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Impacts of Heat and Climate Change on Labor Productivity in Switzerland

Master Thesis

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Abstract

In this master thesis, the potential economic burden of extreme heat on labor productivity in Switzerland up to the year 2065 is assessed. The gridded minimum and maximum daily temperature data from the CH2018 scenarios were used to produce the hazards, corresponding to the hourly wet bulb globe temperature (WBGT) outside and inside buildings. These are combined with the geographical distribution of workers, categorized based on the physical activity level of their professional occupation, using empirical impact functions linking productivity losses to WBGT. The three entities are implemented in the CLIMADA probabilistic natural catastrophe damage model to determine the economic losses that may be encountered. Finally, different adaptation measures and their potential to reduce the productivity loss are assessed.

I find that already today, the loss is significant, with an average value of CHF 250 million a year. I show that this loss may almost double by 2050 under an RCP8.5 scenario. The fraction of the value impacted is heterogenous between economic branches and cantons. Branches that require individuals to be outside and perform physically demanding tasks, as in the construction sector, are likely to lose the highest fraction of their productivity output. The cantons of Geneva, Ticino and Valais will be the most heavily impacted, because of the higher level of heat stress. Adaptation measures show high potential at reducing the productivity losses. Having heat-insulated and cooled buildings, as well as adapting the hours of work can prevent most of the loss.

Contents

0.1 Definitions

Heat Stress Metabolic stress caused by an overaccumulation of heat in the body.

Wet Bulb Globe Temperature (WBGT) Heat stress measurement which considers temperature, humidity, wind speed, sun angle and cloud cover.

Heat Is defined in this work as any hour where the WBGT exceeds 22 °C and can cause productivity losses.

Heat Wave Sustained period of particularly hot temperatures. The exact definition depends on the study refered to.

Hot Days or Heat days Often defined as a percentile of days compared to a reference period or as days exceeding a certain threshold, which depend on the source.

Impact Function In this work, these are functions relating the heat stress to a percentage loss of productivity.

Labor productivity Considered to be equal to the sum of all salaries in Switzerland.

Productivity Loss Sum of the productivity value which is lost over a certain amount of time (usually a year). Sometime refered to simply as loss.

Adaptation Measure Actions that are taken to reduce the loss.

Representative Concentration Pathway (RCP) Scenarios Greenhouse gas concentration trajectories in the atmosphere with time defined by the Intergovermental Panel on Climate Change. The worse-case scenario, where no measures are taken is the RCP8.5, while the best-case scenario is the RCP2.6.

Climate Simulations Ensemble Set of models of the climate system for the same time range and RCP scenario, with slight differences that account for the plausible climate change response for these conditions.

Natural Variability In this works, refers to the variation in temperatures between years in a time series.

Chapter 1

Introduction

Temperatures around the globe keep increasing as a result of anthropogenic activities, with an observed mean positive warming of about 1 °C since pre-industrial levels (Masson-Delmotte et al., 2014). On top of the mean temperature rising, extreme heat events are increasing in their intensity, length and frequency (Alexander et al., 2006; Coumou et al., 2013; Della-Marta et al., 2007). These trends are particularly strong in Central Europe compared to the rest of the world (Donat et al., 2013; Fischer and Knutti, 2014). Since the beginning of the century, Europe has experienced a series of alarming heat events. The most devastating event in Central Europe and Switzerland was the ”mega heat wave” of the summer 2003, which has been estimated to have been by far the warmest European summer since at least 1500 (Luterbacher et al., 2004). A few years later, the heat wave of 2010 touched mainly Eastern Europe and Russia, but its spatial impacts and intensity likely exceeded those of 2003 (Barriopedro et al., 2011). Since then, many summers have brought periods of extreme heat and new records are regularly set. Most recently, two consecutive heat waves reached unprecedented temperature levels in the summer of 2019. The first affecting South Western to Central Europe resulted in the hottest month of June ever recorded on the continent with a few countries experiencing temperatures exceeding 45 °C for the first time since measurements exist (Copernicus Climate Change Service, 2019).
These events can have important societal and economic consequences because of the influence of heat on the human metabolism (Haines et al., 2006). Increased mortality is probably the most disastrous of those and the severity of heat events has commonly been assessed in terms of number of additional deaths (Kjellstrom et al., 2014). But research has started to focus on the impacts of climate change on labor productivity as labor represents a major component of a country’s national product and small changes have repercussions on the overall economy. For the first time in 2014, the Intergovernmental Panel on Climate Change (IPCC) mentioned this issue in their human health report, although no quantitative assessment was included (Smith et al., 2015). A few studies in the last decade have focused on the worldwide potential losses and on those of different regions. Some of them made estimations for Europe or areas of the continent (Costa et al., 2016; Kjellstrom et al., 2009c; Orlov et al., 2019). Kjellstrom et al. (2009c) looked at Central Europe up to year 2100 as part of a global analysis, Costa et al. (2016) predicted the losses of three European cities and different sectors for the period 2081-2100, while Orlov et al. (2019) assessed productivity losses during past heat waves over the continent for the construction and agriculture sectors. These studies can provide us with a first estimation of what could be the present and future losses in a country like Switzerland. But those are based only on macroeconomic data for the geographical areas studied, while no spatially explicit analysis of the impacts were performed, limiting the accuracy of the results and the conclusions that can be drawn. Also, except for Orlov et al. (2019) who constructed impact functions based on observations

of worker's performance in heat, the impact functions used in the two other studies only considered ISO norms for labor safety, which do not describe the real response of workers to heat stress. Finally, except Kjellstrom et al. (2009c) who looked at what would happen under two different climate scenarios, these studies do not tell us how much of the loss can be avoided in the future by reaching more ambitious climate targets.
A previous master thesis focused on the canton of Zurich applying a high-resolution spatial analysis, by considering the geographical location of workers and the heat stress experienced in each of those locations (Nesa, 2019). The study also compared the today's losses to the potential losses up to 2085 under different climate scenarios. The impact functions used in that work were based on studies describing the observed response of workers in different thermal environments. The aim of the present master thesis is to pursue this analysis by expanding the methodology to the level of Switzerland. Doing so requires the use of standard minimum and maximum temperature data (NCCS, 2018). These variables are standard to different climate models, making the study more easily reproduceable for other geographical areas. Another contribution of this work is to quantify the uncertainties through a Monte Carlo simulation. In the master thesis by Nesa (2019), the uncertainties where estimated through a worse and a best-case scenario. Finally, the potential of different adaptation measures is quantitatively assessed, which has previously only been done in the study by Costa et al. (2016) on the level of different cities and which wasn't done for the canton of Zürich (Nesa, 2019). To my knowledge, the present master thesis represents the first Swiss-wide impact study using the CH2018 climate scenario data (NCCS, 2018) and demonstrates how valuable insights can be drawn from such data to take better informed decisions on the topic of climate adaptation. The research questions that I aim to answer are the following:

1. What will be the cost of heat due to a loss of productivity in Switzerland in the next decades under different RCP scenarios?
2. How do these losses differ between sectors and regions?
3. Which adaptation measures can be applied to reduce the losses?
4. How large are the uncertainties stemming from the climate data, from the heat stress computation and from the impact functions?

To answer these questions, I will first give some theoretical background in chapter 2 on the natural science basis of heat, on the human health impacts and on the existing adaptation measures. In chapter 3, the data and the method used to calculate the losses are described in detail. The results are presented in chapter 4 and discussed in chapter 5, followed by policy recommendations and a discussion of the limitations of this study.

Chapter 2

Background

2.1 Natural Science Basis

Sustained periods of particularly hot temperatures are commonly referred to as heat waves, although no universal definition to this term exists (Meehl and Tebaldi, 2004). Temperatures of intensity sufficient to become dangerous to human health or to have negative effects on their performance can occur outside a so-called heat wave. But due to the physical processes described further (see section 2.1.2), these drastically increase the chances of reaching extreme levels of heat. Events qualified as heat waves are also broadly studied, as the consequences of prolonged periods of heat are much higher compared to those of single hours or days. For these reasons, this chapter mostly focuses on heat waves rather than heat itself, while the following quantitative analysis does not differentiate rather a hot hour happens in the context of a heat wave.

2.1.1 Observed and Projected Trends in the Intensity and Frequency of Extreme Heat Events

During the summer of 2003, the seasonal mean temperature anomalies at different stations in Switzerland was as high as 5.1 °C relative to 1864–2000 (Schär et al., 2004). The daily temperature anomaly compared to the period 1958–2002 reached 10 °C over the country (Garcia-Herrera et al., 2010). The Swiss weather services reported in 2015 that many stations in Switzerland recorded the hottest month of July and their highest daily maximum temperature since the beginning of measurements (Meteo Swiss, 2015).
Della-Marta et al. (2007) looked at the length of heat waves in Western Europe in the time period 1880-2005, defining heat waves as the maximum number of consecutive days within a June-August season where the daily maximum temperature exceeds the long-term 95th percentile. They observed that the length of these events had doubled in the last 126 years. Heat waves would last on average 1.5 days in 1880, but this number had increased to 3 by 2005. They also found that the frequency of hot days had tripled in that time period, with hot days defined as those where the maximum temperature exceeds the long term 95th percentile for the summer season.
Looking at the frequency of heat waves, Christidis et al. (2015) observed that events that would occur twice in a century in the early 2000s would statistically occur twice in a decade in 2015. They also found that the exceptional events of 2003 had become 10 time more likely to happen by 2015, with a return period increasing from a thousand years to a hundred.
If current trends in green house gases (GHG) emissions continue, climate models show that events like the heatwaves of 2003 and 2010 will become the norm by the end of this century over Europe and in Switzerland (Beniston, 2004; Fischer and Schär, 2010; Schär et al., 2004). This would be partly due to the shift to a globally warmer climate. But climate models also

predict a change in the variance and the skewness of the distribution of temperature, with increasing daily to inter-annual variability in the summer (Cattiaux et al., 2015; Fischer et al., 2011; Holmes et al., 2016; Schär et al., 2004). This increase in variability under climate change can be explained by changes in the atmospheric circulation and soil moisture content (Fischer and Schär, 2009; Seneviratne et al., 2006; Van Ulden et al., 2007).

2.1.2 Physical Processes Governing Heatwaves

The exact physical processes that govern heatwaves are not entirely understood and their representation in climate models remains imperfect, leading to uncertainties (Rasmijn et al., 2018; Vautard et al., 2013). A necessary condition for their occurrence is the presence of a persistent high-pressure area, referred to as an atmospheric blocking (Meehl and Tebaldi, 2004; Miralles et al., 2014). A blocking situation is associated with clear skies, increased heat advection, as well as hot conditions at the surface (Trigo et al., 2005; Fischer et al., 2007). Under such atmospheric configuration, the surface sensible heat fluxes determine the air temperature and causes positive feedbacks between the atmosphere and the land: high demand of water from the atmosphere caused by heat and dryness leads to a moisture deficit in the soils and reduced evaporative cooling, which again increase the temperature in the atmosphere (Miralles et al., 2012). This process can be referred to as the soil moisture-temperature feedback (Miralles et al., 2014). Precipitations in the previous months additionally influence the occurrence of extreme summer heat due to this feedback. Particularly dry winters/springs can result in either an abnormally high or low frequency of hot days depending on the atmospheric circulation in the summer, while wet preceding seasons inhibit hot extremes from occurring (Quesada et al., 2012). Soil dryness and the resulting feedback were shown to be central during the events of 2003 and 2010 in reaching such extreme, long lasting temperatures (Barriopedro et al., 2011; Fischer et al., 2007; Meehl and Tebaldi, 2004). Under future warming, we can expect soils to have lower humidity contents and atmospheric blockings could become the only condition determining the occurrence of heat waves (Rasmijn et al., 2018).
Miralles et al. (2014) combined both an observational and modelling point of view to validate this theory for the temperatures observed in 2003 and 2010. On top of the soil moisture-temperature feedback, they described a second process which played a critical role in those events. They found that the heat generated during the day could be trapped during the night in a growing atmospheric boundary layer and was able to reenter the atmosphere on the next morning. Through this mechanism, every day would start at a warmer temperature than the last, reaching always higher heat levels.

2.2 Socioeconomic Impacts

2.2.1 Mortality and Morbidity Consequences of Past Heatwaves

The heatwave of 2003 has been estimated to have caused 70'000 additional deaths in Europe, most of which were elderly people and a higher proportion of women (Robine et al., 2008). Grize et al. (2005) estimated that mortality increased by 7% between June and August 2003 in urban areas north of the alps in Switzerland compared to a reference period. They found that the elderly in Basel, Geneva and Lausanne were the most severely affected. In France, increased mortality reached 60% on average between the 1st and 20th of August compared to the average values observed in the same period between 1999 and 2002, with most of the victims being over 65 (Garcia-Herrera et al., 2010). This high value has been explained by the combination of extremely high temperatures with poor air quality, due to ozone formation (Vautard et al., 2007). In 2010, the death toll reached 55'000 people over

Europe (Swiss Re, 2011). It has been estimated that the number of additional deaths could reach an average of 25'000 people a year in the 2020s, with the highest impact in southern and Central Europe, if no adaptation measures were taken (Ciscar et al., 2009).
In 2003, on top of the increase in mortality, an increase in the rate of hospitalization, demand of healthcare and incidence of admissions to the surgical intensive care were recorded (Dhainaut et al., 2004; Johnson et al., 2004). An earlier study in Chicago during the heat wave of July 1995, reported a 11% increase in the rate of hospitalization (Semenza et al., 1999). The authors noted that 59% of this increase was due to cases of dehydration, heat stroke, and heat exhaustion. But they also reported increases in renal failure cases and comorbid conditions, like cardiovascular diseases, diabetes, renal diseases and nervous system disorders.

2.2.2 Physiological Effects of Heat

In 2014, Parsons published a new edition of the book "Human Thermal Environment", extensively describing the effects of different experienced temperatures on human health, comfort and performance. This book provides the basis for the effects of heat on the human body explained in the following paragraph.
Only about 20% of the energy consumed by our muscles is used to perform the work necessary for physical and cognitive activities, while the rest is converted to heat and must be evacuated to keep a constant 37 °C core temperature. The body can release this heat through exchanges with the colder environment, by moving blood from the core to the skin, where heat will be evacuated. But when the surrounding's temperature becomes close to the body's temperature, these exchanges become impaired and only evaporative cooling through sweat can enable the temperature to be regulated. If the humidity content of the air is also high, sweat evaporation can become compromised and the body faces difficulties in maintaining a tolerable temperature. When the core temperature rises above 37 °C, the first signs of heat exhaustion appear, with nonspecific symptoms including nausea and malaise. If the body is unable to regulate its temperature and rises above 40 °C, a heatstroke might occur. On top of hyperthermia, heat strokes are diagnosed based on a dysfunction of the nervous system. Heat strokes can lead to a number of organs being damaged if the temperature is not regulated rapidly, or even to death. Dehydration, because of a lack of water or sodium intake, highly increases the sensibility to heat, as sweating is inhibited. Most cases of heat strokes or heat exhaustion can be avoided through appropriate hydration and rest.
The health-related impacts of a heat event depend on the combination of different factors: high day and night temperatures (Grize et al., 2005), the level of humidity (Conti et al., 2005) and the duration of the event (Trigo et al., 2009). The wind speed and the incoming radiation can also play an important role on a local scale (Parsons, 2014). This is partly because of their link to surface level pollutants like ozone. These factors predominantly impact the health of elderly, infants and people with cardiovascular and respiratory diseases (Basu and Samet, 2002). The effect that these environmental factors will have on an individual additionally depend on their metabolic rate and their clothing. The metabolic rate is influenced by the level of physical activity, as well as by the individual's tolerance to heat (Parsons, 2014). Tolerance to heat can be increased through acclimatization, as it has been shown in extensive research on soldiers and athletes in hot environments (for example Pandolf (1998); Périard et al. (2015); Sawka et al. (2015); Taylor (2000)). When initially exposed to heat, athletes have a higher heart rate and a smaller stroke volume compared to temperate conditions, reducing their performance and increasing the risk of heatstroke (Sawka et al., 2015). With persistent 90 minutes training in the heat over one to two weeks, a number of mechanisms allow the athlete to reach their peak performance again and to drastically reduce the health risks associated to heat (Sawka et al., 2015). Sudden heat expo-

sure in the context of a heat wave might therefore be particularly dangerous for the sensible population and for the people performing physical activities, as opposed to people who are used to live and work in hot conditions. Finally, fit people with high aerobic capacities and high surface/mass ratio also have the ability to acclimatize better, compared to less fit people and people with health problem (Gardner et al., 1996).

2.2.3 Heat Indices

Several indices exist to measure the effects of temperature on the human body. These have different input data and different applications. An index that is widely used to estimate the heat stress experienced by humans in working conditions is the Wet Bulb Globe Temperature (WBGT), which combines humidity, temperature, wind speed and solar radiation (Parsons, 2014). Another index example when considering human health is the physiological equivalent temperature (PET), which represents the indoor temperature equivalent reaction that an individual experiences under more complex outdoor conditions, where wind and radiation for example also play a role (Mayer and Höppe, 1987). These indices reflect well the effects of heat on the body, as they take into account the different influencing factors. But they are often complex to compute, especially on large scales, as the data is not widely available at meteorological stations and can change abruptly on short distances. Combining such indices with large climate data can therefore be challenging. Using and index based only on temperature and humidity would thus be more convenient as these factors are the most important and are widely available. In 2003, in France, the number of deaths in different areas was closely linked to the number of days with temperatures exceeding 35 °C and minimum temperatures not going below 20 °C (Vandentorren et al., 2004). Similar observations considering only temperature were made in other countries. In Switzerland, the Heat Index (HI) is used by the Swiss weather service to warn for the danger of heatwaves. The HI is based solely on temperature and relative humidity (Meteo Swiss, 2019).

