrných letních teploty porostou a četnosti vlny veder, a to i ve střední Evropě. I proto je důležité pochopit zdravotní rizika související s horkem a identifikovat nerovnosti ve zranitelnosti různých skupin populace, například na základě rozdílného pohlaví. V této studii byly analyzovány souvislosti mezi denní teplotou a úmrtností během pěti nejteplejších měsíců roku (od května do září) v České republice za období 1995-2019. Primárním cílem analýzy bylo studium rozdílů v těchto souvislostech na základě pohlaví, tedy mezi muži a ženami. Tyto dvě kategorie byly dále rozděleny podle věku, rodinného stavu, místa bydliště a příčiny úmrtí. Pro zohlednění zpožděných a nelineárních účinků teploty na úmrtnost byly souvislosti mezi časovými řady denních počtů úmrtí a teploty modelovány pomocí Poissonova regresního modelu rozšířeného o distribuovaný nelineární model zpoždění (Distributed lag non-linear model – DLNM). Výstupem modelu byla nelineární funkce znázorňující vztah mezi relativním rizikem úmrtnosti a teplotou, určena zvlášť pro každou populační skupinu. Riziko úmrtí z horka bylo vyjádřeno jako relativní riziko úmrtí na 99. percentilu rozložení letní teploty vůči teplotě minimálního rizika úmrtí.

Výsledky analýzy ukázaly obecně vyšší riziko úmrtí z horka u žen než u mužů. Z hlediska věku bylo největší riziko pozorováno u mužů ve věku 75 až 84 let, zatímco riziko u žen bylo největší ve věkové skupině nad 85 let. Riziko úmrtí mezi ženatými osobami bylo obecně nižší než pro svobodné, rozvedené nebo ovdovělé, přičemž riziko úmrtí u rozvedených žen bylo významně vyšší než u všech ostatních skupin určených na základě rodinného stavu. Z hlediska místa trvalého bydliště bylo zjištěno nejvyšší riziko úmrtí pro ženy žijící Praze, zatímco u mužů bylo zjištěno mírně vyšší riziko u osob žijících v regionech (mimo Prahu). Z hlediska příčiny úmrtí představovalo horko největší riziko pro osoby s kardiovaskulárním nebo respiračními onemocněním v porovnání s ostatními příčinami.

Tato studie ukázala, že sociální a demografické charakteristiky ovlivňují zranitelnost jednotlivých skupin vůči teplému počasí. Výsledky práce upozorňují zejména na rozdílné dopady vysokých teplot na muže a ženy, které pravděpodobně mají nejen fyziologické ale i sociální příčiny. Při navrhování účinných a sociálně spravedlivých opatření pro zmírňování dopadů horka na zdraví obyvatel je proto důležité se podrobněji zaměřit na studium a identifikaci těchto sociálních příčin způsobujících nerovnost mezi oběma pohlavími z hlediska zdraví a kvality života.

Klíčová slova: DLNM, nerovnosti pohlaví/genderu, stres z horka, tepelná zátěž

Contents

List of abbreviations

In the alphabetical order:

- AC: Air conditioning
- AF: Attributable fraction
- AN: Attributable number
- CVD: Cardiovascular disease
- CZSO: Czech Statistical Office
- DLNM: Distributed lag non-linear model
- EIGE: European Institute for Gender Equality
- EU: European Union
- GLM: Generalised linear model
- MMT: Minimum mortality temperature
- RR: Relative risk
- SES: Socio-economic status

Chapter 1

Introduction

1.1 Climate change and heat stress

Climate on Earth is going through changes that have never been that dramatic in thousands of years, as pointed out by the IPCC, the Intergovernmental Panel on Climate Change (IPCC 2021). In their regular and comprehensive reviews of all relevant studies published on the topic, the IPCC showed that climate change was anthropogenic. Human activities (mainly in developed countries) such as agriculture, transport, building usage and industries, are primarily responsible for greenhouse gases emissions such as carbon dioxide or methane, which amplify the greenhouse effect around Earth and thus prevent the accumulated energy from leaving the atmosphere. This surplus of energy participates in melting the ice (whether sea ice, ice-sheets and glaciers) and warming up the oceans, the ground and the atmosphere. Main consequences are the disruption of the water cycle, thus making more intense and regular extreme events such as droughts and floods; and the rise of sea level, putting at risk of submersion a lot of coastal areas.

Another and more direct consequence is the increase in air temperature. In 2017, the global average temperature had increased by 1 °C (likely between 0.8 °C and 1.2 °C) above pre-industrial temperatures (IPCC 2021). Depending on different possible scenarios of carbon emissions, studies projected an increase in global average temperature between 1.5 °C and 5 °C by 2100. In Central Europe, maximum summer temperatures are predicted to rise more than global average (IPCC 2007). Higher temperatures lead to more frequent heat waves (Christidis et al. 2015), which are periods of excessively hot weather that can last from a few days to a few weeks. In 2018, 31 million people over 65 years old were additionally exposed to heat waves in Northern and Central Europe (Watts et al. 2019). The Czech Republic already experienced several heat waves in the past years, in particular the two record-breaking summers of 1994 and 2015 (Urban et al. 2017).

If further consequences of climate change such as increased frequency of natural disasters, destruction of living areas, decline in agricultural yields and scarcity of freshwater resources may lead to dramatic consequences on human societies, the increase in global average temperature and frequency of heat waves represent two of the major issues directly affecting public health.

Indeed, exposure to warm temperatures may cause several consequences on health such as acute kidney injury, congestive heart failure (Watts et al. 2019), heat syncope, heat cramps or heat stroke (Székely et al. 2015), and ultimately death. Increase of mortality after heat waves has already been observed in many studies (Z. Xu et al. 2016). For example, the heat wave that hit Europe in 2003 caused more than 30,000 additional deaths (Jonsson and Lundgren 2015). Heat-related mortality has been shown to particularly impact people with pre-existing cardiovascular diseases (CVD, diseases affecting the heart or the blood vessels) and respiratory diseases (impacting organs involved in breathing such as lungs or trachea) (McMichael et al. 2006, Hanzlíková et al. 2015).

1.2 Social inequalities in vulnerability

Not all humans are affected the same way by climate change, and some people are more vulnerable than others. The effects of climate change obviously vary by geography, and some places are already more impacted by changes such as increased frequency of heat waves. What is more, even within a located area, disparities in vulnerability may be observed, since social domination dynamics are a determining factor in developing resilience or mitigation strategies. In particular, numerous papers insisted on the importance of including sex and gender dimensions when studying the impacts of climate change (McCall et al. 2019, Tenglerová et al. 2020).

Sex and gender

"Sex" and "gender" are two terms and notions that should be distinguished. Although these concepts are complex and co-influencing, the following definitions were elaborated based on various sources (Charkoudian and Stachenfeld 2014, Tenglerová et al. 2020, WHO 2021, UN High Commissioner for Refugees 2021). "Sex" is used to describe biological and physiological characteristics of an individual, that can be observed on different levels such as chromosome patterns, hormone production, gonads or genitals. Male and female are the two main sexes usually differentiated and typically assigned at birth, although a non-negligible number of people (between 0.05% and 1.7%[1]) are born intersex, i.e., with reproductive or sexual anatomy that do not fit a binary differentiation. "Gender" refers to a large set of norms, behaviours, values and preferences that are considered appropriate by a society for each sex. Gender

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[1] According to the campaign UN Free and Equal conducted since 2013 by the United Nations Human Rights Office, see here

is a social construction that depends on the society it evolves in and that can vary in time and space. "Gender identity" refers to an individual's inner and personal experience of gender, and it may or may not correspond to the sex assigned at birth.

When considering differences in health between individuals, sex may have an impact as a result of differences in anatomy and physiology, while gender might create differences in social habits and income and thus access to medical care (WHO 2021). Chardoukian and Stachenfeld (2014) gave as an example that "oestrogens may protect young women from cardiovascular disease, while gender-related inadequate medical care to young women can have the opposite effect on cardiovascular health".

Sex and gender provide a relevant perspective on climate change impacts on health, as multiple studies revealed that men and women were affected differently (Tenglerová et al. 2020). In developing countries, as a result of droughts, women and girls might have to walk further and longer to fetch water (BRIDGE 2008). They also face a higher mortality risk in situation of extreme weather because of care responsibilities (children, elderly) or cultural expectations (Allwood 2014). In the European context, Baćanović (2015) showed that single mothers and women living alone were more vulnerable to the 2014 floods in Serbia. On the other hand, some studies underlined that men were in some cases more vulnerable as they were expected to take more risks; for example, Salvati et al. (2018) showed that more men died in floods or landslides than women in Italy in a 50-year study. Ultimately, evidences of an increase of gender-based violence — on women and girls, but also on LGBTQI+[2] communities — in the aftermath of a climate disaster were repeatedly observed (Allwood 2014, Nguyen and Rydstrom 2018).

Concerning heat specifically, numerous studies conducted in Europe have pointed out a gendered pattern in heat-related mortality, in which women were found to be at higher risk to die as a result of high temperatures. Indeed, Stafoggia et al. (2006) found women more at risk of dying under 30 °C in four Italian cities. In Germany, Gabriel and Endlicher (2011) showed that women were more affected by heat in two periods of heat waves in 1994 and 2006. In a 35-year analysis of almost 50 cities of Spain, Achebak et al. (2018) pointed out that women were systematically more at risk to die from heat in case of circulatory and respiratory diseases. Mari-Dell'Omo et al. (2019) found a higher heat-related mortality risk in women than in men in the city of Barcelona, Spain, and the same result was obtained by Ellena et al. (2020) in the city of Turin, Italy.

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[2] Acronym for lesbian, gay, bisexual, transgender, queer, intersex and other diverse gender identities or sexual orientations

Other social criteria

If sex and gender are major drivers of heat vulnerability, other social aspects such as age, class or race, were also found to have an influence and all these criteria are often interlinked.

It has indeed been identified in multiple papers that age was an important driver of heat vulnerability, i.e., that heat-related mortality risk was increasing with age. Indeed, elderly people were found by Hajat et al. (2007) to be the most heat-vulnerable population group in a 10-year study in England and Wales. Yu et al. (2010) identified a clear association between age and high temperature-induced mortality in Brisbane, Australia. Kenny et al. (2010) highlighted the increasing risk for older people or people with medical conditions to develop a heat-related illness during heat waves. Arbuthnott and Hajat (2017) reviewed studies across the United-Kingdom and pointed out that elderly people consisted in the most vulnerable population group to heat stress. In a comprehensive study on the relation between health and climate change, the Lancet Countdown identified older populations to be particularly vulnerable to heat (Watts et al. 2019). In addition, Watts (2021) pointed out that heat-related mortality in 65+ people was increasing as a result of aging population in Europe and industrialised countries. What is more, the age factor is often interlinked with sex and gender, and elderly women form generally the most vulnerable group to high temperatures, as highlighted by several studies (Canouï-Poitrine et al. 2006, Hajat et al. 2007, Yu et al. 2010, Ellena et al. 2020).

A third factor that has been repeatedly analysed in association with heat-related mortality is the socio-economic status (SES), which informs on the level of income and on the access to medical treatment, information and social support. Papers studying the SES may involve criteria such as the level of education (Hondula et al. 2012, Aubrecht and Özceylan 2013, Klein Rosenthal et al. 2014, Huang et al. 2015, Ellena et al. 2020), the marital status (Fouillet et al. 2006, Gronlund et al. 2015, Inostroza et al. 2016, Ellena et al. 2020) or the household structure (Inostroza et al. 2016, Seebaß 2017, Ellena et al. 2020).

Ultimately, ethnicity has also been identified by a few studies as a driver of heat-related vulnerability and mortality (Uejio et al. 2011, Otto et al. 2017). O'Neill et al. (2005) found that the effects of heat on mortality were greater among Black populations than White populations in the US. Same results were also noted in the review on heat-related mortality in the US conducted by Basu (2009).

