Health effects of heatwaves
Short and long term predictions

Christofer Åström
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ISSN: 0346-6612
Printed by: UmU Print Service, Umeå University
Umeå, Sverige 2017
Prediction is very difficult, especially if it’s about the future

-Niels Bohr
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Acknowledgements

First, I want to thank my wife Sofie. Always supporting my choice to pursue an academic career. In a job that has taken me all over the world, she has always made me want to come back home. My sons Elias and John who helped me keep my work at the office so that I could focus on what is really important in life in my spare time.

I would like to thank my supervisors Bertil Forsberg and Kris Ebi who have guided me through all these years. Bertil for giving me the opportunity and support from day one and providing a stimulating working environment where I really felt the possibility to grow. Working here have gotten me to see places and meet people I never dreamed of, from the county council in Örebro to the climate scientists at NASA. To Kris for helping to put my work into the bigger picture. The struggle of a PhD student can at times feel like a work in the margin, but you always made me feel like I actually made a contribution. And thank you for your warmth and hospitality and for welcoming me into your home in Seattle. The Pacific Northwest really turned out to be one of my favourite places. I’m very grateful for having both of you as colleagues but even happier to have you as friends.

Kristina for chasing me around with all forms and paperwork. I’m just as sorry for not handing these in on time as I am grateful for your tireless work reminding me.

Joacim Rocklöv for taking a chance on me. It is not every day you walk into a stranger’s office and leaves with a master thesis plan and research assistant position.

Daniel who followed me along this journey as a fellow PhD student but also father of two. To have had someone to talk to about research as well as upbringing, in the workplace and on parental leave have made these years more enjoyable. And to finally have found someone to reminisce about the adventures of Ricky, Julian and Bubbles with, really brightened my days.

My fellow former PhD students Andreas, David, Martin, Hans and Johan whom I have bothered with statistical conundrums, formatting issues and just plain nonsense.

 Therese for dotting the i’s and crossing the t’s. Thank you for making me not look as foolish as I might have.
I want to thank all my family and extended family for all the support over the years. Having you around have helped tremendously and allowed me to go on travels and taking meetings that might not have been possible without you guys around.

During my PhD I have had the opportunity and the privilege to work in several different collaborations and projects that really have broadened my perspectives.

My Swedish partners in the Climatools project and at SMHI, who were my first contact with the Swedish research community. Through you I have met a lot of the people that are now my colleagues and some I consider my friends.

In the European projects, Climate-TRAP, PHASE and ACCEPTED I have gotten the chance to meet and work with some of the best and the brightest in this field.
Abstract

Background

Climate change is defined by the Intergovernmental Panel on Climate Change as changes in the state of the climate associated with changes in the mean and/or the variability of its properties. Climate change will affect temperatures both as an increase in mean temperature as well as changes in the frequency of temperature extremes. Health effects associated with extreme heat, both mortality and morbidity, have been observed all over the globe. Groups that are often found to be more vulnerable are the elderly and people diagnosed with certain diseases and/or on taking some specific types of medication. The health effects from climate change in the future depend on a number of underlying sociodemographic and other factors. It is difficult to predict how the underlying societal factors that are likely to alter the health effects from high temperatures will change.

The aim of this thesis is to investigate the influence of the underlying assumptions and factors that are key components when predicting and projecting heat-related illness, both in the short and long term. This work aims to identify and to some extent quantify different sources of uncertainty that will have effects on the outcome of health impact assessments.

Methods

We wanted to evaluate if different statistical models would alter the ability to identify days with elevated heat-related risk. We used observations of temperatures and daily mortality for Greater Stockholm to model different exposure-response relationships (Paper I). Along the observed data, we collected temperature forecasts for the Stockholm area. We defined what constitutes a risk day and compared the model’s ability to identify these days using both observed and forecasted temperatures to evaluate the predictive performance of models based on the different statistical approaches.

To estimate how climate change will alter the heat-related health impacts we used climate change projections from a range of climate change scenarios to be able to get stable estimates as well as a measure of the uncertainty in the climate projections (Paper II-III). We estimated the change in respiratory hospital admissions (Paper II) and the future need for adaptation to keep heat-related mortality at current levels (Paper III) in Europe. We also estimated the change in heat-related mortality due to changes in climate, demographics and health status of the population in Stockholm (Paper IV).
Results

The models using a highly complex exposure-response relationship showed lower predictive performance, especially when looking at a longer time-scale. The more complex models did also estimate a lower mortality increase compared to the less complex ones. There was however high agreement of which days to be considered risk days.

The estimated increase in heat-related illness from the three health impact assessment studies showed impacts on a similar order of magnitude when looking at changes in climate only. Respiratory hospital admissions were estimated to more than double in Europe and heat-related mortality in Stockholm was estimated to increase to around 257% of current levels. Therefore, adaptation needs to lower the vulnerability to heat by around 50% in the European countries. In study III and IV we take changes in demographics into account and find that the future health burden from heat will increase due to the growing elderly population.

Conclusion

To be able to make predictions of future health burdens from heat, both in the long and short term, we need to consider the properties of the epidemiological models and how the choice of model might limit its use within a health impact assessment. Climate change seems to be the main driver of the future health burden from extreme temperatures, but our results suggests that changing demographics will add to the burden considerably unless relevant adaptation measures are implemented. Adding this on top of the challenges posed by climate change, we find that need for adaptation will increase substantially in the future.
Sammanfattning

Hälsoeffekter till följd av klimatförändringar kommer att visa sig både direkt i samband med översvämningar och värmeböljor men även indirekt som t.ex. utbredning av fästingar som kan sprida sjukdomar. Den kanske tydligaste effekten som ett varmare och mer oregelbundet klimat kommer att ha på folkhälsan är ökningen av värmerelaterade dödsfall. Trots att ökade temperaturer nog är den mest omtalade effekten av klimatförändringarna, så är den hälsovisk som kraftigt förhöjda temperaturer för med sig mindre känt.

I delar av världen har det visat sig att dödligheten till följd av höga temperaturer är den väderrelaterade hälsovisk som skördar flest liv. Efter värmeböljor i Europa under 2000-talet har många länder, i ett försök att anpassa sig, skapat varningssystem som skall varna allmänhet och vårdgivare när temperaturen väntas nå en farlig nivå.

Denna avhandling har till syfte att undersöka och förstå vilka hälsoeffekter som höga temperaturer kan föra med sig i framtiden. För att kunna förstå detta måste man även undersöka andra underliggande faktorer som kommer att påverka i vilken grad höga temperaturer kommer att påverka folkhälsan.

Vi fann att de ökande temperaturerna som klimatförändringarna för med sig är den faktor som kommer att påverka den värmerelaterade dödligheten mest. Det faktum att befolkningen i både Sverige och Europa kommer att vara betydligt äldre i framtiden kommer också ha stor påverkan på hur de höga temperaturerna påverkar oss.