2.2.4 Labor Productivity

Heat impacts the comfort of workers and their output, potentially having consequences on the wellbeing of large fraction of the population and on the gross domestic product (GDP). As stated above, for workers performing physical tasks, risks of heat strokes or organ damage exist if they continue to work under a state of heat exhaustion. In France during the summer of 2003, over a thousand additional deaths were observed in the non-elderly adult population, most of which were men, suggesting labor accidents (Hémon et al., 2003). Before such extreme consequences, heat in the workplace leads to diminished physical work capacity, diminished mental tasks ability and increased accident risk (Kjellstrom et al., 2009a). People working outside and performing physical task are the most exposed, but indoor workers in Switzerland could also experience high heat stress as a lot of offices are not equipped with cooling systems. In order not to experience health impacts from heat, workers adapt to the conditions by taking breaks more frequently and working more slowly (Mairiaux and Malchaire, 1985).
The effects of heat on different human activities have been studied in laboratory and field studies since the 1920s. When knowing the exact environmental conditions and energy expenditure, determining the impact on labor productivity is feasible (Day et al., 2019). But assessing the thermal environment to which workers are exposed on a larger scale is a complex task. A study on workers in Australia estimated that heat in the country between 2013 and 2014 caused an average loss of US$655 per person based on sample groups that

self-reported their decrease in productivity and absenteeism (Zander et al., 2015). They estimated that this equals to an economic burden of US$6.2 billion per year, or 0.33 to 0.47% of Australia's GDP. They noted that these years were exceptionally hot but will likely become the norm, showing the need for adaptation measures. Dunne et al. (2013) derived the WBGT from historical global reanalysis data and model projections and combined to those with the US national and international standards for work intensities at various WGBT levels. They estimated that climate change had already reduced work capacity globally by 6% to 10% in the past few decades in the warmest months of the year. They also estimated that the reduction could reach 37% by 2100 in these peak months of heat stress considering the RCP8.5 scenario. Kjellstrom et al. studied the projected changes in productivity by climate region until 2080 under two different climate scenarios, one reaching 2.4 °C above preindustrial level, the other one 3.4 °C. The impact functions were taken from a previous publication by Kjellstrom et al. (2009b) in which the values are again based on international and American working safety standards. In regions of Asia and the Caribbean's, their model predicts a loss between 11% and 27% by 2080. For Europe, they found only a small difference in the number of working days compared to other regions in the world without any adaptation measures (the maximum would be 0.4% days lost in Central Europe in the 2080s considering the pessimist scenario). These results were translated in a later study in terms of loss of GDP, resulting in a global loss of US$2.1 trillion in 2030 (DARA, 2012). In 2014, Kopp et al. (2014) investigated the effects of heat in the US under different climate scenarios, with impact function derived from surveys on allocation of time. Under a high climate scenario, they estimated productivity losses between 0.2% and 2.8% until the end of the century in high risk jobs and between 0.1% and 0.5% for low risk jobs.
Two studies have focused specifically on areas of Europe (Costa et al., 2016; Orlov et al., 2019). Costa et al. (2016) looked at three European cities and estimated the cost of extreme heat on labor productivity in 2081-2100. They focused on the city of London, Bilbao and Antwerp considering an RCP8.5 scenario. They found a reduction of around 0.4% of gross value added in London, 2.1% in Antwerp, and 9.5% in Bilbao, with large differences between sectors. The most impacted were the ones with high proportions of physical work and low elasticity between capital and labor (e.g. construction). Bilbao would be the most impacted, mainly due to its geographical location. And London would be less impacted than Antwerp because of its larger proportion of office workers and low physical intensity work. They reported that one important factor in their estimation were the standard for safe work intensity of the European Union, which they used to determine when the workers started to suffer from the heat. They noted that using the US standards (used in several previously cited studies), the loss in productivity was doubled, illustrating the sensitivity to this element. Finally, a recent study focused only on Europe, specifically on the construction and agricultural sector, and assessed the losses during three past heat waves using meteorological data, monetary transactions and both empirical exposure-response functions and ISO standards (Orlov et al., 2019). They found an average loss during these events of $59–90 per worker in construction, and a loss of $41–72 per worker in agriculture in the top ten impacted countries.

2.3 Adaptation Measures

Diverse adaptation measures exist to limit the impact of heat on workers and some of those are already partially implemented in Switzerland. Maintaining cool temperatures inside buildings is an evident response in European countries, as the vast majority of people work inside. In the previously described case study on European cities by Costa et al. (2016), the authors considered different mitigation effects to reduce the vulnerability of the workers. The highest averted loss came from installing air conditioning. However, they noted that this could be problematic, as many indirect costs may be induced through this measure. The use of air conditioning is known to increase the heat in cities and the risk of those working outside even more (Salamanca et al., 2014). It is also energy demanding and can contribute to global warming depending on the source of the electricity used. Other options to reduce the heat inside buildings, like improving shading, ventilation and roof albedo provide indirect benefits and lower costs on the long term (Lundgren and Kjellstrom, 2013). Porritt et al. (2011) modelled the temperature inside 19th century houses in the UK in the 2080s and tested different adaptation measures to lower the temperature in the summer. They found overheating could be addressed entirely with passive measures, the most efficient being wall insulation, external window shutters and light-colored painting of the exterior wall. A study in Jordan showed that the installation of shading devices on windows, which limited the direct exposition but still let enough light in, was enough to reduce the temperature by 3.25 °C and 3.5 °C on average in July and August respectively (Freewan, 2014). Another study using simulations in Montreal found that proper shading could reduce the cooling energy demand of buildings by 50% (Tzempelikos and Athienitis, 2007). Green roofs can also provide important benefits in buildings, as they provide shading, allow evaporative cooling (provided there is enough moisture) and have a lower albedo compared to dark roofs. The heat uptake of buildings is decreased, additionally reducing their contribution to the urban island effect (Gill et al., 2007). These have many other indirect benefits, as they can for example decrease particulate matter in the air, as well as noise pollution, or even reduce stormwater runoff (Rowe, 2011).

A possible solution for those working outside is the use of cooling clothing, usually in the form of vests designed to reduce the core temperature. These contain biological phase change material (PCM), e.g. frozen gel, salt, wax, etc. (Gao et al., 2010). They have the potential to cool the body at a constant rate, by absorbing latent heat when they change phases (Mondal, 2008). Depending on the material used for the cooling, they might have to be stored and transported in a cold environment (Gao et al., 2010). Working in the shadow instead of in the sun can also reduce the risks. An intervention on sugar cane workers in El Salvador found that workers increased their productivity on average by 5.1% when provided enough water, rest and shaded areas (Bodin et al., 2016). The workers said that they felt the shading had made the biggest difference, as they were previously able to bring water and to take breaks but didn't have access to shaded areas.

Another solution that can be beneficial to all, but especially for people working outside as the temperatures are more variable throughout the day, is adapting the schedule to avoid the hottest hours. Companies can also change their organization to have lighter work performed in the summer, as the cold in the winter will become less of a problem in sectors like construction.

Many governments in Europe have put heat health warning systems (HHWS) in place since 2003 which can also be beneficial to everyone. These are systems that use meteorological forecasts to prepare public health interventions in the case of extreme heat events (Koppe and Jendritzky, 2005). The majority of HHWS have several levels of alerts, which require different measures to be taken (Kovats and Kristie, 2006). These measures can for example be sharing general advice on heat stress avoidance through media announcements, opening cooling centers and telephone help lines or distributing fans (Kovats and Kristie, 2006). In Switzerland, the swiss weather service has a warning protocol for heatwaves between level 3 and 4 (5 being the maximum but is very unlikely to occur in Switzerland). 3 means that there is a heat index exceeding 90 for a minimum of 3 days, while 4 means that the heat index exceeds 93 for at least 5 days (Meteo Swiss, 2019). In this context, special measures could be directed at workers vulnerable to heat. For example, advising to change the working schedule to avoid the warmest hours through a HHWS could avoid losses of efficiency in high risk professions and reduce accidents. Or there could be campaigns to

inform workers on measures to take to tolerate the heat better and heat exhaustion signs to look out for to avoid health issues.
Finally, several measures can reduce the temperatures in cities in general and could also provide benefits for all those working there. In New-York, it was found that the most vegetated areas were on average 2 °C cooler compared to the rest of the city (Susca et al., 2011). Having generally more vegetation or green roofs as explained above therefore have large potential at reducing the urban heat island effect. Also, using materials with a smaller albedo than dark concrete can reduce the heat stored in roads and buildings (Susca et al., 2011).

Chapter 3

Data and Method

To assess the future risk as defined by the IPCC (IPCC, 2014), three different elements were needed: the hazards, or in the case of this work the future temperature under different RCP scenarios in Switzerland, the exposures, or the geographical distribution of salaries and the vulnerability, or how labor productivity is influenced by the temperature. These were brought together in the open-source probabilistic natural catastrophe model CLIMADA (CLIMate ADAptation) to compute the future impact (Aznar-Siguan and Bresch, 2019). Several transformations were required from the readily available data to those entities and each of these steps comprised some uncertainty. To get a probabilistic distribution of the impact, a Monte Carlo simulation was used: the impacts were calculated a thousand times where each time the transformations or variables that entail an uncertainty were randomly picked within a given distribution. This allowed to clearly quantify the uncertainties.

3.1 Hazards

The most complete analysis available so far on climate change in Switzerland comes from the CH2018 Climate Scenarios for Switzerland (NCCS, 2018). This initiative led to the existence of a set of Swiss climate scenario data based on the latest European climate model simulations from the Coordinated Regional Climate Downscaling Experiment (CORDEX) (Giorgi et al., 2009). The CH2018 data provides information on the future climate of Switzerland for three RCP Scenarios defined by the IPCC (2018): RCP8.5, RCP4.5 and RCP2.6. RCP8.5 corresponds to a worst-case scenario where no policies to reduce GHGs emissions are implemented. The radiative forcing reaches greater than $8.5\,\mathrm{W/m^2}$ by 2100 and continues to rise thereafter. On the other end, RCP2.6 represents a scenario where emissions are drastically reduced to a close to zero level, reaching the Paris agreement targets and limiting global warming to 2 °C. In that case, the concentration of greenhouse gases in the atmosphere would start to decrease in about 20 years. RCP4.5 is a middle range scenario, where some actions are taken to reduce climate change but are not sufficient to reach the 2 °C target.
The Daily Gridded minimum and maximum temperature data from the CH2018 initiative were used in this work to provide the hazards for the different RCP scenarios. Each scenario comprises an ensemble of climate simulations: 32 for RCP8.5, 25 for RCP4.5 and 12 for RCP2.6. Several steps were required to get from the raw CH2018 temperature data to the hazards used in the impact calculation. These steps are shown on the diagram in Figure 3.1 and described thereafter.

Each hazard set used to calculate the impact in the model consisted of the heat outside and the heat inside buildings. Those corresponded to the hourly WBGT for the working hours in one year and for one climate scenario, where the WBGT exceeded 22 °C in at least one

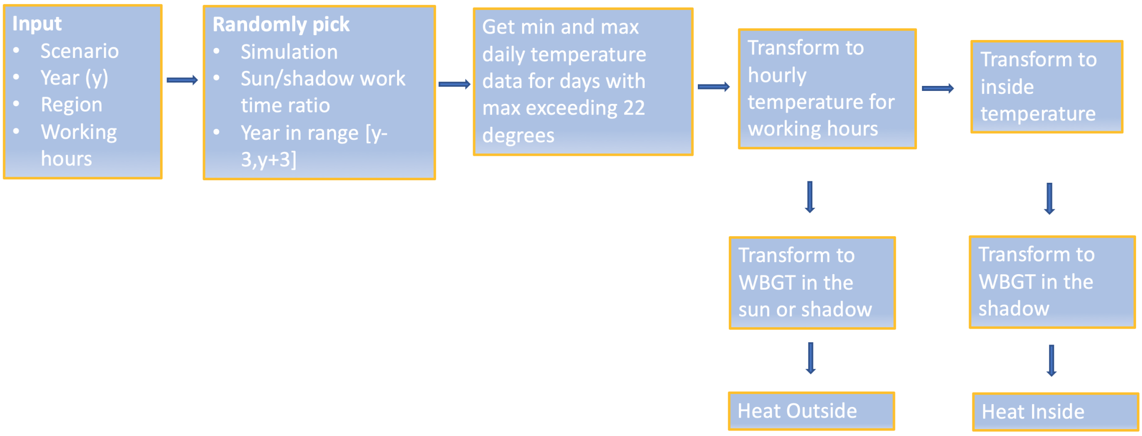


Figure 3.1: Diagram showing the steps necessary to compute the two hazards "heat inside" and "heat outside" from the CH2018 minimum and maximum temperature data.

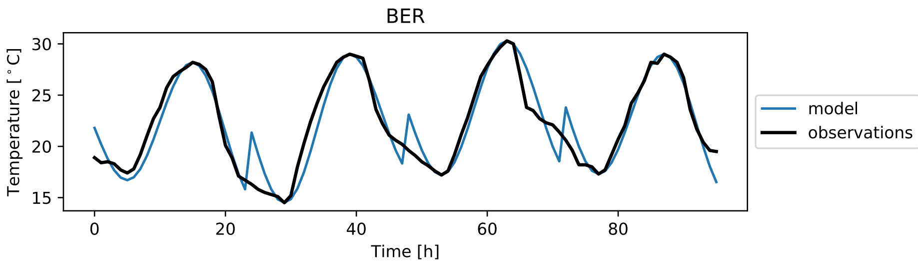


Figure 3.2: Example of a few days fitted with the hourly temperature model and observed hourly temperature for a meteorological station in Bern.

grid point, inside or outside. This way, hours where no impact would occur, according to the impact fonctions, were not considered as hazards. When no adaptation measures were implemented, it was assumed that everyone works from 8:00 to 12:00 and from 13:00 to 17:00. The uncertainties considered in the Monte Carlo simulation are the following:

1. **The transformation from minimum and maximum temperature to hourly temperature.**

   A function for this transformation was found by studying observational data for a few stations in Switzerland for the summer of 2018 (Bern, Geneva, Sion and Lugano). Different models were tested to approximate the hourly temperature from the minimum and maximum. The root mean squared error (RMSE) was then calculated for each station for the model versus the observed hourly temperature, considering only the hours between 6:00 and 22:00. In Figure 3.2, the observed value, as well as the fit used to approximate the hourly temperature are shown as an example for the station of Bern. The "linked days" equation from (Chow and Levermore, 2007) was found to have the smallest RMSE and was chosen for computing the hourly temperature. This equation leads to a spike when changing days but is not of importance in this model, as people were never considered to work at midnight, even when considering adaptation.

   As the RMSE is the standard distribution of the error, the distribution of the transformation to hourly temperature is given as:

$$T(t) = T_{predicted}(t) + N(RMSE; \mu, \sigma) \tag{3.1}$$

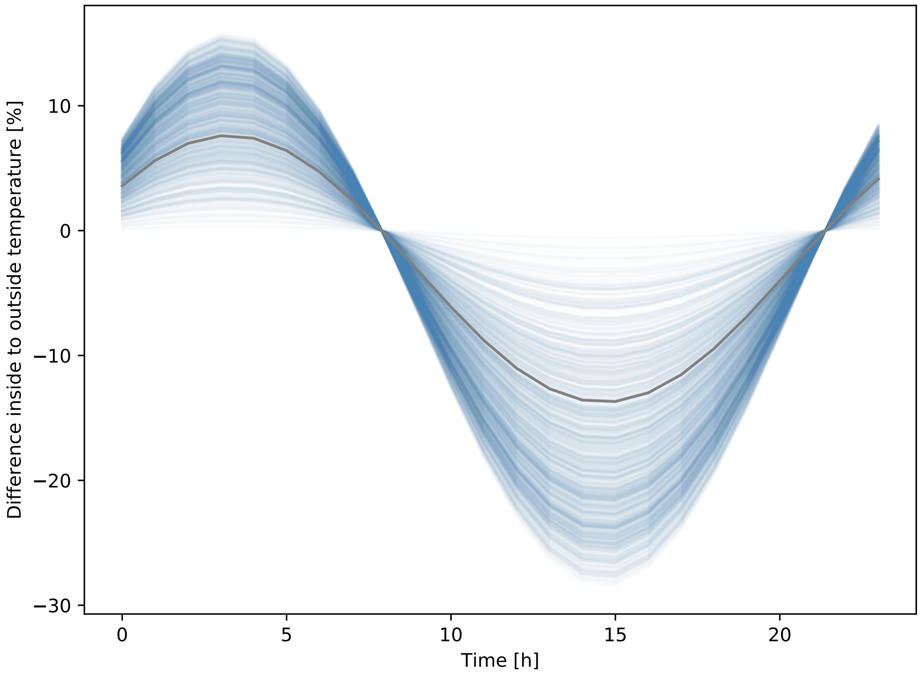


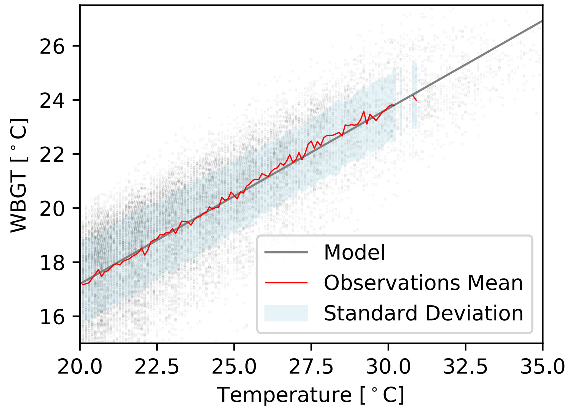
Figure 3.3: Percentage difference of the inside temperature to the outside temperature depending on the hour of the day. The gray line corresponds to the simulation for a typical building in Zurich from Nesa (2019), while the blue lines shows a sample distribution of this transformation considering the uncertainty.

