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A Spatial Computable General Equilibrium Model for the Analysis of Regional Climate Change Impacts and Adaptation Policies

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Abstract

Climate change may affect subnational regions in very different ways. In this paper, a spatial computable general equilibrium (SCGE) model is constructed and a theoretical framework is developed to study impacts of climate change induced extreme weather events and of corresponding adaptation policies on a regional economy, focusing on water-related extreme events. The model makes use of regionalized input-output tables to represent the regional economy and takes into account different zones inside the region which have different socio-economic structures and also different levels of exposure to extreme weather. The model is used to estimate possible spatial effects and regional economic losses of climate change induced flood events in the city of Hamburg, Germany and to evaluate flood adaptation measures.

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1 Introduction

Extreme weather events and other natural disasters usually occur regionally or even locally. In the course of the discussion about climate change, these events have received increasing attention since an increase in their frequency and severity can result in major economic losses. Especially in regions/sectors that are expected to benefit from, e.g., rising average temperature, the issue of coping with extreme weather events and implementing adaptation strategies must not be overlooked.

In order to study the economics of extreme weather events under climate change in more detail, two strands of literature are assumed relevant. First, impacts of natural disasters have been studied by economists for many decades. Simple input-output models have been advanced to more sophisticated ones like the Adaptive Regional Input-Output (ARIO) model (Hallegatte [8], 2008) and also computable general equilibrium models have been used (e.g. Shibusawa/Miyata [18], 2011; Farinosi et al. [6], 2012). An overview about modeling in this field can be found in Okuyama ([16], 2008), Rose ([17], 2004) or, with a focus on cities, Jahn ([11], 2013).
The second strand is that of integrated assessment and similar models, which try to provide a framework to assess future costs of climate change and benefits of mitigation and adaptation. Widespread integrated assessment models are, i.a., DICE-2013R (Nordhaus [15], 2013), FUND3.7 (Anthoff/Tol [3], 2013) or PAGE09 (Hope [10], 2011).
There seems to be a gap in the economic literature between regional (in the sense of subnational) disaster impact models which cover effects of (single) disastrous events on a regional economy and the very aggregated integrated assessment models on a national or international scale. The latter are able to provide estimates of the costs of climate change as a whole but lack regional detail and only some of them include possible future extreme weather impacts explicitly.
The SCGE model constructed in this paper provides a framework to better combine the two strands of models in order to estimate regional or even local spatial socio-economic impacts of climate change as well as costs and benefits of adaptation measures. It can be applied to subnational regions easily, keeping the necessary amount of data at a minimum, at least for the basic version. The main data input for the calibration of the model is an input-output table. As this is not always available on a regional level, methods of regionalization of national input-output tables need to be applied first (e.g. Kowalewski [13], 2013).
Climate change enters the model via changes in probability distributions of extreme weather events. Since different levels of exposure to extreme weather events matter even within a subnational region, the SCGE model considers multiple zones within the region with zone-specific extreme weather impact functions.

The paper is organized as follows: In section 2, the SCGE model is presented in a basic version, first explaining the equations and then commenting shortly on calibration issues and data input. The third section deals with the implementation of extreme weather impacts and adaptation policies into the model, focusing on water-related extreme weather events. Section 4 provides model results for the application of the model to the city of Hamburg, Germany. The final section concludes and provides an outlook on possible model extensions.

2 A Spatial Computable General Equilibrium Model

The starting point is the SCGE model RELUTRAN (Anas/Liu [1], 2007), which was originally designed to study the effects of "a menu of policies spanning capacity expansion, pricing, finance and investment of transportation, building and income taxation, and land-use planning and controls" (Anas/Liu, [1], pp. 416-417) in metropolitan regions. The model used in this paper is a modification of RELUTRAN in some aspects in order to introduce extreme weather impacts and adaptation policies into the framework.

2.1 General properties

In contrast to continental or global models, it can be assumed that climate change is exogenous for a subnational region [1] and therefore modeling greenhouse gas emissions and the climate system is not necessary.
Even though non-market losses like possible destruction of cultural heritage or unique ecosystems can be relevant as well, the focus of the model is on market losses. Regarding floods, the model assumes that the loss function directly affects the utility of households. Therefore, with a corresponding calibration of the loss function, also aspects like the recreational value of a certain location can be included.
Furthermore, the SCGE model is constructed in a way that only additional future losses and additional adaptation efforts are investigated. In the base period of the model, present risks of extreme weather and costs of protection measures are implicitly contained.

Coming to the technical aspects, the model area is divided into N_z zones, representing districts of the considered region. In each zone, there is a given homogeneous productive land area $A_i, i = 1, \dots, N_z$ which is available for housing and production. Production includes the activity of all N_v sectors, which can also be services.
The zones are linked through a transportation network, consisting of a symmetric distance matrix $dist_{ij}$. The time horizon of the model is specified by T time periods ($t = 1, \dots, T$) where the time step (in years) between two periods is given by a parameter t^{step}.

2.2 Households

The main driving force in the model are the households and their endogenous decisions. The total number of $N_t, t = 1, \dots, T$ households in the city and its development over time is exogenously given. Furthermore, it is assumed that every household activity is performed by a single representative household member. Households decide where, i.e. in which zone, to reside, where to work, how much to consume of each of the sectors' products, how much land to rent and how much labor to supply.

In each period, households maximize a Cobb-Douglas utility function with random part subject to a monetary budget and a time constraint. Shopped goods from the zone of residence, housing size and leisure time contribute to utility.
Depending on the zone of residence i and the zone of employment j, the deterministic part of the households' utility in period t, U_{ijt}, is given by:

$$U_{ijt} = \alpha \ln \Big(\sum_v \iota_v \, C_{ijvt}^{\theta} \Big)^{1/\theta} + \beta \ln(q_{ijt}) + \gamma \ln(\ell_{ijt}) + \zeta_i, \tag{1}$$

where α, β and γ are the relative share of shopping, housing and leisure in the utility and thus, in the expenditure of the households. Assumptions are $\alpha, \beta, \gamma > 0$ and $\alpha + \beta + \gamma = 1$.
The consumption part of the utility takes a C.E.S. form with constant elasticity of substitution $1/(1-\theta)$. The C_{ijvt} are the amounts of goods from sector v that a household living in zone i, working in zone j consumes at time t. The substitution parameter θ ($0 < \theta < 1$) represents the taste for sectoral variety in consumption. For $\theta \to 1$, (relative) prices matter and for $\theta \to 0$, variety matters more for the consumption decision.