Värmevarningssystem har visat sig kunna ha en skyddande effekt men vi visar att för att få ett träffsäkert och relevant varningssystem så behöver man tänka på hur man utformar de temperaturmått och varningströsklar man använder med hjälp av temperaturprognoser.
Abbreviations

ARR        Adaptive Relative Risk
DLNM       Distributed Lag Non-linear Model
IPCC       Intergovernmental Panel on Climate Change
PHASE      Public Health Adaptation Strategies to Extreme Weather Events
PPV        Positive prediction value
PWL        Piecewise Linear
RCP        Representative Concentration Pathway
RHA        Respiratory hospital admission
SCB        Statistics Sweden
SRES       Special Report on Emission Scenarios
SRS        Smooth Regression Spline
THR        stepwise Threshold
WHO        World Health Organization
Original papers

The thesis is based on the following papers, which will be referred to by corresponding Roman numerals:


Introduction

Background

It has always been common knowledge that extreme ambient temperatures, both hot and cold, can have severe effects on human health. In 1949, Winslow et al. released a book describing the need for adaptation to temperature extremes during the 2nd World War [1]. They also describe the need for temperature control in the home as well as in public and working environments.

The difference between extreme weather events connected to temperature and events such as storms, flooding or blizzards is which part of the population is affected. The latter will pose challenges to entire societies, but hit more randomly, whereas heatwaves or cold spells are much more hazardous to certain vulnerable individuals and sub-groups of the population. Storms, flooding and blizzards could be described as disasters that will not only affect people’s health but also housing and infrastructure.

Although heatwaves have proven to interfere with public transport (parts of the railway network were shut down in Sweden due to a heatwave), it is usually not in such a dramatic fashion as storms or floods. The scientific evidence points towards different vulnerable sub-groups that will be more affected by unusually high temperature [2-5] and some results even suggest that the individuals usually considered vulnerable could be the only ones with an increased risk of dying [6].

Recent events put heat-related mortality on the agenda in many European countries. The heatwave of 2003, where as many as 70,000 premature deaths occurred, was the definite wake-up call for many European governments [7]. This heatwave was said to be the warmest since the 16th century [8]. When temperatures were this extreme, it was clear that mortality increased across all ages, while more pronounced in some subgroups of the population. The challenges societies and individuals face will likely increase as climate change increases exposure to high temperatures, both as annual mean temperatures rise but also due to more frequent temperatures extremes. To which degree these changes in exposure will affect public health is not only a question of exposure. High temperatures affect different populations differently based on underlying vulnerabilities as well as population resilience due to adaptation. These factors are likely to change with time as higher exposure will trigger both individual and community based adaptation measures. This will alter the exposure, risk and vulnerability in future societies in ways that make the future health impacts of heat uncertain. To identify, control and possibly
reduce these uncertainties is key when assessing future public health impacts.

**Human response to environmental factors**

Humans have a way to adapt to local environments that have made it possible for humans to populate most parts of the planet. As individuals, we need to interact with, and adapt to our local environment. Further, the human body can and will react to local environmental factors. As stated in Parsons et al. [9] “The human body responds to environmental variables in a dynamic interaction that can lead to death if the response is inappropriate...”. The human thermoregulatory system is a combined system of behavioural and physiological responses. Changing clothes, seeking shelter and physical activity are examples of behavioural responses that are the most effective way to regulate body temperature. Examples of physiological responses are direction of blood flow, shivering and sweating. The body can change the way blood is transported in the body to either shield from cold or dispose of excessive heat; shivering is a way for the body to generate heat by muscular activity and sweating will help the body to cool down. These physiological responses will put stress on the cardiovascular system (Fig 1).

**Figure 1.** Zone A: No heat stress. Zone B: Zone of increasing heat stress where sweat loss increases rapidly and nearly linearly but through a large part of the zone, body temperature is not affected. Strain in terms of heart rate increases exponentially. Sweat loss is a good physiological indicator of the heat strain experienced. Zone C: Zone of increasing heat stress where sweat loss approaches or has reached its maximum and can no longer be used as an index of stress or strain. Heart rate and body temperature now rises rapidly and are the best physical indicator of the heat strain experienced. Reconstructed from WHO 1969 [10].
Introduction

Changes in demography and health

The number of deaths attributed to heat stroke is relatively low. The strain put on the body when exposed to high ambient temperatures will have effects on other, often pre-existing, health conditions that usually are recorded as the cause of death.

Changes in demography and health

Europe is going through a demographic transition with an increasing elderly population. The general trends point towards a future where people will live longer and the part of the population that is between 65-79 and 80+ years of age is estimated to increase from 13.3% and 5.1% to 16.6% and 11.8% between 2013 and 2060 according to the 2015 Ageing Report [11]. This will result in a smaller working population, and the ratio between the number of working and retired will decrease from 4 to 2 in the same time period. These changes will put stress on the health care systems as elderly people more often suffer from chronic diseases that will require health care in the same time as the working population that is funding the general health care is diminishing.

The development of chronic disease prevalence is however less clear than the increase in elderly. On a global scale, chronic diseases have historically been considered a problem for the rich and elderly population [12]. Today we can see that chronic diseases in the young and middle-aged population in the wealthy part of the world and these diseases are now the leading cause of morbidity and mortality in Europe. In the Global Burden of Disease report the World Health Organisation (WHO) [13] states that on average around 88% of all deaths in Europe 2015 could be connected to chronic and noncommunicable diseases. The figure varies between European countries, as well as the underlying diseases but still accounts for more than 73% for all countries and more than 85% in 9 out of 10 countries in Europe. The main contributor to these deaths is cardiovascular diseases such as ischaemic heart disease and cerebrovascular disease. WHO projects that the number of deaths due to chronic and noncommunicable diseases in Europe will increase about 1% by 2030. The number of deaths attributable to cardiovascular causes however is estimated to decrease by 6.9% while deaths due to respiratory causes are estimated to increase by 8.2%.

In Sweden, the trends in prevalence of cardiovascular and respiratory diseases in the elderly population are perhaps less clear. For cardiovascular disease in Stockholm, the general trend for the last 15 years is a clear decline in hospitalization rates, while for respiratory symptoms a general increase was observed [14]. Looking at a shorter time span however, one could argue that a peak in respiratory hospitalizations was reached around 2013 and
after that a small decline can be observed. The change in prevalence might, on the other hand, not be a good indicator for the health status of the population. The prevalence for e.g. diabetes is going up, partly as a result of a higher survival rate among patients [15]. These changes in the health status of a population are a key part of trying to assess future health impacts.

**Observed and projected climate change**

Climate change is defined by the Intergovernmental Panel on Climate Change (IPCC) as changes in the state of the climate associated with changes in the mean and/or the variability of its properties [16]. The effects of the observed changes in anthropogenic emissions are clear and the warming of the climate since the 1970s is unprecedented over decades to millennia.

For estimates of future climate, the IPCC established scenarios of greenhouse gas emissions and their drivers. In the IPCC Special Report on Emission Scenarios (SRES) [17] a set of four plausible, internally consistent scenarios was created. The scenarios aligned along two dimensions, one with emphasis on economic or environmental development, and the other with emphasis on regionalization or globalization. These future socio-economic scenarios included narratives and quantifications of population and demographic change, economic growth, and technology development to the end of the century, with each resulting in a different trajectory of anthropogenic greenhouse gas emissions over this century.

The assessments of the climate science in the latest IPCC report (Fifth assessment report AR5 [16]) were based on four pathways of greenhouse gas concentration emissions over the century, named the Representative Concentration Pathways (RCPs). These describe four possible future radiative forcing by 2100, relative to their pre-industrial values. Each RCP is based on limited socioeconomic assumptions (e.g. population and economic growth). Separately, five Shared Socioeconomic Pathways (SSPs) were developed for use in conjunction with the RCPs to develop scenarios of possible changes in climate and development. Not all SSPs are compatible with all RCPs (e.g. it is unlikely that a world aiming to sustainable development would have high population growth and high use of fossil fuels). The projections made under the RCPs generate higher and lower greenhouse gas emissions and thus higher and lower global mean temperatures by the end of the century compared to projections made under the SRES [18].

