Synthesis of existing regional and sectoral economic modelling and its possible integration with regional earth system models in the context of climate modelling

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Synthesis of existing regional and sectoral economic modelling and its possible integration with regional earth system models in the context of climate modelling

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Introduction

While models on the (physical) impact of climate change and on the impact of climate policies are already available on a global scale, the analysis of impacts on a regional scale is moving upwards on the agenda. When considering regional impacts, the most relevant policy area and most suitable option is adaptation combined with mitigation efforts and regional decision makers thus need tools allowing them to evaluate impacts and costs of climate change as well as benefits and costs of adaptation and mitigation measures. Hence, there is a need for regional studies to adequately address these issues.

In this study the methods available to build appropriate regional and sectoral coupled climate-economic models are reviewed and suggestions are given on the existing gaps and on how to provide a sound basis for developing different regional economic or hybrid models that are able to examine those questions.

As an introduction, the present possibilities of global and regional climate system models are reviewed in chapter 2, shedding some light on the methods to obtain regional climate (change) information.

Chapter 3 discusses the theoretical background of two relevant theoretically founded models of a (regional) economy, namely input-output models and (computable) general equilibrium models. Furthermore, existing models of each type with a relation to regional and/or climate issues are discussed.

In chapter 4, four of the most prominent Integrated Assessment Models (IAMs) are compared. These models are mostly global models which couple climate and economic sub-modules to derive costs and benefits of climate change and of mitigation efforts. Some conclusions are drawn regarding features of possible regional IAMs.

Apart from regional aspects, sectoral issues need further investigation as specific impacts can have country-wide as well as regional consequences. Accordingly, some approaches of modelling climate change impacts on a sectoral level are discussed in chapter 5. The considered economic sectors are tourism, energy, transport and health.

Another relevant matter in integrated regional climate and economic modelling is discussed in chapter 6, namely feedback effects. Whereas activities of the regional economy might not significantly influence the global climate, they might still influence the regional or local climate. An important feedback effect can be generated through land use, as e.g. the amount of (regional) soil sealing affects the regional temperature. Different theoretical possibilities of including these feedback effects in a model are presented. Additionally this chapter considers issues that arise when linking (regional) economic models and (regional) climate models with the main challenge being different temporal and spatial scales.

The final chapter concludes and identifies research questions arising from the report.

1. Earth system models in the context of climate modelling

1.1. Global earth system models

The latest generation of global climate models are called "Earth System Models" (ESMs). Earth system models in the context of climate modelling are numerical models of the climate system, based on physical, chemical and biological principles. The core are three-dimensional general circulation models (GCMs). They are the primary tools available for investigating internal climate variability and the response of the climate system to external forcing. Internal climate variability arises from chaotic non-linear processes in the climate system and lead to stochastic variations in climate parameters on different time scales. They are also relevant for multi-decadal time scales of climate projections, especially on regional spatial scales (Hawkins and Sutton, 2009, Deser et al., 2012). External forcing involves factors outside the climate system and comprises natural forcings (e.g. solar variability, orbital variations or volcanic eruptions) and anthropogenic forcings (e.g. emissions of greenhouse gases to the atmosphere, anthropogenic aerosols and land use changes).

In order to represent internal and external driven variability at certain temporal and spatial scales with climate models, the relevant components and processes need to be included in the model. Key components of global climate models are atmosphere and ocean general circulation models (AGCMs and OGCMs), which can be dynamically coupled to atmosphere-ocean general circulation models (AOGMs). Earth system models are the current state-of-the-art models, and they expand on AOGCMs through dynamic coupling of land and ocean biosphere models, and include aerosol processes, atmospheric chemistry and also sea ice and ice sheet dynamics. With such complex ESMs, biogeochemical cycles, such as the Carbon cycle, and their interaction with physical processes within the climate system are represented. Human action is prescribed to the models and their influence on the climate system is simulated.

The mathematical equations, which describe the fluid dynamics in atmosphere and ocean, are solved numerically and discretised using either the finite difference method or the spectral method. For finite differences, a grid is imposed on the atmosphere and ocean. The grid resolution strongly correlates with available computer power. Typical horizontal resolutions of AGCMs for centennial climate simulations correspond to spatial scales between 300 km to 100 km, in some cases up to 50 km, with 30 to 90 vertical atmosphere levels. For ocean circulation models, horizontal resolution corresponds to spatial scales between 160 km up to 10 km, with 40 to 80 vertical levels.

Processes that cannot be explicitly resolved by the spatial model resolution need to be considered by describing their collective effect on the resolved spatial unit. This is done with physical parameterisations which are based on theoretical assumptions, process based modelling and empirical relationships derived from observations. Examples for parameterised subgrid-scale processes in climate models are radiation, convection, processes within the atmospheric and oceanic planetary boundary layers and land surface processes. The fundamental physical understanding behind those parameterisations, combined with the applied numerical methods and model resolutions as well as the treatment of initial and boundary conditions determine the quality of the model simulations. An introduction to climate modelling is given in McGuffie & Henderson-Sellers (2005). An overview of ESMs and their model components can be found in IPCC (2013).

1.2. Regional climate models: towards regional earth system models

For spatial refinement of global climate model simulations, statistical and dynamical downscaling methods are applied. Dynamical downscaling is done with regional climate models (RCMs). Regional climate models are limited area circulation models for a three-dimensional section of the atmosphere, coupled to the earth surface and near-surface soil layer. RCMs are based on the same mathematical equations for fluid dynamics as global models. They are discretised at much finer spatial atmosphere grids (corresponding to spatial scales at 50 km to 2.5 km). At the lateral boundary of the model domain, meteorological conditions from either global model simulations or observational data are prescribed. Within the model domain, finer-scale processes like mesoscale convective systems, orographic and land-sea contrast induced circulations are resolved. Regional climate models apply more detailed lower boundary descriptions, as for topography, land-sea distribution and land surface characteristics. The nested regional modelling technique essentially originated from numerical weather prediction. The use of RCMs for climate application was pioneered by Giorgi (1990). Reviews about RCMs are given, for instance, in Rummukainen (2010) and Rockel (2015).

Regional downscaling is essential if coarse resolution simulations are a priori implausible (e.g. Mearns et al., 2003):

- regions with small irregular land masses and complex coastlines
- areas of complex topography
- areas with heterogeneous landscapes
- areas where resolving meso-scale atmospheric phenomena is critical to reproducing important features of the climate (e.g. monsoon systems)

However, many climate relevant phenomena are still beyond the scales of regional climate models and have to be parameterized. One example is moist convection, which has to be parameterized at grid-scales larger than 3 km. Non-hydrostatic models below 3 km spatial resolution can explicitly resolve deep convection and with this improve the simulation of extreme precipitation (e.g. Prein et al., 2013). They also better represent spatial land cover characteristics and local land-atmosphere interactions. Currently, the next generation of regional climate models that go beyond 3 km grid resolution is developed. These advancements are of high relevance for impact assessments on socio-economic systems, which are strongly related to local scale climate characteristics. This new generation of regional climate models can also enable better connections to regional economic models which are in focus of this paper.

During the last decades, RCMs have been coupled with further climate process models, such as ocean models (e.g. Hagedorn et al., 2000; Schrum et al., 2003; Dieterich et al., 2013; Ho-Hagemann et al., 2013; Su et al., 2014; Sein et al., 2015) and biosphere models (e.g. Davin et al., 2011; Wilhelm et al., 2014; Zhou 2015) towards Regional Earth System Models (RESMs). They are able to represent dynamic interactions between those components and thus can also account for regional to local climate feedbacks. In such RESMs, also land use changes and human land management can be implemented, in order to study the feedbacks on climate (e.g. Paeth et al. 2009, Gálos et al. 2013, Trail et al. 2013). An interactive coupling of RESMs and regional economic models would enable to investigate dynamic interactions of the regional earth system with human activities and would have the large potential to support optimal management and climate adaptation strategies. First activities into this direction are addressed e.g. by Adams et al., 2015.

1.3. Climate projections

A major application of climate models is the simulation of potential future climate changes due to human action. As the future human development cannot be foreseen, only assumptions about plausible future pathways can be made and represented in the models. Potential human pathways are described within global socio-economic scenarios which assume certain developments of human population, politics, technology and economy. For each scenario, emissions of greenhouse gases and aerosols are derived, from which the concentrations of the respective substances in the atmosphere are calculated. The procedure of defining such emission scenarios is described in the Special Report on Emission Scenarios (Nakicenovic et. al. 2000).

The latest generation of climate projections for the 21st century build on Representative Concentration Pathways (RCPs), which are derived from a different scenario process (Moss et al., 2010). RCPs are defined by physical thresholds of different radiative forcings reached at the end of the 21st century. The respective emissions and concentrations of greenhouse gases and aerosols in the atmosphere are derived from four modelling teams working on integrated assessment modelling. The concentrations, in some cases the emissions, are prescribed to climate models, which simulate the response of the climate system to the human external forcing. For historical climate simulations, the observed concentrations of atmospheric substances are prescribed to the models. The results of climate projections are then related to the results of the historical climate simulation in order to derive climate change signals.

Global simulations of the historical climate and global projections of future climate can be dynamically downscaled with RCMs in order to relate global climate changes to regional and local consequences. Climate change patterns simulated by a regional climate model can decisively differ from the simulation results of a global model. The modifications can be caused by regional and local scale features and feedbacks.

Through prescribing different forcings according to different human pathways, a range of potential effects of humans on climate can be projected. Assuming a certain emission scenario we still get a range of possible climate evolutions due to internal climate dynamics. The temporal evolution of internal climate variations largely depends on the initialisation of the state of each climate system component. To consider different temporal evolutions of natural climate variability within climate projections, several simulations are performed with each model, which start at different initialisation states of the climate system.

Climate models give a simplified image of the climate system and they can only provide approximations of climate parameters, which are more or less accurate compared to real values. Modelling uncertainties arise from our incomplete understanding of processes within the climate system and from numerical approximations. Climate models can apply different numerical approaches and physical parameterisations. Those structural differences lead to a range of possible climate responses to anthropogenic forcing, which can be quantified by multi-model-ensemble simulations.

Since 1990, the first model intercomparison projects (MIPs) opened a new era in climate modelling. They provide a standard experiment protocol and a worldwide community-based infrastructure to support model simulations, validation, intercomparison, documentation and data access, and thus the basis for multi-model ensemble simulations. Within the coupledmodel intercomparison projects CMIP5, a set of coordinated experiments of AOGCMs and ESMs, based on the RCPs, has been established. Within the current world wide initiative on coordinated downscaling experiments (CORDEX), a sample of the global climate simulations of CMIP5 are downscaled with different RCMs for most continental regions of the globe (Giorgi et al. 2009). Within the EURO-CORDEX initiative, a unique set of high resolution climate change simulations for Europe on 0.11° horizontal resolution has been established (Jacob et al., 2014). The CORDEX simulations provide the basis for climate change assessments and adaptation on regional to local scale.

2. Regional economic models

2.1. General

A key rationale for having a closer look at possible connections between Earth system models and (regional) economic models include the five reasons for concern regarding the impacts of climate change, which have been identified by the IPCC (IPCC 2007, pp. 64):

- Risks to unique and threatened systems
- Risks of extreme weather events
- Distribution of impacts and vulnerabilities
- Aggregate impacts
- Risks of large-scale singularities

These possible impacts justify a deeper economic analysis and require careful modelling to derive sensible policy recommendations.

Economic models serve to describe economic interrelationships on a global, national, regional or sectoral level and to quantify the effects accompanying with changing conditions (policy measures, behaviour of economic agents). Complex “real” economic conditions are described in a simplified form; however, a great number of economic models are complex mathematical entities, differing in their depth and in the underlying economic theories (Drosdowski and Lehr 2011). Economic models are either partial or aggregate models. Aggregate economy models include growth models, computable general equilibrium models (CGE), the advancement to dynamic stochastic versions (DSGE), input-output (IO) models, econometric models, system dynamic models and agent based computational models (ACE).

The focus in this study is on the two most prominent model types: general equilibrium models, basing on the underlying neoclassical general equilibrium theory, and IO models, allowing for the quantification of effects without considering the assumptions of the neoclassical theory. Although models can be assigned to their respective category corresponding to their theoretical background, the models are neither between nor within the individual categories clearly distinguishable from each other. However, the central data sources for sectoral information are usually IO tables.

In the following, the two approaches are explained and model examples are presented from each class which deal with issues important to regional climate impacts.

2.2. Input-Output-models

Since its introduction in the 1930s by Wassily Leontief, the IO analysis has become one of the most commonly used economic methods (Baumol 2000). It offers the possibility to quantify effects on production, income, employment or other resources which emanate from changes in economic variables thereby including all possible knock-on, lock-in and feedback effects in the economic sectors. Depending on the specification of the applied IO model, the IO analysis can be used both as an economic-sectoral and project-specific impact analysis as well as a forecasting tool.

2.3. General idea

The centrepiece of IO-analysis is the IO table, which describes flows of goods and services between all sectors of an economy within a year, i.e. a certain technology production is assumed (see figure 1). Moreover, it contains necessary information on all primary inputs needed in production processes such as labour, capital, intermediates and land, as well as final demand (Eurostat 2008).

		PRODUCERS AS CONSUMERS								FINAL DEMAND			
		Agric.	Mining	Const.	Manuf.	Trade	Transp.	Services	Other	Personal Consumption Expenditures	Gross Private Domestic Investment	Govt. Purchases of Goods & Services	Net Exports of Goods & Services
PRODUCERS	Agriculture												
	Mining												
	Construction												
	Manufacturing												
	Trade												
	Transportation												
	Services												
	Other Industry												
VALUE ADDED	Employees	Employee compensation								GROSS DOMESTIC PRODUCT			
	Business owners and Capital	Profit-type income and capital consumption allowances											
	Government	Indirect business taxes											

Figure 1 The structure of an input-output table (Miller and Blair 2009)

The rows indicate the distribution of produced outputs to individual industries, whereas the columns contain data on the inputs required by every single industry to produce output. Consequently, the shaded area contains information on the inter-industrial exchange of goods (production technology). The other (final demand) columns describe the sales per industry to sectors other than industry such as private households, government, etc. The rows labelled ‘value added’ report other (primary) inputs to production such as business taxes, imports and so on (Leontief 1970). Conventional IO models treat only productive industries as endogenous. Extended versions include a household-sector and assume it to be endogenous as well, describing different kinds of income changes (the most common conventional IO models).

More elaborate versions of IO models – in the literature referred to as integrated models – are models which conjoin IO and econometric models (IOE). This approach allows for enhancing the strengths and minimising the weaknesses inherent to both model types. Referring to West (2002), the strengths of conventional IO models lie in the detailed description of inter-industrial linkages, those of IOE models in the dynamic structure and the non-linearity. A weakness of this model type is the lack of industry detail whereas conventional IO models assume constant technology (Leontief production function) and unlimited capacities and are characterised by linearity. Hence, they should only be used for short-term analysis.

IOE models are dynamic, characterised by non-linearity and allow for a detailed picture of the economic integration. A variety of econometric estimations, describing the relationship between economic variables, frame the detailed sectoral disaggregation of the IO system. The former are mostly expressed as elasticities and create the basis of the feedback mechanisms between primary factors and final demand (West 1995). On the basis of time series, econometric IO models try to simulate historic changes of economic integration. Building on the information of the past and on econometric estimations, econometric IO models enable projections of future developments of the economic interdependencies and allow, due to their dynamic structure, the analysis of the temporal distribution of the flows throughout the economy (Lehr et al. 2013; West 1995). Unlike CGE models, where neoclassical equilibrium assumptions constitute the empirical basis, IO models make use of comprehensive statistical time series (Lehr et al. 2013). Systems of national accounts and their IO matrices form a fundamental basis of IOE models (Almon 1991).

The concept behind regional IO models is basically the same as behind national IO models. Pure national and regional IO models mainly differ in the focus region (e.g. Germany vs. single federal states) and thus in required data and data availability.

2.3.1. Modelling approaches

Climate change is reflected both in gradual processes of change, such as the slow mean temperature rise, as well as in more frequent and intense extreme weather events, such as storms, heavy precipitation and heat waves. Both have varying impacts on the economy and its sectors. IO analyses can help to determine the direction and extent of the economic impact of climate change.

