Climate Change Impacts in Computable General Equilibrium Models: An Overview

Sebastian Döll

Sebastian Döll
Hamburg Institute of International Economics (HWWI)
Heimhuder Str. 71 | 20148 Hamburg | Germany
Phone +49 (0)40 34 05 76 - 677 | Fax +49 (0)40 34 05 76 - 776
doell@hwwi.org

Climate Change Impacts in Computable General Equilibrium Models: An Overview

Sebastian Döll

Climate Change Impacts in Computable General Equilibrium Models: An Overview

Sebastian Döll[*]

Abstract

This paper gives an overview about existing Computable General Equilibrium (CGE) models dealing with climate impacts focusing on damage calculations and adaptation modelling. Empirical CGE models are used in a broad field of policy analysis. With respect to climate change applications have been focused on the calculation of climate damages and the mitigation of these damages. Facing the non-preventable damages from climate change that occur already in the next decades adaptation is becoming a more important issue in the actual discussion. To our knowledge a model with explicit adaptation at the local level that includes socio-economic effects is missing. Such a regional model can analyse welfare effects where adaptation is implemented and therefore is important for political decision making.

Keywords: Computable General Equilibrium, Global Warming, Adaptation

1   Introduction

In the near future climate change will be more and more perceptible all over the world. The impacts will vary substantially across countries and even across different regions within a country. In order to evaluate the costs and benefits of climate protection and prevention measures at the regional level it is necessary to construct a specific model. This model corresponds to the regional economic structure and to the impact of future changes in socioeconomic variables on the regional development.

The increasing risks arising from climate change impose enormous pressure on politicians and government authorities. They have to take measures in order to adapt to climate change. For example at the end of the year 2008 the German government signed the so called "German Adaptation Strategy to Climate Change" (Bundesregierung 2008). Its long term aim is to lower the vulnerability and to increase the adaptability of natural, social and economic systems.

Furthermore politicians need to demonstrate the economic usefulness of new (large-scale) projects to their voters. In order to offer the authorities a basis for decision-making, economic effects as well as costs and benefits of adaptation measures have to be analysed, especially at the local level.

The objective of this paper is to review the existing literature on models dealing with the economic impacts of (the adaptation to) climate change. Looking at these models pros and cons for an application at the local level can be derived. In the previous environmental economics literature three methodical approaches are predominant. These are Computable General Equilibrium models, growth models and input-output models[1].

In this paper we focus on Computable General Equilibrium (CGE) models. These allow simulating any kind of shock on exogenous variables and their effects on different endogenous variables like output, employment, prices

---

[1] A methododical overview about the input-output model is given by Kowalewski (2009).

and welfare (Bröcker 2004, p. 269). Exogenous shocks are for example a higher concentration of carbon dioxide or an increase of the mean temperature.

The paper is structured as follows. Section 2 deals with the basic CGE model, pros and cons of the general CGE approach and how the impacts of climate change are implemented in CGE models. Section 3 explains the four existing models (DICE and related, MERGE, PAGE and FUND). The focus is on how impacts are translated into monetary damages and how these damages can be reduced via adaptation. Section 4 contains conclusion and suggestions for further research.

2 The basic CGE model

2.1 Setting up a CGE

The basic idea of CGE is to implement theoretical economic models empirically. In order to simulate the welfare effects of different policies a general equilibrium approach is combined with empirical data. The CGE model is based on the Walrasian general equilibrium theory. An equation system representing the demand for goods by consumers, the supply of goods by producers, and the equilibrium condition that supply equals demand on every market is solved simultaneously (Arrow and Debreu 1954, p. 265). However, the CGE model allows for some modifications like imperfect markets and externalities.

In order to explain the term CGE it is useful to proceed by defining word by word. Computable stands for numerical calculations by computer. The term Equilibrium refers to the concept of market equilibrium. This concept includes the micro foundation of profit maximizing firms and utility maximizing households. Hence agents have no incentive to revise their decisions. Finally, the approach is General since all markets are interconnected and not

considered separately in a partial equilibrium.

The Walrasian equation system represents the interdependencies between markets via commodity and corresponding payment flows between market agents. These circular flows represent a closed system. Closed means that there cannot be a payment or commodity flow from one agent that has no recipient. The budgets of all agents have to be balanced. Agents obtain a certain income that can be spent on goods. For further details on the concept of circular flows of commodities and payments see Wing (2004, pp. 4-5). For more information about the basics of CGE a classical introduction can be found in Shoven and Whalley (1984).

The general procedure of a CGE can be explained in nine steps (Bröcker 2004, pp. 273-277) The procedure uses the formalized equation system of Walrasian general equilibrium theory:

1. The first step is to delineate agents (producers, consumers, state) and markets (food, cars ...).

2. The next step is to organize the data for a computer program. In a so called Social Accounting Matrix (SAM) agents appear twice, once in the row with their payments and in the columns with their receipts. In Table 1 a SAM is set up for a static economy with two industries (I_1 and I_2), two factors of production (labour L and capital K) and two households (H_1 and H_2). There is no public sector and there are neither taxes nor savings and investments. I_2 pays four units for inputs that are produced by it, six units for inputs from I_1, four units for labour and seven units for capital (similarly for I_1). Three units of labour income go to H_1, respectively seven units to H_2. Capital income (eleven units) goes to H_1 (five units) and H_2 (six units). H_1 (H_2) spends one unit (eight units) of its income for goods from I_1 and seven units (five units) for goods from I_2. Gross production is 37 units (sum of I_1 and I_2), of which 16 units are intermediate goods (flows from I_1 to itself, to I_2 and

4

Table 1: Social Accounting Matrix for a static economy

	I_1	I_2	L	K	H_1	H_2	SUM
I_1	1	6			1	8	16
I_2	5	4			7	5	21
L	6	4					10
K	4	7					11
H_1			3	5			8
H_2			7	6			13
SUM	16	21	10	11	8	13	79

Source: According to Bröcker (2004, p. 274).

vice versa). The Gross Domestic Product (GDP) is 21 units; this can be either considered as the units produced by the two industries using labour and capital inputs or as the expenditure of the two households for the produced units.