Climate change is already occurring in Europe with the most warming in the Northern Europe during winters, which have become warmer, while in
Southern Europe around the Iberian Peninsula, warming has been mostly during the summers [16]. Warming since the 1950s has resulted in less cold spells and frost days, but more days with unusually high temperatures and tropical nights. Heatwaves of the magnitude of the 2003 event were estimated to occur every 46,000 years, with a lower bound of 9,000 years [19]. In 2006 Europe experienced another heatwave that in parts of Europe were warmer than the one of 2003. In the paper “The Hot Summer of 2010: Redrawing the Temperature Record Map of Europe” Barriopedro et al [20] states that “the anomalous 2010 warmth that caused adverse impacts exceeded the amplitude and spatial extent of the previous hottest summer of 2003”. Since 2001, 16 of the 17 warmest years on record were observed [21].

The regional pattern for Europe is expected to continue in the future with more pronounced warming during winter in Northern Europe and during summer in Southern Europe. These gradual changes are coupled with an increase in unusually high temperatures and in heatwaves, droughts and heavy precipitation events. High temperature events that were expected to occur every 20 years in the period 1961-1990 are likely to occur every year in Southern Europe and every 3-5 years in Northern Europe by the end of this century [22].

**Heat-related health impacts**

The health impacts from unusually high temperatures are a well-known phenomenon that is easy to comprehend and to accept. The heatwaves of the last 20 years show very clearly the health effects high temperatures. In 1995, there were at least 700 excess deaths during a 6-day period with unusually high temperatures in Chicago [23]. Local news reported that temperature was now counted in bodies and not degrees. Europe encountered a devastating heatwave in 2003 where more than 70,000 additional deaths were observed over Europe [7]. This was the onset of the development of heatwave early warning systems throughout Europe; in 2011, 12 out of 33 European countries had early warning systems in place [24]. Since then, additional countries were added to the list. Temperature extremes observed as in 2003 clearly affected public health, but heat-related deaths can be observed at temperatures we might consider hot but not extreme. Heat-related illness is observed in countries all across the globe. A study from 2015 studied 272 communities in 7 countries around the world and found that high temperatures increased the risk of mortality in all countries [25].
Temperature mortality modelling

Efforts to establish the connections and determinants between high temperatures and the daily number of deaths have been made over the last couple of decades but the scientific community has failed to reach a consensus. Even within the nature of the heatwave early warning systems there is a clear disagreement between countries on which temperature measure is the main driver when looking at heat-related health issues. In Europe, heat warnings can be issued based on the minimum, maximum or mean temperature over 2, 3, 5 or 6 days [24]. In some countries, the apparent temperature is used as an indicator of thermal comfort. The rationale behind this is that apparent temperature is a combination between temperature and relative humidity. Humid conditions will limit the body’s possibility to cool through sweating. In Italy, heatwave early warning systems also use synoptic air mass models to predict weather conditions that are more likely to be harmful to public health. Studies that have looked into which temperature measure is the best when trying to estimate impacts from heat have found that the choice of measure is not critical [26] and can be made based on practical concerns [27].

The health effects from high temperatures are usually observed a short time after the event, usually somewhere between the day of the event and up to three days later [28-30]. This is opposite to what has been found with cold temperatures, where the effects are more delayed and can be observed up to 25 days after the event [31-34]. This has led to temperature metrics combining some temperature measure with a lag time, or time window, to describe how temperatures affects human health. A common way to connect temperature and health effects has been the piecewise-linear function where exposure response relationships follow one linear curve until a set temperature threshold where the relationship starts to follow another linear curve [35]. This could also be further expanded to use multiple thresholds [36]. This differs from many other environmental hazards e.g. air pollution where no exposure generates the lowest risk, while for temperature there is an optimal temperature that can be found somewhere in the temperature interval. This makes the use of a piecewise-linear model appropriate.

With the introduction of non-linear modelling approaches, temperature is associated with mortality more directly over the entire temperature range. This modelling approach generally shows similar exposure-response curves for the short time-scale as the piecewise linear model, with small to no effects for colder temperatures to some threshold where the risk starts to increase. Different from piecewise-linear models, non-linear models often follow an exponential curve for higher temperatures, so that a 1°C increase
will result in different effects at different temperatures [29, 37, 38]. This difference might have importance when looking at temperature effects in a changed climate where we might have a different temperature distribution. When compared to an exponential exposure-response model, the linear model might overestimate the effects at moderate temperatures but underestimate effects at more extreme temperatures. A study investigating the ability to predict the temperature mortality relationship beyond observed temperatures showed that depending on how the relationship between temperature and mortality is defined, the extrapolated exposure-response curve could over- and underestimate the impacts [39]. When trying to estimate future health burdens from heat, the decision on how to extrapolate the exposure-response relationship can affect the estimated future impacts.

Some studies reported that temperature itself was not important as long as it was above some set temperature threshold [6, 40, 41]. These studies considered the effects from high temperatures mainly as an effect of the duration of the heat.

There also is the question of whether there is an added heatwave effect to the temperature exposure-response relationship. This effect was found in parts of the world while not in others. For Stockholm, Rocklöv et al [29] found that in addition to the health effects from temperatures themselves, if temperatures stayed above a certain threshold for two days or more, then the health impacts would increase even though the actual temperature did not. A study from three other European cities also found there was an added heatwave effect but that the impact was reduced when introduced into a multi-lag nonlinear model [42].

The latest addition to the modelling aspect of temperature related health impacts is the introduction of the Distributed Lag Non-Linear Modelling (DLNM) [43]. This modelling procedure allows for the health outcome to be fitted to a 2-dimensional surface with time on one axis and temperature on the other. In this way, the exposure-response function is fitted and optimized for all time scales and exposure simultaneously. In this modelling procedure, no assumptions are needed of which time-lag is appropriate for different temperatures.

The health effects from heat in Sweden have been studied in multiple studies focusing mainly on Stockholm, either individually or as part of a multi-city study. The health effects of daily mean and maximum temperature, daily minimum and maximum apparent temperature and radiation temperature have been explored with and without any effects of heatwave duration [6, 28, 29, 44, 45]. All yield similar results and even though the effects of high
temperatures decreased over the last century, the recent trends show that heat-related mortality might be increasing again [44, 45].

**Vulnerable groups**

Heat-related illness is mainly observed in sub-groups of the population considered especially vulnerable. Many studies find that older age-groups can be used as a proxy for the vulnerable population. Some health conditions that increase the vulnerability to heat e.g. respiratory and cardiovascular disease are more prevalent in this group. These conditions can by themselves act as an effect modifier while in some cases it will be the medication that will alter the body’s thermoregulatory functions that would increase vulnerability. A study looking at the population aged 50 or above in the City of Stockholm found that people who had not been hospitalized with any of these conditions did not have higher risk during a heatwave. This could suggest that it is these medical conditions that are the main driver of the heat-related illness [6]. However, the same study showed the impact was the same in the general population as in the group identified as low risk in Rome.