2. **The transformation to inside temperature**

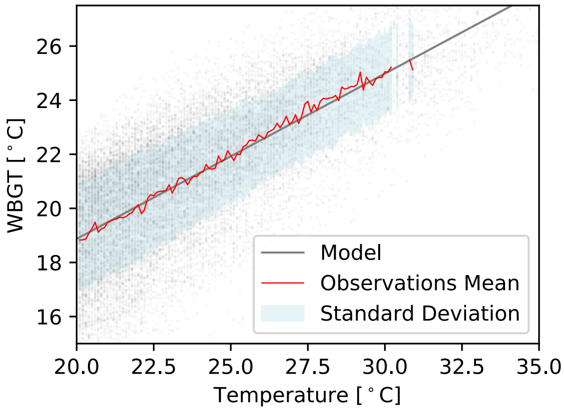
   In order to find the inside heat stress, the simulation done in a previous master thesis in collaboration with the Sustainable Construction Department at ETHZ was used (Nesa, 2019). On two hot days of the summer of 2018, they tested how the temperature of a typical building in Zürich depends on the temperature outside. This relationship was considered, in percentage relative to the temperature outside, as being the most likely temperature inside all buildings. Undoubtedly, a substantial uncertainty exists in this transformation. The possible temperature inside was assumed to have a triangular distribution (Johnson, 1997) and could consequently have values anywhere from the same as outside, to 20% lower than the most likely case (being the function derived from the observations by Nesa (2019)). Again, each time the hazard was computed, a random value in this distribution was chosen. A distribution of the functions predicting the percentage difference between the temperature outside and inside can be seen in Figure 3.3.

3. **The transformation from temperature to WBGT**

   The empirical studies used to determine the impact functions mostly used the WBGT to measure the vulnerability of workers, as temperature is not sufficient to fully account for the heat stress experienced by the human body. Because only the temperature was available as gridded data in the CH2018 initiative, a transformation was again necessary, either of the impact functions or directly of the temperatures. The relationship between temperature and WBGT temperature was studied for past observations at different stations. To calculate the WBGT, the R package *HeatStress* was used (Casanueva, 2019). This package provides tools to calculate the WBGT from meteorological variables. Two functions are available in this package to get the WBGT: one to calculate the WBGT in the shadow (taking into account temperature, humidity



(a)



(b)

Figure 3.4: Temperature and WBGT relationship for temperatures over 20 °C from 2015 to 2018 with the points being observations from stations in Chur, Zurich, Geneva, Lugano and Basel in the shadow (a) or in the sun (b). The black line is the model which is taken to compute the hazards. An average from the standard deviations of the observations at each temperature is taken as standard deviation of the model.

and a constant wind speed) and one in the sun (additionally taking into account the sun radiation). The temperature was plotted against the calculated WBGT both in the sun and in the shadow as shown in Figure 3.4, and linear relationships with normal distributions were chosen. The WBGT in the shadow was always considered for inside heat, while workers outside where randomly set to work a certain amount of the day in the sun as described in the next point. This transformation was performed at each hour independently, which would not be possible if applied on the impact function. It would have likely more significantly contributed to the result's uncertainty, as more extreme values would have been possible. But it could still be considered as a simple way to decrease the necessary calculations in the model.

4. **The number of hours with sun exposition.**

   As seen in figure 3.4, the WBGT does not relate in the same way to the temperature if taken in the sun. People working outside are likely to have to work in sun exposed areas. But again, the number of hours in a day, where people working outside are exposed was not known. To account for this uncertainty, a uniformaly distributed number $h \in [0, 8]$ was picked, corresponding to the number of hours that people work in the sun on average in a day. Then, for each hour, it was randomly determined rather in that hour people outside are working in the sun, with a probability of $h/8$.

5. **The year for which to take the data.**

   Calculating the impact for a specific year is statistically problematic, due to the natural variability which remains in the CH2018 ensembles. In each run, a random year in a $[y - 3, y + 3]$ time range was uniformally sampled, y being the year for which the probabilistic loss is calculated. This also means that more runs were needed in the Monte Carlo to get a stable output. This range was chosen as it appeared to reduce the natural variability to have a meaningful trend, while requiring no more than 1000 Monte Carlo runs for the results to stabilize.

6. **The simulation from the climate change ensembles**

   As explained above, every RCP scenario consists of an ensemble of climate change

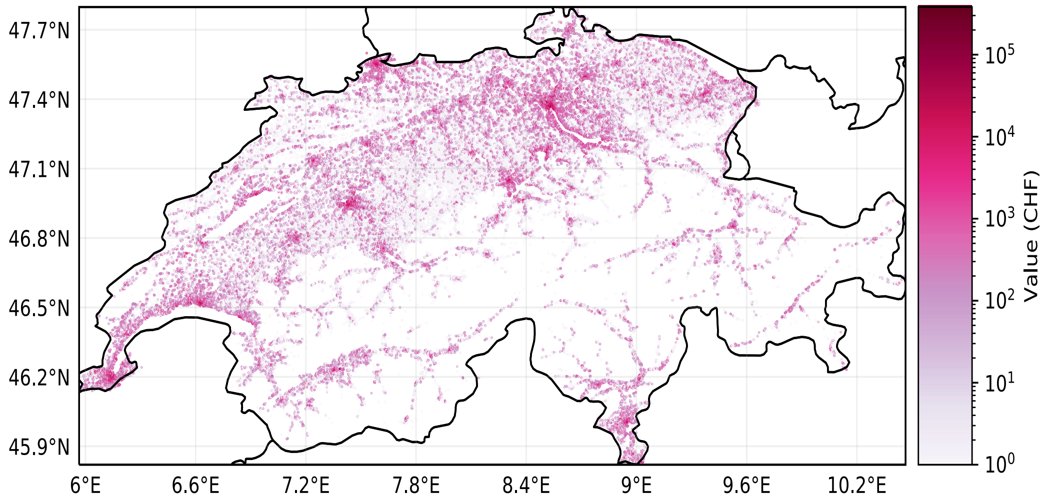


Figure 3.5: Map of the exposures of workers in low physical activity labor branches. The value corresponds to the sum of the hourly salaries in the corresponding branches.

simulations. Averaging those would have resulted in losing the most extreme values, which have an essential role in this application. Therefore, these were considered as the climate model uncertainty and each time the impact was computed, a different simulation within the scenario was randomly picked.

3.2 Exposures

The method to calculate the exposures was taken from (Nesa, 2019), who used the same data but on a cantonal level. The exposure from workers was based on the last available geographical distribution of employees in Switzerland given by the employer's statistics from the Federal Statistical Office (STATENT 2017). This data provides employers per hectare, their work branch, as well as the number of full-time equivalent employees. The later was then multiplied by the mean hourly salary for the branch, also obtained from the Swiss Statistical Office. The loss of productivity due to a hot hour was estimated to be equal to the same percentage of the hourly salary of the workers impacted.
As the loss of productivity depends on the physical intensity activity of the labor, three levels were determined depending on the branch: low, moderate and high. Each of these was linked to an impact function. The hazard used to compute the impacts for a branch also depended on rather people were considered as working outside or inside, which was set to be the same for everyone in a branch. In the end, 4 types of exposures were considered: people working inside at low physical activity, inside at moderate physical activity, outside at moderate physical activity and outside at high physical activity. For example, people working in construction were determined to work outside at high physical activity, while people working in different types of administrations were considered to work inside at low physical activity. The exposures had to be projected from the Swiss CH1903+ / LV95 coordinate system to the WGS 84 Web Mercator system, in order to match the hazards. The precision lost due to this transformation is negligible here as it is in the order of a meter (Swisstopo, 2016).
An example of an exposure map for Switzerland can be seen in Figure 3.5, where the distribution of the low physical activity labor category is shown.

3.3 Vulnerability

Three impact functions relating temperature to productivity losses, for the three types of labor, allowed to link the hazards and exposures as done in (Nesa, 2019). Those functions were assumed to be sigmoidal, which is often the case in impact studies, and which was also the case in the study by Nesa (2019). The three impact functions were however derived with a different method. It was assumed that up to 22 °C WBGT, no loss occurs. It was also assumed that at an unrealistically high temperature of 60 °C, a productivity loss of 100% is experienced by workers in all branches. The different points of the studies were then averaged, where values for at least two temperatures were needed to fit a sigmoid and differentiate the three level of physical activity. All the studies used therefore had to have values for at least two common temperatures. These were mostly found in studies looking at people's performance for different tasks and temperatures. Studies looking at productivity on a larger scale, as on the level of a country, were not considered, as they do not only account for the labor productivity. But with these criteria, few studies exist that could be used meaningfully for this task and even with those, the uncertainty remained large. Also, a significant amount of subjective judgement had to be applied. For these reasons, distributions of impact functions were used in the Monte Carlo simulation, where the mean was considered to be the sigmoid obtained by averaging the points from the different studies for each type. The standard deviation was set to take into account the different study when sampling the functions. To get this distribution, at least two studies had to be considered.

3.3.1 Low Physical Activity Impact Function

The estimated reaction to heat of workers performing a low physically demanding work is shown in Figure 3.6. The first study considered for this category is a 2006 study by Seppänen et al. (2006). This is a meta-analysis where the authors statistically put together previous research on performance in office tasks at different temperatures by weighted them by sample size. They provide a curve for their findings, describing the relative performance as a function of the temperature between 15 and 35 °C, which could be used in our computation of the impact function. The second study looked at students' performance from the National College Entrance Examination China (Graff Zivin et al., 2018). They used data for roughly 2 million tests written between 2005 and 2011. They found that a 3.29 °C temperature increase decreased the score by 1.12%. The temperatures considered though correspond to meteorological values and are not representative of the temperature inside. So, the trend would likely be stronger when considering the real room temperatures that the students were writing their tests in but is not considered here. Finally, the study by (Park, 2017) looked at students' performance on exams again depending on the temperature outside in the United States, similarly to what was done in China by Graff Zivin et al. (2018). A recent study by Almås et al. looked at the performance of students in Kenya and in the US on different economic decision-making and judgment tasks under two different temperature settings. They participants were asked to wait 20 minutes in either the control room at 22 °C or in the target room at 30 °C and then to perform one of the tasks. They found no significant loss of productivity for those cognitive tasks. This study was not taken in consideration in the distribution of the impact function as the hypothesis was that there must be some temperature, however high, where the productivity is decreased. Hypothesizing that the impact function is a sigmoid, there must be at least a very small percentage of productivity lost up to 30 °C. This percentage may however be too small to be captured by the study, perhaps because of the low exposure time or because a temperature of 30 °C corresponds to a smaller WBGT which is too low to see significant effects. However, the points available remain very close to the study by (Graff Zivin et al.,

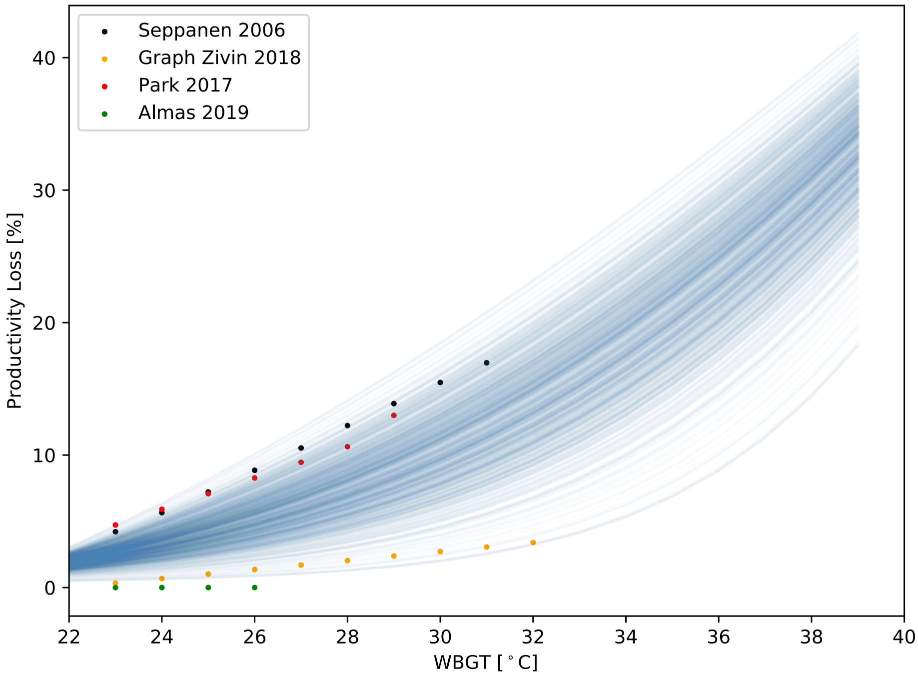


Figure 3.6: Sample distribution of probable impact functions for the low physical activity category of workers. The points correspond to the empirical studies used to estimate the distribution.

2018). The studies used were themselves problematic for our task, as they give the results in terms of temperature and not WBGT, as opposed to the studies used for the two other categories. A rough estimate of 4 °C difference was applied from temperature to WBGT, based on the previous findings for Switzerland and a similar estimation in India by (Sahu et al., 2013), where the difference between WBGT and temperature was 3 °C at the highest. No uncertainty was taken into account for this transformation, as the remaining differences between the studies are much larger.

The study by Hsiang (2010) used by Nesa (2019) was not used here as it looked at all non-agricultural production output in the Caribbean-basin countries, which I don't think can directly account for labor productivity. The results that were used by Nesa (2019) from the literature review by (Dell et al., 2014) also appears to be citing the study included in the impact function here by Seppänen et al. (2006). The study by Niemelä et al. (2002) looking at efficiency in call centers under heat also used in the previous master thesis was included in the analysis by Seppänen et al. (2006) and was not included again.

3.3.2 Moderate Physical Activity Impact Function

Three studies were used for the moderate physical activity impact function shown in Figure 3.7. The first study considered looked the performance of mine workers on different tasks in South Africa Wyndham (1969). Considering a low wind velocity, they found that a WBGT of 30 °C could result in a 4% decrease in productivity, while at a WBGT of 35.5 °C in a reduction of 79%. The second study focused on rice harvesters in India, which corresponds to a moderate to high physical activity level (Sahu et al., 2013). The author found a linear trend, with a 5% decrease in productivity per degree increase in WBGT. For the upper limit, the curve provided by Kjellstrom et al. (2009b) for different working intensities was used, which is based on labor safety standards. For the 200 Watts intensity, they found a loss of productivity of 10% at 30 °C and of 80% at 35. This curve was not based on an

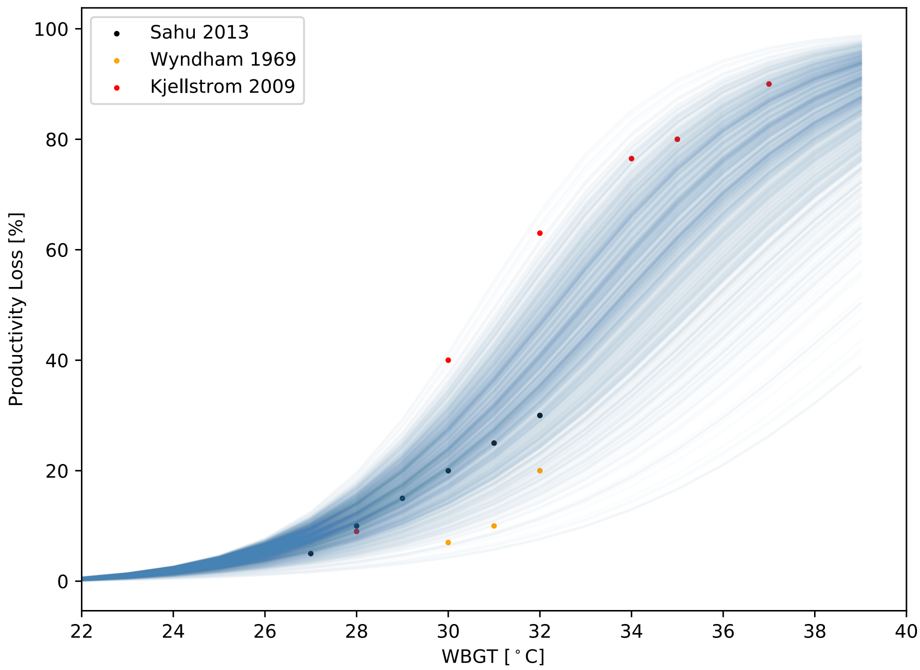


Figure 3.7: Sample distribution of probable impact functions for the moderate physical activity category of workers. The points correspond to the empirical studies used to estimate the distribution.

observational study of workers exposed to heat, but was still used as upper limit of the potential distribution. It was necessary to use this study for the high physical activity impact function, as no other observational study of workers was found which could be applied. It was therefore also used here.

3.3.3 High Physical Activity Impact Function

For the high energy physical activity category shown in Figure 3.8, the studies by Sahu et al. and Kjellstrom et al. were used again. The same number as for the moderate physical activity category were used as lower limit from the study by Sahu et al.. For the second one, the numbers for the high intensity labor were considered (400 Watts), resulting in a productivity loss of 50% at 30 °C WBGT and of 100% at 35 °C WBGT.
Another study was used by Nesa (2019) for this category, where the authors found based on interviews that people in different sectors change their allocation of time according to the daily maximum temperature. They find that at a temperature of 29 °C time allocated to reduce started to decrease and a temperature of 40 °C resulted in 12.5 % less time allocated to labor in high risk occupation (for example construction) (Graff Zivin and Neidell, 2013). I also decided to not consider this study as this number seems extremely low compared to what is found in other studies. The time allocated to labor is perhaps not a good indicator to account for losses of productivity, as most people probably still have to go to their jobs even if their output is decreased.