3. A market form (usually perfect competition) is assumed.

4. An arbitrary benchmark price is choosen.

5. The functional forms of supply and demand are specified to set up the model.

6. The sixth step is the calibration of the model. This is a crucial point. Only one time period is included in the SAM and parameters are chosen, to reproduce the benchmark data. There is no information on reactions of the agents, which is needed to specify the slope parameters (elasticities). Estimation of these slope parameters is only possible with longer time periods. Since this is not the case within the CGE analysis this information has to come from econometric analysis outside the CGE.

7. The next step is to compute the policy effects.

8. The procedure continues with the analysis of welfare effects using methods like Hicksian equivalent variation.

9. The last step is the sensitivity analysis. To reduce the arbitrariness of the chosen elasticities from other research results, sensitivity analysis with varying elasticities is implemented in a CGE procedure.

2.2 Pros and Cons of the basic model

In CGE models like in all general equilibrium models price changes cause simultaneous reactions in all other markets. This property is important for the two main advantages which are the micro foundation and the inclusion of economic feedback processes. The micro foundation consists of the three conditions, namely market clearance, zero profit of firms and income balance of the households. These principles are considered in the formulation of a CGE. Because of the inclusion of economic feedback processes (due to price changes that lead to quantity changes) CGE can be used for long-term perspective analysis (Walz and Schleich 2009, pp. 33-34).

A significant weakness of CGE is the already mentioned poor empirical foundation of the calibration. Only observations from one year are used to calibrate shift parameters. The production and utility functions are constrained to constant elasticity of substitution (CES). The parameters for these functional forms come exogenously from empirical estimation of elasticites and not from the calibration process. These "best guess" values add a large uncertainty into the model. Especially the chosen elasticity has a significant effect on the results (West 1995, p. 217).

2.3 Implementation of Climate Change into CGE Models

CGE models are a commonly used tool for quantifying the costs and benefits of environmental policy. The aim is to simulate how economic activity affects the environment and vice versa. Furthermore CGE models deal with the question how technological development and production are influenced by environmental policies (van Ierland 1999, p. 595).

The impacts of global warming usually enter a CGE model as monetized damages. Aggregate monetized gross damage GD_t is modelled as a function of a climate variable:

$$GD_t = \alpha_i \, \Delta T_t^2 \tag{1}$$

where usually the change of global mean temperature compared to a base year (ΔT_t) is used. Mostly, the functional form is assumed to be quadratic (or at least the power is larger than 1). This allows for increasing impact costs when temperature rises.

The climate impact function is:

$$T_t = \alpha_j \, T_{t-1} + \alpha_k \, EM_t \tag{2}$$

where an increase of carbon dioxide emissions (EM_t) by a certain amount, as the exogenous shock, leads to an increase of the global mean temperature (T_t) compared to the level of the period before.

Usually a carbon dioxide doubling compared to pre-industrial time leads to a temperature increase by around 2.5 to 3 °C above present temperature level. Following the literature (e. g. Pearce et al. 1996) benchmark damages of this temperature increase are assumed to lie in the area of 1.3 to 2.5 per cent of world income. The parameters of a climate impact model are calibrated to reflect this relationship (Tol and Fankhauser 1998, p. 70).

The interactions of climate impacts with the rest of the CGE model con-

tain three major mechanisms. Firstly, the influence of other non-climatic variables on climate is introduced in the model. Secondly, the resulting effects of adaptation processes are considered. Thirdly, the feedbacks of impacts into the rest of the CGE model are analysed. The impacts of climate change on the society and economy depend largely on the interplay with the new climate as well as on the vulnerability to extreme weather events. The degree of vulnerability is determined by factors like technical and financial capability, demographic, socio-economic and behavioural constraints and organization of the society. As these factors vary over time, vulnerability should vary as well (Tol and Fankhauser 1998, p. 70).

However, most models do not take changing vulnerability into account. In the simplest case damage is a constant fraction of GDP. Hence, damages grow linearly with GDP. This linear trend can be influenced by further factors shifting the amount of damages up or down. For example population growth affects the number of people concerned. Then income growth affects people's valuation of impact and this results in a change of tastes affecting valuation.

Adaptation is usually implicitly included in the aggregate monetized damage function (Tol and Fankhauser 1998, p. 70). Adaptation costs (for dikes) are added to the residual damage costs (loss of unprotected land). Because most models are highly aggregated with respect to sectors and regions there is only limited room for feedback loops and adjustment mechanisms. Usually, damages are fed back simply by subtracting monetized market damage from total output. The climate impact model gives no answer to the question which agent is actually affected by the impact (Tol and Fankhauser 1998, p. 70).

3 Applications

In this section four different models DICE (and related models), MERGE, PAGE and FUND are discussed. A focus is put on different specifications of

the damage function as well as on the role adaptation plays in the models.

3.1 DICE/RICE/AD-DICE/AD-RICE

The "Dynamic Integrated Climate and Economy (DICE) model" goes back to Nordhaus (1991). It analyses at a global level not distinguishing sectors or economic and non-economic categories. DICE and related models are based on a Cost-Benefit-Approach. They are used to calculate the optimal balance between greenhouse gas abatement and economic damages from climate change in order to maximize intertemporal welfare. The models include a CES production function with capital and labour inputs that specify gross world product and exogenous technological growth. DICE and related models cover emissions of greenhouse gases as well as an emission reduction function. If emissions are reduced this has a negative impact on the growth rate of gross world product. Formally the abatement costs enter the production function as a fraction of GDP and reduce the potential output that can be produced with a given stock of capital and labour (Nordhaus 2008, pp. 41-42).

