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Climate Change Impacts in Integrated Assessment Models: An Overview

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Abstract

This paper gives an overview about existing Integrated Assessment Models dealing with climate impacts with a focus on damage calculations and adaptation modelling. 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 will occur already in the next decades, adaptation is becoming a more important issue in current 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 at the local level and therefore is important for policy decision making.

Zusammenfassung

Dieser Aufsatz stellt einen Überblick über bestehende integrierte Bewertungsmodelle (Integrated Assessment Models) sowie alternative Modellansätze dar, welche die Auswirkungen des Klimawandels behandeln. Der Schwerpunkt liegt dabei auf der Schadensberechnung und der Modellierung von Anpassung an den Klimawandel.

Im Bereich des Klimawandels lag bisher der Fokus der Anwendungen auf der Bestimmung von Klimaschäden und deren Vermeidung. Angesichts der nicht vermeidbaren Schäden des Klimawandels, welche in den nächsten Dekaden auftreten werden, erhält die Anpassung an den Klimawandel in der laufenden Diskussion eine stärkere Bedeutung. Nach unserem Wissen fehlt ein Modell, welches explizit die Anpassung auf einem lokalen Niveau betrachtet und sozio-ökonomische Effekte berücksichtigt. Solch ein regionales Modell kann die Wohlfahrtseffekte auf der lokalen Ebene analysieren und ist deshalb wichtig für Politikempfehlungen.

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 changes in socioeconomic variables on the future 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 climate change with a focus on different approaches of implementing adaptation. In this paper we concentrate on Integrated Assessment Models, but also show alternative approaches such as an Integrated Assessment Model including a Computable General Equilibrium Model, input-output models, growth models and a damage coefficient approach. All model approaches have their advantages and disadvantages concerning the degree of disaggregation with respect to regions and sectors. Also adaptation plays a different role in the model contexts.

The paper is structured as follows. Section 2 deals with Integrated Assessment Models and how climate change impacts are implemented. Section 3 explains the four existing applications of this model type (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 presents the alternative approaches for implementing climate change impacts. Section 5 contains conclusion and suggestions for further research.

2. Implementation of Climate Change into Integrated Assessment Models

The effects of climate change can be analysed with an integrated tool that combines economic, energy and climate relations into one modelling instrument, a so called Integrated Assessment Model.

Following Fankhauser (1998) the impacts of global warming usually enter an Integrated Assessment 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.

The interactions of climate impacts with the rest of the Integrated Assessment Model contain three major mechanisms. Firstly, the influence of other non-climatic variables on climate is introduced. Secondly, the resulting effects of adaptation processes are considered. Thirdly, the feedbacks of impacts into the rest of the 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.

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 which results in turn in a change of tastes affecting valuation.

Adaptation is usually implicitly included in the aggregate monetized damage function. Adaptation costs (for dykes) are added to the residual damage costs (loss of unprotected land). Some models use induced adaptation. That means that the adjustment to a new equilibrium which results with a new climate causes transition costs. Because most models are highly aggregated with respect to sectoral structure and regional level 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.

3. Applications of Integrated Assessment Models

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" was developed by 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).

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

$$\frac{GD_t}{\mathrm{GDP_t}} = \alpha_1 \, \Delta T_t + \alpha_2 \, \Delta T_t^{\alpha_3}, \text{where } \alpha_1 \text{ is unrestricted}, \; \alpha_2 > 0 \text{ and } \alpha_3 > 1, \tag{3}$$

where GD_t stands for gross damages, GDP_t is Gross Domestic Product and ΔT_t is the temperature change compared to 1900. The parameters α_1, α_2, α_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 proportionately with increasing temperature changes (de Bruin, Dellink and Tol 2009). The calculated damages of climate change enter again the production function by reducing the possible output that can be achieved with the given capital, labour and energy stock (Nordhaus 2008). 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). In RICE, each region has 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 and Boyer 2000).

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

In the adaptation models three categories of damages are 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.

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 and the adaptation level AL_t, adaptation costs depend only on the adaptation level.

The adaptation cost function is:

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

where $\gamma_1 > 0$ and $\gamma_2 > 1$. It is increasing with the adaptation level, because cheaper adaptation measures are implemented first.