Studying heat-related mortality by social categories is essential for providing a consistent baseline on inequalities in vulnerability among the society and thus participating in developing relevant mitigation policies.

1.3 Present state of research

Many environmental epidemiological studies have been conducted on heat-related mortality and multiple methods of statistical regression have been used over the years to estimate the associations between heat and mortality, such as logistic regressions (Canouï-Poitrine et al. 2006, Stafoggia et al. 2006) or Poisson regression (O'Neill et al. 2005, Fouillet et al. 2006). A most recent framework of models, called distributed lag non-linear models (DLNM), has been developed in 2010 by Gasparrini et al. (2010). These models allow to represent non-linear and delayed effects of environmental stressors such as pollution or temperature on human health (i.e., on the development of disease or on mortality). DLNMs have since been widely used in numerous research studying heat-related mortality in different groups of population or in different places of the world (Gasparrini et al. 2015a, Gasparrini et al. 2015b, Huang et al. 2015, Achebak et al. 2018, Marí-Dell'Olmo et al. 2019, Ellena et al. 2020, Petkova et al. 2021, Urban et al. 2021).

In the Czech Republic, Hůnová et al. (2017) investigated the impacts on mortality of the 2003 and 2006 heat waves in Prague, and Urban et al. (2017) those of the 2015 heat wave in the whole country in comparison with the 1994 heat wave. Multiple studies have examined heat-related mortality in the country (Kyselý 2004, Kyselý and Kříž 2008) and a particular focus has been given on cardiovascular mortality (Kyselý et al. 2011, Hanzlíková et al. 2014, Urban et al. 2014, Urban and Kyselý 2014, Hanzlíková et al. 2015, Urban et al. 2016). Some of these studies segregated the analyses by sex and/or age (Kyselý et al. 2011, Hanzlíková et al. 2014, Hanzlíková et al. 2015) or by residence's location, i.e., comparing rural and urban environments (Urban and Kyselý 2014, Urban et al. 2016). However, to date, heat-related mortality in the Czech Republic has not been analysed through combination of social categories and no study focused the investigation on sex and gender inequalities. What is more, no Czech studies used DLNMs.

1.4 Objectives and structure of the study

In this study, a DLNM was developed to estimate the non-linear and delayed effects of summer temperatures on mortality in the Czech Republic for the period 1995-2019. The objective was to quantify heat-related mortality and to identify potential inequalities in heat vulnerability between different population groups of the country. A main focus of the analysis was given on the sex variable, and differentiated analyses for men and women were conducted. Sex was also studied while interlinked with other factors, namely the age, the marital status, the place of residence (whether rural or urban area) and the cause of death. Ultimately, the mortality attributable to heat was evaluated in order to account for the actual burden of heat in the total mortality of each population group.

This report is structured as follows. First, the data and study materials are presented in Chapter 2. Chapter 3 focuses on the methods used in this study: it provides an introduction to DLNMs, a description of the study design and of the method of selection of the model, and an interpretation of the outcomes of the models. The results are then presented and described in Chapter 4, and discussed in Chapter 5. Finally, Chapter 6 summarizes and concludes this study.

Chapter 2

Data

The study area was the Czech Republic (latitude from 48° 44’ 19.716” N to 51° 0’ 13.284” N and longitude from 12° 11’ 41.964” E to 18° 45’ 52.488” E), a country located in Central Europe, member of the European Union (EU) and whose capital city is Prague. Its total population was of about 10.7 million inhabitants in 2021[1] for a total area of almost 79,000 km^2. The climate is temperate, with warm temperatures in summer and cold temperatures in winter.

In order to analyse the associations between heat and mortality in the Czech Republic, two types of time series were used: daily mortality (i.e., the daily number of deaths) and daily average temperature in the country. The mortality data was provided by the Institute of Health Information and Statistics of the Czech Republic (UZIS) and the Czech Statistical Office (CZSO); the selection and pre-processing of the data is detailed in the next section. As for temperature, data was provided by the Czech Hydro-Meteorological Institute (CHMI)[2]; more details are given in section 2.2.

The period of study was defined by the availability of mortality data. It stretches from January 1, 1995 to December 31, 2019 for a total of 25 years, although only the five warmest months of the year (from May 1 to September 30, hereafter called summer months) were used in the models to catch the highest temperatures.

2.1 Mortality

The source mortality data listed all deaths that occurred in the country from 1995 to 2019. A total of 1,079,302 deaths were recorded during the summer months of the period covered by the study. For each deceased, the following pieces of information were collected: the date of death, the sex of the deceased, their age, level of education, nationality, marital status, residence district and the primary cause of death. These variables are detailed below.

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[1] Data from CZSO, available here

[2] Accessible here

Sex

The word « sex » has been chosen to be used when referring to the administrative category in the individual mortality data. Indeed, it usually refers to the sex assigned at birth, typically defined according to the external anatomy of the new-born (UN High Commissioner for Refugees 2021). The mention of sex in the Czech Republic is coded as a binary variable: male or female. During the period of the study, 49.08 % of the deceased were female and 50.92 % were male.

Age

The continuous age variable was transformed into a categorical variable by splitting the age range into categories. In order to have a balanced distribution of deaths among categories, the following four categories were defined: below 64 years old, between 65 and 74, between 75 and 84, and above 85. The distribution of the number of deceased in each category is shown in table 2.1.

Table 2.1: Distribution of the deceased within the age categories.

	0–64	**65–74**	**75–84**	**85+**
Total number	255,221	245,857	332,514	245,710
Proportion (%)	23.65	22.78	30.81	22.77

Level of education

The level of education was specified in the source data with a code representing the highest level of diploma obtained by the deceased. However, the codes having been changed in 2013 and because a lot of data was denoted as "unknown" (see Figure 2.1), this variable was not consistent and was consequently excluded from the analysis. Figure 2.1 represents the time evolution of the number of deaths by category of education level and shows the inconsistency of this variable.

Nationality

Concerning the nationality, only 1% of the deceased did not have the Czech citizenship during the period of study. Hence, this variable was not significant enough to be kept in the analysis. Additionally, no information was available about ethnicity or a potential country of origin, so no analysis was performed according to these criteria.

Marital status

In the source data, the marital status was divided from 1995 to 2013 into 4 categories: single, married, divorced and widowed. In 2013, three new categories were introduced: partnership, cancelled partnership and death of a partner. Indeed, same-sex couples,

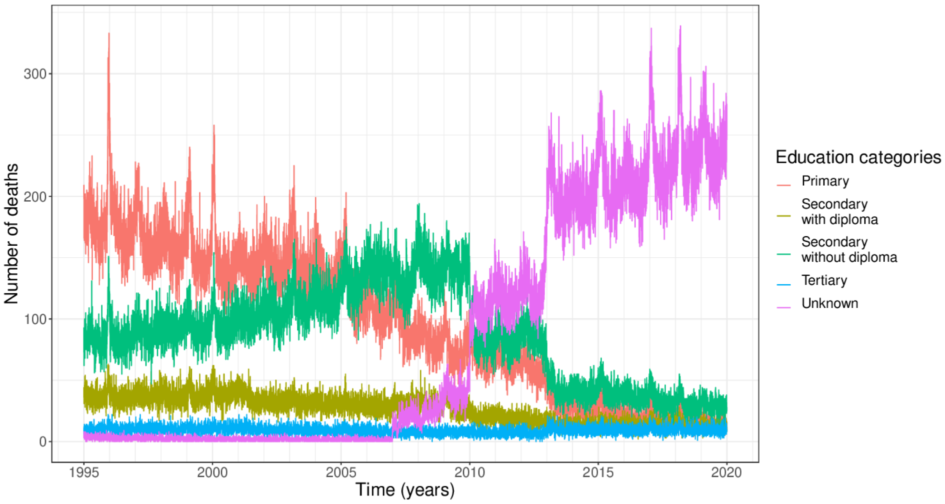

Figure 2.1: Evolution of the daily number of deaths from 1995 to 2019 in the Czech Republic by education category.

who do not have access to (heterosexual) marriage in the Czech Republic, are only entitled since 2006 to registered partnership. Registered partnership is an official union which confers both partners many of the rights of marriage, excluding adoption rights, joint taxes and the title "marriage".

In this study, no distinction was made between heterosexual and homosexual individuals, and all marital statuses were characterised by the following four categories: single, married, divorced and widowed. The distribution of the deceased in these categories is shown in table 2.2.

Table 2.2: Distribution of the deceased within the marital status categories.

	Single	**Married**	**Divorced**	**Widowed**
Total number	87,435	420,791	128,172	442,904
Proportion (%)	8.10	38.99	11.88	41.04

Location of residence

The place of the deceased's residence was encoded in the source data with the ISO 3166-2 code[3], an international standardisation nomenclature for representing the main subdivisions of a country. It splits the Czech Republic into 77 districts (76 "okres" and 1 capital city), as represented in Figure 2.2.

In this study, this variable was kept only as a binary variable differencing the deceased who were living in Prague, the capital city, from those who were living in the other regions of the country (hereafter denoted as the regions). Table 2.3 shows the distribution of the deceased in these two categories. Even if some areas of the regions are also urbanised (in particular around Brno), this distinction allows to have a simplified comparison between the urban and the rural areas of the country.

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[3] Described here

Table 2.3: Distribution of the deceased within the residence's location categories.

	Regions	**Prague**
Total number	951,263	128,039
Proportion (%)	88.14	11.86

It is also consistent with the population size and the economic gap between Prague and the rest of the country. Indeed, while representing only 0.6% of the total area, the capital city gathers 12.5 %[4] of the total population. As for the economic disparities, Prague produces most of the wealth of the country. In 2019, Prague concentrated 27.6% of the national gross domestic product (GDP)[5]. On the EU level, Prague ranked as the 10th richest region (out of the 244 EU regions defined by NUTS2 nomenclature[6]) in terms of GDP per capita in 2020[7], with a GDP per capita twice greater than the EU average. In comparison, the other regions of the country had a GDP per capita lower than the EU average by 25%.

Figure 2.2: Map of the Czech Republic subdivided into 77 districts according to ISO 3166-2 code.

Source: Mapového náložník, Public domain, via Wikimedia Commons

Cause of death

The primary cause of death was encoded in the source data with the International Classification of Diseases 10th revision (ICD-10), which is an international nomenclature for categorizing causes of death, developed among others with the WHO[8].

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[4] Data from CZSO, available here

[5] Data from CZSO, available here

[6] Described here

[7] Data from Eurostat, available here. See with Purchasing Power Standard per inhabitant in percentage of the EU27 average.

[8] Detailed here

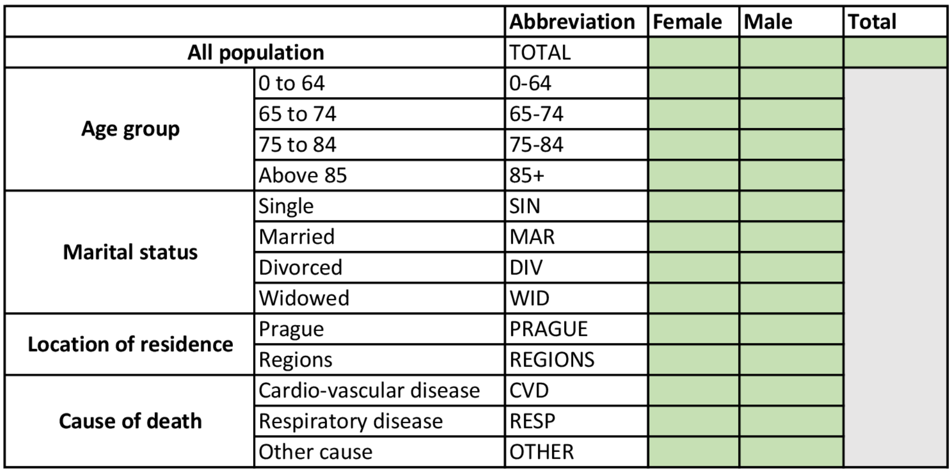
This variable was simplified in this study into three levels: the cardiovascular diseases (CVD, I00-99 in ICD-10), the respiratory diseases (J00-99 in ICD-10) and all the other causes of death. CVD and respiratory diseases were chosen to be observed because they have been documented in the literature to be more impacted by heat than other causes of death as highlighted in Chapter 1. Table 2.4 represents the distribution of the deceased within these three categories.