[1] In fact, also land use, soil sealing and other local characteristics can be relevant for the micro-climate in (urban) regions. It might be an interesting other line of research to integrate those effects to obtain a fully integrated regional assessment model which allows to study feedback effects between climate and socio-economy.

As additional parameters, the ι_v allow to specify the households' propensity to consume products of certain sectors. The parameter ζ_i measures the inherent attractiveness of zone i as a living zone.

The budget consists of the taxed wage, rent and capital income on the one hand and shopping and housing expenses on the other hand. The income of a household living in zone i and working in zone j at time t is given by:

$$Inc_{ijt} = (1 - t^{inc})\Big(w_{jt} \cdot DW_{ijt} + \Big(\frac{1}{N_t}\Big)\Big(Cap_t \cdot r + \sum_k A_k \cdot rnt_{kt}\Big)\Big), \tag{2}$$

where t^{inc} is the flat income tax rate ($0 < t^{inc} < 1$), w_{jt} is the wage rate (per day) and to obtain the wage income, it is multiplied by the (endogenously determined) number of working days in the respective period, DW_{ijt}.

The second source of income is a share of the total capital and land rent income in the region. In order to get the total capital income, the capital stock in period t, Cap_t, is multiplied by the corresponding exogenous (real) interest rate r. The capital stock is endogenously given by $Cap_t = \sum_{k,v} Z_{kvt}$ through the investments of firms, which are discussed later. The total rent income in period t is obtained by summing over the product of land area A_k and corresponding rent level rnt_{kt} in each zone. Both capital and rent income are distributed uniformly to all households.

The households' expenditures have the following form:

$$Exp_{ijt} = \sum_v (1 + t^c) p_{ivt} \cdot C_{ijvt} + rnt_{it} \cdot q_{ijt} \tag{3}$$

where the first summand is the total amount spent for shopping, summing over all sectors v. For the consumption of goods/services, the households face, in addition to the price of production p_{iv}, a given value added tax rate t^c. The second summand is housing expenditure.

The budget constraint requires an equality between income and expenditures for each household in each period. The time constraint requires equality of the exogenous per-period time endowment TE and work time and leisure time

$$TE = DW_{ijt} + \ell_{ijt}. \tag{4}$$

Having stated the constraints, the utility maximization problem can be formulated. Households decide on optimal levels of consumption, housing and leisure for all possible home-work pairs $\{i, j\}$ by solving

$$\max_{C,q,\ell} U_{ijt} \tag{5}$$

subject to 2 = 3 (budget constraint) and 4 (time constraint)

in each time period t.

Internalizing the constraints, the following Lagrangian $LG(C, q, \ell, t)$ is obtained by the method of Lagrange multipliers:

$$LG(C, q, \ell, t) = U_{ijt} + LM^{budget}_{ijt}(Inc_{ijt} - Exp_{ijt}) + LM^{time}_{ijt}(TE - DW_{ijt} - \ell_{ijt}),$$

where LM^{budget}_{ijt} and LM^{time}_{ijt} are the Lagrange multipliers of the budget constraint and the time constraint, respectively. First order conditions then yield utility maximizing quantities.

To account for taste differentiation among households, it is assumed that the utility function includes idiosyncratic utility constants (Anas/Liu [1], 2007). These are modeled by i.i.d. Gumbel distributed random variables ϵ_{ijt} with mean zero and dispersion parameter λ (i.e. $\text{var}(\epsilon_{ijt}) = \pi^2/6\lambda^2$). Consequently, the overall utility $\hat{U}_{ijt}$ is

$$\hat{U}_{ijt} = U_{ijt} + \epsilon_{ijt}. \tag{6}$$

The utility maximization problem then becomes a discrete choice problem for the households, yielding choice probabilities. The probability ψ_{ijt} that a household chooses home-work pair $\{i, j\}$ in period t is given with the help of multinomial choice calculation (Anas/Liu [1], 2007) by

$$\psi_{ijt} = \frac{\exp(\lambda U_{ijt})}{\sum_{i',j'} \exp(\lambda U_{i'j't})}. \tag{7}$$

This completes the discussion of households in the model. Since location and consumption decisions are endogenous, households may respond to shocks, e.g. climate change impacts, in a variety of ways. For example, they can change their place of residence and/or their place of work or they can adjust their consumption behavior.

2.3 Firms

A sufficiently large number of firms of different sectors $v \in \{1, \ldots, N_v\}$ is assumed to produce in the model zones $k \in \{1, \ldots, N_z\}$. The firms produce commodities/services by applying a Cobb-Douglas technology that combines imported sector-specific inputs I_{kvt}, land in the zone of production B_{kvt}, capital Z_{kvt}, labor L_{kvt}, and output from other firms' or their own production, $Y_{vkv'k't}$, as intermediate inputs. With X_{kvt} denoting units of output, the production function of a firm of sector v located in zone k in period t has the following form:

$$X_{kvt} = E_t \cdot I_{kvt}^{\eta_v} \cdot B_{kvt}^{\mu_v} \cdot Z_{kvt}^{\kappa_v} \cdot L_{kvt}^{\nu_v} \cdot \prod_{v'} \left(\sum_{k'} Y_{vkv'k't}^{\rho} \right)^{\frac{\phi_{v'v}}{\rho}}, \tag{8}$$

where E_t is a productivity/technology parameter and ρ is the substitution parameter for the elasticity of substitution between intermediate inputs from different zones. The other parameters $\eta_v, \mu_v, \kappa_v, \nu_v$ and $\phi_{v'v}$ represent the relative cost shares of the different factors in the production. Constant returns to scale are assumed to prevail, so that $\eta_v + \mu_v + \kappa_v + \nu_v + \sum_{v'} \phi_{v'v} = 1$ has to hold for all v.