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 adaptation measures may take more than one year until they are 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 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 an adaptation capital stock in the model.

The adaptation cost function is increasing with the level of adaptation. The simulation results of AD-DICE show that the first 15 per cent of gross damages 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.

In the AD-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 AD-DICE (4). The gross damage function is:

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

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. In addition residual damages depend on the gross damages $GD_{t,r}$ and the level of adaptation. Mitigation is not explicitly modelled in AD-RICE. Implicitly mitigation enters the model by specifying the input of carbon energy.

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).
- optimal adaptation and no mitigation (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.

The results in Table 1 show that the total costs of climate change per year increase over time. 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).

Table 1: 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 –optimal adaptation and no mitigation	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

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.

3.2. MERGE

MERGE stands for "Model for Evaluating Regional and Global Effects of greenhouse gases reduction policies" and was 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 to calculate 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.

In order to estimate damages at first a business as usual scenario is calculated. GDP increases exogenously by taking growth rates from the IPCC Working Group III (1990). Here 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. 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 determined by $d_{2,r}$. Here the model follows Nordhaus (1992) 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.

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 uses region-specific increases in temperature and regional GDP, while AD-RICE considers only a global change in temperature and regional GDP. MERGE expresses the damages as total damages (see equation (7)), while AD-DICE and AD-RICE instead denote damages as a fraction of output (see equations (4) and (6) respectively).

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 occurring from 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. 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 computed for developed countries and are estimated as a 1.99 per cent loss of GDP (Warren et al. 2006).

3.3. PAGE

The "Policy Analysis for the Greenhouse Effect (PAGE) model" was developed by Hope et al. (1993) and modified by Plambeck et al. (1997). PAGE 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. 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.

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 in each of the 250 runs in order to choose 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.

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). 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.

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:

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

where $D_{t,d,r}$ are damages for each period $t = 1, \ldots, 10$ and region r. They are 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.

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 $GDP_{t,r}$. The uncertain power varies between 1 and 3 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).

Comparing (8) 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 AD-DICE (4).

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. 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. The plateau parameter gives the maximum absolute change of global temperature that can be tolerated (Hope et al. 1993).

Conceptually, adaptation is modelled as means of a reduction or avoidance of the impacts of climate change. Instead of means, 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 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 respect to joint adaptation where there are many beneficiaries, this kind of adaptation will be only efficient through government action. Externalities and policy changes affect the price of land and other related assets. If externalities exist, it cannot be assumed any longer that adaptation is automatically optimized by market agents (Mendelsohn 2000).

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 2 the value of economic impacts for the European Union ranges from a -0.1 to 1 per cent loss of GDP with a mean of a 0.5 per cent loss. The damages from non-economic impacts are higher than the economic impacts. The

Table 2: Impact parameters in PAGE

PAGE impact parameters	Mean	Min	Mode	Max
Economic impact*	0.5	– 0.1	0.6	1
non-economic impact*	0.73	0	0.7	1.5
Regional weighting factor for**				
Eastern Europe and former Soviet Union	– 0.35	– 1	–0.25	0.2
USA	0.25	0	0.25	0.5
China and East Asia	0.2	0	0.1	0.5
India and South Asia	2.5	1.5	2	4
Africa	1.83	1	1.5	3
Latin America	1.83	1	1.5	3
Other OECD	0.25	0	0.25	0.5

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

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).

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 and when they occur. The effect of aggressive adaptation is that sectors face no damages from a 2 °C rise in temperature until the year 2000. If temperature rise is higher than 2 °C, further implemented measures reduce the impacts of each additional °C of temperature rise until the year 2050 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 of 17.5 trillion Euro, hence adaptation should be implemented to a large extent (Hope et al. 1993).

3.4. FUND

The FUND (Climate Framework for Uncertainty, Negotiation and Distribution) model, developed by Tol (1997), 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.

The model presented here relates to Warren et al (2006). It 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. These 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 storylines:

- A1B 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. The B stands for the sub-scenario with a balanced consumption of fossil and non-fossil fuels.
- 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.