Table 2.4: Distribution of the deceased within the cause of death categories.

	CVD	**Respiratory disease**	**Other**
Total number	531,523	50,379	497,400
Proportion (%)	49.25	4.67	46.09

Study plan

In total, only five categories were kept: the sex, the age, the marital status, the location and the cause of death. Considering the focus of this thesis on differences between men and women, the categories of age, marital status, location and cause of death were not studied independently but only in combination with sex, defining in this way 29 categories. Table 2.3 lists the studied categories and specifies their abbreviations. For each category, the records of individual deaths were aggregated into the daily number of deaths, thus creating 29 time series to analyse. The total number of deaths per category is represented in Figure 2.4.



		Abbreviation	**Female**	**Male**	**Total**
All population		TOTAL	🟩	🟩	🟩
Age group	0 to 64	0-64	🟩	🟩	▨
	65 to 74	65-74	🟩	🟩	
	75 to 84	75-84	🟩	🟩	
	Above 85	85+	🟩	🟩	
Marital status	Single	SIN	🟩	🟩	
	Married	MAR	🟩	🟩	
	Divorced	DIV	🟩	🟩	
	Widowed	WID	🟩	🟩	
Location of residence	Prague	PRAGUE	🟩	🟩	
	Regions	REGIONS	🟩	🟩	
Cause of death	Cardio-vascular disease	CVD	🟩	🟩	
	Respiratory disease	RESP	🟩	🟩	
	Other cause	OTHER	🟩	🟩	

Figure 2.3: Summary of the 29 population groups analysed and their abbreviations.

2.2 Temperature

The source temperature data consisted in the daily mean temperature from 1995 to 2019 recorded in 16 stations spread across the Czech Republic, whose locations are shown in Figure 2.5.

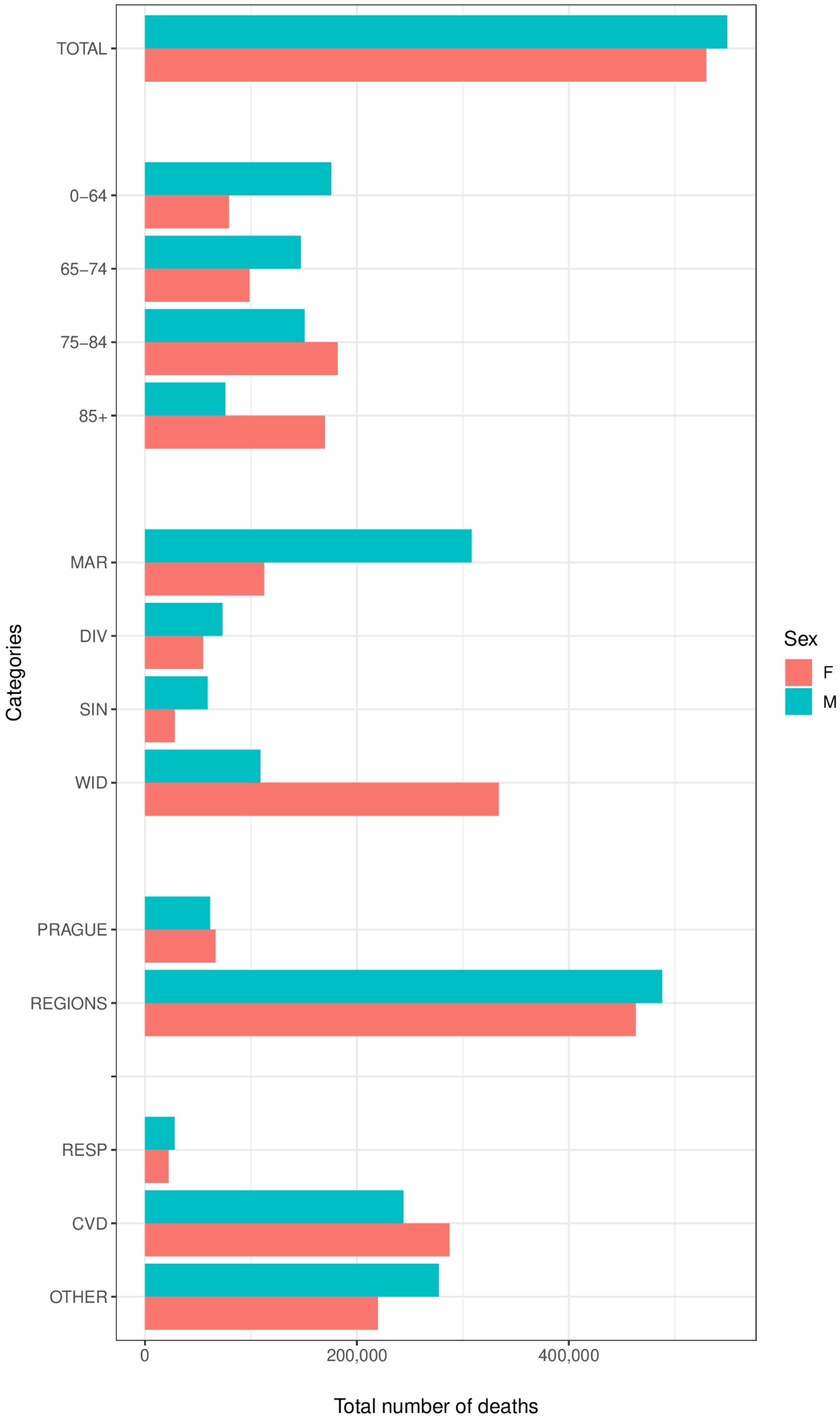


Figure 2.4: Total number of deaths by population group in the Czech Republic during the summer months of the period 1995–2019.

In most of the study, mortality was not analysed at a particular geographic location but for the country as a whole. Hence, it was associated with daily mean temperature in the whole country, which was computed by averaging the records of all 16 stations. As described in the previous section, only the deaths aggregated by sex and location were dependant on the geographical position: whether Prague or the regions. These four time series were associated accordingly with the daily mean temperature in Prague, taken from Prague-Ruzyně station, or with the daily mean temperature in the regions, which was obtained by averaging the 15 remaining stations.

Figure 2.5: Distribution in the Czech Republic of the 16 stations providing the daily temperature records.

Chapter 3

Methods

3.1 Introduction to DLNMs

Statistical regression modelling consists in finding a relationship between predictor variables and a response variable, in order to explain, analyse or predict a given phenomenon. The simplest approach is the linear model, that expresses the response variable as a linear combination of the predictors. In this case, the error of the response variable is supposed to follow a normal distribution. The generalised linear model (GLM) extends the linear model to all exponential families of error distribution (including normal but also binomial, Poisson and Gamma distributions) (Wood 2006). In GLMs, it is not directly the response variable, but a certain function of the expected value of the response variable, that is expressed as a linear combination of the predictors. This function is called the link function and depends on the chosen probability distribution. A GLM can be represented by the following equations:

$$\begin{cases} g(\mu_t) = \beta_0 + \sum_{i=1}^{n} \beta_i x_{ti} \\ \mu_t = \mathrm{E}(Y_t) \end{cases} \tag{3.1}$$

where $t = 1, \ldots, T$ is the time, Y_t the response variable that follows a given distribution with expected value μ_t, x_{ti} the i^{th} predictor with $i = 1, \ldots, n$, g the link function and β_i the parameters to estimate. The parameters β_i of a GLM are generally fitted with maximum-likelihood estimation (Wood 2006).

Non-linearity can be introduced in a GLM thanks to the use of a basis (Drury 2017), a space of functions describing smooth curves which apply a transformation to the predictors. The transformed variables are included in the linear combination and the equations become:

$$\begin{cases} g(\mu_t) = b_0 + \sum_{i=1}^{m} \beta_i x_{ti} + \sum_{i=m+1}^{n} s_i(x_{ti}, \boldsymbol{\gamma}_i) \\ \mu_t = \mathrm{E}(Y_t) \end{cases} \tag{3.2}$$

where the predictors $x_1, \ldots, x_m$ are modelled as a simple linear combination and $x_{m+1}, \ldots, x_n$ via smooth functions s_i with parameters $\boldsymbol{\gamma}_i$. Although the transformations applied by smooth functions are non-linear, the resulting equation conserves its linear property (Perperoglou et al. 2019).

Usually, the smooth functions used in GLMs are polynomial or spline functions. Spline functions are piecewise polynomial functions, in which pieces are separated by internal knots (Perperoglou et al. 2019). The number of knots is called the degree of freedom, and it should not be confused with the degree of the spline, which corresponds to the degree at most of the polynomials used in the spline. Splines of degree 2 and 3 are respectively called quadratic and cubic.

However, in some problems, the response variable is not instantly impacted by the exposure to the predictors; the effects are delayed in time. This can specifically be observed when modelling the effects of environmental stressors such as air pollution or temperature on human health. Indeed, studies have shown that the effect of temperature on mortality can be delayed. Anderson and Bell (2009) stated that cold effects could occur up to 25 days of lag, and that heat-related mortality was usually associated with shorter lags, from 1 to 2 days. Moreover, heat-related mortality often presents a mortality displacement pattern, also called harvesting effect, which is a period of deaths deficit following a period of deaths increase. It often suggests that vulnerable people who were in any case going to die in the near future, died earlier because of heat stress (Zanobetti 2000, Hajat et al. 2005).

Although GLMs allow to model a large range of problems, they do not catch such delayed effects. Distributed lag non-linear models (DLNM) are a family of models introduced by Gasparrini (2010) that allow to describe non-linear and delayed effects of an exposure to stressors — in particular environmental stressors. As their predecessors the distributed lag models (DLM) (Zanobetti 2000), these models rely on introducing in the linear combination values of the predictors at past lags.

The specificity of a DLNM resides in defining a cross-basis. A cross-basis is a 2-dimensional basis that describes the relationships along both the exposure-response dimension and the lag-response dimension. It is generated by combining 2 spaces of functions: one describing the exposure-response relationship and the other describing the lag-response relationship. The obtained cross-basis matrix may be integrated in the GLM model.

Different statistical tools enable the application of GLMs and DLNMs, among which the programming language R, specifically conceived for statistical computing. Gasparrini developed the R package dlnm (2011) that includes functions for designing, fitting and predicting DLNMs. Designing a DLNM within a GLM consists in defining the family distribution, the shape of the functions in both spaces of the cross-basis, and potentially the shape of other predictors. Many options are possible for setting the parameters, depending on the data specificities and the aim of the study. The design chosen for this study is described in the next section.

3.2 Study design and selection of the model

In this study, a case-crossover study design was applied to analyse the effect of heat on mortality among selected population groups in the Czech Republic (from 1995 to 2019) stratified by sex, age group, marital status, place of residence and cause of death. More specifically, a time series regression using a generalized linear model (GLM) following a quasi-Poisson family was applied separately on each population group to estimate group-specific temperature-mortality associations. To analyse the short-term associations between temperature and mortality, times series were adjusted for long-term trend and seasonal patterns. The effect of temperature on mortality was reported as relative risk (RR), which means the ratio of the probability of dying in the exposed versus unexposed population. To take into consideration the delayed effects of thermal conditions on mortality, the exposure-response association was modelled using a distributed lag non-linear model (DLNM). This study focusing on the effects of heat, only the five warmest months of the year (from May to September) were used in the model.