The firms' optimization problem is formulated as a cost minimization problem. The cost function is given as:

$$Cost_{kvt} = pr_v I_{kvt} + rnt_{kt} B_{kvt} + r Z_{kvt} + w_{kt} L_{kvt} + \sum_{v'} \sum_{k'} (p_{k'v't} + MTC_{k'k}) Y_{vkv'k't}, \tag{9}$$

where pr_v denotes the exogenous price for imported inputs and $(p_{k'v't} + MTC_{k'k})$ denotes the delivered price of an intermediate good in zone k, produced by a firm of sector v' in zone k'. In addition to the production price $p_{k'v't}$, the receiving firm has to pay transportation costs $MTC_{k'k}$. This parameter is explained in detail in section 2.5.

The cost minimization problem for a firm of sector v located in zone k at time t can be formulated as follows:

$$\min_{I,B,Z,L,Y} Cost_{kvt} \tag{10}$$

subject to 8 (C.-D. production function)

Perfect competition is assumed to prevail, so that in equilibrium, the price of a commodity equals the marginal production cost, which is independent of the level of output.

After having obtained the factor input demands by solving the cost minimization problem, one can substitute the factor demands back into the cost function and gets the marginal costs for a firm of sector v located in zone k at time t:

$$\begin{aligned} MC_{kvt} =& \Big(E_t \eta_v^{\eta_v} \mu_v^{\mu_v} \kappa_v^{\kappa_v} \nu_v^{\nu_v} \prod_{v'} \phi_{v'v}^{\phi_{v'v}} \Big)^{-1} pr_v^{\eta_v} rnt_{kt}^{\mu_v} r^{\kappa_v} w_{kt}^{\nu_v} \\ & \times \prod_{v'} \Big(\sum_{k'} (p_{k'v't} + MTC_{k'k})^{\frac{\rho}{\rho-1}} \Big)^{\frac{\phi_{v'v}(\rho-1)}{\rho}} \end{aligned} \tag{11}$$

2.4 The government sector

In this model, the government levies sales and income taxes and consumes goods. Taking into account the income and consumption of households, the tax revenue in period t is given by:

$$TREV_t = N_t \sum_{i,j,v} t^c p_{ivt} C_{ijvt} \psi_{ijt} + N_t \sum_{i,j} t^{inc} Inc_{ijt} \psi_{ijt}, \tag{12}$$

where the first summand denotes sales tax revenue and the second denotes income tax revenue. The government expenditures are then given by

$$p_{kvt} C_{kvt}^{pub} = \frac{\iota_v}{N_z} TREV_t, \tag{13}$$

where C_{kvt}^{pub} denotes the amount of goods from sector v that the government consumes in zone k and period t. The factor ι_v/N_z means that the government spends its budget according to shares of sectors in the regional final demand and uniformly across zones.

2.5 Transportation costs

In the underlying model RELUTRAN (Anas/Liu [1], 2007), the traffic system is more detailed with mode and route choice and with households facing monetary and time costs when commuting and making shopping trips, but this is omitted in this versionFirms are assumed to face monetary transportation costs MTC to obtain intermediate inputs. The transportation cost for a firm in zone j to receive one unit of intermediate good from zone i is given by $MTC_{ij} = co \cdot dist_{ij}$ and thus, it is just proportional to the exogenous distance with cost parameter co. Subsequently, $(p_{ivt} + MTC_{ij})$ denotes the delivered price in zone j of a good from sector v, produced in zone i.

2.6 Equilibrium conditions

In equilibrium, endogenous land rents, wages and commodity prices clear the spatially differentiated markets for land, labor and commodities in each period t. The equations determining the general equilibrium are collected in the following.

The land markets determines the rents rnt_{it} for the different zones in each period t. Land is used by households for housing and by firms for production. The amount of available land A_i is assumed to be constant over time. Thus, the following equation has to hold for an equilibrium in the land market:

$$N_t \sum_j \psi_{ijt} \cdot q_{ijt} + \sum_v B_{ivt} = A_i. \tag{14}$$

The labor market is differentiated for the model zones and yields wage levels w_{jt}. Labor is provided by households and employed by firms. This gives the following equilibrium condition:

$$\sum_v L_{jvt} = N_t \sum_i \psi_{ijt} \cdot DW_{ijt}. \tag{15}$$

The goods of the different sectors are produced by firms and consumed by either households, government, firms (as intermediate inputs) or they are exported. The market clearing condition for the commodities is:

$$N_t \sum_j \psi_{kjt} \cdot C_{kjvt} + Export_{kvt} + C^{pub}_{kvt} + \sum_{v',k'} Y_{v'k'vkt} = X_{kvt} \tag{16}$$

The prices of the commodities are assumed to be equal to the marginal costs of production, yielding the equilibrium conditions $MC_{kvt} = p_{kvt}$.

Finally, the regions' exports and the trade balance need to be considered. As common for CGE models, the terms of trade with the 'rest of the world' are balanced. Here, exports are financed by the imports and the monetary travel costs arising from transportation activity in the city.
The overall transportation costs in period t, $SMTTC_t$ look as follows:

$$SMTTC_t = \sum_{v,k,v',k'} Y_{vkv'k't} \cdot MTC_{k'k}. \tag{17}$$

Thus, for balanced terms of trade it has to hold for the exports that

$$p_{kvt} \cdot Export_{kvt} = \frac{\tau_v}{N_z} \Big(\sum_{k',v'} pr_{v'} I_{k'v't} + SMTTC_t \Big), \tag{18}$$

where it is assumed that the foreign demand from outside the region splits uniformly over all zones and the shares of the different sectors is specified by τ_v.

This concludes the presentation of the SCGE model and aspects of the model calibration are discussed next.

2.7 Calibration

Calibration of CGE models can be a difficult task, especially on a regional level since data is not always available (e.g. Jahn [11], 2013). In the best case, a social accounting matrix is available. However, many countries do not even provide national social accounting matrices. In order to calibrate the parameters of the production functions of this paper's model, regionalized input-output tables are used. The latter can be estimated from national input-output tables by, e.g. , location quotients as described in Flegg/Webber ([7], 1997). The method was investigated and applied, e.g. by Kowalewski ([13], 2013).