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 coastal protection is missing in the model. Therefore a statement about inefficient adaptation that may occur with joint adaptation and policy changes is not possible. The adaptation costs are only modelled implicitly while explicit adjustment costs are missing.

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 these values for a scenario, three steps are taken. 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).

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

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

where $W_{t,r}$ denotes the change in water resources at time t in region r and depends on the income change between ($GDP_{t,r}$) and its value in the year 1990, 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 in the business as usual scenario show a small benefit from climate change for a very moderate increase of about 0.5 °C above 1990 levels at a global level. 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.

The results of the sector specific effects in the energy, water, health, agriculture and ecosystems sectors 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 decline over time. Ecosystems contribute a small negative effect to global GDP.

The impacts of climate change differ regionally quite strongly. 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 up 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 °C above the level of 1990, West Asia, North America and Europe even benefit from climate change. For a rise of more than 3 °C the impacts become negative.

4. Alternative approaches

The four models described in the previous section incorporate physical relations of climate change and economic effects of damage functions. The economic system is based on a highly aggregated intertemporal optimization framework. Details about regional or sectoral interdependences are not implemented. Also regional impacts from climate change as well as dynamic effects on the growth rate are not considered.

Therefore some alternative approaches, namely the inclusion of Computable General Equilibrium into the Integrated Assessment Model in WIAGEM (Kemfert 2002), input-output models (Koschel et al. 2006), growth models (Fankhauser and Tol 2005) and a damage coefficient approach (Houba and Kremers 2009), are presented each with an application with respect to climate change.

4.1. WIAGEM

The model WIAGEM developed by Kemfert (2002) tries to emphasise the economic feedback system in more detail and combines a Computable General Equilibrium Model with an energy and climate submodel. The concept of general equilibrium consists of three conditions. The first condition claims that the model determines prices that clear all markets. On each market demand and supply are in equilibrium. The zero profit condition holds because profit maximizing firms face perfect competition. Consumers maximize utility but income must equal expenditures, so that the income balance condition is fulfilled.[1]

The core of WIAGEM is an intertemporal general equilibrium model that includes 25 world regions and 14 economic sectors. Substitution between factor inputs is possible, depending on the substitution elasticity given by a nested CES production function. So the emission level depends on the amount of output and the mix of used labour, capital and energy inputs. The time horizon until 2050 (with five year steps) is quite short compared to other models (AD-DICE 2155, FUND 2100). Prices and quantities of all non-energy data are based on GTAP 4.

The energy submodel consists of three fossil fuel sectors and one non-energy sector. A composite energy good is produced by either conventional fossil fuels or from a carbon-free backstop technology which is available in infinite supply but at a multiple price of the conventional fossil fuels. In the long run fuel prices will increase which makes the backstop technology relatively cheaper as an input factor.

The climate submodel contains the greenhouse gases carbon dioxide, methane and nitrous dioxide which affect the global mean temperature and the sea level. Energy related emissions are calculated according to the energy development of each period. The related greenhouse gas emissions are taken from MERGE. The potential temperature PT_t^{β} is influenced by radiative forcing which is again affected by the concentration of greenhouse gases. Total damages are calculated with the following equation:

1 There are some more studies that have attempted to evaluate the economic effects of climate change using General Equilibrium Models but focus only on certain economic sectors or single countries. In a series of papers from the Fondazione Eni Enrico Mattei the effects of climate change were analysed separately for the three different dimensions tourism (Berrittella et al. 2006), coastal erosion (Bosello et al. 2007) and human health (Bosello et al. 2006). The IGEM model simulates the effects of climate change for 35-sectors of the US economy (Jorgenson et al. 2004).

$$\Delta DAM_t^r = \alpha_t^r \left(\Delta PT_t^\beta * \frac{y_t^r}{y_0^r} \right) + \mathrm{PC}_t^r \qquad (10)$$

with DAM_t^r as total impact damages, y_t^r as the per capita income, α and β are parameters and PC_t^r stands for protection costs due to sea level rise in region r and time t.

In WIAGEM adaptation is not a decision variable. As can be seen in equation (10) protection costs due to sea level rise just add up to the total impact damages. There is no possibility to reduce total damages by increasing adaptation costs and thus decrease negative impacts.