There are other factors, not connected to health that could make heat more dangerous. Some studies found that living alone and living either on the floor directly under the roof or the bottom floor could increase risk during an event with high temperatures [5, 46]. Apartments on the top floor of a building will be the warmest while the apartments on the bottom floor will be less likely to keep windows open during night time, which would limit the possibility of cooling down the apartment. Social isolation has also been shown to be a risk factor in some studies [5, 23]. The location of the building itself might alter the exposure to high temperatures because of the urban heat island (UHI). This phenomenon is explained by the fact that materials common in the urban setting such as e.g. concrete and asphalt encapsulates heat during the day and can keep the urban setting warmer during the night, limiting the possibility to cool during the cooler hours [47].
Adaptation measures

WHO published general guidelines on how to prevent the health effects of heat [48]. The document lists measures to take on an individual level to lower exposure and vulnerability to heat, such as

- Keep your home cool by keeping shutters and windows closed during times of the day when outside temperatures are above the indoor temperature. Use night air to cool down your home.
- Electric fans could help cooling but when temperatures rise above body surface temperature fans would rather warm the body.
- Keep out of the heat if possible. Limit outdoor physical activities to the morning and evening.
- Keep body cool and hydrated by wearing light clothes, light bed linen and sheets, drink much fluids but avoid alcohol, caffeine and sugar and eat small meals often.
- Seek advice if you are suffering a chronic medical condition or use medicines that could alter the thermoregulatory capacity of the body.

These individual measures are intended to be carried out on a rather short time scale and during an episode of high temperatures. Many of these responses could be considered natural and would be easy to carry out for a healthy and able person while it could prove to be a hard task for others.

On a societal level, the needs are of a different nature. Public Health England suggests that information should be distributed to both people of the community and people visiting e.g. tourists [49]. Distribution of drinking water could be necessary during a prolonged heatwave as there may be regulations regarding water use. The community could provide shelter and maps where e.g. air-conditioned spaces are marked could be distributed. In the different heatwave action plans in European countries, several actions to limit the short-term effects of heat are included. Most countries identify vulnerable parts of the population, focusing on the elderly and chronically ill, to be able to facilitate information distribution within these groups. Some countries have tailor-made warnings, information and guidelines to health care providers to limit the effects among care takers. The need for tailored guidelines for the vulnerable population mainly aims to find people that are considered vulnerable due to medical conditions or medication use but are not under direct care from the health care system. A Swedish study, in people above 65, showed that the increase in risk from dying during a heatwave was lower for people admitted to a hospital compared to the rest of the population [50]. Giving information to the vulnerable part of the
population and making them aware that they are at risk is crucial when trying to lower the health impacts from heat. A study from the UK showed that a minority of the participants, all of which were classed as vulnerable, knew that their own age and health condition classified them as vulnerable [51]. The participants with some knowledge regarding the relationship between temperature and health effects could identify others who were vulnerable but would not class themselves as such. Some participants acknowledged that elderly people could be at risk, but usually defined elderly people as older than themselves [52].

Long-term adaptation to mitigate the health effects of high temperatures incorporates a range of different actions. Architecture, city planning, urban vegetation and lowering air pollution emissions are examples of measures to lower exposure. Buildings should be constructed to increase indoor thermal comfort by reducing cooling loads through design and ventilation. Such interventions could come with co-benefits, such as reductions of noise exposure, asthma and other respiratory conditions and cardiovascular disease [48].

City-planning and urban vegetation are measures to mitigate the effect of the UHI. Natural materials will lower the radiative temperature and encapsulating effects of the urban setting and are therefore an effective way to lower the UHI effect. The general trend however is to densify urban areas based on strong economic incentives. As more and more people live in urban areas, by 2050 two thirds of the world’s population is expected to live in an urban setting [53], it is important to make these areas healthy to live.

Some preventive measures have been taken in countries around Europe but few evaluations have been made to evaluate the effectiveness of the interventions. A review found 7 studies evaluating the effectiveness of heatwave early warning systems and found that 6 out of them reported that the implementation of a warning system resulted in fewer heat-related deaths [54].

During the summer of 2006 France experienced the first severe heatwave since 2003 and the observed excess mortality estimated to be 2065. Had the exposure-response relationship been the same as in 2003, an additional ~4400 excess deaths would have been expected [55]. This reduction in mortality can be linked to the introduction of a heatwave early warning system as well as a heightened awareness within the population.

Efforts have been made to quantify the degree to which adaptation could lower future heat-related mortality. Different approaches have been
implemented, including the use of analogue exposure-response functions, shifts in the absolute threshold for temperature mortality relationships [56-58], a relative shift in thresholds [59], reduction of the slope, as well as combinations of these [60, 61]. In a comparative study looking at these adaptation assumptions found that the uncertainty added to the results by these different assumptions were even greater than uncertainty introduced by the climate change projections [62].

With a changing climate that will increase the exposure to high temperatures dramatically, the need for adaptation is clear. Heatwave early warning systems are part of the solution. Accurate temperature forecasts over the short time frame are important both because of the fact that accurate warnings might save lives but also that inaccurate warnings will lower the trust and confidence in the system that in the long run could be harmful. Information on future impacts and the main factors contributing to the burden would help taking the corrective actions needed to mitigate the negative health effects of heatwaves, in the long and short term.
Data and Methods

Data sources and analytical approach

My thesis combines two types of quantitative analyses, epidemiological modelling of current exposure-response relationships, and health impact assessment of potential future impacts based on projected changes in temperature exposures. With my focus on the associations between heat and adverse health effects, these analyses include different types of temperature and health data. For the epidemiological approach, we used temperature observations and daily mortality data and for the future impact assessments, we used projected climate data, population and demographic projections as well as potential changes in health conditions in a population, likely to affect temperature related health issues.

Paper I

The main aim of the first paper was to explore the potential influence that the choice of underlying epidemiological model could have on identifying risk days within a heatwave early warning system. Data on daily mortality, observed temperatures and temperature forecasts were collected for 1998-2007 for Stockholm County from the National Board of Health and Welfare and the Swedish Meteorological and Hydrological Institute (SMHI). Temperature forecasts were available up to three days in advance. These forecasts were used as an evaluation tool in the analyses. In addition, because forecast temperatures showed a clear bias with lower skill levels forecasting the highest temperature, we used linear regression to adjust forecasts to lower this bias; these adjusted forecasts were also used in the analyses.

We used a rather simple model informed by previous work investigating heat-related mortality in Stockholm and the experiences from other European heatwave early warning systems [24, 29]. The temperature-mortality relationships were modelled using four approaches. The main model was defined as: Mortality~Poisson($\mu_t$):

$$\log(\mu_t) = \text{intercept} + w_{d_t} + S(trend_t) + f(temperature_t)$$

where $w_{d_t}$ is day of the week, $S(trend_t)$ is a smooth trend function over the time period and $f(temperature_t)$ is the temperature-mortality relationship. The four ways to model this relationship were a stepwise threshold model (THR), a piecewise linear model (PWL) with two different linear segments, a smooth regression spline (SRS) and a distributed lag non-linear model (DLNM). The THR, PWL and SRS models used the 3-day mean of daily
maximum temperature as temperature metric. The DLNM incorporated the temperatures from the 3 days individually. An example of the differences among the exposure-response functions is shown in Fig 2.

Figure 2. An illustration showing the difference between the four approaches used to model the exposure-response relationship to show how temperature affects risk under the different modelling approaches.