Regionalized input-output tables provide information about the composition of the output of each sector in a specific year. Usually, output is assumed to consist of the input categories intermediate inputs, imported inputs, taxes and gross value added. After deducting taxes from the sectoral output values, it is possible to derive the coefficients of the production function for the different inputs from the table. The inter-industry coefficients $\phi_{vv'}$ and the coefficient for imported inputs η_v for each sector can be extracted from the table without further calculations. By considering the regional gross value added of each sector, denoted by Γ_v^{reg}, the other coefficients can be obtained. For later notation, let Λ_v be the regional share of gross value added in the regional output values (without taxes) for each sector.
To derive the labor, capital and land coefficients, national sectoral data is used. Let ls_v^{nat} be the sectoral labor share on the national level, i.e. the share of compensation of employees in the gross value added. Since the aggregate compensation of employees on the regional level, CE^{reg}, is assumed to be known, a factor $f^{lab} = CE^{reg} / \sum_v ls_v^{nat} \Gamma_v^{reg}$ is used to correct the national values to obtain regional values $ls_v = ls_v^{nat} \cdot f^{lab}$ that are consistent with that aggregate. The resulting regional sectoral labor coefficients are then given by $\nu_v = ls_v \cdot \Lambda_v$.
In order to determine the land and capital coefficients, information about the sectoral gross fixed assets on a national level is used. It is distinguished between building assets and non-building assets. The share of the non-building assets, denoted by nbs_v is used to derive the capital coefficient, since 'capital' in this model is meant to represent equipment and capital that is mobile to a certain extent. The capital coefficient κ_v is given by $\kappa_v = nbs_v \cdot (1 - ls_v) \cdot \Lambda_v$. The remaining land coefficient μ_v is then calculated from the share of building assets in the gross fixed assets to be $\mu_v = (1 - nbs_v) \cdot (1 - ls_v) \cdot \Lambda_v$. Here, the assumption is made that expenditures for building assets (floor space) are a suitable indicator for the expenditures for ground.

The values of the parameters ι_v and τ_v can be calibrated from the shares of the sectors in the local and foreign demand. The total final demand (local and foreign), which is given through the regionalized input-output table, is split onto these two categories according to the national share for each sector.

Regarding the utility function parameters, these can be calibrated from empirical household expenditures for housing (β) and labor supply data (γ). The actual distribution of households between the zones can be used to calibrate the location attractiveness parameters ζ_i.

Substitution parameters for consumption and inputs are more uncertain, but plausible values from the literature are used. Other parameters like the number of households and the (productive) land area in each zone are assumed to be available for the considered region.

3 Extreme weather impact modeling

Extreme weather events can have opposing and overall ambiguous effects on a regional economy in the medium term. Destruction of capital, infrastructure and disruption of services such as water and energy supply yield short-term losses (Hallegatte [8], 2008; Jahn [11], 2013). On the other hand, when reconstruction activities start, a region can also increase its output in the aftermath of an extreme weather event. Empirical evidence for the latter effect are provided, e.g. , by Berlemann/Vogt ([4], 2007) who estimate that for the major river flood event in the German state Saxony in 2002, the positive economic effects on the regional value added outweighed the negative ones, at least for the year of the flood and the following two years. However, one has to be careful with the interpretation. The authors state that the measured positive effects can be due to flood assistance from outside the region, where economic growth then might have been lower than it could have. Another source of positive medium-term impacts can be overshooting reconstruction activity. This aspect is an important feature of the ARIO model (Hallegatte [8], 2008), thereby providing a theoretical foundation for the analysis of the opposing economic effects in the aftermath of a disaster.

The issue of extreme weather impacts in the context of climate change is, however, a different one, as we speak of long-term effects and as patterns of extreme weather events change, negative impacts dominate. This is in line with the role of extreme weather events in integrated assessment models, if treated at all. In the FUND3.7 model (Anthoff/Tol [3], 2013), economic impacts from (tropical) storms are captured as a power function of temperature increase and thus, are always negative under a warming climate scenario.

3.1 Modeling impacts via loss functions

Extreme weather events enter the SCGE model via loss functions which use probability distributions of extreme weather occurrence, or more precisely, the change of these probability distributions as an input.
Water-related extreme weather events are assumed to affect productivity of land and utility that households can derive from renting land. The effect of a potential complete loss of land is not investigated in this paper, but might be a relevant effect to consider, especially for coastal regions.
It is empirically verified (e.g. Dobes et al. [5], 2014) that flood events can lower property prices in affected areas. This can be explained economically by a lower productivity of land or, from the the households' perspective, by less utility that can be derived from renting the affected piece of land.

Therefore, a parameter D_{kt} is introduced to capture the loss of productivity and utility of land in each zone in each time period. The modeling approach of including flood losses (flood risk) as a factor in the housing part of the utility function of households is due to Hirte et al. ([9], 2014). The loss parameter is given by:

$$D_{kt} = \omega_k^1 [F_1(H^{noad})^{\omega_2} - F_t(H^{noad})^{\omega_2}], \tag{19}$$

where F_t denotes the distribution function of the maximum water level at some reference location in period t. It is evaluated at a certain critical water level H^{noad}, the water level below which no significant losses occur if no additional adaptation measures are taken. The parameters ω_k^1 and ω_2 describe the loss function. Here it is assumed that the exponent is constant across zones and time and that the factor can differ across zones, reflecting different levels of exposure to floods. Further assumptions are $0 \leq \omega_k^1 \leq 1$, $\omega_2 > 1$.

Using the distribution of the maximum of some quantity (here: water level) is especially suited when averages do not have major economic impacts. The form of the specific flood loss function has two further implications. First, losses in period t can only occur if the probability of a flood exceeding H^{noad} in period t is greater than in period 1. Second, in case of exceedance the loss parameter increases nonlinearly.
For other types of extreme weather events, other relevant probability distributions and thresholds have to be identified. Impact channels can also be different, as, e.g., heat waves might rather lower labor productivity than land productivity.