Compared to the previous studies where significant impacts occur in the long run, WIAGEM even shows for its shorter horizon of 50 years strong impacts of climate change. Especially developing countries suffer from welfare losses and GDP reductions compared to a no climate change impact scenario. Potential total damages are expressed in GDP percentage containing impacts on the sectors forestry, agriculture, water resources and ecosystem changes as well as protection costs due to sea level rise.

Looking at the different impact categories, negative impacts on forestry occur for Eastern Europe and Russia as well as Latin America. On the contrary, the USA and Europe gain positive effects of forestry changes. Regarding water resources all world regions except China will have negative impacts from climate change. Because of increasing temperatures the energy demand for space heating goes down in most of the world regions so that positive impacts are induced. But the energy demand for space cooling increases and generates negative economic impacts. Total impacts including ecological impacts, vector borne diseases, forestry and water, heating and cooling and mortality show that all world regions will have negative impacts in all periods. Most affected in terms of percentage of GDP in 2050 are developing regions like Asia (–5.9), China (–3.5), Sub-Saharan Africa (–2.3) and Latin America (–2.2). Developed regions like the USA, Japan and Western Europe (all –0.7 per cent) have much lower negative impacts. The reason why Asia is more affected than Africa is the fast economic growth in these regions. Together with high population increases the negative impacts in economic terms are very high.

Direct cost methods ignore that climate change impacts may change prices. These price effects may spill over to other markets and in the end affect investments. With the dynamic computable general equilibrium approach, WIAGEM is able to look in more detail at all economic effects of climate change impacts on different sectors. But some critical aspects have to be pointed out. Firstly, the impact of climate change on the economy is quite strong. A 2.5 °C increase of temperature results in a negative impact on GDP in the range of 5.4 per cent up to 53.8 per cent depending on the chosen parameter value. This is much higher than the estimates of other models and also in the IPCC report. Secondly, there are some methodological issues. For example general equilibrium effects are summed up with direct costs of climate change instead of comparing these two. Another point is the large indirect growth effect in the model. With a savings rate of 20 per cent a loss of 1 per cent in GDP reduces investment by 5 per cent. In the DICE model a 1 per cent reduction in GDP lowers investment by only 1 per cent. Although there are some more inconsistencies in the model, it is still a clear improvement in the field of Computable General Equilibrium Models dealing with climate change impacts (Roson and Tol 2006).

4.2. Input-output models

Input-output models are related to Computable General Equilibrium models because they use the same statistical information for their inter-industrial analysis. The input-output table, the starting point for an input-output analysis, includes information about the quantitative transactions between economic sectors, the sales to the final demand sector and the value added of each sector (Ardent et al. 2009). Only the information about the distribution of the production factors between households and the disaggregated demand of specific households is missing.

The input-output model consists of a linear system of equations, which captures the interdependencies between intermediate goods and final demand:

$$\begin{array}{lllll} x_{11} + \ldots + x_{1j} & + \ldots + x_{1n} & + FD_1 & = Y_1 \\ \vdots \quad\quad \vdots & \quad\vdots & \vdots & \vdots \\ x_{i1} + \ldots + x_{ij} & + \ldots + x_{in} & + FD_i & = Y_i \\ \vdots \quad\quad \vdots & \quad\vdots & \vdots & \vdots \\ x_{n1} + \ldots + x_{nj} & + \ldots + x_{nn} & + FD_n & = Y_n \end{array} \tag{11}$$

where the x_{ij} represent the intermediate outputs between the sectors i and j. FD_i is the final demand of private households and/or the state. Intermediate outputs and final demand in each sector add up to the total output Y_i.

Climate change enters the model as an exogenous shock in final demand FD_i . This leads to a direct effect on total output Y_i. But through the backward linkages to other sectors this final demand change affects intermediate outputs in other sectors and leads to a multiplier effect (for more details see Kowalewski 2009). For example specific sectors that are located close to rivers or the waterside are flooded with a certain probability and in the case of a flood may suffer temporary production losses. On the other hand the construction sector may gain from climate change because to prevent these damages dykes have to be built. This leads to positive effects on output but also on employment in the construction sector and related sectors. Therefore, for quantifying the overall effects of climate change, one has to define the new vector of final demands and then analyse the direct as well as the indirect effects.