The Poisson family allows to model count variables (i.e., discrete positive variables) assuming that their variance equals their expected value. Quasi-Poisson family relaxes this restriction by allowing the variance to be proportional to the expected value, which is appropriate when the data is over dispersed (i.e., the variance is higher than the mean) (Wedderburn 1974). This is a common feature of mortality data, especially within population groups with low number of daily deaths (Istiana et al. 2020). Figure 3.1 shows the mortality distribution of each population group. In this context, the quasi-Poisson family was consequently particularly relevant. The corresponding link function is the log function.

Using the same algebraic formulation than Ellena et al. (2020), the final model designed in this study can be described as follows:

$$\begin{cases} log(\mu_t) = \alpha + cb + DOW_t & + ns(DOY_t, df = 2) : factor(year_t) \\ & + ns(time, df = 1\,per\,decade) \\ \mu_t = \mathrm{E}(Y_t) & \end{cases} \tag{3.3}$$

where Y_t is the daily count of deaths, μ_t its expected value, α the intercept, cb the cross-basis matrix, DOW the categorical variable of the day-of-the-week, DOY the day-of-the-year and ns stands for natural spline.

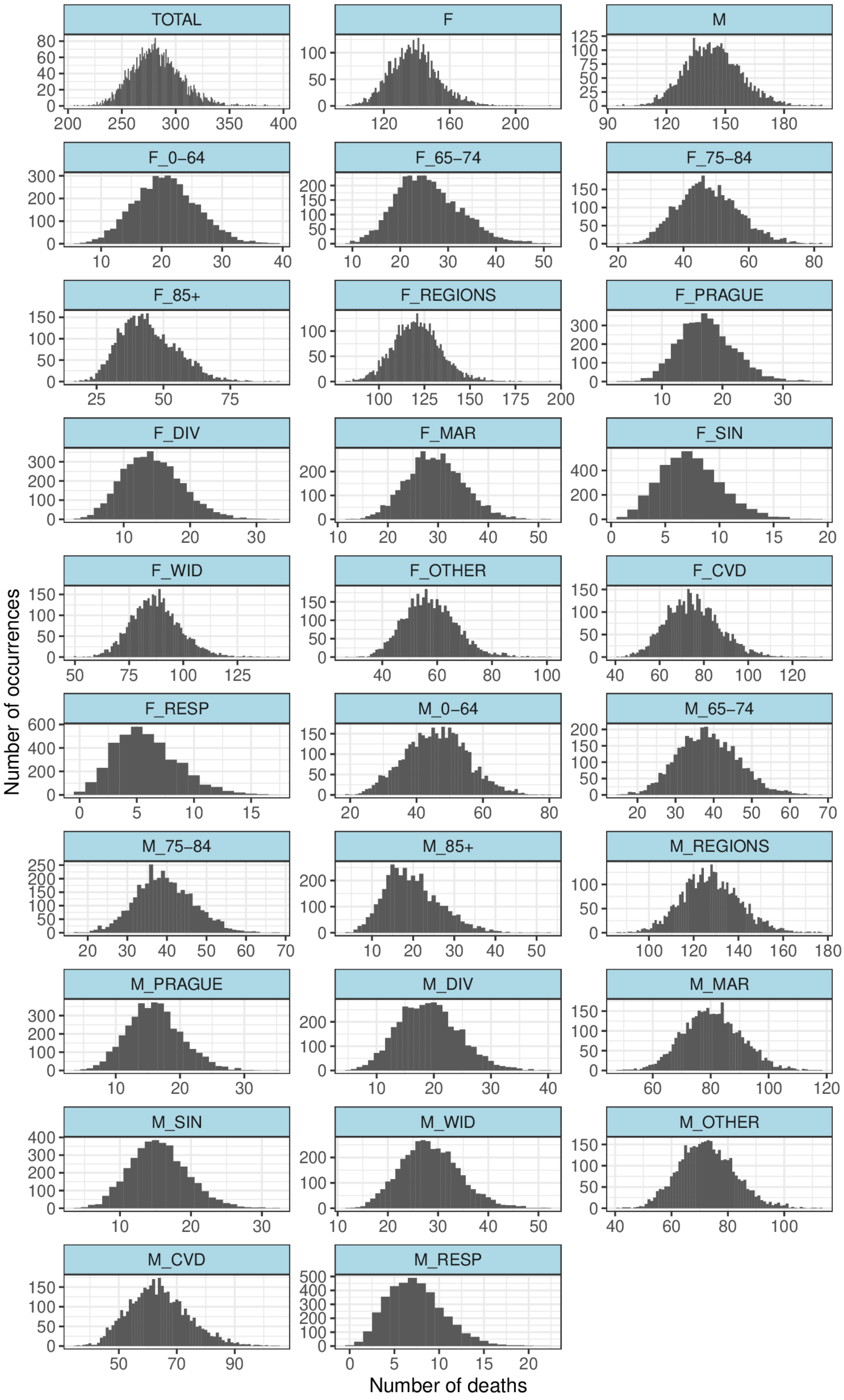


Figure 3.1: Distribution of the daily number of deaths during the summer months of the period 1995–2019 in the Czech Republic by population group.

The DOW is a factor variable with 7 levels (i.e., 7 days of the week) which allows to catch the weekly pattern of mortality.

The DOY allows to describe the seasonal pattern. Following previous research, the DOY was modelled with a natural cubic spline with 2 degrees of freedom per year. An interaction (denoted as ":" in the above formula) between the spline and the year was also included in order to allow the degrees of freedom to vary from one year to another (Achebak et al. 2018, Ellena et al. 2020).

Since the total annual mortality level changed over time due to demographic and socio-economic factors, the time variable allows to catch these long-time trends. With reference to prior research (Achebak et al. 2018, Ellena et al. 2020), it was modelled with a natural cubic spline with 1 degree of freedom per decade.

The non-linear and delayed effects of temperature on mortality were modelled by a cross-basis combining two functions describing respectively the temperature-mortality and the lag-mortality associations. The temperature-mortality curve was described by a quadratic spline with 1 internal knot placed at the 75^{th} percentile of temperature. The lag-mortality curve was controlled by a natural cubic spline with 2 internal knots equally spaced on the log scale. The lag period was extended to 14 days.

The design choices were based on models presented in previous papers (Achebak et al. 2018, Ellena et al. 2020). Additionally, the number and position of knots in the temperature-mortality space as well as the number of lags in the lag-mortality space were chosen after performing a sensitivity analysis. All combinations of number of lags from 7 to 14, and of position of knots among 0.5, 0.75, 0.9 and both 0.5 and 0.9 were tested on 10 times series (mortality by sex and by sex and age).

It is common to compare GLMs with the Akaike information criterion (AIC, Akaike 1974), an indicator that balances the complexity of a model (i.e., its number of parameters) with its goodness of fit to the data (via with its likelihood). It gives an information on the quality of a model relatively to others. However, for quasi-models such as quasi-Poisson models, only quasi-likelihood functions can be defined (Wedderburn 1974). By extension, the quasi-AIC (QAIC) can be calculated (Bolker 2009) to compare quasi-Poisson models between each other.

The models tested in the sensitivity analysis were compared with the QAIC. Figure 3.2 represents the averaged QAIC obtained with each combination of parameters and shows that the higher the lag and the better (smaller) the QAIC.

All models and calculations were implemented and executed on the software R (version 4.1.2), with the use of the package dlnm (version 2.4.7) developed by Gasparrini (2011).

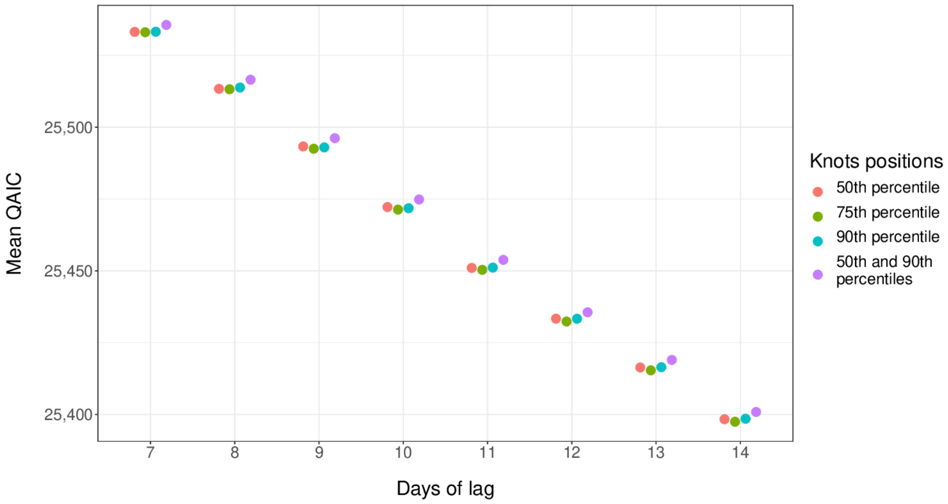


Figure 3.2: Evolution of the quasi-Akaike information criterion (QAIC) averaged over 10 models by lag and knots position.

3.3 Interpretation of heat-related mortality

The main outcome of (quasi-)Poisson regression models are regression coefficients of the modelled variables whose exponents are equal to the relative risk (RR) of mortality. In environmental epidemiology, coefficients of the exposure variable (e.g., temperature or air pollution) are of main interest. In the case of GLMs, the RR of exposure-related mortality is equal to a linear change in mortality per each unit of increase/decrease in the exposure variable (e.g., change in temperature by 1 °C) above/below a certain threshold.

Compared to GLMs, DLNM results have an additional time dimension and provide an estimation of the response given an exposure for each lag. In this case, the RR of mortality is expressed as the overall ratio between the probability of response at a given exposure and the probability of response at a reference exposure, while taking into account the lagged effects. In particular, in this study, the RR expresses how many times higher the risk of dying at a given temperature is, relatively to a reference temperature.

The reference temperature (also called the MMT for minimal mortality temperature) corresponds to the centring value of the temperature-mortality basis. The centring value does not impact the fit of the model and is only used as a reference for prediction (Gasparrini 2011). In this study, the MMT was defined for each model in two steps. First, it was set by default to the mean temperature and a first prediction of RRs was computed. Then, this first prediction was used to adjust and change the reference temperature into the temperature situated between the 50^{th} and the 90^{th} percentile for which the predicted RR was minimal.

As the resulting outcome of a DLNM is a 3-dimensional matrix (temperature, lag, RR), it is useful to compute the overall exposure-response function by summing all the contributions of each lag. It allows to reduce the number of dimensions (temperature, overall RR) and to characterize the overall effect of temperature over the whole lag period (i.e., taking into account the effect of mortality displacement). Finally, the unidimensional benchmark that is usually used to assess and compare the heat-related mortality risk between different groups of population is the overall RR at a specified temperature percentile. In this study, the 99th percentile of May-September daily mean temperature distribution over the study period (hereafter noted 99th RR) was chosen following many other studies (Gasparrini et al. 2015b, Achebak et al. 2018, Marí-Dell'Olmo et al. 2019, Ellena et al. 2020, Petkova et al. 2021). The 99th percentile allows to account for the effect of extreme temperatures. Figure 3.3 represents the summer temperature distribution in the Czech Republic, Prague and the regions and the corresponding 99th percentiles in red.

