Adaptation to Extreme Climate Events at a Regional Scale

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The faculty accepted this work as dissertation on the 06.04.2017 at the request of the two advisors Prof. Dr. Gunter Stephan and Prof. Dr. Philippe Thalmann, without wishing to take a position on the view presented therein.

To my family

Preface

I consider myself lucky to have been given the opportunity to write this thesis under the supervision of Gunter Stephan at the University of Bern. I am grateful for the trust, directness, support and encouragement he provided throughout my time as a Ph.D. student. He helped me to develop the expertise in the field of general equilibrium modeling, which was necessary to write this thesis. Additionally, he helped me to improve my economic thinking as well as my writing skills. I would also like to thank Philippe Thalmann for co-supervising my thesis.

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I would like to express my deepest gratitude to the most important people in my live, my family. I thank my son Arthur for every minute he enticed me away from my desk. I thank my husband Sebastian for his unconditional love, patience, support and encouragement. Thanks for being in my life and mastering this exciting time together! I would like to express my deepest gratitude to my parents Roland and Katrin, my sister Lisa Marie and my grandparents Klaus and Rosemarie for always believing in me. My family has always given me the opportunity to ambitiously pursue my aims. None of this would have been possible without this supportive and loving family. I thank Skjona for sustaining my peace of mind.

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Chapter 1

Introduction

According to the fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the atmospheric carbon concentration is expected to rise further during the 21st century. This will lead to a significant increase of the frequency, the intensity and the duration of extreme climate events (Pachauri et al., 2014). In recent decades, Switzerland has already been increasingly affected by extreme climate events. The Swiss cannot forget the heat waves of 2003 and 2006, and the floods of 1999 and 2005, because of the devastation and damage these extreme events caused.

For more than two decades, mitigation, i.e. strategies which aim to reduce greenhouse gas emissions, has been the main objective of international climate policy. However, due to already high atmospheric carbon concentrations and the inertia of the climate system, climate change is unavoidable to some degree, even if today's emissions were almost completely cut back. Along with the high uncertainty concerning future climate change policies, this fact has focused attention towards measures which allow for reducing the climate vulnerability of communities and regions without the need of international cooperation. As for example Buob and Stephan (2013) have shown, optimal climate change strategies require a combination of both mitigation and adaptation strategies, and should include measures of adjustment to the actual or expected climate and its effects (Pachauri et al., 2014). These measures can be implemented on a national or regional scale with sufficient speed and scope.

The Swiss Federal Councils strategy, *Adaptation to climate change in Switzerland*, was published in two parts in 2012 and 2014 by the Swiss Federal Office for the Environment (FOEN). The report presents a summary of goals, challenges and fields of action. Heat stress as well as an increased risk of flooding are identified as two (out of eight) main adaptation challenges in Switzerland. Furthermore, the rise of the snowline is mentioned, which further increases the risk of flooding. In its report, the Swiss Federal Council formulates several principles according to which adaptation should be organized in Switzerland.[1] The first principle requires policy makers to adapt sustainably, which means that adaptation measures have to be flexible and the precautionary principle has to apply. The second principle says that natural regulation processes should be used, if possible, as well as measures with the best cost-benefit ratio, considering market and non-market damages. No-regret measures and those with a secondary benefit are to be favored. The third principle states that adaptation funding should follow the costs-by-cause principle, but that, if necessary, the solidarity principle applies. A further principle is to base all actions on scientific findings and to use a risk approach as well as robust measures to deal with uncertainties. Adaptation measures have to account for different time scales and should be evaluated periodically. Another main principle of the Swiss adaptation strategy is that adaptation measures have to be implemented as a result of cooperation between the confederation, the cantons and the municipalities (FOEN, 2012), which are the three levels of Swiss governance. Finally, the report explicitly mentions that adaptation is a "complementary element of Swiss climate policy in addition to the urgent need to reduce greenhouse gas emissions" (FOEN, 2012).

Because of the threatened increase of extreme climate events, and they damage they can cause, my thesis has three aims: (1) to better understand the economic impacts of extreme climate events in Switzerland; (2) to develop policy recommendations for financially funding adaptation measures; and (3) to analyze the drivers of both.

The following chapters focus on heat waves and floods. What these two extreme events have in common is that they have already caused major damage in Switzerland, and their frequency, intensity and duration is expected to increase

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[1] These principles will be taken into account throughout this thesis.

further as atmospheric carbon concentrations rise during the 21st century (FOEN, 2012). However, these two event types differ strongly with respect to the damage they cause. On the one hand, there is so-called market damage such as destroyed capital and land. This damage can be expressed directly in monetary units by using market prices for capital and land. On the other hand, there is non-market damage for which no prices exist such as, for example, fatalities, a decrease in biodiversity, or heat stress. While heat wave damage is predominantly a non-market type - e.g. an increase in heat induced morbidity and mortality (Grizea et al., 2005; EM-DAT, 2016) - damage from floods can almost completely be expressed in monetary units e.g. destroyed land, mobile and immobile capital. While an extreme can produce direct damage, we also observe indirect effects resulting from an economy's response to the direct damage, independent of the nature of the extreme climate event. Destroyed input factors and output losses always cause indirect or general equilibrium effects. This is true in the case of heat waves and in the case of floods and fatalities (which in economic terms, refers to the loss of consumers and labor supply). Therefore, in chapters 3 and 4, I use general equilibrium models to measure direct and indirect damage caused by extreme climate events, and to analyze different adaptation strategies meant to moderate their impact.

To understand the economics of adaptation, we have to distinguish between different forms of adaptation. On the one hand, adaptation might be in the self-interest of economic agents and would therefore be carried out autonomously by private agents. Such examples include the decision to buy insurance or to choose a specific region of residence depending on the region's exposure to climate extremes. On the other hand, adaptation can have the characteristics of a (local) public good. Such examples include investing in flood-resistant public infrastructure, pursuing spatial planning measures, or running information campaigns to raise public awareness of the potential risks of extreme climate events. In many cases, we may observe spillover effects since the agents who benefit from adaptation are typically not identical to those who bear the costs of such. The Swiss adaptation policy stresses both autonomous and public adaptation, as well as the costs-by-cause principle.

Private agents (i.e. autonomous adaptation) and public authorities should coordinate their actions (FOEN, 2012; Mendelsohn, 2000).

Adaptation measures differ with respect to timing. Proactive or anticipatory adaptation measures must be planned in advance to become effective. Such examples include building dams or pursuing spatial planning. In contrast, reactive measures, such as piling sandbags, almost immediately provide some protection against extreme events. Based on the results of Burton (1996) and Bosello (2004), we assume that proactive adaptation is more effective and more efficient than reactive adaptation. Additionally, since the precautionary principle is part of the Swiss adaptation strategy, this implies that proactive measures are to be preferred to reactive ones.

Adaptation measures also differ with respect to their spatial scope. While there are measures which only affect small areas such as, for example, a dam or a protective forest, there are also other measures, such as information campaigns, which have effects on at least the national level. The Swiss adaptation strategy identifies this problem and aims to coordinate all actions between responsible public authorities. Just how many adaptation measures get implemented usually depends on a political decision-making process. Results vary from full adaptation (where there are no residual damages left), to no adaptation at all, with, at intermediate stages first and second-best solutions. In the case of first best solutions, the optimal level of adaptation is derived from maximizing social welfare. In this situation, the marginal costs of providing adaptation equal the value of the marginal benefits (prevented direct damages) from adaptation. Assuming that adaptation has the properties of a public good, the government has different options to levy taxes in order to finance the necessary adaptation measure. Depending on the tax base, different general equilibrium effects might be observed. By analyzing different funding strategies, this thesis will prefer tax schemes that follow the costs-by-cause principle first, and the solidarity principle second. This is in accordance with the Swiss adaptation strategy.

The disastrous European heat wave of 2003 triggered a variety of studies that aimed (1) to estimate heat wave induced excess mortality rates (Vandentorren et al., 2004; Conti et al., 2005; Grizea et al., 2005; Fouillet et al., 2006); (2) to identify risk factors (Vandentorren et al., 2006; Foroni et al., 2007); and (3) to estimate benefits expected from adaptation strategies (Ebi et al., 2004; Kovats and Kristie, 2006; Wolf et al., 2010). The existing literature typically reports benefits only in terms of numbers of reduced fatalities, or as reduced rates of additional (excess) mortality and morbidity (Grizea et al., 2005; Mendelsohn and Saher, 2011). Therefore, in chapter 2[2], we develop a damage function to assess, in monetary terms, the (predominantly) non-market damage from heat waves. In order to decide on adaptation strategies, we have to acquire knowledge about the costs and benefits of adapting to heat waves. While it is relatively straightforward to calculate the costs of an adaptation measure, calculating expected benefits (measured in prevented damages) is substantially more demanding. This is especially true for heat waves, which are predominantly characterized by non-market damage. We need a credible empirical method to estimate damage from heat waves in order to evaluate and compare different adaptation strategies.

An important issue in this context is the question of how to evaluate the cost of a certain adaptation measure against the number of lives saved. While this issue does not arise from an ethical point of view, it has to be answered during the political process of implementing adaptation measures, where the costs and benefits of measures have to be evaluated and compared. Our analysis is related to a paper by Mendelsohn and Saher (2011). To estimate a damage function for fatalities and market damage for a variety of extreme climate events, they used a worldwide data set and ordinary least square regressions. Chapter 2 contributes to this discussion by assessing heat wave caused fatalities in terms of financial cost by using the "value of a statistical life" approach. Our contribution to the empirical literature on damage functions is twofold: (1) we support the idea that any assumption on a functional form and/or model parameter of a theoretical damage function should be rigorously tested; (2) we take a novel econometric approach to deriving a non-market damage function based on an exponential hurdle model. This accounts for the specific properties of non-

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[2] Chapter 2 is co-authored with Stefan Boes

market damage, which is zero in years with no heat wave and positive when a heat wave occurs. The hurdle model separates modelling zero damage from the conditional-on-positives part, thus closely following the theoretical literature. Using longitudinal data and an exponential hurdle model, we derive a damage function that accounts for the impacts of climate change over time and socio-economic data. This approach can be used for policy recommendations, because it enables us to estimate the expected damage of heat waves in monetary units and evaluate them in comparison with the costs of any adaptation measure.

While floods usually have a regional impact, heat waves have a greater spatial impact. Both disastrous heat waves in 2003 and 2006 affected almost all European countries. This fact, along with the comprehensive database, enables us to extend the spatial scope of our analysis from Switzerland to Europe.

Our results indicate that the probability of observing a heat wave is determined by the average temperature, precipitation and temperature variability in ten 5-year intervals from 1960 to 2009. Our results are consistent with those from earlier studies (e.g., Schär et al. (2004)). However, we do not find that climate variables are associated with non-market damage in the conditional-on-positives part, although there is some indication that both the age ratio (the share of citizens older than 65 relative to those aged 15-64) and the population density are positively associated with damage. Contrary to our presumption, we do not find evidence that non-market damage is associated with GDP or the degree of urbanization. With regards to the degree of urbanization, it is possible that the data are not expedient enough on a national basis. However, the main implication of our study is that demographic characteristics seem relatively more important than the economic factors for non-market damage from heat waves. This finding supports the strategy that adaptation should mainly target vulnerable groups in the population.

Chapter 3 takes a computable general equilibrium approach to analyze direct and indirect effects of heat waves in Switzerland as well as strategies to adapt to them. Taking general equilibrium impacts into account is important for the following reasons. First, not only do heat waves cause excessive deaths, they also have an indirect effect on labor supply and the demand for consumption goods and leisure. Hence, both the allocation of resources and the distribution of income are affected. Second, if adaptation is a (local) public good, spillover effects might occur. Third, both the public good character and the time delay between the decision to implement adaptation measures and their first effects lead to a discrepancy between the beneficiaries and those who bear the adaptation costs. Fourth, the population is not uniformly hit by heat waves. As the impact literature reports (Johnson et al., 2005; Haines et al., 2006), heat wave impacts depend on age, income and the degree of urbanization in regions where affected individuals reside. Those who suffer most are very young and very old people, as well as those with pre-existing diseases. Poor people have fewer resources to protect themselves than the wealthy. The so-called heat-island effect implies that the urban population is more affected because of the infrastructure, architecture and the limited amount of green areas. Urban areas heat up much faster and cool down more slowly than rural ones (Baccini et al., 2008). As a consequence, certain general equilibrium effects are systematically neglected when analyzing damage from heat waves and adaptation strategies to them by sole focusing on excess death or the monetarization of fatalities with the value of a statistical life. However, these effects are important in designing efficient adaptation strategies (Hallegatte et al., 2007).

On the one hand, the approach in chapter 3 is an improvement over the approach used in chapter 2 because it takes a more global perspective. On the other hand, the damage module of chapter 3 is much simpler than the one derived in chapter 2. This is because we aim to monetarize damage in chapter 2, while we analyze general equilibrium effects and account directly for fatalities in chapter 3. The damage module of chapter 3 is based on estimates made by Grizea et al. (2005) on heat wave excess mortality[3] during the 2003 heat wave in Switzerland.

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[3] "[Heat wave excess mortality is the] mortality above what would be expected based on the non-crisis mortality rate in the population of interest. Excess mortality is thus mortality that is attributable to the crisis conditions. It can be expressed as a rate (the difference between observed and non-crisis mortality rates) [...]" (Checci and Roberts, 2005).

Chapter 3 aims to answer two main research questions: (1) What is the order of magnitude of general equilibrium impacts of a 2003-like heat wave on the Swiss economy? (2) If adaptation to heat waves is a public good, what are the diverse economic effects of policies for financially funding optimal adaptation to heat waves?

In contrast to an integrated assessment, we are running a policy evaluation analysis, where heat waves are taken as given and where we analyze the effect of policy driven adaptation to heat waves in Switzerland. Although an Auerbach-Kotlikoff overlapping generations (OLG) model seems to be the most natural way of introducing an age structure, it also requires one to assume that agents are clairvoyant (Rasmussen and Rutherford, 2004). This assumption contradicts the analysis of low-probability and high-impact events like heat waves. To avoid this problem, we develop a static Computable General Equilibrium (CGE) model which zooms into one single period of a standard Auerbach-Kotlikoff model.

While we observe private and instantaneous adaptation in reaction to price changes, we explicitly model adaptation as a public good with financial funding realized through taxing either labor, capital, consumption or inheritance. As our approach accounts for secondary effects, we are able to differentiate between welfare losses and damage in the output, i.e. market damage that results from lower labor supplies and total demand for consumer goods. We differentiate the demand side with respect to three characteristics: age, income and urbanization of the region of residence. We do this because these three characteristics to a great extent define the vulnerability and adaptation capacity of households to heat waves. Our model is based on Swiss income data that describe different income type distributions between household groups of different age, income and residential region.

Our approach has two main advantages: first, it makes it possible to do a regionally differentiated analysis without requiring regional input-output tables. Secondly, it enables us to compare different strategies to fund the provision of the public good adaptation. We are able to show that heat waves impact cohorts utility in an unadapted economy in substantially different ways. While young and less vulnerable cohorts profit (in welfare terms) from heat waves, vulnerable but surviving cohorts have decreased welfare. This result shows that without adaptation, vulnerable cohorts are worse off and might have fewer possibilities to invest in private adaptation. Due to the capital flow to young cohorts, a heat wave in a non-adapted economy increases overall social welfare. This positive impact of heat waves comes at the expense of old and vulnerable cohorts that suffer either because they lose their lives, or because they survive but face decreased utility.

These results support the findings of chapter 2, where we see that adaptation measures should mainly target the vulnerable groups of the population. Additionally, the results of chapter 3 show that (1) heat waves might cause a high number of fatalities combined with a distribution effect, from which young, high income people in suburban and urban regions can profit; (2) governmental provision of an optimal adaptation stock can reduce heat wave excess mortality at the expense of a relatively low labor (0.4%), capital (0.5%) or consumption (0.2%) tax; and (3) an inheritance tax is unsuitable to finance an optimal adaptation stock, because an increase in mortality increases the tax basis. Overall, we show that it is possible, at relatively low economic costs (about 0.2% of the GDP), to reduce mortality from heat waves drastically, and also to prevent strong distribution effects caused by a heat wave in an unadapted economy.

Chapter 4 focuses on the economic impact of floods and adaptation to them in Switzerland. The main purposes of this chapter are as follows: (1) to better understand the direct and indirect economic impacts of floods; (2) to analyze the issue of efficient flood adaptation from a regionally diversified perspective; and (3) to analyze the issue of financing adaptation in a federal system, where there is an interplay between local and national governmental authorities in the provision of local public good adaptations.

Chapter 4 has been developed within the context of the Sinergia project, “Climate change extremes and adaptation strategies considering uncertainty and federalism” (CCAdapt), which is financed by the Swiss National Fund. CCAdapt intends to develop tools and methods that facilitate a more detailed characterization of climate change adaptation from an economic and policy analysis perspective. We develop a theoretical framework for analyzing adaptation within a federalist setting by taking an interdisciplinary approach which integrates environmental economics, hydrology, meteorology and political sciences. In a second step, this approach is taken for a Computable General Equilibrium (CGE) analysis of Switzerland to evaluate feasible adaptation strategies. As such, CCAdapt aims to deliver a refined theory of adaptation, improved tools for quantifying adaptation strategies, and a better understanding of efficiency-equity tradeoffs as well as political barriers to adaptation.

Our numerical thought experiments in chapter 4[4] are based on a dynamic, spatially differentiated Ramsey type Computable General Equilibrium Model. The basis is a regional Input-Output table for Switzerland; with regions that are determined by exposure and vulnerability to floods and not identical with area municipalities. We derive the regional Input-Output table by using the location quotient-based interregional input-output (IRIOLQ) framework proposed by Jahn (2015). Again, taking a CGE approach is important because it allows us to observe indirect effects. The impact floods can have on economies goes beyond the direct local effects when water is coming into contact with infrastructure, buildings and other properties. Because of inter-linkages within and across regional economies, a sequence of feedback reactions inside and outside the flooded area can be set off, which typically last much longer than the flood itself.

While private adaptation is observed indirectly in our model via reactions to price changes caused by floods, when adaptation has the features of a local public good, it has to be modeled explicitly. There are two categories of governments: a federal government on the one hand, and regional governments on the other. The latter can be understood as a federation of local communities, which are characterized by high, medium or low exposure to floods. They are not identical to local authorities. Depending on the funding scenario, the local governments levy taxes on land or output for financing flood adaptation measures. The federal government collects taxes on output for financing governmental consumption, adaptation measures and/or transfers to the regional governments for co-financing adaptation measures. Additionally, we assume that adaptation measures which

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[4] Chapter 4 is co-authored with Gunter Stephan.

are implemented by regional governments are more effective in preventing damage than those which are implemented by the national government. This difference in effectiveness is because of information deficits. Another important characteristic of adaptation is that costs for adaptation arise in the case of proactive adaptation, before the adaptation measure is actually implemented. To implement direct damage in our model, we take the damage function approach proposed by Carrera et al. (2015). It takes the spatial extent and the duration of the damage into account.

Our analysis yields three major findings: (1) General equilibrium effects that are caused by flood damage in highly vulnerable regions also lead to considerable welfare and GDP losses in regions of low vulnerability. (2) By providing the local public good adaptation, it is, at low economic cost, possible to significantly reduce negative impacts on welfare, GDP as well as the allocation of resources between regions and sectors. Finally, (3) funding the local public good with a regional land tax should be preferred over a national output tax, or a combination of both, with transfers from the national to regional governments.

To conclude, this thesis has three self-contained chapters that contribute to our understanding of direct, indirect, market and non-market impacts from extreme climate events. Additionally, this thesis provides insights into efficient strategies to finance the (local) public good adaption. The first part shows the derivation of a damage function for heat waves that also accounts for fatalities. The second part provides insights into general equilibrium impacts from heat waves, and compares different strategies to finance adaptation to heat waves. The third part analyzes direct and indirect impacts of floods and adaptation to them in a spatially differentiated setting that accounts for the different decision and funding levels in a federal system.

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Chapter 2

Empirical Derivation of a Damage Function for Heat Waves in Europe

2.1 Introduction

According to the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the atmospheric carbon concentration is expected to rise further during the 21st century. This will not only lead to an increase in mean temperatures and changes in the patterns of precipitation, but it also implies that the frequency, intensity and duration of extreme weather events, and heat waves in particular, will increase significantly in the future (IPCC, 2013; Perkins et al., 2012). The IPCC defines a heat wave as a ”period of abnormally and uncomfortably hot weather”, which is operationalized as multi-day heat extreme with daily maximum temperatures above a high (usually the 90th) percentile relative to a late 20th century reference period (Fischer and Schär, 2010; IPCC, 2013; Perkins et al., 2012). The IPCC projections are based on climate models that simulate the observed features of heat waves very well, indicating a high reliability of the model based simulations (IPCC, 2013).

Figure 2.1 shows that based on such simulations Europe will be especially affected by rising summer temperatures over the next decades. High-percentile summer temperatures will increase faster than mean temperatures, and summer warming will be more intense in Mediterranean regions as well as in Central and Northern Europe (IPCC, 2013). Consequently, heat stress, which is defined as the combined effect of high temperatures and humidity, is expected to increase in Europe. This will generate human discomfort, morbidity and mortality (IPCC, 2014).

Overall, these projections do not come at a surprise. During the past 20 years Europe has been the most heat wave affected region in the world, and since the 1960s, more than 80% of all extreme event excess deaths resulted from heat waves (see figure 2.1).

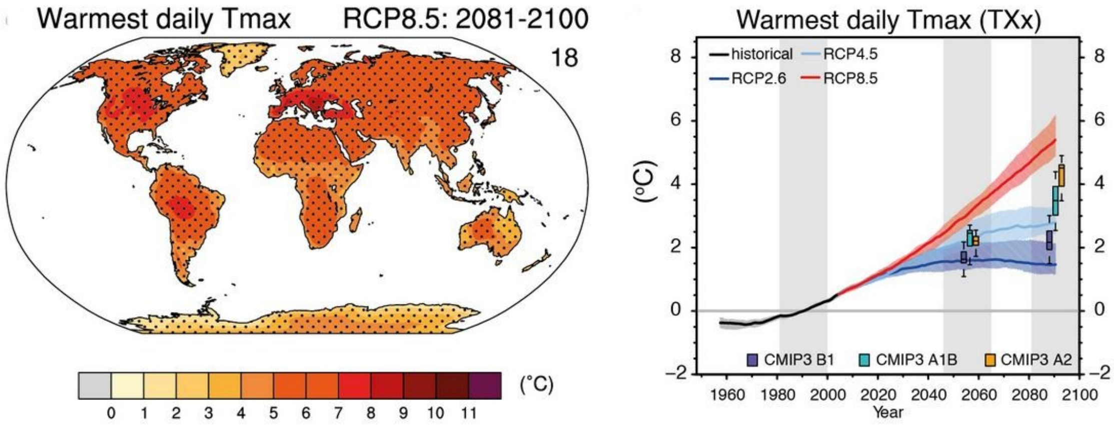

Figure 2.1: Projection of warmest daily temperatures under different scenarios

Source: IPCC (2013), *Note:* Simulation of the warmest daily temperature (Tmax) in case of amitigation scenario (RCP2.6), a stabilization scenario (RCP4.5) and a scenario with high greenhouse gas emissions (RCP8.5) for the period 2081-2100.

For adapting efficiently to heat waves, one has to strike for a balance between costs and benefits. While it is relatively straightforward to calculate the costs of an adaptation measure, the estimation of expected benefits (usually measured in prevented damages) is substantially more demanding. This is especially true in the case of heat waves. First, research on the effectiveness of adaptation measures to heat waves is still in its early stages. Second, damages from heat waves are to a large extent non-market damages and not directly appraisable in monetary units. There are only a few attempts in the literature so far on the representation of non-market damages in a damage function. However, a persuading empirical method to estimate both market and non-market damages from heat waves is

Extreme Event	Frequency	Fatalities	Damage (in US$)
Drought	26	0	19‘217.31
Mass movement	45	3‘608	2‘663.8
Flood	351	7‘859	99‘024‘720
Heat wave	45	76‘705	12‘123‘050
Storm	352	6‘052	88‘407‘495

Source: EM-DAT (2016)

Table 2.1: Damages from extreme climate events in EU27 countries and Switzerland between 1960 and 2013.

the basis to analyse, evaluate and compare different adaptation strategies to heat waves in Europe.

In this paper, we estimate a non-market damage function for heat waves in Europe following the approach in Mendelsohn and Saher (2011) and Nordhaus (2010). The contribution of our paper is threefold: First, and in contrast to the previous literature that predominantly relies on cross-sectional data, we use longitudinal data because we deem it essential to account for time effects in the model. Second, our analysis focuses on non-market damages and a monetary assessment of heat wave caused fatalities. In health economics, different methods on the valuation of a statistical life have been developed and they are often used for policy analysis (e.g., Zweifel et al. (2009)). Third, we estimate an exponential hurdle model that accounts for the specific properties of non-market damages, which are zero in years with no heat wave and positive when a heat wave occurs. The hurdle model separates the modelling of the zero damages and the conditional-on-positives part, closely following the theoretical literature.

Using climate and mortality data for 27 European countries, our results indicate that the probability of observing a heat wave is determined by the average temperature, precipitation and temperature variability in ten 5-year intervals from 1960 to 2009, which is consistent with earlier studies (e.g., Schär et al. (2004)). We do not find an association of the climate variables with non-market damages in the conditional-on-positives part, but there is indication that the age ratio (the ratio of citizens older than 65 relative to those aged $15 - 64$ and the population density are positively associated with damages. We do not find evidence for an association of non-market damages with GDP or the degree of urbanisation. The main implication of our study is that demographic characteristics seem relatively more important for non-market damages from heat waves than the economic factors, which supports the notion that adaptation strategies should mainly be targeted at the vulnerable groups of the population.

The remainder of the paper is structured as follows: Section 2.2 summarises the empirical and theoretical literature on damage functions in climate economic modelling. Section 2.3 presents the theoretical framework. Section 2.4 gives an overview of the data. Section 2.5 describes the empirical model, and section 2.6 presents the results. Section 2.7 concludes the paper.

2.2 Literature Review

In the following we provide an overview of the different approaches on how to quantify damages from extreme weather events. First, we discuss damage functions that have typically been used to analyse adaptation in the Computable General Equilibrium (CGE) and in the Integrated Assessment (IA) frameworks. Second, we show how the existing literature econometrically derives damage functions and briefly summarise the main results.

In general, the literature distinguishes between market and non-market damages. Market damages can be evaluated in terms of standard accounting systems. Non-market damages are impacts of climate change that cannot be directly valued in monetary units, e.g., species losses or a reduction in human well-being (Buob and Stephan, 2011). Damage functions are used to link the predictions from climate models with potential changes in the economy. This linkage requires an assumption on the functional form of the relationship between climate variables and (non-) market damages and different suggestions for the shape of the damage function have been made, with very different implications regarding the economically efficient level of mitigation and adaptation (Warren et al., 2006).

There are three main objections to the damage functions that have been used in the CGE and in the IA frameworks so far:

(1) Model parameter are often arbitrarily chosen, without satisfactory explanation or justification (Ackerman et al., 2009; Stanton et al., 2009)

(2) Damage functions are assumed to be continuous (Stanton et al., 2009)

(3) Different impacts from climate change are merged in a single number (Müller-Fürstenberger and Wagner, 2007)

The first point relates to the fact that the majority of theoretical models use damage functions of the following (or similar) form (Warren et al., 2006).

$$D_{it} = \alpha \Delta T_{it}^{\beta} \cdot GDP_{it} \tag{2.1}$$

D_{it} measures damages in region i at time t as a fraction of the gross domestic product GDP and ΔT describes the change in average temperatures. The parameter α and β are chosen in accordance to the assumptions made about the form of the functional form of the relationship between temperature change and damages. In the majority of the models, like MERGE [1], DICE and AD-DICE [2] a quadratic damage function is used (Stanton et al., 2009; Nordhaus and Boyer, 2003; De Bruin et al., 2009; Warren et al., 2006). Other approaches include further climate variables that may influence damages, like precipitation (Schenker and Stephan, 2012). They use an additive functional form and account for the level of temperature already reached (Mendelsohn, 2000). The majority of models do not account for non-market damages.