In the threshold model, we chose the same thresholds used in the development of the Swedish heatwave early warning system, 27 and 30°C. We used the estimated relative risk (RR) for day with temperatures between 27-30°C and above 30°C. To be able to compare the estimated risk increases for the different models we estimated the mean risk increase for all days in the two temperature intervals rather than only at 27 and 30°C.

We also calculated risk increases using forecast temperature metrics that consists of observed temperatures combined with temperature forecasts, producing metrics up to three days in advance. This was done with the adjusted forecasts as well.

To evaluate predictive performance, we decided that the estimated risk increase for the PWL model at 26°C, which corresponds to a 6% increase in mortality, would be used as threshold and as an indicator for a risk day. The ability to identify these risk days by the different models was evaluated using the different temperature and forecast metrics. Sensitivity and positive prediction values (PPV) were calculated for each model using both forecast and adjusted forecast metrics. Sensitivity is a measure of how well the model identifies risk days. PPV describes how large the proportion of the risk days classified by the model were actual risk days.
**Paper II**

In this paper, we estimated the future number of respiratory hospital admission (RHAs) in four different European regions attributable to high temperatures. This was done by comparing the estimated number of heat-related RHAs between 1981-2010 and 2021-2050. Gridded climate data were collected from the Rossby Centre regional atmospheric climate model RCA3 for 5 climate change projections. These climate change projections were based one of two scenarios, A1B and A2 from the SRES. Gridded population data was collected from the History Database of the Global Environment theme within the Netherlands Environmental Agency [63]. Spatial data on total population was available on similar resolution as the climate data.

Rates for RHAs for the EU27 countries were collected from the European Health for All Database (http://data.euro.who.int/hfadb) provided by the World Health Organization (WHO), for the years 2005 through 2010.

To estimate the number of RHAs attributable to heat, we used the exposure-response relationship from a European Multi-city study [64]. We used relative risks (RRs) calculated for northern continental and Mediterranean cities. These RRs were defined as the increase in RHAs per degree increase above the 90th percentile of summer temperatures. Countries bordering the Mediterranean Sea and Portugal were assigned the meta-coefficient for Mediterranean cities and the rest were assigned the RR for the northern continental cities. The study used a 0-3 day lag of daily maximum apparent temperatures as temperature metric.

For each climate change projection, the estimated number of RHAs was compared between the baseline and future period. By using a percentile based threshold, rather than a set temperature threshold, and by comparing within climate projection, we minimized any potential biases introduced by any differences between the climate change projections.

**Paper III**

This study aimed to estimate how much future adaptation needs to lower vulnerability to keep heat-related mortality at present day levels. The variable describing this was called the Adaptive Risk Reduction (ARR). The ARR presents the heat-related health effects of climate change in terms of what challenges we are facing, rather than an estimated impact.

In this study, climate change projections were collected from the new climate change projections using RCP4.5 and RCP8.5 greenhouse gas emission
scenarios. Temperature and relative humidity were extracted from 18 future climate realizations, 9 representing each of the representative concentration pathways (RCPs), which were downscaled with the Rossby Climate regional climate model RCA4. We calculated the impacts in a baseline period, 1981-2010, and a future period, 2036-2065, which were then compared to estimate the change in heat-related impacts. The climate data had a spatial resolution of 50x50km.

Data and projections on total and above 65 population were collected on a spatial scale of a similar resolution as the climate data for 2010 and 2050 [65]. Each population data point was connected to the climate data point closest to it.

To measure harmful exposures, we used the framework from a European multi-city study within the PHASE project. The estimated risk increase in that study was based on the difference in mortality between the 75th and the 99th percentile of summer daily mean temperatures. We assigned 0 as exposure to all days with temperatures below the 75th percentile and assigned 1 to days with temperatures at the 99th percentile. The exposure value assumed to increase in a linear fashion between the 75th and 99th percentile and beyond. For each grid, we calculated the total exposure over the two time periods.

We calculated the impacts with changes in climate, population and demography separately as well as jointly to distinguish the effects of these variables. We used a mean population increase scenario that projects very small population changes with rather substantial demographic changes. The results were summarized on national, regional and European level where the impacts within each level were weighted based on population size.

Paper IV

In the fourth study, we further investigated underlying factors that might alter the outcome of a health impact assessment. We collected climate data for 16 locations in the Stockholm area. The climate data comes from a regional downscaling model from the SMHI that uses coarse scale climate data and downscales it from 50x50 to 12.5x12.5 km. The climate data collected were the locations closest to the data point representing Stockholm in the coarser data. This was done to assess the variation in impacts based on resolution and location of the climate projections used in the HIA. We investigated the possible effects of changing demographics, changes in
the prevalence of chronic and non-commutable diseases, as well as possible adaptation.

We used exposure-response relationships from a study investigating the population above 50 years of age, divided into age-groups 50-74 and 75+, in the Greater Stockholm area and how the mortality risks were affected by heat. This study investigated the change in risk of dying during a heatwave day for people diagnosed with different chronic or non-commutable diseases. If temperatures reached above the 95th percentile for two consecutive days, the second day and two days after were considered heatwave days.

Current population and mortality rates for Stockholm and Sweden were collected from Statistics Sweden (SCB) [66, 67]. In addition, we collected future projections of mortality rates for Sweden [68]. The relative change in mortality rates for Sweden were used to scale mortality in Stockholm, collected from the epidemiological study, to get estimates of future mortality rates. We calculated future impacts based on two scenarios of future mortality. One where the mortality decreases in both age-groups (MS1) and another with the decrease in the 50-74 ag-group only (MS2).

We collected age-specific hospitalization data from the Board of Health and Welfare for 2000-2014 to indicate prevalence data for the diseases investigated in the epidemiological study [14]. We calculated two scenarios on the development of chronic and noncommunicable disease, PS1 and PS2, using linear extrapolation of data from either the whole or the latter half of the period; this was done because the trend in hospitalisations appeared to change in the latter part of the period.

To assess the effects of future adaptation, we investigated three future scenarios where the exposure-response relationships for the two age-groups converged to the same RR, as suggested by Bobb et al [69]. For the three scenarios, the coefficients converged either to the mean of the two coefficients (AS1), or to the coefficient for the younger (AS2) or the older age-group (AS3). This results in estimates based on different levels of adaptation or maladaptation.

The effects of these changes in mortality, hospitalization rates and possible adaptation or maladaptation were compared with a main scenario where only the climate, demography and population changed over time.
Results

Paper I

In the study exploring the potential influence of the choice of underlying epidemiological model on forecasting high risk days, the models using the same temperature metric produced comparable risk estimates for the less extreme interval (Table 1). There was less conformity for the higher interval. The strikingly higher estimates in the thresholds model made it necessary to perform a sensitivity analysis that meant adding an indicator variable to the PWL and SRS models for days where the 0-2 lag of daily maximum temperature was above 30°C. This resulted in estimated risk increases of an additional 8.9 and 11.1% (P-values of 0.179 and 0.093). Although these were not significant, they indicated there might be something unaccounted for in the top of the temperature interval and explain the differences in risk estimates.

Table 1. Estimated risk increases for the four models in the two temperature intervals in percent.