Like in Computable General Equilibrium Models until now adaptation to climate change has not played a big role in input-output models. The focus was more on mitigation issues and costs of climate change impacts. Looking at regional or local analysis with a long term perspective, studies are relatively rare. The dominating field here is the analysis of the regional costs after extreme weather events like earthquakes, hurricanes or floods.

A mentionable approach for a long term perspective is the impact analysis of different mitigation policies on a regional level within the project INKLIM by Koschel et al. (2006). This project attempts to determine long run effects on the economy of climate change impacts on the regional level of a federal state in Germany. The input-output model considers the following effects: investment and further demand, budget and financing, energy consumption and income effects. The investment effects are calculated as follows. Investment costs for each sector come from scenario analysis with a specific model, called TIMES. These results are converted via investment matrices into an additional investment vector. The budget and financing effect on production and employment is negative because assuming a constant budget of the state, mitigation measures lead to a crowding out of private consumption. The energy consumption effect covers a reduction of fossil energy usage and a reduction of overall electricity usage. The affected sectors will lower their production and employment in these sectors will decrease. The income effect describes how a reduction of output production affects the disposable income and hence the consumer demand. Via a Keynesian income multiplier downstream employment effects due to income effects can be considered.

All these effects are calculated separately with scenario techniques. The vector with any sector demand (investment demand, household demand) enters the input-output model as an exogenous shock. In a second step a negative financing effect is introduced. Production and employment effects are finally determined by comparative-static analysis.

The quantitative analysis shows small positive effects of all measures together on gross production and employment. Splitting up the total effect shows great differences between sectors. Engineering, construction as well as agriculture and forestry gain from the demand shock in all scenarios. The effect on the service sector is undetermined. The energy and mineral oil sector is affected exceptionally negative. This is because of the reduction of consumption of these goods. Looking at the net effects when the negative financing effects are considered sectors with a high consumption ratio such as trade, food and traffic benefit because of the induced effects.

The advantage of the input-output model is its ability to produce results with justifiable effort. Because of the low complexity the results are easy to communicate to policy makers. But the main disadvantage is that there are no feedback processes from the economy to climate change. Also because technology parameters and prices are fixed, results from long run estimates are questionable.

4.3. Growth models

Economic impact studies usually neglect dynamic interlinkages with respect to time. In a specific time period climate affects social welfare only in the same period. Intertemporal effects are ignored. There are two dynamic effects Fankhauser and Tol (2005) studied in growth models. The main dynamic effect is capital accumulation. If climate change has a negative (positive) effect on output and a constant savings rate is assumed, the amount of investments is reduced (increases). Less investment lowers the capital stock, which leads to a lower GDP and less consumption per capita (or vice versa). In an endogenous growth context, lower investments also slow down technical progress and improvements in labour productivity or human capital accumulation.

The second effect concerns savings. Assuming a world with perfect information, agents should be forward-looking and anticipate climate change when choosing their savings behaviour. This affects the amount of capital that is available for investments and, hence GDP growth. Integrated Assessment Models usually incorporate the capital accumulation effect and sometimes the savings effect, because their design is based on neo-classical growth theory. But the dynamic effects are normally not explicitly separated.

To look at the dynamic effects in more detail a standard Ramsey-Cass-Koopmans growth model can be used, in which a social planner maximizes the utility of identical consumers leading to the following intertemporal optimization problem:

$$\max \int_0^\infty u(c, T)\, e^{(n-\varrho)t}\, \Delta t \tag{12}$$

subject to:

$$\dot{K} = Y(K, L, T) - cL - \delta(T)K \tag{13}$$

$$\dot{L} = n(T)L,\ L_0 = 1 \tag{14}$$

where u denotes the utility function, c is per capita consumption, Y the output, K the capital that depreciates with the rate δ and ϱ is the discount rate. L is labour supply which grows at rate n, starting from the normalized level L_0. Here the growth in labour supply is exogenous and represents population growth. Climate change enters the model as an exogenous time independent variable T (temperature). The larger the temperature T, the larger is the negative depreciating effect on the capital stock K and hence the smaller is the growth of the capital stock.