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[1] MERGE: Model for Estimating the Regional and Global Effects of greenhouse gas reductions combines a de-tailed energy-economy model with carbon and climate models. Regional damage functions account for market and non-market damages separately. Both are quadratic in temperature, and non-market damages also depend on regional income (Parson et al., 1997)

[2] DICE: Dynamic Integrated Climate-Economy integrate[s] in an end-to-end fashion the economics, carbon cycle, climate science, and impacts in a highly aggregated model that allow[s] a weighing of the costs and benefits of taking steps to slow greenhouse warming. The damage function is in the 2013 updated version of the form $\Omega(t) = \psi_1 T(t) + \psi_2 (T(t))^2$ (Nordhaus and Boyer, 2003). The AD-Dice model additionally accounts for adaptation but applies the same damage function as the dice model (De Bruin et al., 2009).

An exception is MERGE, which assumes an S-shaped relationship between the willingness-to-pay to prevent non-market damages and per capita income (Manne et al., 1995; Manne and Richels, 2005)

Large non-CGE models, for example FUND[3] and PAGE[4], use a more complete representation of damages and differentiate between market and non-market damages. PAGE uses the traditional damage function in equation 2.1 and derives values between 1 and 3 for the parameter β using Monte Carlo analysis (Ortiz and Markandya, 2009; Hope, 2006; Ackerman et al., 2009). FUND has a damage module that is dynamic in climate and socio-economic vulnerability and accounts for different durations of the damage memory. It measures damages in monetary units as well as number of fatalities and is the first model that accounts for different damages from different extreme events (Ortiz and Markandya, 2009; Tol, 2002). Parameter in the model are chosen by a mixture of informed guess, theoretical assumptions of experts, estimations and extrapolations events (Tol, 2002; Anthoff and Tol, 2013).

As an alternative to the calibration of parameter in a theoretical damage function, econometric methods have been proposed to empirically infer a damage function (Mendelsohn and Saher, 2011). Socio-economic variables that influence damages from extreme weather events can be identified from data and the size and direction of their impact can be estimated. Mendelsohn and Saher (2011) use a least squares regression for time-averaged cross sectional data between 1960 and 2010 to project damages from different extreme weather events with and without global climate change. Market damages and fatalities are used as the dependent variables. Income, population density, mean and variance of temperature and precipitation are used as the explanatory variables. Concerning heat waves, Mendelsohn and Saher (2011) find that income, population density, life expectancy and the variance in precipitation have a positive and significant effect on market damages and fatalities.

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[3] The FUND model uses the standard functional form of the damage function but differentiates parameter by loss category and region.

[4] In the PAGE model, damage estimates correspond to a 2.5°C increase in temperature, the mean expected warming for a doubling of CO2. Impacts are computed for each region, sector, and analysis period as a power function of regional temperature increase above the tolerable level. An adaptive policy can mitigate these impacts.

Nordhaus (2010) estimates damages from hurricanes in the United States. The dependent variable, costs as share of GDP, is regressed on the maximum wind speed, sea surface temperature and a time trend. Kellenberg and Mobarak (2008) use panel data to show that the risk of disaster damages depends quadratically on income. Dorland et al. (1999) aim to find the impact of climate change on North-Western European storm damages in housing using the number of objects, the postal code area and the storm speed as explanatory variables.

Most of the empirical studies look at market damages from extreme weather events, but to the best of our knowledge, there is no derivation so far of a non-market damage function that would evaluate heat wave caused fatalities in monetary terms. This will be a main contribution of our study. We also add to the literature by proposing a modelling framework that explicitly separates the zero damages in regions and years without a heat wave from the positive non-market damages in years with a heat wave. Since we do not expect the climate variables and the socio-economic characteristics to have the same influence on the two parts, we deem this a relevant methodological extension to the related literature.

2.3 Theoretical Approach

A theoretical approach for assessing the damages from extreme weather events needs to take into account three multiplicatively combined elements (Mendelsohn and Saher, 2011):

(1) the probability π_{it} that a heat wave occurs,
(2) the damage reducing adaptation function A_{it}, and
(3) the magnitude of the damages CD_{it}, on the occurrence of a heat wave;

$$D_{it} = \pi_{it} \cdot (1 - A_{it}) \cdot CD_{it} \tag{2.2}$$

We assume that the probability π_{it} at which a heat wave occurs in region i at time t is determined by a set of climate variables. The modelling of the probability has already been studied elsewhere, e.g., Schär et al. (2004), and will not be a main focus of our analysis.

The adaptation function A_{it} accounts for the fact that the magnitude of damages in case of a heat wave is reduced were adaptation measures implemented. The adaptation function can take values between 0 (no damage preventing adaptation) and 1 (complete adaptation, no residual damages). A_{it} is typically assumed an increasing and concave function in the adaptation stock, which like capital stock can be accumulated over time and describes any measure that can prevent damages from heat waves (Bucher and Guelden Sterzl, 2011; De Bruin et al., 2009).

The third variable, CD_{it}, describes the damages conditional on the occurrence of a heat wave as a function of climate variables and socio-economic factors that determine the vulnerability, exposure and adaptation capacity of region at time. In the existing theoretical literature (see Section 2.2), the functional form for the impact of temperature and income on damages is often assumed quadratic, which can be tested by means of an econometric model. The hypothesised impact of the other determining variables is presented in Section 2.4.2.

Based on the theoretical framework, our empirical analysis aims at estimating equation 2.2 by explicitly taking into account two of the above-mentioned components. In a first step, we approximate the probability that a heat wave occurs as a function of different climate variables. In a second step, we describe the expected damages in the case of a heat wave as a function of climate variables, socio-economic and demographic characteristics of the country. We are not able to separate adaptation mechanisms from the estimation of the conditional non-market damage function and therefore our results must be interpreted to incorporate both.

2.4 Data and Descriptive Analysis

The data we use stem from different sources because no single data set is available that would contain all the information needed for our analysis. The created panel data cover 27 European countries plus Switzerland (EU27CH) except Malta, which is too small to find reliable climate data over the ten 5-year time intervals between 1960 and 2009.

2.4.1 Dependent Variables

As discussed above, there are two types of damages from heat waves to differentiate: market and non-market damages. While market damages represent a relatively small part of the overall damages from heat waves, the share of fatalities is relatively high compared to other extreme events making non-market damages particularly important (Alberini et al., 2006a). For this reason, we consider fatalities and non-market damages as our main dependent variables:

Fatalities: This variable measures the number of excess deaths caused by heat waves as count data in every 5-year interval. This information is provided by CRED/EM-Dat.

Non-market Damages: This variable is a non-monotonic transformation of fatalities. Excess deaths are weighted with an age adjusted Value of Statistical Life (VSL_{it}) measured in 1000 US$ in the 5-year periods. Own calculations are based on studies that provide the VSL in different countries in Europe. The detailed derivation of this variable is described below.This variable is a transformation of the variable fatalities.

Measuring heat wave caused fatalities does not come without problems. The number of deaths related to heat waves might be underreported because heat wave is no official cause of death. Although the main health impacts from heat waves are confirmed to be caused by cardiovascular and respiratory diseases (Kenney et al., 2014; Analitis et al., 2014), time lags between emergence and admission to hospital and problems in considering sudden death complicate the statistical coverage of heat wave caused fatalities. Reported fatalities can be interpreted as excess deaths caused by heat waves net of so called early harvest. They are measured by using Poisson models to estimate the excess mortality compared to a past average level during the respective period of time in the year. Net of early harvest means to account for short-term mortality displacement. Monthly deviations from predicted mortality are then cumulated from the heat wave event onwards for some months to get an estimate of the number of heat wave caused fatalities. If excess mortality had been caused by early harvest, cumulative excess mortality would have decreased to zero very shortly after the heat wave.

Table 2.2 summarises fatalities and, for comparison reasons, market damages from heat waves in the EU27CH countries since 1960. It can be observed that some countries are more exposed and/or vulnerable to heat waves than others. It should be noted that we do not consider morbidity as opposed to mortality because there is no data set available that measures morbidity from heat stress in a sufficient quality and comparability across countries.

EU27CH countries	Number of heat waves	Fatalities	Market Damages in ’000 $
Austria	5	357	280’000
Belgium	7	2’133	0
Bulgaria	9	76	50
Cyprus	0	0	0
Czech Republic	5	467	0
Denmark	0	0	0
Estonia	2	4	0
Finland	0	0	0
France	12	24’110	5’172’000
Germany	10	13’975	1’950’000
Greece	7	1’129	3’000
Hungary	5	662	0
Ireland	0	0	0
Italy	8	20’169	4532601
Latvia	4	86	0
Lithuania	5	87	0
Luxembourg	1	170	0
Netherlands	5	1’966	100’000
Poland	14	1’799	0
Portugal	4	2’737	0
Romania	18	516	0
Slovakia	5	128	150’000
Slovenia	1	289	80’000
Spain	8	15’616	1’804’300
Sweden	1	0	0
Switzerland	6	1’050	280’000
United Kingdom	7	319	47

Source: EM-DAT (2016)

Table 2.2: Damages from heat waves in EU27CH countries 1960 - 2013

We calculate non-market damages by evaluating every fatality caused by a heat wave with the value of a statistical life (VSL) by country and time. This approach has been proposed in a similar manner by Alberini et al. (2006b) and Sgobbi and Carraro (2008) to calculate non-market damages from extreme weather events and to quantify the benefits from adaptation. In a first step, we reviewed the literature to find credible estimates of the VSL in the EU27CH countries. Our main sources are Braathen et al. (2009); Baccini et al. (2008) and

Miller (2000). Because there are different methods and contexts used to estimate the VSL, we rely whenever possible on the willingness to pay approach reported for environmental risks. We prioritise according to the age of the studies and prefer actual results to older ones. For some countries only VSL estimates from 1995 or those that account for health and traffic risks are available, but we assume that they serve as good approximations. For Bulgaria, Cyprus, Estonia,Latvia, Lithuania, Luxembourg, Romania, Slovakia and Slovenia there are no VSL data available and thus the EU average reported by Miller (2000) is used. All damages are adjusted to the base year 2005, corrected for inflation, and expressed in US$. We calculate non-market damages from the fatality data by evaluating every fatality caused by a heat wave with the value of a statistical life. This approach has been proposed in a similar manner by Alberini et al. (2006b) and Sgobbi and Carraro (2008) to calculate non-market damages from extreme weather events and to quantify the benefits from adaptation. nt for health and traffic risks are available, but we assume that they serve as a good approximation. For Bulgaria, Cyprus, Estonia, Latvia, Lithuania, Luxembourg, Romania, Slovakia and Slovenia there are no data on the value of a statistical life available and thus the EU average reported by Miller (2000) is used. All damages are adjusted to the base year 2005, corrected for inflation, and expressed in US$.

To account for the dependence of the VSL on age and life expectancy, we adjusted VSL by evaluating the remaining life years. In accordance with Alberini et al. (2004) and Aldy and Viscusi (2008) and due to the lack of consistent empirical results on the impact of age on the VSL (Schleiniger and Blöchliger, 2006), every life year has been valued identically. Thus, the number of remaining years is used to adjust for age effects, but not for the willingness to pay in different periods of life. The number of remaining life years is calculated as the difference between the average life expectancy in a country and the age of 60, an age threshold for those that suffer a higher risk from heat waves. This threshold value is taken from earlier studies (Grizea et al., 2005; Michelozzi et al., 2005; Baccini et al., 2008; WHO, 2009).

2.4.2 Explanatory Variables

The impact of specific extreme weather events on non-market damages in a region is determined by the region's exposition to the change in the climate system, its sensitivity to climate change impacts and the capacity to adapt to it (Ebi and Meehl, 2007). Any damage function must be able to display the vulnerability of a region to extreme weather events, which we seek to achieve by including a number of possible explanatory variables.

Climate Data

We use historical climate data on *temperature* and *precipitation* provided by the ENSEMBLE project, which is supported by the European Commission. The data used in this paper are the mean values of five different regional climate models. Monthly data are averaged over 5-year intervals. We use the mean summer temperature (June-July-August) at two meters measured in degrees Celsius, and the mean summer precipitation measured in mm/day. The relationship between health impacts and daily temperature in general is assumed to be quadratic; see section 2.2 and WHO (2009); Pattenden et al. (2003); Michelozzi et al. (2007); Reeves et al. (2010). We will test this assumption in the context of non-market damages from European heat waves below. The impact of precipitation is not clear in advance. On the one hand, higher precipitation may cool down the atmosphere and reduce damages from heat waves. On the other hand, humidity may increase heat stress and thus generate even stronger health impacts.

Several studies suggest that an increase in mean temperature accounts for most of the changes in heat wave frequency. However, heat wave intensity/amplitude is highly sensitive to changes in temperature variability and the shape of the temperature distribution. Schär et al. (2004); Beniston (2004) and Katz and Brown (1992) conclude that it is not only the increased mean temperature but also the increasing variance in temperatures that causes an increase in the probability of heat waves. Schär et al. (2004) find that a 50% increase in the standard deviation of long-term summer temperatures increases the probability of a 2003-like event by the factor of about 150. We follow these studies and include *standard deviations of summer temperature and precipitation* in the model for the occurrence of a heat wave, although it is not clear a priori whether the variability has a direct impact on non-market damages.

Socio-economic and demographic data

Socio-economic variables describe how vulnerable a region is to damages from heat waves and how high the adaptation capacities are. If a vulnerable population experienced heat waves in the past, then the awareness of the danger coming from heat waves will be higher in general and adaptation measures are considered more seriously (Reeves et al., 2010). This effect was observed for example after the severe heat wave in 2003. The adaptation capacity, however, determines the potential mitigation of future damages. We use the following socio-economic variables to explain damages from heat waves in the past.

The impact of *GDP* on market and non-market damages can be positive as well as negative. On the one hand, a higher GDP gives the potential for higher market damages, because there are more consumption and capital goods that are potentially destroyed. On the other hand, the higher the GDP is, the higher may be the adaptation capacity (ECW, 1998). A relatively low number of newly introduced early warning systems for heat waves in Europe (12 countries in 2011), the insufficient implementation of other measures and a relative high GDP indicate that there is both a high adaptation capacity and potential in Europe (Lowe et al., 2011). With regards to non-market damages, Mendelsohn and Saher (2011) and Nordhaus (2010) find a positive effect of GDP on non-market damages and fatalities. This means, the higher the GDP the more fatalities we face during heat waves. This result may mainly be driven by the dependence of the VSL on the GDP. However, a higher GDP may also be associated with a better health care system and better medical care helps to reduce the number of heat wave caused fatalities.

Due to the heat island effect, vulnerability to heat waves is usually strongly increasing with the degree of *urbanisation*. Due to their infrastructure, architecture and very small green areas, cities are heating up much faster and cooling down much slower than rural areas. This is confirmed by the significantly higher number of deaths in cities compared to rural areas (ECW, 1998; Michelozzi et al., 2005; Ebi and Meehl, 2007; Baccini et al., 2008). Additionally, air pollution is an enforcing factor for the negative health effect of heat waves. Usually the degree of air pollution is much higher in urban than in rural areas which adds to the heat island effect (ECW, 1998; Lowe et al., 2011). The variable measuring the degree of urbanisation is provided by the Department of Economic and Social Affairs of the United Nations and measures the share of people who live in urban regions. From the above reasoning, we expect the effect of the degree of urbanisation on damages from heat waves to be positive.

Data on the *population density* in the EU27CH countries are provided by EUROSTAT. It is calculated as the average number of inhabitants of a country per squared km. This variable is used as alternative proxy to account for the heat island effect because it is closely related to (although not collinear with) the degree of urbanisation. We expect that the vulnerability to heat waves increases with the population density (WHO, 2009; Reeves et al., 2010).

The risk of suffering from negative health impacts from heat waves increases with age. Older people on average are more strongly exposed to weather-related threats due to their physical condition, an effect that may be aggravated by special risk factors like the lack of selfsufficiency, living alone, suffering from pre-existing diseases, deprivation and social isolation (WHO, 2009; Ebi and Meehl, 2007; ECW, 1998). The variable *age ratio* (in the demography literature also known as dependency ratio) is intended to account for this impact. Table 2.3 summarises the mean values, standard deviations, minimum and maximum values of all dependent variables and the explanatory variables included in our dataset.

	Mean	SD	Minimum	Maximum
A. Outcomes				
Fatalities	284	2’017	0	20’089
Non-market damages (1000 US$)	175’000	1’340’766	0	18’200’000
B. Determinants of the damage function				
Temperature	17.41	3.81	10.71	27.51
Precipitation	2.48	0.77	0.06	4.53
Temperature SD	1.38	0.32	0.60	2.18
Precipitation SD.	0.45	0.16	0.04	0.97
GDP p.c. (in US$)	13’107	13’753	80	98’086
Age ratio in %(n65+/n15-64)	13.10	2.65	5.80	19.84
Degree of urbanization	0.65	0.14	0.28	0.97
Population density (n/km2)	120.41	91.58	14.70	482.58
Notes: N=270; 27 countries over ten 5-year intervals				

Table 2.3: Descriptive statistics

There are a several other explanatory variables that could have been included in our analysis, including expenditures for the public health system, supply of public health services and the ratio of overweight and obese people to normal weight people. We tested those in our regressions, but they turned out to be poor (small and statistically insignificant) predictors.

2.5 Empirical Methodology

An econometric model describing non-market damages from European heat waves should closely follow the theoretical considerations in Section 2.3. In specifying the empirical damage function, we need to acknowledge that there are two possibly related statistical parts, one that describes whether there are positive damages (equivalent to modelling the probability of the occurrence of a heat wave), and another that describes the amount of damages conditional on the occurrence of a heat wave. Formally, this can be expressed as

$$D_{it} = 1(H_{it} = 1) \times D^*_{it} \tag{2.3}$$

where observed damages D_{it} are either zero, or positive. The first term on the right-hand side of 2.3 is an indicator function $1(H_{it} = 1)$, which equals one if a heat wave H_{it} occurs in country i and year t, and equals zero in case of no heat wave (and accordingly no damages). D^*_{it} denotes the amount of damages when a heat wave occurs, i.e. $D_{it} = D^*_{it}$, if the indicator function $1(H_{it} = 1)$ equals one. We assume a probit structure for the first part of the model, i.e., the probability of $H_{it} = 1$ is modeled with a probit link function of different climate variables. For the second part, i.e., damages D^*_{it} , we specify the following exponential model

$$D^*_{it} = \exp(X'_{it}\beta + \alpha_i + \gamma_t + \varepsilon_{it}) \tag{2.4}$$

where D^*_{it} (fatalities or non-market damages) is expressed as a log-linear function of a vector of explanatory variables X_{it} including climate variables, socio-economic and demographic characteristics, country-specific heterogeneity α_i, time effects γ_t, and a time-varying error ε_{it}. The parameter vector β is the objective of our analysis. It describes how the components in X_{it} are related to non-market damages in the case a heat wave occurs. Parameter β can be interpreted as semi-elasticities, i.e.,$100\% * [exp(\beta_j \Delta x_j) - 1]$ shows the relative change in damages D^*_{it} for a change in the jth regressor by Δx_j. Due to the limited amount of data and because we want to develop a prediction model for non-market damages from heat waves, time effects γ_t are assumed linear (quadratic) in our model. Estimation of β is carried out in a maximum likelihood framework under a random effects assumption on the error components, i.e., we assume uncorrelated heterogeneity α_i and errors ε_{it}.

We conducted several tests on the statistical relationship between the two parts of the model, with the one extreme being independence (exponential hurdle model) and the other extreme being perfect statistical dependence (as in traditional Tobit models); see Wooldridge (2010) for a discussion of these models. We could reject the model with perfect statistical dependence against the hurdle model and against a model that allows for a correlation between the two parts by assuming random effects with joint normal distribution (referred to as exponential type-II Tobit); Vuong-test p-value < 0.001. In the exponential type-II Tobit we could not reject the null hypothesis of a zero correlation between the two parts, and therefore we present the results for the exponential hurdle model only (Stata 14 command -churdle-).

2.6 Estimation Results

2.6.1 Descriptive Evidence

As a first step towards evaluating the impact of heat waves on fatalities and non-market damages, we provide a refined set of descriptive statistics where we distinguish between the country-year records where a heat wave occurred during the study period (35 observations) and the country-year records where no heat wave occurred (235 observations). Table 2.4 combined with Table 2.3 shows the two parts in the number of fatalities: we observe zero fatalities in years without heat wave and we observe on average almost 2,200 fatalities in years when a heat wave occurred, with a standard deviation of 5,280. The number of fatalities translates into non-market damages of 1.35 billion US$ on average. We see a number of differences in the explanatory variables when comparing the country-year records with and without a heat wave. In particular, the average temperature and precipitation as well as temperature variability are higher in years with a heat wave. We also observe a significantly higher GDP per capita, a larger age ratio and a higher population density, indicating that different countries experienced heat waves during the study period and that this heterogeneity needs to be accounted for when modelling a non-market damage function.

2.6.2 Occurrence Equation

In a second step, we provide estimates for the first term in equation 2.3, namely a probit model for the probability that a heat wave occurred during our study period. The dependent variable in this model equals 1 for the country-year records where a heat wave was observed, and equals zero otherwise.

	Years without heat wave		Years with heat wave	
	Mean	SD	Mean	SD
A. Outcomes				
Fatalities	0	0	2'191	5'280
Non-market damages (1000 US$)	0	0	1'349'998	3'548'198
B. Determinants of the damage function				
Average temperature	17.15	3.83	19.18	3.16
Average precipitation	2.42	0.81	2.89	0.03
Temperature SD	1.36	0.32	1.52	0.32
Precipitation SD.	0.45	0.16	0.44	0.15
GDP p.c. (in US$)	9'249	12'846	22'538	14'229
Age ratio (n65+/n15-64)	18	2.41	15.87	1.94
Degree of urbanization	0.65	0.14	0.28	0.97
Population density (n/km^2)	115.30	87.86	154.75	108.76
Number of observations	235		35	

Notes: 27 countries over ten 5-year intervals

Table 2.4: Mean values by occurrence of heat waves

As explanatory variables we use the climate variables (average temperature and precipitation, temperature and precipitation variability in the 5-year intervals) and a linear time trend. Here, and in the following regressions, we adjust the standard errors for clustering at the country level because within-country observations are likely dependent.

Table 2.5 displays the estimated coefficients of four different specifications of the probit model. Column 1 shows the results for the climate variables excluding the linear time trend, column 2 adds the linear time trend, and columns 3 and 4 restrict the sample to the years 1985 to 2010.

	Sample 1960-2010		Sample 1985-2010	
	(1)	(2)	(3)	(4)
Average temperature	1.518***	1.222***	1.034***	1.209**
	(0.414)	(0.365)	(0.283)	(0.369)
Average temperature squared	−0.0370***	−0.0336***	−0.0267***	−0.0333**
	(0.0106)	(0.0102)	(0.00757)	(0.0103)
Average precipitation	1.474**	0.772**	1.107**	0.772*
	(0.461)	(0.249)	(0.339)	(0.361)
Temperature SD	0.518	2.807***	1.597*	2.820***
	(0.497)	(0.837)	(0.633)	(0.841)
Precipitation SD	−0.398	−0.941	0.149	−0.885
	(0.952)	(1.329)	(1.117)	(1.337)
Time trend (year)		0.153***		0.150***
		(0.0218)		(0.0235)
Constant	−20.57***	−323.1***	−15.69***	−316.9***
	(5.124)	(46.15)	(3.438)	(49.51)
Number of observations	270	270	135	135

Notes: The table shows the estimated coefficients of a probit model for the occurrence of a heat wave in a 5-year interval using country-level data for 27 European countries over the time frame stated at the top of the table. Standard errors in parentheses adjusted for serial correlation within countries. Significance levels: $^{*}p < 0.05$,$^{**}p < 0.01$,$^{***}p < 0.001$

Table 2.5: Probit results for occurrence of heat waves

The latter restriction is imposed to evaluate the sensitivity of results to the choice of study period as Europe was affected by heat waves mainly from the mid 1980s onwards. The results of the probit model indicate that average temperature, average precipitation, and temperature variability are strongly associated with the occurrence of heat waves, which is consistent with earlier studies (e.g., Schär et al. (2004). The results also indicate that the inclusion of a linear trend has a significant impact on model predictions and gives more stable results irrespective of the chosen time frame. The estimated coefficients are interpreted best by translating them into average probability effects for the occurrence of a heat wave. For precipitation we find that an increase by 0.5

mm/day on average is associated with an increase in the probability of a heat wave by approximately 3.5 percentage points. For the average summer temperature, we find a significant inverse u-shaped relationship, which translates into predicted probabilities as shown in Figure 2.2. Low mean summer temperatures (less than 13 degrees Celsius) are associated with a probability of a heat wave close to zero, which goes up to approximately 30% for mean temperatures around 19 degrees Celsius, and then levels off. The results shown in Figure 2.2 are average predictions, i.e., predicted probabilities are averaged over the particular climate conditions in a given country and year.

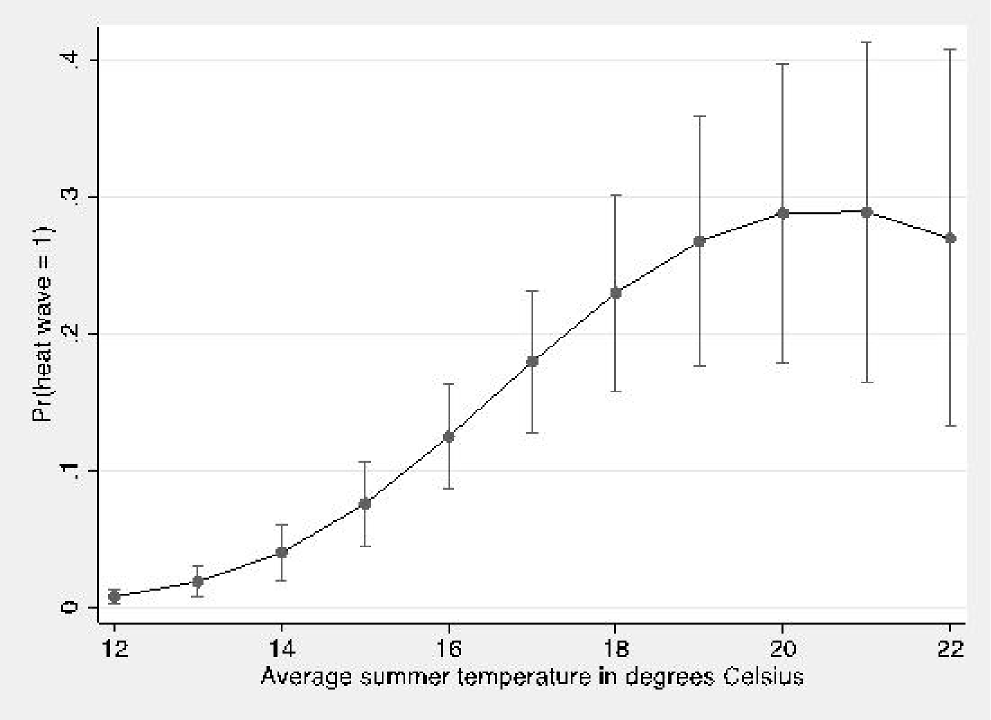

Figure 2.2: Predicted probabilities for occurrence of heat wave by average temperature

Notes: Predictions are calculated based on estimation results shown in Table 2.5 (column 1). 95%-confidence interval with standard errors adjusted for clustering at the country level.