3.3.1.1 The Adaptive Regional Input Output (ARIO) model

Disaster impact analyses are a common application field of the IO analysis. There are a number of studies to assess the economic impact of natural disasters, such as storms and storm surges. Many of them use IO models in order to estimate the direct cost for reconstruction but also the indirect cost by changes in demand (e.g. Haimes and Jiang 2001; Bockarjova et al. 2004; Cochrane 2004; Okuyama et al. 2004). In addition to direct physical damages, which are reported by the insurance companies, and indirect demand-side effects caused by shock-like changes in intermediate, capital and consumer goods demand, the effects of natural disasters on different economic sectors can be studied with these models.

Hallegatte (2008) developed an Adaptive Regional Input Output (ARIO) model, which also takes into account the supply-side effects, which may result from reduced production capacity such as the limited mobility of labour and the limited availability of goods. Furthermore, ARIO also enables the identification of particularly vulnerable sectors of the economy and the estimation of the time required for their reconstruction. The model was first used for the comprehensive assessment of the indirect damage by Hurricane Katrina in the U.S. state of Louisiana (Hallegatte 2008). Since then, it was also used for the evaluation of flood risks under climate change in Copenhagen (Hallegatte et al. 2011), in Mumbai (Ranger et al. 2011) and in an expanded version in London (Crawford-Brown et al. 2013). In principle, the model can also be used for the evaluation of other types of extreme weather conditions that lead to damages or limitations in production.

The ARIO model is based on the assumption that a natural disaster will cause damages to production facilities, public infrastructure and private assets. In a subsequent reconstruction phase, these losses are completely recovered by insurance funds, private reserves, and liabilities as well as with government support. The reconstruction triggers an additional demand for goods in the economic sectors and households. This demand is satisfied by local production and imports.

In contrast to the conventional IO models, the ARIO model takes into account the occurrence of bottlenecks in the domestic production and imports. The latter may be caused by damages to the local transport infrastructure. Damages to production facilities and an increased demand for goods for reconstruction in the domestic production can lead to bottlenecks. The constraints require rationing of goods. Priority is given to the provision of intermediate and capital goods for businesses and goods for the reconstruction of public infrastructure. It is based on the assumption that companies prefer B2B (business to business) relations more than B2C (business to consumers) relations. In addition, it is conceivable that after a disaster the reconstruction of the production and transport infrastructures is a top priority. However, bottlenecks in local production can be substituted by imports in part if the local transport capacities allow.

The ARIO model is dynamic. With a one-month time step the lost production capacity and damaged infrastructure will be restored taking into account the gradually declining freight bottlenecks. The reconstruction is completed when the pre-disaster level is reached again. The model calculates indirect damages as production losses that arise during the reconstruction.

The ARIO model is based on a regional IO table, which is derived from the national IO table due to a lack of alternatives. Further inputs to the model are the direct damages in the economic sectors. They are determined by using model-exogenous damage functions. In addition, the model has several behavioural parameters to account for the allowance of over-production in the sectors, the temporal shift of demand, the shift to imported goods, and the change in a number of commodity prices during the reconstruction phase. However, Hallegatte (2008) points out that the determination of these parameters' behaviour is associated with large uncertainties.

The analysis of potential flood damages for the City of Copenhagen, carried out with ARIO, showed that a present day one on a 100-year flood event, the total cost amounts to an estimated 3.1 billion euros (Hallegatte et al. 2011). Excluding the effects of coastal protection, this would increase at a sea level rise of 50 cm to 5 billion euros and at a sea level rise of 100 cm up to 7.4 billion euros (Hallegatte et al. 2011). In the aftermath of such events thousands of additional jobs in the construction sector would be created. However, in other sectors thousands of jobs would disappear.

At a future 100-year event and a sea level rise of 50 cm the total production achieves its initial level after 1 year. Subsequently, production exceeds the initial level and after 5 years reconstruction would be fully completed (Hallegatte et al. 2011).

The most important finding, which was obtained from the work with the ARIO model, is that the EAR, which measures the ratio of total damage to direct damage, increases with the size of the disaster. For an event such as Katrina, with direct damages in the domain of 100 billion dollars, the EAR is 1.39. For an event with direct costs of 200 billion dollars, the EAR even reaches a value of 2.00 (Hallegatte 2008).

3.3.1.2 Leontief-Szyld-Duchin (LSD) model

In order to estimate the economic effects of climate change on the development of a specific sector, namely of tourism, Zimmermann et al. (2013) used a dynamic, nonlinear Leontief-Szyld-Duchin model (LSD-model) which is mainly based on the work done by Duchin and Szyld (1985) and Edler and Ribakova (1993).

Zimmermann et al. (2013) examined which impact changes in day and overnight visitors in the federal state of Mecklenburg-Western Pomerania could have on employment and income in the region by 2030. The used LSD model can be characterised as a simple demand-driven, open and dynamic IO model. The final demand is exogenous to the model, based on scenarios. The exception is endogenised investment demand. The LSD model dynamically determines the capacity expansion in the economic sectors. In contrast to the conventional IO models, the time and sectoral capital stocks, the latter described as a potential sectoral output, were explicitly introduced into the model.

Capacity and actual output are interrelated via a number of decision functions that determine the ability of capacity adjustment to keep up with the development of output. Capacity expansion constitutes the second part of demand (i.e. the investment into the typical capital stock goods necessary to produce a specific quantity of some type of goods).

Throughout the model, all constants in the matrices of input and capital coefficients should be equipped with updated values. However, Zimmermann et al. (2013) point out that this is only possible in ex-post simulations. Computations carried out for future periods rely on unchanged input and capital coefficients for all periods.

In order to apply the model in a regional context, the regional input coefficients were derived from the national IO table due to lack of original regional IO tables. Regional input coefficients are necessary in order to assess the impact of final demand in the region on the local companies and households. The regionalisation was carried out with the FLQ method, introduced by Flegg and Webber (1995). It is based on the idea that on the one hand, the relative size of the selling and purchasing industry and on the other hand, the size of a region in conjunction with its propensity to import, will determine the trade coefficients. Recent comparisons of FLQ-derived coefficients and multipliers with those of survey-based regional tables have shown much better performance of FLQ than of other conventional non-survey methods (see Bonfiglio and Chelli (2008) as well as Tohmo (2004) and Flegg and Tohmo (2010)).

The application of the LSD model in Zimmermann et al. (2013) is further described in section 5.1.1 below.

3.3.1.3 The multisectoral macroeconomic model INFORGE

A frequently used econometric IO (IOE) model is the macroeconomic model INFORGE created for Germany, developed by GWS. Being founded on the INFORUM philosophy (Almon 1991), the model rests on two basic fundamentals, namely bottom-up construction and total integration. The term bottom-up construction refers to modelling each industrial sector individually and calculating macroeconomic variables through explicit aggregation. Hereby each sector is embedded within the economic context and industrial interdependencies are explicitly incorporated and used to explain economic interaction. Total integration describes complex and simultaneous solution processes, allowing for inter-industrial dependence, income distribution and state redistribution effects as well as the use of income for goods. This means the IO tables are fully implemented in the national accounts (Mönnig et al. 2013; Ahlert et al. 2009; Distelkamp et al. 2003; Ulrich et al. 2012; Barker et al. 2011; Lindenberger et al. 2010).

Furthermore macroeconomic indicators are determined by aggregation of 59 industries (according to the European 2 digit NACE classification of economic activities). Through output and unit costs, labour market specifics are consistently embedded in the macroeconomic context. In contrast to a majority of CGE models, evolutionary economic theory (Nelson and Winter 1982) forms the background of INFORGE by allowing technological change, interdependencies, imperfect competition or partially sticky prices as components of the model. INFORGE is described by non-linear functions, is dynamic over time and solves simulations simultaneously. Parameters and elasticities are estimated econometrically, using time series for a great number of variables (Mönnig et al. 2013). The expectations of agents are thus myopic, following routines developed in the past (Lutz et al. 2014).

Consumption patterns are estimated by 41 purposes of use, resulting from real disposable income and relative prices. This approach differs markedly from other macroeconomic models (e.g. CGE models), in which private consumption is estimated according to utility maximisation behaviour of a representative individual (Deaton and Muelbauer 1980), assuming bounded rationality. INFORGE allows for long-term changes in consumption behaviour or demographic indicators by using trends as explanatory variables. Industrial production determines production investments in 59 industries. In INFORGE prices are estimated econometrically, which greatly differs from equilibrium prices used in CGE models. Basic prices result from unit costs and mark-up pricing. Consequently in contrast to other IO models INFORGE is not driven by only one market side. In fact demand and supply components are considered in the model similarly. Production is determined by the demand side which, in turn, is determined by the supply side accounting for the pricing behaviour of the companies. By taking into account the cost situation and import prices, companies set their prices and thus influence the demand behaviour of the consumers, who consequently determine production by this means (Ahlert et al. 2009).

3.3.1.4 The environmental economic model PANTA RHEI

PANTA RHEI is an environmental extended version of INFORGE (Lutz et al. 2014). It has been used, for instance, to evaluate employment effects of renewable energy promotion (Lehr et al. 2012) or economic impacts of a number of energy scenarios that have constituted the basis for the German energy concept in 2010 (Lindenberger et al. 2010). Welfens and Lutz (2012) applied PANTA RHEI for the evaluation of green ICT.

In addition to the economic core INFORGE, PANTA RHEI captures land use, resource use (Meyer et al. 2012) and dwelling, transport, energy consumption and air pollutants in detail. In this module the linkage between economic development, energy consumption and CO_2 emissions is modelled, meaning that economic activities (e.g. industrial production processes or final consumer demand) directly influence energy demand and that simultaneously expenditures for energy consumption influence economic variables and CO_2 emissions. Besides the economic core the energy module plays a prominent role, as it is fully integrated into the economic part of PANTA RHEI. At the core of the energy module is the full energy balance, containing primary energy input, transformation and final energy consumption for 20 energy consumption sectors, 27 fossil energy carriers and the satellite balance for renewable energy (AGEB 2013). In total energy consumption is divided into 30 energy carriers (Lutz et al. 2014).

The transport module describes fundamental factors like the stock of vehicles and average consumption, whereas in the housing module heating requirements of the dwelling stock are modelled (Lehr et al. 2011).

The individual model components are closely related to each other and consistently linked via prices and volumes. The transport module, for example, gives information about the consumption of gasoline in litres, which is – multiplied by the gasoline price-, part of the final demand of households and of the intermediate demand of industries. Changing tax rates or international oil prices directly cause changes in gasoline consumption, tax rates and the related economic behaviour in Germany (Lutz 2011).

Currently PANTA RHEI is used to quantify the economic effects of adaptation to climate change in Germany. The model offers a soft link between gradual temperature changes and economic development by enabling the introduction of heat degree days in econometric estimations. Taking only one sector (tourism) into consideration, modelling results indicate slight positive effects related to climate change in Germany (only economic effects of climate change and not of adaptation measures have been analysed yet). The quantification of the economic effects of extreme weather events is much more complex and challenging due to an even higher degree of uncertainty (when and where will it arise and with which intensity?). First results of modelling economic effects of future flood events, similar to the floods in 2002 and 2013, indicate slight negative overall economic effects in the very short run, whereas some economic sectors will benefit (e.g. the construction sector). The works that have been already carried out are a very initial attempt to model effects of climate change with PANTA RHEI but further work must still be done. In particular, a regionalisation of climate change impacts is of major interest for local players. First attempts to regionalise economic effects with PANTA RHEI, have taken place– albeit in a different context – by designing PANTA RHEI REGIO.

3.3.1.5 The PANTA RHEI REGIO approach

PANTA RHEI REGIO is an extended version of PANTA RHEI, emphasising the linkage of the macroeconomic model INFORGE to land consumption in a regional context. It has been used to project and analyse the settlement development in the administrative and urban districts of Germany (Distelkamp et al. 2011). In this context land use aspects with respect to climate change are currently analysed (e.g. Hoymann et al. 2012).

Basically the concept behind PANTA RHEI REGIO is the same as the national models INFORGE and PANTA RHEI. PANTA RHEI REGIO differs from the other models in its detail and aggregation levels.

Driving forces for construction (housing, plants and office buildings) were, for example, implemented in the model and major variables of the national model are described on a regional level, meaning that modules forecasting economic development had to be regionalised and linked to demographic changes in the individual regions. For Germany 439 regions are modelled, corresponding to NUTS3 regions. The regionalisation of PANTA RHEI follows top-down as well as bottom-up approaches.

The former is expressed by the linkage of nation-wide developments (e.g. structural and technological change) to the economic development in the regions. This enables the projection of major economic indicators (the same is true for employment and productivity which are linked to the development of disposable income in the regions). The latter is required to model housing and construction as changes in population and in the total number of private households, which strongly influence the demand for housing and thus regional construction activities (Distelkamp and Ulrich 2009).

The “Land Use Scanner” (Hoymann and Goetzke 2014) and the way it was designed shows how a regional macroeconomic model can be integrated in assessment models linked to climate change scenarios. Not only can datasets on a district level be further regionalised to raster cells. The effects of changing conditions can also be assessed with the model. So far scenarios in PANTA RHEI REGIO were linked either to land value changes or to assumptions about demographic changes and growth patterns until the year 2030. Further model development may put emphasis on assessing effects of regional events and changes (floods, increasing drought) as well as establish links to physical indicators in general.

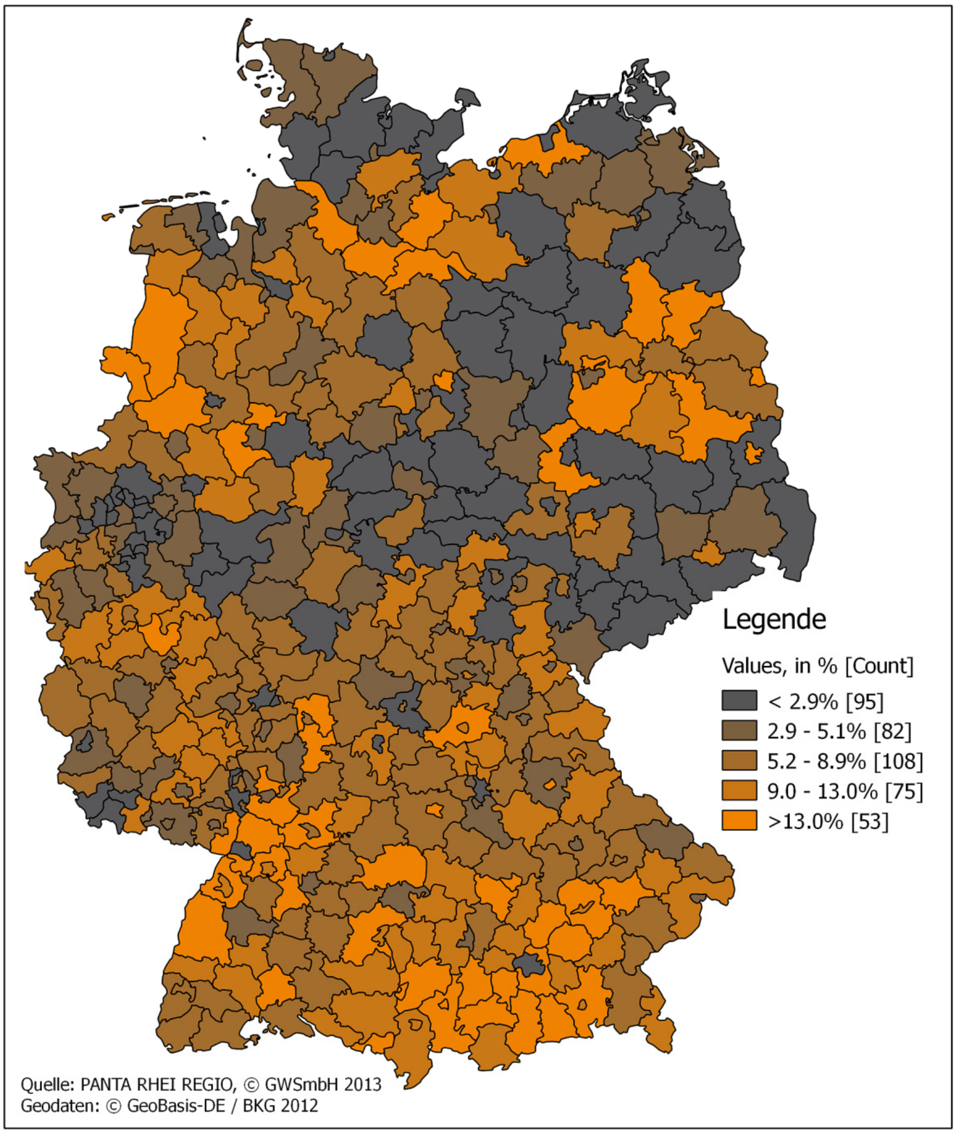

Figure 2 Change of built and adjacent areas between 2010 und 2030, “Growth scenario”, 12-2011 (PANTA RHEI REGIO 2013, Geodata: © Geobasis-DE / BKG 2012)

2.4. CGE models

Computable General Equilibrium (CGE) models are based on the general equilibrium theory developed by Léon Walras in the 19th century in the context of the neoclassical economic theory. In the 1950s, Arrow and Debreu formalised these ideas and laid the basis for modern applied computable general equilibrium models (for an early survey of these models see Shoven and Whalley 1984). Nowadays, CGE models are a widely used tool to analyse the effects of shocks on an economy and especially to evaluate policy options as well as impacts of policies (concerning efficiency and distribution) by specifying production and demand parameters and incorporating data reflecting real economies (Sue Wing 2004).