Climate change affects the intertemporal optimization at up to four levels. Non-market impacts like damaged environmental assets directly affect the utility function via the temperature indicator T and are assumed to be negative. Market impacts like a change in agricultural yields enter the production function. An increase in temperature T lowers the production of output Y. Health and mortality impacts like a more widespread malaria disease negatively affect population growth. The longevity of capital will decrease. With increasing climate change as well as more extreme weather events like storms adaptation like building dykes requires more and more capital. Therfore the capital stock will decrease faster. This can be captured by an increased speed of capital depreciation.

The question is how significant climate change alters the growth rate in the long run. The results are implying an increasing impact on growth rates over time because of reinforcing dynamic effects. But the overall effect is not substantial enough to reverse the growth path into a negative one. Only if direct impacts are at least 15 per cent of GDP for a 3 °C warming, growth paths turn negative. To conclude negative climate change impacts may reduce the rate of economic growth, but the effect is not so strong that the growth path is reversed.

Growth models can study the impacts on the growth rate in detail. But they lack integrating other aspects as explicit modelling of mitigation and adaptation or analysing damages in different sectors. For these aspects Integrated Assessment Models are the better choice.

4.4. Damage coefficients

A regionalised approach to estimate the costs of climate change in the agricultural sector is the concept of damage coefficients by Houba and Kremers (2009). In this approach damages of climate change have two effects. Firstly, they directly enter the production technology of the firm via the damage coefficients. In the case of agriculture this can be seen as the sensitivity of crops to temperature changes. Secondly, inputs of the production function can be degraded by climate change. For example less precipitation levels affect the process of plants to uptake nutrients and therefore decrease the productivity of fertilizers. Assuming a constant to scale production function with a Leontief specification, damage coefficients $d_i > 0$ enter the production function as follows:

$$f(x_1, \ldots, x_n) = d_0 * \min \{(d_1 a_1)x_1, \ldots, (d_n a_n)x_n\} \tag{15}$$

The damage coefficient d_0 represents the effect on the productivity of the technology and $d_1, \ldots, d_n$ refer to the damages on the productivity of the input factors. With this extension the model distinguishes between economy related influences on productivity on the parameter a_i and influences from climate change covered by the damage coefficients d_i. The range of values is $0 < d_i < \infty$. Values of the damage coefficient smaller than one indicate a deteriorating effect, while values larger than one represent beneficial effects. All impact coefficients are exogenous.

Kemfert and Kremers (2009) use the concept of damage coefficients in order to estimate the cost of climate change in a specific economic sector in a small region, namely the German fruit vegetation sector in the so called "Altes Land" region in Northern Germany. Estimates for the production parameters a_i come from regression analysis. Per assumption only d_0 occurs in the production function. This damage coefficient is derived from the difference of the observed data about the productivity of apple growing $a_{L,t}$ and its estimated values $\hat{a}_{L,t}$ for each time period:

$$d_{0,t} = a_{L,t}/\hat{a}_{L,t} \tag{16}$$

The result is an average damage coefficient of 1.027 which indicates a positive influence of climate change on the productivity of apple growing. Actual productivity exceeds the estimated productivity, so there must be an additional positive impact on production which is the damage coefficient that relates to climate change. The climate damage coefficient is the result of the development of certain climate related variables. For the apple production the important climate variables are the minimum regional temperature during the blossoming season W_{Temp} and the annual average or mean precipitation W_{Prec}:

$$d_{0,t} = b^*W_{Temp} + c^*W_{Prec} \tag{17}$$

Results from a second regression using regionalized data from the IPCC scenario A1B in combination with WETTREG show that both temperature and precipitation positively influence the damage coefficient (b=0.0098 and c=0.015).

The costs of climate change are defined as the change in profitability of land used in the fruit vegetation sector. Because land can be used for different economic purposes, given actual prices, it will be used where it is most profitable. Assuming perfect competition, the land price will be set such that profits equal costs, so the price per land unit will be equal to the profit per land unit. If land is most profitably used in the current production of apples at the current market prices for goods p_0 and land p_L, profitability of land can be expressed in terms of the output price:

$$p_L / p_0 = d_0 \, a_L \tag{18}$$

This equation distinguishes the economic effects a_L from climate related effects d_0 on the profitability of land p_L / p_0.