An increase in the standard deviation of summer temperatures by 0.3 (which is approximately one standard deviation in the summer temperature variability) is associated with a 7.6 percentage points higher probability of observing a heat wave. We do not find evidence for a significant association of the probability of a heat wave with the precipitation variability. We extended the probit regressions of Table 2.5 by the socio-economic characteristics listed in Section 2.4.2 to test whether these variables are associated with the occurrence of heat waves (results available upon request). None of the variables had a robust and statistically significant relationship with the occurrence of heat waves in our two longitudinal samples (1960-2009 and 1985-2009), indicating that some of the previously found relationships might be due to neglected country heterogeneity and/or underlying time trends (Mendelsohn and Saher, 2011). We also tested for a quadratic relationship in the precipitation variable, but this turned out statistically insignificant (p-value of the squared term 0.832).

2.6.3 Conditional Damage Function

In a third step, we estimate the conditional non-market damage function using the exponential hurdle model structure. We present the results separately for the number of fatalities (Table 2.6) and for the monetary assessment of non-market damages (Table 2.7).

Number of fatalities: We find a strong and significant relationship between the age ratio and the population density and the number of fatalities (Table 2.6). For the population density in the full model (column 5), an increase in the number of inhabitants by 10 per squared kilometre (which is about one tenth of a standard deviation) is associated with an increase in the number of fatalities by 7.8%. For the age ratio, we find an inverse u-shaped relationship and thus the association depends on the level of the age ratio. If evaluated at 15% (about the mean value in the heat wave sample), then an increase by one percentage point is associated with an increase in the number of fatalities by approximately 28%. We do not find significant associations with the degree of urbanisation and GDP per capita. It turns out that the latter two included alone in a model for the number of fatalities are significantly and positively associated, but the associations are driven by related demographic characteristics of the country, which would be consistent with the positive impact of GDP found in Mendelsohn and Saher (2011).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Average temperature	0.0474	−0.0995	1.118	1.232	1.352	0.0248	
	(1.004)	(1.105)	(0.910)	(0.935)	(0.939)	(0.1234)	
Average temperature squared	−0.0058	0.0011	−0.0309	−0.0344	−0.0364		
	(0.0271)	(0.0301)	(0.0237)	(0.0250)	(0.0245)		
Average precipitation						4.925	
						(16.304)	
Temperature SD							−0.214
							(3.047)
Precipitation SD							1.381
							(0.918)
Population density (n/km2)		0.00756*	0.00773***	0.00813**	0.00749***	0.00730**	0.00896**
		(0.00297)	(0.00219)	(0.00280)	(0.00222)	(0.00232)	(0.00269)
Age ratio (n65+/n15-64)			8.145***	8.427***	8.153**	7.078**	6.993**
			(2.268)	(2.486)	(2.521)	(2.575)	(2.381)
Age ratio squared			−0.253***	−0.261***	−0.255**	−0.224**	−0.224**
			(0.0729)	(0.0788)	(0.0788)	(0.0861)	(0.0741)
Degree of urbanization				−1.128	−1.462	0.0704	−1.151
				(3.233)	(3.426)	(3.104)	(3.601)
Log GDP p.c. (in US$)					0.377	0.394	0.389
					(0.589)	(0.631)	(0.656)
Time trend (year)	−0.0848	−0.111	−0.133	−0.138	−0.144	−0.132	−0.111
	(0.103)	(0.102)	(0.0999)	(0.106)	(0.114)	(0.116)	(0.100)

Notes: 270 Observations, The table shows the estimated coefficients of an exponential hurdle model. The estimates can be interpreted as semi-elasticities, e.g., the coefficient 0.00749 for the population density in model (5) implies that an increase by 10 inhabitants per squared kilometre is associated with a 7.78% higher number of fatalities when a heat wave occurs (calculated as $(exp(0.00749 * 10) - 1) * 100\% = 7.78\%$). Standard errors in parentheses adjusted for serial correlation within countries. Significance levels: $^{*}p < 0.05, ^{**} p < 0.01, ^{***} p < 0.001$

Table 2.6: Exponential hurdle regression results for number of fatalities

The baseline model (column 1) suggests an inverse u-shaped relationship between average summer temperatures and the number of heat wave caused fatalities, with a turning point at a temperature lower than the observed minimum, which indicates a downward sloping function. However, the relationship is very sensitive to the inclusion of socio-economic and demographic information and it turns positive on average in the model with all characteristics included (columns 5 and 6). The point estimates suggest that with each additional degree in average summer temperatures the number of fatalities increases by approximately 2.5%. Given that the within country standard deviation in average summer temperatures is only about 0.3, this relationship is relatively weak and statistically insignificant.

The results for the other climate variables suggest positive relationships between the number of heat wave caused fatalities and average precipitation and temperature variability, and a negative relationship with precipitation variability. However, in all cases the relationships are weak and statistically insignificant (p-values larger than 0.2). This result indicates that the climate variables relate to the number of fatalities mainly through the occurrence equation, but not through the conditional-on-positives part of the damage function.

Non-market damages: Overall, we confirm the results from the number of fatalities for the amount of non-market damages (Table 2.7). The associations between the population density and the age ratio with non-market damages are slightly stronger (+9.3% for an increase in the number of inhabitants by 10, and +39.9% for a one percentage point increase in the age ratio from 15% to 16%). The association between GDP and non-market damages is stronger compared to the equation for the number of fatalities, with an increase in GDP by 1% associated with an increase by 0.9% in non-market damages (compared to 0.3% for fatalities), but the association is not statistically significant (p-value = 0.17). As for the number of fatalities, we do not find evidence that the climate variables are significantly related to non-market damages in the conditional-on-positives part (p-values all larger than 0.4).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Average temperature	−1.115	−1.332	0.317	0.241	0.538	−0.208	
	(1.289)	(1.404)	(1.036)	(1.003)	(1.047)	(0.158)	
Average temperature squared	0.0179	0.0282	−0.0164	−0.0141	−0.0192		
	(0.0353)	(0.0389)	(0.0276)	(0.0272)	(0.0275)		
Average precipitation						3.499	
						(21.97)	
Temperature SD							1.077
							(1.217)
Precipitation SD							1.200
							(3.413)
Population density (n/km2)		0.0112^{**}	0.0107^{***}	0.0105^{**}	0.00888^{***}	0.00915^{**}	0.0100^{**}
		(0.00427)	(0.00247)	(0.00343)	(0.00239)	(0.00337)	(0.00341)
Age ratio (n65+/n15-64)			9.137^{**}	8.949^{**}	8.275^{**}	8.155^{*}	7.076^{**}
			(3.111)	(2.922)	(2.847)	(3.424)	(2.979)
Age ratio squared			-0.277^{**}	-0.271^{**}	-0.256^{**}	-0.254^{*}	-0.225^{**}
			(0.103)	(0.0974)	(0.0938)	(0.112)	(0.096)
Degree of urbanization				0.750	−0.0721	0.3001	0.3788
				(3.813)	(3.640)	(3.298)	(3.913)
Log GDP p.c. (in US$)					0.927	0.910	1.124
					(0.687)	(0.693)	(0.780)
Time trend (year)	−0.0682	−0.107	−0.174	−0.171	−0.187	−0.179	−0.165
	(0.110)	(0.103)	(0.0971)	(0.105)	(0.115)	(0.110)	(0.107)

Notes: 270 Observations, The table shows the estimated coefficients of the exponential hurdle model. The results can be interpreted as semi-elasticities, e.g., the coefficient 0.00888 for the population density in model (5) implies that an increase by 10 inhabitants per squared kilometre is associated with a 9.29% higher number of fatalities when a heat wave occurs (calculated as $(\exp(0.00888 * 10) - 1) * 100\% = 9.29\%$). Standard errors adjusted for clustering at the country level in parentheses. Significance levels: ${}^{*}p < 0.05, {}^{**}p < 0.01, {}^{***}p < 0.001$

Table 2.7: Exponential hurdle regression results for non-market damages

2.6.4 Discussion of Results

We can draw three main conclusions from our results. First, we support the findings of Schär et al. (2004) who argue that climate variability, and temperature variability in particular, has a stronger impact on the occurrence of heat waves than the average summer temperatures and average precipitation in a country.

Second, European policy-makers continue to debate about the economic impacts of demographic change. Our results indicate that the predicted growth in the age ratio (the share of citizens aged 65 and older to citizens aged 15-65) and rise in the population density in Europe will likely result in an increase in heat wave induced fatalities and non-market damages if no adaptation measures are initialized. Although insignificant once the population density and age ratio are controlled for, the impact of the degree of urbanisation on the amount of non-market damages from heat waves signals a potential starting point for such measures. To this end, several studies support the idea that urban planning, e.g., planting of cities, planning of wind aisles and corridors and adapted building constructions can reduce the urban heat island effect (e.g., Golden (2004); Kleerekoper et al. (2012)).

The third conclusion relates to our statistical methodology and the estimation of a non-market damage function for heat waves. General problems to consider are the special characteristics of the dependent variable(s) and the low number of observations that hamper the econometric derivation of a damage function. We tackle these problems in two ways while keeping the ideas of earlier studies (Mendelsohn and Saher (2011); Nordhaus (2010)). First, we aggregate climate and mortality data and the socio-economic and demographic characteristics by country over ten 5-year intervals from 1960 to 2009. The resulting longitudinal data offer more variation and a bigger sample size while retaining the ideas of the impact of climate change. Second, earlier studies have not attempted to disentangle the damage function into two parts, one explaining the occurrence of heat waves and the other explaining the conditional non-market damages (conditional on positive damages). The exponential hurdle model suggested here thus provides a refined set of estimates on the determinants of heat wave caused fatalities. In particular, our results indicate an asymmetry with the climate variables more relevant at the extensive margin (for the occurrence of heat waves), and the socio-demographic variables more relevant at the intensive margin (positive non-market damages).

We also estimated the non-market damage function with a random effects Poisson model, which does not make the distinction between zero and non-zero damages. This model gave results very similar to Mendelsohn and Saher (2011). However, we deem it essential for a better understanding of the underlying mechanisms to use a more flexible statistical model as it is not clear a priori whether the different determinants of heat wave caused fatalities, and non-market damages from extreme weather events more generally, are equally relevant in all parts of the outcome distribution. We selected a parametric exponential hurdle model due to the (still) relatively small sample size, which makes it difficult to fit semi- or non-parametric alternatives (like quantile or distributional regressions).

2.7 Conclusion

Damage functions provide an important tool for policy-makers i) to assess the impacts of extreme weather events, and ii) to evaluate the expected benefits of adaptation measures to climate change. In this paper, we estimate a function for non-market damages from heat waves in Europe. Non-market damages are calculated from heat wave caused fatalities using the value of statistical life approach, and we suggest a novel econometric approach to the derivation of the non-market damage function based on an exponential hurdle model.

In a related paper, Mendelsohn and Saher (2011) employ a worldwide data set to estimate a damage function for a variety of extreme weather events. Compared to their study, we confine ourselves to data from 27 European countries and non-market damages from heat waves. This restriction is imposed for several reasons. First, for the use of longitudinal data, we need reliable information over a long time frame (from 1960 to 2009), which might be less critical in developed countries with their longer history of data reporting in the areas relevant to our study (climate and mortality data, socio-economic and demographic characteristics). Second, we focus in our analysis on heat wave caused fatalities and non-market damages, which is a topic of major importance for the European countries given the recent projections of the IPCC (IPCC, 2013, 2014). Third, non-market damages are derived from the fatalities using the value of statistical life approach, where again more reliable information is available for the developed countries, and Europe in particular. On the downside, our results need to be interpreted as evidence for the narrower set of European countries.

To conclude, our study provides a first attempt to estimate a non-market damage function for heat waves in Europe using a monetary assessment of heat wave caused fatalities. This and the estimation of an exponential hurdle model provide new evidence regarding the economic impacts of climate change. In particular, we find that the population density and the age ratio are positively associated with non-market damages, whereas the climate variables, GDP and the degree of urbanisation are insignificant in the conditional damage function. We see our paper as complementary to Mendelsohn and Saher (2011) and Nordhaus (2010). We add to the literature by suggesting a statistical approach that helps to better understand the underlying mechanisms of the impact of climate variables and socio-economic characteristics of a country on (non-) market damages from extreme weather events. We also support the idea of this literature that any assumption on functional form and/or model parameter of a theoretical damage function should be rigorously tested with data that stem from different contexts (extreme weather events) and different regions in the world.

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Chapter 3

Do We Need to Adapt to Heat Waves? A General Equilibrium Analysis for Switzerland

3.1 Introduction

According to the fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the atmospheric carbon concentration is expected to rise further during the 21st century. This will not only lead to an increase of mean temperature and changes in the patterns of precipitation, but it also implies that the frequency, the intensity and the duration of extreme events such as heat waves will increase significantly (e.g. IPCC (2014)). Heat waves are usually understood as "period(s) of abnormally and uncomfortably hot weather". This is not a very precise definition. However, even today, an exact and unique definition is missing, as is shown in the IPCC reports, where heat waves are identified as multi-day heat extremes relative to daily maximum temperatures above a high (usually 90th) percentile relative to a late-20th century reference period (for further clarification, see Fischer and Schär (2010); Perkins et al. (2012)).

Climate models are very good at reproducing heat waves that have been observed in the past. This indicates high reliability of model-based simulations, which project that the frequency, the duration, the intensity and the spatial extension of heat waves will significantly change in the near future. Europe will especially be affected by rising summer temperatures. As model simulations forecast, in Europe high-percentile summer temperatures will rise faster than mean temperatures, and summer warming will be more intense in Mediterranean regions as well as Central and Northern Europe. Consequently, heat stress, which is defined as the combined effect of high temperature and humidity, is expected to increase in Europe. This will generate additional discomfort; morbidity and mortality (IPCC, 2014).

Overall, these projections are not surprising. In the last twenty years, Europe has been the most heat wave affected region in the world. No other natural catastrophe in the modern age has caused as many excess deaths in Europe as heat waves. Since the early 1960's more than 80% of all extreme events excess deaths in Europe have been the result of heat waves. The 2003 heat wave in Switzerland caused an estimated number of 975 fatalities and market damage [1] of about US$ 280 million (EM-DAT, 2016; Grizea et al., 2005). This is one of the reasons that heat stress (triggered by climate change, which is expected to increase significantly over the coming decades) has received public attention.

Mitigation of greenhouse gases is the most important policy response to the threat of global warming. However, due to the inertia of the climate system, climate change is unavoidable to some degree, even if greenhouse gas emissions are reduced radically. This, and the lack of progress in the negotiations of a successor of the Kyoto Protocol, has turned attention towards measures which can be implemented on a national or regional scale with sufficient speed and scope, and which allow for moderating the negative effects of climate change as well as for reducing the climate vulnerability of communities and regions. Indeed, optimal climate change strategies require a combination of both mitigation and adaptation strategies (Buob and Stephan, 2011). Without investing in appropriate adaptation measures, damage caused by heat waves will significantly increase.

For adapting efficiently, one has to strike a balance between costs and benefits.

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[1] Market damage are damage, which can directly be expressed in monetary units. For example, in case of agriculture harvesting losses can directly be evaluated at market prices. In contrast, non-market damage are damage, which cannot be directly expressed in units of a national accounting system. Typical examples are species losses or health effects.

This means benefits of adaptation, which are measured in terms of damage prevented, have to match the costs of adaptation measures (Mendelsohn, 2000). While costs are relatively well known, there is a lack of information about the benefits. The majority of heat wave impacts are non-market damage. For example, the decrease in quality of life caused by heat stress or the increase in heat induced morbidity and mortality. Because these damage are difficult to express in monetary units, the existing literature typically reports only the numbers of fatalities or rates of additional (excess) mortality and morbidity (Mendelsohn and Saher, 2011; Grizea et al., 2005). However, heat waves do not only cause excess death. Heat waves can affect the labor supply and might reduce the demand for consumption and leisure. In other words, heat waves affect the societies' productivity and influence the labor-leisure decision, hence affecting both the allocation of resources and the distribution of income. As such, a sole focus on excess death implies that general equilibrium effects of heat waves are systematically neglected, however, important in designing efficient adaptation strategies.

Taking general equilibrium effects of heat waves into account is furthermore important for two reasons. First, at least to the extent that adaptation has the property of a local public good, there might be spill-over effects and those who benefit from adaptation must not be identical to those who bear the costs of adaptation.

Second, people are not uniformly hit by heat waves. As the impact literature tells (Haines et al., 2006; Johnson et al., 2005), heat wave impacts depend on at least three factors: (1) the age, (2) the income, and (3) degree of urbanization of the residence region of affected individuals. Very young and very old people, as well as those with preexisting diseases, are suffering most during heat waves. Poor people have less means for self-protection than the wealthy. The so-called heat-island effect, which characterizes regions with a high degree of urbanization, implies that townspeople are more affected by heat waves than people, who live in rural areas. Because of their infrastructure, architecture and very small green areas, cities are heating up much faster and cooling down much slower. Therefore, the number of excess deaths from heat waves is significantly higher in cities than in rural areas (Baccini et al., 2008).

This paper deals with two principal research questions: (1) What is the magnitude of general equilibrium impacts of a 2003-like heat wave on the Swiss economy? (2) If adaptation to heat waves has the characteristic of a public good, what are the diverse economic effects of different policies for financially funding optimal adaptation to heat waves? Analyzing general equilibrium effects of heat waves, in particular, requires analyzing the secondary effects that are initially caused by direct impacts of heat waves. The direct impact is the increase in excess mortality, which then results in changes in the economic system. Parameter, which allow determining these direct impacts, are drawn from an analysis of Grizea et al. (2005) on heat wave excess mortality[2] ($HWEM$) during the 2003 heat wave in Switzerland and adjusted to our needs. Using these data, we are able to determine both the direct and indirect effects a 2003 like heat wave event would have if it shocks the Swiss economy in 2020.[3]

Note that we are not aiming for an integrated assessment analysis of heat waves, which takes all complex interactions between economics activities, global climate change and heat waves systematically into account. Instead, we are running a policy evaluation analysis, where heat waves are taken as given and where the effect of policy driven adaptation to heat waves in Switzerland is analyzed. Some adaptation has the features of a private good and is in the self-interest of economic agents, hence is automatically done. Some adaptation, however, has the properties of a local public good and requires governmental intervention. Typical examples are the increase of green areas in cities, governmental campaigns to increase the awareness for the risk of morbidity and mortality or the extension of resistance of public infrastructure like schools, to heat waves. Therefore, an important second aim of this analysis is to compare the economic effects of different policies for financially funding adaptation.

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[2] "[Heat wave excess mortality is the] mortality above what would be expected based on the non-crisis mortality rate in the population of interest. Excess mortality is thus mortality that is attributable to the crisis conditions. It can be expressed as a rate (the difference between observed and non-crisis mortality rates) [...]"(Checchi and Roberts, 2005)

[3] This procedure is motivated by the findings of Beniston (2004) who argues that it is highly reasonable to assume that because of climate change, future summers will show 2003 like heat wave events.

To that end, a computable general equilibrium model is developed which allows us to distinguish between different economic agents according to the three afore mentioned characteristics: age, income, urban form. Some might argue that the most natural way of introducing a somewhat realistic age structure into general economic analysis would be to use some variant of the Auerbach-Kotlikoff overlapping generations (OLG) model. However, any variant of the standard Auerbach-Kotlikoff model requires assuming that agents are clairvoyant (Rasmussen and Rutherford, 2004). This assumption contradicts the analysis of low probability, high impact events like heat waves. To avoid this problem and to keep the model deliberately simple, a static Computable General Equilibrium (CGE) model is developed that can be understood as a zoom into one single period of a standard Auerbach-Kotlikoff model.

Overall, our results show that (1) heat waves might cause a high number of fatalities combined with negative welfare and distribution effect, (2) governmental provision of an optimal adaptation stock can reduce heat wave excess mortality at the expense of a relatively low labor (0.4%), capital (0.5%) or consumption (0.2%) tax.

The remainder of the paper is organized as follows: Section 3.2 presents the model framework upon which the simulations are based. Section 3.3 discusses the data and the calibration process. Section 3.4 discusses the results of a comparative static analysis as well as the sensitivity analysis. Section 3.5 concludes.

3.2 The Modeling Approach

The following analysis is based on a static Computable General Equilibrium (CGE) model.It combines a stylized description of production, governmental activities and labor-leisure choice with a detailed characterization of heat wave vulnerability of households, where direct impacts of heat waves are modeled in terms of excess mortality. As mentioned above, this heat wave induced effect depends on at least two factors: (1) the age structure of a society and (2) the degree of urbanization. Additionally, the households' labor-leisure decision is strongly influenced by its income. Therefore, the demand side of the economy is disaggregated into 14 different age-cohorts (generations), where each generation is further split into sub-cohorts according to income and degree of urbanization at the place of residence. In other words, any household is a member of a sub-cohort $\{a, h, t\}$, where a denotes age, h income and t the urban form, which could be either rural (r) , suburban (s) or urban (u).

Impacts of heat waves can be moderated through investing into adaptation. Some adaptation measures are private and investing in these measures is the self-interest of agents. However, many measures for reducing excess mortality caused by heat waves, have the feature of a (local) public good, like urban planning measures or governmental campaigns to increase the awareness for the risk of morbidity and mortality. In such cases providing optimal adaptation requires policy interventions and is in the center of interest of this analysis. Note that there are three homogenous commodities only, which are traded on perfect markets: labor, tangible capital and a composite commodity, which is produced and can be used for consumption by private households and/or for investing into adaptation.

3.2.1 Households

Let $N_{a,h,t}$ be the size of cohort $\{a, h, t\}$ relative to the total of all cohorts. Households of a particular cohort $\{a, h, t\}$ are viewed as identical and each cohort $\{a, h, t\}$ behaves as if it were represented by a single agent, who maximizes the cohort's utility.

$$N_{a,h,t}u_{a,h,t}(c_{a,h,t}, \ell_{a,h,t}) = N_{a,h,t}\left[\varphi_h(c_{a,h,t})^{\sigma_h^{c\ell}} + (1-\varphi_h)(\ell_{a,h,t})^{\sigma_h^{c\ell}}\right]^{\frac{1}{\sigma_h^{c\ell}}} \tag{3.1}$$

subject to the budget constraint of cohort $\{a, h, t\}$ (see 3.2 below). $u_{a,h,t}$ is the utility function of the representative agent of cohort $\{a, h, t\}$ and depends on per capita consumption $c_{a,h,t}$ of produced commodities as well as per capita leisure $\ell_{a,h,t}$. $\sigma_h^c l$ defines the elasticity of substitution between consumption and leisure, φ_h is the consumption share parameter. We assume that both, φ_h and σ_h^{cl} only depend on the income of the cohort. The reasoning behind this assumption is: (1) there is no evidence that the urban form has an impact on either parameter,

(2) for Switzerland, or at least Europe, no empirical data on the impact of age exist.

Any member of cohort $\{a, h, t\}$ can earn income from two sources: (1) income from selling the individual capital endowment $k_{a,h,t}$, and (2) labor income. The latter is generated through selling the share $l_{a,h,t} = \omega_{a,h,t} - \ell_{a,h,t}$ of the individual's total labor endowment $\omega_{a,t,h}$, which is measured in efficiency units (see Section 3.3 below) minus leisure $\ell_{a,h,t}$.

As mentioned above, heat wave adaption can have the properties of a public good. For financing the investment into adaptation measures, the government can, among other things, levy taxes either on capital income, labor income or consumption expenditure. Taking this into account, the budget constraint of cohort $\{a, h, t\}$ is given by

$$N_{a,h,t} p^C (1 + \tau^c) c_{a,h,t} \leq N_{a,h,t} \left[p^L (1 - \tau^l)(l_{a,h,t}) + p^K (1 - \tau^k) k_{a,h,t} \right]. \tag{3.2}$$

p^x, $x \in \{c, l, k\}$ denotes the price of the consumption good, the wage rate and the capital interest rate, respectively. τ^z, $z \in \{c, l, k\}$ identifies the tax on per capita consumption c, labor income l and capital income k, respectively.

3.2.2 Production

To keep the model as simple as possible, the supply side is highly aggregated. Suppose there is a single production sector, which produces a single, composite output. Inputs into production are capital and labor, which are viewed as homogenous across all cohorts. Suppose further that there is perfect competition on all markets and that gross production Y is characterized by constant elasticity of substitution (CES), i.e.

$$Y = \left[\beta^Y L^\varepsilon + (1 - \beta^Y) K^\varepsilon \right]^{\frac{1}{\varepsilon}}. \tag{3.3}$$

$K = \sum_{a,h,t} N_{a,h,t} k_{a,h,t}$ and $L = \sum_{a,h,t} N_{a,h,t} \left(\omega_{a,h,t} - \ell_{a,h,t} \right)$ denote the aggregated physical capital and labor inputs, respectively. $1/(1 - \varepsilon)$ is the elasticity of substitution between capital and labor and β^Y is a share parameter of inputs.

3.2.3 Damage and Adaptation

Damage

As was mentioned above, heat waves affect economies in different ways. There are direct impacts and there are general equilibrium effects, which result from the economies' response to direct impacts. Typical examples of direct impacts are damage to the infrastructure, losses in agriculture production due to heat stress or shortage in water supply during periods of heat and drought. These will be called market damage, since they can directly be expressed in monetary units. On the other hand, there are non-market damage such as heat wave induced fatalities, since no prices exist for such kinds of effects.

Excess fatalities are by far the most severe direct impacts of heat waves. In Europe, between 1960 and 2013, 80% of all fatalities that were caused by extreme weather events are caused by heat waves, while only 6% of all market damage that are caused by extreme weather events resulted from them (EM-DAT, 2016). This motivates us to focus the analysis on excess mortality. Therefore, let $\Pi_{a,h,t}$ denote the heat-wave-induced excess mortality rate, which is taken as exogenously given. I.e., $\Pi_{a,h,t}$ represents the percentage of excess mortality in cohort $\{a, h, t\}$ due to heat waves.

Indirect impacts, which are called general equilibrium effects in the following, result from the economies' response to heat-wave-induced excess mortality. These general equilibrium effects can be summarized as follows: The consumption of goods and leisure, as well as the factor supply of capital and labor of agents, who fall victim to a heat wave, is reduced to zero. However, the diverse nature of factor supplies causes an important difference in the impact on production. While the labor supply of heat wave fatalities vanishes entirely, the aggregat capital stock is fixed in the short run. Resulting changes in factor and output prices also induce changes in the factor supply and consumption, as well as leisure demand of surviving cohorts.

Adaptation

Impacts of heat waves can be moderated through investing into adaptation. Typical examples of adaptation to heat waves are urban planning, which aims at reducing the heat island effect in urban and suburban areas through increasing the share of green areas and maintaining wind aisles; governmental campaigns to increase the awareness for the risk of morbidity and mortality through heat waves, and investment into early warning systems. This shows that adaptation covers a wide range of heterogeneous measures, which, according to Smit et al. (1999), can be classified according to attributes such as timing, temporal and spatial scope. What the three aforementioned examples have in common is that they fall, with respect to timing, into the category of proactive or anticipatory adaptation because they require investing into protection infrastructure and stocks. On the other hand, there are reactive measures through which climate impacts can be moderated almost instantly, like for example to increase nursing staff in hospital and residential care homes for elderly; the provision of water and shaded areas at public places; securing the energy supply of cooling dependent power stations for public and private cooling and transport facilities. (Bosello et al., 2009; De Bruin et al., 2009). Because of the static character of our analysis, we limit ourselves to reactive adaptation. What these measures have in common is that they have the properties of a local public good, so their spatial scope is regional not national.