2.4.1. General idea

CGE models consider the state of a simultaneous equilibrium on all markets of the economy (goods, labour, etc.), referred to as the “general” equilibrium. The supply and demand functions on a market are usually determined by utility functions (households) and production functions (firms). Thereby it is assumed that households make their demand decisions by maximising utility and that firms decide on profit maximising input demands. Dynamic CGE models consider an intertemporal equilibrium, where decisions are optimised over time. Typical for CGE models is a welfare concept. Utilities of different agents and/or at different points in time are aggregated to a welfare function. Policies and shocks (e.g. climate-related) are then evaluated by looking at the resulting welfare change. Regarding inter-industry linkages, CGE models can also be constructed on the basis of IO tables. CGE models in particular consider rebound and substitution effects.

2.4.2. Modelling approaches

In the present state of climate-economic research, regional integrated climate-economic models have not yet been developed. However, much can be learnt from existing CGE models of different scales, as climate change impacts have already been studied with the help of CGE models on the national or international scale. Therefore, the first part of this section will deal with the links from climate to economy considered in these larger scale CGE models.

In terms of regional climate change effects, disaster impact CGE models are another relevant category. Extreme weather events are the most severe natural disasters regarding economic losses (cf. Jahn 2013) and as one of the IPCC’s “five reasons for concern”, they are arguably the most important driver of economic climate change impacts. Since for the economic theory, the cause of disasters (e.g. geophysical events, weather events) is of minor importance, existing regional disaster impact models seem to be a suitable starting point to study regional climate change in CGE models.

3.4.2.1 The GEM-E3 model (PESETA II)

The GEM-E3 model is a dynamic CGE models, developed in multinational research initiated by the European Commission. The focus for this study is on the application of the model to climate change impacts in Europe, which has been done in the PESETA and PESETA II projects (Ciscar et al. 2011).

The GEM-E3 model considers households and firms as agents and different geographical regions which are connected through trade flows. The firms use a CES production technology, combining capital, labour, energy and intermediate goods as inputs. The development of the capital stock is given through the dynamic investment decisions of firms. The treatment of consumers’ decisions has two noticeable features. First, it is distinguished between durable and non-durable goods/services. Thereby it is assumed that the consumption of these two types is directly linked. Second, utility from durable goods can only be generated when supplied above a subsistence level. This corresponds to a Stone Geary utility function. The total demand (households, public and intermediate) is split between domestic and imported products using the Armington assumption.

Regarding emissions, gases included in the model are, i.e., carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_20) sulphur hexafluoride (SF_6), hydro fluorocarbon (HFC) and per fluorocarbon (PFC). Because the model also contains a detailed tax and social security system, it is possible to derive decent estimates of welfare impacts of policies such as greenhouse gas abatement measures.

In the PESETA II project, the following biophysical impacts where identified and included in the CGE model according to the table below.

Table 1 Biophysical impacts (Ciscar et al. 2014)

Impact category	Impacts from the biophysical model		Impacts into the CGE model
	in biophysical units	in economic units	
Agriculture	Crop yields (t/Ha)		Yes
Energy	Households and service sector heating and cooling demand (toe)		Yes
River floods	People affected	Expected annual damage (€)	Yes
Droughts	Expected cropland affected (1000s km^2/year), expected people affected (million/year)		No
Forest fires	Burnt area (ha)	Restoration costs (€)	Yes
Transport infrastructures		Costs of asphalt and of bridge scouring (€); Costs of flooding and winter conditions (€); Potentially inundated roads due to sea level rose and sea storm surges (km)	Yes
Coasts (Sea level rise)		Sea floods (€); Migation costs (€)	Yes
Tourism		Tourism expenditure (€)	Yes
Habitat suitability of forest tree species	Index of habitat suitability (100)		No
Human health	Mortality (number of deaths)		Yes

The precise link of these biophysical impacts to model variables is shown below. Productivities, input factors availability (capital stock and labour) and forced consumption are key impact channels.

Table 2 Biophysical model output and impact channels (Ciscar et al. 2014)

Impact	Biophysical model output	Model implementation
Agriculture	Yield	Productivity change for crops
Energy	Heating and cooling demand	Energy demand changes in residential and service sectors
River floods	Residential buildings damages	Additional obliged consumption
	Production activities losses	Capital loss
Forest fires	Burnt area	Capital loss
	Reconstruction costs	Additional obliged consumption
Transport infrastructure	Changes in cost of road asphalt binder application and bridge scouring	Additional obliged consumption
	Net change in costs related to extreme flooding and winter conditions	Capital loss[45]
Coastal areas	Migration costs	Additional obliged consumption
	Sea floods costs	Capital loss
Tourism	Tourism expenditure	Changes in destination and tourism expenditure by bilateral import preferences
Human health	Hours lost due to morbidity and mortality	Change in labour supply
	Additional health expenditures (morbidity)	Additional obliged consumption of health services
	Warmer temperature	Labour productivity change in agriculture and construction sectors
	Mortality	Welfare loss (ex-post)

3.4.2.2 The MMRF model (Garnaut Review)

The Monash Multi Regional Forecasting (MMRF) model is a multiregional and multisectoral dynamic model of the Australian economy. It was applied to study the effects of climate change on the Australian economy/society in the context of the Garnaut Review. This review is sometimes seen as the Australian analogue of the more famous Stern Review (2006).

The general structure of the MMRF model is described in Adams (2007). Considered production factors are labour, land and capital. Consumption goods are separated into basic and luxury goods, differing in their price elasticities. For luxury goods, household consumption is more responsive to relative price changes.

Firms also react to relative price changes regarding the composition of factor inputs. As these become large, firms can also invest in technology to reduce the dependence on the respective input. Otherwise the model contains a relatively detailed energy sector, considering i.e. fuel substitution in power generation, the national electricity market and renewable energies.

Regarding climate impacts, the following were modelled for the Garnaut Review (cf. Table 6.1 in Garnaut 2008):

- Primary production: cropping (dryland and irrigated), livestock (dairy, sheep, beef cattle)
- Human health: heat stress (deaths and hospitalisations), vector-borne dengue viruses, bacterial gastroenteritis
- Critical infrastructure (human settlements): water supply infrastructure in major cities, electricity transmission and distribution networks, buildings in coastal settlements, ports operations and maintenance
- Tropical cyclones: impacts on residential dwellings
- International trade

More details are discussed in Garnaut (2008). To summarise, it has become clear that it will hardly be possible to represent all known climate change impacts in a CGE model. Therefore, these models will always cover only some aspects, usually those that are closely related to markets.

Building the bridge to the smaller geographical scale, three regional CGE models are considered below. The first can be seen as a disaster impact model and emphasises the role of resilience/adaptation. The second focuses on spatial effects on the regional level and the third uses a simplified structure of the second and includes climate change impacts.

3.4.2.3 Portland Disaster Impact Model

In Rose and Liao (2005) a regional CGE model has been developed to study the economic effect of the disruption of the water supply in the Portland metropolitan region as a consequence of potential earthquakes. As scarcity of various inputs like water or electricity could be one consequence of climate change, is worthwhile giving further investigation to the modelling technique.

The (critical) inputs enter the CGE framework via the production function. The latter is a nested constant elasticity of substitution (CES) function which combines five types of inputs in four tiers. The CES structure allows incorporating the possibility of substituting one type of input for another, which firms might be willing and able to do in a scarcity situation to limit the output loss.

The approach also discusses further the reactions of the economy in an input scarcity situation. The substitution decisions of firms described above can be seen as a market mechanism which is referred to as “inherent resilience”. Additional reactions are captured under the term “adaptive resilience” which means that model parameters change. For example, extra effort or conservation of inputs belongs to the latter category. The recalibration of the respective parameters requires additional data, which is not always available.

The lesson learnt from Rose and Liao (2005) is that the size of economic losses from some phenomenon, e.g. from climate change, depends on the assumptions made with regard to the behaviour of agents under changing conditions, i.e. the assumptions on economic resilience. The CGE framework provides sufficient possibilities to model both inherent and adaptive resilience, but an accurate parameterisation remains difficult.

3.2.4.4 The RELUTRAN model

Another issue worthwhile being discussed is spatial effects such as location decisions. These might become very relevant under climate change since even locations within a region might have very different levels of exposure to climate change and therefore revised location decisions are a likely reaction of firms and households. A regional model which takes into account spatial effects is the RELUTRAN (Regional Economy Land Use TRANsportation) model presented in Anas and Liu (2007). The RELUTRAN model is a dynamic spatially disaggregated CGE model of an urban economy and its land use. RELU considers micro decisions of households, firms and landowners. Households endogenously decide on their residential location, their work location while individual labour supply and consumption decisions (goods and services, land, housing, etc.) are simultaneously determined. Firms of different industries decide on their location of production as well as the amount and composition of labour, land and further intermediate inputs. Landowners decide whether to offer floor space for rent or withhold it from the rental market, depending on expectations concerning (future) profits of renting land. RELU equilibrates floor space, land and labour markets, and the market for the products of industries by endogenously adjusting housing prices, land rents, wages, and prices of industry commodities as well as prices of final consumption goods and services. On the other side, the TRAN algorithm treats travel mode choices, transport-related energy consumption/CO_2 emissions and equilibrium congestion on the road network based on a stochastic user equilibrium. The interplay between RELU and TRAN then determines the economic and spatial structure of the regional/urban economy (population and employment densities for different urban districts, commuting patterns,business activity, land and housing prices, etc.). Based on RELUTRAN, a wide range of policy issues can be analysed, for example issues related to housing, transportation and a wide range of environmental aspects. Relying on regional CGE models of an urban economy will become more and more important in the future. According to the UN, about 50 per cent of the world’s population in 2007 was residing in cities. A rise to a share of 60 per cent in 2030 is expected. More importantly, the number of people living in cities will rise to about 6.5 billion by 2050, which is only a little less than the whole world’s population of 2007. On the other side, cities are also disproportionately vulnerable to a changing climate.

Many large agglomerations are located in (low elevation) coastal zones or are located close to rivers, and thus are especially prone to flood risks. Hence, they fall under the areas mostly affected by rising sea levels, increasing storm surges, and intensifying heavy rainfall.

The challenge mentioned above arises from the difference between the effects of single weather events and the more abstract phenomenon of climate change. Single events have ambiguous effects on the regional economy (cf. Jahn 2013) whereas an extremer climate is very likely to have distinct negative effects.

3.2.4.5 Spatial Regional CGE Model

The spatial regional CGE model (Jahn 2014) provides a framework – a simplification of the RELUTRAN framework - to model the regional spatial, economic and welfare impacts of climate change due to the risk of extreme weather events.

It makes use of regionalised IO tables to represent the regional economy and takes into account different zones inside the region which have different socio-economic structures and also different levels of exposure to extreme weather. The model is used to estimate possible spatial effects and regional economic losses of climate change induced flood events in the city of Hamburg, Germany, and to evaluate flood adaptation measures (Jahn 2014). By focusing on probabilities of occurrence, with its increase having a clear negative effect on the economy, it overcomes the problem of modelling the ambiguous effects of single extreme weather events on economic activity.

The precise impact channel of floods is that a shift in their probability distribution is assumed to lower the utility that households can derive from an affected piece of land and also the productivity of land for firms. Therefore, sectoral vulnerability to floods is mainly represented through the dependence of the sectors on land as a production factor.

In the model, investments into flood adaptation can lower the impact of higher probabilities of occurrence on the utility/productivity of land but must be financed through taxes and therefore, a cost-benefit analysis of adaptation measures is possible.

3.2.4.6 Urban CGE Model

Another model also based on the RELUTRAN model, though with different modifications concerning externalities and a simpler housing model, is used to analyse welfare effects, spatial effects, redistribution effects, environmental effects and changes in transport of policies for mitigation (e.g. Tscharaktschiew and Hirte (2010) on emission charges; Hirte and Tscharaktschiew (2013), on electric vehicles; Hirte and Nitzsche (2013) on mitigation). In an extension of the model, regular city flooding due to climate change is modelled as change in land quality. As land is used as input in production, for infrastructure and housing, severe damages occur on different markets. This model has been applied to discuss pro-active and re-active adaptation and the efficiency of adaptation given unknown productivity of investment into adaptation (Hirte et al. 2014).

Eventually, there are two research directions for regional climate change CGE modelling. First, to provide a powerful economic model at the levels of cities/regions that allows the analysis of a wide range of climate impacts, and second, to transfer mechanisms of short or medium term disaster impacts to long term climate change impacts influencing regional economic conditions. The principal channels remain the same for the economy: input factor availability and factor productivity on the supply side and consumption preferences on the demand side. As CGE models work with a utility concept, impacts can also directly act on the utility function.

2.5. Conclusions

In this chapter the two main categories of economic models have been discussed, namely general equilibrium models, based on the underlying neoclassical general equilibrium theory, and IO models, following an evolutionary economic approach with bounded rationality. Whereas simple IO models differ from CGE models in that they are linear, demand driven and do not consider price effects (among others), a comparison between the most elaborated versions of CGE and econometric IO models shows that the lines between both model types are becoming more blurred. The INFORUM family of IOE models1, for example, considers price responses to changes in demand. At the same time CGE models have been developed, allowing for states of disequilibrium, e.g. on the labour market or with respect to energy use (West 1995).2 In the last decades both model categories have become indispensable tools for the evaluation of policy measures and the quantification of impacts induced by changing economic circumstances or framework conditions, like tax increases, renewable energy promotion, etc.

Climate change is a global phenomenon and will affect different world regions in various ways, meaning that not only the expected climate change (respectively the impacts) in South-East Asia will differ from the one in Central Europe. Moreover, even southern Germany, for example, will probably be hit differently than northern Germany. Consequently it is of great interest for local residents, politicians and companies, how climate change will impact the respective regions. This means that not only the regionalisation of climate models is of major importance, but also the regionalisation of economic models. This has already been carried out, among others, by disaster impact models. These models, basing on a CGE or an IO structure are used to quantify damages or costs, resulting from disaster events (e.g. floods, hurricanes) on a regional basis. In Germany, climate change will, besides a slow rise in average temperature, lead to an increase in the number and intensity of extreme weather events. This is why disaster impact models represent an interesting approach in quantifying regional impacts of extreme weather events.

CGE and IO models are qualified tools to model regional economic effects of climate change. To derive regional economic parameters from national data, methods of regionalisation willbe necessary. Approaches to regionalise a national CGE model with the help of transportation data is proposed, for example by Standardi and Bosello (2014). IO matrices for single

[1] The aforementioned models INFORGE and PANTA RHEI are part of this model family.
[2] More detailed information about the structure of IO and CGE models can be found in West (1995), West (2002).

regions can, for example, be constructed with the help of location quotients from national tables as described by Flegg and Webber (1995).