Coming back to the flood loss function, an implementation into the utility function changes the housing part of the utility of households living in zone i in period t to $\beta \cdot \ln[(1 - D_{it})q_{ijt}]$

and thus, the deterministic utility of households including flood losses, U^D_{ijt}, can be written as:

$$U^D_{ijt} = U_{ijt} + \beta \ln(1 - D_{it}). \tag{20}$$

The land part of the production function of a firm of sector v operating in zone k in period t becomes $[(1 - D_{kt})B_{kv}]^{\mu_v}$, which yields the updated production function

$$X^D_{kvt} = X_{kvt} \cdot (1 - D_{kt})^{\mu_v}. \tag{21}$$

Interestingly, Dobes et al. ([5], 2013) also find that updated flood risk information can cause a decline in property prices and that, at least for the examined situation in Brisbane, Australia, price reactions resulting from updated risk information are similar to price reactions resulting from an actual flood event. Although these price effects might be linked to flood risk in a non-monotonic way (Dobes et al. [5], 2013), this indicates that the utility loss function in this SCGE model can also be explained by risk instead of actual damages.

3.2 Adaptation measures

Before adaptation policies are discussed, it shall be noted that the general equilibrium effects of the impacts described above already contain a certain level of adaptation of production processes and consumption decisions through prices. In this section, additional public adaptation policies are addressed.

3.2.1 Modeling adaptation measures

It is assumed that the government can invest into adaptation measures. Flood adaptation measures can increase the critical water level to $H^{ad}_t (> H^{noad})$. In principle, this idea is similar to adaptation modeling in integrated assessment models as in the PAGE09 model (Hope [10], 2011) where adaptation measures increase a certain tolerable level of climate change. Note that, in the setup used here, H^{ad}_t can change over time and therefore has an index t. When simulating adaptation strategies, one should be aware of the fact that adaptation measures to floods are often long-term projects and the amount of possible change of H^{ad}_t from one period to the following is limited.

The loss parameter including adaptation, D^{ad}_{kt}, is given by

$$D^{ad}_{kt} = \omega^1_k [F_1(H^{noad})^{\omega_2} - F_t(H^{ad}_t)^{\omega_2}]. \tag{22}$$

Note that it can be desirable to use zone-specific critical water levels and probability distributions to consider zone-specific adaptation. This requires more detailed data on flood risk.

3.2.2 Financing mechanism

In order to finance public adaptation measures, the government levies additional taxes. Here, it is assumed that (all) households have to pay a land tax, but financing through sales or income tax is also possible. The revenue needed for additional adaptation measures to floods at time t, denoted by $ADREV_t$, is

$$ADREV_t = \xi(H^{ad}_{t+h} - H^{noad})^{\Theta}, \tag{23}$$

with $\xi > 0$ and $\Theta > 1$ and thus, adaptation costs increase nonlinearly with the protection level H^{ad}_{t+h} of the period $t + h$, with h being a parameter which accounts for the fact that costs for adaptation arise before the adaptation is actually implemented. The instrument of varying tax levels could be used by the government to direct households and firms away from potentially flood prone zones. This would lead to smaller flood losses and thus, can be considered an adaptation measure on its own. However, this possibility is not examined in this paper. The corresponding model equation to determine t_t^{land} looks as follows:

$$ADREV_t = N_t \sum_{i,j} t_t^{land} \cdot rnt_{it} \cdot q_{ijt} \cdot \psi_{ijt} \tag{24}$$

The government is assumed to spend the additional budget according to its general spending behavior as described in equation (13), so government consumption becomes $C_{kvt}^{pub} = \frac{1}{p_{kvt}} \frac{\iota_v}{N_z}(TREV_t^{base} + ADREV_t)$. With more specific information about the type of adaptation measure, it is possible to account for the fact that, e.g., for dike building measures, a large part of the revenue will be spent in the construction sector.

3.3 Evaluating losses from extreme weather events and benefits of adaptation

Although households do not optimize an intertemporal utility function, different economic and climate scenarios as well as different adaptation strategies can be compared by looking at a (present value) welfare function. Since the households' utilities contain a random part (see equation 6), one can only speak of an expected welfare function, which depends on the distribution of the random utility components. The corresponding expression in the case of i.i.d. Gumbel distributed random components is described in Anas/Xu ([2], 1999) and yields the following expected welfare function

$$UTI = \sum_{t=1}^{T} \Big(\sum_{i,j} U_{ijt} \cdot \psi_{ijt} - \frac{1}{\lambda} \sum_{i,j} \psi_{ijt} \ln \psi_{ijt} \Big) (1+\delta)^{-t^{step} \cdot t}, \tag{25}$$

where future welfare is discounted exponentially with (annual) rate δ.

To compare different pathways, for example with and without climate losses or with and without adaptation, the difference between the welfare functions is monetized by looking at the compensating variation. Assuming that the utility functions are expressed in their indirect form (Anas/Liu [1], 2007), indirect welfare levels associated with the different paths are given by $UTI(m_t^0, p_t^0)$ and $UTI(m_t^1, p_t^1)$ with price vectors p_t^0 and p_t^1 and income m_t^0 and m_t^1, indexed by 0 and 1. The compensating variation cv is defined as the amount of money for which it holds that $UTI(m_t^0, p_t^0) = UTI(m_t^1 + cv, p_t^1)$.
In other words, the compensating variation is the amount of money that each household would have to receive in each period of path 1 so that the value of the social welfare coincides with that of path 0. The total present value cost of the welfare difference is then given by:

$$TC = \sum_{t=1}^{T} t^{step} \cdot N_t \cdot cv \tag{26}$$

4 Application: Adaptation to floods in Hamburg

The purpose of this paper is the presentation of an economic model that incorporates effects of changing extreme weather risk and corresponding adaptation measures on a regional economy. Therefore, the application shown in the following is meant to demonstrate the capability of the model. The results are only a brief summary and do not include a sensitivity analysis, which will be needed to derive more profound implications.

The model is applied to the city of Hamburg, Germany. The goal is a) to estimate the welfare impact of climate change induced flood events and b) to evaluate the effect of an increase of the flood protection level of the city which is currently being implemented. Some aspects of the calibration of the model to Hamburg are discussed in this section, but additionally, parameter values are shown in the annex.

4.1 Hamburg and its exposure to floods

The model region is divided into 7 zones, corresponding to the 7 administrative districts of the city, Altona (AT), Eimsbüttel (EB), Hamburg-Nord (HN), Bergedorf (BD), Hamburg-Mitte (HM), Harburg (HB) and Wandsbek (WB). The economy is divided into 7 sectors, listed in the input-output table (Table 5). The regionalized input-output table was estimated using data from 2010. The model consists of 10 time periods, with time steps of 5 years between the periods and with year 2010 being the base period.