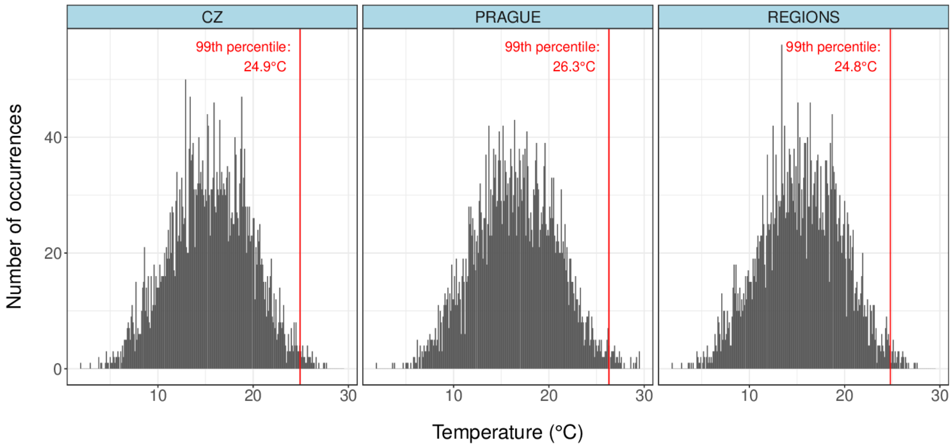


Figure 3.3: Summer temperature distribution in the Czech Republic, Prague and the regions over the period 1995–2019 (in grey) and the corresponding 99th percentiles (in red).

The 99th RR was computed for each of the 29 groups analysed in this study. A significance analysis of the 99th RRs was performed by sex in order to assess the sex differences in the results. The statistical significance of the difference between the individual population groups was evaluated by an interaction test according to Altman and Bland (2003, 2011), using the following formula:

$$Z = \frac{E_1 - E_2}{\sqrt{SE_1^2 + SE_2^2}} \tag{3.4}$$

where Z is the Z-test, E_1 and E_2 are the log transformation of the RR estimates of 2 groups and SE_1 and SE_2 are their respective standard error.

While the 99th RR characterizes the mortality risk after heat exposure and allows comparison between groups, it does not assess the actual impact of heat on mortality.

The attributable fraction (AF) of deaths represents the portion of deaths among all summer deaths associated with high temperatures, and the attributable number (AN) their absolute number (AN=AF*number of all summer deaths). They are a way to express the burden of heat-related mortality upon the total mortality. The AFs and ANs for each of the 29 groups were calculated for the 95th percentile of May–September daily mean temperature distribution over the study period, which is usually considered as the heat wave threshold. These computations were performed with the R function attrdl (attributable risk from distributed lag non-linear models) developed by Gasparrini and Leone (2014).

Chapter 4

Results

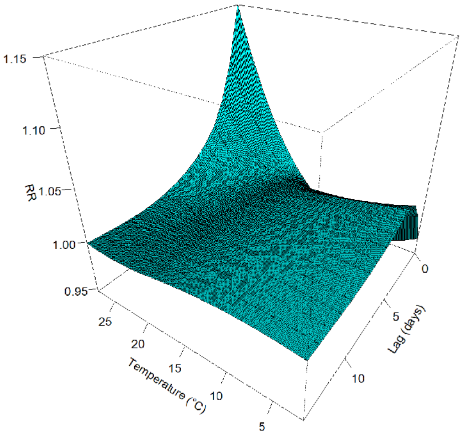
The 29 time series representing mortality from 1994 to 2019 in the Czech Republic in different population groups have been modelled using DLNMs with quasi-Poisson family distribution, as presented in the previous chapter. For each of them, relative risks (RR) have been obtained for the whole range of summer temperature and lags from 1 to 14 days.

Figure 4.1 shows the variations of the RR depending on lag and temperature on 3-dimensional plots for the total population (4.1a), men (4.1c) and women (4.1b). The surfaces are shaped as expected: high mortality RRs associated with high temperature in the first days of lag, followed by a decrease towards RR=1.

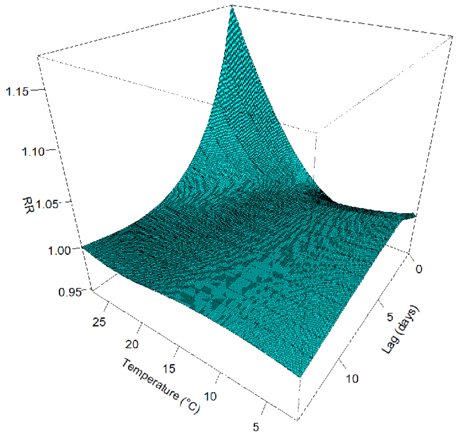
Figure 4.2 provides a visualisation of the results in 2 dimensions.

Subfigure 4.2a depicts the RR variations as a function of the lag at the 99th percentile of summer temperature (24.9 °C) for the total population (in blue), men (in green) and women (in red). The curves present the same shape: an exponential decrease starting from significantly positive mortality RRs just after the exposure to heat down to RR values lower than 1. This decrease below 1 (from around 7 days of lag in these 3 cases) corresponds to the mortality displacement phenomenon in which the first days with excess mortality are followed by a period of deaths deficit.

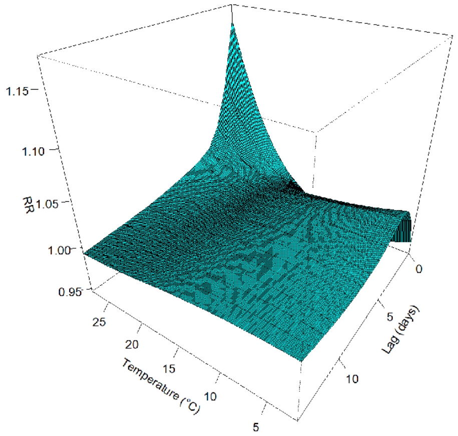
Subfigure 4.2b shows the variations of the overall RR (i.e., the RR aggregated over the whole period of 14 days) depending on temperature for the total population, men and women (respectively in blue, green and red). The vertical lines represent the MMT of each group (respectively 18.9 °C, 19.4 °C and 15.7 °C) as well as the 99th percentile of temperature in purple (24.9 °C). The 3 curves follow the usual U-shape of temperature-mortality association, with mild risk in low temperature (slightly over 1), minimal risk at the MMT (RR=1) and a significant increase in risk in high temperature.



(a) Total population

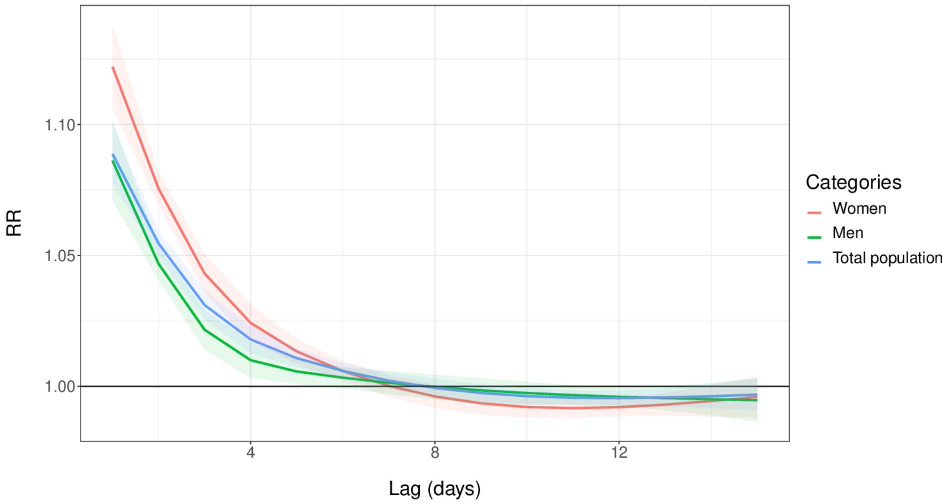


(b) Women

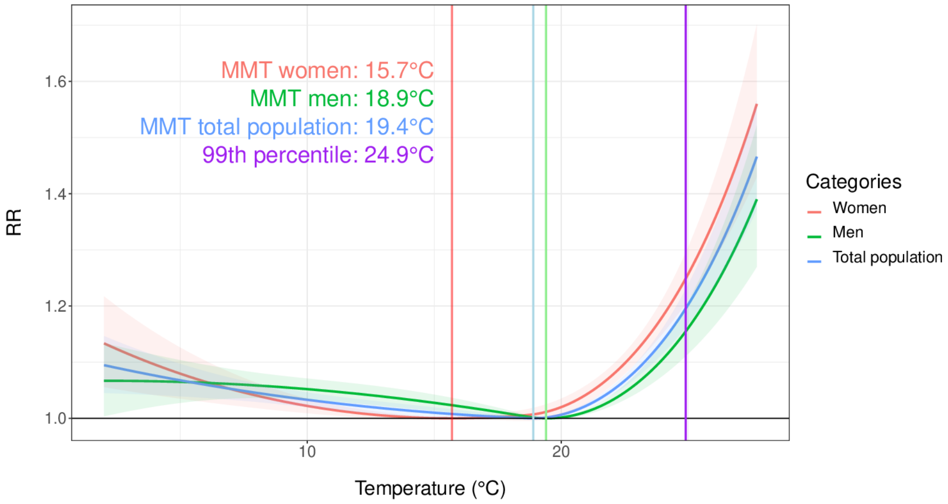


(c) Men

Figure 4.1: Temperature-lag-mortality association between summer temperatures, days of lag and mortality relative risk (RR) in the Czech Republic over the period 1995–2019 by sex.



(a) Lag-mortality association between the days of lag and mortality relative risk (RR) at the 99th percentile of summer temperatures (24.9 °C) by sex.



(b) Overall temperature-mortality association between the summer temperatures and the mortality relative risk (RR), and the Minimum Mortality Temperature (MMT) by sex.

Figure 4.2: Lag-mortality association at the 99th percentile of summer temperature (a) and overall temperature-mortality association (b) in the Czech Republic over the period 1995–2019 by sex.

Similar curves have been obtained for the other 26 groups, although for readability reasons, they are not displayed in this report. However, table A.1 in appendix provides a summary of the number of deaths, the MMT, the 99th RR and their 95% confidence intervals of each group. The 99th RRs and their 95% confidence intervals can also be visualised in Figure 4.3.

The outcomes of the significance analysis performed by sex on the 99th RR differences are displayed on a heatmap in Figure 4.4. The colors represent different p-value thresholds (from 0.05 to 0.0001). 99th RR differences were considered significant for a p-values smaller than 0.05.