CGE models as well as IOE models are characterised by a wide variety of specifications, leading to the fact that models are neither within nor between the individual categories that are clearly definable from each other. Despite all the differences in detail, both model categories are closely related and the distinction has become more blurred over the last couple of years. However in the following table, an attempt is made to capture some main properties of IO and CGE models. A more detailed discussion can be found in West (1995), West (2002) or Koch et al. (2003).

Table 3 A comparison of features of input-output and CGE models (own figure)

IOE	CGE
mainly demand driven	mainly supply driven
price effects may be included	complete price effects
primary factor demand by econometric functions	usually CES or Cobb-Douglas production function
describes economy "as it is" (no optimization)	optimization behavior of rational agents
no welfare concept, consumption function	welfare concept arising from utility functions
short-term analysis	long-term analysis
dynamic character	primarily static character

Regarding the choice of the model for a regional integrated assessment of climate and economy, no definite statement can be made.

Both model categories have their strengths and weaknesses. Planners should consider carefully which model attributes are of major importance for them, being aware that this decision is certainly influenced to some extent by personal attitudes and beliefs concerning the behaviour of all economic players and the processes behind their action.

3. Integrated Assessment Models

3.1. General

An Integrated Assessment Model (IAM) in the context of climate change means the coupling of climate and economic models, taking into account mutual influences and feedbacks between the Earth system and the socio-economy. The purpose of IAMs usually is to answer at least one of the following policy-relevant questions:

- What are the (economic) impacts of climate change at global or continental scale?
- What is the Social Cost of Carbon (SCC), i.e. what is the price of emitting?
- What are good or optimal climate change mitigation or adaptation strategies?
- The general integrated assessment modelling concept is illustrated below.

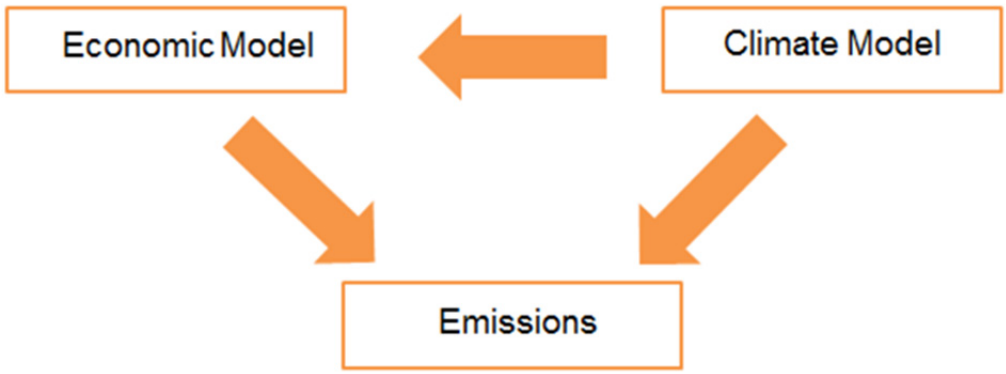

Figure 3 Structure of Integrated Assessment Models (own figure)

In most models the socio-economy is assumed to influence the climate mainly through greenhouse gas (GHG) emissions. The climate is assumed to influence the socio-economy through impact functions.

These functions can represent physical damages (if the purpose of the analysis is to quantify costs of climate change) or they can be emission mitigation costs (if the purpose is to quantify the costs of maintaining a certain emission or temperature target). Thus, these functions are often called damage function and abatement function, respectively (Stanton et al. 2009).

In the following, an overview of IAMs is given. There are many different modelling approaches and even for an overview, it is necessary to concentrate the analysis on a few model features. The considered models are classified according to four categories:

Detail:

IAMs vary not only regarding their considered time interval and region but also in the complexity of their atmospheric chemistry, climate and socio-economic modules. Each module is analysed and the modelling approach is classified as either simple or complex. This is adopted from Kelly and Kolstad (1999).

In this chapter a model is considered as complex with respect to these three different modules if it fulfils various criteria listed below:

Table 4 Classification of complex IAMs (own figure)

Atmospheric chemistry model	Climate model	Socio-economic model
At least 2 endogenous GHG included	At least 2 different parameters (e.g. temperature, sea level rise) are drivers of climate change	Impacts on at least 2 different sectors are considered

Optimisation:

Most models optimise some type of objective function. If that is the case, the precise objective (welfare, costs, etc.) is denoted. Models that do not include optimisation can be described as 'evaluation' models (Kelly and Kolstad 1999).

Impact functions:

Many IAM review articles put an emphasis on the impact functions used in the models (e.g. Ortiz and Markandya 2009), as these have a big influence on the model results. In this category, general properties of the functions and sector specificities are collected and described.

Adaptation:

For a regional integrated assessment of Earth system and socio-economy, adaptation becomes relatively more important than mitigation. Therefore, under this category, it is described how the considered (global or continental) IAMs deal with adaptation.

The rest of the chapter is organised as follows: First, the four most prominent IAMs DICE, FUND, PAGE and MERGE (cf. Nordhaus and Sztorc 2013; Anthoff and Tol 2013; Hope 2011a; Manne et al. 1995) are analysed in detail with respect to the categories defined above. A table in the annex provides more condensed information about these and 14 other IAMs.

3.2. Selected models

3.2.1. DICE

One of the most popular IAMs is the dynamic integrated climate-economy (DICE) model by William D. Nordhaus. Its first version was presented in 1992 (Nordhaus 1992). This paper discusses the current version of 2013 (Nordhaus and Sztorc 2013).

The DICE model is a global model. It runs from the year 2010 to 2310. The time step between the model periods is five years. DICE consists of relatively simple modules for the atmospheric chemistry, the climate and the socio-economy. It only models industrial carbon dioxide (CO_2) emissions endogenously. The climate is only represented by the global temperature development. The climate module consists of a carbon-cycle, a radiative forcing equation, climate change equations and a climate-damage relationship. Finally, the socio-economy is not distinguished into different sectors. The economy produces output that can be consumed or invested to trigger utility or production. The modules are linked via emissions and abatement efforts that influence the climate and damages that affect the socio-economy.

The DICE model is a policy optimisation model since it is based on an objective function that is aimed to be maximised over time. However, it can also be applied in a policy evaluation mode. The objective function is a standard social welfare function represented by the discounted sum of the population-weighted utility of per capita consumption. As a simplification, the model includes only one commodity that can be consumed or invested (also in abatement) and which should be interpreted as representing market and non-market goods like environmental services. By optimising consumption and hence determining investment, the accumulation of capital is derived endogenously. Population growth and technological change are exogenous.

Industrial CO_2 emissions result from production and an exogenous level of carbon intensity. The cumulative industrial emissions are limited by 6000 gigatons of carbon (GtC), representing limited availability of fossil fuels. Together with exogenous land use emissions they add up to total carbon dioxide emissions. These emissions enter the carbon cycle consisting of a three-reservoir model with diffusion: carbon in the atmosphere, carbon in the upper oceans and the biosphere, and carbon in the deep oceans. The radiative forcing equation depends on the amount of carbon in the atmosphere and some exogenous forcings.

Finally, the revealed radiative forcing influences the mean surface temperature and the temperature of the deep oceans. The temperature of the surface in turn enters the damage function.

Climate change impacts influence the socio-economy via output. Due to a scale factor in the production function, damages reduce net output. The scale factor is embodied by the damage function that has been simplified compared to earlier versions of the DICE model. Sectoral estimates turned out to be outdated and unreliable. Therefore the current version relies on a single damage function, a quadratic function of the temperature change. The function is calibrated to correspond to current estimates of climate change damages, e.g. by the IPCC, and in addition for not yet considered non-market damages. Yet, it refers to temperature changes in the range of 0-3°C and does not account for thresholds or tipping points.

In addition to emissions and the resulting damages, potential emission abatement couples the socio-economic and climate module. A fraction of output can be invested to reduce industrial carbon dioxide emissions and thus to prevent damages. The ratio of abatement cost to output is a power function of the emissions reduction rate. The emission reduction rate in turn enters the industrial emissions function which apart from that depends on output and carbon intensity as described above. In addition, DICE takes into account a backstop-technology which might enable a carbon free energy supply in the future. The backstop technology is modelled by setting the price for full abatement in the abatement cost equation equal to the backstop price for each year. Initially, the price for this technology is designed to be very high, but it decreases over time with technological progress.

A far reaching characteristic of the original DICE model is that it does not include any form of adaptation. For that reason, an expansion of the 1999 version of the DICE model was developed, the Adaptation in DICE (AD-DICE) model (de Bruin et al. 2009). It implements adaptation within the framework of the DICE model and thereby takes into consideration the trade-off between mitigation and adaptation. In this model adaptation is explicitly formulated as a decision variable. Damages can be reduced at the cost of investment into adaptation. The residual damages and these adaptation costs add up to the net damages. Both elements depend on the level of protection, while the residual damages also depend on the gross damages.

Another well-known expansion of the DICE model disaggregates the global DICE model into a model with several regions. It was presented by Nordhaus and Yang (1996) and is called Regional Integrated model of Climate and the Economy (RICE). It distinguishes 12 regions in its current version (Nordhaus and Sztorc 2013). The structure of the RICE model is roughly identical to the DICE model but regions have specific levels and trends for output, population, emissions, damages and abatement. Moreover, each region has its own welfare function and hence optimises consumption, investment and abatement respectively.

3.2.2. FUND

Another widely used IAM is the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) originally developed by Richard S. J. Tol (Tol 1997). Subsequent versions of FUND were co-developed by David Anthoff (e.g. Anthoff and Tol 2013).

FUND version 3.7 divides the world into 16 regions. The model starts in 1950 to initialise climate impacts and runs to the year 3000 with one year time steps.

The socio-economic module of FUND design is quite complex, at least in regards to its consideration of climate change impacts. It models demographic developments like migration and takes into account several health impacts affecting the population. By that complexity it makes an analysis of non-market impacts of climate change possible. The atmospheric chemistry can be considered relatively complex as well, and several GHGs are also modelled endogenously. Moreover, the representation of the climate itself can be considered as complex. FUND includes equations for the atmospheric concentrations for several greenhouse gases, a radiative forcing equation and temperature and sea level rise specifications. Hence, it depicts climate change by more than just the temperature change. Furthermore, the climate-damage relations coupling the climate and socio-economic modules are relatively complex and detailed. Various individual damage functions exist for several sectors like agriculture or human-health.

Like the DICE model it is a policy optimisation model with an objective function. The objective function is a welfare function depending on population and gross domestic product (GDP), and damages of climate change for each region. Exogenous scenarios determine GDP growth, population growth and the assumptions regarding the allocation of investment and consumption. Due to these specifications, capital accumulation is not optimised endogenously. The only control variable is greenhouse gas emission reductions. A unique feature of the model is that it can be solved in different global interaction scenarios. FUND is able to allow for international capital transfers as a climate policy, a feature that was the original purpose of the model. In addition, the 16 regions may coordinate or may not coordinate their climate change policies.

Industrial CO_2 emissions are derived with the help of the so-called Kaya identity linking emissions to the carbon intensity of energy use, that is the energy intensity of production and GDP. Both intensities are modelled to depend partly on exogenous developments and on policy interventions. CO_2 emissions from land use and deforestation are exogenous in FUND and moreover there is no possibility to abate them. Other greenhouse gases included are methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), sulphur dioxide (SO_2) and emissions from the terrestrial biosphere. They are either modelled exogenously or in a simple way. The greenhouse gas emissions fall into equations modelling the atmospheric concentrations. Methane, nitrous oxide and sulphur hexafluoride are geometrically depleted. For obtaining carbon dioxide concentrations a so-called five-box model is used (Hammitt et al. 1992; Maier-Reimer and Hasselmann 1987). For sulphur no concentrations are derived. The greenhouse gas concentrations then enter the radiative forcing equation. The determined radiative forcing in turn enters the global temperature specification. Finally, the global mean sea level rise is modelled with the global mean temperature.

Both, temperature and sea level rise reach their equilibrium values through geometric build-ups over time. The regional temperatures depend on the global temperature and a parameter covering the spatial climate change patterns.

Climate change impacts are modelled as tangible and intangible damages and affect the scenarios for economic and population growth. Intangible damages directly fall under the welfare function as explained above. Climate change deaths reduce population. Depending on the specific kind of impact only the non-productive or urban population is affected, in other cases the whole population suffers. Yet, all damages are monetised. Tangible damages lower investment and consumption and, thus, economic growth and welfare. Damages are derived by various individual damage functions specific for each sector or even subcategory. The FUND version 3.7 models impacts affecting agriculture, forestry, water resources, energy consumption, sea level rise, ecosystems, human health, and extreme weather. The damage functions have different functional forms for each sector and depend on miscellaneous variables. The rate of climate change and the vulnerability to climate change in particular are often included in addition to the level of temperature change which is commonly the only variable used in most other IAMs. Vulnerability is usually represented by population, economic growth and technological progress. In several sectors like agriculture an optimal value of temperature is considered. Hence, impacts depend on whether the temperature moves closer to the optimum or not. For respective sectors sea level rise or emission concentrations are used as explanatory variables in addition to or instead of temperature variables.

As explained above, industrial carbon dioxide emissions can be reduced by policy interventions. Emission reductions are designed to be permanent or temporary reflecting technological lock-ins and potentially reversed policies. The related emission reduction costs depend on the rates of reduction, the pool of knowledge and a parameter that assures that emission reductions depend on the current level of emission intensity. By that emission reductions are cheaper in regions with high intensities. The pool of knowledge is also modelled for each region. It is influenced by the global pool of knowledge and the accumulated emission abatement efforts. More experience reduces the costs. In addition to carbon dioxide emissions also methane and nitrous oxide emissions can be reduced. The respective cost curves are quadratic. The emission reduction costs lower investment and consumption. In contrast to DICE, FUND does not take into account a potential carbon free backstop technology.

Adaptation is only included implicitly in a very easy to grasp way. Some of the climate change damages depend on the impact of the rate of temperature change of the year before and therefore represent gradual adaptation. By that it is aimed to model a kind of reactive adaptation process, as damages from the rate of temperature change slowly become less intense. So obviously, adaptation is generally not designed as an endogenous choice variable. An only exception is the protection of coast lines, which is modelled somehow endogenously by assessing costs and benefits based on Fankhauser (1995).

3.2.3. PAGE

The Policy Analysis for the Greenhouse Effect model measures in its latest version (PAGE09 v.1.7) the effect of climate change and the costs of adaptation and mitigation policies for eight world regions and ten time periods in increasing steps up to the year 2200 under uncertainties (Hope 2011a).

PAGE09 is an edited version of the prior PAGE2002 model. The update has been made to include newer scientific and economic information referring in particular to the fourth Assessment Report of the IPCC (Hope 2011a). The differences between both versions and the extensions of PAGE09 are described in greater detail subsequently.

All calculations in PAGE09 are carried out probabilistically and while certainty is assumed for functional forms, each of the approximately 80 uncertain model parameters is presented as a probability distribution through Latin Hypercube Sampling (LHS) (Pycroft et al. 2011, p. 3). The authors justify their decision to use LHS rather than Monte Carlo Sampling by referring to a greater coverage of the extent of the input parameters and a more accurate estimation of the output regarding the cumulative distribution function and mean of each variable (Hope 2011a).

According to the definition of complexity in the introductory part of this chapter, PAGE09 can be seen overall as complex with respect to its atmospheric chemistry-, climate and socio-economic module. It thereby uses rather simple equations, i.e. a limited amount of variables and an aggregated form of impacts, to estimate complex climate change effects.

The atmospheric chemistry here comprises and explicitly models CO_2, CH_4, N_2O and the combination of hydro fluorocarbons (HFCs), per fluorocarbons (PFCs) and SF_6 as a fourth gas. The latter three gases are, according to the author, low in their concentration and their contribution to radiative forcing is increasing linearly regarding their concentration in the atmosphere (Hope 2011a).

The economic module considers the four impact sectors: economic, non-economic, sea level and discontinuities. Economic impacts in this case are those directly included in GDP (e.g. agricultural losses and air-conditioning costs) and non-economic ones such as environmental and social impacts (e.g. human health), it is further assumed that only one discontinuity occurs and then lasts permanently (Hope 2011b, pp. 5 ; Hope 2006, p. 21).