Regarding extreme weather impacts, the flood water level distribution function at the reference location 'St. Pauli' is estimated from data collected by the Hamburg Port Authority (Source: Portal Tideelbe). After some modification, a generalized extreme value distribution is fitted to the annual maximum water levels (Figure 1), yielding maximum likelihood estimates $\hat{k}^{gev} = 0.0215$ for the shape parameter, $\hat{\sigma}^{gev} = 0.5891$ for the scale parameter and $\hat{\mu}^{gev} = 4.2633$ for the location parameter.
For the future development, it is assumed that the location parameter of the distribution will increase by 0.01m per year until the final model year 2055, mainly to capture possible sea level rise which is estimated to be 0.55m to 1.15m in the North Sea (Dutch Coast) until the end of this century (Katsman et al. [12], 2011) and may be similar for the German Bight which is relevant for the water level in Hamburg. The scale parameter σ^{gev} is assumed to be constant due to lack of information on possibly increasing flood level variability. In general, the model is capable of including different (climate) scenarios as far as they are characterized by different parameters of future probability distributions of extreme weather events.

The exposure to floods of the different zones is estimated from the flood risk map (Figure 2). It shows in blue the area that would be flooded in case of a storm surge if there was no flood protection. The approximate share of flood prone area in each of the zones' total area is used to derive the scale parameter ω_k^1 of the loss function. The exponent takes the value 3, such that, in the district with the highest exposure to floods, Bergedorf, utility and productivity of land would decrease by 2.8% if the distribution changed in a way that a 100-year flood event became a 50-year event. If a 100-year event became a 10-year event, this would reduce utility and productivity by 22.9%.

4.2 Modeling the impact of an increase in the critical water level

The adaptation policy is to increase the critical water level (cf. German: 'Bemessungswasserstand') from $H^{noad} = 7.3$m to $H^{ad} = 8.1$m to adapt to expected higher storm surges. The costs (for the whole city) are assumed to be about 700 million € [2010 value] (LSBG [14], 2007). Regarding the parameters of the adaptation cost function, the exponent is assumed to be $\Theta = 1.8$ to capture nonlinearity. The actual costs are transformed into an annuity of 49 million € by assuming a financing horizon of 20 years and an interest rate of 3.5%. For sake of simplicity, it is assumed that maintenance costs do not arise in the first twenty years and after that, are equal to the annuity. Together, the exponent and annuity yield the scale parameter ξ.

The analysis is focused on some key figures. Table 8 shows the monetized present value welfare difference between three different pathways. Path A describes the case where flood probabilities remain constant at the level of the base year and where no adaptation measures are taken. This is the base path. Path B includes a climate change induced increase in flood risk without adaptation and path C represents the case of an increase in flood risk combined with the implementation of the adaptation policy described above. The resulting sectoral value added in the final period is shown in Table 7. The effects of flood risk and adaptation measures on the distribution of households is shown in Figure 3.

The results show that the expected future increase in flood risk would have a negative effect on the regional socio-economy if no adaptation measures were taken. The estimated total loss of welfare resulting from future (until 2055) flood events corresponds to a monetized value of 8.79 billion € of 2010 value (Table 8). Spatial effects such as relocation of households (Figure 3) are small but visible. Unsurprisingly, flood risk pushes households to less affected zones and adaptation measures counter this tendency. Increasing flood risk affects the output of all sectors similarly (Table 7). This can be due to the fact that the sectoral structure in the zones is similar, mostly because of the lack of more specific data.

Regarding the costs and benefits of adaptation, the considered flood adaptation measure of increasing the critical water level from 7.3m to 8.1m is estimated to increase the welfare above the level of path A. In fact, the considered adaptation measure can be seen as a no-regret measure which also increases welfare in the absence of any increase in flood risk. In total, the welfare difference of path C to path A case has a monetized value of 9.57 billion € (Table 8). One driver of this result may be the return period of a flood level exceeding the current protection level of 7.3m, which (in contradiction to higher official values) is estimated to be only 133 years under the base path A and therefore additional adaptation will always be highly desirable as long as costs are moderate. Furthermore, one could ask whether more adaptation would be even more beneficial. This would point to the problem of an optimal level of adaptation, which could be studied in a future application of the model.

5 Conclusion and outlook

The regional SCGE model presented in this paper provides a framework for a theoretically founded economic analysis of climate change induced extreme weather events and adaptation measures at a regional or even local scale. Because of the flexible structure, the model can be calibrated to subnational regions and even cities and takes into account local vulnerabilities. It concentrates on climate change induced extreme weather impacts, which are modeled through the (changing) probabilities of occurrence. Thereby it overcomes the problem of the ambiguous effects of single extreme weather events on regional economic activity and allows for an interpretation of economic losses from floods as a consequence of changing probabilities of occurrence.

Regarding the SCGE model as such, the presented basic version of the model might be improved by a more detailed modeling of some aspects. First, different household types could be considered with different levels of income and distribution across the zones which have different vulnerabilities to extreme weather and also different levels of contribution to the tax revenue needed to finance adaptation measures. A more detailed real estate market and/or different land use classes, a more detailed traffic system as well as a broader role of the government are possible extensions. In particular the role of the government in the regional land use could be investigated further. Taking into account the government land use for the provision of infrastructure, recreational areas and ecosystem services can be a relevant feature in the assessment of climate change impacts and adaptation measures on a regional scale. Including fully dynamic decisions of households and firms over savings and investment provides another opportunity for a model advancement.

The model also allows the inclusion of different types of climate change impacts. Flood events, the focus of this paper, are assumed to affect the value, i.e., the utility of land for households and the productivity of land for firms. In this regard, considering zone-specific flood probability distributions provides an opportunity for a model refinement, if information on these are available.
The concept as such can be used also for other extreme weather events like droughts, which might affect utility and productivity of land as well. Heat events might rather affect labor productivity.
Introducing sector-specific loss functions, thereby taking into account regional sectoral vulnerability (beyond the dependence on a certain production factor) would help to make more detailed statements about economic impacts. Furthermore, climate change induced shifts in the demand, i.e., consumption preferences for goods of certain sectors like energy could be integrated into the model framework.