Let the effect which investing into adaptation has on heat wave excess mortality, be expressed by the adaptation function $\Psi(AS)$, where, similar to Schenker and Stephan (2012), AS denotes the expenditure for adaptation measures. $\Psi(AS)$ determines by how much the excess mortality can be reduced depending on the available adaptation expenditure. The direct impact of heat waves on mortality is given by $\Pi_{a,t}$. This parameter measures the number of additional, heat-wave-caused fatalities in percentage. However, the heat wave induced excess mortality can be moderated by adaptation. Hence $M_{a,h,t}$, which represents the relative size of cohort $\{a, h, t\}$ that survives the heat waves, is given by

$$M_{a,h,t} = N_{a,h,t} \left[1 - \Pi_{a,h,t}\Psi(AS)\right]. \tag{3.4}$$

Condition 3.4 implies that the higher the excess mortality caused by a heat wave, and the lower the effect of adaptation measures in preventing fatalities, the lower is the fraction of a sub-cohort that survives a heat wave. Furthermore, let the effect investing into adaptation has on heat wave excess mortality be characterized by decreasing marginal benefits of adaptation expenditure AS, i.e.,

$$\Psi(AS) = e^{-\psi AS}, \tag{3.5}$$

where ψ is the efficiency parameter of adaptation, i.e., the higher ψ, the more effective are the adaptation expenditures.

Finally, let us assume that the government aims for a first best solution in the sense that the optimal level of adaptation is derived from maximizing social welfare. Social welfare is defined as the sum over cohorts of individual utility weighted by the cohorts share in total population, i.e.

$$W(AS, u_{a,h,t}) = \sum_{a,h,t} N_{a,h,t} \left[1 - \Pi_{a,h,t}\Psi(AS)\right] u_{a,h,t} \tag{3.6}$$

In order to finance the optimal level of adaptation, the government can, as indicated in condition 3.2, levy taxes on consumption expenditure, labor or capital income of households. Another possible way to finance adaptation is to levy an inheritance tax τ^{Inh} on capital that is released by heat wave victims and bequeathed to heat wave survivors. In this case the inheritance tax revenue R used to finance the adaption stock AS is

$$R = \tau^{Inh} \sum_{a,h,t} N_{a,h,t}\Pi_{a,h,t}\Psi(AS)k_{a,h,t} \tag{3.7}$$

Because we assume the government's budget to be balanced, the tax rates to finance the adaptation expenditure are determined endogenously.

3.3 Data and Calibration

3.3.1 Social Accounting Matrix and Key Parameter of the Model

For analyzing the effects of a heat wave on the Swiss economy numerically, we specify several numerical inputs. This includes a Social Accounting Matrix (SAM) on the one hand and parameter of the theoretical model on the other. Through merging the 2008 Swiss Input-Output Table (IOT) (BFS, 2009) with an aggregation of the Swiss Household Budget Survey (HABE) for the time span of 2006 to 2008 (BFS, 2016) we created a stylized Swiss Social Accounting Matrix (SAM) in four steps: First, we adjusted the existing symmetric IOT such that it fits the structure of the model economy with one macro production sector and a highly disaggregated household sector (see Section 3.2). Second, we use the HABE data to compute for every cohort per capita labor as well as per capita capital income. Third, we use data on the average net income on community level (BFS, 2012) to determine the number of individuals per cohort $\{a, h, t\}$. Fourth and finally, we use the results of steps two and three to compute the shares of any cohort $\{a, h, t\}$ in the total of both labor and capital income. The resulting SAM is presented in appendix 3.A.

Among the model parameter, which have to be specified numerically, the most important ones are: (1) structure of the Swiss population with respect to age, income and regions, (2) labor endowment of cohorts and (3) direct impacts (damage) of a 2003-like heat wave.

Structure of the Swiss population by age and region

2010 data on the population shares $N_{a,h,t}$ are provided by the Stat-tab database of the regional population distribution in Switzerland (BFS, 2010). In our view, these data give a good approximation of the population structure in 2008. By neglecting differences in the distribution of income, Figure 3.1 represents the relative size of cohorts depending on the age group $\{20-24, 25-29, ..., 85-90\}$ and the location of residence, which can be urban $\{u\}$, suburban $\{s\}$ or rural $\{r\}$.

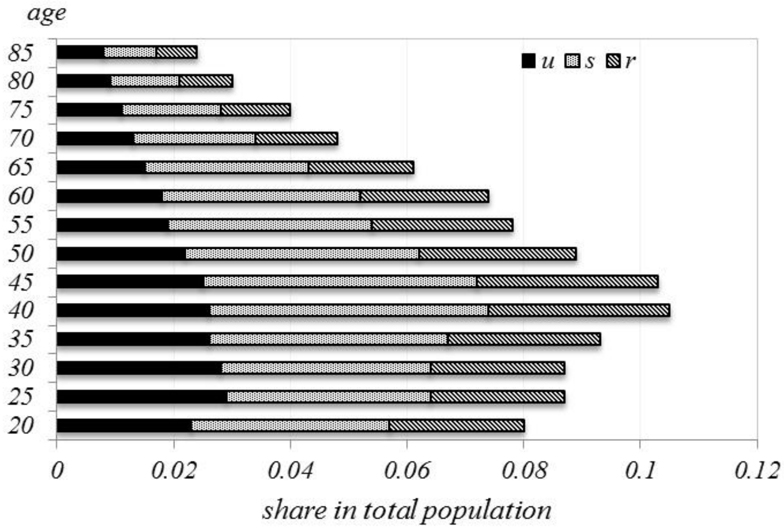


Figure 3.1: 2010 Swiss population shares by age and region

Source: BFS (2015a)

Labor endowment by age, region and income group

As was mentioned above, the time endowment $\omega_{a,h,t}$ of cohort $\{a,h,t\}$ is measured in efficiency units and hence depends on the productivity of labor. I.e., if the labor endowment is measured in efficiency units, any increase of productivity has the same effects as if more labor were effectively available. Labor productivity in turn depends on several factors of which age and income are the most important. A standard approach in the literature (see for example Rasmussen and Rutherford (2004); Rausch (2009)) is to assume that the labor productivity is hump shaped, such that productivity is positively correlated to income but negatively to age. Note that the urban form has by assumption no impact on labor productivity. Equation 3.8 reflects these assumptions.

$$\omega_{a,h} = \zeta_h^{scale} \frac{e^{4.47+\zeta_h^{age} \cdot a - \zeta_h^{age2}} \cdot a^2}{e^{4.47}} \tag{3.8}$$

If measured in efficiency units, labor supply will decrease with age and increase with income, if the parameter ζ_h^{scale}, ζ_h^{age} and ζ_h^{age2} are chosen as in Table 3.1. Thus, households retire if their labor productivity is low enough that the value of leisure is higher than the income from labor. Additionally, Table 3.1 shows the income dependent consumption share parameter φ_h and the elasticity of substitution between consumption and leisure σ_h^{cl}: The higher the household's income is, the higher is its elasticity of substitution between consumption and leisure and its consumption share in the utility function.

Income quantile	σ_h^{cl}	φ_h	ζ_h^{scale}	ζ_h^{age}	ζ_h^{age2}
1	1.05	0.575	0.80	0.0700	0.0028
2	1.10	0.625	0.85	0.0725	0.0026
3	1.15	0.650	0.90	0.0750	0.0024
4	1.20	0.650	0.95	0.0775	0.0022
5	1.25	0.675	1.00	0.0800	0.0020

Table 3.1: Parameter specification

Damage Parameter

Remember, we intend to analyze the general equilibrium effects that a 2003 like heat wave can have on the Swiss economy. Remember further that $\Pi_{a,h,t}$ is the heat-wave-induced excess mortality rate in case that a 2003 like heat wave hits Switzerland. Theoretically, the heat-wave-induced excess mortality rate depends on age, income and the residence region of the affected household (see Section 3.2). However, because we have no data that show how heat wave excess mortality depends on income in Switzerland (or even Europe), we are not differentiating the heat wave excess mortality rate with respect to income.

In the following, let $\Pi_{a,t}$ denote the modified heat wave mortality rate. For estimating $\Pi_{a,t}$ we use the results of Grizea et al. (2005). Based on daily data on all-cause mortality and a Poisson approach, Grizea et al. (2005) estimate the heat-wave-induced excess mortality in Switzerland for June to August 2003 depending on age and urban form independently of each other. However, as our modeling approach requires information on the expected excess mortality of a 2003-like heat wave event conditional on age and urban form, we have to merge the both separate results of Grizea et al. (2005). Therefore, we compiled optimistic and pessimistic values for the parameter $\Pi_{a,t}$ based on their estimates and 95% - confidence intervals.

The first part of Table 3.2 shows the results of Grizea et al. (2005). In the first column we find the regional and age subgroups, in the second column we find the number of estimated heat wave excess death. The third column reports the heat wave induced increase in mortality in percentage. Column four and five present the significance of these results with the 95% confidence interval and the p-values. The second part of Table 3.2 summarizes the results of our data derivation for $\Pi_{a,t}$ by age *and* region.

While the estimated excess deaths are, as expected, higher the older the age group, the regionally diversified results attract attention because the number of excess death is higher in suburban compared to urban regions. This result is because of the heat island effect, counterintuitive, but not discussed in Grizea et al. (2005). We assume that it is caused by the very high number of communities that has been classified by the BFS in 2000 as suburban regions although they have a strong urban character. The old definition principles have been based on the total number of inhabitants of a community and did not take the population density into account. This procedure has been improved by the BFS in 2014 (Forster, 2014) but our data base still depends on the old definition.

Results of Grizea et al. (2005)

	Estimated Excess Death	Variation	95%CI	p-value
Switzerland	975	6.9%	4.9 – 8.8	< 0.001
Region-Degree of urbanisation				
urban	387	7.9%	4.6 – 11.3	< 0.001
suburban	544	10.2%	6.9 – 13.6	< 0.001
rural	40	1.0%	−2.6 – 4.7	0.59
age groups				
20-39	13	3.8%	−7.7 – 16.8	0.53
40-59	70	5.0%	−1.1 – 11.5	0.10
60-79	161	3.3%	0.1 – 6.7	0.05
80+	659	8.8%	6.0 – 11.6	< 0.001

Results of Parameter $\Pi_{a,t}$ derived from results of Grizea et al. (2005) in %

Age	60			65			70			75			80			85		
region	u	s	r	u	s	r	u	s	r	u	s	r	u	s	r	u	s	r
Optimistic	3.3	6.7	0.1	3.3	6.7	1.0	4.6	6.7	3.3	6.7	6.7	4.7	7.9	10.2	6.0	11.6	11.8	8.8
Pessimistic	4.6	6.9	0.1	6.7	6.9	1.0	7.9	10.2	3.3	7.9	10.2	3.3	8.8	13.6	4.7	11.3	13.6	4.7

Table 3.2: Estimated excess death in Switzerland from June to August 2003.

Source: Grizea et al. (2005)

Inheritance

Although we cannot identify the offspring of heat wave victims directly, there are three possibilities to represent the redistribution of capital that is released by heat wave victims to inheritors. The first one is to distribute the released capital stock according to the initial distribution of capital in the generations who inherit capital. The second possibility is a per capita distribution that accounts for the size of the succeeding cohort. The third and favored option makes two assumptions to identify the cohorts who profit from inheritance. (1) Capital is bequeathed to age cohorts according to the probable age of the inheritor. (2) The initial distribution of capital, with respect to income and residence region, is kept. Implementing the first assumption, we use data on the age at parenthood in Switzerland in 2010 to derive the probable age of the offspring of heat wave victims. Table 3.3 shows the number and share of Swiss citizens who became parents at a certain age. As we know how many Swiss citizens became parents at a certain age, we also know what the age of the offspring of these citizens is when they die. For example, because 34% of all Swiss citizens became parents between 30 and 34, we assume that heat wave victims between 70 and 74 bequeath their capital endowment with a probability of 34% to cohorts of age $40 - 44$. Thus, the probability to start parenthood at a certain age determines the distribution of the inheritance to inheritor cohorts by age.

	20	25	30	35	40	45	50
Parenthood at age of	9644	32631	54474	41309	15565	3815	998
share	0.06	0.21	0.34	0.26	0.1	0.02	0.01

Source: BFS (2014b)

Table 3.3: Parenthood (Number of persons having their first child by age group) of mother and father in Switzerland in 2010

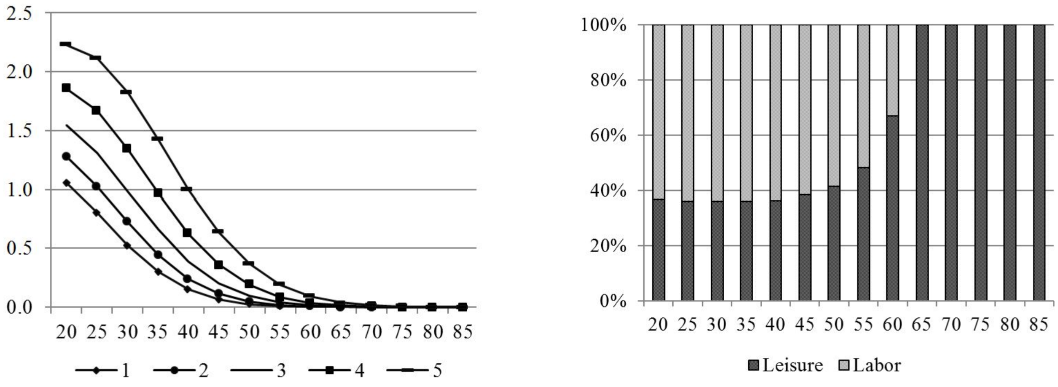
3.3.2 Calibration

Because of the stylized character of the model, we apply the naive calibration approach that is similar to the one proposed by Rasmussen and Rutherford (2004). This procedure has the advantage of being independent of the production side of the economy. Nevertheless, it ensures consistency between the households individual optimization problem and the aggregated economy (described by the social accounting matrix) by introducing an endogenous scaling factor for the total labor endowment, ω. In our approach, however, the retirement decision is endogenous and depends especially on parameter values for $\sigma_h^{c\ell}, \varphi_h, \zeta_h^{scale}, \zeta_h^{age}$ and ζ_h^{age2} (see Table 3.1). Therefore, the results of the calibration process, the cohort individual labor endowment in efficiency units as well as the labor-leisure decision of the households are the main results of the calibration process.

Calibration Results

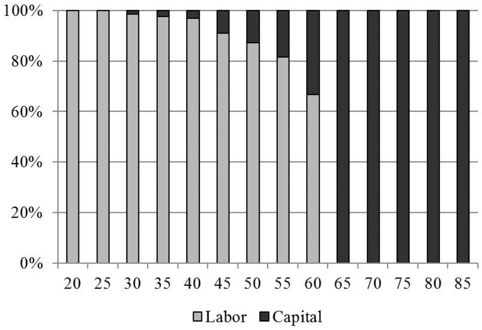
The solution to the cohorts optimization problem depends on the productivity profile, the consumption share, and the substitution elasticity. Because these parameter are differentiated by age and income, we also find cohort dependent solutions to the optimization problem. As Figure 3.2 shows, the households labor productivity decreases with age. Additionally, high income cohorts are characterized by higher labor productivity. These characteristics are independent of the territorial region of the household. With the applied parameterization, the predominant share of cohorts retires at the age of 65, which is the official Swiss retirement age.

Figure 3.2 presents the cohorts labor-leisure decision. Cohorts younger than 50 spend slightly more than 60% of their total time endowment for working. This value decreases to about 30% for cohorts who are 50 to 64. The majority of cohorts of age 65 are retired. The labor-leisure decision also mirrors the income structure of households of different age. Figure 3.2 presents the age dependent income composition of cohorts using the example of $\{h = 2, t = s\}$. Because of the high labor productivity at the age of $20 - 29$ (see Figure 3.2), households generate their income at this age exclusively from labor. Between the age of 30 and 64, the share of capital in total income increases to slightly more than 30%. Retired cohorts of age 65 and older generate their whole income from capital.



(a) Productivity profile $\omega_{a,h}$ by age and income

(b) Time allocation by age



(c) Income over life-cycle

Figure 3.2: Main calibration results

3.4 Results of Numerical Simulation

This paper analyzes direct and indirect, i.e. general equilibrium effects of heat waves, public adaptation to heat waves and different ways of financing adaptation measures.

3.4.1 Scenarios

As is shown in Table 3.4, we discern between two states of the world and two states of the Swiss economy. The two states of the world are: (A) There is no heat wave. (B) There is a 2003 like heat wave. The two states of the Swiss Economy are differentiated in category I: (1) there is no adaptation at all. (2) There is optimal adaption. In the benchmark case, there is no heat wave and the economy is not adapted to them (a combination of state (A) and (1)). As we are interested in the effect of adaptation if a heat wave hits the Swiss economy, state of the world B (there is a heat wave) is the focus of our analysis. In the first scenario, Non-Adapt, the Swiss economy is hit by a 2003 like heat wave but not adapted. In this scenario the reference case is the benchmark without heat wave and adaptation. All other, optimal adaptation scenarios use the scenario Non-Adapt as reference to show the impact of adaptation in a world that is hit by an heat wave. If an economy optimally adapts to a heat waves through governmental interventions, the issue of how to finance public adaptation measures matters. In the following, we discriminate between four different policy options for financially funding optimal adaptation to heat waves. These are labeled *Cap-Tax, Lab-Tax, Con-Tax* and *Inh-Tax*, respectively. In both *Cap-Tax* and *Lab-Tax* the government levies taxes on factor income, i.e. on capital income in scenario *Cap-Tax* and on labor income in scenario *Lab-Tax*. In scenario *Inh-Tax*, the government levies taxes on the share of capital that cohorts receive in form of inheritance from heat wave victims. In contrast, in the fourth type *Con-Tax* the government taxes expenditure on consumption goods. Table 3.4 gives an overview on the derived scenarios.

<table>
<tr><th colspan="2">State of the World</th></tr>
<tr><td colspan="2">A - There is no heat wave</td></tr>
<tr><td colspan="2">Benchmark without heat waves and adaptation</td></tr>
<tr><td colspan="2">B - There is a heat wave</td></tr>
<tr><td colspan="2"><i>State of the Swiss Economy</i></td></tr>
<tr><td><i>No Adaptation</i>
Scenario <i>Non-Adapt</i></td><td><i>Optimal Adaptation</i>
Scenario <i>Cap-Tax, Lab-Tax, Con-Tax, Inh-Tax</i></td></tr>
<tr><td>Economy is not adapted to a 2003 like heat wave</td><td>Economy is optimal adapted to a 2003 like heat wave, optimal adaptation is financed by revenue from capital, labor, consumption, or inheritance taxes</td></tr>
</table>

Table 3.4: Overview on the five scenarios to analyze heat wave and adaptation impacts

3.4.2 Assessment of Heat Wave Impacts in a Non-Adapted Economy

Let us start the analysis by considering scenario *Non-Adapt* in which a non-adapted Swiss economy is hit by a 2003-like heat wave. We split the analysis of the impacts in two parts: first we present the direct impacts, i.e. the impact on mortality. Second, we describe the general equilibrium impacts that result from the heat wave induced shock in mortality. Throughout chapter 3.4.2, we use the benchmark (no heat wave and no adaptation) as reference.

3.4.2.1 Impact on mortality

The impact of a 2003-like heat wave on mortality of cohorts of age 60 and older in a non-adapted economy is summarized in Table 3.5. The first column shows the average number of deaths per month in Switzerland between June and August if no heat wave occurs. There are no official projections of mortality rates available for Switzerland. Therefore, we used the population projections for 2020 (BFS, 2015b), the cohort shares in 2010 (BFS, 2015a) and the average monthly mortality between 2004 and 2013 (BFS, 2014a) to derive expected death per month between June and August in 2020.

We use the optimistic and the pessimistic data set derived on basis of Grizea et al. (2005) (see chapter 3.3.1) to estimate the number of excess death if a 2003 like heat wave hits Switzerland in 2020. The results are presented in column two and three of Table 3.5. In the optimistic case we estimate 1509 heat-wave-caused excess deaths in 2020. In the pessimistic case these number increases to 1581 heat-wave-caused excess deaths in 2020. For comparison, Grizea et al. (2005) estimated 975 heat-wave-caused excess deaths between June, July and August (JJA) in 2003.

Remember that neither an increase in intensity or duration of heat waves, nor the impact of demographic change has been taken into account to derive heat wave excess death for 2020. Therefore, we have to take into account that these projections are rather underestimated, because, for example, demographic trends predict an increase in the share of older cohorts compared to young.

		Death per month between June and August		Fatalities in Scenario Non-Adapt from			
				$HWEM^{opt}$		$HWEM^{pes}$	
		2010	2020	2010	2020	2010	2020
60	u	59	70	2	2	3	3
	s	111	133	7	9	8	9
	r	72	86	0	0	0	0
65	u	78	93	3	3	5	6
	s	145	173	10	12	10	12
	r	93	111	1	1	1	1
70	u	104	149	5	7	8	12
	s	167	241	11	16	17	25
	r	112	161	4	5	4	5
75	u	158	215	11	14	12	17
	s	244	332	16	22	25	34
	r	172	235	9	11	6	8
80	u	248	302	20	24	22	27
	s	331	403	34	41	45	55
	r	248	302	15	18	12	14
85	u	662	977	77	113	75	110
	s	745	1099	88	130	101	149
	r	579	855	51	75	27	40
65+		4328	5937	1092	1509	1143	1581

Table 3.5: Impact of a 2003-like heat wave on mortality in Scenario *Non-Adapt*

3.4.2.2 General Equilibrium Impacts in Scenario Non-Adapt

In a second step, we analyze general equilibrium effects that are caused by an increase in mortality if a 2003 like heat wave hits the non-adapted Swiss economy. Therefore, we differentiate between impacts on (1) labor supply, (2) output, (3) prices (4) consumption and (5) welfare. Table 3.6 presents the impact of a heat-wave-induced excess mortality on labor supply. Given the specification of our model, effects of heat waves on labor supply depend directly on the heat wave excess mortality in working age and indirectly on changes of (reservation) wages and income. Labor supply decreases for all age groups, independently of the use of the optimistic or the pessimistic data set for heat wave excess mortality. The higher the cohorts age, the greater the decrease in labor supply. The greatest decrease of 10% is with the most vulnerable working cohort, who is of low income, age 70 and living in suburban regions. The impact increases the higher the income of the cohort, with the exception of the youngest. The older the cohort, the greater the decrease in labor supply for cohorts of suburban, followed by urban regions.

		$HWEM^{opt}$			$HWEM^{pes}$		
		u	s	r	u	s	r
20	1	−0.196	−0.196	−0.196	−0.214	−0.214	−0.214
	3	−0.112	−0.112	−0.112	−0.121	−0.121	−0.121
	5	−0.075	−0.075	−0.075	−0.081	−0.081	−0.081
30	1	−0.025	−0.017	−0.095	−0.029	−0.019	−0.110
	3	−0.256	−0.321	−0.301	−0.296	−0.370	−0.347
	5	−4.452	−5.071	−1.195	−5.144	−5.859	−1.380
40	1	−0.023	−0.023	−0.122	−0.030	−0.030	−0.158
	3	−0.196	−0.347	−0.322	−0.254	−0.449	−0.416
	5	−2.830	−4.814	−1.040	−3.658	−6.221	−1.345
50	1	−0.036	−0.040	−0.206	−0.045	−0.050	−0.257
	3	−0.248	−0.521	−0.455	−0.310	−0.652	−0.570
	5	−5.876	0.000	−1.302	−7.355	0.000	−1.630
60	1	−3.347	−6.750	−0.435	−4.648	−6.950	−0.440
	3	−3.646	−8.031	−0.952	−4.955	−8.262	−0.960
70	1	−4.435	−6.537	0.000	−7.690	−9.994	0.000

Table 3.6: Impact of $HWEM$ on labor supply in scenario *Non-Adapt* using the example of income cohorts $\{h = 1, 3, 5\}$ and age $\{a = 20, 30, ..., 70\}$ in percentage change

Table 3.7 presents the impact of a 2003-like heat wave excess mortality on output Y and changes in factor prices for labor (PL) and capital (PK). The production function is of CES type. Thus, a decrease in the total labor supply with constant total capital supply reduces the production output by 0.47%, respectively 0.1% in the pessimistic case. In equilibrium, the elasticity of substitution equals the percentage change in the capital-labor-ratio relative to the percentage change in the wage-interest-ratio; $\sigma = (\%\Delta K/L)/(\%\Delta w/r)$. Because of a positive elasticity of substitution, the increase in the capital-labor-ratio results, as expected, in an increase in the wage-interest-ratio (see Table 3.7). Production output is solely used for private consumption. Thus, overall private consumption is reduced in consequence of the decrease in production. Figure 3.3 compares the impact on private consumption using the optimistic and the pessimistic data set for heat wave excess mortality.

Scenario *Non-Adapt*		
	$HWEM^{opt}$	$HWEM^{pes}$
Y	−0.470	−0.102
PL	0.163	0.199
PK	−0.235	−0.286

Table 3.7: Impact of a 2003-like heat wave on mortality in an optimally adapted Swiss Economy

All age wise, invulnerable cohorts ($a < 60$) increase their consumption by between 0.19 and 11.98%, while all age wise, strongly vulnerable cohorts ($a > 60$) decrease their consumption by between −0.95 and −13.85%. Besides age, the consumption adjustment depends also on the regional vulnerability. Cohorts of age 60 in rural regions increase their consumption while vulnerable ones in suburban and urban regions decrease theirs.

While vulnerable cohorts in suburban and urban regions decrease their consumption by between −3.61 and −12.01%, less vulnerable cohorts in rural regions decrease their consumption by only −0.95 to −9.01%. The consumption increase for cohorts between 30 and 50 depends also heavily on their income level. While the consumption of cohorts in the lower income group $\{h = 1, 2, 3\}$ increase their consumption by about 1%, cohorts in the highest income group (5) increase their consumption by up to 14.5% ($\{a = 35, h = 5, t = s\}$).

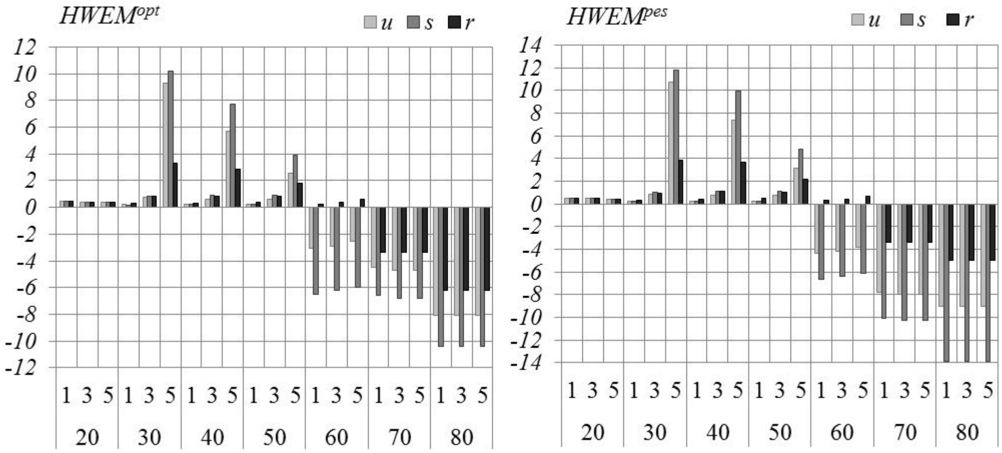


Figure 3.3: Impact of 2003-like $HWEM$ on private demand for consumption in scenario *Non-Adapt* using the example of income cohorts $\{h = 1, 3, 5\}$ of age $\{a = 20, 30, ..., 80\}$ in percentage change.