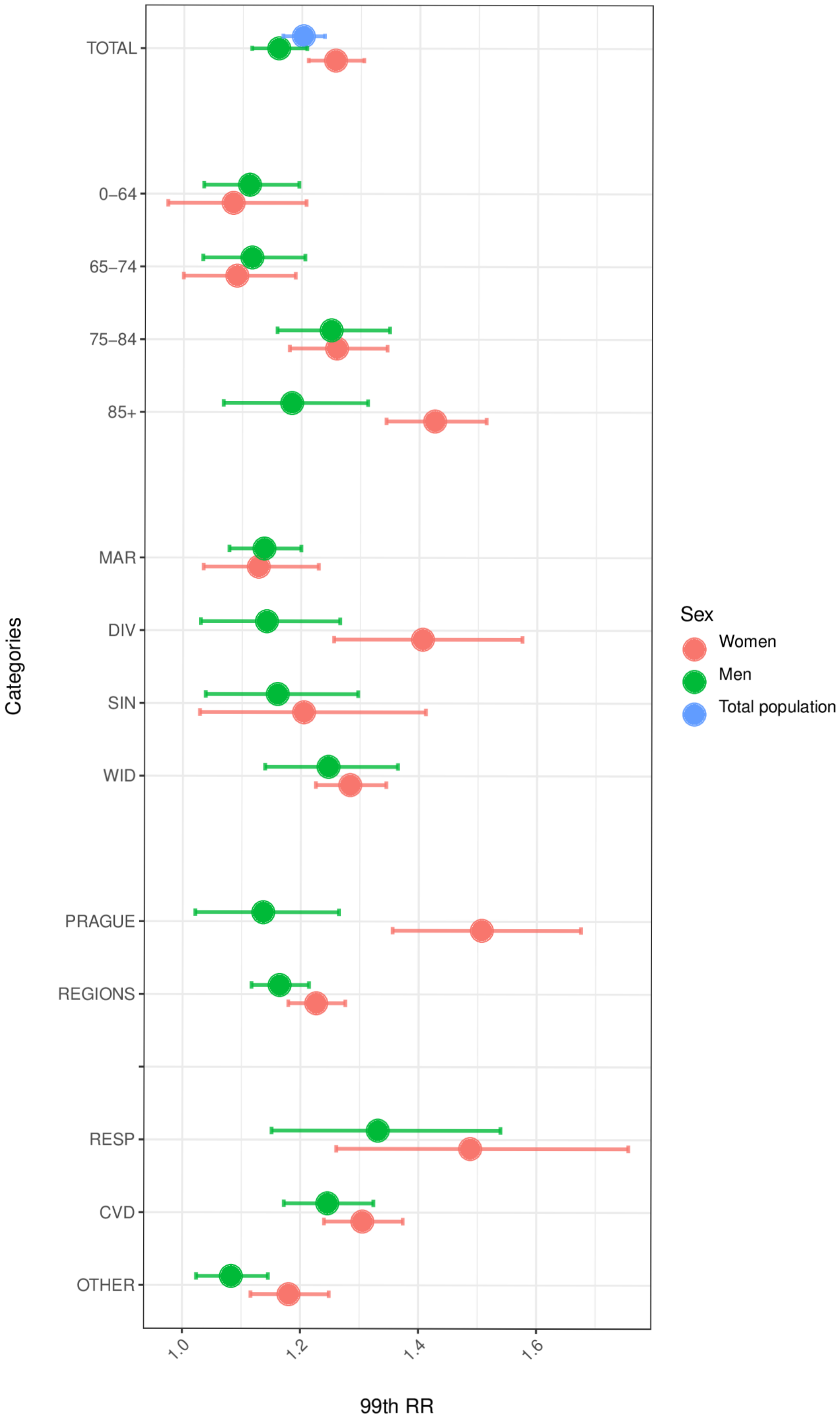


Figure 4.3: 99$^{\text{th}}$ RR and their 95% confidence intervals by population group.

Table A.2 in appendix gathers the AF and AN values obtained for each population group, i.e., respectively the fraction and absolute number of summer deaths in each

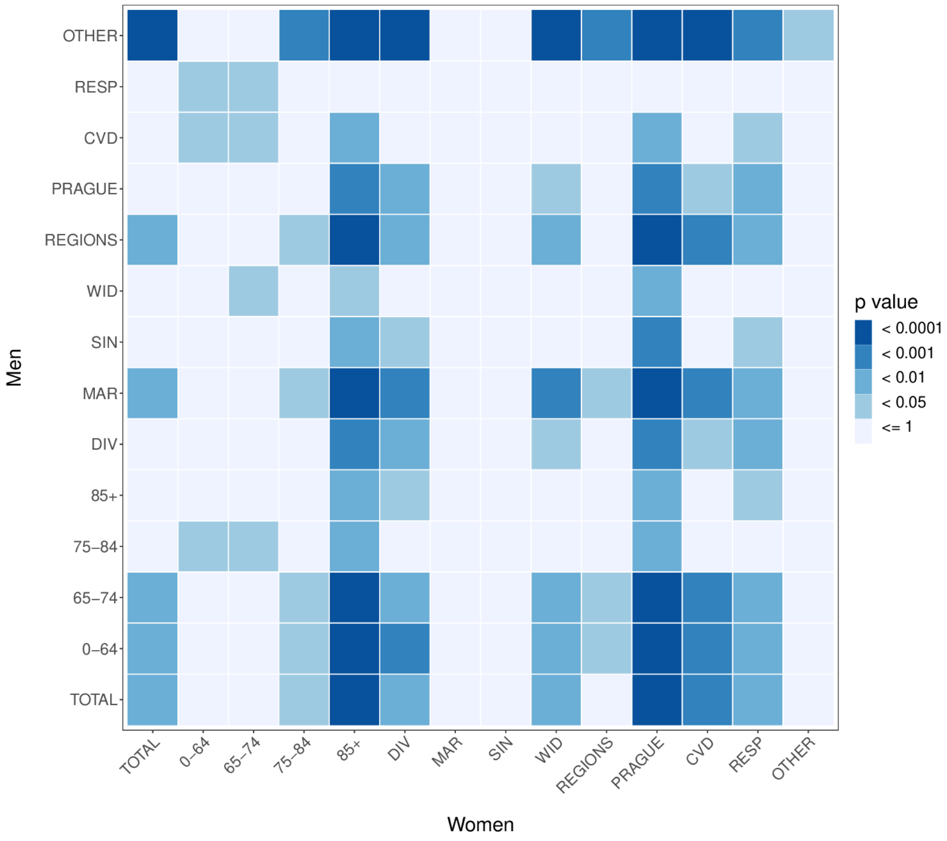


Figure 4.4: P-values of an interaction test determining the statistical significance of the 99th RR differences between the individual population groups.

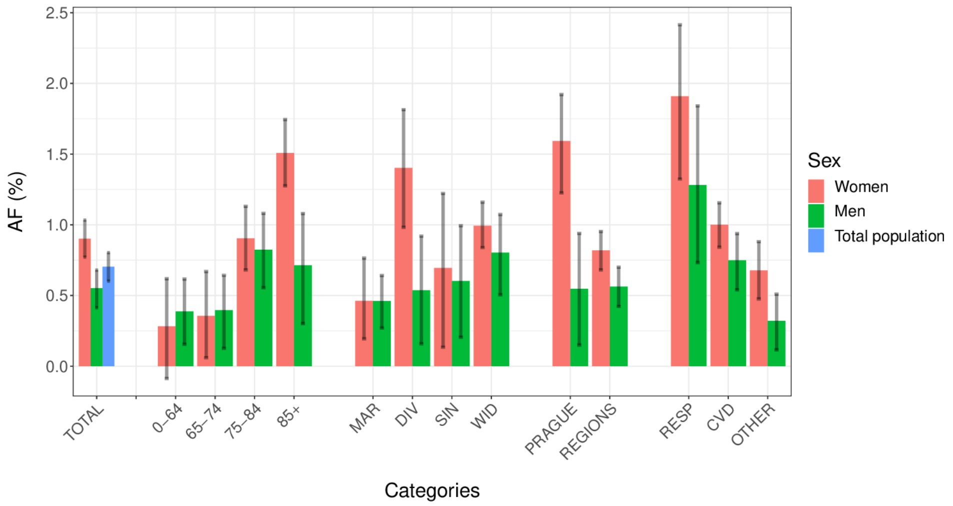
population group that are attributable to heat. These figures are also displayed in the form of bar-plots in Figure 4.5.

The figures introduced and displayed above provide an overview of the results. They are described thoroughly by social groups in the following sections.

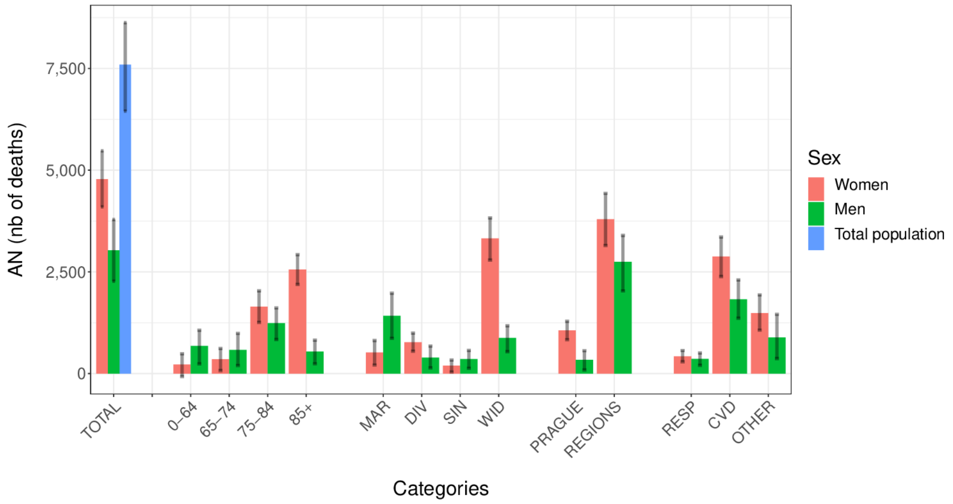
4.1 Sex

Figure 4.2 shows different vulnerability to heat between men and women. Indeed, at the 99th percentile of temperature, the risks for women were higher than those for men in the first 7 days after exposure; and the mortality displacement was thus greater afterwards (Figure 4.2a). On the whole lag period, the MMT was found lower by 3.7 °C for women (15.7 °C) than for men (19.4 °C). What is more, women presented a higher overall mortality risk than men at temperatures higher than the MMT (Figure 4.2b). In particular, at the 99th percentile of temperature, the overall mortality risk was significantly higher (p-value < 0.01) among women (1.26, 95% confidence interval: 1.21–1.31) than among men (1.16, 1.12–1.21).

Sex inequalities in heat vulnerability were also observed through the other cate-



(a) AF



(b) AN

Figure 4.5: Attributable fraction (AF) and attributable number (AN) and their 95% confidence intervals obtained by population group in the Czech Republic over the summer months of the period 1995–2019.

gories (age, marital status, residence location and cause of death). The values of the 99$^{\text{th}}$ RRs for women were higher than those for men in 10 out of 13 sub-categories; and those differences were significant for 4 of them (people above 85, divorced, living in Prague and who died from other cause than CVD or respiratory disease). In the 3 sub-categories for which the 99$^{\text{th}}$ RRs were greater for men than for women (0–64, 65–74 and married), the differences were not found significant.

4.2 Age

The risks in each age category presented almost no disparity between men and women, except for the "85+" category.

Indeed, for both sexes, the lowest risk was found among people younger than 74 years old (categories "0–64" and "65–74"). The 99th RRs obtained for men younger than 74 were slightly higher than those for women younger than 74, but the differences were not found significant.

For women, the risk grew with age, and the highest risk for women was found among women older than 85 (1.43, 1.34–1.51). In contrast, the highest risk for men was smaller and was found among men between 75 and 84 (1.25, 1.16–1.35).

Women above 85 had a much higher risk than men above 85 and the difference between the 99th RRs of these two categories was significant (p-value < 0.01): 1.43 (1.34–1.51) for women versus 1.18 (1.07–1.31) for men.

4.3 Marital status

A similar pattern was found when considering the marital status: apart from the "Divorced" category, the risks in each of the other categories were quite similar for men and women.

For both sexes, the lowest risk was obtained among married people, but the 99th RR was slightly higher for married men than for married women: respectively 1.14 (1.08–1.2) and 1.13 (1.03–1.23), although the difference was not found significant.

Women had the highest risk when they were divorced (1.41, 1.26–1.57), while men had the highest risk when they were widowed (1.25, 1.14–1.36). Divorced women were found to be significantly more (p-value < 0.01) at risk than divorced men: 1.41 (1.26–1.57) versus 1.14 (1.03–1.27).

4.4 Residence location

Concerning the residence location, the risk among women was higher for the women living in Prague than for those living in the regions: 1.47 (1.31–1.64) versus 1.23 (1.18–1.28). On the contrary, the risk among men was higher for men living in the regions: 1.17 (1.12–1.22), than for those living in Prague 1.11 (0.99–1.24).

Women living in Prague were found to be particularly more vulnerable to heat than any other group of this category. The 99th RR differences between them and men, whether living in Prague (p-value < 0.001) or in the regions (p-value < 0.0001), were statistically significant.