Adaptation measures are evaluated by comparing avoided losses to costs, where the latter are assumed to be financed by the government through taxes. In future model applications, the role of varying tax levels (e.g. across zones) as one aspect of the adaptation policy could be studied. This can be important as higher taxes in zones with higher levels of exposure could lower losses as households and firms (partly) relocate to other zones in response to the tax. Eventually, the model might also help to derive optimal levels of adaptation to climate change induced extreme weather events.

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6 Annex

Table 1: Scalar parameters

name	description	value
T	number of periods	10
t^{step}	time between periods [years]	5
N_v	number of sectors	7
N_z	number of zones	7
TE	per period time endowment [days]	250
α	consumption share utility	0.655
β	housing share utility	0.195
γ	leisure share utility	0.15
θ	substitution parameter consumption	0.1
λ	dispersion parameter utility	7
ρ	substitution parameter inputs	0.3
tax^c	sales tax rate	0.15
tax^{inc}	income tax rate	0.229
ω_2	exponent loss function	3
H^{noad}	critical water level without adaptation [meters]	7.3
ξ	scale adaptation cost	73
Θ	exponent adaptation cost	1.8
δ	(annual) welfare discount rate	0.015

Table 2: Time-dependent parameters

name	description	value
N_t	no. of households	$972000 \cdot (1.003)^{t^{step}(t-1)}$ for $t < 5$, 1032012 for $t \geq 5$
E_t	productivity	$(1.005)^{t^{step}(t-1)}$
F_t	distribution water level	$GEV(\mu_t^{gev}, \sigma^{gev}, k^{gev})$
μ_t^{gev}	location GEV	$4.2633 + t^{step} \cdot (t-1) \cdot 0.01$
σ^{gev}	scale GEV	0.5891
k^{gev}	shape GEV	0.0215

Table 3: Zone-specific parameters

name	description	AT	BD	EB	HM	HN	HB	WB
A_i	land area [million m^2]	37.645	30.238	28.590	57.050	29.517	34.628	73.432
ζ_i	inherent attractiveness	0.029	-0.157	0.128	-0.053	0.193	-0.115	-0.025
ω_k^1	exposure to floods	0.1	0.95	0.05	0.9	0.2	0.6	0.05

Sources: own calculations, www.statistik-nord.de

Table 4: Sector-specific parameters

name	description	AGR	PRI	ENE	CON	TRA	FIN	SER
κ_v	capital coefficient	0.0821	0.0812	0.0490	0.1103	0.0727	0.0014	0.0426
ν_v	labor coefficient	0.1032	0.1543	0.1310	0.2503	0.2708	0.2106	0.4657
μ_v	land coefficient	0.1611	0.0232	0.2424	0.0850	0.1120	0.3597	0.2063

Sources: own calculations

Table 5: Regionalized I-O Table for Hamburg 2010 [million € of 2010 value]

sector	AGR	PRI	ENE	CON	TRA	FIN	SER	Interm.	Local	Foreign	Total dem.
Agriculture, Forestry, Fishery	3.9	79.4	0.002	0	1.5	0.6	1.6	87.1	85.6	35.5	208.2
Producing industries	21.4	4195.3	78.3	219.7	1110.8	154.8	277.9	6058.1	8168.7	22730.0	36956.8
Energy and water	5.8	420.9	250.9	7.5	228.5	67.0	119.3	1099.9	1975.9	354.4	3430.2
Construction	3.5	78.0	51.4	151.4	149.9	268.9	129.3	832.3	3726.1	16.2	4574.6
Trade, hospitality, traffic	14.0	2160.0	144	329.6	8818.6	1332.9	994.9	13794.0	27431.2	13417.3	54642.5
Financial services	25.2	1910.9	351.2	507.1	5208.9	9757.5	1359.4	19120.2	24102.7	9077.6	52300.5
Public and private services	1.7	170.3	94.6	49.0	328.2	341.0	853.0	1837.8	19266.5	75.2	21179.6
Intermediate inputs	75.7	9014.7	970.3	1264.2	15846.4	11922.7	3735.4	42829.5	84756.7	45706.3	173292.5
Imported inputs	57.1	18239.6	967.2	1256.0	13457.3	10134.6	2101.9	46213.6			
Taxes	5.1	192.5	76.1	28.8	831.9	810.0	728.1	2672.5			
Gross value added	70.4	9510.0	1416.6	2025.6	24506.9	29433.2	14614.2	81576.9			
Output	208.2	36956.8	3430.2	4574.6	54642.5	52300.5	21179.6	173292.5			
Output w/o taxes	203.1	36764.3	3354.1	4545.8	53810.5	51490.5	20451.5	170620.1			

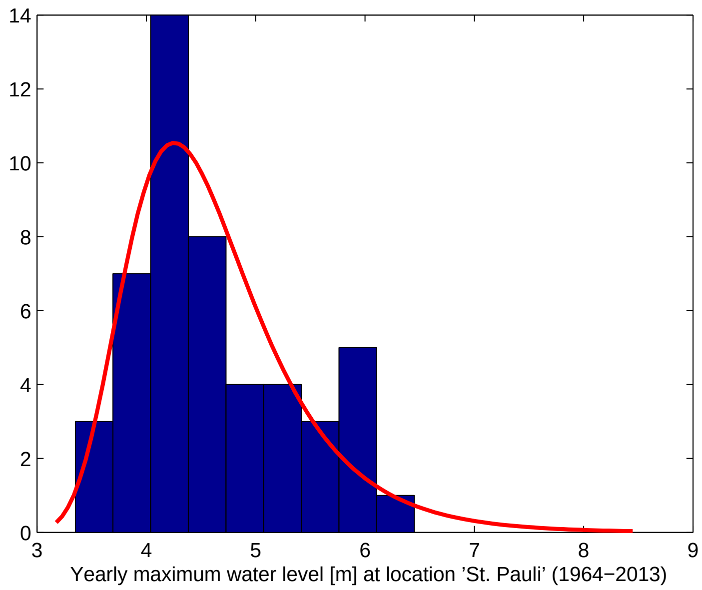
Sources: own calculations, VGRDL, destatis