Greenhouse gases are responsible for global warming and affect temperature. The damage function relates the average increase of global temperature to monetary damages of climate change:

$$\frac{GD_t}{GDP_t} = \alpha_1 \, \Delta T_t + \alpha_2 \, \Delta T_t^{\alpha_3} \tag{3}$$

where α_1 is unrestricted, $\alpha_2 > 0$ and $\alpha_3 > 1$. GD_t stands for gross damages, GDP_t is Gross Domestic Product and ΔT_t is the temperature change compared to 1900. The parameters $\alpha_1, \alpha_2, \alpha_3$ relate temperature change to damages. The values of the parameters are obtained from the calibration process, in which benchmark data for damages and temperature changes for the base year are inserted into (3). Because α_3 is defined larger than 1, costs grow more than proportionally with increasing temperature changes

(de Bruin, Dellink and Tol 2009, pp. 67-69). The calculated damages of climate change enter the production function by reducing the maximum output that can be achieved with the capital, labour and energy stock (Nordhaus 2008, pp. 41-42). Considering the time steps of ten years that are used in the model, it is justified to assume that damages occur only in one period and do not continue any longer.

The "Regional Integrated Climate and Economy (RICE) model" is a regionalized version of the DICE model (Nordhaus and Yang 1996). It has only one total damage category but splits the world into 13 regions.With RICE, various emission reduction strategies in these regions can be studied. Either the regions are fully cooperative in their common emission strategy or the different regions follow strategies to maximize their local benefits. In the non-cooperative case, only very modest emission reductions are obtained (van Ierland 1999, p. 599). In RICE, each region is assigned a different climate damage function, based on the same impact categories. The global (DICE) and regional (RICE) aggregate damage functions are derived from a climate impact analysis. This analysis is based on a willingness to pay approach to estimate the value of preventing future climate change (Nordhaus 2000).

DICE and RICE do not take adaptation as a decision variable into account while their extensions AD-DICE and AD-RICE do (de Bruin, Dellink and Tol 2009, de Bruin, Dellink and Agrawala 2009). In these models adaptations decrease the potential damages of climate change.

In the adaptation models three categories of damages are defined and linked in (4):

- Gross damages GD_t occur when no adaptation is implemented.

- Residual damages RD_t are the damages that result when adaptation takes place at a level AL_t.

- Net damages D_t add the adaptation costs AC_t (costs of implementing

adaptation) to the residual damages (de Bruin, Dellink and Tol 2009, p. 67).

In the gross damage function the assumption is represented that the protection costs and the residual damages are separable and can be expressed as a fraction of GDP_t:

$$\frac{D_t}{GDP_t} = \frac{RD_t(GD_t, AL_t)}{GDP_t} + \frac{AC_t(AL_t)}{GDP_t} \tag{4}$$

where residual damages depend on gross damages as well as the adaptation level AL_t and adaptation costs depend only on the adaptation level (de Bruin, Dellink and Tol 2009, p. 67).

The adaptation cost function is:

$$\frac{AC_t}{GDP_t} = \gamma_1 AL_t^{\gamma_2} \tag{5}$$

where $\gamma_1 > 0$ and $\gamma_2 > 1$. It is increasing with the adaptation level, because cheaper adaptation measures are implemented first (de Bruin, Dellink and Tol 2009, p. 68).

The level of adaptation is chosen every time period, which is 10 years in the model. Having in mind the horizon until 2200, too small time steps would increase the time required for the computation process. It is also sensible to assume that the implementation of adaptation measures may take more than one year until it is accomplished.

Per assumption adaptation in one time period does not affect damages in the next period. This implies that both costs and benefits of adaptation fall in the same time period and the same trade-off between costs and benefits occurs each period. As long as adaptation is applied optimally, de Bruin, Dellink and Tol (2009) argue that with this implication the benefits of adaptation will always outweigh the costs. This kind of modelling belongs to the category of reactive adaptation. Anticipatory adaptation like building seawalls allows for time-lags in costs and benefits which could be included by

11

an adaptation capital stock in the model (de Bruin, Dellink and Tol 2009, p. 68).

The adaptation costs function is increasing with the level of adaptation. The simulation results of AD-DICE show that the adaptation costs of the first 15 per cent of gross damage reduction can be avoided at very low costs. If additional adaptation is implemented costs increase very strongly. The calibrated model finds an optimal level of adaptation between 0.09 and 0.45 of gross damages, with an average of 0.33 . That means that considering cost-benefit aspects it is optimal to choose an adaptation level in the amount of 33 per cent of gross damages. It can never be optimal to fully adapt to climate change because adaptation costs are increasing. Neither is it the best solution to mitigate all future damages. For an optimal policy with minimum costs (damages plus implementation costs) a mixture of mitigation and adaptation policy has to be implemented (de Bruin, Dellink and Tol 2009, p. 70).

In the RICE model some colder northern regions benefit from climate change (Northern Europe, Russia and Canada). Therefore adaptation has to be implemented in a different way than in DICE (4). The gross damage function is:

$$\frac{D_{t,r}}{GDP_{t,r}} = \frac{RD_{t,r}(GD_{t,r}, AL_{t,r}, AB_{t,r})}{GDP_{t,r}} + \frac{AC_{t,r}(AL_{t,r}, AB_{t,r})}{GDP_{t,r}} \tag{6}$$

where damages $D_{t,r}$ are again the sum of residual damages $RD_{t,r}$ and adaptation costs $AC_{t,r}$, but now differentiated for each region. The adaptation level in (4) is split up into two effects. In (4) the adaptation level AL_t includes adaptation to climate change damages, now denoted as $AL_{t,r}$. In order to represent possible benefits of adaptation measures like more productive agriculture in northern countries the additional variable $AB_{t,r}$ is incorporated. Adaptation costs and residual damages depend on both kinds of adaptation. Residual damages depend on the gross damages $GD_{t,r}$ and the level of adaptation (de Bruin, Dellink and Agrawala 2009, p. 47). Mit-

igation is not explicitly modelled in AD-RICE. Implicitly mitigation enters the model by specifying the input of carbon energy (de Bruin, Dellink and Agrawala 2009, p. 16).