3.4 Impact Calculation

The impact calculation provided two outputs for Switzerland. The first one was the total loss in the country for each exposure category and each run in the Monte Carlo simulation, for the given years and scenarios. This allowed to analyze the distribution of the probabilis-

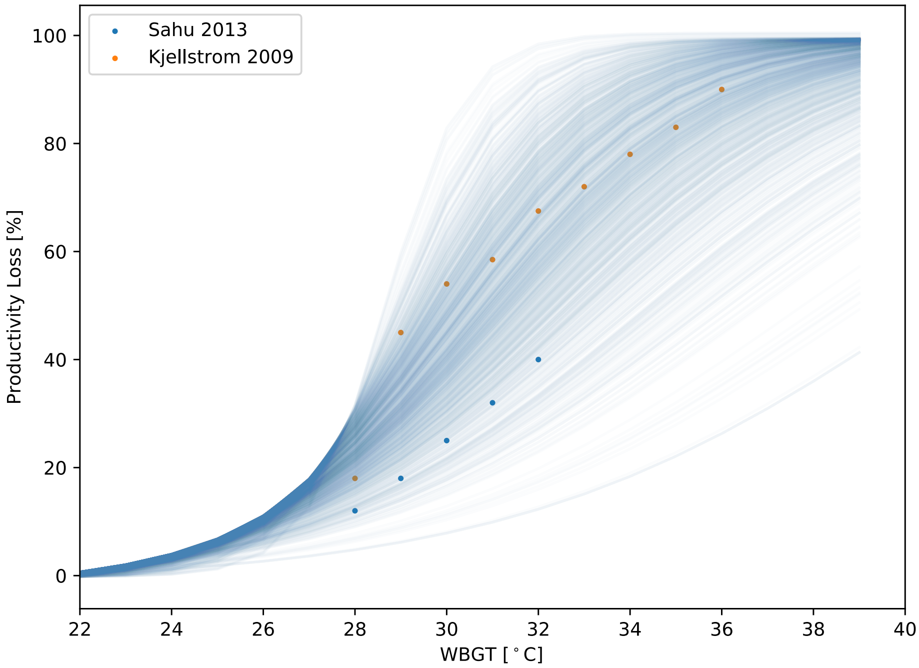


Figure 3.8: Sample distribution of probable impact functions for the high physical activity category of workers when running the model 1000 times. The points correspond the empirical studies used to estimate the distribution.

tic costs. The uncertainty was considered as being the 90 percent confidence interval from the thousand runs. The median cost of the realizations was considered as the 'best estimate' predicted loss, the 5% percentile was considered as the minimum, or best-case scenario and the 95% percentile as the maximum probabilistic loss, or the worst case scenario. A second output was the median impact matrix, which enabled to visualize the geographical distribution of the losses. It also allowed to get the median losses for different cantons without running the simulation again.
The data for the cantons were obtained in the hazards, exposures or impacts using shapefiles with their boundaries from the swissBOUNDARIES3D data (Swisstopo, 2020). The simulation was performed independently for the canton of Zurich to get the full probabilistic distribution and compare the results to those of (Nesa, 2019). The percentage of the exposure lost for the median case in a few different cantons were derived from the median impact matrix from the simulation for Switzerland and compared to each other.
To analyze a branch, the simulation also had to be done independently, as this information is not retained in the results for Switzerland. The impacts for the construction sector in Geneva were analyzed, as I hypothesize that construction may be one of the most vulnerable branches in Switzerland and the canton of Geneva is likely to experience high heat stress. The construction sector corresponds to the three branches "Tiefbau", "Hochbau" and "Vorbereitende Baustellenarbeiten, Bauinstallation und sonstiges Ausbaugewerbe" from the STATENT data.

3.4.1 Adaptation Measures

Three types of adaptation measures were implemented in the model. These measures are:

1. **Adapting working hours**

   In this case it was considered that people work from 6:00 to 10:00 and from 16:00 to 20:00. This was expected to greatly reduce the impact for people working outside, as they are not exposed to the hottest hours of the day. The simulation had to be performed again as the hazard changed.

2. **Protecting workers from the sun**

   Instead of randomly picking a fraction of the time that people outside are exposed to the sun, this number was fixed to 0 out of 8 hours. Exactly how this is achieved was not set. This could correspond to having protecting clothing, that insulate from the sun, having protecting vents over the construction site or performing tasks without sun protection at times only when the sun is low. The simulation had to be done again in this case as well.

3. **Improving buildings insulation and cooling**

   The last measure consisted of setting the impact inside buildings to zero, as would be the case if all buildings were built to be less sensible to outside temperature variations and had cooling systems in case this was not sufficient. Again, exactly how this is achieved was not fixed, as the measure may not be the same for different buildings and the model does not portray such precision. But the studies discussed in section 2.3 can provide a first overview of how this could be done. Modelling different types of Swiss buildings with those measures could then provide further answers. For this measure, the results from the simulation for Switzerland were used again, considering that no loss occurs for those inside.

For these three measures, the cost/benefit ratio was not considered, as the exact cost is hard to estimate and is variable depending on the place in Switzerland and the exact measures implemented.

3.4.2 Sensitivity Analysis

A sensitivity analysis was performed for the canton of Bern, to limit the computational power needed compared to doing it for the entire country. Bern was considered to be well representative of the country, as it is located in Central Switzerland and comprises a large city, as well as rural and mountainous areas.
To perform this analysis, the different uncertainties were set to their most probable value (e.g. the peak of the normal or triangular distributions) except for one, each after the other. Those uncertainties were all the transformation required to get the hazards from the CH2018 data, the impact functions, the RCP scenarios and the natural variability from year to year. The distribution of the difference of the realizations to the median realization were then studied. For the climate simulations, a most probable case could not be defined, so a random simulation from the ensemble was fixed for the analysis of the other elements. The data was taken only for the year y when varying the other uncertainties, in order to ignore the natural variability. As the effects are not linear, taking a warmer or colder year or a different simulation from the ensemble may have changed the spread between the extreme realizations. But this analysis at least provided a way of comparing the different elements of the model when using the same temperature data. It also allowed to compare what the uncertainties are from taking the same raw temperature data and sampling the different elements of the model compared to only varying the temperature data used, even if the first may differ if another set of temperature data was used.

Chapter 4

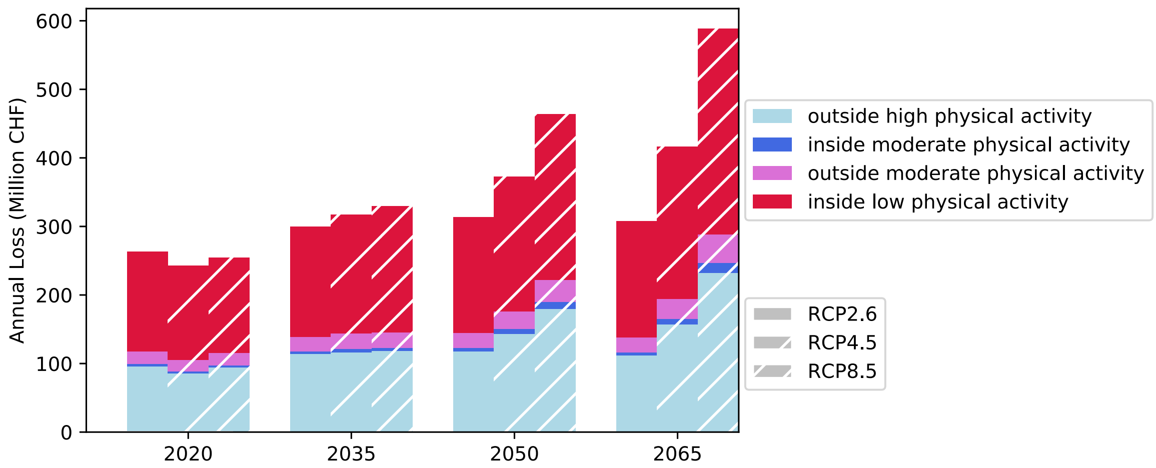
Results

4.1 Switzerland

Applying the previously described method provides us with a total loss today in Switzerland of about CHF 250 million, with a worst-case scenario corresponding to the 95th percentile of the Monte Carlo simulation, at about CHF 900 million. In 2050, the total productivity loss barely increases in the case of the RCP2.6 scenario but is almost doubled of today, at about CHF 480 million, for an RCP8.5 scenario. In that case, the 95th percentile reaches CHF 1.75 billion. The median cost for that case corresponds to about 0.13% of the total exposures' value, 0.1% for the low physical activity exposures and 0.5% for the high physical activity. For all years and scenarios, between 50 and 53% of the losses are experienced by the low physical activity exposure type. This is due to the fact that this category represents 67% of the total exposure value, as most workers belong in this category and their salary also tends to be higher. The high physical activity type represents 35 to 37%, which means that a much higher percentage is affected, considering that only 10% of workers belong to that category and that salaries are lower. This ratio changes slightly when considering the 95th percentile realization, with 39 to 40% of the loss occurring in the high physical activity category and 50% in the low. In 2020, no clear trend can be seen between the scenarios as the difference is likely smaller than the remaining natural variability.

The spatial extend of the productivity loss in 2050 in the case of an RCP8.5 scenario, as a percentage of the total exposures value potentially lost, is shown in Figure 4.2 for both the high and low physical activity exposures type. This value reaches 0.2 percent for some points in Switzerland for the inside low physical activity type, with the highest values appearing on extended areas in Geneva, Ticino and Valais. The same areas are visible for the high physical activity exposure type, with value reaching more than 1% of the yearly exposures value in some points.

The geographical distribution of the losses can be compared to the maps available for the CH2018 data. The percentage of value lost at each exposure appears to correlate very closely to the number of hot days in each point given on the CH2018 web atlas as shown in Figure 4.3 (NCCS, 2018). Hot days are there defined as days having a maximum temperature reaching at least 30 °C. This correlation is then studied in more details in Figure 4.4 for two categories, which also provides a function relating the number of heat days according to the CH2018 web atlas and the impacts. Applying a pearson correlation test to these relationships confirm the hypothesis of a strong correlation, with an r=0.92 for the inside low physical activity category, and r=0.97 for those working outside at high physical activity.



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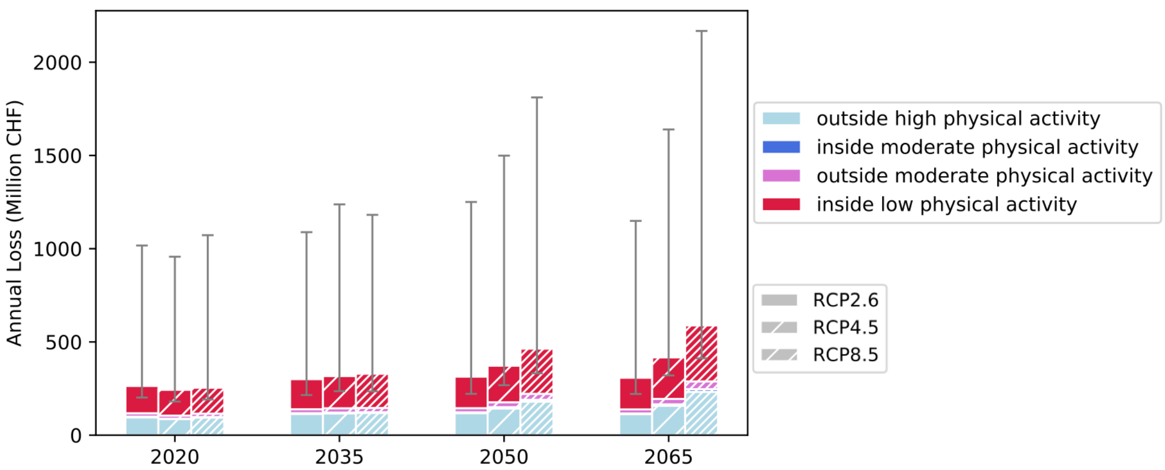


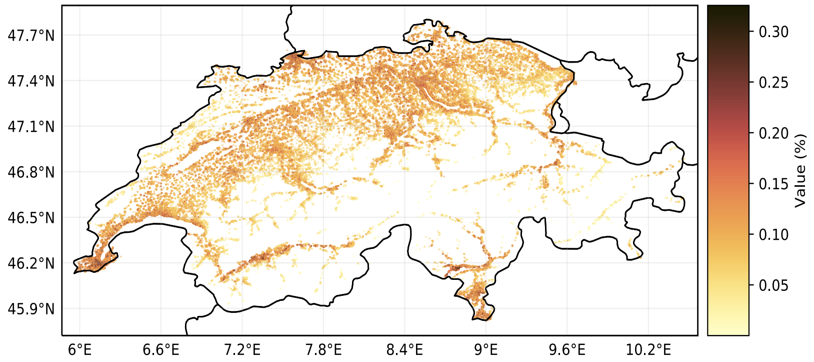
(b)

Figure 4.1: Median of the productivity losses calculated in the Monte Carlo simulation for the years 2020, 2035, 2050 and 2065 and for three RCP scenario. In (b), the error bar corresponding to the 90% confidence interval is added.

4.2 Cantons

When comparing different cantons, as is show in Figures 4.5, between 0.08 to 0.12 of the productivity is lost for the low physical activity work type in the median case, with small differences between cantons. For the high physical activity category, more variance exists between the cantons. In Geneva, the loss reaches 0.8% of the yearly productivity, while in Luzern, this value is 0.4%.
In Figure 4.6, the construction sector in Geneva is studied in more detail. This sector represents 70% of the high physical activity category in the canton. The uncertainty remains large and the productivity loss could be anywhere between 0.2% to 1.75% of the yearly value depending on the climate scenario and the parameters of the model. In Figure 4.7, the geographical spread of the impact in 2050 in Geneva for the construction sector are shown considering an RCP8.5 climate change scenario.

The losses for the canton of Zurich are shown in Figure 4.8 and serve as a comparaison to the results from Nesa (2019). The expected damage for the year 2035 under an RCP8.5



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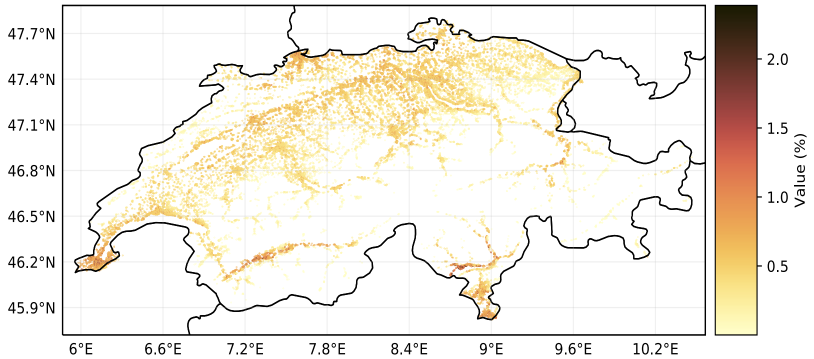
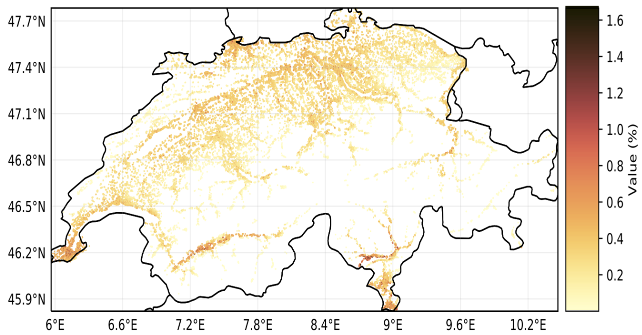
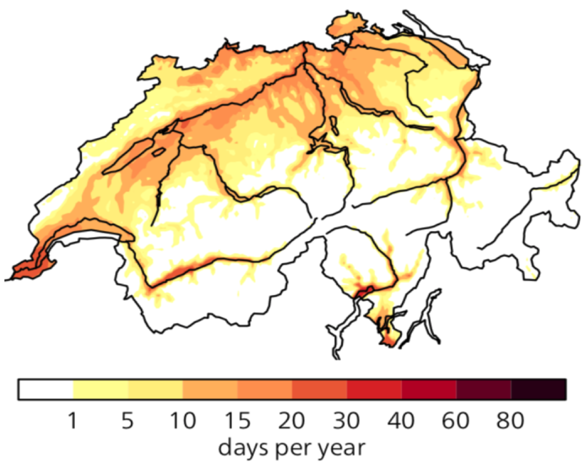


(b)

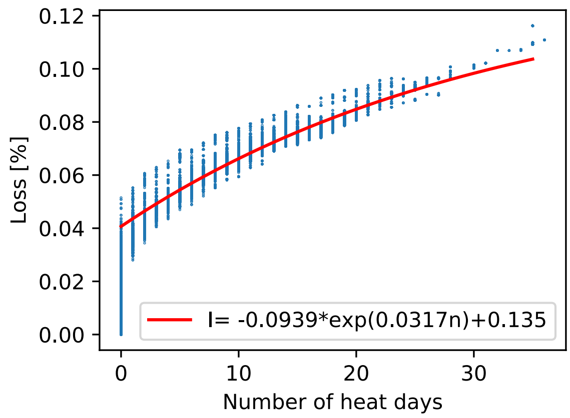
Figure 4.2: Map showing the percentage of the exposures yearly value that is lost in each point in the year 2050 for an RCP8.5 scenario in (a) for the inside low physical activity exposures and in (b) for the outside high physical activity exposures.





(a) (b)

Figure 4.3: Comparison of the percentage loss in the year 2035 under an RCP8.5 scenario for the outside high activity level workers (a) and the CH2018 number of hot days in 2035 under an RCP8.5 scenario from the NCCS (2018) CH2018 web atlas (b).