In PAGE09 impacts of climate change on the economic and non-economic sector are a polynomial function of temperature change and defined as a percentage loss of GDP, based on consumption losses. These changes in consumption are then turned into utility functions, referring to the elasticity of the marginal utility of consumption. In this way consumption per capita in poorer regions, where the initial amount is rather small – and each additional unit is thus more important – is given more weight over time compared to richer regions and vice versa (Pycroft et al. 2011, p. 3).

This specification directly links the damage to GDP. To prevent impacts from exceeding 100 per cent of GDP, which was possible in the former version of this model, and to demonstrate thereby a limit of vulnerability of economic and non-economic sectors, a saturation level is set, at which impacts leave the polynomial path and drop onto a logistic one, as soon as a certain level of consumption is crossed. This level though can be set to 100 per cent of GDP in the case that saturation is not expected earlier (Hope 2011a).

The output variables are determined as an increase in global temperature, caused damages, and adaptation and mitigation costs. The calculations referring to those are repeated for the different stochastic parameters. Economic and population growth as well as greenhouse gas emissions are exogenous and set out according to the IPCC A1B scenario (Hope 2011 a).

The model compares two different emission scenarios with respect to their underlying damages in order to measure the effects and benefits of mitigation policies, i.e. decreasing CO_2 emissions.

PAGE09 is the only policy evaluation model introduced in this chapter, i.e. a model where the optimal policy is not found endogenously but exogenous policies are assessed.

To monetise climate change impacts, net present values (NPV) are calculated and presented as a probability density function for the whole period of time and losses are compared to the total world production.

In a final step the social costs of CO_2 are calculated determining the changes of the NPV of impacts as a result of a reduction in emissions by one ton in order to relate prices to CO_2 emissions (Hope 2011 b, pp.12). In PAGE09 temperature rise is not a direct input of the damage function but leads to various impacts. Those are weighted, depending on the affected region and sector, and included afterwards into the damage function. This approach is therefore distinct from the DICE and MERGE models where a direct linkage of increasing temperature and damages is established (Döll 2010, p. 43).

Adaptation in PAGE09 is modelled exogenously and includes various policy variables as inputs in three sectors (economic, non-economic and sea level) for all of the eight regions and it is modelled with the aim to both increase the level of temperature that is tolerable and reduce the impacts of climate change that still occur. An example of how adaptation can change tolerable temperature and limit climate change impacts is illustrated in Figure 4.

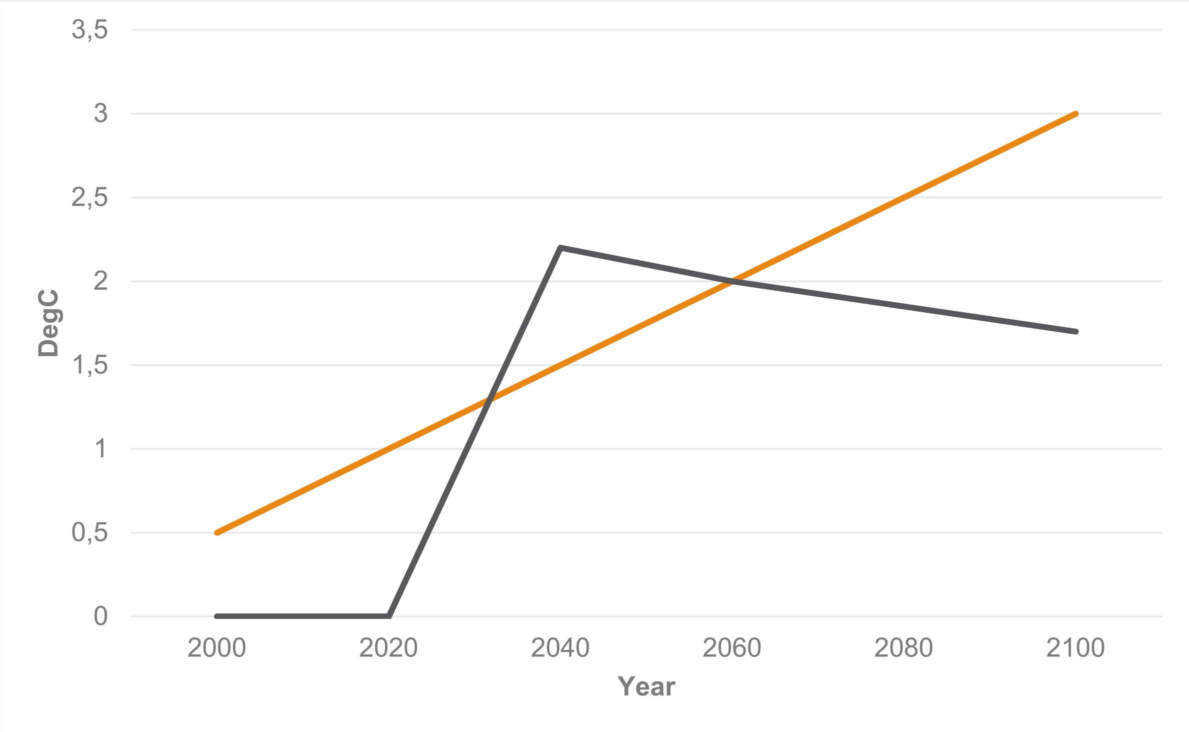

Figure 4 Adaptation and tolerable temperature (Hope 2011a – modified)

As long as the rise of temperature (orange) remains below the tolerable level (anthracite), climate change impacts are non-existent in the model. In this figure an adaptation policy starts in 2020 and lasts for 20 years until it is fully implemented. In the years between 2030 and 2060 temperature increase remains below the tolerable level and the impacts are set to zero. A higher level of tolerable temperature (as a result of adaptation policies) therefore implies a longer interval without impacts despite the increasing temperature and, depending on the plateau, the year in which the adaptation policy is implemented and the length of duration until its effect is fully accomplished. All of these three criteria can be determined individually by the user.

The slope of the curve defines therefore the maximum rate of temperature increase that is still tolerable (Döll 2010, p. 43). Adaptation costs as a percentage of GDP are calculated per unit of adaptation bought for each region. This is a modification to the PAGE2002 model where costs are specified in million dollars per unit instead (Hope 2006).

Marginal costs of abatement are illustrated on a continuous curve (see Figure 5) where the first mitigation unit as well as a small amount of CO_2 (Gt) reduction is associated with negative costs while larger cutbacks lead to higher and therefore positive marginal costs. These calculations are being made for each gas in each region. The curvature is determined by the two parameters “CURVE_BELOW” and “CURVE_ABOVE”.

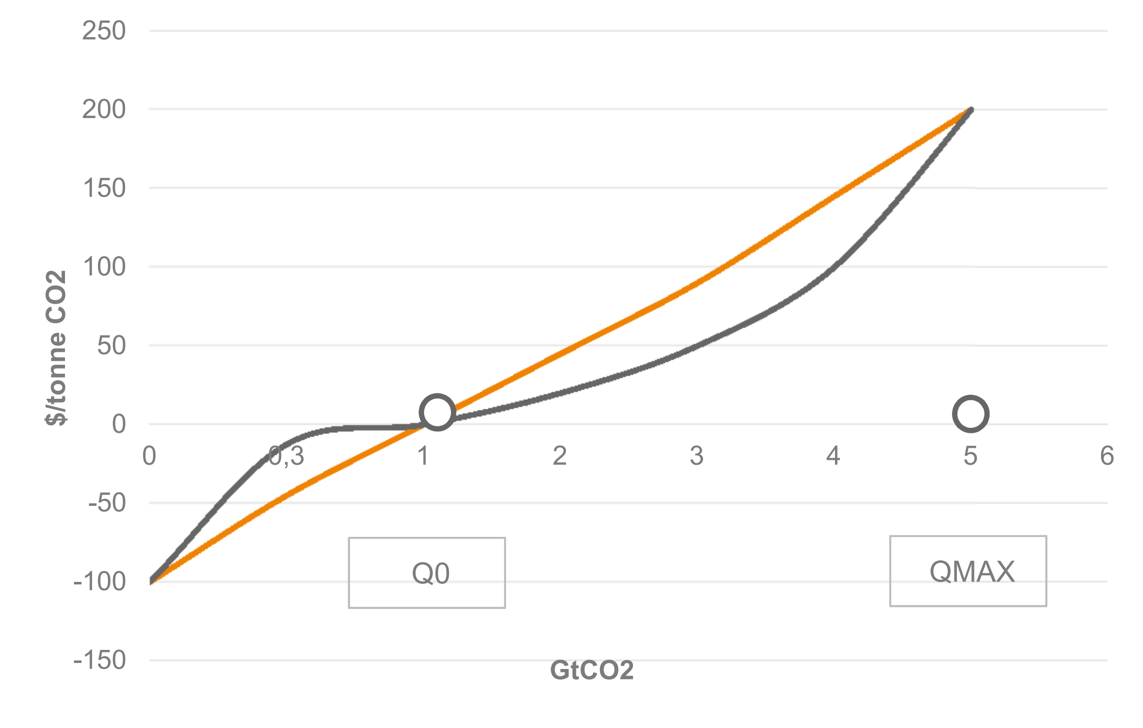

Figure 5 Costs of mitigation (Hope 2011a - modified)

The former one is defined as one minus the costs between zero and Q0 prorated to the costs emerging if the curve was linear and the same applies for the latter one which is specified under the same criteria as one minus the costs between Q0 and QMAX, where Q0 can be seen as the limit at which cutbacks are possible for negative costs and QMAX as the maximum possible cutback at positive costs. As long as these two parameters are between zero and one the curvature of the maximum abatement cost curve divagates from the shape of a linear curve (Hope 2011 a).

The total costs of climate change are finally calculated by minimising a function of the sum of climate change impacts as well as mitigation and adaptation costs. One distinction of PAGE09 compared to other IAM models like MERGE can be seen in its damage function where damages are calculated for one focus region and those estimates are weighted with respect to time and region to be applicable to all the other regions in the model. This approach poses the question of accuracy regarding the calculated damages.

3.2.4. MERGE

MERGE (Model for evaluating regional and global effects of GHG reductions) by Manne et al. (1995) is a policy optimisation model and consists of three submodels. It is complex with respect to its atmospheric chemistry and socio-economy but simple in the climate module.

The module Global2200 deals with costs of various emission levels that could affect the economy on a regional and global basis. The climate submodel describes the relationship between the emissions of three major GHGs and the impacts on temperature as a result of an increase in their atmospheric concentration. The damage assessment model finally aims to quantify the impacts of climate change. Figure 6 gives an overview of these submodels and their relation to each other while a further description is given subsequently.

Global2200, a fully integrated applied general equilibrium model, contains five geopolitical regions: USA, other OECD countries (Australia, Canada, Japan, New Zealand and Western Europe), FSU (the former Soviet Union), China and the ROW (rest of the world). Each of those regions is seen as a price taking agent, independent from the others and subject to an intertemporal budget constraint. The model covers the time between 1990 and 2200 using time intervals of ten year steps up to the year 2050 and steps with lengths of 25 years afterwards.

The international market prices of commodities in the energy sector (oil, gas, carbon emission rights and coal) and additional commodities outside this sector determine the equilibrium of supply and demand at each point in time. The objective is to maximise a region's utility and investment decisions at each point in time, using a "special case" (Manne et al. 1995, p. 19) utility function that relies simply on the logarithm of consumption.

Economic activity in each region within the energy sector is only classified between electric and non-electric energy while all economic activity outside this sector is expressed by the real purchasing power.

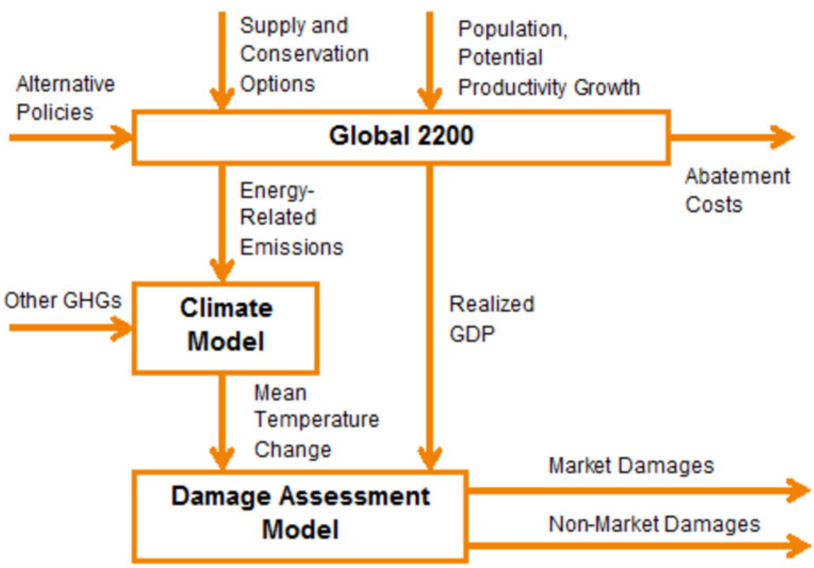

Figure 6 MERGE submodels (cf. Manne et al. 1995, p.18 - modified)

The electricity supply contains on the one hand sources that existed before 1995 such as gas, oil and hydroelectric but also those of the new generation that were supposed to become available in the upcoming decades afterwards e.g. carbon free technologies at low as well as high costs covering various kinds of technologies such as solar, wind and nuclear.

Nine different sources are included in the non-electric energy supply like natural gas and synthetic fuels, as well as low cost renewable and high cost backstops, all of them differing in their costs and carbon emission rates. Demand in the energy sector is determined by GDP growth which itself depends on population growth and per capita productivity. Gross output of the economy-wide production function includes the four inputs capital (K), labour (L), electric (E) and non-electric (N) energy and has a non-linear form in the long-run determined by various assumptions like constant returns to scale, a unit elasticity of substitution between the first two (K and L) and the second last inputs (E and N), as well as a constant elasticity of substitution between these two pair of inputs.

The climate submodel in MERGE models three major greenhouse gases, namely CO_2, CH_4 and N_2O and analyses the relationship between rising emissions and increasing temperature. Emissions of each gas are split into the two categories: energy and non-energy. While the non-energy emissions enter the model exogenously the others are predicted endogenously by fuel type up to the year 2200. Future CO_2 emissions are predicted by a reduced form carbon cycle model of Maier-Reimer and Hasselmann (1987) in which emissions are divided into different classes based on their lifetime in the atmosphere. The amount of CH_4 and N_2O in the atmosphere in t+1 is defined as the amount in time t remains in the atmosphere additionally to new generated emissions.

Impacts in MERGE are merely driven by changes in temperature which is assumed to be the global mean for temperate countries and half of that in tropical ones. In order to quantify the impact of increasing GHG emissions in the atmosphere in the upcoming decades on global welfare, the damage assessment submodel divides damages into two categories: market and non-market. Market damages include those that can be expressed by prices and are commonly included in measurements of national income, such as damages on the primary sector (e.g. agriculture or forestry) or loss of property (dry land loss). Market damages are thereby calculated as a quadratic function of temperature change and GDP.

Non-market damages on the other hand, such as a loss in bio-diversity (e.g. wetland loss) or human well-being (e.g. migration or air pollution), cannot be observed and valued based on prices, but need alternative preferences (Manne et al. 1995). The approach used in MERGE is based on the willingness of consumers to pay in order to prevent ecological damages. The willingness to pay (WTP) is assumed to be S-shaped and depends both on temperature rise as well as on GDP per capita. While the willingness to pay for non-market damages is low at low-income, it increases with higher income and remains constant afterwards.

Figure 7 illustrates the WTP to avoid a 2.5°C increase in temperature above 1990 levels. Consumers are willing to pay almost 2 per cent as soon as per capita income is higher than 40000 dollars (US1990). Non-market damages in this model are valued the same by each region no matter whether they occur in a region's boundary or far away. According to the authors (Manne et al. 1995, p. 26) the S-shaped form of the curve implies that non-market damages will be higher in developed countries as a result of a higher WTP. This might be true for the amount effectively paid to cope with those damages but is an insufficient view on non-market damages and costs for developing countries that are likely to experience the worst consequences of climate change and are least able to pay for those impacts respectively to avoid them.