With AD-DICE and AD-RICE the effects of different mitigation and adaptation levels can be simulated. The four reference scenarios are:

- no adaptation and no mitigation (S1).

- optimal adaptation and mitigation (S2).

- no mitigation and optimal adaptation (S3).

- no adaptation and optimal mitigation (S4).

The utility levels for the reference scenarios are calculated as the objective of the optimisation procedure from DICE and RICE. The highest utility level is reached in the S2 optimal scenario. S3 (no mitigation, optimal adaptation) and S4 (no adaptation, optimal mitigation) follow with an almost equal level of utility. S1 with no action is in terms of utility by far the worst option (de Bruin, Dellink and Agrawala 2009, pp. 20-21).

The results in Table 2 show that the total costs of climate change per year increase over time.

Table 2: Build-up of climate costs in the reference scenarios

Annual costs (billion US Dollar)	S1 - no adaptation and no mitigation	S2 - optimal adaptation and mitigation	S3 - no mitigation and optimal adaptation	S4 - no adaptation and optimal mitigation
Period 2025-2034				
Adaptation costs	0	7	7	0
Mitigation costs	0	21	0	30
Residual damages	204	170	174	199
Total Costs	204	198	181	229
Period 2095-2105				
Adaptation costs	0	247	361	0
Mitigation costs	0	367	0	610
Residual damages	5430	3026	3920	3824
Total Costs	5430	3640	4281	4434
Period 2145-2155				
Adaptation costs	0	1013	1903	0
Mitigation costs	2	1672	2	2902
Residual damages	22083	6926	14437	12033
Total Costs	22085	9611	16342	14935

Source: Agrawala et al. 2009, p. 22.

While in the early period 2025-2034 the saving effect of an optimal adaptation and mitigation strategy (S2) compared to no action (S1) with cost reduction of 3 per cent is very small, the benefits of action increase very strongly over time. The largest benefits are possible in the last period 2145-2155. In this period with an optimal strategy of combined mitigation and adaptation the total costs per year can be reduced by over 50 per cent. It can also be seen that in the short term pure adaptation (S3) leads to lower

costs than pure mitigation (S4). In the long run the result is reversed. The highest benefits except for the first period follow from the optimal mixture of mitigation and adaptation (S2) (de Bruin, Dellink and Agrawala 2009, pp. 22-23).

AD-RICE splits up the global effects of climate change to analyse regional differences. Its damage function (6) is of the same form as AD-DICE (4) but includes adaptation benefits in some regions. The results from AD-RICE show that there are some regions like Russia and Eastern Europe with very low net benefits from climate change.

On the other hand the simulated gross damages are very large especially in developing countries and regions like India and Africa. These regions will be affected by climate change very strongly and will face gross damages of 4.6 and 4.2 per cent of GDP per year respectively.

In order to lower the gross damages these regions have to make the largest adaptation efforts. However these efforts can reduce gross damages by a large amount. For example Africa can reduce its gross damages by 35 per cent with adaptation in the amount of 7 per cent of gross damages. These numbers show that damages from climate impacts can be reduced significantly in developing countries when adaptation takes place (de Bruin, Dellink and Agrawala 2009, pp. 23-24).

3.2 MERGE

MERGE stands for "Model for Evaluating Regional and Global Effects of greenhouse gases reduction policies" and has been developed by Manne et al. (1995). It builds on DICE/RICE (Nordhaus 1991; Nordhaus and Yang 1996), but includes five world regions and has two damage categories (market and non-market). The design allows calculating the optimal balance between greenhouse gas abatement and economic damages from climate change.

It consists of three submodels. Each submodel represents one of the major processes of interest. The first one deals with the costs of reducing emissions

of greenhouse gases. The second one analyses the composition of the natural system and reactions to the emissions of these gases. The third one simulates the reaction of human and natural systems to changes in the climate system.

The model uses a nested Cobb-Douglas function with four inputs. On the first stage capital and labour are combined into a composite input as well as electric and non-electric energy into another composite input. On the second stage these two composite inputs create one output unit for each of the five world regions. Autonomous energy-efficiency improvements are included by a scaling factor for the energy-non-energy composite good (Manne et al. 1995, pp. 18-21).

In order to estimate damages first a business as usual scenario is calculated. GDP increases exogenously by taking growth rates from IPCC Working Group III (1990). In the base line scenario constant energy prices are assumed. The different energy sources used in the production process lead to a certain amount of emissions which has an effect on temperature (Manne et al. 1995, p. 21). The relationship between temperature increase and monetized damages can be seen in the regional damage function for market impacts:

$$D_{t,r} = d_{1,r} * \Delta T_{t,r}^{d_{2,r}} * GDP_{t,r} \tag{7}$$

where $D_{t,r}$ stands for the market damages in period t in region r. $\Delta T_{t,r}$ is the temperature change relative to the temperature in 1990 and $GDP_{t,r}$ is gross domestic product. The parameter $d_{1,r}$ results again from the calibration in the benchmark scenario. The assumption about the shape of the curve is replicated by $d_{2,r}$ (Manne et al. 1995, p. 25). The model follows Nordhaus (1992, p. 1316) by assuming that damages rise quadratically with temperature increase. Hence $d_{2,r}$ is equal to two.

For non-market damages a willingness to pay approach is used. Because calculating direct damages is not possible the question is asked how much consumers in each region would be willing to pay to avoid ecological damages (Manne et al. 1995, p. 26).

All variables in MERGE have a regional index representing five world regions. Because of the regional structure MERGE is similar to RICE and AD-RICE. Both simulate region specific damages. However, MERGE calculates with region-specific increases in temperature and regional GDP, while AD-RICE considers only a global change in temperature and regional GDP. MERGE expresses in (7) the damages as total damages. AD-DICE and AD-RICE instead denote in (3) damages as a fraction of output.