For quantifying the costs for the time horizon 2010 to 2050 two different scenarios of the profitability of land are compared. The first one is a benchmark scenario where the damage coefficients are equal to one, so there are no positive or negative impacts from climate change but only economic effects on productivity. The counterfactual scenario includes damage coefficients which are derived by using temperature and precipitation forecasts. The average damage over the period 2010 to 2050 is 1.2861 which indicates a positive impact of climate change on productivity in the amount of 28.6 per cent.

The costs of climate change are the difference between total counterfactual profitability and benchmark profitability. The results show that the apple production benefits from climate change. According to A1B scenario the minimum temperature during the annual blossoming season and in mean precipitation levels increase in the period 2010 to 2050. This leads to productivity levels that are – except for a few years – higher than what can be explained by economic or technological progress.

The approach of damage coefficients tries to overcome the shortages of the global models to identify costs or benefits from climate change on a regional level. Unfortunately adaptation to climate change is not explicitly integrated in the model. In the context of apple growing in Northern Germany climate change might have positive net effects. Therefore it might be helpful to analyse the impacts of climate change on a more regionalised level to take specific characteristics and regional climate data into account.

5. Conclusion

Five different categories of models for analysing impacts of climate change were presented: Integrated Assessment Models (including Computable General Equilibrium Models), Input-output models, growth models and the damage coefficient approach.

In the field of Integrated Assessment Models most climate change impact applications are based on the presented models AD-DICE/AD-RICE, MERGE, PAGE and FUND. The models differ with respect to 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 impacts. Occurring damages are calculated as percentage loss of GDP, but there is no feedback effect on GDP growth within the model.

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 represent more interactions between economy and climate.

PAGE uses the aggregate level with economic and non-economic costs as well as computing results for world regions and the world in total. 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 presented Integrated Assessment 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.

Looking at the alternative approaches the WIAGEM model tries to improve the Integrated Assessment Model by integrating a General Equilibrium Model. Economic feedback processes and a more detailed economic structure can be studied in this model. In addition to some inconsistencies adaptation is also not yet included in this model. Input-output models concentrate on inter-industrial linkages at a very high sectoral disaggregation. But feedbacks from the economy to climate as well as price and substitution effects are missing. Also adaptation to climate change is not implemented in the models so far. Growth models give an insight on how economic growth is affected by climate change. However no information about different sectors and adaptation measures can be derived. The damage coefficient approach benefits from using regionalised climate data instead of global trends. This approach might be reasonable for sectors like agricultural sector. For other economic sectors the relation between climate change and its impact on the economy on a regionalized level are still unclear. In this model adaptation to climate change is also not explicitly included.

Since adaptation will play a much bigger role in the next decades and because adaptation measures are implemented at the local level, the adaptation mechanisms of the global models have to be introduced into regional models. This might be a favourable approach for further research.

Table 4: Overview of Integrated Assessment Models

Source	Model	Damage functional form	Regions	Impact parameter	Damage categories	Adaptation	Results	Economic mechanisms and interactions with climate
de Bruin, Dellink and Tol (2009)	AD-DICE/ AD-RICE	quadratic	global/ 13	global mean temperature	1	as policy/ decision variables	– developing countries affected most – optimal mix of adaptation and mitigation policy – benefits of prevented damages outweigh costs in the analysed scenarios	– GDP growth is scale down with damages
Hope et al. (1993)	PAGE	Quadratic	8	regional mean temperature	non-economic and economic	policy variable, increases "tolerable level"	– developing countries affected most – 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 the calibration of the damage function	– developing countries affected most – 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 – impacts on human health affect population
Kemfert (2002)	WIAGEM	Linear	25	global mean temperature	14 economic sectors	Implicit adaptation via protection costs	– developing countries affected most – ecological impacts are larger than vector borne diseases and forestry and water, heating and cooling – no results for adaptation	– impacts and protection costs lower other investments, economic growth is reduced

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