<table>
<thead>
<tr>
<th>Temperature interval</th>
<th>THR</th>
<th>PWL</th>
<th>SRS</th>
<th>DLNM</th>
</tr>
</thead>
<tbody>
<tr>
<td>27-30°C</td>
<td>10</td>
<td>9.4</td>
<td>8.8</td>
<td>4.3</td>
</tr>
<tr>
<td>&gt;30°C</td>
<td>20.5</td>
<td>12.7</td>
<td>11.1</td>
<td>13</td>
</tr>
</tbody>
</table>

By our definition, 98 days were defined as risk days. 70 of these days were identified by 3 or more of the models and 93 by two or more.

When used together with forecast temperatures to identify risk days, the DLNM model performed worst. The other models performed fairly well as far as two days in advance, while all models had low sensitivity scores with a 3-day forecast (Table 2). The adjusted forecasts increased the score to some degree. All models except the DLNM had high positive prediction scores even for the 3-day forecasts.

This means that regardless of the epidemiological model, if a day was identified as a risk days, the likelihood of the model being correct was very high even 3 days in advance. However, the likelihood of the models failing to identify a risk day was quite high, especially 3 days in advance.
### Table 2. Sensitivity and positive prediction scores for the different models using the forecast temperature metrics and the adjusted forecast temperature metrics.

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1-day</td>
<td>2-day</td>
<td>3-day</td>
<td>1-day</td>
<td>2-day</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Forecast</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DLNM</td>
<td></td>
<td>0.62</td>
<td>0.05</td>
<td>NA</td>
<td>0.67</td>
<td>0.10</td>
</tr>
<tr>
<td>GAM</td>
<td></td>
<td>0.78</td>
<td>0.53</td>
<td>0.16</td>
<td>0.86</td>
<td>0.72</td>
</tr>
<tr>
<td>PWL</td>
<td></td>
<td>0.79</td>
<td>0.56</td>
<td>0.19</td>
<td>0.88</td>
<td>0.72</td>
</tr>
<tr>
<td>THR</td>
<td></td>
<td>0.70</td>
<td>0.30</td>
<td>0.09</td>
<td>0.84</td>
<td>0.57</td>
</tr>
<tr>
<td>Positive Prediction</td>
<td>Forecast</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1-day</td>
<td>2-day</td>
<td>3-day</td>
<td>1-day</td>
<td>2-day</td>
</tr>
<tr>
<td>DLNM</td>
<td></td>
<td>1.00</td>
<td>1.00</td>
<td>NA</td>
<td>0.88</td>
<td>0.50</td>
</tr>
<tr>
<td>GAM</td>
<td></td>
<td>1.00</td>
<td>0.98</td>
<td>0.94</td>
<td>0.99</td>
<td>0.94</td>
</tr>
<tr>
<td>PWL</td>
<td></td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.98</td>
<td>0.97</td>
</tr>
<tr>
<td>THR</td>
<td></td>
<td>0.96</td>
<td>0.95</td>
<td>1.00</td>
<td>0.97</td>
<td>0.91</td>
</tr>
</tbody>
</table>

### Paper II

The numbers of heat-related RHAs in the studied European region were projected to more than double between the baseline and future period. While the estimated proportion of the total number of RHAs attributed to heat in the future period was relatively small, only 0.4% (Table 3), this amounted to an estimated 26,000 cases annually. This should be compared to about 11,000 cases in the baseline period. The estimated increase showed variation both geographically and between climate change projections. Southern Europe was estimated to have the greatest increase in heat-related RHAs (178%). This can be compared to Eastern Europe where an 82% increase was estimated. Estimates for Southern Europe were consistently higher regardless of which climate change model or scenario was used.

### Table 3. Heat-related RHAs as the proportion of annual number of RHAs and the relative increase, the absolute change and range of the absolute changes, depending on climate change projection. (%)

<table>
<thead>
<tr>
<th>Region</th>
<th>Baseline</th>
<th>Future</th>
<th>Relative increase</th>
<th>Change</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern</td>
<td>0.17</td>
<td>0.31</td>
<td>82</td>
<td>0.14</td>
<td>0.01 – 0.32</td>
</tr>
<tr>
<td>Northern</td>
<td>0.13</td>
<td>0.27</td>
<td>108</td>
<td>0.14</td>
<td>0.08 – 0.20</td>
</tr>
<tr>
<td>Southern</td>
<td>0.23</td>
<td>0.64</td>
<td>178</td>
<td>0.41</td>
<td>0.14 – 0.64</td>
</tr>
<tr>
<td>Western</td>
<td>0.18</td>
<td>0.39</td>
<td>117</td>
<td>0.20</td>
<td>0.06 – 0.30</td>
</tr>
<tr>
<td>EU27</td>
<td>0.18</td>
<td>0.40</td>
<td>122</td>
<td>0.21</td>
<td>0.07 – 0.32</td>
</tr>
</tbody>
</table>
When inspecting country specific estimates, a clear pattern is visible in the estimated impacts as well as the ranges of the projections between the regions. Countries in Southern Europe have the widest range in projections and the largest impacts while the estimates for Northern Europe showed the narrowest range and smallest impacts. This indicates that uncertainty in both impacts and climate change projections has a geographical pattern.

Figure 3. The range of the estimated increases in heat-related respiratory hospital admissions presented as the proportion of the annual average.

Paper III

Our approach to create a variable describing the need for adaptation lead to the suggestion that the region with the greatest needs to manage future exposure to high temperatures is Southern Europe. For the rest of Europe, climate change would pose lesser challenges. The main differences between these regions is likely due to the demographic transitions within the regions.

In a future without climate change, population projections suggest that Europe as a whole will experience slightly smaller impacts in the future. This European mean estimate is mainly driven by the large reduction of impacts in Eastern Europe, with an estimated negative Adaptive Risk Reduction (ARR) of 17.2% (Table 4). All other regions were estimated to have to lower
their vulnerability to avoid increased impacts in the future with estimated ARRs ranging from 2.2% to 7.0%.

Table 4. Estimates of how much reduction in vulnerability is needed to maintain health effects from high temperatures at current day level. (%)

<table>
<thead>
<tr>
<th>Region</th>
<th>Present Climate</th>
<th>RCP 4.5</th>
<th>RCP 8.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>47.0 (33.7, 54.9)</td>
<td>46.8 (33.3, 54.4)</td>
<td>52.9 (34, 63.2)</td>
</tr>
<tr>
<td>Northern</td>
<td>45.0 (31.7, 54.6)</td>
<td>46.1 (32.4, 55.2)</td>
<td>53.6 (44, 62.9)</td>
</tr>
<tr>
<td>Western</td>
<td>45.1 (29.7, 53.3)</td>
<td>48.9 (34.5, 56.4)</td>
<td>53.4 (29.8, 64)</td>
</tr>
<tr>
<td>Eastern</td>
<td>45.6 (29.5, 52.1)</td>
<td>36.6 (18, 44.1)</td>
<td>53.4 (21.6, 51.7)</td>
</tr>
<tr>
<td>Southern</td>
<td>53.5 (44.4, 61.2)</td>
<td>54.8 (46.2, 63.3)</td>
<td>61.7 (47.9, 69.5)</td>
</tr>
</tbody>
</table>

Estimates based on climate change alone yield very different results. On average, Europe would have to lower its vulnerability by around 47% and 53%, for RCP4.5 and RCP8.5 respectively, to maintain heat-related mortality at present day levels. Including both population and climate change resulted in larger differences between the regions, with an estimated ARR of 36.6% and 41.7% in Eastern Europe and 54.8% and 61.7% in Southern Europe for RCP4.5 and RCP8.5, respectively.