Adaptation affects the model as follows. An assumed certain degree of adaptation leads to a certain amount of adaptation costs. On the other hand adaptation lowers damages that result from impacts of climate change. These mechanisms are not explicitly modelled. They are considered implicitly in the calibration of the damage function, where increases in temperature define the level of damages.

MERGE estimates market and non-market damages. Most of the damages occur in non-market categories. The loss for a projected 2.5 °C rise in temperature amounts in the business as usual scenario to a discounted global loss of 1.4 per cent of GDP (Manne et al. 1995, p. 30). Market damages for developed countries amount to a loss of 0.25 per cent of GDP, in developing countries 0.5 per cent. Non-market damages are only estimated for developed countries and are estimated as 1.99 per cent loss of GDP (Warren et al. 2006, p. 28).

Different policies like the introduction of a tax on carbon emissions can be studied. In such a carbon tax scenario with a tax starting at one US Dollar per tonne in 2000 and increasing at 5 per cent per year, China has the highest net benefits in monetary terms. Also the United States, other OECD countries and the former Soviet Union reach positive net impacts. Only the region "Rest of the World", especially the tropics, suffers from negative impacts (Manne et al. 1995, p. 30).

3.3 PAGE

The "Policy Analysis for the Greenhouse Effect (PAGE) model" from Hope et al. (1993) uses relatively simple equations to approximate complex climatic phenomena. Economic effects are also described in a highly aggregated form for economic and non-economic damages and eight world regions. The main goal of PAGE is to compare the effects of different policies for mitigation of and adaptation to climate change.

The model includes uncertainty by incorporating parameters from a random sample and repeated runs. Each input parameter is represented by a triangular probability distribution. The distribution is continuous and shaped like a triangle. It is generated by the assumption about three points, namely the minimum, the maximum and the mode. These three parameters define the nature and characteristics of the entire distribution (Plambeck et al. 1997, p. 87).

PAGE runs 250 calculations of the output variables which are temperature rise, resulting damages from climate change, costs of mitigation and costs of adaptation. Latin hypercube sampling (for more details see McKay et al. 1979) is used to choose in each of the 250 runs a different set of values for the uncertain input parameters. This method is used rather than random Monte Carlo sampling because it improves the coverage of the range of input parameters. The estimation of the cumulative distribution function and mean of each output variable is more precise than with Monte Carlo (Plambeck et al. 1997, p. 96).

Instead of specific sectors the model analyses the two categories economic and non-economic costs. Economic costs have a direct quantifiable market impact like capital costs of flooding damages. Non-economic costs are for example the loss of biodiversity, which has no direct market value and is difficult to monetize.

The model simulates explicitly the emissions of the primary greenhouse gases and the resulting effect on global warming. The temperature changes

are modelled at a regional level. PAGE calculates regional economic growth to investigate the market and non-market impacts of climate change in terms of a percentage loss of GDP per year in each region (Warren et al. 2006, p. 30). The estimation process is as follows. First GDP is calculated assuming an exogenous growth rate of 2 per cent globally or varying for different regions and time periods according to the Energy Modelling Forum (1994). Knowing the potential GDP and emissions costs for adaptation and mitigation as well as damage impacts are estimated that reduce GDP (Manne et al. 1995, p. 790).

Two similar policy or emission scenarios are compared in order to derive social costs of carbon dioxide emissions. PAGE computes the differences in damages for the two policies or two emission scenarios to derive the marginal benefits of reduced carbon emissions. The non-linear damage function is:

$$D_{t,d,r} = \left(\frac{IMP_{t,d,r}}{2.5} \right)^{POW} * W_{d,r} * \left(\frac{1 - AP_{t,d,r}}{100} \right) * GDP_{t,r} \qquad (8)$$

where $D_{i,d,r}$ are damages for each period $t = 1, \ldots, 10$ and region r calculated for the economic and non-economic category ($d = 0$ or 1 respectively). Uncertainty is represented in the non-linear damage function by the uncertain power parameter POW (Plambeck et al. 1997, p. 94).

The damage function depends on an impact $IMP_{t,d,r}$ of an uncertain temperature change (here the benchmark case is 2.5 °C). $W_{d,r}$ stands for the weight that allows for differences of the impacts in each sector and region. The impacts can be mitigated through adaptation policies $AP_{t,d,r}$. Damages are expressed as a percentage loss of gross domestic product $GDP_{t,d,r}$. The uncertain power varies between one and three with mode 1.3. Variation of POW allows for sensitivity analysis because this parameter influences the results to a large extent. The function is calibrated so that it fits with a benchmark estimate from Cline (1992) where mean temperature rises by 2.5 °C over pre-industrial level (Warren et al. 2006, pp. 30-31).

Comparing (9) with the damage functions from DICE and MERGE, the functional form is different. Temperature change does not cause damages directly but leads to impacts which enter the damage function on a second stage. Instead of calculating damages for each region explicitly like MERGE, PAGE calculates damages for a reference region. The reference result is then adjusted by the weighting factor $W_{d,r}$. Adaptation occurs in PAGE as a factor that is set for each sector, region and time period. It has a lowering influence on damages, which is similar to the adaptation implementation in (4) in AD-DICE.

The potential for adaptation to climate change is included by the assumption that impacts only occur for temperature rises above some tolerable rate of change. Adaptation can increase this tolerable level of temperature rise and reduce negative impacts. In the model the extent of adaptation in each year, region and sector can vary. In the PAGE model, adaptation can affect the date or temperature level at which negative impacts of climate change start to occur. Also, the curvature of the damage function can be chosen in different ways. Thus, impacts result in higher or smaller damages (Plambeck et al. 1997, pp. 93-96). These effects are modelled by using a slope and a shift parameter for each sector and each region. The slope parameter determines the maximum rate of change in global temperature that can be tolerated in an impact sector without adverse impacts. The plateau parameter gives the maximum absolute change of global temperature that can be tolerated (Hope et al. 1993, p. 330).