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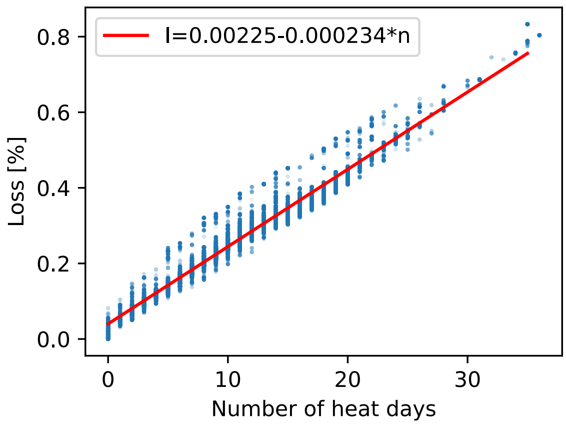


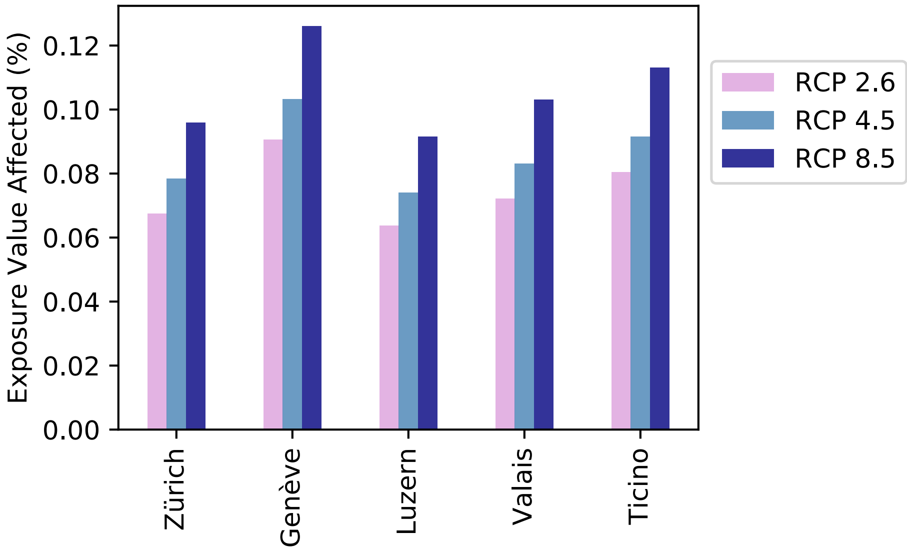
(b)

Figure 4.4: Relationship between the number of heat days and the percentage value lost in (a) for the inside low physical activity exposures and in (b) for the outside high physical activity exposures. The blue points correspond to the results and the red line to the regression.

scenario is CHF 50 million and the 95th percentile is CHF 200 million. In 2050, this number becomes CHF 75 million for the median case and CHF 350 million for the 95th percentile. The trends don't appear to be as clear as those for Switzerland, as the natural variability may play a larger role on this more local level.

4.3 Sensitivity Analysis

In Figure 4.9, the extent to which the different elements play a role in the uncertainty of the calculated productivity loss is tested. When looking at the model's variables, the same hazard data had to be used. This means that the same climate change simulation from the ensemble and the same year were taken. Analyzing the natural variability independently of the simulations requires to only take the data from one climate simulation. The same goes for the uncertainty from the climate simulation, where the data for only one year had to be analyzed. However, one of those may not be representative for the entire set of data. For this reason, I repeated the analysis three times by setting a different climate simulation and year to get an idea of how these may differ. When simulating the losses using different hazard data (considering different years and using different simulation from the ensemble), the contribution of the different uncertainties from the model remains proportional. But the contribution of the natural variability from different simulations of the ensembles varies substantially. Moreover, using a different set of years does not result in the same spread from the climate model simulations. No general conclusion can therefore be made regarding the exact contribution of the natural variability and of the spread of the climate model simulations. What can be said however, is that the spread between the ensemble simulations contributes at least as much as the most uncertain element of the model to the overall uncertainty. The natural variability is also substantial, meaning that the loss could be very different from year to year, even if this cannot be quantified.
In the impact model, the transformation to inside temperature appears to contribute the most to the uncertainty. This is most certainly due to the large panel of potential temperatures that buildings may have inside for a specific temperature outside. On the other hand, the uncertainty in the impact functions interestingly appears to have little contribution to the overall uncertainty. This is likely due to the fact that the productivity loss is fixed at



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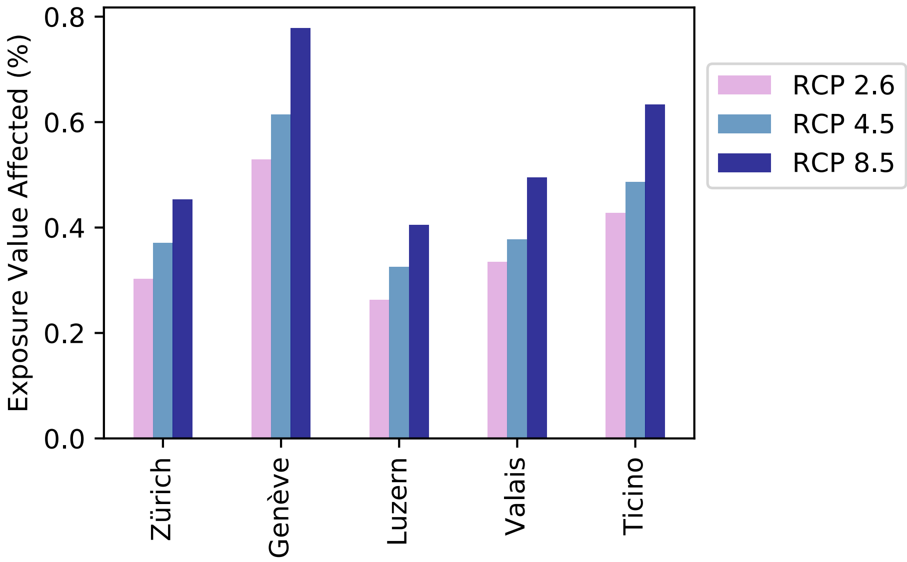


(b)

Figure 4.5: Percentage of the exposures value lost in the year 2050 for the three RCP scenario for the median realization in different cantons in (a) for the inside low physical activity exposures and in (b) for the outside high physical activity exposures.

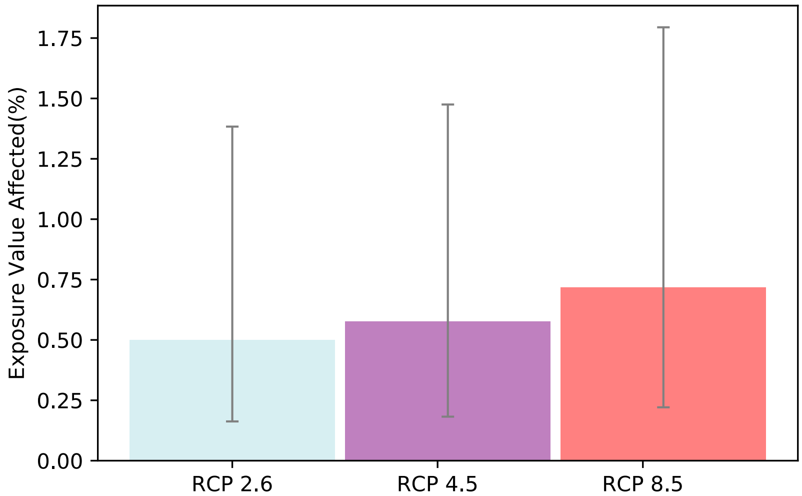


Figure 4.6: Percentage of productivity lost in the construction sector in the canton of Geneva in the year 2050. The error bar shows the 90 percent confidence interval.

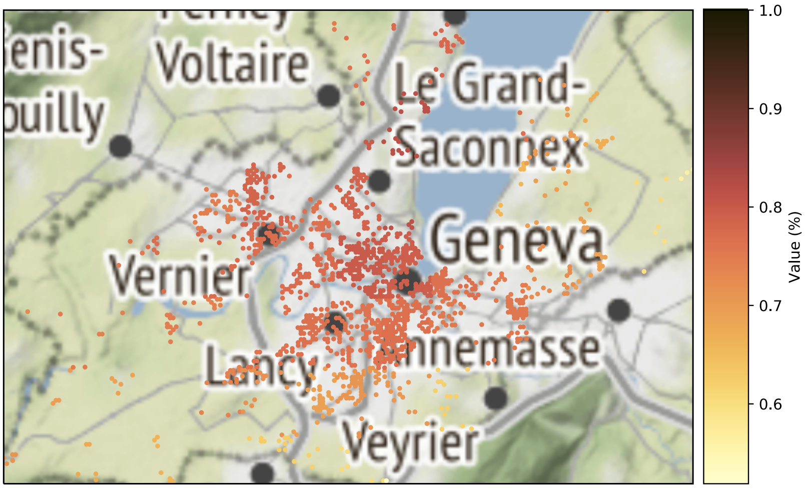


Figure 4.7: Percentage of productivity lost in the construction sector in the canton of Geneva at each exposure in the year 2050 for the median case for an RCP8.5 scenario.

0% for 22 °C WBGT and at 100% for 60 °C WBGT, and that a sigmoid function is always used. The uncertainty is therefore mostly located as from 30 °C WBGT and onwards, which are rarely reached in Switzerland, even considering climate change. This was for example never the fact in the summer 2018 at the stations considered, going back to Figure 3.4 showing the transformation to WBGT.

4.4 Adaptation Measures

The averted productivity loss for the different adaptation measures in Switzerland in 2050 considering an RCP8.5 scenario can be seen in Figure 4.10a.
Having efficient buildings is the adaptation measures with the most drastic effect, as most of the productivity loss occurs for workers in offices and this measure could reduce this impact to zero. The reduction of the productivity loss is of 55% for the median loss. Then, adapting the working schedule to hours where the temperature is lower outside has the

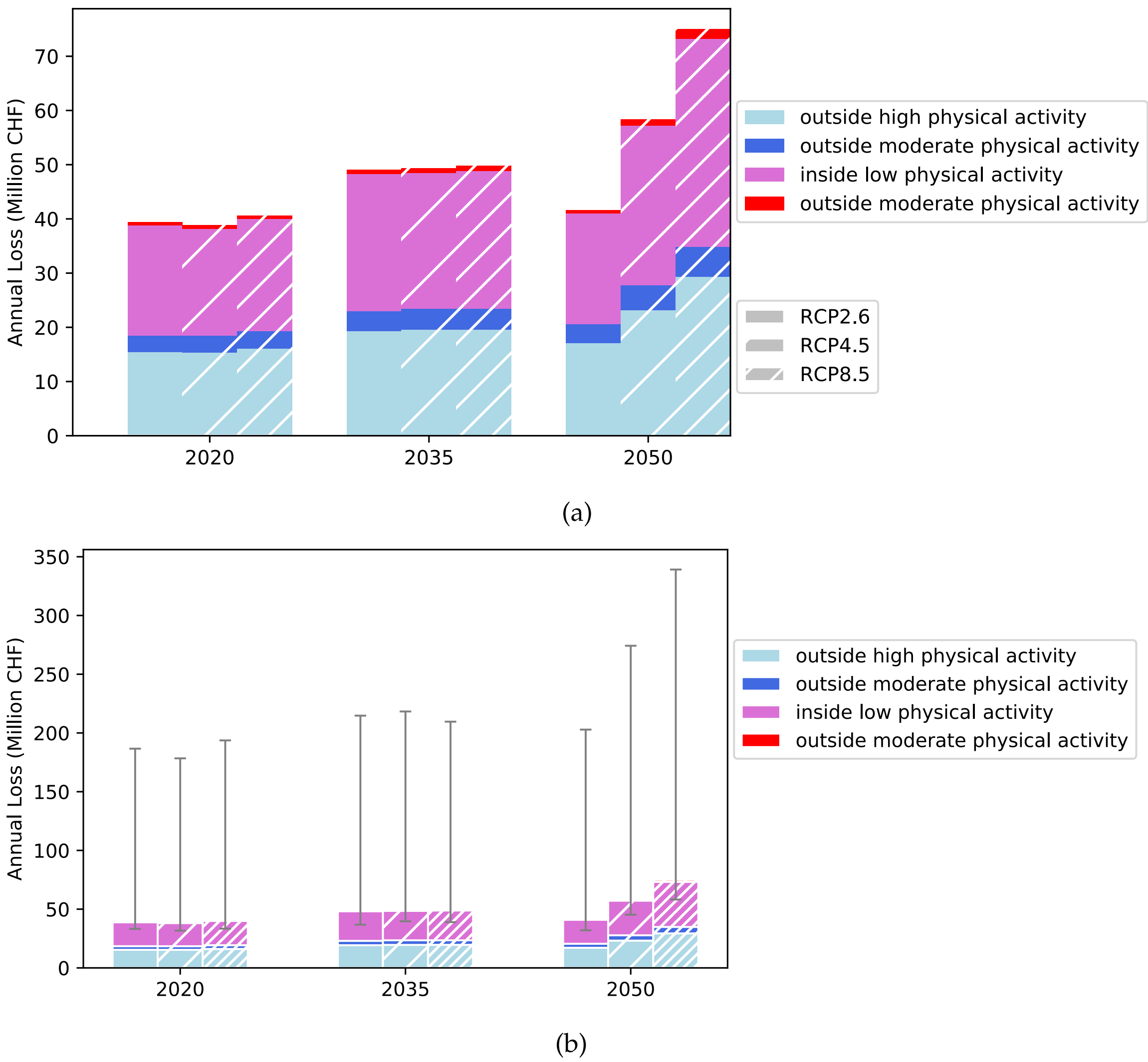


Figure 4.8: Median of the productivity losses in the canton of Zurich calculated in the Monte Carlo simulation for the years 2020, 2035, 2050 and 2065 and for three RCP scenario. In (b), the error bar corresponding to the 90% confidence interval is added.

potential to greatly reduce the productivity loss, this time very much for those working outside. 52% of the total loss can be averted, and 72% for those working outside at high physical activity levels. The measure with the least potential benefice is the one where people working outside are protected from the sun, with 18% of the productivity loss being averted. This means that rather the transformation from temperature to WBGT in the shadow or in the sun is used doesn't dramatically influence the total cost. Still, as this measure only plays a role for those working outside, it still represents close to half of the productivity loss related to this exposure type and would probably be the easiest measure to implement. In Figure 4.10b, the adaptation measures for the 95th percentile of the realization is shown. The ratio of the averted loss to remaining loss seems to remain constant, meaning that the adaptation measures would still be as meaningful in a worse-case scenario.
However as seen in Figure 4.11 showing the adaptation measures for the canton of Luzern, this may not be the case on a more regional level as the potential of those measures highly depends on the distribution of the working force in the different categories. In Luzern, less value inside is at risk proportionnaly to the value outside for example and the measure mostly targeting those people have higher effects.

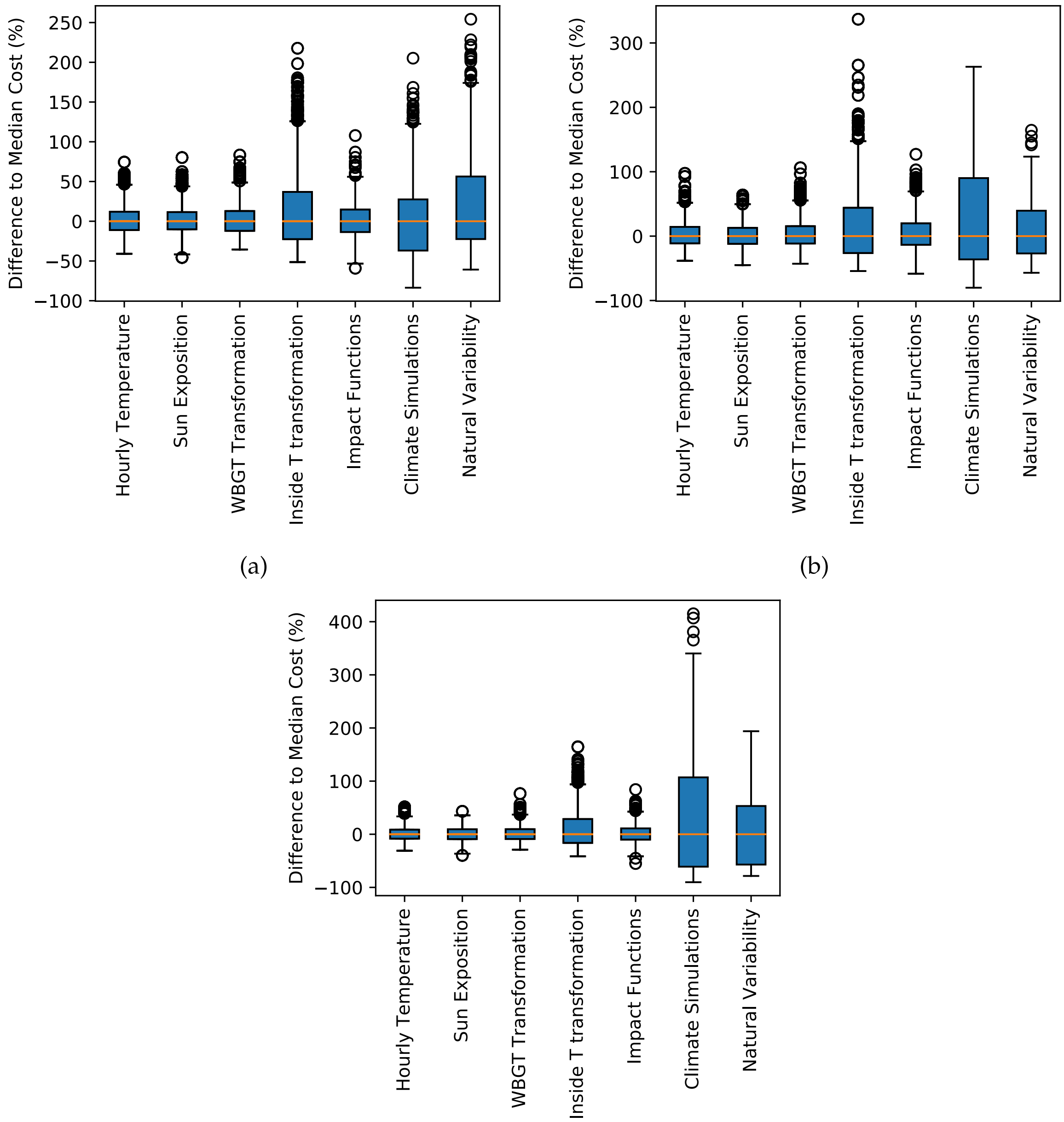
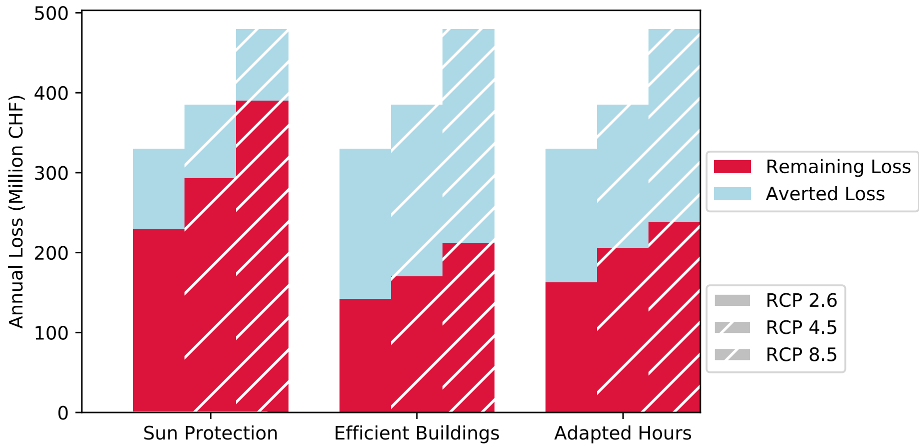
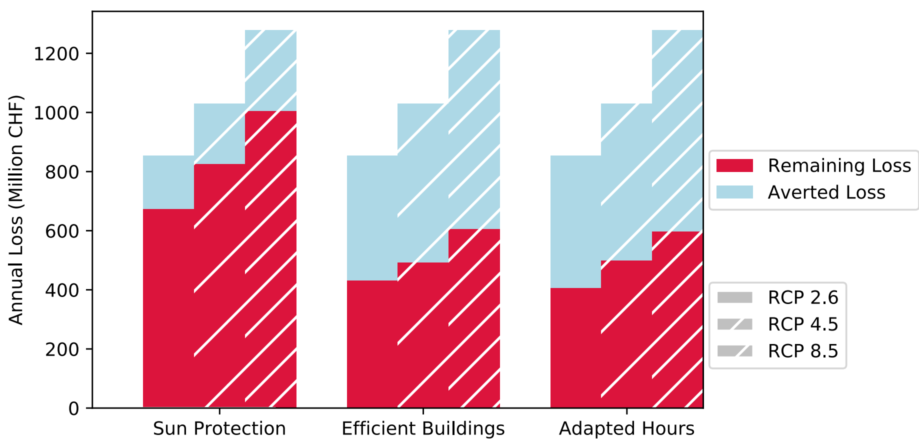