Taking the demographic transition into account, the need for adaptation is even clearer. Looking at the change in the 65+ population alone, we estimated the ARR for this sub-group to almost 39%, without climate change. Eastern Europe, which had an estimated ARR of negative 17.2% based on change in total population, had an estimated ARR of 38% in the 65+ age group. This suggests that in 2050, Eastern Europe would have less people in total but would experience a relatively large increase in people above 65 years of age. When looking at the combined effects of population, demographic and climate change under RCP8.5, we estimated an ARR of 71.4% in the 65+ age group for Europe, ranging from 69.3% to 78.5% in the
four regions. For Southern Europe, with an estimated ARR of 78.5%, this means that vulnerability needs to be reduced to a fifth of current levels by adaptation policies and programs.

**Paper IV**

In the local impact assessment, the demographic transition in the Stockholm County population showed a clear increase in the number of people above 50. The population above 50 will increase by 84% in 2050. Above age 75, the increase was projected to 169%. This influenced the future number of heat-related deaths to almost the same degree as climate change (Table 5). Using the same age-structure as 2050 on the 2010 population, we estimated a 58% increase in heat-related deaths. When looking at the future population and demography, not accounting for climate change, we estimated an increase in heat-related mortality of 146%.

<table>
<thead>
<tr>
<th>Table 5. Yearly heat-related mortality compared to baseline scenario. Within brackets is the range for the different climate locations.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate 2010</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Climate 2050</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Looking at the effects of climate change on heat-related mortality alone, we projected the number of heat-related deaths to increase by 157%, slightly higher than the joint effect of population and demographic change. In the main scenario where we combine the two factors, we estimated an increase of the heat-related deaths of 532%.

SCB has projected how the mortality rates in Sweden will decrease by 2050. This would also result in fewer deaths related to heat. Assuming that this decrease in mortality will occur in the entire population above 50 years of age, we estimate a 31% lowering of the number of heat-related deaths, resulting in an estimated total increase in mortality 338% (Table 6). Assuming this change in mortality would only occur among people in the 50-74 age group, we estimate a reduction in the heat-related deaths by 8%.
Table 6. Estimated relative change in heat-related mortality due to changing vulnerabilities and the estimated total increase in mortality taking account to these changes in vulnerabilities. This figure should be compared to the main scenario.

<table>
<thead>
<tr>
<th>Vulnerability</th>
<th>Relative change</th>
<th>Total Mortality increase</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Changing Mortality Rates</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decline in MRs</td>
<td>MS1 -31%</td>
<td>338%</td>
</tr>
<tr>
<td>Decline 50-74 MR</td>
<td>MS2 -8%</td>
<td>480%</td>
</tr>
<tr>
<td><strong>Changing vulnerability</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cardiovascular disease</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prevalence Scenario 1</td>
<td>PS1 -9%</td>
<td>474%</td>
</tr>
<tr>
<td>Prevalence Scenario 2</td>
<td>PS2 -23%</td>
<td>389%</td>
</tr>
<tr>
<td>Respiratory disease</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prevalence Scenario 1</td>
<td>PS1 7%</td>
<td>578%</td>
</tr>
<tr>
<td>Prevalence Scenario 2</td>
<td>PS2 7%</td>
<td>576%</td>
</tr>
<tr>
<td>Changing RRs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Converging RRs</td>
<td>AS1 -7%</td>
<td>485%</td>
</tr>
<tr>
<td>Decreasing RRs</td>
<td>AS2 -19%</td>
<td>412%</td>
</tr>
<tr>
<td>Increasing RRs</td>
<td>AS3 4%</td>
<td>558%</td>
</tr>
</tbody>
</table>

The decreasing trend in cardiovascular disease could have a large effect on future heat-related mortality. Assuming cardiovascular disease would decrease in a similar fashion as in the period 2008 to 2014, the future number of heat-related deaths would be reduced by 23% and using the trend for 2000-2014, the estimated reduction would be 9%. The change in respiratory disease would have limited effects on heat-related mortality and was estimated to increase the number of heat-related deaths by 7% in both scenarios.

The different adaptation scenarios resulted in a change in heat-related mortality ranging from a 4% increase to a 19% decrease. Lowering the increase in the risk of dying during a heatwave day for above 75 year olds from 9 to 7%, resulted in a 19% decrease in the estimated heat-related mortality for the 50+ population.

In the most positive of future scenarios with adaptation, lower mortality rates and less cardiovascular disease in 2050, we still estimated an increase in heat-related mortality.
Discussion

Climate change will impact and increase the burden of disease attributable to environmental factors. The papers supporting my thesis elaborate on the extent to which some health outcomes could increase, and identify opportunities for preparing for, and managing impacts expected over coming decades. The knowledge generated is highly relevant for moving towards climate resilient health systems.

Difficulties in predicting health outcomes even on a short time scale were highlighted in paper I. The choice of underlying epidemiological model influenced the predictive performance, with the differences attributed mainly to the temperature metric used. A combined metric using temperatures over several days proved to be more robust than other options. Our analyses led to the conclusion that the use of forecast temperatures, not just historic observations, should be integral to evaluating the underlying epidemiological model within a heatwave early warning system.

What has also been made clear is that underlying assumptions, modelling choices as well as how these are presented, limit the potential use of model results outside that specific study. In the early stages of paper II, the analyses incorporated future projections of both mortality and hospital admissions associated with increasing temperatures in Europe. The study on hospitalizations used the 90th percentile of summer temperatures as the threshold, whereas the mortality study used set temperature thresholds derived for each individual city. To use a percentile and, more importantly, the same across all cities, made it possible to conduct a meta-analysis and to calculate individual thresholds for each grid cell in the climate data for each climate change projection. Although each projection differed slightly, even in historic data, a threshold based on the percentile would still be applicable in the analyses. If the projections were compared to fixed temperatures, there are possibilities for large differences between the baseline estimates for the different projections, something that a percentile threshold would keep to a minimum. This made us exclude the mortality analysis from the study. The epidemiological study used in the health impact assessment (HIA) in paper III and IV also used a threshold based on percentiles. In paper IV, the thorough presentation of the data in the epidemiological study made it possible to bridge and use the results with other input data.

When conducting epidemiological studies on temperature and health, one should think about the external validity and usefulness of the model in another setting. One should consider the possibility to use a model that might not be the best performer, and weigh the ability to use and compare
the model and model outcomes in other studies. Results that cannot be readily compared and contrasted with other research, and that cannot lead to further research and insights, might not be the best practice and the way forward for research in this field.

In paper II, the availability of a suitable epidemiological model helped us produce impact estimates that were easily comparable between climate change projections. However, the lack of age-stratified population projections limited the potential of our study. As the population of Europe becomes older, with more adults in the ages where respiratory hospital admissions mainly occur, our impact estimates are likely to be understated. In paper III we further explored how aging populations in Europe could alter the future impacts from rising temperatures. The large differences in estimates for the total population and the part of the population above 65 confirmed the concerns identified in paper II. Changing demographics were close behind climate change as the main contributor to future health burdens from higher temperatures.