Changes in labor supply and consumption have an impact on cohorts utility, which is of CES type with leisure and consumption as arguments. Premature death reduces cohort sizes and hence their sums of utilities.

Figure 3.4 presents Hicksian equivalent variation in percentage change. From it we can draw the conclusion that welfare impacts of heat waves depend predominantly on the age of the respective cohort. Cohorts at an age with a high probability to inherit capital from heat wave fatalities increase their consumption and thus their utility level. With respect to the income group, this result is the strongest for wealthy cohorts, because they received the highest share of heritage and use it to increase consumption. On the other hand, Hicksian equivalent variation of young survivors ($a < 60$), with a lower or middle income ($h < 4$) amounts to 0.12 and 1.33%. Relating to the urban form, we find suburban and urban young cohorts benefiting most, for two reasons. First, the parents of these cohorts have the highest fatality rates and second, these cohorts own already in the initial situation the highest share of capital and profit now from inheritance. In consequence of $HWEM$, the size of vulnerable cohorts of age 70 to 85 is reduced and their share in total population decreases. Fatalities leave the economy and their utility from consumption and leisure no longer contribute to the cohorts utility. As a result, we find a negative Hicksian equivalent variation of between $-0.04(-0.07)$ and $-0.18\%(-0.22\%)$ in case of the optimistic (pessimistic) data set. The decrease in welfare is higher, the higher the income group is. Vulnerable cohorts of age 60 and 65 benefit, in terms of utility, more from inheritance than they lose because of the increase in heat wave excess mortality.

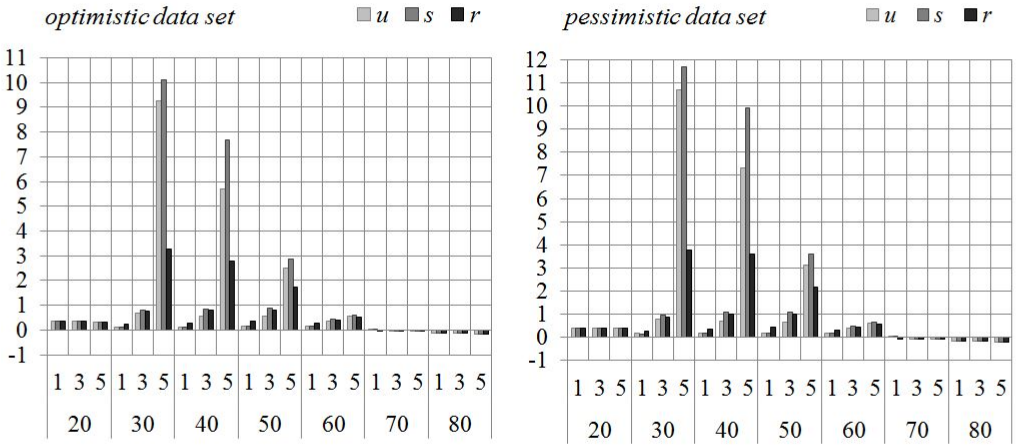


Figure 3.4: Hicksian equivalent variation in scenario $1 - NA$ using the example of income cohorts $\{h = 1, 3, 5\}$ in percentage change.

To evaluate the results from a social welfare perspective, the aggregated equivalent variation is computed as sum of the cohort-size-weighted equivalent variation of survivors, see equation 3.9.

$$EV^{Scenario} = \sum_{a,h,t} \left[\frac{M_{a,h,t} u_{a,h,t} - N_{a,h,t} u^0_{a,h,t}}{N_{a,h,t} u^0_{a,h,t}} \right] \tag{3.9}$$

The overall aggregated equivalent variation in the case of the optimistic (pessimistic) data set for $HWEM$ measures $-0.010\%(-0.011\%)$.

We can summarize the key results of this section as follows. If a stylized, non-adapted economy, that features the characteristics of the Swiss household structure with respect to age, region and income distribution between 2006 and 2008, is shocked with a 2003-like heat wave excess mortality, general equilibrium effects result in negative welfare impacts for the aggregated economy, although some young cohorts, especially those with high income in urban and suburban areas increase their utility. In consequence, we find next to the negative welfare effect also a negative impact on the distribution of income.

3.4.3 Assessment of Heat Wave Impacts in an Optimally Adapted Economy

Compared to the non-adapted economy, the number of fatalities is reduced in an optimally adapted economy to nearly zero. Only the oldest cohorts ($a \geq 80$) suffer from an excess mortality that results in 16 heat wave caused fatalities. Thus, although all age groups, especially young cohorts, have to pay taxes in order to finance adaptation, social welfare maximization results in an almost fully adapted economy (see Table 3.12).

3.4.3.1 Impact on Mortality in an Optimally Adapted Economy, Scenario Lab-Tax

Compared to the non-adapted economy, the number of fatalities decreases in an optimally adapted economy to nearly zero. Only the oldest aged cohorts ($a \geq 80$) suffer from an excess mortality that results in 9 heat wave caused fatalities. This result changes only slightly if instead of the optimistic, the pessimistic data set on HWEM is used. Thus, although especially young cohorts have to pay labor taxes in order to finance adaptation, social welfare maximization results in an almost fully adapted economy (see Table 3.8).

2020	60			65			70			75			80			85			60+ JJA
	u	s	r	u	s	r	u	s	r	u	s	r	u	s	r	u	s	r	
$HWEM^{opt}$																			
Non-Adapt	2	9	0	3	12	1	7	16	5	14	22	11	24	41	18	113	130	75	1513
Lab-Tax	0												0	1	0	1	2	0	12
$HWEM^{pes}$																			
Non-Adapt	3	9	0	6	12	1	12	25	5	17	34	8	27	55	14	86	149	40	1510
Lab-Tax	0												0	1	0	1	1	0	9

Table 3.8: Impact of a 2003-like heat wave on mortality in an optimally adapted Swiss economy

3.4.3.2 General Equilibrium Impacts in an Optimally Adapted Economy, Scenario Lab-Tax

In this section we assume that the government provides optimal adaptation that is financed via a labor tax. Thus, cohorts at working age bear the burden to finance the decrease in excess mortality of cohorts older than 60 if a 2003 like heat wave occurs. Again, we analyze the impact on (1) labor supply, (2) output, (3) prices (4) consumption and (5) welfare. As reference we use the scenario *Non-Adapt*.

Table 3.9 summarizes the impact of a 2003 like heat wave in an optimally adapted economy in which the adaption stock is financed with taxes on labor, compared to the scenario *Non-Adapt*. The labor supply increases if we assume optimistic (pessimistic) data on HWEM by between 0.01(0) and 9.17% (12.73%). This impact is higher the more vulnerable the cohort is.

Compared to the baseline scenario without heat waves and adaptation, capital becomes, because of the taxation of labour, relatively cheaper. Thus, labour supply decreases by between -0.008 and -1.542% and we find an overall decrease of -0.058%. This impact is higher for cohorts of higher age and income.

The impact on output and prices in an optimally adapted economy is presented in Table 3.10. Independently of the use of the optimistic or the pessimistic data set for HWEM, the labor tax rate to finance optimal adaptation amounts to 0.4%. The production output decreases in both scenarios. However, production increases in case of optimal adaption compared to the scenario *Non-Adapt* by 0.43, respectively by 0.531%. In case of optimal adaptation, the prices for capital and labor decreases, compared to the benchmark, but, the price for labor is stronger than the price for capital.

Private consumption decreases strongly if a non-adapted economy is hit by a heat wave (see Figure 3.3). The contrary is true if the economy is optimally adapted. Compared to the scenario Non-Adapt, the impact on consumption behaves mirror-inverted. The provided adaptation results in a decrease of the consumption advantage for younger cohorts and a decrease of the consumption disadvantage for vulnerable cohorts of age 60 and older. Compared to the baseline

		$HWEM^{opt}$			$HWEM^{pes}$		
		u	s	r	u	s	r
20	1	0.188	0.188	0.188	0.206	0.206	0.206
	3	0.093	0.093	0.093	0.102	0.102	0.102
	5	0.048	0.048	0.048	0.053	0.053	0.053
30	1	0.017	0.009	0.087	0.020	0.011	0.101
	3	0.236	0.301	0.281	0.275	0.350	0.327
	5	4.582	5.256	1.171	5.341	6.134	1.360
40	1	0.014	0.014	0.112	0.021	0.021	0.148
	3	0.174	0.323	0.298	0.231	0.425	0.392
	5	2.822	4.917	1.003	3.702	6.485	1.313
50	1	0.023	0.027	0.176	0.032	0.037	0.226
	3	0.200	0.443	0.384	0.261	0.572	0.497
	5	5.416	0	1.125	7.064	0	1.454
60	1	3.376	7.105	0.169	4.779	7.347	0.166
	3	3.417	7.447	0.199	4.824	7.699	0.181
70	1	4.294	6.608	0	7.935	10.666	0

Table 3.9: Impact of a 2003-like heat wave on labor supply in an optimally adapted economy compared to Non-Adapt in %, Scenario *Lab-Tax*

scenario without heat waves and adaptation, the consumption decreases if a heat wave hits an optimally adapted economy by maximal -0.4%.

Similar to consumption, we also find the strong cohort dependent impact of a heat wave in a non-adapted economy on utility nearly fully erased if the economy is optimally adapted to a 2003 like heat wave (see Figure 3.4 and 3.6). However, this impact is stronger if we assume the optimistic data set for heat wave excess mortality.

This effect of optimal adaptation becomes more obvious if we compare the impact of a heat wave on a non-adapted and an optimally adapted economy to the benchmark. Compared to these benchmarks in a non-adapted economy, cohorts of age $30-55$ profit greatly, in terms of utility, from the heat wave (EV of up to 12%, see Figure 3.6) we find much weaker and less cohorts de-

	Non-Adapt *compared to Benchmark*		***Lab-Tax*** *compared to Non-Adapt*	
	$HWEM^{opt}$	$HWEM^{pes}$	$HWEM^{opt}$	$HWEM^{pes}$
Y	-0.470	-0.102	0.430	0.531
PL	0.163	0.199	-0.538	-0.589
PK	-0.235	-0.286	0.233	0.284

Table 3.10: Impact of a 2003-like heat wave on output and factor prices in Switzerland in the optimal adaptation scenario *Lab-Tax*

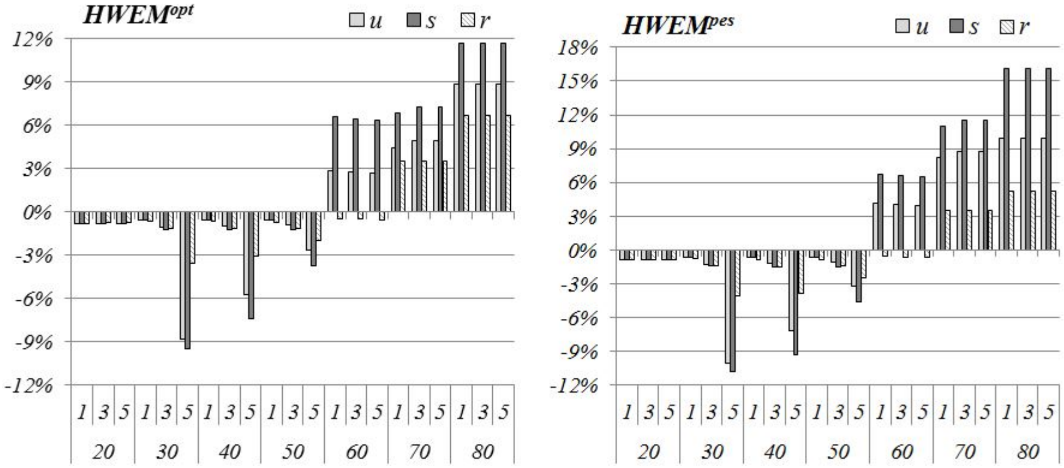


Figure 3.5: Impact of 2003-like $HWEM$ on private consumption in an optimally adapted Swiss economy (scenario *Lab-Tax* compared to *Non-Adapt*)

pendent results for an optimally adapted economy. For cohorts of age 20 to 55 we find in an optimally adapted economy an EV of between 0 and -0.29%. This decrease is less extreme for high income groups. The EV in an optimally adapted economy lies for cohorts older than 60 between -0.18 and 0.014%. However, there is virtually no change in the utility of cohorts older than 65 and of high income. The overall equivalent variation that compares total welfare effects of a heat wave in an optimal versus a non-adapted economy is presented in Table 3.11.

We can summarize the key result of a heat wave shock to a stylized, optimally adapted economy that finances the optimal adaptation with labor taxes and features the characteristics of the Swiss households with respect to

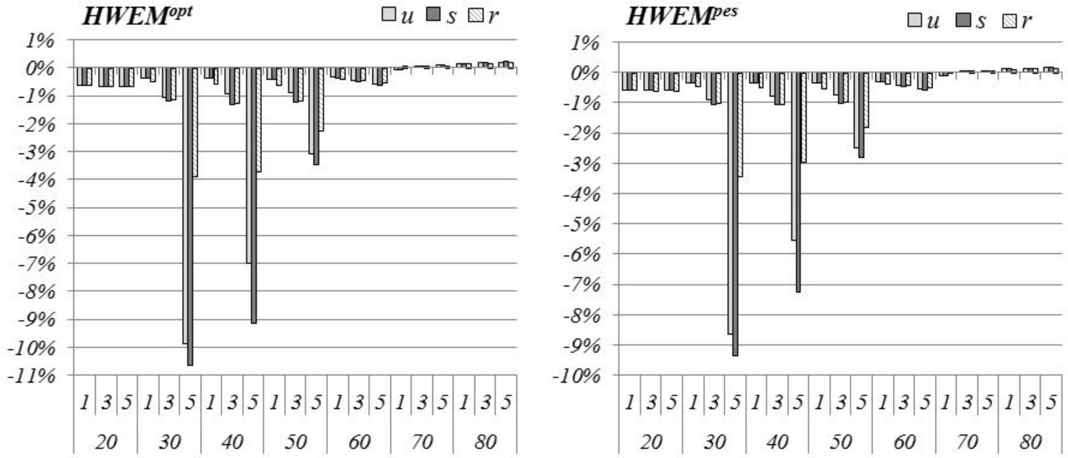


Figure 3.6: Hicksian equivalent variation in case a heat wave hits an optimally adapted Swiss economy (scenario *Lab-Tax* compared to *Non-Adapt*)

	$HWEM^{opt}$	$HWEM^{pes}$
EV in % change	0.008	0.009

Table 3.11: Welfare impact of heat waves in scenario *Lab-Tax* compared to *Non-Adapt*

age, region and income distribution between 2006 and 2008 as follows: The main distribution impacts that result from heat waves in a non-adapted economy are eliminated at relatively low expenses. The optimal adaptation reduces the decrease in labor supply strongly, although labor taxes are used to finance adaptation. Consequently, we find a strong decrease of negative impacts on output, consumption and welfare.

3.4.4 General Equilibrium Impacts in an Optimally Adapted Economy

In this chapter we compare different strategies to finance optimal adaptation to heat waves in Switzerland by analyzing general equilibrium impacts of heat waves in the four scenarios of category II (see Table 3.4). The reference case is the scenario Non-Adapt. Because we compare the impact in all four different scenarios, we present in this section only the results of the optimistic data set for heat wave excess mortality.

In this section we assume that the government provides an optimal adaptation level that is financed via a capital (scenario *Cap-Tax*), labor (scenario *Lab-Tax*), consumption (scenario *Con-Tax*) or an inheritance tax (scenario *Inh-Tax*) in order to maximize total welfare in a heat wave affected economy. Similar to chapter 3.4.2.2, we differentiate between impacts on (1) labor supply, (2) output, (3) prices (4) consumption and (5) welfare. Impacts are evaluated in comparison to scenario *Non-Adapt*.

Table 3.13 presents the impact of a heat-wave-induced excess mortality on labor supply. Compared to scenario *Non-Adapt*, the direct impact of excess mortality on labor supply behaves nearly mirror inverted. Consequently, the direct impact of heat waves on labor supply via the reduction of the size of cohorts at working age urban forms to zero. However, changes in factor prices and income because of taxation drives the impact on labor supply compared to the baseline scenario in the four different optimal adaptation scenarios. On the one hand, the impact on labor supply is, compared to the scenario *Non-Adapt* and independent of the taxation strategy, clearly reduced. On the other hand, the impact increases, similar to the scenario *Non-Adapt*, with age.

			Death per month between June and August			
		Non-Adapt	***Cap-Tax***	***Lab-Tax***	***Con-Tax***	***Inh-Tax***
	u	2	0			
60	s	9	0			
	r	0	0			
	u	3	0			
65	s	12	0			
	r	1	0			
	u	7	0			
70	s	16	0			
	r	5	0			
	u	14	0			
75	s	22	0			
	r	11	0			
	u	24	0			
80	s	41	0	1	0	0
	s	18	0			
	u	113	1	1	1	1
85	s	130	2	2	2	2
	s	75	1	0	1	1
$60 + JJA$		1509	12	12	12	12

Table 3.12: Impact of a 2003-like heat wave on mortality in optimally adapted economy by funding strategy

In scenario *Cap-Tax*, cohorts of age 30 and older, and especially more productive, high income cohorts increase their labor supply by low margin of maximal 0.49%. Factor demand for labor becomes, because of the taxation of capital, relatively cheaper and is thus increased. Overall, the labor supply increases slightly by 0.004%.

The contrary is true for Scenario *Lab-Tax*; capital becomes, because of the taxation of labour, relatively cheaper. Thus, labour supply reduces by between −0.008 and −1.542% and an overall decrease of −0.058%. Again, we find higher impacts for cohorts of higher age and income.

In scenario *Con-Tax*, adaptation is financed by the taxation of consumption. This form of funding distributes the tax burden between all cohorts and has the least impact on factor supply. The demand for consumption goods decreases only slightly and thus also production and the demand for factor inputs only adjust minimally. Labour supply decreases in cohorts slightly by between -0.005 and -0.262% and overall by -0.017%. The funding of adaptation by an inheritance tax in scenario *Inh-Tax* has the least impact on labour supply. The overall decrease amounts to only -0.002%. Because the inheritance tax is a special form of the taxation of capital, we again find some cohorts which increase their labour supply. These are especially cohorts of age $60, 65$ and 70 living in rural regions.

		Cap-Tax			***Lab-Tax***			***Con-Tax***			***Inh-Tax***		
20	1	0.193	0.193	0.193	0.188	0.188	0.188	0.192	0.192	0.192	0.196	0.196	0.196
	3	0.105	0.105	0.105	0.093	0.093	0.093	0.101	0.101	0.101	0.111	0.111	0.111
	5	0.065	0.065	0.065	0.048	0.048	0.048	0.059	0.059	0.059	0.073	0.073	0.073
30	1	0.022	0.014	0.093	0.017	0.009	0.087	0.020	0.012	0.091	0.024	0.016	0.095
	3	0.251	0.316	0.296	0.236	0.301	0.281	0.246	0.311	0.291	0.255	0.320	0.300
	5	4.665	5.350	1.204	4.582	5.256	1.171	4.636	5.317	1.192	4.650	5.331	1.206
40	1	0.020	0.020	0.120	0.014	0.014	0.112	0.018	0.018	0.118	0.022	0.022	0.122
	3	0.191	0.344	0.318	0.174	0.323	0.298	0.185	0.337	0.311	0.194	0.346	0.320
	5	2.923	5.082	1.049	2.822	4.917	1.003	2.888	5.024	1.033	2.901	5.037	1.046
50	1	0.034	0.039	0.212	0.023	0.027	0.176	0.030	0.035	0.200	0.034	0.039	0.202
	3	0.252	0.539	0.469	0.200	0.443	0.384	0.234	0.505	0.440	0.242	0.512	0.447
	5	6.471	0.000	1.360	5.416	–	1.125	6.104	–	1.278	6.116	0.000	1.291
60	1	3.433	7.165	0.523	3.376	7.105	0.169	3.413	7.144	0.400	3.440	7.173	0.557
	3	3.824	8.982	1.167	3.417	7.447	0.199	3.683	8.448	0.830	3.874	9.152	1.276
70	1	4.701	7.032	0.000	4.294	6.608	–	4.559	6.885	–	4.552	6.878	0

Table 3.13: Impact of $HWEM$ on labor supply in optimal adaptation scenarios using the example of cohorts $\{h = 1, 3, 5\}$ and $\{a = 20, 30, ..., 80\}$ in percentage change compared to scenario Non-Adapt

Table 3.14 presents the impact of a 2003-like heat wave excess mortality on output Y and changes in factor prices PL and PK in an optimally adapted compared to a non-adapted economy. We find a production decrease of about

0.47% in a non-adapted economy. Compared to this, the production increase in an optimal compared to a non-adapted economy measures between 0.32 and 0.45%. This results, compared to the baseline scenario, in a decrease in the production shortage in all four optimal adaptation scenarios by between -0.148% (*Cap-Tax*) and -0.02% *(Con-Tax)*.

Comparing the tax shares of each scenario, we clearly see that the decrease of taxation base from scenario *Con-Tax* to *Cap-Tax* to *Lab-Tax* to *Inh-Tax* results in an increase of the tax rate. On the one hand, taxing all (consuming) cohorts results in a low consumption tax of 0.2%. On the other hand, the tax base in scenario *Inh-Tax* is not even high enough to finance optimal adaptation. Each heir would need to pay twelvefold of his heritage to finance optimal adaptation. Thus, they have to decrease their capital stock slightly.

	Non-Adapt	***Cap-Tax***	***Lab-Tax***	***Con-Tax***	***Inh-Tax***
Y	−0.470	0.323	0.430	0.452	0.441
PL	0.163	−0.313	−0.538	−0.169	−0.190
PK	−0.235	−0.093	0.233	0.245	0.275
τ	-	0.005	0.004	0.002	12.7

Table 3.14: Impact of $HWEM$ on output & factor prices in optimal adaptation scenarios by financing strategy compared to each other (in percentage change)

On the one hand, the funding strategy for adaptation determines which cohorts have to share the main burden from taxation. Consequently, the impact on consumption varies by optimal adaptation scenario. On the other hand, because mortality is so drastically reduced in all four optimal adaption scenarios, we find, compared to scenario *Non-Adapt*, mirror-inverted impacts on consumption and consequently also on utility, nearly independently of the funding strategy for optimal adaptation. Therefore, Figure 3.7 shows representative for all other funding strategies the impact of a 2003 like heat wave in an optimal compared to a non-adapted economy, where the adaptation is financed via capital taxes.

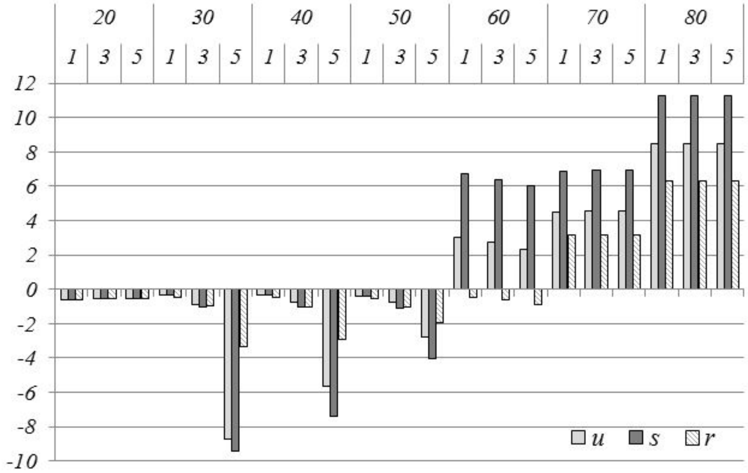


Figure 3.7: Impact of 2003-like $HWEM$ on private demand for consumption in scenario *Cap-Tax* compared to scenario *Non-Adapt* using the example of cohorts $\{h = 1, 3, 5\}$ and $\{a = 20, 30, ..., 80\}$ in percentage change

To get further insights on the impact of the funding strategy, we compare results of all four optimal adaptation scenarios with the benchmark case, see 3.8. In scenario *Cap-Tax* older cohorts and those of high income groups are especially affected as they own the main share of capital. Thus, we find a decrease in consumption for these cohorts of between -0.195 and -0.328% compared to the benchmark. With respect to age, the contrary is true for Scenario *Lab-Tax*. The main burden of taxation is carried by labour supplying cohorts between 20 and 55. They decrease their consumption by up to -0.403%. Some high income cohorts of age 60 and 65 even increase their consumption slightly by between 0.005 and 0.02%. Consumption of cohorts older than 65 decreases only slightly by maximal -0.002% and is mainly caused by (the low number) of heat wave fatalities. The tax burden is shared most equal between all cohorts in Scenario *Con-Tax*, because they all use their income for consumption expenditure only. Consequently, the consumption decrease for all cohorts is relatively small and lies between -0.191 and -0.245%.

In scenario *Inh-Tax* we find the tax burden is even higher than the heritage and concentrated on cohorts of age 60 and 65. This is the consequence of the strong decrease in heat wave excess mortality through adaptation that causes only a few heat wave fatalities of age 80 and 85. Thus cohorts of age 60 and 65 share the burden of adaptation to heat waves. Cohorts older than 70 increase their consumption slightly. Because the factor supply stays nearly constant, the production decrease is only caused by a shortage in consumption demand of cohorts of age 60 and 65 that is partly outweighed by an increase in consumption of older cohorts. With respect to income, we find, similar to scenario *Cap-Tax*, a stronger decrease on consumption for high income cohorts as they own the highest share of capital before and after taxation.