Table 6: Distance for a trip between zones [km]

zone	AT	BD	EB	HB	HM	HN	WB
AT	4.58	23	7.3	27.9	8	14	22.6
BD	23	4.88	23.9	34.9	15	23.1	29.6
EB	7.3	23.9	4.15	28.8	8.9	6.7	14.4
HB	27.9	34.9	28.8	7.2	19.9	28	34.5
HM	8	15	8.9	19.9	7.37	8.1	14.6
HN	14	23.1	6.7	28	8.1	4.39	7.7
WB	22.6	29.6	14.4	34.5	14.6	7.7	5.51

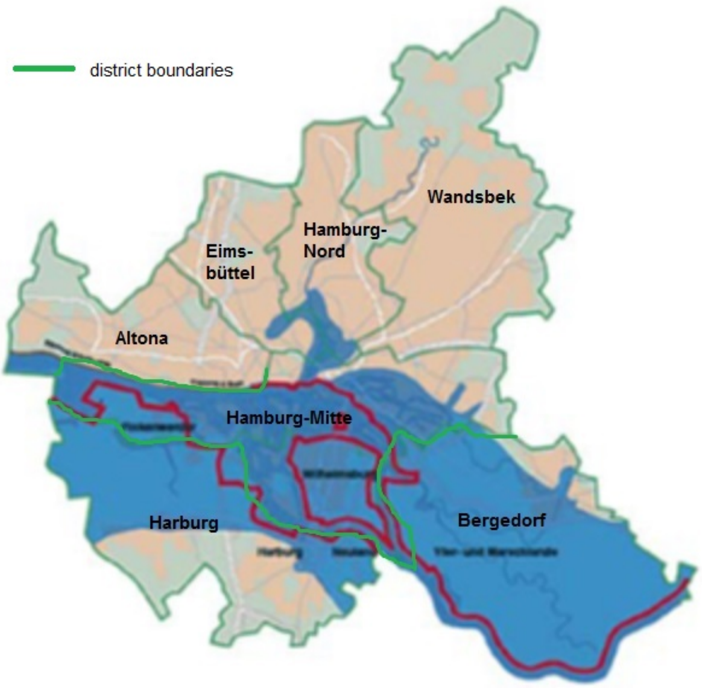
Source: own calculations

Figure 1: Water level data and fitted generalized extreme value distribution



Source: www.portal-tideelbe.de

Figure 2: Flood risk map Hamburg



Source: Behörde für Inneres und Sport Hamburg (2012): Sturmflutschutz – Hinweise für die Bevölkerung

Table 7: Sectoral value added for different flood/adaptation paths

Sectoral value added in 2055 [million € of 2010 value]

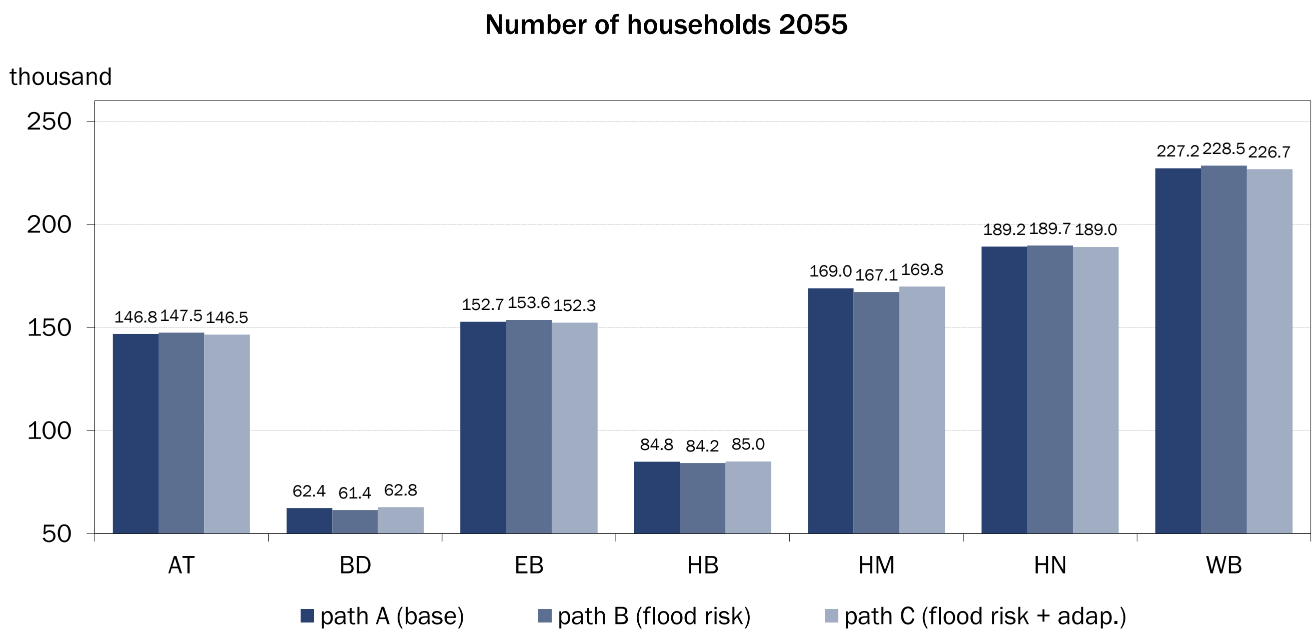
sector	path A (base)	path B	change [%]	path C	change [%]
AGR	136.7	136.2	-0.367	136.9	0.146
PRI	20815.5	20740.6	-0.361	20854.1	0.185
ENE	2793.9	2783.2	-0.363	2799.2	0.189
CON	3953.7	3939.6	-0.358	3961.1	0.187
TRA	54076.8	53882.6	-0.360	54176.4	0.184
FIN	62471.0	62243.6	-0.365	62588.3.6	0.187
SER	29392.8	29288.0	-0.358	29447.4	0.185
total	**173640.4**	**173014.4**	**-0.362**	**173963.5**	**0.186**

Table 8: Monetized welfare differences of the paths

	path A	path B	path C
Loss* relative to path A [bln € (2010)]	**0**	**8.79**	**-9.57**

**A negative loss corresponds to a benefit.*

Figure 3: Distribution of households in 2055



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