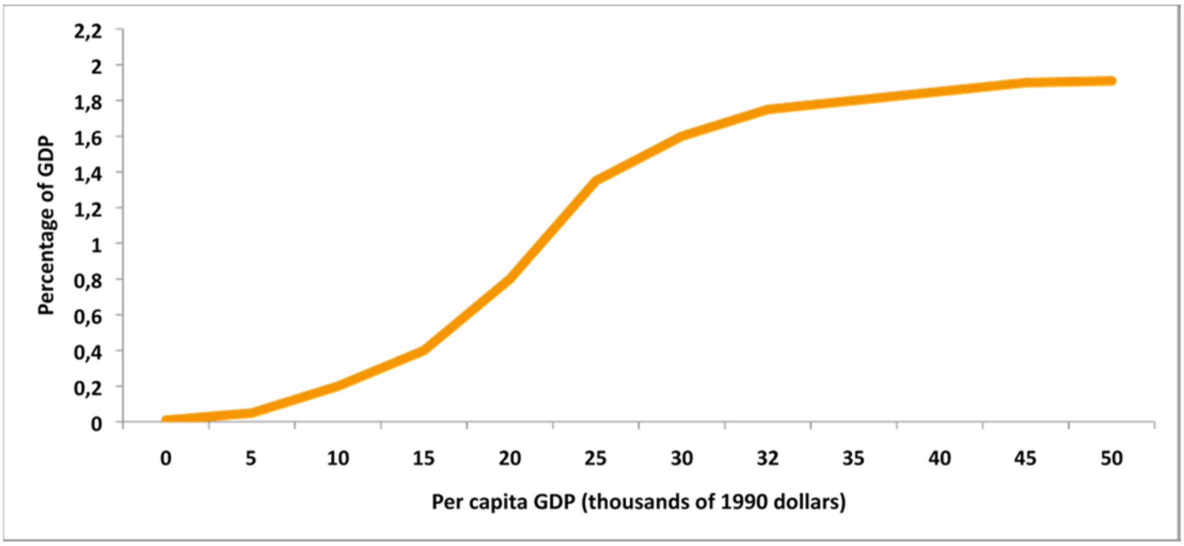

Figure 7 Willingness to pay (WTP) for non-market damages (Manne et al. 1995, p.26 - modified)

Adaptation to climate change is not modelled explicitly and could, if at all, be implicated through possible changes in the market prices as a reaction on global climate change impacts.

3.3. Conclusions for a regional IAM

The presented IAMs differ in many aspects. Each of the models has its own characteristics and priorities. Therefore it is useful to compare and discuss the advantages and disadvantages of the models in particular with regard to creating a regional IAM.

As outlined in the introduction, an important feature of an IAM is its degree of detail. The complexity of a model mainly depends on its purpose and application range. The DICE model by Nordhaus is clearly one of the simplest models. However, largely due to its simplicity and transparency, it became one of the most famous and commonly applied IAMs.

The more complex and detailed a model is, the more vulnerable it becomes to the so-called “black-box-critique” which is often attached to IAMs. Yet, the degree of information yielded by such simple models is usually quite low. By taking into account respective characteristics and vulnerabilities, information regarding impacts should generally become more realistic. FUND is one of the few models that explicitly models impacts like extreme weather events. PAGE09 is an overall complex model with respect to the defined categories.

It endogenously includes all relevant GHGs of the Kyoto protocol, analyses four different sectors and explicitly models sea level rise as a lagged linear function of temperature (Hope 2011a). This is an additional difference to MERGE, which also has a complex module of atmospheric chemistry and socio-economy, but where climate is only driven by changes in temperature.

As Stanton et al. (2009) state, an ideal climate-economics model needs to be transparent, but still complex enough to map the most important features of the climate and economy.

Modelling a regional/local IAM differs in many ways compared to the IAMs presented above. Emissions on a local basis will most likely only have a minor impact on global climate change. Therefore, mitigation policies become less relevant and the focus is shifted to adaptation. Because of this, endogenous modelling of GHGs might not be very reasonable in a local IAM. Instead exogenous emission scenarios should be used, leading to a simple atmospheric chemistry module. Yet, climate change should be determined by more than just the temperature change to be able to model specific local impacts. In particular, precipitation and discontinuities could play a major role on a local basis. So, a complex climate module should be preferred. Moreover, to analyse the impacts of climate change on the regional economy, sector specific modelling would be necessary to give a more precise overview of the damages. Hence, a complex socio-economic module might be fundamental for assigning impacts.

As explained above IAMs are usually distinguished to either be a policy optimisation or a policy evaluation model. Policy optimisation models have an explicit objective function that is maximised. They consider costs and benefits of climate change policies and aim to find the optimal one. Corresponding consumption and investment paths are optimised as well and dynamic decision making is the common feature.

According to Kelly and Kolstad (1999) evaluation models enable on the one hand a much more precise analysis of complex climate change phenomena regarding social, economic and physical aspects compared to optimisation models, but their results on the other hand depend heavily on the user's ability to predict future decision making. Their greater accuracy originates from their ability to include historically observed data while optimisation models need to use values which are based on assumptions of equivalence theorems. It remains rather unclear though what the drivers and reasons of the observed outcomes in the evaluation models have been.

The results of all IAMs are highly sensitive to the parameter choices. DICE, FUND and MERGE are examples of this. Instead, policy evaluation models like PAGE assess an exogenously determined policy and its effects. They are recursive or general equilibrium models that model certain variables but do not optimise outcomes (Nordhaus and Sztorc 2013). An advantage of policy evaluation models like PAGE09 is the possibility to focus on achievable policies due to the exogenous specifications. However, the quality of the results is determined and constrained by the chosen policy paths and is not necessarily optimal. They are more vulnerable to the "black box-critique" due to their vagueness. On a local level both policy optimisation and evaluation models can be reasonable depending on the purpose of the model. The results of an evaluation model might be more applicable and thus more accepted by local politicians.

Another important and often very controversially discussed feature of IAMs is the damage function, above all its functional forms.

Several IAMs use a quite simple temperature-impact-relationship: damages are a power function of temperature. The DICE model, e.g., uses such a function with exponent two. This functional form and particularly the choice of the exponent are often criticised as highly random and often not plausible (Stanton et al. 2009). These choices are lacking theoretical or empirical foundation and in many cases none is existent. A further problem is that such functional relationships do not account for phenomena like tipping points or catastrophic outcomes, which might not be completely unlikely.

Another fundamental difference is that several IAMs use a general damage function, while others like FUND and PAGE09 use sector specific ones. Surely, it seems to be more reasonable that each sector is affected differently and relies on specific parameters. With regard to a local model this procedure might be particularly more beneficial and effective.

Models with a simple climate module like DICE and MERGE include only temperature changes to model climate damages. Others consider additional drivers like sea level rise and discontinuities. Unfortunately precipitation is not taken into account even though its impact might be immense. Due to the high heterogeneity of precipitation patterns the resulting impacts would be hard to estimate for large geopolitical regions. With regard to a local IAM the advantage of more homogeneity should be exploited to explicitly include precipitation.

Finally, it is highly controversial how damages affect the socio-economy. Stanton et al. (2009) criticise that they are often modelled as losses of income or consumption. In these cases they would only affect the economy once and not permanently. However, in the DICE and FUND model the capital stock is indirectly influenced by investment and consumption decisions, and thus by damages. According to Pindyck (2013) climate change impacts should influence the growth rate of GDP instead of its constant level in order to model permanent reductions of resources available for research and development (R&D) and capital investment. In the same vein, Stanton et al. (2009) point out that IAMs should model damages at least partly as losses of the capital stock and/or a decrease in productivity. Depending on the sector, damages might either affect capital stocks, e.g. with regard to sea level rise, or productivity, e.g. with regard to health effects. This distinction once again emphasises the reasonability of sectoral disaggregation.

The presented IAMs also vary with regard to the design of the abatement costs and the inclusion of a backstop technology. As in the case with climate change impacts, it is questionable whether productivity is affected or not. Abatement costs are often modelled as a loss of income that decreases welfare. Yet, Stanton et al. (2009) argue that wisely carried out abatement should be seen more as an addition to capital than a dead-weight loss to income since it might spur job creation or income. Clearly, this idea might be seen as controversial and potential effects depend on specific cases. In DICE abatement costs are subtracted from output while in FUND they lower investment and consumption like damages do. Hence, no potential additions to capital are taken into consideration. On the contrary, in FUND investment is actually reduced.

Finally, IAMs differ in their consideration of adaptation. In most cases, a complex representation of adaptation is missing. On a local level however adaptation is more important compared to mitigation. Explicit and sector specific modelled adaptation is therefore essential. The design of the adaptation cost function is thereby fundamental. The functional forms between the different drivers and the inputs of the equation have to be specified. Especially the relationship between the level of adaptation and costs is very crucial. Moreover, aspects like technological development and knowledge might also play a major role in determining the costs of adaptation.

4. Sectoral approaches

4.1. General

In recent years a large strand of literature has emerged which deals with the impacts of climate change on so-called sectors. The understanding of the term sector differs according to the background of those studies. Those publications rooted in the domain of climate change adaptation policy usually are the result of interdisciplinary work. This leads to a broad understanding of the term sector, ranging, for example, from coastal protection over urban planning or biodiversity to human health. While the discipline of economics can contribute its expertise to all of those fields, its own understanding of the term sector is narrower in the sense that an economic sector is defined as the aggregation of similar economic activities or institutions. This is commonly reflected in national account data. In our contribution we focus on the interpretation of the term sector as an economic sector although we are aware that the issue of climate change has much more far reaching consequences.

The reason to include sectoral approaches in this report is manifold. Firstly, there are huge differences with regard to the consequences of climate change between economic sectors. Some sectors might suffer, some might benefit and in some the effects are ambiguous. Secondly, the channels via which climate change actually affects economic sectors differ and also depend on the question whether gradual changes or more frequent and/or severe events are addressed. Identifying some of those channels gives a better comprehension of the necessities and flaws of actual and potential linkages between earth system models on the one hand and economic approaches on the other hand. Besides, economic sectors differ with respect to their regional relevance. This holds true from an international as well as from a national perspective. Thus, for national and regional policy makers alike a better understanding of the interplay between climate change and sectoral impacts and how to address this via different measures should be of great interest.

In the following sections some exemplary economic sectors are addressed with regard to recent modelling attempts of climate change impacts and the ensuing results. This is by no means meant as a thorough overview but rather as a collection of selected highlights which need more work and clarification in future research. The regional focus is on German regions due to own previous work. The selected sectors are tourism, energy, transport and health, where the order of representation has no implications about the importance of these sectors.

4.1.1. Tourism

Climate Change impacts on the tourism sector

Due to its weather and climate sensitivity, the tourism sector is one of the most affected economic sectors by climate change. Mild changes in climate conditions might fundamentally change people's travel behaviour in their respective nations and abroad and influence the national tourism sector and the associated branches positively as well as negatively.

Germany can be visited all year and offers a wide variety of possibilities for travellers. For the summer experts expect shifts in tourist flows from Southern Europe to the German coast, resulting from warmer summer days in Germany and a gradual increase in average surface temperature (daytime highs of about 40°C) in the South of Europe. Additionally, an increase in tourist demand in the off-season is expected. Estimates show for example that the bathing season at the North Sea Coast could be prolonged in the future by 60 days (Heinrich and Bartels 2011) and that the number of people visiting Germany could rise by roughly 25 to 40 per cent (Bundesregierung 2008; Hamilton and Tol 2009). This trend would probably influence the tourism sector and its associated branches positively. Simultaneously the German coast will also be exposed to risks: a predicted rise in sea level could lead to higher waves and intensify coastal erosion. As a consequence beaches could diminish or erode. Conflicts between necessary coastal protection and the economic interests of sea side tourist sites could occur (this is expected by no later than the end of the century). Mass tourism threatening the nativeness of the region could in turn reduce the attractiveness of the region (Heinrich and Bartels 2011).

Milder temperatures in Germany will lead to a considerable reduction in snow reliability in the German Alps and the Central German Uplands in the winter months and a higher temperature level in spring will lead to a shortening of the skiing season in comparison to today. Until 2030 winter sports will not be possible any longer in the Central German Uplands (Ehmer and Heymann 2008) and an increase of average surface temperature of about 1°C will reduce the alpine skiing areas where snow is assured by 60 per cent (OECD 2007). The German winter-sports regions will become less important. Artificial snowmaking is today an alternative to snowfall but in the future it will not be practicable any longer in lower lying areas because of the need for air temperatures to be lower than 4°C. Furthermore installation and maintenance of snow guns are quite costly and the operation requires large amounts of water and energy. Throughout the Alps 95 m³ water and 600 million kWh electricity are used each year for artificial snow-making (Ruckriegel 2008). Consequently a lower reliability of snow combined with a growing need for artificial snow-making would lead to higher prices for travelling to winter-sports regions. It is very likely that the effects described above lead to a movement of tourists to regions at higher altitudes, which can be found in other European Alpine countries (Bürki 2000). In the case of not promoting alternative travel programmes (e.g. hiking, recreational holidays) the tourism sector and its associated branches in the regions concerned will suffer from a considerable decrease in the number of tourists.

Extreme weather events are additional factors influencing travel behaviour – at least temporarily. Damages to infrastructure and lodging establishments resulting from disaster events like heavy rain or floods could lead to a decline in the number of overnight stays and burden the businesses concerned. Regions being hit frequently by extreme events could lose their tourist appeal. However, it is assumed that better conditions for the bathing season overcompensate for the risks related to extreme events (Ehmer and Heymann 2008).

The growing share of city trips and health-related travel will not be influenced by a gradual temperature increase, which will affect the future development of the whole tourism sector positively. However, extreme weather events pose a threat to city trips as tourists are often unaware of the possible risks and adaptation measures (UBA 2005).

Cause-and-effect chains

The tourism “sector” is not an autonomous sector as for example the construction or transport sector. It is rather an umbrella term for all branches directly or indirectly related to tourism. Therefore it is a cross-sectoral industry, showing a quite heterogeneous structure. Due to the specific character of the tourism sector a quantification of the tourism-related value added is quite challenging. For this reason a Tourism Satellite Account (TSA) for Germany was designed. According to the German TSA, table 5 gives an overview of the branches directly or indirectly related to tourism and the possible effects of a gradual temperature increase.

An increasing average temperature and a rising demand for Germany as a travel destination during the summer months will affect the lodging and catering industry positively in regions focusing on summer tourism (e.g. near to the North/Baltic Sea and inland lakes). Contrary to this the above mentioned industries will probably suffer from climate change in winter-sports regions due to a decline in the number of guests. Rail transport, local transport and other road transport will benefit, whereas the demand for air transport will probably decrease since travelling within Germany by train, bus and car is more common than by plane. Further effects are conceivable e.g. a decreasing demand for trips booked via travel agencies or the strengthening of retail trade in (summer) tourist areas. An increase in demand for accommodation and catering leads to a rising need for hotels, restaurants and so on, consequently the construction sector in summer holiday regions will benefit from climate change. The same is true for employment. More service staff will be needed in hotels, pensions and restaurants, as well as more workers in the construction sector, amongst others.

Table 5 Tourism and its related branches (own figure)

		Temperature increase	
		Summer tourism	Winter tourism
Branches directly related to tourism	Lodging industry	(+)	(-)
	Real estate	(+)	(-)
	Catering industry	(+)	(-)
	Rail transport (passenger services only)	(+)	(-)
	Local transport and other road transport (passenger services only)	(+)	(-)
	Shipping traffic (passenger services only)	(?)	(?)
	Air transport (passenger services only)	(-)	(=)
	Renting of automobiles to 3.5t	(+)	(?)
	Travel agencies and tour operators	(-)	(-)
	Automobile and retail trade	(+)	(=)
	Health service	(=)	(=)
	Cultural, sports and recreational services	(=)	(=)
Further tourism-related branches	Expositions and fairs	(=)	(=)
	Prevention and rehab clinics	(=)	(=)
	Foodstuff	(+)	(-)
	Camper and trailer	(+)	(=)
	Fuel	(+)	(-)
	Bicycles	(+)	(?)

The situation in winter sports regions will be the opposite. Even if nowadays only a relatively small share (3 per cent) of tourists in Germany spends the holidays in winter-sports regions, tourism has a significant economic impact for the local population. Years with little snow at the end of the 1980s already showed how serious the situation could become for Alpine regions in the context of a progressing climate change. Several Alpine communities were confronted with severe socio-economic consequences, like massive reductions in income (UBA 2005).