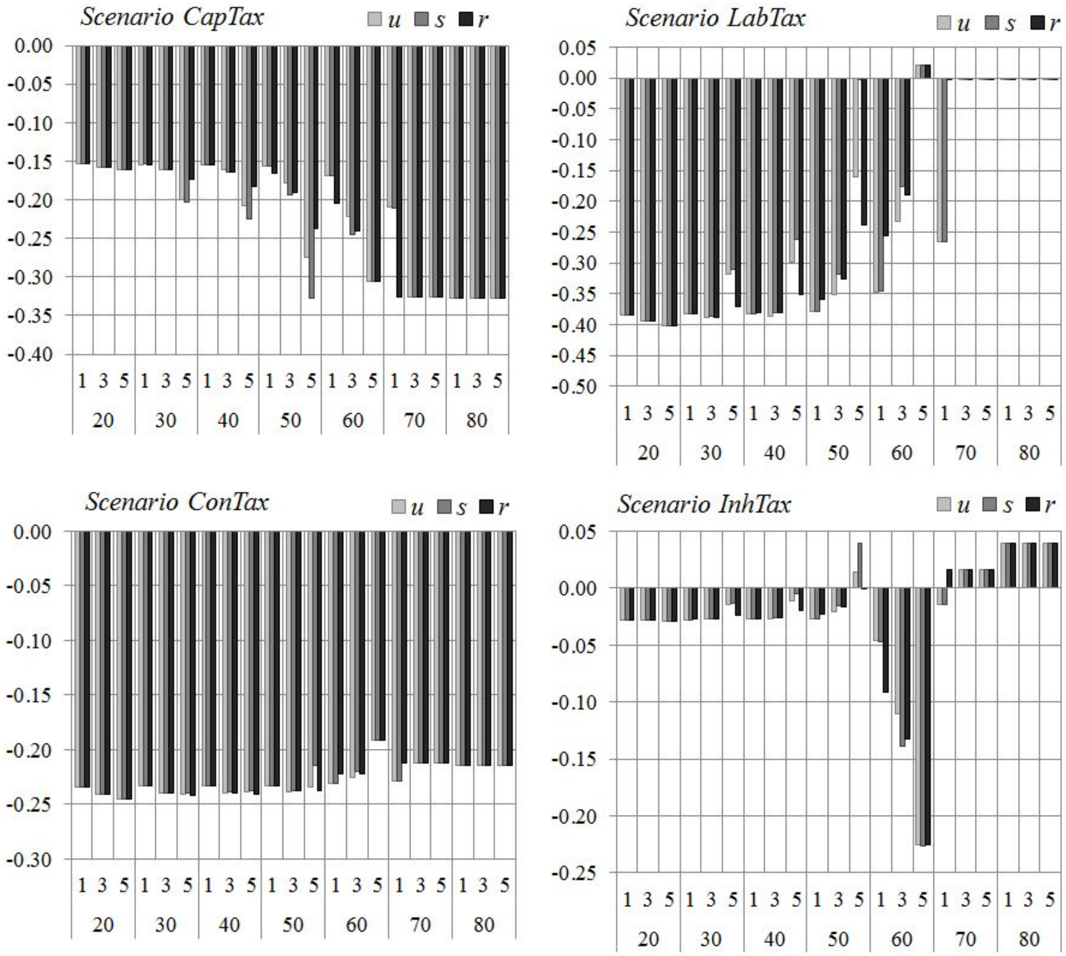


Figure 3.8: Impact of 2003-like *HWEM* on private demand for consumption in scenario *Cap-Tax* compared to scenario *Non-Adapt* using the example of cohorts $\{h = 1, 3, 5\}$ and $\{a = 20, 30, ..., 80\}$ in percentage change

Similar to Figure 3.7, we see in Figure 3.8 the mirror-inverted impact on cohort's utility in the optimal adaptation scenario *Cap-Tax*, representative of all other optimal adaptation scenarios, compared to the Scenario *Non-Adapt*.

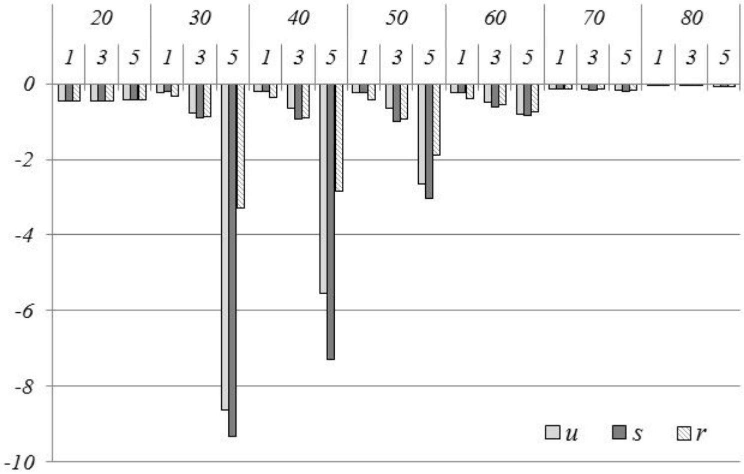


Figure 3.9: Impact of 2003-like $HWEM$ on private demand for consumption in scenario *Cap-Tax* compared to scenario *Non-Adapt* using the example of cohorts $\{h = 1, 3, 5\}$ and $\{a = 20, 30, ..., 80\}$ in percentage change

To get further insights on the impact of the funding strategy on the utility of cohorts, we compare all four optimal adaption scenarios with the benchmark scenario. Figure 3.10 presents Hicksian equivalent variation compared to the benchmark in percentage change. Because of the structure of our model, we can draw the conclusion that welfare impacts in an optimally adapted economy predominantly depend on changes in consumption behavior caused by taxation. Because of the strongly reduced heat waves excess mortality, there are virtually no changes in labor leisure choice.

The overall aggregated equivalent variation in all 4 scenarios compared to scenario *Non-Adapt* is summarized in table 3.11. Scenario *Inh-Tax* has the highest welfare increase, while the taxation of labor results in the smallest increase.

We can summarize the results of this section as follows: If a stylized, optimally adapted economy that features the characteristics of the Swiss household sector with respect to age, region and income distribution is shocked with a 2003-

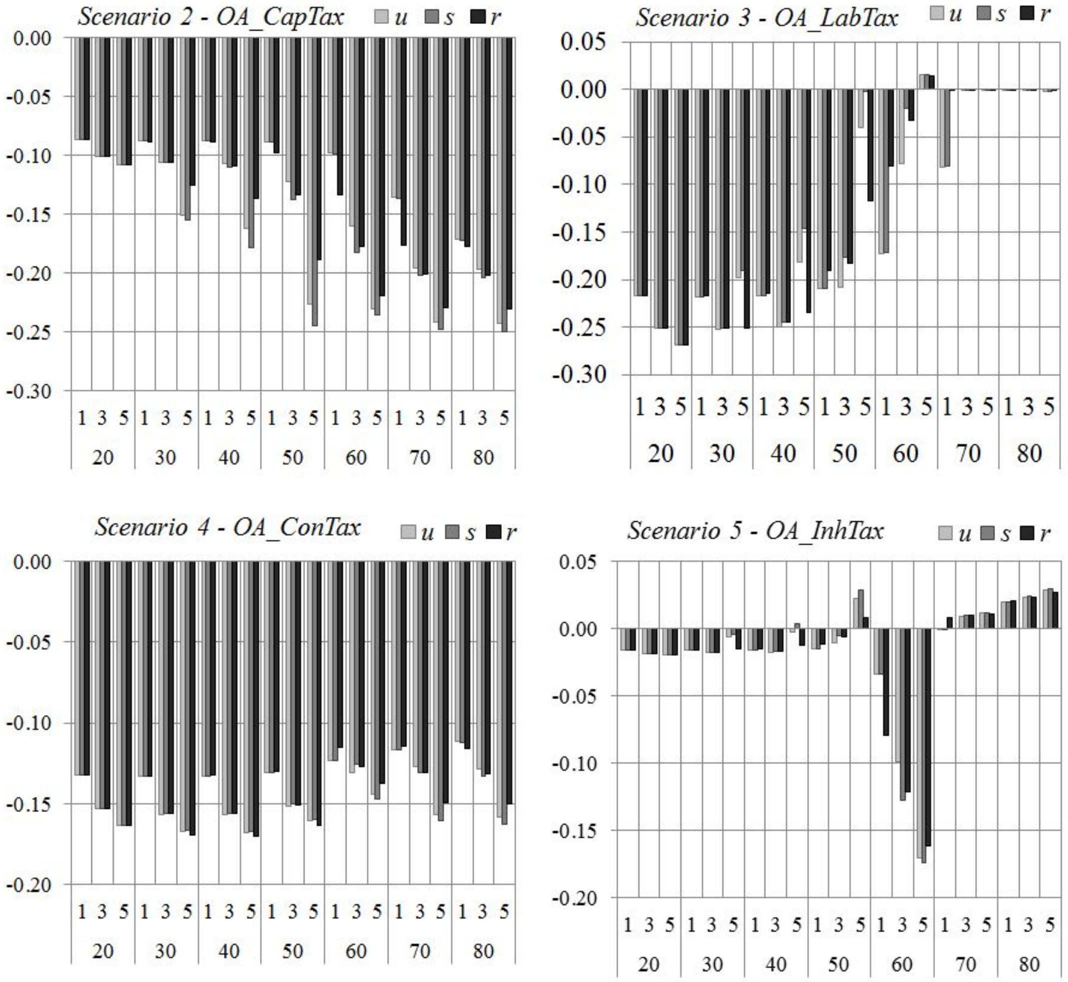


Figure 3.10: Hicksian equivalent variation in optimal adaptation scenarios using the example of cohorts $\{h = 1, 3, 5\}$ and $\{a = 20, 30, ..., 80\}$ in percentage change.

like heat wave, welfare, output and distribution impacts depend on the funding strategy to finance adaptation. However, all four funding strategies for optimal adaptation result in a strong decrease of $HWEM$ compared to the scenario without any adaptation.

Levying taxes on capital has the worst impact on overall production output, compared to the benchmark. Vulnerable cohorts bear the main burden of financing adaptation. On the one hand, this approach may not fit the principle of burden sharing. On the other hand, this scenario mirrors private adaptation best because a part of the capital of vulnerable cohorts would be used to invest

	Cap-Tax	***Lab-Tax***	***Con-Tax***	***Inh-Tax***
$EV\%^{opt}$	0.008	0.0080	0.0082	0.0095
$EV\%^{pes}$	0.010	0.0096	0.0098	0.0112

Table 3.15: Welfare impact of heat waves in an optimally adapted economy by financing strategy compared to scenario *Non-Adapt*

in a (private) adaptation.

The contrary is true for scenario *Lab-Tax*. Here, tax base is slightly increased and the invulnerable majority of the population bears the burden of taxation. Additionally, the decrease in production output is, compared to scenario *Cap-Tax*, greatly decreased from -0.148 to -0.042%.

In scenario *Con-Tax* additionally increased and thus we find a low consumption tax rate of only 0.2%. The tax burden is almost equally shared between all cohorts and therefore vulnerable, as well as invulnerable cohorts have to pay for adaptation to heat waves that reduce the excess mortality in high age cohorts. The consumption tax result in the lowest impact on production output compared to all other scenarios.

In scenario *Inh-Tax*, the government would need to introduce a penalty tax for those cohorts who would profit from residual excess mortality in form of inheritance. However, to reach the adaption stock that is necessary to optimally adapt to heat waves, these cohorts would have to pay a multiple of their inheritance. This approach is clearly not feasible and puts a very high burden on a small share of the population. Additionally, it is important to keep in mind that this is not the share of the population that would profit most from inheritance in a non-adapted economy, because these are the $30 - 40$ years old cohorts.

To check the robustness of the results, a sensitivity analysis of all crucial parameter values was carried out. Parameter which influence our results can be differentiated by one important characteristic. On the one hand, we have parameter that describe the optimization problem of the households and change the results of the calibration. These parameter are σ_h^{cl}, the elasticity of substitution between consumption and leisure, φ_h, the consumption share parameter, the interest rate and ζ_h^{scale}, ζ_h^{age} and ζ_h^{age2} the parameter which describe the productivity profile of the households. On the other hand, we have parameter that influence the results of the core of our analysis, the impact of heat waves and adaptation to them. These results are mainly driven by the heat wave excess mortality $\Pi_{a,t}$ and the adaptation efficiency parameter ψ. For the first group of parameter we know from economic theory how the up or down scaling of the parameter values will influence our results. However, analyzing the magnitude of this change requires a change in the calibration output. That would cause our analysis to be influenced by a whole new data basis which also would not fit the official Swiss retirement age.

3.5 Concluding Thoughts

Within the framework of adaptation to extreme climate events in developed countries, this paper gives an approach on how to evaluate non-market damage from climate extreme events in a general equilibrium approach. This allows us to overcome the procedure of evaluating non-market damage, in particular fatalities, from climate extreme events by counting the number of excess death and, sometimes, evaluating them with a value of statistical life. The new approach allows us first, to determine the magnitude of general equilibrium impacts of a 2003-like heat wave on the Swiss economy and second, to compare the economic impacts of different strategies to finance optimal adaptation to heat waves if it has the characteristic of a public good.

We claimed that general equilibrium effects are crucial to overcome the commonly used approach of measuring non-market damage from extreme weather events by evaluating the number of fatalities with the value of a statistical life. Our approach accounts for secondary effects and thus, makes it possible to differentiate between welfare losses and damage in the output, i.e. market damage that result from lower labor supply and total demand for consumption goods. We are able to show how cohorts of different age, income and region are affected, because we differentiate the demand side with respect to these three characteristics that define the vulnerability to heat waves. This enables us to show that there are substantial differences in the impact of heat waves on cohorts utility if an economy is not adapted. While young and not vulnerable cohorts profit (in welfare terms) from heat waves, vulnerable but surviving cohorts utility decreases. This result shows that without adaption, vulnerable cohorts are worse off and may have fewer possibilities to invest in private adaptation. Either they lose their lives, or they survive, but face a decrease in their utility. Thus heat waves result in negative welfare and distribution impacts. So, the answer to the title question is, yes, if we want to prevent redistribution effects that harm already vulnerable cohorts.

Our model is based on Swiss income data that describe the distribution of different types of income between household groups of different age, income and residential region. This approach has two main advantages. Firstly, it allows a regionally differentiated analysis without deriving regional input-output tables. Secondly, it enables us to compare different strategies to fund the provision of the public good adaptation.

The tax base for the inheritance tax is reduced with the reduction of heat wave victims. Thus this tax is not suitable to finance an optimal adaptation stock. The least welfare loss is generated if adaptation is financed with a capital or consumption tax (depending on the optimistic or pessimistic data set). Funding adaptation to heat waves with taxes on consumption, results in a moderate welfare loss and a very low decrease in production output. Scenario labour tax causes next to the largest welfare loss also the second largest (but still moderate) decrease in production output. Overall, we showed that it is possible, at relatively low economic costs (about 0.2% of the GDP), to reduce mortality from heat waves drastically and to prevent strong distribution effects that are caused by a heat wave if there is no adaptation.

Obviously, there are further options for extending the present analysis. The most important one could be to enlarge the model to a dynamic one. To overcome the problem of perfect foresight in standard OLG models, it may be one opportunity to use a stochastic version. This extension would allow for uncertainty. This is a reasonable assumption in the context of climate extreme events, which are characterised by low probability to occur, but a high impact if they do occur. However, the possibility to simulate these models may be limited. We leave these extensions to future research. Additionally, our model is not able to image the potential welfare decrease of young households because they grieve for the heat wave fatalities. Also, costs of increasing morbidity are not taken into account because we have no reliable data that show this impact. The same problem arises when it comes to the impact of heat waves on labor productivity. We know from other studies (see for example Hübler et al. (2008) and Hallegatte et al. (2008)) that there is an impact, but we have no data on the impact of a heat wave on Swiss labor productivity, especially because there are only a few occupational groups affected.

3.A Social Accounting Matrix

	OUT	CON	r.1	r.2	r.3	r.4	r.5	s.1	s.2	s.3	s.4	s.5	u.1	u.2	u.3	u.4	u.5
OUT	666.49	−666.49															
CON		666.49	−13.35	−23.17	−24.25	−33.16	−23.11	−3.11	−18.69	−41.37	−86.11	−211.71	−1.90	−12.89	−19.13	−67.41	−87.14
LAB	−393.73		8.44	15.94	17.81	25.48	13.81	1.78	12.21	29.04	60.08	94.27	1.15	7.87	14.63	44.27	46.95
CAP	−272.76	3.74	6.68	6.38	8.32	9.97	1.03	5.66	11.90	26.07	119.17	0.52	4.04	4.31	23.88	41.09	

Table 3.16: Social accounting matrix

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Chapter 4

Regional Flood Impacts and Adaptation in a Federal Setting: A Spatial Computable General Equilibrium Analysis for Switzerland

4.1 Introduction

According to the fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the atmospheric carbon concentration is expected to rise further during the 21st century. This could, combined with a growing population and inappropriate land use, lead to a significant increase in the frequency, intensity and the duration of water-related extreme events such as floods (e.g. IPCC (2014)). Feyen et al. (2012), for example, estimate that in Europe the annual damage caused by river flooding will more than triple till the end of the century. Based on recorded observations, the Advisory Body for Climate Research of the Swiss Federal Government (OcCC, 1999) reports that in the Alps autumn and winter precipitation has already risen by more than 30%

during the last 100 years[1]. And model based predictions suggest that climatic warming will cause significantly more and severe flood events in the Swiss Central Plateau (Mittelland) and southern Switzerland, which could imply additional flood-related costs in the order of magnitude of several hundred million Swiss francs per year.

Economic impacts of floods are complex and difficult to assess (Jahn, 2014). First, there are direct effects. Examples are damage on buildings and machinery as well as the destruction of infrastructures such as roads or electricity and water supply systems. Most of these damage can directly be expressed in monetary units. For this reason, they are called market damage[2] in contrast to non-market damage such as injuries, losses of cultural heritage or psychological distress. The latter ones are difficult to translate into monetary units and will be neglected in our analysis. Secondly, there are indirect effects. The impact, which floods can have on economies, goes beyond the direct local effects when water is coming into contact with infrastructure, buildings, and other properties. Damages of existing capital stocks and infrastructure can cause reductions, in more severe cases even a disruption of economic activities. Because of interlinkages within and across regional economies, this can set off a sequence of feedback reactions inside and outside the flooded area, which typically last much longer than the flood itself.

While the analysis of direct market impacts is well established (for an overview, see Penning-Roswell et al. (1996)), less knowledge is accumulated with respect to indirect effects of flood events. In particular, economic aspects are poorly understood so far. To our best knowledge, only a limited number of papers discuss both direct and indirect impacts of flood disasters from an economic perspective (Cochrane, 2004; Messner, 2007; Hallegatte and Przyluski, 2010; Green et al., 2011; Carrera et al., 2015). These papers have in common that they combine a spatial analysis, which captures direct flood impacts, with a computable general equilibrium (CGE) model of a national economy, through which indirect effects become visible.

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[1] Historical climate records indicate that extreme precipitation events might occur significantly more often than in recent years and the resulting damage could far exceed currently known levels (OcCC, 1999).

[2] According to Hallegatte and Przyluski (2010) market losses include all damage, which can be repaired or replaced through purchases on markets.

What these papers do not consider, however, is how to protect a given region against the adverse effect of flooding through adaptation. It is the main purpose of this paper to analyze the latter issue and hence to give an answer to the question, how to adapt efficiently to climatically caused flood events.

Mitigation and adaptation are the two major responses to global climate change. Mitigation covers all strategies, which, through reducing greenhouse gas emissions, are designed to solve this problem from the root. Adaptation denotes the "process of adjustment to actual or expected climate and its effects" (IPCC, 2014). For more than two decades, mitigation was the main objective of international climate policy. But due to already high atmospheric carbon concentrations and due to the inertia of the climate system climate change is unavoidable to some degree, even if today emissions were cut back almost completely. This combined with high uncertainty about future climate change policies has turned attention towards measures, which allow for reducing the climate vulnerability of communities and regions and which can be implemented on a national or regional scale with sufficient speed and scope.

As was shown by Buob and Stephan (2011) moderating the negative effects of climate change through investing into adaptation is a key element of any rational climate change policy. Some adaptation is in the self-interest of agents and hence has the properties of a private good. But the majority of measures to adapt to the rising risk of flood disasters has the features of a (local) public good. Examples are land use planning, establishing protected areas or investing into flood protection infra-structure such as dams. Seen from this perspective, the optimal provision of flood adaptation requires policy interventions. However, the adaptation to climate change is a rather complex challenge. On the one hand a variety of measures exist, which differ in important aspects as the just mentioned examples illustrate. On the other hand, adaptation very much depends on local circumstances, which are known to local authorities, while a central governmental authority often lacks the necessary information. It is the aim of our analysis (1) to gain a better understanding of the economic impacts of floods, (2) to analyze the issue of efficient flood adaptation from a regionally diversified perspective, and (3) to analyze the issue of financing adaptation in a federalist system, where local and central governmental authorities interplay in the provision of local public good adaptation.

As mentioned above, answering these questions requires a regional CGE model. Despite the fact that the regionalization of CGE models is well established, applying them to the issue of flood adaptation is a relatively new one. To our knowledge, Jahn's (2014) paper "A Spatial CGE Model for the Analysis of Regional Climate Change Impacts and Adaptation Policies" is so far the only one. It is based on the RELU-TRAN model (Anas and Liu, 2007) and was adopted for analyzing the impacts of flood events and adaptation measures in the region of Hamburg. To this end, Jahn (2014) had to down scale a national Input-Output table to this specific region. In contrast to that, our CGE model is not based on a down scaled Input-Output table. Instead, we discern between regions according to the degree of their exposure and vulnerability with respect to floods events. Based on data of the Swiss Federal Institute for Forest, Snow, and Landscape Research (WSL), which contains information about any flood event in Switzerland for the time period 1970 to 2014, including the corresponding damage (expressed in CHF) on community level, we are considering three different regions[3] of Switzerland. (1) A region of high exposure with high/catastrophic damage above 2 million CHF or fatalities, (2) a region of medium exposure with damage between 0.4 and 2 million CHF, (3) a region of low exposure damage (between 0.1 and 0.4 million CHF) or of no exposure at all. An advantage of our approach is that we account also for national impacts of regional events and adaptation measures. Additionally, we are able to analyze the cooperation between regional and national governmental authorities in financing regional adaptation measures via different taxing and transfer scenarios.

Our results indicate three major findings: (1) General equilibrium effects, which are caused by flood damage in highly vulnerable regions, also lead in regions of low vulnerability to considerable welfare and GDP losses. (2) By providing the local public good adaptation, it is, at low economic cost, possible to reduce negative impacts on welfare, GDP as well as the allocation of resources between

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[3] Note that these regions must not coincide with existing ones. They are artificially constructed and represent a collection (set) of communities with similar properties with respect to flood exposure and vulnerability.

regions and sectors significantly. Finally, (3) funding the local public good with a regional land tax should be preferred to a national output tax or a combination of both with transfers from national to regional governments.

The rest of the paper is organized as follows. Section 4.2 presents a description of the modeling framework upon which our numerical analysis is based. Section 4.3 discusses data and numerical inputs into the analysis. Section 4.4 presents the scenarios, section 4.5 the results and conclusions are drawn in Section 4.6.

4.2 Theoretical Modeling Approach

Our numerical thought experiments are based on a dynamic, spatial differentiated Ramsey type Computable General Equilibrium (CGE) model. The degree at which a specific region might be affected by flood events depends on the region's exposure and vulnerability. Vulnerability refers to the propensity of suffering losses. It is determined by physical, social, political, economic, cultural and institutional factors and can be moderated through investment into adaptation measures. Exposure primarily is a geographical attribute. It characterizes areas, in which people and economic assets are exposed to the hazard of flooding (for details, see UNISDRS (2015)). According to that, the Swiss economy is divided into R regions, which differ with respect to their flood exposure.

In each region $r = \{1, ..., R\}$ a representative consumer maximizes the discounted sum of the logarithm of consumption over the time horizon of T periods $t = \{1, ..., T\}$. Instantaneous consumption depends on produced commodities on the one hand and services of land for residential purposes on the other. The production side of the regional economies is differentiated into S sectors. Sectors differ with respect to the degree at which they are vulnerable to flood events. For example, the flood vulnerability of sectors such as forestry, agricultural production or transportation is significantly higher than the vulnerability of the banking sector. Each sector $s = \{1, ..., S\}$ produces a specific, composite commodity and uses land, labor, capital as well as outputs from others sectors as inputs into production.

There are two categories of governments: R regional governments on the one hand and a federal government on the other. Governments perform two functions. They collect taxes and finance adaptation measures for preventing against negative impacts of flood events and thus for reducing the regions' vulnerability to floods.

4.2.1 Land and Impacts of Flood Events

Land plays a particular role in our analysis: (1) Land is immobile and hence fixed to a specific region. (2) Land is an input into both regional production and consumption. (3) Land is exposed to damage through floods.

As mentioned above, for analyzing the economic impacts of floods we have to discern between direct and indirect impacts. Direct impacts concern flooding, erosion, mudflow, sedimentary deposition and obstruction or damage caused by driftwood. Land, as well as property assets that come into contact with water, mud or flotsam, can be destroyed. To implement direct damage in our model we apply the damage function approach proposed by Carrera et al. (2015). Let $L_r(t)$ denote the total gross endowment of land of region r at date t and let $D^L_{f,r}(t)$ denote damage, i.e. the fraction of land[4], which is covered with water in case that a reference flood f hits region r during period t. Consequently, during period t only the remaining fraction is at region's disposal for both consumption and production purposes, i.e.,

$$L^{net}_r(t) = L_r(t)(1 - D^L_{f,r}(t)) \geq l^H_r(t) + \sum_s l^F_{r,s}(t). \tag{4.1}$$

$l^H_r(t)$ is the fraction of land, which the representative consumer of region r uses during period t for residential purposes, while $l^F_{r,s}(t)$ is the fraction, which, in region r, sector s uses as input into regional production.[5] The impact a flood has on the supply of land, $D^L_{f,r}(t)$, depends on (1) the share $\left(\frac{A_{f,r}(t)}{L_r(t)}\right)$ of the total area $L_r(t)$ of land in a region that cannot be used for residential or production

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[4] As will be explained below at some more detail, negative impacts of flood events can be moderated through investing into adaptation. Therefore, damage depend on investment into flood protection.

[5] As such there are four types of use for land: (1) residential, (2) agricultural, (3) industrial and commercial, (4) for transportation and other services.

purposes any more and (2) on the duration $\left(\frac{Dur_{f,r}(t)}{12}\right)$ of flooding i.e. time period (in month) during which the land cannot be used for residential purposes or as factor of production, respectively. Therefore, we are able to construct damage parameter for every reference flood f as follows:

$$D^L_{f,r}(t) = \left(\frac{A_{f,r}(t)}{L_r(t)}\right)\left(\frac{Dur_{f,r}(t)}{12}\right). \tag{4.2}$$

Indirect economic impacts can be positive as well as negative. On the one hand destroyed input factors can lead to economic losses especially in the sectors that use those most. Furthermore there are indirect impacts on welfare because (1) the supply of consumption goods is presumably reduced and (2) land cannot be used for residential purposes. On the other hand, when it comes to reconstruction activities there are potentially positive economic impacts (Berlemann and Vogt, 2007). Using the CGE approach, we will be able to identify both types of indirect impacts.

4.2.2 Adaptation as Local Public Good

Flood damage can be moderated through implementing adaptation measures. Some adaptation has the features of a private good and is in the self-interest of economic agents, hence is autonomously done. Typical examples are choosing a residence region that is not exposed to floods or buying flood insurance. Some adaptation measures, however, have the properties of a local public good and require governmental intervention. Typical examples are dams, spatial planning measures or information and persuasion policies. While in our model private adaptation is observed indirectly via reactions on price changes caused by floods, adaptation, which has the features of a local public good is explicitly modeled. There are two categories of governments: a federal government on the one hand and regional governments on the other. The latter ones can be understood as a federation of local communities, which are characterized by either high, medium or low exposure to floods. They are not identical with real existing local authorities.

Local governments levy taxes on land for financing flood adaptation measures. The federal government collects taxes on output for financing governmental consumption, adaptation measures and/or transfers to the regional governments for co-financing adaptation measures. The latter aspect is of particular importance since it allows for analyzing distributional effects in the sense that those, who contribute to financing a certain adaptation measure in a certain region may not be the ones, who directly profit from this investment. Additionally, we assume that adaptation measures, which are implemented by regional governments are more effective in preventing damage than those, which are implemented by the national government because of information deficits of the later one. Another important characteristic of adaptation is that costs for adaptation arise, in case of proactive adaptation, before the adaptation measure is actually implemented.