Figure 4.9: Boxplot of the resulting productivity loss for the different elements of the model for which an uncertainty exists for the year 2050 and the RCP8.5 scenario, when those are varied independently. In each subfigure, a different climate model simulation and specific year was blocked when varying the other variables: a) SMHI-RCA_NORESM_EUR44_RCP85 and 2050 b) DMIHIRHAM_ECEARTH_EUR11_RCP85 and 2047 c) CLMCOMCCLM4_MPIESM_EUR44 and 2053.



(a)



(b)

Figure 4.10: Comparison of the three adaptation measures in the year 2050 for the different RCP scenarios for the median (a) and the 95th percentile (b).

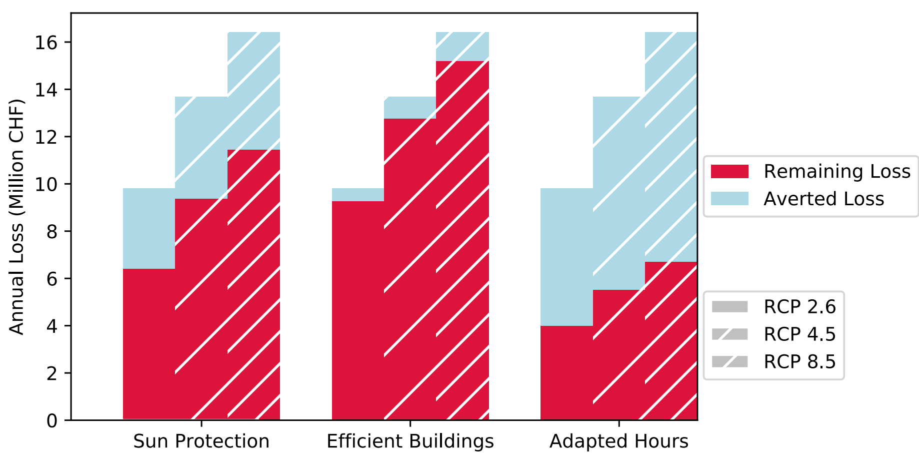


Figure 4.11: Comparison of the three adaptation measures for the median case in the year 2050 for the different RCP scenarios for the canton of Luzern.

Chapter 5

Discussion

5.1 Discussion of the Results

I find in this work that we are already today experiencing a loss of productivity in Switzerland due to heat amounting to CHF 250 million, about half impacting people working outside and half those inside. This loss may double by 2050 if we do not act to limit global warming. If we do reach a 2 °C warming target, the productivity loss could be almost kept at today's level.

Due to the lack of air conditioning consideration in the model and the uncertainties added when estimating the temperature inside buildings, the productivity losses outside are more likely to represent the reality compared to the productivity losses inside. A quick calculation, considering that half of the office buildings in Switzerland would be cooled, would mean that about half of the productivity loss inside could be averted and the loss would be about CHF 180 million today and 300 million in 2050 under an RCP8.5 scenario. Even when considering that every single building would be completely insulated from heat, the productivity loss would still amount to at least CHF 200 million by then, considering the highest RCP scenario and that no adaptation measures would be implemented. This is due to the fact that workers outside are very vulnerable to heat stress. For those economic branches where people are directly exposed to the weather as in construction or agriculture, heat is likely to lower a significant percentage of their productivity throughout the next decades.

An important finding is that the losses appear to strongly correlate with the number of heat days, suggesting that it may not be necessary to go into the level of detail of this model to get to similar results. The relationship found between the heat days and the loss could be useful in reducing the complexity of a future analysis.

Looking at the losses for the canton of Zürich allows to compare the results of this thesis to those of Nesa (2019). She found a loss of CHF 200 million in her best estimate scenario for an RCP8.5 scenario in 2035 and the loss could reach CHF 1 billion considering the worst-case scenario, where all uncertainties were taken at their highest level. I here find a loss of CHF 50 million for the canton of Zurich and a 95th percentile realization of 225 million. The median loss that I find is therefore four times lower compared to her best estimate, and the worst case even lower. One thing to take into account is the fact that the numbers of this present work are based on the Swiss mean salaries for each branch, while those of Nesa (2019) were based on the Zurich average. The mean salary is the same for the people working at low physical activity between the canton of Zürich and Switzerland, while it is 10% higher in Zurich for those having an occupation requiring high physical activity and 5% for those having a moderate physical activity. This would have a mild influence on the results at a cantonal level. Interestingly, the impact functions were produced by using different studies and a different method, but the median impact function of the

distribution in this work and the best estimate by Nesa (2019) have very close values for the WBGT that would realistically occur in Switzerland. This suggests that the difference in the results must come from the transformation from temperature to WBGT in this work or the transformation from WBGT to PET in the work by Nesa (2019). It could also be that basing the daily temperature curves on the 4th and the 5th of August 2018 in the work by Nesa (2019), which happened during a heat wave (Meteo Swiss, 2018), led to overestimations. Hot days are defined by (NCCS, 2018) as reaching 30 °C, which can easily happen independently of a heat wave and still have lower temperatures throughout the rest of the day. Another difference to consider is the spatial resolution of the heat data used. The heat map used by Nesa (2019) is precise enough to account for the urban heat effect, which may cause the heat in areas of the city of Zurich, where most value is located, to be higher. The data used in the present work has a too small spatial resolution to account for such local effects. In my work, an underestimation is also very likely in the moderate physical activity group, as for those working inside the loss is lower in percentage compared to the loss for those having a low physical activity. This is likely caused by the difference in steepness in the impact functions at temperatures close to 22 °C. This element is further discussed in section 5.3 on the limitations of the model.
The results from this model can further be compared to those of other studies looking at productivity losses in Europe. Kjellstrom et al. (2009a) predicted losses of 0.1% on average over Central Europe in the 2050s considering an equivalent to the RCP8.5 scenario. This number is very close to my estimation, except that they did consider changes in labor patterns, which is not the case here. From the study by Costa et al. (2016), Antwerp is probably the city that would resemble the most to cities in Switzerland. They found a loss of 2.1% in the 2080s. Our analysis stopped at 2065, where the loss was 0.2%. This number is significantly lower than the estimations by Costa et al. (2016) but is not surprising as they considered data from urban heat models and used impact functions from safety standard data, which appear to predict higher productivity losses for a same heat stress.
Finally, the sensibility analysis shows that some elements in the impact model do not play much of a role in comparison to others, and to the uncertainty inherent to the climate model data. The WBGT for example can be complicated to calculate from climate data, as was the case in this work and appeared like a big obstacle in the beginning. However, it seems like the uncertainty induced by transforming the temperature to WBGT, only played a small role in the final result. This may only be the case for continental climates, where heat is often associated with low humidity levels. But it can help simplify the modelling of heat impacts in Europe. This could for example be valuable in estimating the mortality and morbidity consequences associated with those events. Another such transformation is going from minimum and maximum to hourly temperature. In the context of climate risk, the uncertainty induced by this transformation is acceptable. The largest uncertainty coming from the model is transforming the outside temperature to inside temperature. In the model, it seems that a WBGT of 22 °C is rarely exceeded inside. But one additional hour that is too hot inside can immediately have a significant contribution to the yearly productivity loss, as most workers are concerned. Being able to model more precisely the different kinds of buildings would therefore be a key factor in reducing the uncertainty of spatial models that depend on the temperature inside.

5.2 Policy Implications

Today, the costliest natural hazards in Switzerland are floods, debris flows and fall processes which together costed an average of around CHF 305 million per year between 1972 and 2017 (Federal Office for the Environment, 2018). These events can be acute and cause substantial productivity losses in a short amount of time. Heat waves have been increasing in the last decades and it is almost certain that they will continue doing so. We will likely experience productivity losses in the country of the same magnitude as those extreme weather events, even if the impacts may be less obvious. Heat also comes with several other consequences, which will contribute to its societal cost. The health impact on the vulnerable population will be a big part of that. But there are also additional potential costs that are not linked to the effects of heat on humans. These are for example the impacts on agriculture, mainly because of the co-occurrence of drought, and those on the electric grid, due to a mix of increased electricity demand and reduced transmission efficiency because of the heat. Overall, the economic burden of heat could be very high in Switzerland. Being aware of these costs can help understand the full burden of climate change and those should be taken into account when considering the benefits of investing in GHGs emissions abatement measures.

As the loss is already substantial today and will certainly continue to increase even in the best-case scenario, adaptation measures should be implemented. This study shows that these have a high potential at reducing the losses. An important factor to consider is the fact that these maintain their potential at reducing the loss even when considering the most extreme case. Moreover, the potential of each remains proportional to the losses. This means that the uncertainties don't influence which measure is the most meaningful, which should facilitate the decision process. enen for the canton of Luzern, the measures should still be considered on a regional level, as there are differences in the structure of the economy and the same measure would have different effects depending on the geographical area.

For those economic branches where workers are directly exposed to the weather, heat is likely to lower a significant percentage of their productivity throughout the next decades. But, adaptation measures can greatly reduce their risk. Working at colder hours and having protection from the sun do have a very high potential at reducing the impact. These measures are already applied to some level nowadays and the results of this study confirms how important they are. These measures are also crucial for the safety of those workers, as high heat stress is more than a question of productivity for this portion of the population. A limitation to the application of adapting working hours in Switzerland could come from regulations. Nowadays, it is common practice to start earlier in the day in the summer at construction sites for example. But the flexibility of employers is limited, as they are required to take extra measures against noise between 7PM and 7AM if they are closer than 600m from habitations (BAFU, 2011). Also, work between 8PM and 6PM is considered as night work which requires special authorizations and higher pay (Arbeitsgesetz, 1964). These regulations may discourage companies in taking those measures and could be reconsidered for times of extreme heat.

Limiting the loss for those working inside is also very important, as a lot of value is at risk. This would mean increasing the insulation from heat inside buildings and considering air conditioning if the temperature cannot be brought to comfortable levels with passive measures. As discussed in section 2.3, many other measures can greatly cool buildings and entail fewer down sides. In some cantons, authorizations are required to install air conditioning in office buildings and their necessity must be proven. Requiring those measures to be taken first could reduce the unnecessary installation of air conditioning.

Finally, taking general measures to reduce the urban heat island effect would reduce the exposition of workers in cities and the one of the populations in general. As this effect is more pronounced at night, it could also cause the indirect effect of a lack of sleep which is not considered in this model, but which likely has a large influence on productivity. As a reminder from section 2.3, these measures would mainly be increasing the vegetation inside cities and using construction materials with lower albedo.

5.3 Limitations of the Model

There exists a number of limitations to the model that one must know when looking at the results or that should be considered for further analysis. Most limitations come from the simplifications that were required, often due to a lack of data.

- **Cooling Systems**
  The first simplification is the lack of consideration of air conditioning and other cooling systems. No statistics exist on a Swiss level, neither do they seem to be calculated on a cantonal level. This is likely to lead to an overestimation of the cost, as the losses inside could be entirely avoided through this measure.
- **Buildings**
  Independently of air conditioning, the model does not directly take into account different types of buildings. This uncertainty is considered in the transformation from outside to inside temperature, meaning that the spread of the final productivity loss likely includes the reality. However, as seen in the sensitivity analysis, this uncertainty has a sizable influence on the final result and having more detailed information on the different types of office buildings could greatly reduce the spread of the probable productivity losses.
- **Urban Heat Island Effect**
  A third element which was not taken into account is the urban heat island effect. The CH2018 data is mapped on a 2km grid and thus cannot account for such small spatial scale effects. This uncertainty is also difficult to quantify and is not taken into account in the model. As most value is located in the cities, not considering this effect could largely underestimate the losses.
- **Constant Exposures**
  The exposures are considered to be fixed at today's levels when computing the impacts. This assumption is not realistic, as the working force distribution will likely change over time. It could be that there will be overall more workers, therefore more potential impact. But is also likely that less human productivity will be needed to produce the same output, therefore reducing the value that might be impacted by heat. This is especially likely to be the case in high physical activity labor, in sectors like construction or in agriculture, as always more manual labor can be substituted by machines.
  As the exposures is the entity which takes most time to compute, especially when getting the those for a canton, it could require an unrealistic amount of time if the exposures were to be varied in the Monte Carlo.
- **Impact Functions**
  The scientific literature that can be used to create impact functions is very limited. The studies used in this work are the few which provide enough numbers to create a curve. To have sufficient data for all types of exposures, some studies that are not well suited for our task still had to be used. For example, the study by Graff Zivin et al. (2018) looked at temperatures outside, which likely do not represent the temperatures to which the subjects were actually confronted. Also, the work taken as the highest estimate in the moderate and high physical activity exposures did not technically perform an observational experience but is based on international standards (Kjellstrom et al., 2009b). But it was a necessity to have at least two studies in order to create a distribution, and this study was considered as the most applicable. Most of these studies were alos performed in different climates or on specific groups of people. For example, two of the studies used to create the impact functions for

the moderate physical activity work type were performed in India and South Africa, where it is likely that people are already adapted to the heat. If a heat wave happens suddenly in a summer, at time when the temperatures are not that high, the productivity losses could be higher than the observations of these studies. The effects could also be very different for people who are not completely healthy, which is likely to be the case with an aging population. It could therefore still be that the distribution does not contain the reality, or that the distributions are too small to account for productivity losses for different people and situations.
The percentage for those working inside at moderate physical activity (percentage maps given in the appendix) appears to be lower compared to the loss for those working inside at low physical activity. This is likely because the impact function is less steep at low WBGT for the moderate physical activity categories. This is very unlikely to be the case in reality and this impact function should be reconsidered for further research.

- **Adaptation Measures**
  It is already likely the case today that adaptation measures are implemented in the case of a heat wave, as people working outside would for example organize to not work in the sun at hours when it is very high in the sky. Also, it is common practice for example in the construction sector to work earlier in the morning in the summer to take advantage of the cooler hours.

- **Other Effects of heat**
  A number of effects cannot be integrated in the model as they cannot be quantified for now. An example of such a limitation is the fact that people likely do not rest well when temperatures are high and would likely perform less well in their work on the following day. Also, heat waves often last a few days or even weeks and it is likely that the length of the heat wave would play a role in the way that people experience heat. Perhaps they eventually get adapted or their productivity would decrease more and more throughout the heat waves. All empirical studies look at people performance on tasks over a maximum of a few hour, but it would be very difficult to analyze the response of people on longer time periods.

- **Productivity gains in the Winter**
  A final limitation is that I here only look at the effects of climate change on labor productivity in the summer but ignore those in the winter. However, having milder temperatures in the winter may allow those working outside to have better conditions and be more productive. This could even be the case for those inside. In turn, the loss of productivity in the summer could be compensated by higher productivity in the winter.