Paper IV considered factors not available at the larger European scale and focused on Stockholm. The results point towards a future where some of the health issues associated with high temperatures might be reduced because of lower mortality rates, lower prevalence of chronic and non-commutable diseases, and some long-term adaptation that might take place. Adding these factors into the analysis considerably increases the uncertainty in the estimates. Observed and projected trends in mortality e.g. in Stockholm and the trends in heat-related mortality were explored to a certain degree. How and if these could affect future heat-related mortality in the vulnerable sub-groups are uncertain. As some studies suggest these sub-groups might be the only ones affected by high and extreme temperatures, understanding such trends would increase accuracy of future HIAs. While studies from Stockholm showed that even if the risk from high temperatures decreased over time, that trend did not continue over the last decade [42, 43]. In the PHASE project, we found the exposure-response function for Stockholm generated higher RRs after 2003 compared to before [30]. In general however, it seems that susceptibility to heat and heatwaves is decreasing over time [70].

Changes in the prevalence of chronic and non-commutable diseases will affect the health impacts of high temperatures. Valid data can be hard to obtain and trends or future projections even harder. Using patient hospitalization rates as a proxy for chronic disease, this means paper IV and similar publications, may contain biases. Political decisions that e.g. change the economic prerequisites for health care facilities, can alter the number of
people admitted, which may not reflect the change in underlying health status. Health conditions that might have led to hospitalization before, might now be treated with medication instead. This might not necessary lower the vulnerability of the population although a lower number of people hospitalized might indicate a healthier population.

When looking at high temperatures, the increase in exposure follows a geographical pattern that is similar in papers II and III, with the largest estimated impacts in Southern Europe and the smallest in Eastern Europe. This is alarming for the southern parts of Europe since studies already show that they might suffer the largest burden and experience the greatest impacts from high temperatures today [71, 72]. Results from paper III also suggest that changing demographics could affect southern Europe the most by 2050. Based on our estimates under the RCP8.5 scenario, adaptation policies and programs would need to reduce vulnerability by about 60% in the total population and up to almost 80% for the population above age 65 in Southern Europe to keep heat-related mortality at current levels. The study by Gosling et al. (2016) explored six adaptation assumptions and how they could affect heat-related mortality in 14 European cities, six of which would be considered Southern European according to the definitions in Paper III. Each set of assumptions had different levels of adaptation; across these, three could reduce vulnerabilities by more than 60%, the amount of adaptation needed for the total population, as identified in paper III and two would satisfy the threshold for the population above 65 years except for Turin. These two adaptation assumptions however, shift the temperature threshold from a percentile in the present temperature distribution to the same percentile in the future temperature distribution. This essentially eliminates the effects of the change in mean temperature and only assesses the impacts from the change in the temperature variation. The decrease in heat-related mortality, based on these two adaptation assumptions, was estimated between 89 and 108%.

Other HIAs reported results similar to our conclusions. A study on heat-related hospitalizations in New York estimated the number of heat-related respiratory hospital admissions in 2080-2099 to be 2-6 times higher than in the baseline period [73]. In Australia, the increase in heat-related hospital admissions was estimated as 217-223% [74].

Heat-related mortality in New York increased an estimated 47 and 95% depending on the climate change scenario and adaptation assumptions [75]. A study carried out on European cities estimated the change in heat-related mortality by 2030 under different climate change projections [71]. The estimates range from a decrease in heat-related of 22% in Valencia to an
increase in Athens of 80%. Most HIAs estimated the future increase in relative or absolute terms. The concept of Paper III is a novel approach where we estimated to what degree population vulnerability would need to decrease to keep heat-related mortality at present day levels. This is an effort to enhance understanding of how climate change could affect public health.

Climate change projections show discrepancies even on fine geographical resolutions. Paper IV found that across the 16 locations included, a difference of 49 days identified as heatwave days occurred in the baseline period and 197 days were projected in the future period. This should be compared with a mean of 261 heatwave days in the baseline period and 672 in the future. This difference is based on one climate change projection only. A HIA based on a larger range of climate change projections, such as in paper III, would provide an even greater range. Although the projections used in paper IV were at a rather high geographical resolution, the projection was still too coarse to resolve any influence from urban heat islands. Especially for Stockholm, it would be helpful to account for any such effect because the city is expected to grow even further in the future. A study showed that the city was expected to be the fastest growing city in Europe in the period 2015 to 2020 [76]. Presenting the health effects of further urbanisation and densification of the city could be a useful tool for decision makers to make informed and sustainable decisions.

Knowledge about the geographical distribution of exposure could also facilitate developing and implementing relevant and accurate warnings for a heatwave early warning and response system. Demographic structures also follow geographical patterns; future demographics will affect the risks expected in a certain geographical area. As shown in paper III and IV, demographic change will have a significant impact on future health outcomes separate from the impacts of climate change.

**Future research**

Conducting additional traditional research on exposure-response relationships to understand the mechanics behind heat-related mortality might be of limited use. As shown in numerous studies, the effects of heat on health will differ between regions, which could be due to differences in underlying factors, some of them exemplified in paper IV. These factors have and will continue to change. To limit the negative health effects from high temperatures, policies and programs should target high-risk individuals [77]. Studies identifying these risk factors on the local scale and in the local environment are of greater importance when trying to mitigate health effects from high ambient temperatures [78]. Also, studies looking at other health
Discussion

Future research outcomes than mortality would also deepen our understanding of the public health implications from high temperatures.

Oudin et al. [6] showed that the risk in the general population and the part of the population considered as “low risk” in Rome is basically the same. The estimated RR during a heatwave day for the general population was estimated to 1.22 and in the low risk group 1.20. In the same study, in Stockholm the RR for the same groups are estimated to 1.08 and 1.01. The results from Rome suggest that it is possible to reduce the difference in risk between the healthy and unhealthy, while the results from Stockholm show that in a moderate climate it might be possible to totally remove the risk for the healthy population. An optimistic conclusion of this result is that heat-related mortality possibly could be eradicated. More research is needed to understand which result is representative of other regions, to inform interventions to reduce vulnerability during heatwaves.

One cornerstone when conducting HIAs is the underlying epidemiological model. Most epidemiological studies find different exposure-response relationships in different cities and regions. This makes it hard, on a broader scale, to compare outcomes of different epidemiological approaches. Emphasis is put on the uncertainty in climate, health status and population data while the single epidemiological model that is the foundation of the impact projections is generally put under less scrutiny. Conducting HIAs using multiple epidemiological models, climate change projections and adaptation assumptions would help further understanding and quantifying uncertainties, which in turn would help making informed decisions. An important move forward to increase the quality of future HIAs is to strive towards more generalizable and transparent models to be able to assess the uncertainty covered in the epidemiological model assumptions.
References


References


References


70. Arbuthnott, K., et al., Changes in population susceptibility to heat and cold over time: assessing adaptation to climate change. Environmental Health, 2016. 15.


76. Stein, P., *Stockholm växer snabbast i Europa*, P. Stein, Editor. 2016, Stein Brothers: [http://www.fastighetsagarna.se/BinaryLoader.axd?OwnerID=7481e567-4591-435c-9c8f-cb908a57302&OwnerType=0&PropertyName=RelatedInfoFiles&FileName=Sveriges+rekordsnabba+befolkningstillv%C3%A4xt+och+fastighetsmarknader+i+storstadsregionerna.pdf&Attachment=True](http://www.fastighetsagarna.se/BinaryLoader.axd?OwnerID=7481e567-4591-435c-9c8f-cb908a57302&OwnerType=0&PropertyName=RelatedInfoFiles&FileName=Sveriges+rekordsnabba+befolkningstillv%C3%A4xt+och+fastighetsmarknader+i+storstadsregionerna.pdf&Attachment=True).