Let the effect, which adaptation has on flood damage in region r, be expressed by the function $\Psi_r(AD_r(t-v))$, where similar to Stephan and Schenker (2012), $AD_r(t-v)$ denotes the expenditure for adaptation measures that reduce flood damage. In our approach $AD_r(t-v)$ equals governments expenditure in all sectors s of region r, i.e. $AD_r(t-v) = \sum_s p^x_{r,s} ada_{r,s}$. The parameter v accounts for the possible time lag between expenditure and first effective use of the adaptation measure. The adaptation function $\Psi_r(AD_r(t-v))$ determines by how much the flood damage can be reduced depending on expenditure for adaptation, i.e.:

$$L_r^{net}(t) = L_r(t)(1 - D^L_{f,r}(t)\Psi_r(AD_r(t-v))). \tag{4.3}$$

The damage decreasing adaptation function is equal to one if the adaptation spending is zero and converges to zero if the adaptation spending goes to infinity. Furthermore, let the effect of adaptation on floods be characterized by decreasing marginal benefits of adaptation, i.e.,

$$\Psi_r(AD_r(t-v)) = e^{-\psi_G AD_r(t-v)}, \tag{4.4}$$

ψ_G is the efficiency parameter of adaptation provided by the regional $(G = R)$ or the national $(G = N)$ Government. The higher ψ, the more effective are the adaptation expenditures. We set $\psi_R \geq \psi_N$, because we assume adaptation expenditure of regional authorities to be more efficient in preventing damage than adaptation expenditure of the national government for legal and political reasons.[6]

Finally, let us assume that every government aims for a first best solution in the sense that the optimal level of adaptation is reached if the value of marginal benefits of adaptation equals the value of marginal costs of adaptation. Benefits from adaptation are measured in prevented damage ($PD(t)$), i.e. gross damage in case no adaptation is in place minus net damage in case a reference flood occurs in an adapted economy.

$$PD_r(t) = L_r(t)D^L_{f,r}(t) - L_r(t)D^L_{f,r}(t)\Psi_r(AD_r(t-v))) \tag{4.5}$$

In case of optimal adaptation, the value of marginal benefits of adaptation equals the value of marginal costs of adaptation. In order to implement adaptation, the (regional) government spends the earned tax revenue on (regional) sector outputs. Marginal costs of adaptation (in a certain region) are therefore determined by the prices for (regional) sectors output. The value of marginal benefits is determined by the price of land (in a certain region) times the marginal benefit of adaptation, i.e.

$$\frac{\partial PD_r(t)}{\partial AD_r(t-v)} p^l_r(t) = \sum_s p^x_{r,s}(t-v) \tag{4.6}$$

Independently on the funding scenario, we assume the governments' budgets to be balanced period by period.

4.2.3 Consumption

As mentioned above we are using a Ramsey type of a dynamic equilibrium model. I.e., consumers are clairvoyant and maximize the discounted sum of expected utilities subject to an intertemporal budget constraint. For being more precise,

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[6] This assumption is discussed in more detail in chapter 4.3.3.

let

$$U_r = \sum_{t=1}^{T} \left(\frac{1}{1+\rho}\right)^t \left[\alpha_r \ln\left(\sum_s \varphi_s c_{r,s}^{\sigma}(t)\right)^{\frac{1}{\sigma}} + \beta_r \ln\left(l_r^H(t)\right)\right] \tag{4.7}$$

be the intertemporal utility function of the representative consumer of region r, where $1+\rho$ is the utility discount factor. In any period t the consumer's instantaneous utility depends on the consumption of produced commodities $c_{r,s}(t)$ as well as the use of land $l_r^H(t)$ for residential purposes. σ is the elasticity of substitution between produced commodities. α_r and β_r denote the relative shares of consumption and land use, respectively.

As is usually assumed in a general equilibrium framework, consumers are the owners of the factors of production. Let $K_r(t)$ and $W_r(t)$ denote the endowments of capital and labor, respectively, which the representative consumer of region r owns in period t. Both factors are completely flexible and are traded on open interregional markets under perfect competition at present-value prices $p^i(t)$, $i = K, W$. Furthermore suppose that the representative consumer owns the regions endowment of land $L_r^{net}(t)$. If the government levies taxes on both mobile and immobile factors, then the intertemporal budget constraint INC_r of the representative consumer in region r is given by

$$\begin{aligned} INC_r = \sum_{t=1}^{T} [(1-\tau^K)p^K(t)K_r(t) + (1-\tau^W)p^W(t)W_r(t) \\ +(1-\tau_r^L)p_r^L(t)\sum_s l_{r,s}^F(t)] \end{aligned} \tag{4.8}$$

$\tau^i, i = K, W, L$ is the tax rate on mobile capital, labor, and land, respectively. $p_r^L(t)$ denotes the region specific present value price of land.

Expenditure EXP_r of consumer r must cover (1) his spending for the consumption of produced commodities $c_{r,s}(t)$, (2) his savings, i.e., investment

$i_r^K(t)$ into the mobile capital stock and (3) his payments for land use $l_r^H(t)$, i.e.,

$$EXP_r = \sum_{t=1}^{T} \sum_{s} p_s^x(t) \left[(1-\tau^c) c_{r,s}(t) \right] + \sum_{t=1}^{T} \left[i_r^K(t) + p_r^L(t) l_r^H(t) \right]. \tag{4.9}$$

$p_s^x(t)$ denotes the present value prices of produced commodities from sector s, which are traded on interregional open markets, while τ^c are taxes on consumption. Note that because of Walras' law every representative consumer has to stay on his budget constraint. The accumulation of total stock of mobile capital over time is described by

$$K(t+1) = (1-\delta^k) K(t) + \sum_{r} i_r^k(t), \tag{4.10}$$

where $K(t+1)$ is the total stock of mobile capital and δ^k is the depreciation rate.

4.2.4 Production

In each region r, there are S production sectors. Each sector s produces a sector-specific composite commodity. Inputs into sectoral production are factors, which are traded nation-wide on open markets such as labor, capital and intermediate inputs from other sectors, but also the immobile factor land. Production is characterized by constant returns to scale and is described by a nested Cobb-Douglas-CES production function. Let $X_{r,s}(t)$ denote the net output of sector s in region r during period t. The first stage of the sectoral production function is given by

$$X_{r,s}(t) = V_{r,s}(t)^{\alpha_s} l_{r,s}^F(t)^{\beta_s} \prod_{s} \left(\sum_{r} Y_{r,s}(t)^{v^s} \right)^{\frac{\gamma_s}{v^s}}, \tag{4.11}$$

which combines in a Cobb-Douglas fashion value added $V_{r,s}(t)$, land $l_{r,s}^F(t)$ and a CES aggregate $\prod_s \left(\sum_r Y_{r,s}(t)^{v^s} \right)$ of intermediate inputs from other sectors and regions. Value added $V_{r,s}(t)$ is a CES aggregate of the mobile factors capital $k_{r,s}(t)$ and labor $w_{r,s}(t)$,

$$V_{r,s}(t) = \left[\kappa \left(k_{r,s}(t) \right)^{\varrho_s} + (1-\kappa) \left(w_{r,s}(t) \right)^{\varrho_s} \right]^{\frac{1}{\varrho_s}}. \tag{4.12}$$

κ is the share parameter of mobile capital inputs and ϱ_s denotes the elasticity of substitution between both input factors. Note that because of constant returns to scale $\alpha_s + \beta_s + \gamma_s = 1, \forall s$.

4.3 Data and Model Implementation

The theoretical model will be applied in a numerical analysis to gain a better understanding of direct and indirect impacts of floods on the Swiss economy on the one hand and to analyze and compare different strategies of financing adaptation measures in Switzerland on the other. To that end, several numerical inputs have to be specified. These are (1) parameter of the basic theoretical model, (2) a regional Input-Output table and (3) data on the damage and adaptation module of the model.

Periods are 5 years in length, 2010 is the initial year and the time horizon covers 16 periods, i.e. 80 years. Basic theoretical model parameter like the interest rate (0.05), the growth rate (0,01), the depreciation rate (0.07) as well as the utility discount factor (0.962) are taken from the literature on standard Ramsey growth models.

We calibrate the relative cost shares of the Cobb-Douglas part of the production function (value added, land, intermediate inputs) and the utility function (consumption aggregate and land used for residential proposes) to the regional input-output table discussed below.

Substitution elasticities parameter have to be assigned for (1) intermediate inputs in the production function, (2) for capital and labor inputs in value added and (3) for consumption goods from different sectors in the consumption aggregate of the utility function. All three parameter are set to 2 initially. The impact of the substitution elasticities on the results are discussed in the sensitivity analysis.

4.3.1 Regional Input-Output Table and Basic Model Parameter

A regionalized Input-Output Table of Switzerland serves the empirical basis of our analysis. This table is compiled from the official Input-Output Table of Switzerland published by the Swiss Federal Statistical Office (BFS) by using the location quotient-based interregional input-output (IRIOLQ) framework (Jahn, 2016). We use this non-survey-based approach, because, in contrast to usual spatially differentiated CGE models, the regions of our model do not coincide with existing economic, political or organizational regions of Switzerland.

Instead, for the purpose of our analysis, Switzerland is divided into three regions $\{h, m, l\}$, which differ with respect to their exposure to flood events. h indicates high exposure, m medium exposure, while l indicates low or no exposure at all. Communities are assigned to regions on the basis of information from the Swiss flood and landslide damage database of the Swiss Federal Institute for Forest, Snow, and Landscape Research (WSL). This data set contains data about any flood event in Switzerland for the time period 1970 to 2014, including the corresponding damage (expressed in CHF) on community level. Since data are available on community level they have to be aggregated to our three regions $r = \{h, m, l\}$. We use the classification of the WSL, which distinguishes between high/catastrophic damage (more than 2 million CHF or fatalities), medium damage (between 0.4 and 2 million CHF) and low or no damage at all damage (less than 0.4 million CHF).

After determining the regions, we use the location quotient-based interregional input-output (IRIOLQ) framework (Jahn, 2016) to develop an interregional input-output table. This method combines the advantages of the location quotients approach (developed by Flegg and Webber (1997)) and a variation of the interregional input-output (IRIO) framework (Canning and Wang, 2004) and maintains consistency of the regional input-output table with the national one (Jahn, 2016). Literature that compares different non-survey-based methods to derive location quotients shows that the approach of Flegg and Webber (1997) outperforms others, in particular since it simultaneously accounts for the size of the selling industry, the purchasing industry and the region (Kowalewski, 2013).

Not only do regions but also production sectors differ with respect to their vulnerability to floods. This aspect is taken into account through aggregating the 44 production sectors of the 2008 Swiss Input-Output Table to the three production sectors $s = \{I, II, III\}$. I denotes the primary sector, which includes agriculture and forestry in particular. II represents the industry sector, while III is the tertiary sector that includes services. A higher disaggregation is because of data availability problems not possible. To identify the inter-sectoral flow of (intermediate) goods and services between sectors and regions, we first need to estimate sectoral output at the smallest available administrative unit, which is the community level. We use cantonal data on sector output and employment data in full-time equivalents on community level to estimate sectoral output on community level, assuming that employment data are a good proxy for sectoral output on community level. Finally, we again aggregate community data with respect to regions and sectors. Data on land use and productivity are provided by the BFS and allow us to determine the use of production factors land, capital and labor depending on sector and region.

4.3.2 Damage

To construct damage parameter of reference floods, hydrological information about the type of flood, the expected return period and the dependence on climate change are used together with WSL data on estimated damage. During the last two decades, Switzerland was affected exceptionally often by severe floods, which mostly have a return period greater than 150 years. We selected two out of 12 major floods that hit Switzerland since the 1970s. Both differ strongly with respect to the underlying hydrological process, the affected region, the duration and the damage they caused: The first reference flood, *F-99*, persisted from February to May 1999 and affected the catchments of Thur, Aare, Linthkanal and Bodensee. This event caused estimated market damage of about 577.25 million CHF (WSL, 2014). In contrast to 1999, the second reference flood, in August 2005, lasted only five days. However, this flood in the catchments of Aare and Reuss was the largest historical event in terms of damage, which amounted to about 3109.3 million CHF (FOEN, 2008). Table 4.1 summarizes the main characteristics of these two events.

Characteristics					Damage Parameter				
Reference Flood	Catchment	Return period	Damages in mCHF	Duration		$\frac{A^C_{f,r}}{L_r}$	$\mu_{f,r}$	$\frac{Dur_{f,r}}{12}$	$D^L_{f,r}(t)$
05/1999	Thur,Aare, Linthkanal, Bodensee	> 150	751.1	3 month	l	0.134	0.1	0.33	0.004
					m	0.303	0.2		0.020
					h	0.555	0.3		0.056
08/2005	Aare, Reuss	> 150, 30	3109.3	5 days	l	0.262	0.1	0.21	0.007
					m	0.553	0.3		0.041
					h	0.686	0.4		0.069

Table 4.1: Characteristics of selected reference floods

Based on (1) WSL data on flood damage on community level and (2) BFS data on community areas, we are able to derive the damage parameter $A_{f,r}(t)$ and $Dur_{f,r}(t)$. We do not know the exact value of $A_{f,r}(t)$, because there are no data on the exact share of the damaged area in every community. However, what we know is, which community is affected and its area$A^C_{f,r}(t)$. Thus, we have to assume a share μ_r of the given area that is affected, i.e. $A_{f,r}(t) = \mu_r A^C_{f,r}(t)$. Because region l covers also a high share of communities that ar not affected at all, we assume $\mu_{r=l} < \mu_{r=h,m}$. The impact of the assumed values (see table 4.5) will be revealed in the sensitivity analysis.

4.3.3 Adaptation Strategies

Remember, there are two crucial characteristics of adaptation to floods in Switzerland, we have to account for in our analysis: (1) There is a time lag between the decision to adapt (proactively) and the first effects of adaptation measures if a flood occurs. (2) The federal political system in Switzerland allows for different financing schemata. The Federal Government and/or regional authorities (at different levels canton, community) can be in response. Table 4.2 summarizes the characteristics of the main possible adaptation measure to floods in Switzerland.

	Infrastructural incentive system		Spatial Planning			Information and Persuasion	
	Dam, lake level regulation, retention basins, river redirection	Mobile walls	Protection forest	Richtplan	Hazard Map	Research Monitoring	Alarm system
Time lag between decision and effects in years	5 – 10	2 or less	30	20	10	30	5
Effectiveness to prevent floods	measurable			uncertain			rather measurable
Level of decision-making	regional/local		multilevel	inter-regional	regional	mostly national /cantonal	
Target group for implementation	regional/local		multilevel	local	regional/ local	mostly national /cantonal	
Level of finance	multilevel			regional	multilevel	national/ cantonal	multilevel

Table 4.2: Characteristics of flood protection measures in Switzerland

Source: This overview is the result of an investigation undertaken by the CCAdapt team. Please find the sources in Appendix E.

Proactive measures (all, except mobile walls, and alarm systems) need a lead time between 10 and 30 years. Additionally we assume that there is a time lag between the decision to adapt and the first actual expenditure to finance adaptation. Therefore, and as our model runs in 5 year time intervals, the parameter v can take values between two and five and is set to $v = 3$ initially. While decision making and target group of infrastructural incentive systems and structural measures are rather in hands of regional authorities, information and persuasion policies are in hands of the national government. Remember, that we assume regional adaption expenditure to be more efficient than national ones, i.e. $\psi_R \geq \psi_N$. Major reasons are: (1) National authorities are not allowed to discriminate between regions. While national law applies in all regions equally, regional regulations are adapted to the specific characteristics of the respective region. (2) Using national instead of regional funds is strictly preferred by regional authorities and thus the political process of acquiring national funds may result in a politically driven and not necessarily most effective (in terms of preventing damage) allocation of adaptation expenditure to regions. (3) Regional authorities may be better informed about the vulnerability and adaptation capacity of their region and (4) the transformation of the enhanced knowledge of research and monitoring measures (responsibility of the Federal Government) into policy is usually uncertain and long-lasting[7].

4.4 Scenarios

There are two characteristics through which the scenarios are classified we use in our counterfactual analysis. These are the type of a flood on the one hand and the schema for financing adaptation measures on the other.

4.4.1 Type of Floods

As mentioned above there are two reference floods. Based on their characteristics, we assume in the following three flood scenarios: Scenario F-99 assumes a 1999-like flood and Scenario F-05 a 2005-like flood to hit Switzerland in 2040. The third scenario F-9905 assumes a 1999-like flood to hit Switzerland in 2025 and a 2005-like flood to hit Switzerland in 2055 (see Table 4.3).

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[7] see sources no 2,3,4,11,13,16,20 in appendix E

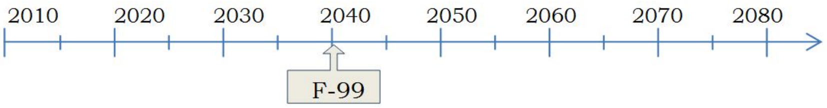
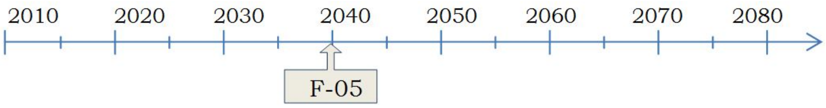
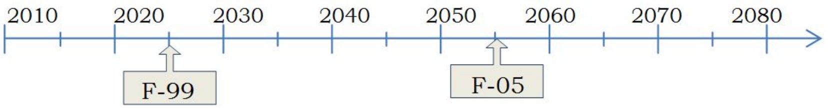
Flood Scenarios	
F-99	
F-05	
F-9905	

Table 4.3: Flood scenarios

4.4.2 Funding of Adaptation Strategies

In order to analyze the impact of different financing strategies on welfare, production output and damage prevention, three options for financing adaptation are considered. We differentiate not only between the regional or national authority that is in charge, but also between funding adaptation measures by taxes on output and land. Of course, financing through other sales or income tax is possible as well. Table 4.4 gives an overview on the three funding Schema. In the first one (R), the regional government levies taxes on land. In the second one (N), the national government taxes the output of production sectors, which is mobile across regions. In the third one (T), we assume a financial equalization approach between the two governmental levels. While regional governments levy a tax on land (exogenously determined), the national government levies an (endogenous) production tax in order to co-finance regional adaptation via transfers (TR_r) to the regional government. In all three scenarios, the governments budgets are balanced period by period, i.e. their total revenue equals their total expenditure for adaptation measures and transfers.

Remember, we aim for optimal adaptation. Consequently, the level of adaptation expenditure is determined by the decision rule price of adaptation expenditure in region r and sector s equals the value of marginal benefits (prevented damage) of adaptation (see equation 4.6). Table 4.4 summarizes the three different funding scenarios to finance adaptation expenditure and the budget constraints of the responsible regional and/or national governments that are balanced period-by-period.

Funding scenario		Budget constraint
R	Adaptation is exclusively financed by regional governments	Regional government: $\tau_r^L(t)p_r^L(t)L_r = AD_r(t)$
N	Adaptation is exclusively financed by the national government	National government: $\sum_{r,s}\tau_{r,s}^x(t)p_{r,s}^x(t)x_{r,s}(t) = \sum_r AD_r(t)$
T	Adaptation is financed by exogenous regional land tax and financial equalization, i.e. the national government pays transfers to regional governments	Regional governments: $\tau_r^L(t)p_r^L(t)TR_r = AD_r(t)$ National government: $\sum_{r,s}\tau_{r,s}^x(t)p_{r,s}^x(t)x_{r,s}(t) = TR_r$

Table 4.4: Funding options

Through combining options to finance adaptation with flood events, we get nine scenarios in total. Nicknames of scenarios are combination of short cuts introduced above, for example $F05 - R$ would indicate a scenario, where a 2005 like flood hits Switzerland in 2040 ($F05$) and where adaptation is financed by regional governments only.

4.5 Results

4.5.1 Direct and Indirect Impacts of Floods without Adaptation

Let us start the analysis by considering the direct and indirect impacts of 1999 ($F-99$) and/or 2005 ($F05$) like reference floods on an unadapted Swiss economy. For comparison the benchmark economy is by assumption the Swiss economy, which is neither hit by any flood nor adapted to floods. First, we analyze direct impacts of all three flood scenarios. The third column of table 4.5 shows the damage parameter, which we derived according to the damage function approach proposed by Carrera et al. (2015) and which are based on the parameter specified in table 4.2. Remember, we have only information on the overall damage in land supply but no information about the share of land used by households or firms that is destroyed. The reduction of the overall land supply increases the price for land and consequently reduces the demand for land by households and the production sectors. However, while in high exposed regions $r = h$, private households land use is reduced (slightly) stronger than by all production sectors together, we see the opposite impact in medium and low exposed regions $r = m, l$.

		Damage parameter	Direct impacts		Indirect impacts on			
Flood Scenario	Region	$D^L_{f,r}(t)$	l^H_r	$\sum_s l^F_{r,s}$	$s = I$	$s = II$	$s = III$	Welfare
$F - 99$	l	0.004	-0.246	-0.477	-0.044	0.305	-0.062	-0.049
	m	0.020	-1.841	-2.079	0.158	-0.170	-0.149	-0.056
	h	0.056	-5.817	-5.492	0.206	-0.121	-0.047	-0.065
$F - 05$	l	0.005	-0.322	-0.589	-0.028	0.305	-0.058	-0.056
	m	0.034	-3.224	-3.488	0.175	-0.170	-0.154	-0.067
	h	0.057	-5.908	-5.596	0.252	-0.119	-0.044	-0.072
$F - 9905$	l	like $F - 99$ in 2025 and like $F - 05$ in 2055			-0.028	0.305	-0.058	-0.056
	m				0.175	-0.170	-0.154	-0.067
	h				0.252	-0.119	-0.044	-0.072

Table 4.5: Damage - direct and indirect impacts (change rate in percent) caused by reference floods in an unadapted economy

While direct impacts of floods capture only damage caused by destroyed land, indirect impacts take general equilibrium effects into account. Table 4.6 presents the percentage change of prices compared to the baseline values for land in region $r = h$ caused by reference floods in an unadapted economy. As expected, the price of land increases in consequence of increased scarcity of land that is on the one hand used as production input and entering the utility function of households on the other.

	<2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080
F-99	0.00	0.00	0.00	0.00	8.23	1.10	0.70	0.90	1.15	1.47	0.00	0.00	0.00
F-05	0.00	0.00	0.00	0.00	8.66	1.10	1.41	1.80	1.15	1.47	0.00	0.00	0.00
F-9905	0.00	8.32	1.06	1.36	1.30	1.10	1.41	9.91	2.30	2.94	1.85	2.38	3.03

Table 4.6: Change of price for land in region $r = h$ in percentage

Column 6 - 8 of table 4.5 summarize the impact of the three reference floods on sector outputs in the three regions (summed over all periods). Independently of the flood scenario and the region, the overall output in sector III decreases (by between -0.058 and -0.357%). Also the output of sector II in regions $r = m, h$ decreases (by between -0.17 and -0.401%), independently of the flood scenario. To compensate the decrease of the production output in sector II (by between -0.119 and -0.282%) and III (by between -0.044 and -0.106%) in region $r = h$, the production output of sector I in region $r = m, h$ increases (by between 0.158 and 0.567%) as well as the production output of sector II in region $r = l$ (by between 0.305 and 0.715%). While the output of sector II and III in region $r = h$ decreases clearly, the output of the clearly smallest production sector I is increased. Overall, regional output decreases in region $r = h$, depending on the scenario, by between -0.07 and -0.167% and increases in region $r = l$, depending on the scenario by between 0.109 and 0.258%. Regional welfare decreases in all flood scenarios by between -0.049 and -0.116% (table 4.5, column 9). Independently of the flood scenario, the welfare loss is largest in high exposed regions $r = h$ and smallest in region $r = l$.

4.5.2 Direct and Indirect Impacts of Floods in an Optimally Adapted Economy

In contrast to section 4.5.1, we now analyze the impact of reference floods in case of an optimal adapted economy depending on the financing options discussed above. Remember, all results presented in chapter 4.5.1 and 4.5.2 include autonomous adaptation by the economy in consequence of price changes etc. However, this chapter summarizes the impacts of the explicit implementation of adaptation measures. Table 4.7 summarizes for every combination of flood and financing scenarios the (1) direct impacts (residual damage), (2) adaptation expenditure, (3) tax rates and (4) indirect impacts on regional and sectoral output as well as welfare in reaction on price changes. In case of financing scenarios R and T, optimal adaptation results in a reduction of land supply by -0.005% in region $r = l$, by -0.006% in region $r = m$ and -0.003% in region $r = h$. Because of information asymmetries, nationally financed adaptation (N) is less efficient. Consequently, compared to scenario R and T despite of higher adaptation expenditure less land damage are reduced. In most vulnerable regions $r = h$ land supply is reduced by between -0.025 and -0.031%. However, this is a strong improvement compared to a reduction of land supply by about -5.5 to -6% in case without adaptation at comparably low costs. Because of the higher tax base, tax rates are lower if adaption is financed by output tax compared to land tax.

Flood scenario	Adaptation scenario	Region	Direct impact l_r^H	$\sum_s l_{r,s}^F$	Adaptation expenditure in mill CHF	Tax rate$*100$	Indirect impact on Output in $s =$			Welfare
			in $t = 2040$ bzw. $t = 2025, 2055$				I	II	III	$*100$
F-99	R	l	−0.005	−0.005	1.450	0.011	1.281	0.014	−0.015	−0.018
		m	−0.006	−0.006	1.943	0.017	−0.113	−0.043	−0.176	−0.023
		h	−0.003	−0.003	2.465	0.012	2.052	0.042	0.047	−0.018
	N	l	−0.002	−0.003	2.001	0.0005	4.766	−0.013	−0.093	−0.045
		m	−0.009	−0.010	2.142		2.524	−0.198	−0.006	−0.048
		h	−0.031	−0.029	2.094		−0.126	−0.128	−0.018	−0.053
	T	l	−0.005	−0.005	1.450	0.0005	5.069	−0.096	−0.068	−0.038
		m	−0.006	−0.006	1.943		2.956	−0.163	0.034	−0.041
		h	−0.003	−0.003	2.465		−0.132	−0.129	−0.017	−0.040
F-05	R	l	−0.005	−0.005	1.525	0.011	1.429	0.010	0.03	−0.018
		m	−0.006	−0.006	2.120	0.018	−0.009	−0.006	−0.172	−0.024
		h	−0.003	−0.003	2.471	0.012	1.429	0.010	0.031	−0.018
	N	l	−0.002	−0.004	2.025	0.0005	5.650	0.001	−0.092	−0.046
		m	−0.015	−0.016	2.148		2.699	−0.376	0.009	−0.051
		h	−0.027	−0.025	2.160		−0.135	−0.129	−0.018	−0.052
	T	l	−0.005	−0.005	1.525	0.0005	9.602	−0.040	−0.168	−0.030
		m	−0.006	−0.006	2.120		−0.179	−0.376	0.022	−0.031
		h	−0.003	−0.003	2.471		−0.129	−0.128	−0.016	−0.036
F-9905	R	l	−0.005	−0.005	2.975	0.011	0.304	0.011	0.007	−0.028
		m	−0.006	−0.006	4.063	0.018	−0.165	0.021	−0.017	−0.035
		h	−0.003	−0.003	4.937	0.012	0.096	−0.072	−0.011	−0.028
	N	l	−0.001/ −0.002	−0.003/ −0.004	4.047	2025: 0.0005, 2055: 0.0004	9.473	0.065	−0.171	−0.084
		m	−0.018/ −0.015	−0.012/ −0.010	4.430		2.049	−0.403	−0.078	−0.090
		h	−0.025/ −0.027	−0.028/ −0.029	4.213		−0.300	−0.302	−0.041	−0.092
	T	l	−0.005	−0.005	2.975	2025: 0.0005, 2055: 0.0004	18.294	−0.130	−0.258	−0.097
		m	−0.006	−0.006	4.063		−0.497	−0.485	−0.092	−0.100
		h	−0.003	−0.003	4.937		−0.274	−0.298	−0.041	−0.097

Table 4.7: Optimal adaptation scenario

With respect to output changes the results can be summarized as follows:

(1.) In financing scenario R, highly vulnerable regions $r = h$, and in scenario T and N, less vulnerable regions ($r = m$ and/or l) increase their production output. Figure 4.1 illustrates this result for flood scenario F-05 and aggregated over all three sectors.