Extreme weather events might hit summer and winter tourism equally. For the regions hit by the flood 2013 for example, financial damages amounted to 100 million euros, taking into consideration direct damages like destruction of hotels and restaurants as well as indirect effects like financial losses resulting from the absence of tourists. The ones to suffer are certainly first and foremost uninsured businesses, but likewise insured businesses due to a possible future rise in the insurance premium.

In section 3.3.1.2 the LSD-model and its use in a paper by Zimmermann et al. (2013) was introduced. With regard to the tourism sector, three scenarios were employed which have the function to integrate exogenous variables into the model and assess their impact on production, employment, and income over time, assuming certain patterns of development of these exogenous factors. In particular the aim was to quantify the impact of climate change related variables on regional production, which manifests itself in three distinct scenarios of future tourism demand.

The three scenarios are based on the past development of the number of overnight stays, and on a number of other influencing factors. These include the state of society (e.g. demographics and travel preferences), economy (e.g. growth of disposable income, economic growth in general, competitive strength of other tourist destinations), ecology (e.g. natural scenery, water quality, biodiversity), and political measures (e.g. overall impact of government policy).

The three scenarios are: (1) baseline, (2) strong growth, and (3) weak growth. Scenario (1) continues observed development in the number of overnight stays in Mecklenburg-Western Pomerania. It assumes a continuous interest by tourists to come to the region, accompanied by continued investment in tourism related infrastructure as well as stable natural environment quality. Scenario (2) exhibits a strong increase in visitors' interest to come to the region. This was derived from climate change mitigation policies increasing the costs of long distant travel as well as continued good environmental quality. Furthermore, it was assumed that tourism infrastructure investment is strongly promoted. However, scenario (3) draws a completely opposite outlook to scenario (2). Visitors' interest declines due to changing preferences, which do not match the region's profile. Additionally, natural environment quality deteriorates as a consequence of climate change and this further discourages tourists to spend their time in the region. Moreover, low government income in Mecklenburg-Western Pomerania does not allow for substantial improvements in tourism infrastructure.

The already important tourism for the state of Mecklenburg-Vorpommern (share of 9 per cent of gross value added in 2009) could continue to grow under the influence of climate change and other socio-economic factors to regional economic importance by 2030. Thus, the gross value added by tourism of 2.8 billion euros in 2009 could rise to up to 3.7 billion euros in the best case scenario by 2030. However, it is important that both the public authorities and companies use their adaptation possibilities to tap into this potential.

In order to improve the quality of the model's results, the aim of further work on the model is to largely endogenise the components of final demand and to introduce more flexible inputcoefficients. Thus, the model presented here would continue to converge with the full IOE models and would be more appropriate in the establishment of forecasts.

Conclusion

The impacts of climate change on the tourism sector in Germany are often estimated as being slightly positive due to the fact that a positive trend in summer tourism compensates for the decline in the appeal of German winter-sports regions. This is comprehensible as winter-sports regions, attracting only 3 per cent of tourists in Germany, will probably be the only ones to suffer from climate change, whereas the most popular regions, like the German coasts or cities, benefit from or are only slightly affected by climate change. First results of modelling the effects of climate change on the German tourism sector with the macroeconometric model PANTA RHEI by enabling the introduction of heating degree days in econometric estimations support this intuitive assertion. Albeit the entire tourism sector in Germany might benefit from climate change, this is not true for single regions in which tourism plays a crucial economic role and which are hit either by extreme weather events or a warming climate. For regions like the Alps, suffering from a gradual temperature increase or some parts of East Germany being threatened by more frequently occurring floods or extreme heat events, it is of major importance to get more detailed information about the possible change of the regional climate and the possible consequences for leading economic sectors. This provides reasoning for the need to analyse climate change impacts on a regional basis.

4.1.2. Energy

Impacts of Climate Change on the Electricity Sector

Within the scientific debate, the impact of climate change on the electricity sector has been paid increasing attention (e.g. Rubbelke and Vogele 2011; Schaeffer et al. 2012; Vine 2012; van Vliet et al. 2012). Climate change affects the electric power generation, its transmission and distribution almost independently from the resources used to generate electricity (see figure 8). However, the specific impact of climate and weather depends strongly on location, type of generation and design of infrastructure. Besides the infrastructure, electricity demand also reacts according to climatic conditions, in particular on the ambient temperature.

A frequently mentioned major risk of climate change is a possible increase of frequency and intensity of extreme weather events in Europe (Schönwiese and Trömel 2006; Schönwiese 2007). Thus, an intensification of heavy storms is seen as major problem of future climate with respect to the electricity grid (Cortekar and Groth 2013). This mainly is a problem for overhead transmission lines of the high voltage grid, as the medium and low voltage distribution grids mainly consist of underground cables. Storms also are a major hazard with respect to wind turbines, which are exposed to damage by strong wind gusts. Furthermore, wind turbines and the transmission grid are harmed by white frost. Photovoltaic systems are exposed to infrastructural damage by hail or storm.

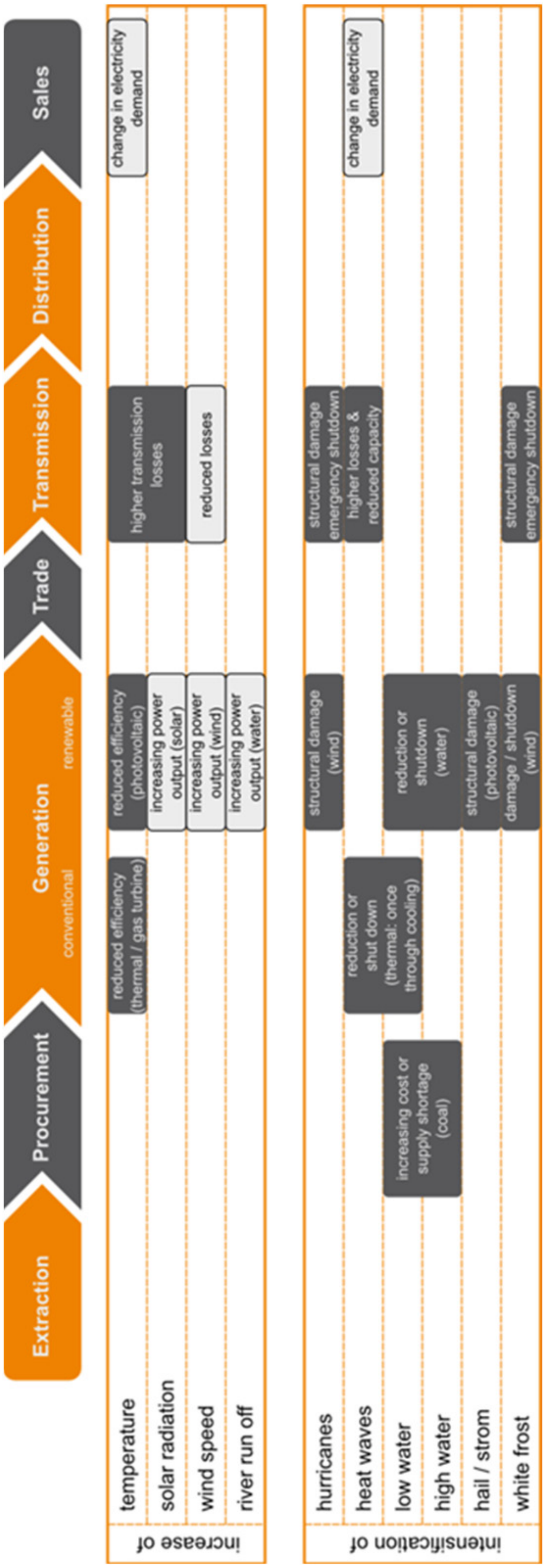

Figure 8 Impacts of climate and weather along the supply chain of the electricity sector (own figure)

Another highly relevant weather phenomenon is a combination of heat waves with low water levels. Steam power plants with a once-through cooling system are particularly vulnerable to an increase of temperature, because environmental protection laws restrict the withdrawal of water and the emissions of used (and therefore heated) cooling water into the river (Förster and Lilliestam 2009; Koch and Vögele 2009). A reduction or even a deactivation of energy production is the consequence. A current study from Weisz et al. (2013) estimates a yearly efficiency reduction up to 2-3 per cent in the especially dense industrialised regions in South-West Germany. This problem already was observed in Germany during the heat waves of 2003 and 2006. Also the efficiency of water power plants is reduced by low water and in the case of excess of water the plants are shut down. The PIK estimates a reduction in these phenomena of 12 per cent a year (Weisz et al. 2013). Even though water power plants generate only 5 per cent of Germany`s electricity production they gain importance by their ability to generate at peak load.

Increasing ambient temperature reduces the efficiency of conventional thermal power plants (Schaeffer et al. 2012; Daycock et al. 2004), photovoltaic systems (Fidje et al. 2006; CCSP 2008; Neumann and Price 2009; Scheele and Oberdörffer 2011) and the theoretical capacity of the transmission grid (Deb 2000; Hu et al. 2006). Furthermore, the transmission loss increases (Stephen et al. 2002; Rothstein and Halbig 2010). Moreover, temperature has a noticeable effect on electricity consumption, owing to heating and cooling demand (Hitchin and Pout 2001; Amato et al. 2005; Wilbanks 2008; Neumann and Price 2009). Moderate increasing wind speeds considerably increases power output of wind turbines (Rothstein and Halbig 2010) and slightly increases the theoretical capacity of the transmission grid by intensified convective cooling (Kießling et al. 2001). The PIK evaluated a 4.5 per cent higher yearly supply for Germany, especially in middle and northern Germany (Weisz et al. 2013; PIK 2013). Increasing river run off in principle increases power output of water power plants. However, if the intake capacity of the turbine is exceeded, further run off reduces power output, owing to the reduced drop height (Lehner et al. 2005; Rothstein and Halbig 2010; Grossmann and Koch 2011). Solar radiation and thereby clouding directly affect the energy supply of solar power plants and photovoltaic systems (Fidje et al. 2006). Studies fromdifferent regions in the USA conclude efficiency reductions between 6-20 per cent (Neumann and Price 2009; Scheele and Oberdörffer 2011). Furthermore, to a lesser extent overhead lines are heated by solar radiation, resulting in a slight increase of transmission loss (Weibel et al. 2006). In general, climate change is expected to have a slight to moderate negative impact on the energy sector.

However, these impacts not only cause revenue losses or damage for the utilities, but also have implications for the economy and the society as a whole. Primary impacts on generation, distribution and demand result in increasing transmission fees and generation cost. This would affect industry and private households by increasing prices, in particular industries with a high demand for electricity such as manufactures of metal and metal products (e.g. steel, aluminium or automobile plants), the chemical industry and paper manufactures (AG Energiebilanzen 2013). Furthermore, serious economic damage would be caused in the case of a power outage. An increasing risk of blackouts could harm the economy and private consumption strongly.

	Electric power generation with		
	fossil fuels - steam power plants with a once-through cooling system -	**renewable energy sources**	**Electricity transmission and distribution** underground distribution grid (medium and low voltage)
Potsdam Institute for Climate Impact Research (PIK) (calculation until 2055)	yearly efficiency reduction up to 2-3%; affected stretch of water: Rhine-Main; Upper Weser; Neckar	**hydroelectric power**: yearly efficiency reduction of 12% (approx. 2.5 TWh pa) **wind power**: increase of the yearly supply of 4.5%; benefited regions: Middle & Northern Germany	
Cologne Institute for Economic Research (IW) scale from -5 (great risk caused by climate change) to +5 (great potential caused by climate change)	Climate Risk: -2 among - oil: -2 - natural gas: -3 - hard coal: -2 - lignite: -1 - nuclear Energy: -2	Climate Risk: -0,8 among - wind power: -1 - water power: -2 - solar energy: -1	Climate Risk: -2
Ecologic Institute	permanent efficiency reduction of thermal power plants of 10%: 4 b. € costs per heat wave: 60 m €		340 m € per extreme storm force
Various studies		**solar energy**: fall in output of 6-20%, owing to stronger cloud formation other risks: infrastructural damage owing to hail and storm force	

Figure 9 Impacts of climate change to the energy sector (Weisz et. al. 2013; Bardt et.al. 2013; Bräuer et.al. 2009; Neumann and Price 2009; Scheele and Oberdörffer 2011)

An analysis of direct and indirect economic effects of the impact of climate change

To better understand the impact of heat waves on the German electricity trade, an economic optimisation model was used (Pechan and Eisenack 2014). It analyses the impact of power reduction on the spot price of electricity and which costs accrue for different actors. It was shown, that the 2006 heat wave resulted in a moderate increase of production costs.

However, the capacity reduction results in a noticeable increase of spot market prices and producers' surplus, in particular in times of peak load.

To analyse in more detail the local and regional impacts of climate change, the geographical data of grid and generation infrastructure was collected in a GIS-database. Using this data in an economic-technical load-flow model of the German energy system, including the transmission grid, allows the evaluation of the effects of local and regional impacts on market prices and the sharing of costs within different actors and regions.

Changing the electricity price in a macroeconomic IO-model, a localisation of direct and indirect economic effects of the impacts of climate change on production could furthermore be calculated (Lutz and Meyer 2007; Prognos et al. 2010). The analysis could also quantify indirect impacts of production changes according to the (missing) electricity inputs of different industries. Moreover, the macroeconomic model can be used to analyse the effects on employment of the affected industries and to develop different scenarios concerning the industries possibilities of adaption to climate change impacts.

Summary

So far climate change is not considered in future energy system planning. Also, a detailed analysis of the interaction between the diverse regional impacts on different elements of the energy system and an evaluation of distribution of cost across regions and actors is still pending. The previously discussed improvements aim at answering these research questions.

Moreover, the regional composition of the future energy system is highly unknown, owing to the ongoing conversion of the energy system in Germany, the “Energiewende“. The progress of the “Energiewende“, as well as sharing the burden of costs of future impacts of climate change, strongly depends on energy policy. Thus, for estimating the impacts of climate change on the energy sector, the economic analysis of instruments, e.g. the market design or the regulative scheme has to be integrated in the analytical framework. Therefore, with an improved formulation of the diverse impacts of climate change on the energy system, it is possible to integrate the exogenous data of different climate projections in the existing economic and energy models. Thereby, the impacts on generation, transmission and demand are central.

4.1.3. Transport

Transport Sector in Germany

The on-going change in climate has direct impacts on infrastructure and transport systems which in turn can have severe effects for an economy. In Germany, 5 per cent of the land is used for transport purposes, which includes road and rail networks, as well as train stations, harbours, and airports. The total road network in Germany amounts to 650,000 km of which 230,800 km are supra-local roads, while the rail network sums to around 37,700 km (Statistisches Bundesamt 2013). Altogether, the value-added by the German transport industry was 88 billion euros in 2010, which equalled 3.9 per cent of the gross value-added in Germany at that time (Statistisches Bundesamt 2013). The net worth of the German transport infrastructure in place in 2010 was 773 billion euros of which roads and bridges accounted for 62 per cent alone (Statistisches Bundesamt 2013, p.19).

A system of such size needs extensive development and maintenance, which required investments of approximately 20 billion euros in 2010 alone. Consequently, the well-being of the transport industry has direct implications for the German economy: it employed 2 million workers in around 87,500 companies that were active in this industry in 2010 (Statistisches Bundesamt 2013). Changes in investment and related factors within this industry will therefore have major impacts on employment and other economic indicators. This extends to industries that will indirectly suffer from resulting delays in goods deliveries, especially to those industries using the “just-in-time” production system. Frequent delays will eventually lead to a competitive disadvantage which can bring about the necessity to lay off workers or even cease production.