4.5 Cause of death

With regard to the cause of death, the 99th RRs ranked the categories in the same order for both men and women, with higher risks for women than for men. The highest 99th RRs were found for the respiratory diseases (1.33, 1.15–1.54 for men and 1.49, 1.26–1.76 for women) and then for cardiovascular diseases (1.25, 1.17–1.32 for men and 1.31, 1.24–1.37 for women). The other causes of death obtained lower but non-negligible 99th RRs (1.08, 1.02–1.15 for men and 1.18, 1.12–1.25 for women).

4.6 Attributable fractions (AF) and attributable numbers (AN)

The results of AF (see Figure 4.5a) showed that the deaths which occurred during the summer months of the study period among the total population were attributable to heat in 0.7% (0.60–0.81) of the cases. Women were proportionally more affected by heat than men (0.9%, 0.77–1.03 for women versus 0.55%, 0.43–0.69 for men). The smallest AF was found for women younger than 64 (0.28%, 0–0.62) and the highest for women who died from respiratory diseases (1.91%, 1.28–2.53). The values obtained for women living in Prague (1.59%, 1.24–1.9), women above 85 years old (1.51%, 1.28–1.73), divorced women (1.40%, 0.99–1.78) and men who died from respiratory diseases (1.28%, 0.74–1.82) were also noteworthy (greater than 1.25%).

The results of AFs were consistent with the 99th RRs as they ranked the categories in the same order in terms of heat vulnerability.

However, ANs (see Figure 4.5b) provide a different perspective on the overall burden of heat on the total mortality as they show the actual number of deaths attributable to heat between 1995 and 2019. According to the results, almost 7,600 (6,499–8,688) deaths that occurred among the whole population during the summer months of the study period were caused by heat. Among them, more women (4,780, 4,074–5,473) died because of heat than men (3,030, 2,274–3,796). The other categories in which heat was found to cause a large number of deaths (above 2,500) during the summers of the study period were the men and women living in the regions (respectively 2,747, 2,034–3,463 and 3,793, 3,143–4,472) and the women who were widowed (3,320, 2,799–3,845) or above 85 years old (2,560, 2,182–2,921) or who died from CVD (2,875, 2,402–3,396).

Chapter 5

Discussion

This study assessed the effects of summer temperatures on mortality in the Czech Republic over 25 years, with results segregated by sex, age, marital status, residence's location and cause of death. The relative risks at the 99th percentile of daily summer temperature (99th RRs) obtained for each category ranged between 1.08 and 1.51, which is inline with similar studies using DLNMs in European countries (Gasparrini et al. 2015b, Petkova et al. 2021). Studies conducted in Southern Europe usually obtained higher 99th RRs (Achebak et al. 2018, Marí-Dell'Olmo et al. 2019, Ellena et al. 2020) which is consistent with warmer climate (Urban et al. 2021).

The results obtained in this study showed that heat-related mortality risk differed by each analysed category. Indeed, higher risks were obtained among women than among men in the whole population and in almost all sub-categories. Elderly, in particular women above 85 years old, were found to be at higher risk than younger people. Non-married people and specifically divorced women were found more vulnerable than married people. Residence's location also had an influence on heat vulnerability: women living in Prague were found at higher risks than women living in the regions. Finally, deaths from respiratory diseases and CVD were found more sensitive to heat than other causes of deaths.

In general, results confirmed the expected hypothesis that social criteria affected the vulnerability to heat and, in particular, that sex and gender inequalities existing in the society were visible through heat vulnerability. If sex and gender are an important social drivers, it is important to inter-link them to social class, a determining factor in an individual's access to all types of resources and health care. It can be characterized by the socio-economic status (SES), which is a sociological measurement of the social and economical position of an individual in the society based on the level of education, the income and the occupation. In this study, although no direct indicator of the SES of the deceased was available in the individual mortality data, results can nevertheless provide useful information when crossed with general socio-economic data provided by the Czech Statistical Office (CZSO).

5.1 Socio-economic status (SES) in the literature

Strong linkages between the socio-economic status and the heat-related mortality did not always show through the 99^{th} RR values found in the literature. For example, Arbuthnott and Hajat (2017) have not found any particular influence of the SES while reviewing studies treating the heat vulnerability in the United Kingdom. However, they underlined that a link was found in United States studies (O'Neill et al. 2003, Schwartz 2005). Several other studies (Stafoggia et al. 2006, Basu 2009, Otto et al. 2017) also suggested that low levels of education or low incomes could enhance the vulnerability to heat.

This greater vulnerability may arise from less comfortable housings, with potentially less aeration, less use of air conditioning (AC) and more humidity. In urban areas, lower SES could mean less access to green infrastructures (Otto et al. 2017); and for working people, it could suggest more time working outdoor or manual work, found to be risk factors (Watts et al. 2021, Y. Xu et al. 2013). Finally, poverty might lead to more health conditions and presence of co-morbidities, which also increase the vulnerability to heat.

5.2 Sex and gender

In this study, women were found to be at higher risk than men, and this result is in line with numerous other studies. For example, during the 2003 French heat wave that caused 15,000 excess deaths in three weeks, the overall excess mortality was 75% higher among women than among men (Fouillet et al. 2006). Greater heat-vulnerability among women was also highlighted in other studies conducted in different regions of Europe, e.g., in Italy (Stafoggia et al. 2006, Ellena et al. 2020), Germany (Gabriel and Endlicher 2011), Spain (Achebak et al. 2018, Marí-Dell'Olmo et al. 2019), or of the world, such as in Brisbane, Australia (Yu et al. 2010) or China (Huang et al. 2015).

This disparity by could be caused by some physiological differences. Indeed, some historical studies suggested that women had less capability than men to regulate the temperature of their body under heat stress (Fox et al. 1969, Burse 1979). However, Yanovich et al. (2020) highlighted a certain bias in past research with regard to female thermoregulation, and Charkoudian and Stachenfeld (2014) pointed out that historical studies were often confounded by disparities in anthropometric measurements (e.g., body size, fitness level) of the men and women subjects. More recent and "well-controlled" studies have shown that there were no major physiological differences between men and women regarding thermoregulation in situation of exercising (Yanovich et al. 2020) or body heating (Charkoudian and Stachenfeld 2014). Charkoudian and Stachenfeld (2014) also underlined that, although reproductive hormones (oestrogen, progesterone and testosterone) had an actual impact on thermoregulation, they did not lead to major sex differences in heat regulation; and Lei et al. (2017) found that menstrual cycles were not affecting the “heat loss responses” at rest or during exercise. Hence, although more studies would be needed, physiological differences between men and women does not appear as the major factor of a greater heat vulnerability.

Another suggestion is that differences in the impact of heat stress between men and women could be linked to economic inequalities. According to the CZSO report “Focus on men and women” (2021), the gender pay gap in the Czech Republic was the 5th highest in the European Union, with men being paid on average 18.9% more than women in 2018. This same report also pointed out that women were less professionally active than men, and this was because, in a majority of cases, they were in charge of taking care of adults with disabilities or children. They were also more likely to be unemployed (especially when they have children) or to have definite-period or part-time contracts. These disparities in employment and income may lead to more fragile economic level in women. According to the European Institute for Gender Equality (EIGE 2017), 10% of women were at risk of poverty in the Czech Republic in 2017, against 7% of men.

Finally, it has been underlined that mortality and health risks could be acquired through gendered roles and behaviours in place in the patriarchal society (Oksuzyan et al. 2010). Otto et al. (2017) suggested for example that women were more exposed to heat as they spend on average more time inside, potentially without proper aeration or AC.

Nevertheless, the categorisation of sex and gender used in this study has some limitations. The original individual mortality data only provided a mention of sex as a “male” or “female” category, which fails at depicting the large continuum of gender identities existing in the society. In about 15 countries such as Germany, a third sex or gender option has been introduced in the jurisdiction, and this allows to account for non-binary[1] and/or intersex people (ILGA-Europe 2018). The binary mention of sex might also misrepresent the experience of sex and gender of transgender people[2], whether they go or not through legal gender recognition[3]. No consistent data was found on the number of people who disrupt the binary sex and gender categorisations in the Czech Republic, but introducing more complexity in the data collection might enrich the discussion on sex and gender inequalities. It would also allow to describe social vulnerability to heat more precisely, and consequently to help in elaborating

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[1] People whose gender identity falls outside of the male-female binary (UN High Commissioner for Refugees 2021)

[2] People whose gender identity does not correspond to the sex they were assigned at birth (UN High Commissioner for Refugees 2021)

[3] which currently in the Czech Republic, requires “a psychiatric diagnosis, hormone therapy, surgery and sterilisation, and divorce” (ILGA-Europe 2015)

fairer adaptation strategies.

5.3 Age

Elderly people (older than 75, i.e., categories 75–84 and 85+) revealed in this study to be at higher risk of dying in hot temperatures than younger people. This finding was consistent with multiple other studies (Canouï-Poitrine et al. 2006, Hajat et al. 2007, Yu et al. 2010, Kenny et al. 2010, Huang et al. 2015, Arbuthnott and Hajat 2017, Watts et al. 2019).

This greater vulnerability might be due to a diminishing ability of thermoregulating the body when growing older. Kenney and Munce (2003) suggested that age per se may not be responsible for reduced thermoregulatory responses, but rather that co-existing factors, such as lower fitness condition or chronic diseases, would be. A report on heat waves and health conducted by the World Health Organisation (WHO) in 2015 (McGregor et al. 2015) also mentioned that advanced age was associated with higher risk of renal failure, of cardiac rhythm disturbance, thrombosis and nervous system dysfunction, which are all risk factors. Other medical conditions common in elder people like diabetes, cardiovascular and respiratory diseases (Watts et al. 2019) or the use of medications (Arbuthnott and Hajat 2017) may also increase the risks. What is more, social isolation and decrease in income that often come with age may also have a negative influence on access to quality health care. Ultimately, Arbuthnott and Hajat (2017) suggested that, because of social norms, elderly would limit their behavioural adjustment to heat and hence be more exposed to heat stress.

However, sex and age could hardly be treated separately. Indeed, if the results showed that elderly in general were more at risk than younger people, they also indicated a significantly greater vulnerability of elder women compared to elder men (above 85). This observation has also been highlighted in other studies (Canouï-Poitrine et al. 2006, Hajat et al. 2007, Yu et al. 2010, Ellena et al. 2020).

It is in line with what is sometimes called the “female-male health survival paradox” (Oksuzyan et al. 2009, Oksuzyan et al. 2010, Romero-Ortuno et al. 2014), which refers to the observation that women live longer but have worse health conditions than men. Romero-Ortuno et al. (2014) observed in most European countries, among which the Czech Republic, a significantly shorter healthy life expectancy (i.e., without frailty nor limitation) for women than for men.

In this study, the average age of death calculated over the studied period (1995 –2019) was of 77.17 years for women versus 69.57 for men. Figure 5.1 depicts the evolution of the life expectancy (plain line) and the healthy life years (dashed lines) in the Czech Republic by sex from 2004 to 2019. It shows that women had longer life expectancy and healthy life years than men. However, it is worth noticing that the difference by sex in healthy life years (0.9 year in 2019) is considerably lower that the one in life expectancy (5.8 years in 2019). This means that, even if health self-rating might also be subject to gender biases (Spiers et al. 2003, Oksuzyan et al. 2009), women spend proportionally more time of their life with health problems.