Conceptually, adaptation is modelled as averages of a reduction or avoidance of the impacts of climate change. Instead of averages, more accurate estimates of the costs of adaptation measures could take into account the complexity of the adaptation process. The PAGE model assumes that markets are efficient and therefore that adaptation is efficient. Without any externalities, adaptation will be optimal and reduces the costs of climate change. Private adaptation will take place because of agent's self-interest. But with

20

respect to joint adaptation where there are many beneficiaries, this kind of adaptation will be only efficient through government action (Mendelsohn 2000, p. 593). Externalities and policy changes affect the price of land and other related assets. If externalities exist, it can not be assumed any longer that adaptation is automatically optimized by market agents (Mendelsohn 2000, p. 587).

As main outputs the PAGE model computes equity-weighted impacts in millions of US Dollar, which can be translated into regional or global percentage losses of GDP. The sum of economic and non-economic impacts is modelled to lie between a 2 per cent reduction in GDP and a 0.1 per cent increase in GDP for a 2.5 °C temperature rise. As can be seen in Table 3 the value of economic impacts for the European Union ranges from a -0.1 to a 1 per cent loss of GDP with a mean of a 0.5 per cent loss. The damages from

Table 3: Impact parameters in PAGE

PAGE impact parameters	Mean	Min	Mode	Max
Economic impact*	0.50	-0.10	0.60	1.00
Non-economic impact*	0.73	0.00	0.70	1.50
Regional weighting factor for				
Eastern Europe and former Soviet Union	-0.35	-1.00	-0.25	0.20
USA	0.25	0.00	0.25	0.50
China and East Asia	0.20	0.00	0.10	0.50
India and South Asia	2.50	1.50	2.00	4.00
Africa	1.83	1.00	1.50	3.00
Latin America	1.83	1.00	1.50	3.00
Other OECD	0.25	0.00	0.25	0.50

* for Western Europe as percentage loss of GDP for 2.5 °C increase of global mean temperature
Source: Warren et al. (2006), p.32.

non-economic impacts are higher than the economic impacts. The regional weighting factor for Eastern Europe and the former Soviet Union is negative. The interpretation is that compared to the European Union, it is the only region that actually benefits from climate change. India and South Asia suffer the most, followed by Africa and Latin America. China, the United States of America and other OECD countries are affected to a lower extent than the European Union (Warren et al. 2006, pp. 31-32).

The results of adaptation are as follows. The model compares the no adaptation and aggressive adaptation cases. In the no adaptation case impacts are accepted as they occur and when they occur. The effect of aggressive adaptation is that sectors face no damages from a 2 °C rise in temperature until 2000. If temperature rise is higher than 2 °C, further implemented measures reduce the impacts of climate change by up to 90 per cent compared to the no adaptation scenario. But adaptation should only be implemented if benefits are larger than costs of adaptation. The estimation results show that costs of 0.5 trillion Euro avoid costs of climate change impacts by 17.5 trillion Euro, hence adaptation should be implemented to a large extent (Hope et al. 1993, p. 334).

3.4   FUND

The FUND (Climate Framework for Uncertainty, Negotiation and Distribution) model is based on the DICE model, but it contains a regional specification like AD-RICE and MERGE. FUND also includes interregional capital flows and a detailed specification of the functions to assess the damage costs of climate change (Tol 1997).

The model is defined for 16 world regions and nine key-areas like agriculture, ecosystems and human health. Population and per capita income enter exogenously from emission scenarios. There are the four scenarios A1B, A2, B1 and B2 from the Special Report on Emissions Scenarios, published by the Intergovernmental Panel on Climate Change. The scenarios have different

22

storylines:

- A1 represents a future world of very rapid economic growth, global population growth until the mid-century and rapid introduction of new and more efficient technologies.

- A2 simulates a heterogeneous world with continuously increasing population and differences in regional economic growth.

- B1 assumes the same population pattern as A1 but adds rapid changes in economic structures toward a service and information economy and introduction of clean and resource-efficient technologies.

- B2 focuses on local solutions to economic, social and environmental sustainability. Population is continuously increasing but lower than in A2 and intermediate economic development.

Carbone dioxide emissions are calculated endogenously and depend on energy use, GDP and population. For Germany it can be noted that GDP from 1990 to 2007 rose by 30.4 per cent but emissions were reduced by 18.4 per cent. For industrialised countries it seems that emissions and GDP are decoupled. The reason is that in the same period energy productivity grew faster than GDP and hence total energy use declined (Statistisches Bundesamt 2008). This mechanism is included in FUND in the emissions equation, where autonomous energy efficiency improvement reduces the carbon intensity of energy use. Keeping GDP constant this leads to lower emissions (Warren et al. 2006, p. 45).

Adaptation occurs in the model via the agriculture sector. A parameter that denotes the speed of adaptation lowers the impact of climate change on this sector. This can be classified as private adaptation that will occur at an efficient level. Joint adaptation like costal protection is missing in the model. Therefore a statement about inefficient adaptation that may occur with joint adaptation and policy changes are not possible. The adaptation

costs are only modelled implicitly while explicit adjustment costs are missing (Warren et al. 2006, p. 48).

FUND simulates damages from climate change in key-areas such as agriculture, forestry, water resources, energy consumption, sea level rise, ecosystems, human health and mortality. Damages in the FUND model are in monetary units or in percentage loss of GDP. To calculate for example these values for the business as usual scenario, there are three steps to proceed. The first step is to calculate the potential population and economic growth as well as the resulting emissions using the data from the exogenous scenarios. The second step is to estimate the corresponding damages from conventional air pollution (direct effects of the emissions). The third step is to calculate the indirect effect of the emissions, hence the climate change and its impacts on humans and on the economy (Tol 1997, p. 157).