Despite the limitations, the model allows to quantify what would be the loss due to heat with climate change if the exposure would stay constant and we would not implement any adaptation measures. This allows us to conceive the importance of this risk in relation to others and to take informed decision on how to reduce it.

Chapter 6

Conclusion

I find in this work that the costs resulting from a loss of productivity due to heat waves in Switzerland are already substantial and that those may double by the mid-century, if we do not limit global warming. The productivity loss is heterogenous between sectors and regions. The construction sector and the canton of Geneva are likely to have the highest percentage of value lost. This effect of heat is difficult to observe compared to impacts from other natural hazards, as many different variables come into play in the productivity of a country. Also, these effects only impact a small percentage of the total value. But as the exposure is the productivity of the country itself even this small percentage can account for a large total loss. This analysis tells us that the impacts of heat waves are perhaps already today on average as high as the costliest extreme events in the country, even if the effects of heat are much more spread out and less striking. The other exposures that are impacted by heat waves should be assessed, to really understand the full costs of heat and how it is influenced by climate change in Switzerland. The methodology developed in this work can hopefully be helpful in doing so. The sensitivity analysis may also help to understand what the most important factors are, and which elements could be simplified. It would also be interesting to make a similar analysis for other European countries; which may be at higher risk than Switzerland.
Finally, adaptation measures have a large potential at reducing the productivity loss. The highest total aversion comes from having buildings that are well insulated from the temperature outside and that are equipped with cooling systems in case of extreme heat. The most severe productivity loss, which would happen for people working outside at high physical activity, can be mostly avoided by adjusting schedules and limiting the hours spent with direct sun exposure.

Chapter 7

Aknowledgments

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Bibliography

Alexander, L. V., Zhang, X., Peterson, T. C., Caesar, J., Gleason, B., Klein Tank, A. M., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F., Tagipour, A., Rupa Kumar, K., Revadekar, J., Griffiths, G., Vincent, L., Stephenson, D. B., Burn, J., Aguilar, E., Brunet, M., Taylor, M., New, M., Zhai, P., Rusticucci, M., and Vazquez-Aguirre, J. L. (2006). Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research Atmospheres*.

Almås, I., Auffhammer, M., Bold, T., Bolliger, I., Dembo, A., Hsiang, S. M., Kitamura, S., Miguel, E., and Pickmans, R. (2019). Destructive Behavior, Judgment, and Economic Decision-making under Thermal Stress. *NBER Working Paper Series*, page 25.

Arbeitsgesetz (1964). Bundesgesetz über die Arbeit in Industrie, Gewerbe und Handel (Arbeitsgesetz, ArG); 17b.

Aznar-Siguan, G. and Bresch, D. N. (2019). CLIMADA v1: A global weather and climate risk assessment platform. *Geoscientific Model Development*.

BAFU, B. f. U. (2011). Baulärm-Richtlinie. Technical report.

Barriopedro, D., Fischer, E. M., Luterbacher, J., Trigo, R. M., and García-Herrera, R. (2011). The hot summer of 2010: Redrawing the temperature record map of Europe. *Science*.

Basu, R. and Samet, J. M. (2002). Relation between elevated ambient temperature and mortality: A review of the epidemiologic evidence.

Beniston, M. (2004). The 2003 heat wave in Europe: A shape of things to come? An analysis based on Swiss climatological data and model simulations. *Geophysical Research Letters*.

Bodin, T., García-Trabanino, R., Weiss, I., Jarquín, E., Glaser, J., Jakobsson, K., Lucas, R. A., Wesseling, C., Hogstedt, C., Wegman, D. H., Abrahamson, M., Apelqvist, J., Aragón, A., Arias, E., Ekström, U., Faber, D., Peraza, S. A., and Rojas, M. (2016). Intervention to reduce heat stress and improve efficiency among sugarcane workers in El Salvador: Phase 1. *Occupational and Environmental Medicine*.

Casanueva, A. (2019). HeatStress: Calculate heat stress indices. R package version 1.0.7.

Cattiaux, J., Douville, H., Schoetter, R., Parey, S., and Yiou, P. (2015). Projected increase in diurnal and interdiurnal variations of European summer temperatures. *Geophysical Research Letters*.

Chow, D. H. and Levermore, G. J. (2007). New algorithm for generating hourly temperature values using daily maximum, minimum and average values from climate models. *Building Services Engineering Research and Technology*.

Christidis, N., Jones, G. S., and Stott, P. A. (2015). Dramatically increasing chance of extremely hot summers since the 2003 European heatwave. *Nature Climate Change*.

Ciscar, J.-C., Goodess, C. M., Christensen, Ole, B., Iglesias, A., Garotte, L., Moneo, M., Quiroga, S., Feyen, L., Dankers, R., Nicholls, R., Richards, J., Bosello, F., and Roson, R. (2009). Climate change impacts in Europe - Final report of the PESETA research project. Technical report.

Conti, S., Meli, P., Minelli, G., Solimini, R., Toccaceli, V., Vichi, M., Beltrano, C., and Perini, L. (2005). Epidemiologic study of mortality during the Summer 2003 heat wave in Italy. *Environmental Research*.

Copernicus Climate Change Service (2019). Record-breaking temperatures for June.

Costa, H., Floater, G., Hooyberghs, H., Verbeke, S., and De Ridder, K. (2016). Climate change, heat stress and labour productivity: A cost methodology for city economies. *Centre for Climate Change Economics and Policy Working Paper No. 278*.

Coumou, D., Robinson, A., and Rahmstorf, S. (2013). Global increase in record-breaking monthly-mean temperatures. *Climatic Change*.

DARA (2012). Climate Vulnerability Monitor 2nd Edition. A Guide to the Cold Calculus of a Hot Planet. Technical report.

Day, E., Fankhauser, S., Kingsmill, N., Costa, H., and Mavrogianni, A. (2019). Upholding labour productivity under climate change: an assessment of adaptation options. *Climate Policy*.

Dell, M., Jones, B. F., and Olken, B. A. (2014). What do we learn from the weather? The new climate-economy literature.

Della-Marta, P. M., Haylock, M. R., Luterbacher, J., and Wanner, H. (2007). Doubled length of western European summer heat waves since 1880. *Journal of Geophysical Research Atmospheres*.

Dhainaut, J. F., Claessens, Y. E., Ginsburg, C., and Riou, B. (2004). Unprecedented heat-related deaths during the 2003 heat wave in Paris: Consequences on emergency departments.

Donat, M. G., Alexander, L. V., Yang, H., Durre, I., Vose, R., Dunn, R. J., Willett, K. M., Aguilar, E., Brunet, M., Caesar, J., Hewitson, B., Jack, C., Klein Tank, A. M., Kruger, A. C., Marengo, J., Peterson, T. C., Renom, M., Oria Rojas, C., Rusticucci, M., Salinger, J., Elrayah, A. S., Sekele, S. S., Srivastava, A. K., Trewin, B., Villarroel, C., Vincent, L. A., Zhai, P., Zhang, X., and Kitching, S. (2013). Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset. *Journal of Geophysical Research Atmospheres*.

Dunne, J. P., Stouffer, R. J., and John, J. G. (2013). Reductions in labour capacity from heat stress under climate warming. *Nature Climate Change*.

Federal Office for the Environment (2018). Natural hazards: In brief.

Fischer, E. M. and Knutti, R. (2014). Detection of spatially aggregated changes in temperature and precipitation extremes. *Geophysical Research Letters*.

Fischer, E. M., Lawrence, D. M., and Sanderson, B. M. (2011). Quantifying uncertainties in projections of extremes-a perturbed land surface parameter experiment. *Climate Dynamics*.

Fischer, E. M. and Schär, C. (2009). Future changes in daily summer temperature variability: Driving processes and role for temperature extremes. *Climate Dynamics*.

Fischer, E. M. and Schär, C. (2010). Consistent geographical patterns of changes in high-impact European heatwaves. *Nature Geoscience*, 3:398.

Fischer, E. M., Seneviratne, S. I., Lüthi, D., and Schär, C. (2007). Contribution of land-atmosphere coupling to recent European summer heat waves. *Geophysical Research Letters*, 34(6).

Freewan, A. A. (2014). Impact of external shading devices on thermal and daylighting performance of offices in hot climate regions. *Solar Energy*.

Gao, C., Kuklane, K., and Holmér, I. (2010). Cooling vests with phase change material packs: The effects of temperature gradient, mass and covering area. *Ergonomics*.

Garcia-Herrera, R., Díaz, J., Trigo, R. M., Luterbacher, J., and Fischer, E. M. (2010). A review of the european summer heat wave of 2003.

Gardner, J. W., Kark, J. A., Karnei, K., Sanborn, J. S., Gastaldo, E., Burr, P., and Wenger, C. B. (1996). Risk factors predicting exertional heat illness in male Marine Corps recruits. *Medicine and Science in Sports and Exercise*.

Gill, S. E., Handley, J. F., Ennos, A. R., and Pauleit, S. (2007). Adapting cities for climate change: The role of the green infrastructure. *Built Environment*.

Giorgi, F., Jones, C., and Asrar, G. (2009). Addressing climate information needs at the regional level: the CORDEX framework. *... Organization (WMO) Bulletin*.

Graff Zivin, J. and Neidell, M. (2013). Temperature and the Allocation of Time: Implications for Climate Change. *Journal of Labor Economics*.

Graff Zivin, J., Song, Y., Zhang, P., and Tang, Q. (2018). Temperature and High-Stakes Cognitive Performance: Evidence From The National College Entrance Examination in China. *SSRN Electronic Journal*.

Grize, L., Huss, A., Thommen, O., Schindler, C., and Braun-Fahrländer, C. (2005). Heat wave 2003 and mortality in Switzerland. *Swiss Medical Weekly*.

Haines, A., Kovats, R. S., Campbell-Lendrum, D., and Corvalan, C. (2006). Climate change and human health: Impacts, vulnerability and public health. *Public Health*.

Hémon, D., Jougla, E., Clavel, J., Laurent, F., Bellec, S., and Pavillon, G. (2003). Surmortalité liée à la canicule d'Août 2003 en France. *BEH*.

Holmes, C. R., Woollings, T., Hawkins, E., and de Vries, H. (2016). Robust future changes in temperature variability under greenhouse gas forcing and the relationship with thermal advection. *Journal of Climate*.

Hsiang, S. M. (2010). Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America. *Proceedings of the National Academy of Sciences of the United States of America*.

IPCC (2014). *Summary for Policymakers*.

IPCC (2018). Summary for Policymakers SPM. *Global Warming of 1.5 degrees. An IPCC Special Report on the impacts of global warming of 1.5 degrees above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of cli*.

Johnson, D. (1997). The triangular distribution as a proxy for the beta distribution in risk analysis. *Journal of the Royal Statistical Society Series D: The Statistician*.

Johnson, H., Kovats, S., McGregor, G., Stedman, J., Gibbs, M., Walton, H., and Cook, L. (2004). THE IMPACT OF THE 2003 HEAT WAVE ON MORTALITY AND HOSPITAL ADMISSIONS IN ENGLAND. *Epidemiology*.

Kjellstrom, T., Gabrysch, S., Lemke, B., and Dear, K. (2009a). The 'hothaps' programme for assessing climate change impacts on occupational health and productivity: An invitation to carry out field studies. *Global Health Action*.

Kjellstrom, T., Holmer, I., and Lemke, B. (2009b). Workplace heat stress, health and productivity-an increasing challenge for low and middle-income countries during climate change. *Global Health Action*.

Kjellstrom, T., Kovats, R. S., Lloyd, S. J., Holt, T., and Tol, R. S. (2009c). The direct impact of climate change on regional labor productivity. *Archives of Environmental and Occupational Health*.

Kjellstrom, T., Lemke, B., Otto, M., Hyatt, O., and Dear, K. (2014). Technical Report 2014 : 4 Occupational Heat Stress. (December):1–52.

Kopp, R., Rasmussen, D., and Mastrandrea, M. (2014). American Climate Prospectus: Economic Risks in the United States. *Rhodium Group*.

Koppe, C. and Jendritzky, G. (2005). Inclusion of short-term adaptation to thermal stresses in a heat load warning procedure. *Meteorologische Zeitschrift*.

Kovats, R. S. and Kristie, L. E. (2006). Heatwaves and public health in Europe.

Lundgren, K. and Kjellstrom, T. (2013). Sustainability challenges from climate change and air conditioning use in urban areas.

Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M., and Wanner, H. (2004). European Seasonal and Annual Temperature Variability, Trends, and Extremes since 1500. *Science*.

Mairiaux, P. and Malchaire, J. (1985). Workers self-pacing in hot conditions: A case study. *Applied Ergonomics*.

Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M., and Waterfield, T. (2014). Climate Change 2013 - The Physical Science Basis. *Climate Change 2013 - The Physical Science Basis*.

Mayer, H. and Höppe, P. (1987). Thermal comfort of man in different urban environments. *Theoretical and Applied Climatology*.

Meehl, G. A. and Tebaldi, C. (2004). More intense, more frequent, and longer lasting heat waves in the 21st century. *Science*.

Meteo Swiss (2015). Monthly Weather Bulletins. Technical report.

Meteo Swiss (2018). Klimabulletin August 2013. (August).

Meteo Swiss (2019). Beschreibung zu den Gefahrenstufen. Technical report.

Miralles, D. G., Teuling, A. J., Van Heerwaarden, C. C., and De Arellano, J. V. G. (2014). Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. *Nature Geoscience*.

Miralles, D. G., Van Den Berg, M. J., Teuling, A. J., and De Jeu, R. A. M. (2012). Soil moisture-temperature coupling: A multiscale observational analysis. *Geophysical Research Letters*.

Mondal, S. (2008). Phase change materials for smart textiles - An overview. *Applied Thermal Engineering*.

NCCS (2018). CH2018 – Climate Scenarios for Switzerland. Technical report, National Centre for Climate Services, Zurich.

Nesa, V. (2019). *The impact of heat on labour productivity in Zurich*. Master thesis.

Niemelä, R., Hannula, M., Rautio, S., Reijula, K., and Railio, J. (2002). The effect of air temperature on labour productivity in call centres - A case study. In *Energy and Buildings*.

Orlov, A., Sillmann, J., Aaheim, A., Aunan, K., and de Bruin, K. (2019). Economic Losses of Heat-Induced Reductions in Outdoor Worker Productivity: a Case Study of Europe. *Economics of Disasters and Climate Change*.

Pandolf, K. B. (1998). Time course of heat acclimation and its decay. *International Journal of Sports Medicine*.

Park, J. (2017). Hot Temperature, Human Capital and Adaptation to Climate Change. *Harvard University Economics Department*.

Parsons, K. (2014). *Human thermal environments: The effects of hot, moderate, andcold environments on human health,comfort, and performance, third edition*.

Périard, J. D., Racinais, S., and Sawka, M. N. (2015). Adaptations and mechanisms of human heat acclimation: Applications for competitive athletes and sports.

Porritt, S., Shao, L., Cropper, P., and Goodier, C. (2011). Adapting dwellings for heat waves. *Sustainable Cities and Society*.

Quesada, B., Vautard, R., Yiou, P., Hirschi, M., and Seneviratne, S. I. (2012). Asymmetric European summer heat predictability from wet and dry southern winters and springs. *Nature Climate Change*.

Rasmijn, L. M., Van Der Schrier, G., Bintanja, R., Barkmeijer, J., Sterl, A., and Hazeleger, W. (2018). Future equivalent of 2010 Russian heatwave intensified by weakening soil moisture constraints. *Nature Climate Change*.

Robine, J. M., Cheung, S. L. K., Le Roy, S., Van Oyen, H., Griffiths, C., Michel, J. P., and Herrmann, F. R. (2008). Death toll exceeded 70,000 in Europe during the summer of 2003. *Comptes Rendus - Biologies*.

Rowe, D. B. (2011). Green roofs as a means of pollution abatement. *Environmental Pollution*.

Sahu, S., Sett, M., and Kjellstrom, T. (2013). Heat exposure, cardiovascular stress and work productivity in rice harvesters in India: Implications for a climate change future. *Industrial Health*.

Salamanca, F., Georgescu, M., Mahalov, A., Moustaoui, M., and Wang, M. (2014). Anthropogenic heating of the urban environment due to air conditioning. *Journal of Geophysical Research*.

Sawka, M., Periard, J., and Racinais, S. (2015). HEAT ACCLIMATIZATION TO IMPROVE ATHLETIC PERFORMANCE IN WARM-HOT ENVIRONMENTS. *Sports Science Exchange*.

Schär, C., Vidale, P. L., Lüthi, D., Frei, C., Häberli, C., Liniger, M. A., and Appenzeller, C. (2004). The role of increasing temperature variability in European summer heatwaves. *Nature*.

Semenza, J. C., McCullough, J. E., Flanders, W. D., McGeehin, M. A., and Lumpkin, J. R. (1999). Excess hospital admissions during the July 1995 heat wave in Chicago. *American Journal of Preventive Medicine*.

Seneviratne, S. I., Lüthi, D., Litschi, M., and Schär, C. (2006). Land-atmosphere coupling and climate change in Europe. *Nature*.

Seppänen, O., Fisk, W., and Lei, Q. (2006). Effect of Temperature on Task Performance in Office Environment. *Lawrence Berkeley National Laboratory*.

Smith, K. R., Woodward, A., Campbell-Lendrum, D., Chadee, D. D., Honda, Y., Liu, Q., Olwoch, J. M., Revich, B., Sauerborn, R., Confalonieri, U., Haines, A., Chafe, Z., and Rocklov, J. (2015). Human health: Impacts, adaptation, and co-benefits. In *Climate Change 2014 Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects*.

Susca, T., Gaffin, S. R., and Dell'Osso, G. R. (2011). Positive effects of vegetation: Urban heat island and green roofs. *Environmental Pollution*.

Swiss Re (2011). Natural catastrophes and man-made disasters in 2010: a year of devastating and costly events. Technical report.