(2.) dependently of the flood and the financing scenario, sector II's output tends to decrease most and sector I outputs tends decrease less (or even increases).

Although the first production sector depends most on land, this sector even increases its output in some scenarios. Because about 1/3 of the Swiss area are agricultural areas while only ca. 7.5% of the Swiss area are used for settlement and by the second and third production sector (BFS, 2016), the relative scarcity of land is the lowest in the first production sector. Additionally, we can, due to data availability problems, not distinguish which share of land (meaning used by which sector or by households for settlement) is hit most by a flood and therefore not account for eventually larger damage in land used by the first in contrast to the second and third production sector.

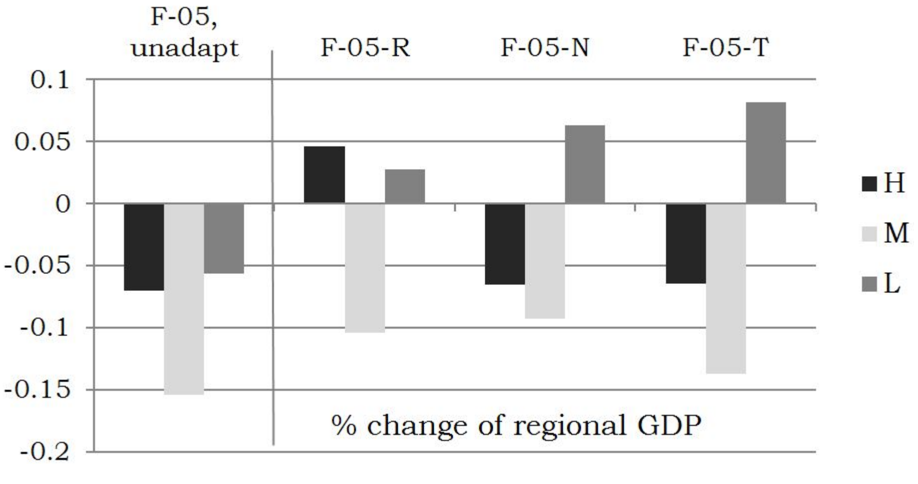


Figure 4.1: Percentage change of regional GDP in an unadapted economy (left) and depending on the financing scenario (right)

With respect to welfare changes there are two conclusions mainly:

(1.) The welfare loss from floods in an optimally adapted economy is smallest in case of financing scenario R (regional government, tax on land).

(2.) The impact on welfare, if adaptation to F-99 and F-05 is financed by the national government with an output tax (Scenario N), is worse, compared to the situation that it is financed via transfers (Scenario T). However, in flood scenario F-9905 optimal adaptation has a worse effect on welfare if it is financed via transfers and land tax (Scenario T) in contrast to a national output tax (Scenario N).

Figure 4.2 shows the impact of the reference flood F-05 on welfare in the three regions, without explicit adaption and depending on the scenario to finance adaptation.

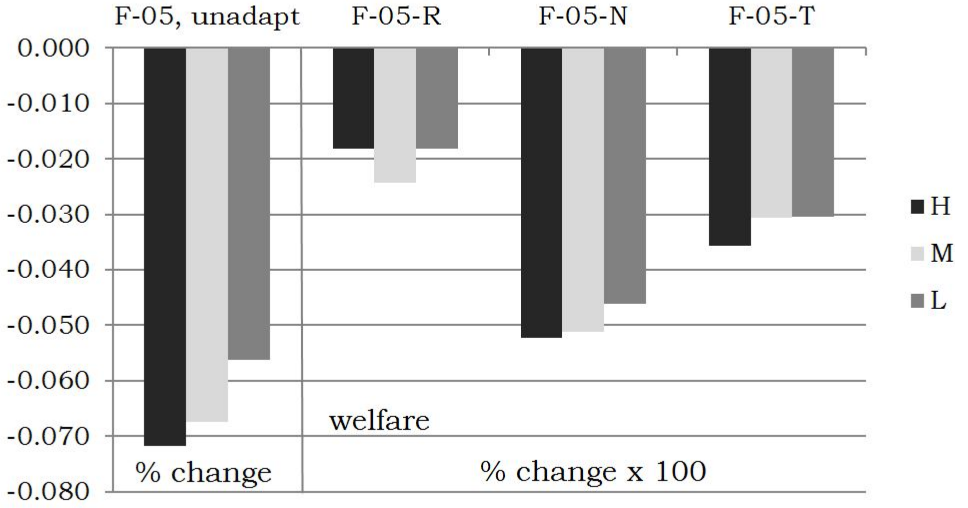


Figure 4.2: Percentage change of welfare in an unadapted economy (left) and depending on the financing scenario (right)

4.5.3 Insights from Sensitivity Analysis

As usual in General Equilibrium analyses, results very much depend on numerical inputs and model parameter specification. To evaluate the impact of defined values for elasticity of substitution for intermediate inputs from other sectors (υ^s), inputs from different sectors in the consumption aggregate (σ) and capital and labor input in value added (ϱ), we conduct a sensitivity analysis assuming instead of $\{\upsilon = \sigma = \varrho = 2\}$ the values $\{\upsilon = \sigma = 4, \varrho = 1.2\}$ and $\{\upsilon = \sigma = 0.5, \varrho = 4\}$, respectively.[8] With respect to direct damage in an unadapted economy we find, independently of the flood scenario, for the parameter combination $\{\upsilon = \sigma = 0.5, \varrho = 4\}$ a slightly stronger decrease in land use by firms and a slightly less strong decrease in land use by households in region $r = l$ and $r = m$. The opposite effect is true for region $r = h$. The most obvious difference concerning indirect impacts is the considerable adjustment of outputs depending on the production sector, independently of the region and the flood scenario. The output of sector I increases strongly (by between 10.4 and 24.5%) in the least vulnerable region $r = l$. However, the output in sector II and III decreases. We find a less strong reduction of welfare (between -0.035 and -0.085%) for the parameter combination $\{\upsilon = \sigma = 0.5, \varrho = 4\}$ compared to the parameter combination $\{\upsilon = \sigma = \varrho = 2\}$ (between -0.049 and -0.116%).

If we assume elasticities of substitution $\{\upsilon = \sigma = 4, \varrho = 1.2\}$ we again find that in regions $r = l, m$ the reduction in land use by firms is stronger and reduction of land use by households is less strong, compared to the initial situation $\{\upsilon = \sigma = \varrho = 2\}$. However, in the most vulnerable region $r = h$, we find the opposite impact. The impact of floods in an unadapted economy on regional and sectoral output changes only marginally and only in terms of the size, not in the direction of the impact. But, compared to the initial situation $\{\upsilon = \sigma = \varrho = 2\}$ and the parameter combination $\{\upsilon = \sigma = 0.5, \varrho = 4\}$ we find the worse impact on welfare (between -0.062 and -0.09% in Flood Scenario $F - 99$ and $F - 05$).

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[8] A detailed overview on the results of the sensitivity analysis can be found in appendix 4.D and 4.C

4.6 Conclusion

Within the framework of an intertemporal General Equilibrium approach, this paper gives insights into direct and indirect impacts of floods as well as optimal flood adaption from a regionally diversified perspective. Furthermore it compares different strategies for financing adaptation in a federalist system, where local and national governmental authorities, which have different information, interplay in the provision of the local public good.

Our results suggest that general equilibrium effects are crucial, if national adaptation strategies should be defined. Regions, which are not directly affected from flood events nevertheless suffer from indirect effects and therefore might also be interested in an efficient adaptation. Our approach in particular accounts for secondary effects and hence allows for differentiating between welfare losses and damage in the output, i.e. market damage that result from lower land supply and total demand for consumption goods. Furthermore, based upon our results we are convinced that our approach to define regions depending on their vulnerability to floods and not on area municipalities gives insights on (1) how areas, which are indirectly affected via general equilibrium effects, suffer, (2) if and how the cooperation between affected and not affected regions in case of adaptation to floods is feasible.

Conditional to the assumption that because of information asymmetries, regionally financed adaptation is more effective, we are able to show that the least negative impact on regional output and welfare is achieved if adaptation to flood events is financed and implemented by regional governments. Only output in region $r = m$ decreases marginally less, if adaptation to flood events is financed by a national output tax. While in flood scenarios F-99 and F-05, the results of the transfer scenario T are predominantly better compared to a scenario, where the national government finances adaptation (always in terms of welfare), the transfer scenario T has the worst impact on output and welfare if we assume flood scenario F-9905. Obviously, there are several options for extending the present analysis further. The most important one could be to introduce uncertainty by using a stochastic version of the model. On the one hand this is a reasonable assumption in the context of climate extreme events, which are characterized by low probability to occur, but a high impact if they occur. On the other hand, the possibility to simulate these models may be limited. We leave these extensions to future research. Furthermore, if special adaption measures should be analyzed, it would be possible to account for the fact that adaptation expenditure are concentrated on specific sectors.

4.A Input-Output Table

		I			*II*			*III*			*CON*			*INV*
		l	*m*	*h*	*l*	*m*	*h*	*l*	*m*	*h*	*l*	*m*	*h*	
I	*l*	9736	−128	−103	−5298	−407	−364	−583	−52	−42	−835	−657	−1153	−114
	m	−128	3967	−42	−426	−1858	−149	−40	−204	−17	−344	−271	−476	−12
	h	−103	−42	3151	−345	−135	−1444	−33	−17	−159	−273	−215	−378	−7
II	*l*	−1573	−125	−101	138601	−6755	−6033	−29669	−2635	−2142	−12580	−10073	−16537	−50378
	m	−128	−520	−40	−6755	56638	−2362	−1961	−9962	−838	−4607	−3689	−6056	−19720
	h	−115	−44	−445	−6034	−2362	49952	−1752	−921	−8530	−3895	−3119	−5119	−17616
III	*l*	−1145	−81	−66	−32860	−2545	−2272	176507	−7693	−6253	−33225	−27690	−50473	−12204
	m	−106	−533	−35	−3417	−14817	−1195	−7693	93216	−3287	−16619	−13850	−25246	−6418
	h	−99	−35	−417	−2777	−1087	−11549	−6253	−3288	75015	−13212	−11011	−20071	−5216
	LAB	−5015	−2340	−1672	−43801	−17052	−15046	−128393	−67540	−53497	99732	86444	148180	0
	CAP	−132	−12	−23	−29510	−7696	−7630	−65	−452	−125	8964	12772	23909	0
LAN	*l*	−1192	0	0	−7378	0	0	−65	0	0	8635	0	0	0
	m	0	−107	0	0	−1924	0	0	−452	0	0	2483	0	0
	h	0	0	−207	0	0	−1908	0	0	−125	0	0	2240	0
	INV	0	0	0	0	0	0	0	0	0	−31741	−31124	−48820	111685

Table 4.8: Regional Input-Output Table

4.B Overview of Severe Flood Events in Switzerland since 1999

Time	Catchment	Canton	Magnitude	Return period	Damages in m CHF	Duration	Short Information
05/1999	Thur, Aare, Linthkanal, Bodensee	Zrich/ Bern	$1129\frac{m^3}{s}$ $613\frac{m^3}{s}$	> 150 > 150	751.1	3 Month	Extensive damage: Differs in many aspects to 2005 (from hydrological point of view)
10/2000	Lago Maggiore in Wallis, Tessin	Vallis/ Tessin	$777.4\frac{m^3}{s}$			7 days	Could serve as an example of a lake case, which may differ from other floods w.r.t. adaptation measures and spatial development.
08/2005	Aare, Reuss	Bern/ Uri	$605\frac{m^3}{s}$ $523\frac{m^3}{s}$	> 150 30	(805) (365) 3109.3	5 days	The largest historical event in terms of damage
08/2007	Birse, Aare	Jura/ Bern	$383\frac{m^3}{s}$ $524\frac{m^3}{s}$	> 150 62	722.2	3 days	similar to 2005 in terms of underlying processes. Could be interesting in order to understand how adaptive behavior has reduced costs relative to 2005.
2011	Kander	Bernese	Kander $65\frac{m^3}{s}$, Lötschtal $120\frac{m^3}{s}$	> 100 $30 - 100$	118.2 (55 CHF)	2 days	This process may increase in frequency due to climate change

Table 4.9: Overview of Severe Flood Events in Switzerland since 1999

4.C Sensitivity Analysis - Damage

		Damage Parameter	Direct Impacts		Indirect Impacts			
Flood Scenario	Region	$D^L_{f,r}(t)$	l^H_r	$\sum_s l^F_{r,s}$	$s = I$	$s = II$	$s = III$	Welfare
	l	0.004	-0.254	-0.473	10.493	-0.150	-0.074	-0.035
$F - 99$	m	0.020	-1.859	-2.070	0.132	-0.183	-0.156	-0.041
	h	0.056	-5.804	-5.498	0.241	-0.066	-0.005	-0.052
	l	0.005	-0.331	-0.584	10.404	-0.148	-0.072	-0.040
$F - 05$	m	0.034	-3.244	-3.478	0.173	-0.178	-0.156	-0.051
	h	0.057	-5.894	-5.603	0.247	-0.062	-0.003	-0.057
	l	like $F - 99$ in 2025 and like $F - 05$ in 2055			24.537	-0.350	-0.172	-0.064
$F - 9905$	m				0.372	-0.423	-0.366	-0.074
	h				0.603	-0.153	-0.009	-0.085

Table 4.10: Sensitivity analysis for $v = \sigma = 0.5, \varrho = 4$

		Damage Parameter	Direct impacts		Indirect impacts on			
Flood Scenario	Region	$D^L_{f,r}(t)$	l^H_r	$\sum_s l^F_{r,s}$	$s = I$	$s = II$	$s = III$	Welfare
	l	0.004	-0.236	-0.482	-0.054	0.322	-0.047	-0.062
$F - 99$	m	0.020	-1.818	-2.091	0.150	-0.149	-0.153	-0.068
	h	0.056	-5.833	-5.483	0.174	-0.196	-0.112	-0.078
	l	0.005	-0.310	-0.595	-0.012	0.325	-0.041	-0.076
$F - 05$	m	0.034	-3.198	-3.501	0.174	-0.150	-0.147	-0.087
	h	0.057	-5.928	-5.586	0.217	-0.198	-0.108	-0.090

Table 4.11: Sensitivity analysis for $v = \sigma = 4, \varrho = 1.2$

4.D Sensitivity Analysis - Adaptation Scenarios

Flood Scenario	Adaptation Scenario	Region	Direct impact l_r^H in $t = 2040$ bzw. $t = 2025, 2055$	$\sum_s l_{r,s}^F$	Adaptation expenditure in mill CHF	Tax rate∗100	Indirect impact Output I	II	III	Welfare ∗100
F-99	R	l	−0.005	−0.005	1.450	0.011	1.488	0.012	0.018	−0.016
		m	−0.006	−0.006	1.943	0.017	−0.147	−0.074	−0.173	−0.021
		h	−0.003	−0.003	2.465	0.012	1.220	0.007	0.020	−0.017
	N	l	−0.002	−0.003	2.070	0.0005	6.947	−0.106	0.004	−0.034
		m	−0.010	−0.011	2.093		3.108	−0.377	−0.101	−0.036
		h	−0.030	−0.029	2.100		−0.168	−0.130	−0.019	−0.042
	T	l	−0.005	−0.005	1.450	0.0005	10.826	−0.118	−0.015	−0.031
		m	−0.006	−0.006	1.943		0.616	−0.368	−0.272	−0.032
		h	−0.003	−0.003	2.465		−0.175	−0.129	−0.018	−0.034
F-05	R	l	−0.005	−0.005	1.525	0.011	0.536	0.008	0.010	−0.017
		m	−0.006	−0.006	2.120	0.018	−0.068	−0.015	−0.054	−0.023
		h	−0.004	−0.003	2.471	0.012	0.406	−0.041	0.002	−0.017
	N	l	−0.002	−0.003	2.138	0.0005	9.532	−0.120	−0.066	−0.037
		m	−0.015	−0.016	2.150		2.875	−0.376	−0.125	−0.042
		h	−0.027	−0.026	2.151		−0.144	−0.129	−0.018	−0.044
	T	l	−0.005	−0.005	1.525	0.0005	7.850	−0.118	−0.037	−0.036
		m	−0.006	−0.006	2.120		3.502	−0.325	−0.112	−0.039
		h	−0.003	−0.003	2.471		−0.150	−0.129	−0.018	−0.038
F-9905	R	l	−0.005	−0.005	2.975	0.011	3.268	0.002	0.021	−0.022
		m	−0.006	−0.006	4.063	0.017	−0.319	−0.284	−0.249	−0.030
		h	−0.003	−0.003	4.937	0.012	3.223	0.038	0.055	−0.024
	N	l	−0.001/ −0.002	−0.003	4.238	2025: 0.0005 2055: 0.0004	7.473	−0.072	0.081	−0.058
		m	−0.008/ −0.015	−0.010/ −0.016	4.298		4.279	−0.527	−0.172	−0.063
		h	−0.031/ −0.027	−0.030/ −0.026	4.240		−0.393	−0.305	−0.044	−0.067
	T	l	−0.005	−0.005	2.975	2025: 0.0005 2055: 0.0016	19.174	−0.300	−0.088	−0.078
		m	−0.006	−0.006	4.063		5.319	−0.569	−0.315	−0.081
		h	−0.003	−0.003	4.937		−0.347	−0.304	−0.043	−0.080

Table 4.12: Optimal adaptation - sensitivity analysis for $\upsilon = \sigma = 0.5, \varrho = 4$

Flood Scenario	Adaptation Scenario	Region	Direct impact		Adaptation expenditure in mill CHF	Tax rate*100	Indirect impact on			
			l_r^H	$\sum_s l_{r,s}^F$			Output			Welfare
			in $t = 2040$ bzw. $t = 2025, 2055$				I	II	III	$*100$
F-99	R	l	-0.005	-0.005	1.450	0.011	0.405	0.060	-0.184	-0.015
		m	-0.006	-0.006	1.943	0.017	0.598	0.324	-0.180	-0.019
		h	-0.004	-0.003	2.465	0.012	2.382	-0.032	0.181	-0.017
	N	l	-0.001	-0.003	2.097	0.0005	0.866	-0.001	-0.167	-0.065
		m	-0.009	-0.011	2.107		-0.153	0.486	0.056	-0.061
		h	-0.031	-0.029	2.096		-0.088	-0.126	-0.018	-0.058
	T	l	-0.005	-0.005	1.450	0.0005	0.296	-0.049	-0.167	-0.025
		m	-0.006	-0.006	1.943		0.012	0.484	0.180	-0.024
		h	-0.004	-0.003	2.465		0.019	-0.125	-0.016	-0.033
F-05	R	l	-0.005	-0.005	1.525	0.011	0.264	-0.018	-0.128	-0.022
		m	-0.006	-0.006	2.120	0.018	4.900	0.195	-0.390	-0.028
		h	-0.004	-0.003	2.471	0.012	1.050	0.286	0.240	-0.021
	N	l	-0.001	-0.003	2.145	0.0005	0.931	0.144	-0.167	-0.058
		m	-0.015	-0.017	2.140		-0.170	0.176	-0.012	-0.064
		h	-0.027	-0.026	2.154		-0.079	-0.127	-0.017	-0.065
	T	l	-0.005	-0.005	1.525	0.0005	1.310	-0.020	-0.108	-0.044
		m	-0.006	-0.006	2.120		-0.176	0.340	0.031	-0.046
		h	-0.004	-0.003	2.471		-0.090	-0.127	-0.016	-0.046

Table 4.13: Optimal adaptation - sensitivity analysis for $\upsilon = \sigma = 4, \varrho = 1.2$

4.E URL-Sources for an Overview on Adaptation Measures

Quelle	URL
Leitbild Bevlkerungsschutz	http://www.bebende.ch/download/leitbild-d.pdf
Planat-Hochwasser	http://www.planat.ch/de/fachleute/risikomanagement/vorbeugung/vorsorge/; http://www.planat.ch/de/fachleute/strategie-naturgefahren/
Monitoring-Landschaft	http://www.bafu.admin.ch/landschaft/00524/01676/01682/index.html?lang=de
Monitoring-Klimawandel	http://www.bafu.admin.ch/klimaanpassung/11529/index.html?lang=de
Kantonale Richtplne	http://www.are.admin.ch/themen/raumplanung/00234/00363/index.html?lang=de
Bsp Gefahrenkarten Sarnen	http://www.bafu.admin.ch/naturgefahren/11421/11424/index.html?lang=de&printstyle=yes
Gefahrenkarten/ Gefahrengrundlagen	http://www.bafu.admin.ch/naturgefahren/11421/index.html?lang=de
Gefahrenkarte-ZH	http://www.awel.zh.ch/internet/baudirektion/awel/de/wasserwirtschaft/naturgefahren/gefahrenkarte.html
Funkberwachung	http://www.polyscope.ch/site/assets/files/28665/ps5142627.pdf
Beobachter-Gefahren in CH	http://www.beobachter.ch/natur/forschung-wissen/artikel/naturgefahrenwo-es-in-der-schweiz-am-gefaehrlichsten-ist/

Quelle	URL
Damm soll Camping schtzen-BE, http://tt.bernerzeitung.ch/region/freiburg/Damm-soll-Camping-schuetzen-/story/18619625	
Sanierung Hagneckkanal	http://www.hagneckkanal.bve.be.ch/hagneckkanalbve/de/index/navi/index/ueberuns/publikationendownloads.assetref/dam/documents/BVE/AWA/de/GWRHagneck/GWRHagneckAustellungsplakat.pdf
Mobiler Hochwasserschutz - Entscheidungshilfe	http://vkf.ch/getmedia/fee52668-ce6f-4e89-8dce-1520515ed30e/EntscheidungshilfeHochwasserschutzd.pdf.aspx
Funnkberwachung gegen Naturkatastrophen	http://www.geopraevent.ch/wp-content/uploads/2013/03/zhaw2313WebES.pdf
Klimanderung und Wasserkraftnutzung	http://www.hydrologie.unibe.ch/projekte/ccwasserkraft.htmltop
Rhonekorrektur	https://www.vs.ch/NavigData/DS12/M16522/de/RhonerapportimpactD.pdf
Rhonekorrektur, BAFU	http://www.bafu.admin.ch/naturgefahren/01916/10139/10140/index.html?lang=de
Linthkanal	http://www.bafu.admin.ch/naturgefahren/01916/10139/10142/index.html?lang=de
Kt. Wallis-Rhonekorrektur	http://www.vs.ch/Navig/nservice.asp?MenuID=806&Language=de
Waldschutz	http://www.wsl.ch/fe/walddynamik/waldschutz/indexDE
Wiederaufforstung	http://www.ecoeng.ch/de/competences-prestations/foret-environnement.html
Richtplan-ZH	http://www.are.zh.ch/internet/baudirektion/are/de/raumplanung/kantonalerrichtplan.html
Richtplan-Revision-BL	http://www.baselland.ch/2006-291txt-htm.276630.0.html
Gefahrenkarten AG	https://www.ag.ch/media/kantonaargau/bvu/dokumente2/umweltnaturlandschaft/hochwasserschutz1/gefahrenkartehochwasser1/gefahrenkarte

Quelle	URL
GEWISS, BAFU (Gewsser EZG)	http://www.bafu.admin.ch/hydrologie/01835/02114/02116/index.html?lang=de
Finanzieurng Wasserkraft Sanierung	http://www.admin.ch/ch/d/gg/pc/documents/2460/Sanierung-Wasserkraftanlagen-FinanzierungModulde.pdf
PLANAT-Alarmsystem	http://www.planat.ch/de/fachleute/risikomanagement/bewaeltigung/einsatz/
Hochwasserschutz - KGV	http://vkf.ch/getmedia/e9ff22fd-2d59-4b2e-9d7d-54328716e85e/MobilerHochwasserschutzd.pdf.aspx
Hochwasserschutzprojekte Kt. ZH	http://www.awel.zh.ch/internet/baudirektion/awel/de/wasserwirtschaft/hochwasserschutzundrenaturierung.html
Rckhaltebecken	http://www.baukader.ch/?rub=677
Der Boden als Rckhaltebecken	http://www.soil.ch/cms/fileadmin/Medien/medien/MMHochwasserschutz.pdf
Rckhaltebecken statt Klranlage	http://www.aargauerzeitung.ch/schweiz/rueckhaltebecken-statt-klaeranlage-1454704
HWS Rckhaltebecken	http://www.umweltschutz2.zh.ch/db/pdf/zup55-08hochwasserrueckhaltebecken.pdf
Entlastungsstollen Thun	http://www.bve.be.ch/bve/de/index/wasser/wasser/wasserregulierung/entlastungsstollenthun.html
Prognoseregulierung Bielersee	http://www.bve.be.ch/bve/de/index/wasser/wasser/wasserregulierung/prognoseregulierung.html
Seeregulierung Kanton Bern Hochwasserschutzkonzept	http://www.news.admin.ch/NSBSubscriber/message/attachments/15141.pdf
Kleine Emme	https://hochwasserschutz-emme-reuss.lu.ch/-/media/HochwasserschutzEmmeReuss/Dokumente/Gesamtprojekt/20060324planungsbericht136.pdf?la=de-CH

Quelle	URL
Waldgesetz	http://www.admin.ch/opc/de/classified-compilation/19910255/201307010000/921.0.pdf
Natur-&Heimatschutzgesetz	http://www.admin.ch/opc/de/classified-compilation/19660144/index.html
ShowMe	http://map.bafu.admin.ch/?Y=660000.00&X=190000.00&zoom=1&bgLayer=ch.swisstopo.pixelkarte-grau&layersopacity=0.7&lang=de&topic=ech&layers=ch.bafu.showme-kantonehochwasser
Sektion Hochwasserschutz, BAFU	http://www.bafu.admin.ch/org/organisation/00180/00188/index.html?lang=de
Bundesamt für Bevölkerungsschutz	http://www.bevoelkerungsschutz.admin.ch/
Nationale Alarm Zentrale	https://www.naz.ch/
Schutzwald, BAFU	http://www.bafu.admin.ch/naturgefahren/01920/index.html?lang=de
Anpassung Klimawandel Waldwirtschaft	http://www.bafu.admin.ch/klimaanpassung/11502/11819/index.html?lang=de
Anpassung Klimawandel Wasserwirtschaft	http://www.bafu.admin.ch/klimaanpassung/11502/11817/index.html?lang=de
Umgang mit Naturgefahren	http://www.bafu.admin.ch/klimaanpassung/11502/11818/index.html?lang=de
Raumplanungsgesetz	http://www.admin.ch/opc/de/classified-compilation/19790171/index.html
Gewsserschutzverordnung	http://www.admin.ch/opc/de/classified-compilation/19983281/index.html
Gewsserschutzgesetz	http://www.admin.ch/opc/de/classified-compilation/19910022/201406010000/814.20.pdf
Kantonales Waldgesetz Bern	https://www.sta.be.ch/belex/d/9/92111.html
Wasserversorgungsgesetz Bern	https://www.sta.be.ch/belex/d/7/75232.html
Umweltschutzgesetz	http://www.admin.ch/opc/de/classified-compilation/19830267/201407010000/814.01.pdf

Table 4.14: URL sources for adaptation measures Switzerland

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Selbständigkeitserklärung

Ich erkläre hiermit, dass ich diese Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen benutzt habe. Alle Koautorenschaften sowie alle Stellen, die wörtlich oder sinngemäss aus Quellen entnommen wurden, habe ich als solche gekennzeichnet. Mir ist bekannt, dass andernfalls der Senat gemäss Artikel 36 Absatz 1 Buchstabe o des Gesetzes vom 5. Sptember 1996 über die Universität zum Entzug des aufgrund dieser Arbeit verliehenen Titels berechtigt ist.

Bern, 22. Januar 2017

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