For example the damage function for the water sector has the form:

$$W_{t,r} = a_r (1 - \tau)^{t-1990} \left(\frac{GDP_{t,r}}{GDP_{1990,r}} \right)^{\beta} * T_t^{\gamma} \tag{9}$$

where $W_{t,r}$ denotes the change in water resources at time t in region r and depends on the income ($GDP_{t,r}$) and global mean temperature T_t^{γ} as well as on the parameters , α_r, τ, β and γ.

For the period 2000-2100 the results of FUND show for the business as usual scenario at a global level a small benefit from climate change for a very moderate increase of about 0.5 °C above 1990 levels. But for higher temperature increases, damages rise as global warming increases. For a 3 °C rise in temperature, damages will amount to between 1.2 and 2.7 per cent of global GDP per year. For a 2 °C rise the damages are still between 0.5 and 1.0 per cent. Compared to the results of the DICE model (0.5 per cent loss for a 2 °C increase), the damage estimates are very similar (Warren et al. 2006, p. 60).

The results of the sector specific effects in the energy, water, health, agri-

culture and ecosystems sector are as follows. The energy sector dominates the calculation of the impacts, because assumed higher energy use is responsible for most of the negative impacts. This result depends on the assumption of a greater need of energy for cooling, especially in high temperature regions like Africa. Water plays a much smaller role when it comes to damages from climate change. On the other hand the model finds net benefits for health and agriculture, but these benefits declinie over time. Ecosystems contribute a small negative effect to global GDP.

The impacts of climate change differ quite strongly regionally. While northern regions are less negatively affected, southern regions suffer to a large extent. Africa faces the greatest negative impact of global warming. South America, South Asia, Central America and Australasia face negative impacts out to 2100, but to a much smaller extent than Africa. For the other regions it depends on the level of temperature increase. For moderate temperature increases up to 3 ℃ above the level of 1990, West Asia, North America and Europe even benefit from climate change. For a rise of more than 3 ℃ the impacts become negative (Warren et al. 2006, p. 61).

4   Conclusion

In the field of CGE most climate change impact applications are based on the presented models. As can be seen in Table 4 the models differ with respect to certain characteristics like the specific form of the damage function, the interaction of economy and climate and how adaptation is implemented.

While MERGE has its advantage in the explicit modelling of how greenhouse gases lead to climate change and how global warming could be avoided, it does not say much about adaptation. Only implicitly adaptation enters MERGE via the damage function, where it reduces the damages of climate impact. Occurring damages are calculated as percentage of GDP loss but it has no feedback effect on GDP growth within the model.

Table 4: Overview of Climate Impact Models

Source	Model	Functional form	Regions	Impact parameter	Damage categories	Adaptation	Results	Feedback from climate impacts on base line GDP growth
deBruin et al. (2009)	AD-DICE / AD-RICE	quadratic	global / 13	global mean temperature	one	as policy / decision variable	- developing countries most affected - optimal mix of adaptation and mitigation policy - benefits of prevented damages outweigh costs in the analysed scenarios	- GDP growth is scaled down with damages
Hope et al. (1993)	PAGE	quadratic	8	regional mean temperature	non-economic and economic	policy variable, increases "tolerable level"	- developing countries most affected - call for aggressive adaptation	- no feedback from climate to GDP (only occurring damages are summarized)
Manne et al. (1995)	MERGE	quadratic	5	regional mean temperature	Non-market and market	implicit adaptation via calibration of the damage function	- developing countries most affected - non-market damages are larger than market damages - no results for adaptation	- no feedback from climate to GDP (only occurring damages are summarized)
Tol (1997)	FUND	second-order polynomial	16	global mean temperature	9 key areas	induced adaptation via agricultural sector	- damages in the energy sector dominant - developing countries suffer most - no results for adaptation	- damages in economic sectors reduce consumption and investment of GDP - impacts on human health affect population

FUND analyses the effects of climate change at a regionalised level with 16 world regions as well as for nine key areas. The mitigation aspect is well addressed but adaptation takes place only implicitly via the agricultural sector. In FUND damages in economic sectors and impacts on health affect GDP growth and population and hence this model represents more interactions between economy and climate.

PAGE uses the aggregated level with economic and non-economic costs as well as computes results for the world in total and world regions. While mitigation is explicitly studied, adaptation is no decision variable. The level of adaptation and the impacts of adaptation measures can be influenced by choosing an adaptation policy, but the result focuses on the mitigation effect due to global warming.

AD-DICE/AD-RICE finally add adaptation as an endogenous decision variable to the CGE model. Optimal levels of adaptation and mitigation compared to single and no action strategies can be studied. Adjustment costs of adaptation are considered. GDP growth is reduced within the model via downscaling with occurring damages.

With regard to the results all models show that developing countries will be most affected. PAGE calls for aggressive adaptation. In the scenarios of AD-DICE the optimal policy is a mix of adaptation and mitigation.

The models assume perfect markets. Hence the optimal adaptation and mitigation levels will be implemented by market agents. However in joint adaptation with many beneficiaries externalities occur. These questions have to be considered in more detail.

All the presented models are global or world regions models that deal with adaptation in a specific way though the decision about implementing adaptation measures is made at the local level. In order to address these questions the mechanisms of the adaptation models have to be introduced into regional models that take care of the specific characteristics of a region and the impacts that occur in that region.

References

Arrow, K. J. and Debreu, G. (1954). Existence of an equilibrium for a competetive economy, *Econometrica* **22**: 265–290.

Bröcker, J. (2004). Computable general equilibrium analysis in transportation, *in* D. A. Hensher, K. J. Button, K. E. Haynes and P. R. Stopher (eds), *Handbook of Transport Geography and Spatial Systems*, Vol. 5, Elsevier, Amsterdam, The Netherlands, pp. 269–291.