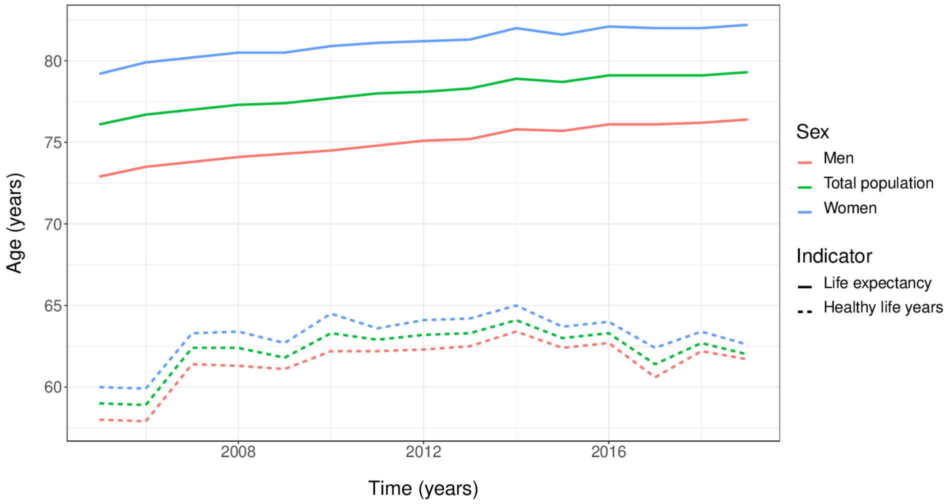

Figure 5.1: Evolution of the life expectancy and the healthy life years in the Czech Republic over the period 2004–2019 by sex.
Source: data from the European Institute for Gender Equality (EIGE), available here.

Hence, elder women seem to be confronted to more health conditions than elder men. They may also face larger isolation, as they are more likely to be widowed than men. Altogether with other sex and gender disparities already exposed in the previous section, these situations may explain the greater susceptibility of this group of population to heat stress.

5.4 Marital status

Concerning the marital status, a lower effect of heat on mortality was observed in married people, with smaller risks obtained among the married category than among the single, divorced and widowed categories in both sexes. Similar results were also observed in several studies (Stafoggia et al. 2006, Canouï-Poitrine et al. 2006, Fouillet et al. 2006, Gronlund et al. 2015, Ellena et al. 2020).

This difference might be due to disparities in the respective economic situations of married and not-married people, as two-adult-household incomes are likely to be higher than single-household incomes. According to a CZSO study (2015), households with only one adult in charge were by 14.6% more at risk of poverty than other households in the Czech Republic in 2013. Another suggestion would be that married people are expected to be less socially isolated and to find support and care more easily.

Although all “alone” categories showed a higher heat-vulnerability than married category, the category of divorced women distinguished itself by showing a significantly higher susceptibility to heat than divorced men. No study presenting similar results was found in the literature.

Nevertheless, economic and social inequalities between divorced women and divorced men should be stressed. Indeed, Symoens et al. (2014) stated that divorced women were often facing a decrease of their relative income, as men are still often the main earners of households. They also underlined the fact that divorced women obtained most of the time the custody of their potential children, which means more expanses and less availability to work full time and to evolve professionally. In the Czech Republic, 90% of the single-adult households with children were run by women (CZSO 2015). The economic situation of divorced women could also worsen with age. A study conducted in the United States (Haider et al. 2003) highlighted that one quarter of divorced women aged more than 65 lived in poverty, and, conversely, 15% of the poor women aged more than 65 were divorced. This same study also pointed out that divorced women reported more health conditions than other women.

Nevertheless, it is worth noticing that the marital status is a legal denomination that does not necessarily depict the actual situation of the deceased. Indeed, single, divorced and widowed people might be involved in unofficial relationships, and married people might be separated. It does not necessarily reflect neither the household structure of the deceased. Thus, there are some limitations in analysing this category, and more precised data such as the total income or the number of occupants of a household would be useful.

5.5 Location

With regard to the residence’s location, the results indicated a higher risk for women living in Prague than for women living in the regions. On the contrary, men were found at higher risk when they lived in the regions than when they lived in Prague. What is more, the difference of risk between men and women living in Prague was found particularly significant.

Results found in the literature usually suggest that people living in urban areas are more at risk than those living in rural areas (Hajat et al. 2007, Tan et al. 2010, Gabriel and Endlicher 2011, Urban et al. 2016). Several reasons were raised to explain this greater vulnerability in urban areas, such as a lack of access to green spaces and vegetation (Reid et al. 2012, Y. Xu et al. 2013, Burkart et al. 2016), a lack of AC (Reid et al. 2009) and the effects of heat islands (Tan et al. 2010).

More sociological research would be relevant to analyse the gendered difference observed in this category. Moreover, the urban and rural areas have been simplified in this study into capital city and regions; thus, a more complex categorisation of the variable could be suggested to catch more nuances on the effects of urban environment on heat-related mortality.

5.6 Cause of death

Results by cause of death showed that deaths from respiratory diseases were significantly more sensitive to heat than any other causes of death, and deaths from CVD revealed intermediate risk values. This finding is in line with many other studies: Hajat et al. (2007) observed a stronger increase in deaths from respiratory diseases in the UK; Basu (2009) found higher risks for deaths from CVD (and particular myocardial infarction, ischemic heart disease and congestive heart failure) and respiratory diseases; Arbuthnott and Hajat (2017) highlighted a higher sensitivity to heat in respiratory deaths than in CVD deaths in the UK. In the Czech Republic, several studies highlighted a greater association of cardiovascular mortality to heat (Hanzlíková et al. 2014, Hanzlíková et al. 2015).

Although deaths from CVD and respiratory diseases were found more vulnerable to heat, the category of other causes of deaths still showed important risks for both men and women. Further analysis would be interesting to investigate more on the heat sensitivity of other pathologies.

Chapter 6

Conclusion

Climate projections have suggested an increase in temperature and more recurrent heat waves in the Czech Republic, which have been proven to lead to excess mortality. Previous literature have underlined the existence of inequalities in vulnerability to heat, with disparities in mortality risk in case of warm temperature depending on factors such as sex and gender, social class or ethnicity. The aim of this study was to assess the impact of heat on mortality in the Czech Republic in different population groups and to identify potential sex and gender inequalities in heat-related mortality.

Non-linear and delayed effects of summer (May–September) daily temperature on mortality in the Czech Republic over the period 1995–2019 have been modelled using a quasi-Poisson regression model including a distributed lag non-linear model (DLNM). The analysis was performed for the whole population and by sex, and both sex categories were further divided by age, marital status, residence's location and cause of death. The mortality risk due to heat for each population groups were assessed and compared with the relative risk (RR) at the 99^{th} percentile of summer temperature.

The results provided different values of heat-related mortality risk in each population group, showing that social position had an impact on heat vulnerability. In particular, women were found to be at higher risk than men. In the great majority of the sub-categories, higher RR values were obtained among women than among men, but these values varied depending on the category, which showed the inter-linkage of social drivers. Older women (above 85) were found more vulnerable to heat than men in the same age group. People in official partnerships were found to be less sensitive to heat than single, divorced or widowed persons. Women living in Prague also revealed particularly vulnerable to heat. Higher risks were found in the case of deaths by CVD or respiratory diseases than by other causes of death.

Results have been compared with past literature and were found consistent with the results obtained in studies conducted in other regions of the world — mainly in Europe. Possible explanations of the results have been discussed. Although physiological and biological differences (e.g., between men and women, or young and old people) have often been proposed, recent studies suggested that physical differences per se may not be responsible for differences in body thermoregulation. Other factors have been evoked, such as economic inequalities (in terms of income, housing conditions, access to medical resources), the presence of other medical conditions, or the existence of social norms and habits.

By lack of data, all aspects of social vulnerability have not been studied. More precise data collection of sex and gender and of socio-economic indicators would enrich the analysis. A more complex characterisation of urban and rural areas and a deeper analysis by causes of death would also be valuable to better understand heat vulnerability across the society.

As recommended by different institutions and studies, conducting research segregated by social criteria, such as by sex and gender, is crucial to identify vulnerabilities in the society and engage in efficient mitigation and adaptation strategies.

Appendix A

Tables of results

Table A.1: Number of deaths, MMT in °C, 99^{th} RR and its 95% confidence interval by population group.

Sex	**Subcategory**	**Total deaths**	**MMT (°C)**	**99^{th} RR**	**95% CI**
TOTAL	TOTAL	1,079,302	18.9	1.20	1.17–1.24
F	TOTAL	529,740	15.7	1.26	1.21–1.31
M	TOTAL	549,562	19.4	1.16	1.12–1.21
F	0–64	79,355	19.3	1.08	0.97–1.21
	65–74	98,722	15.0	1.09	1.00–1.19
	75–84	181,854	15.7	1.26	1.18–1.35
	85+	169,809	14.9	1.43	1.34–1.51
M	0–64	175,866	18.6	1.11	1.03–1.20
	65–74	147,135	20.0	1.12	1.03–1.21
	75–84	150,660	19.5	1.25	1.16–1.35
	85+	75,901	19.3	1.18	1.07–1.31
F	REGIONS	463,155	15.6	1.23	1.18–1.28
	PRAGUE	66,585	19.8	1.51	1.36–1.67
M	REGIONS	488,108	19.4	1.16	1.12–1.21
	PRAGUE	61,454	18.4	1.14	1.02–1.26
F	DIV	54,962	18.8	1.41	1.26–1.57
	MAR	112,550	18.7	1.13	1.03–1.23
	SIN	28,222	14.9	1.20	1.03–1.41
	WID	334,006	15.4	1.28	1.23–1.34
M	DIV	73,210	19.0	1.14	1.03–1.27
	MAR	308,241	19.7	1.14	1.08–1.20
	SIN	59,213	17.5	1.16	1.04–1.30
	WID	108,898	19.4	1.25	1.14–1.36
F	OTHER	219,908	17.2	1.18	1.12–1.25
	CVD	287,539	16.0	1.31	1.24–1.37
	RESP	22,293	14.9	1.49	1.26–1.76
M	OTHER	277,492	19.3	1.08	1.02–1.15
	CVD	243,984	19.6	1.25	1.17–1.32
	RESP	28,086	14.9	1.33	1.15–1.54

Table A.2: Attributable fraction, attributable number and their 95% confidence intervals by population group.

Sex	**Subcategory**	**AF (%)**	**95% CI (%)**	**AN**	**95% CI**
TOTAL	TOTAL	0.70	0.60–0.80	7,592	6,452–8,625
F	TOTAL	0.90	0.77–1.03	4,779	4,098–5,477
M	TOTAL	0.55	0.41–0.68	3,030	2,272–3,786
F	0–64	0.28	-0.09–0.62	224	-71–487
	65–74	0.36	0.06–0.67	351	72–618
	75–84	0.90	0.68–1.13	1,644	1,259–2,035
	85+	1.51	1.28–1.75	2,560	2,193–2,925
M	0–64	0.39	0.15–0.62	681	238–1,065
	65–74	0.40	0.13–0.64	583	197–989
	75–84	0.82	0.56–1.08	1,240	838–1,615
	85+	0.71	0.30–1.08	542	241–821
F	REGIONS	0.82	0.68–0.95	3,793	3,150–4,430
	PRAGUE	1.59	1.23–1.92	1,061	835–1,286
M	REGIONS	0.56	0.42–0.70	2,747	2,033–3,397
	PRAGUE	0.55	0.15–0.94	336	91–563
F	DIV	1.40	0.98–1.81	771	550–995
	MAR	0.46	0.19–0.77	520	209–814
	SIN	0.69	0.13–1.22	196	40–332
	WID	0.99	0.84–1.16	3,320	2,791–3,826
M	DIV	0.54	0.16–0.92	393	140–675
	MAR	0.46	0.27–0.64	1,421	867–1,974
	SIN	0.60	0.20–0.99	357	131–570
	WID	0.80	0.51–1.07	875	539–1,177
F	OTHER	0.68	0.48–0.88	1,489	1,068–1,934
	CVD	1.00	0.84–1.16	2,875	2,384–3,356
	RESP	1.91	1.32–2.41	426	290–567
M	OTHER	0.32	0.12–0.51	890	369–1,457
	CVD	0.75	0.54–0.94	1,827	1,362–2,302
	RESP	1.28	0.73–1.84	360	202–507

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