Swisstopo (2016). Formulas and constants for the calculation of the Swiss conformal cylindrical projection and for the transformation between coordinate systems. page 18.

Swisstopo (2020). No Title.

Taylor, N. A. (2000). PRINCIPLES AND PRACTICES OF HEAT ADAPTATION. *Journal of the Human-Environment System*.

Trigo, R. M., García-Herrera, R., Díaz, J., Trigo, I. F., and Valente, M. A. (2005). How exceptional was the early August 2003 heatwave in France? *Geophysical Research Letters*.

Trigo, R. M., Ramos, A. M., Nogueira, P. J., Santos, F. D., Garcia-Herrera, R., Gouveia, C., and Santo, F. E. (2009). Evaluating the impact of extreme temperature based indices in the 2003 heatwave excessive mortality in Portugal. *Environmental Science and Policy*.

Tzempelikos, A. and Athienitis, A. K. (2007). The impact of shading design and control on building cooling and lighting demand. *Solar Energy*.

Van Ulden, A., Lenderink, G., Van Den Hurk, B., and Van Meijgaard, E. (2007). Circulation statistics and climate change in Central Europe: PRUDENCE simulations and observations.

Vandentorren, S., Suzan, F., Medina, S., Pascal, M., Maulpoix, A., Cohen, J. C., and Ledrans, M. (2004). Mortality in 13 French cities during the August 2003 heat wave. *American Journal of Public Health*.

Vautard, R., Beekmann, M., Desplat, J., Hodzic, A., and Morel, S. (2007). Air quality in Europe during the summer of 2003 as a prototype of air quality in a warmer climate. *Comptes Rendus - Geoscience*.

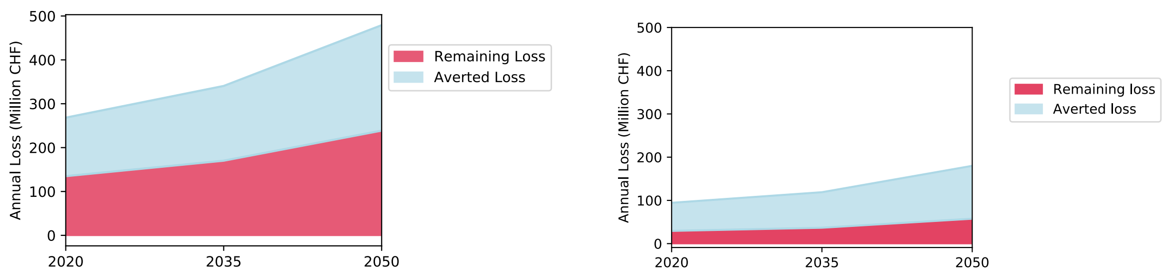
Vautard, R., Gobiet, A., Jacob, D., Belda, M., Colette, A., Déqué, M., Fernández, J., García-Díez, M., Goergen, K., Güttler, I., Halenka, T., Karacostas, T., Katragkou, E., Keuler, K., Kotlarski, S., Mayer, S., van Meijgaard, E., Nikulin, G., Patarčić, M., Scinocca, J., Sobolowski, S., Suklitsch, M., Teichmann, C., Warrach-Sagi, K., Wulfmeyer, V., and Yiou, P. (2013). The simulation of European heat waves from an ensemble of regional climate models within the EURO-CORDEX project. *Climate Dynamics*.

Wyndham, C. H. (1969). Adaptation to heat and cold. *Environmental Research*.

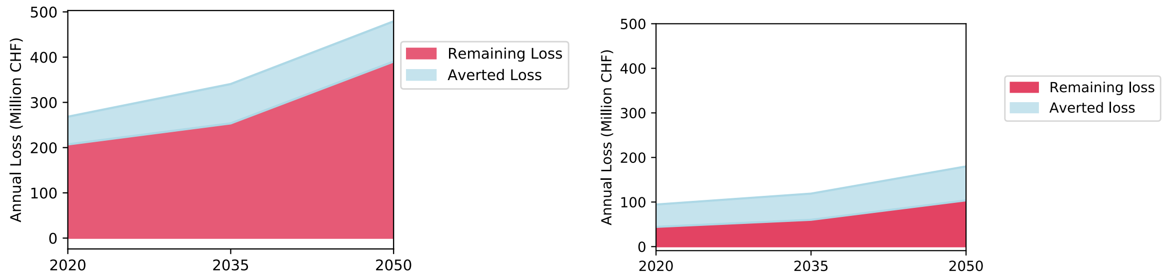
Zander, K. K., Botzen, W. J., Oppermann, E., Kjellstrom, T., and Garnett, S. T. (2015). Heat stress causes substantial labour productivity loss in Australia. *Nature Climate Change*.

Appendix

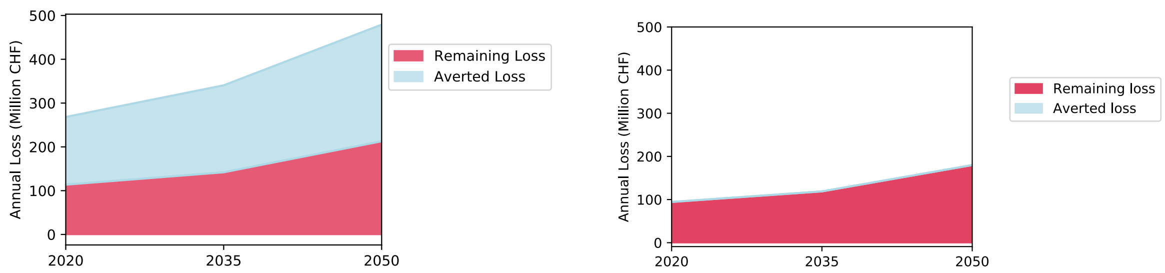
Figures



(a) Adapting Hours

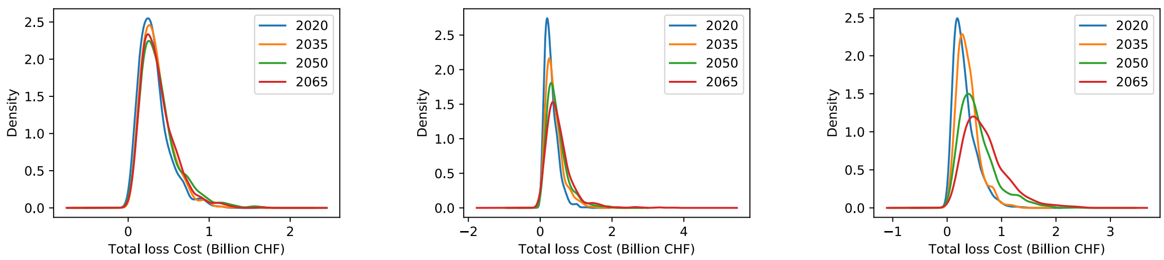


(b) Sun Protection



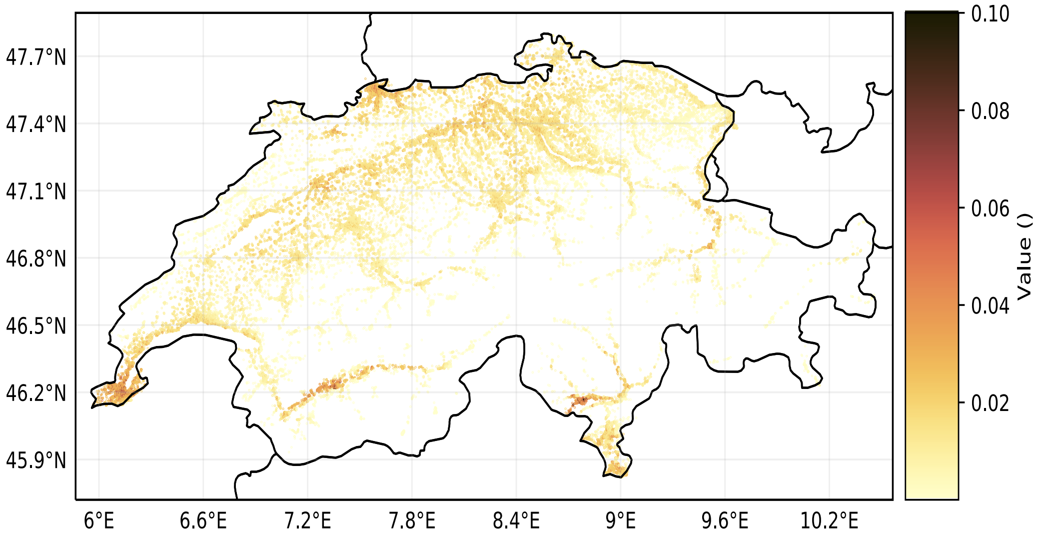
(c) ”Efficient” Buildings

Figure 1: Averted productivity losses for the different adaptation measures over the years considering and RCP8.5 scenario. Left is for the total exposures, right only for those working outside at high physical activitiy

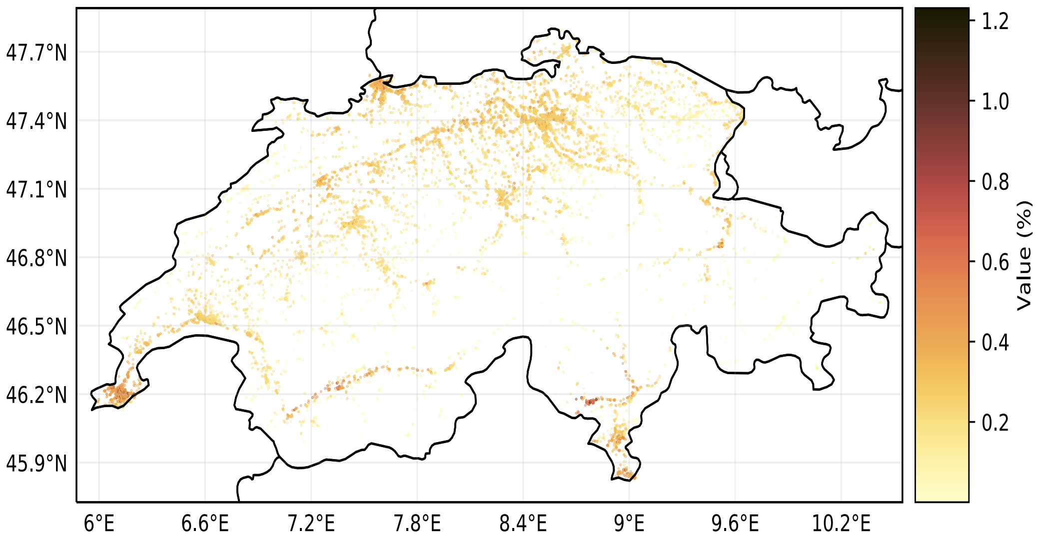


(a) RCP2.6 (b) RCP4.5 (c) RCP8.5

Figure 2: Kernel density estimation of the total loss in Switzerland from the Monte Carlo for the different scenarios and years



(a)



[H]

Figure 3: Map showing the percentage of the exposures yearly value that is lost in each point in the year 2050 for an RCP8.5 scenario in (a) for the inside moderate physical activity exposures and in (b) for the outside moderate physical activity exposures.

Data

Table 1: sample of the data used to get the relationship between the temperature and WBGT. The WBGT and WBGT in the sun were calculated using the R package heat stress by Casanueva (2019)

	station	time	radiation	temp	dwp	wind	wbgt	wbgt_sun
2367	BAS	2.015041e+09	295.0	20.3	1.2	1.6	13.909073	14.909279
2368	BAS	2.015041e+09	296.0	20.7	0.9	1.5	14.094148	15.128720
2369	BAS	2.015041e+09	297.0	20.4	-0.2	0.8	13.684347	15.208826
2388	BAS	2.015041e+09	303.0	20.1	1.7	1.3	13.892958	15.100688
2389	BAS	2.015041e+09	306.0	21.2	1.8	1.7	14.594437	15.601686
2390	BAS	2.015041e+09	306.0	21.4	1.8	1.4	14.717472	15.855806
2391	BAS	2.015041e+09	310.0	21.4	1.4	1.2	14.631854	15.907608
2392	BAS	2.015041e+09	314.0	21.5	1.1	0.9	14.630488	16.170492
2393	BAS	2.015041e+09	316.0	20.4	1.6	1.6	14.057088	15.184411

Table 2: sample of the data used to determine the level of physical activity of different professions and rather people work inside or outside, as well as the salary. The methodology was taken from Nesa (2019).

GIS_Data_code	Department	Occupation_category	Indoor/Outdoor	Hourly salary (CHF/h)
B170801VZA	Landwirtschaft, Jagd und damit verbundene Tätigkeiten	H	O	26.5
B170802VZA	Forstwirtschaft und Holzeinschlag	H	O	45.01875
B170803VZA	Fischerei und Aquakultur	H	O	#N/A
B170805VZA	Kohlenbergbau	H	O	41.5
B170806VZA	Gewinnung von Erdöl und Erdgas	H	O	41.5
B170807VZA	Erzbergbau	H	O	41.5
B170808VZA	Gewinnung von Steinen und Erden, sonstiger Bergbau	H	O	41.5
B170809VZA	Erbringung von Dienstleistungen für den Bergbau und für die Gewinnung von Steinen und Erden	H	O	#N/A
B170810VZA	Herstellung von Nahrungs- und Futtermitteln	M	I	36.575
B170811VZA	Getränkeherstellung	M	I	43.3875
B170812VZA	Tabakverarbeitung	M	I	74.9375
B170813VZA	Herstellung von Textilien	M	I	37.03125
B170814VZA	Herstellung von Bekleidung	M	I	33.2125
B170815VZA	Herstellung von Leder, Lederwaren und Schuhen	M	I	32.51875
B170816VZA	Herstellung von Holz-, Flecht-, Korb- und Korkwaren (ohne Möbel)	M	I	38.98125
B170817VZA	Herstellung von Papier, Pappe und Waren daraus	M	I	41.6375
B170818VZA	Herstellung von Druckerzeugnissen; Vervielfältigung von bespielten Ton-, Bild- und Datenträgern	M	I	40.50625
B170819VZA	Kokerei und Mineralölverarbeitung	M	I	49.33125
B170820VZA	Herstellung von chemischen Erzeugnissen	M	I	54.375
B170821VZA	Herstellung von pharmazeutischen Erzeugnissen	M	I	71.0625
B170822VZA	Herstellung von Gummi- und Kunststoffwaren	M	I	40.0375
B170823VZA	Herstellung von Glas und Glaswaren, Keramik, Verarbeitung von Steinen und Erden	M	I	41.98125
B170824VZA	Metallerzeugung und -bearbeitung	M	I	40.56875
B170825VZA	Herstellung von Metallerzeugnissen	M	I	40.225
B170826VZA	Herstellung von Datenverarbeitungsgeräten, elektronischen und optischen Erzeugnissen	M	I	47.84375
B170827VZA	Herstellung von elektrischen Ausrüstungen	M	I	46.30625
B170828VZA	Maschinenbau	M	I	46.575
B170829VZA	Herstellung von Automobilen und Automobilteilen	M	I	39.6625
B170830VZA	Sonstiger Fahrzeugbau	M	I	46.9625
B170831VZA	Herstellung von Möbeln	M	I	39.85625
B170832VZA	Herstellung von sonstigen Waren	M	I	43.35625
B170833VZA	Reparatur und Installation von Maschinen und Ausrüstungen	M	I	43.65
B170835VZA	Energieversorgung	M	O	55.6875
B170836VZA	Wasserversorgung	M	O	46.43125
B170837VZA	Abwasserentsorgung	M	O	41.60625
B170838VZA	Sammlung, Behandlung und Beseitigung von Abfällen; Rückgewinnung	M	O	40.45625

Equations

The equations to transform the temperature in WBGT in the shadow or in the sun are given by:

$$WBGT_{shadow}(T) = 4.22085354 + 0.64879697T \tag{7.1}$$

$$WBGT_{sun}(T) = 4.664870352 + 0.61111305T \tag{7.2}$$

The percentage of productivity lost at each temperature are determined by the following sigmoids:

$$loss_{high}(T) = \frac{42.37272625}{1 + exp(-k * (113.54748065 - 0.40890878))} - 2.30529882 \tag{7.3}$$

$$loss_{moderate}(T) = \frac{35.38151739}{1 + exp(-k * (101.03316744 - 0.13034868))} - 5.01346911 \tag{7.4}$$

$$loss_{high}(T) = \frac{30.68646024}{1 + exp(-k * (102.18236029 - 0.40890878))} - 2.30529882 \tag{7.5}$$

The hourly temperature from the minimum and maximum temperature was found using the following equation by Chow and Levermore (2007):

$$T_{predicted}(t) = (\frac{temp_{next} + temp_{prev}}{2}) - [(\frac{temp_{next} - temp_{prev}}{2}) * \cos(\frac{\pi(t - t_{prev})}{t_{next} - t_{prev}})] \tag{7.6}$$

Where $temp_{next}$ is the next known temperature:

$temp_{next} = T_{min,d}$ and $t_{next} = d$ for $h < h_{min} = 5$
$temp_{next} = T_{min,d+1}$ and $t_{next} = d + 1$ for $h >= h_{max} = 15$
$temp_{next} = T_{max,d}$ and $t_{next} = d$ for $h_{min} <= h < h_{max}$

And $temp_{prev}$ is the previous know temperature:

$temp_{prev} = T_{max,d-1}$ and $t_{next} = d - 1$ for $h < h_{min} = 5$
$temp_{prev} = T_{max,d}$ and $t_{next} = d$ for $h >= h_{max} = 15$
$temp_{prev} = T_{min,d}$ and $t_{prev} = d$ for $h_{min} <= h < h_{max}$

Finally, the difference between outside and inside temperature is given by:

$$percentage\ difference = (0.27614082 * \sin(0.27614082T_{out} + 0.67076506) - 0.04965493) * 100 \tag{7.7}$$

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