Cline, W. (1992). *The Economics of Global Warming*, Insitute for International Economics, Washington, D.C.

de Bruin, K. C., Dellink, R. B. and Agrawala, S. (2009). Economic aspects of adaptation to climate change: Integrated asessment modeling of adaptation costs and benefits, *OECD Environment Working Papers* **6**.

de Bruin, K. C., Dellink, R. B. and Tol, R. S. J. (2009). AD-DICE: an implementation of adaptation in the DICE model, *Climate Change* **95**: 63–81.

Hope, C., Anderson, J. and Wenman, P. (1993). Policy analysis of the greenhouse effect - an application of the PAGE model, *Energy Policy* **21**: 327–338.

IPCC (1990). Climate change: The IPCC scientific assessment, *Technical report*, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

Kowalewski, J. (2009). Methodology of the input-output analysis, *HWWI Research Paper* **1-25**.

Manne, A., Mendelsohn, R. and Richels, R. (1995). MERGE - a model for evaluating regional and global effects of GHG reduction policies, *Energy Policy* **23**: 17–34.

McKay, M. D., Beckman, R. J. and Conover, W. J. (1979). A comparison of three methods for selecting values of inout variables in the analysis of output from a computer code, *Technometrics* **21**: 239–245.

Mendelsohn, R. (2000). Efficient adaptation to climate change, *Climate Change* **45**: 583–600.

Nordhaus, W. (2008). *A Question Of Balance: Weighing The Options On Global Warming Policies*, Yale University Press, New Haven, Conn.

Nordhaus, W. D. (1991). To slow or not to slow: The economics of the greenhouse effect, *The Economic Journal* **101**: 920–937.

Nordhaus, W. D. (1992). An optimal transisstion path for controlling greenhouse gases, *Science* **258**: 1315–1319.

Nordhaus, W. D. (2000). *Warming the World*, MIT Press, Massachusetts.

Nordhaus, W. D. and Yang, Z. (1996). A regional general-equilibrium model of alternative climate-change strategies, *The American Economic Review* **86**: 741–765.

Pearce, D. W., Cline, W. R., Achanta, A. N., Fankhauser, S., Pachauri, R. K., Tol, R. S. J. and Vellinga, P. (1996). The social costs of climate change: Greenhouse damage and benefits of control, *in* J. P. Bruce, H. Lee and E. F. Haites (eds), *Climate Change 1995: Economic and Social Dimensions - Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, pp. 179–224.

Plambeck, E. L., Hope, C. and Anderson, J. (1997). The page95 model: Integrating the science and economics of global warming, *Energy Economics* **19**: 77–101.

Shoven, J. B. and Whalley, J. (1984). Applied general-equilibrium models of taxation and international trade: An introduction and survey, *Journal of Economic Literature* **22**: 1007–1051.

Statistisches Bundesamt (2008). Nachhaltige Entwicklung in Deutschland - Indikatorenbericht.

Tol, R. S. J. (1997). On the optimal control of carbon dioxide emissions: anpllication of fund, *Environmental Modeling and Assessment* **2**: 151–163.

Tol, R. S. J. and Fankhauser, S. (1998). On the representation of impact in integrated assessment models of climate change, *Environmental Modeling and Assessment* **3**: 63–74.

van Ierland, E. C. (1999). Environment in macroeconomic modelling, *in* J. C. J. M. van den Bergh (ed.), *Handbook of environmental and resource economics*, Edward Elgar Publishing Ltd., pp. 593–609.

Walz, R. and Schleich, J. (2009). *The Economics of Climate Change Policies*, Pyhsica-Verlag, Heidelberg.

Warren, R., Hope, C., Mastrandrea, M., Tol, R., Adger, N. and Lorenzoni, I. (2006). Spotlighting impacts functions in integrated asessment, *Tyndall Centre for Climate Change Research Working Paper* **91**.

West, G. R. (1995). Comparsion of input-output, input-output + econometric and computable general equilibrium impact models at the regional level, *Economic Systems Research* **7**: 209–227.

Wing, I. S. (2004). Computable general equilibrium models and their use in economy-wide policy analysis, *Technical Report 6*, MIT Joint Program on the Science and Policy of Global Change.
URL: *http://globalchange.mit.edu/pubs/technotes.html, (downloaded at June 17th, 2009).*

HWWI Research Papers
by the HWWI Research Programmes
"Economic Trends" and "Hamburg and Regional Development"

7. Ein makroökonometrisches Modell für Hamburg
   Norbert Kriedel, Hamburg, Mai 2007

6. Managementstrategien im Fußball: „Big Push" oder Kontinuität?
   Ein dynamisches Modell zum sportlichen Auf- und Abstieg von Vereinen
   Henning Vöpel, Hamburg, Februar 2007

5. Ein Transfermarktmodell und Implikationen für die strategische Transferpolitik
   der Vereine in der Fußball-Bundesliga
   Henning Vöpel, Hamburg, November 2006

4. Gender Equality in the Labour Market: Attitudes to Women's Work
   Sylke Viola Schnepf, Hamburg, Oktober 2006

3. Ein „ZIDANE-Clustering-Theorem" und Implikationen für den Finanzausgleich
   in der Bundesliga
   Henning Vöpel, Hamburg, Juli 2006

2. Doping im Radsport als kollektives Gleichgewicht
   Henning Vöpel, Hamburg, Juli 2006

1. Long Waves of Economic Development and the Diffusion of General-Purpose
   Technologies – The Case of Railway Networks
   Norbert Kriedel, Hamburg, Januar 2006

The **Hamburg Institute of International Economics (HWWI)** is an independent economic research institute, based on a non-profit public-private partnership, which was founded in 2005. The University of Hamburg and the Hamburg Chamber of Commerce are shareholders in the Institute .

The HWWI's main goals are to:
• Promote economic sciences in research and teaching;
• Conduct high-quality economic research;
• Transfer and disseminate economic knowledge to policy makers, stakeholders and the general public.

The HWWI carries out interdisciplinary research activities in the context of the following research programmes: Economic Trends, Hamburg and Regional Development, World Economy and the Migration Research Group.