Climate Change Impacts on Infrastructure

The expected increase in summer temperatures is accompanied by an increase in the number of hot days resulting in several negative impacts for both the infrastructure and the transport sector. Possible impacts include accelerated erosion such as the increase of ruts and other heat-related damages in the pavement (Chinowsky et al. 2013). This increase in damages will require more frequent repair and maintenance activities that further raise the financial burdens for municipalities and federal states. As a consequence, roads may then have to be repaved with better, heat resistant materials (Umweltbundesamt 2012). Persistently high temperatures not only affect road networks but also the deformation of tracks for rail networks. The hot summer in the UK in 2003 caused deformations that led to repair payments of 1.3 million British Pound Stirling (Bräuer et al. 2009). Another issue arising with persistent heat is the functionality of air conditioning systems in trains. In 2010 and 2011, the Deutsche Bahn had to pay 2.7 million euros in compensation to the 23,000 passengers affected by deficient air conditioning systems and further had to invest in the preparation of its trains for higher temperatures (Doweideit and Jansen 2013). The increase in average temperatures also relates to a decrease of frost days in winter. This in turn has positive effects on the infrastructure as less winter maintenance is required and the risk of accidents decreases.

Negative impacts on the infrastructure are to be expected from the increase in precipitation during winter causing floods, overload of drainage systems, and wash-outs, which can all possibly cause damages in the infrastructure (Enei et al. 2011). Precipitation, in all forms, decreases the friction of the road surface as well as the visibility which leads to an increase in the likelihood of an accident for all modes of transport. Estimates concerning the magnitude of this impact vary widely, depending on the amount of precipitation, road pavement, velocity, and type of tyre in use (Enei et al. 2011). This can further cause economic damages through material damages and production delays.

Extreme events display the most imminent form of negative impact on both infrastructure and the transport industry. Floods are regarded as having one of the largest damage potentials as they damage roads, rails, and bridges through washouts or erosion of the road foundation. They can further cause severe damages within cities where tunnels and subways are flooded, resulting in harm to both people as well as materials (Bräuer et al. 2009). Heavy rains or storms directly damage infrastructure, which then requires large amounts of repair, related to, for example, falling trees, cleaning or other related damages. This can lead to blocked roads and accidents, which eventually decrease traffic flow and traffic speed. The impacts on the rail network are similar to the ones on the road. Fallen trees and other objects can block the tracks and heavy rains can further cause washouts and landslides as well as erosion of the track foundation.

Damages on contact wires will disturb or even paralyse parts of the entire system. A decrease in the reliability of trains further reduces the attractiveness of utilising the system, causing passengers to switch to other modes of transport (Bräuer et al. 2009; Zebisch et al. 2005).

Cause-and-Effect Chains

While several prior studies qualitatively analysed the impacts of climate change on the transport system, quantitative studies are rare. The broad range of potential impacts on the transport systems makes it particularly difficult when searching for optimal methods to quantify them. This section develops cause-and-effect chains with detailed analysis of underlying mechanisms, with the purpose of finding approaches to quantify them. Figure 5.3 below gives an overview of both the direct as well as indirect economic repercussions following the different potential changes in climate.

One of the most imminent impacts is the likelihood of accidents, which is predicted to increase both through the increase in temperature and the increase of days with heavy rain. A study from the Federal Road Research Institute found that an inside temperature of above 32°C increases the number of accidents by 13 per cent outside and 22 per cent as a mean percentage within a city. While weather conditions are only the main cause for 4.4 per cent of road accidents, human failure accounts for 85 per cent of accidents (Arminger and Bonne 1999). In Germany, 6,033 of the 40,068 accidents in 2008 were primarily caused by slippery streets from snow and ice and 8,672 due to rain. In comparison, technical defects in vehicles accounted for 4,158 accidents (Leviäkangas et al. 2011).

The increase in accidents will lead to more congestions and delays through blocked roads. This effect is amplified by an increase in maintenance and reconstruction of roads necessary due to the accelerated erosion and damages. Studies from the USA and Germany suggest that 40 per cent of congestion on highways is caused by high traffic density, 25 per cent are caused by accidents and 10 per cent by construction works (Doll et al. 2014). Research in Europe found traffic speeds in the Netherlands reduced by 7 per cent while capacity on German motorways reduced by 10-60 per cent during snowfall (Enei et al. 2011). Models that simulate traffic flows can be used in order to estimate the magnitude of delays to be expected. For this purpose, these models may be fed with data on the increase of reconstruction for the re-pavement of roads from previous studies (Chinowsky et al. 2013). In contrast, the increase in temperature has positive effects for the traffic in winter, as the amount of accidents is likely to decrease. Enei et al. (2011) further found that the fixed annual costs on motorways amount to 4,251 euros per km and variable costs per snow day of 99 euros; expenditures that would significantly decrease with warmer winters.

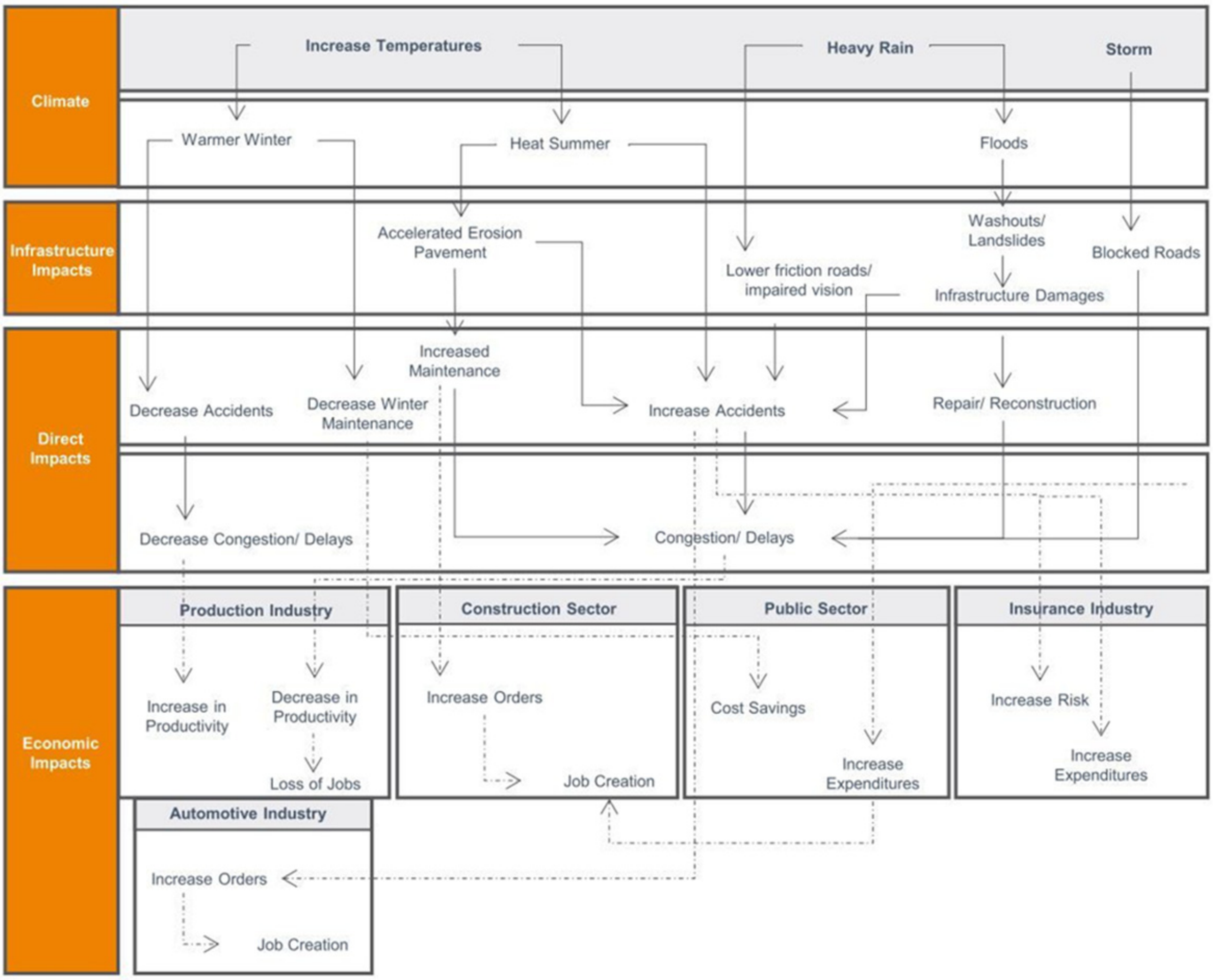

Figure 10 Cause-and-effect chains (own figure)

As a final step, these direct impacts on the infrastructure are linked to implications for the economy as a whole. Due to the complexity of these interactions, the effects on sectors can be very different and even offset each other. Congestions and subsequent delays strongly affect all industries that are dependent on timely deliveries of their goods. Research on the number of companies which are dependent on timely deliveries could provide an idea of the scope of possible repercussions. Furthermore, the insurance sector will face an increase in claims and potential losses with the increase in accidents as well as company failures, raising costs in the long-term. In contrast, the construction sector will profit from the increasing need for reconstruction and re-pavement of roads, which will create more jobs in that sector. As most roads are under the jurisdiction of municipalities or federal states, this will be financed by public expenditure. Increases in public expenditure on infrastructure usually have to be financed by cuts in other sectors with potentially severe negative repercussions for the economy.

Summary

The complex task of assessing the impacts of climate change on the transport sector requires a careful step-by-step analysis of the dynamic interactions of the diverse factors involved. Different approaches for a quantitative evaluation can be found, however, they have to be considered with caution as they incorporate significant uncertainties.

Clearly, none of the factors can be seen as separate occurrences. Similarly, the different consequences can have the same indirect impacts which potentially (more than) reinforce their single effects for the economy. Due to the differences in climate conditions between regions, the use of regional climate models is important. The same applies to the question of whether it is possible to use studies from other countries. Different climates as well as different traffic systems can render predictions from imprecise to insignificant. Furthermore, it is difficult to predict the development and changes in passenger behaviours. Significant increases in traffic density on roads could worsen the effects of climate change. New technologies that help to increase transport safety in turn could reduce them. Therefore, it is important to develop methods that can deal with uncertainties as well as correlations between different factors.

4.1.4. Health

The consequences of climate change are increasingly addressed in scientific publications (IPCC 2014) including the focus on human health effects. While the (mainly negative) impacts of climate change on health is well documented and can be quite accurately identified by now, the economic or monetary effects are still vague. One of the main problems is that "[o]nly some of the many potential effects were fully quantifiable" (WHO 2009, p.24).

The relation between climate change and health

The impact of climate change on human health can be identified by four main channels pictured in figure 5.4: (1) extreme weather events, (2) infections through water and food, (3) respiratory diseases and (4) the spread of diseases (Eis et al. 2010; Helmholtz 2009; Haines et al. 2006).

- Extreme weather events such as extreme heat, natural disasters, variable rainfall patterns and floods lead to a variety of health effects. Extreme heat causes a rising number of deaths especially in the high risk group due to cardiac infarction, cardiovascular and respiratory diseases as well as disorders of metabolism. The high risk group consists of (very) old people, infants, chronically sick persons, socially or physically isolated persons or persons with low socioeconomic status (Helmholtz 2009; Eis et al. 2010). An adaptation process to the higher temperatures that attenuate the negative effect is possible. Natural disasters can have immediate effects on physical injuries and mortality and long-run effects on mental health. The extent of the effects depends on the vehemence of the natural disaster, the degree of exposure (e.g. damage on infrastructure) and adaptation/reaction possibilities (e.g. early warning system, contingency plan) (Eis et al. 2010).

- Longer periods of warm weather facilitate the spread of germs in drinking water and food resulting in a higher risk of infections in the form of diarrhoea, anacatharsis or fever. The climate warming lengthens the transmission seasons increasing the probability of infections.

- New types/more aggressive pollen, prolonged pollen flights and a higher amount of pollen release raise the number of allergic persons. The allergic reactions can be more intense. In combination with air pollution the number of respiratory diseases could grow.

- The geographic range of vector-borne diseases can widen increasing the spread of diseases. Existing (endemic) infectious agents can be complemented by new infectious agents (Stark 2009) and aggravate disease patterns.

However, climate change need not necessarily result in negative effects. Human health can profit from more days of sun, outdoor activities, a higher vitamin D production, lower winter mortality, less injuries related to ice and snow etc. (Eis et al. 2010).

Moreover, human health is not only subject to climate change: “in reality climate change will be experienced against a background of other global changes—e.g. population growth, urbanisation, land use changes, and depletion of fresh water resources—that themselves have implications for health and that could, in some instances, interact with climate change to magnify the impacts” (Haines et al. 2006).

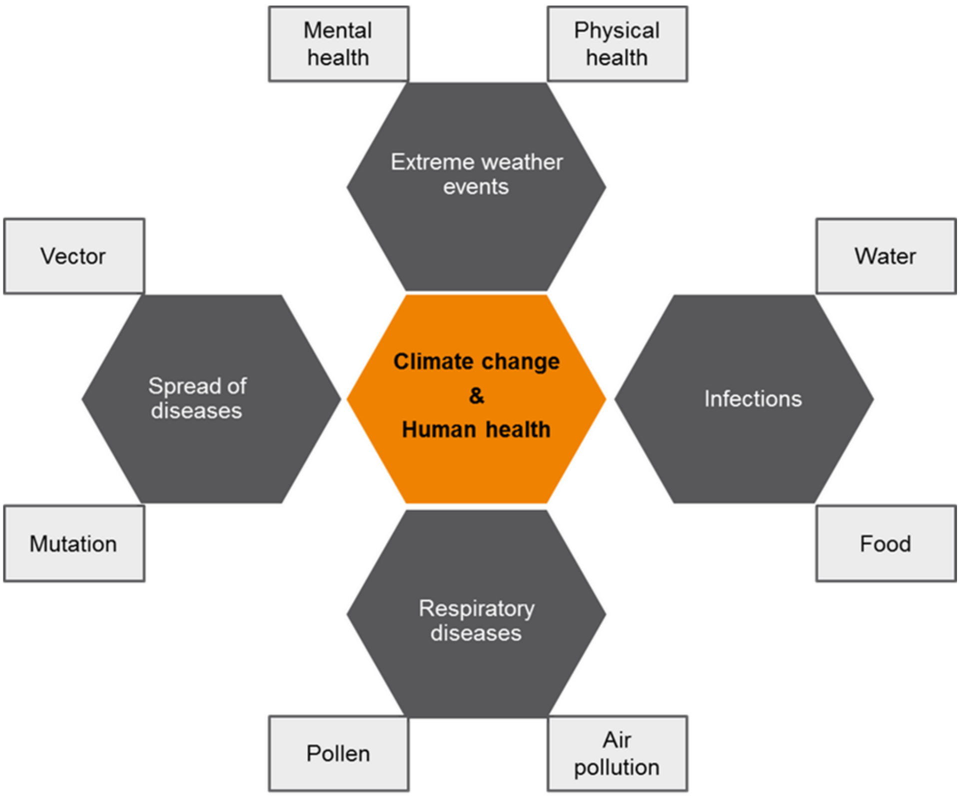

Figure 11 Transmission of climate change on human health (Helmholtz Zentrum München 2009 – own figure)

The health sector system does not follow the official classification system of the national accounts in that it is one economic activity. Rather it is part of different economic activities within manufacturing, retail trade, public administration and defence, compulsory social security as well as human health activities and social work activities. Using a sectoral account the value added of the health sector can be quantified. In 2012 it amounted to almost 260 billion Euros (BMWi 2013).

As main contributors of the health sector the following economic activities can be identified within the classification of the German Statistical Office:

- 21 Manufacture of basic pharmaceutical products and pharmaceutical preparations
- 26.6 Manufacture of irradiation, electro-medical and electrotherapeutic equipment
- 32.5 Manufacture of medical and dental instruments and supplies
- 47.74 Retail sale of medical and orthopaedic goods in specialised stores
- 86 Human health activities
- 87 Residential care activities.

The health sector is interconnected with other economic activities by intermediate demand and supply. Thus, the impact of climate change on health will not only show up directly in the economic performance of the health related sectors but also in indirect effects through the inter-sectoral relations.

Interaction between health sector and climate change

From the point of view of the society, illness and death are solely negative events. The welfare and happiness should decline with an increasing number of sick people. Thus, the impact of climate change via human health is negative for social economic aspects. On the economic level, positive consequences can be found that can compensate for some of the negative effects.

Qualitative analysis

Combining the functional chains with the transmission channels, the economic impact of climate change on the health sector can be described. A brief overview of the different transmission processes is given below. Generally, climate change via human health induces shifts in production and consumption patterns (substitution) and may also increase or reduce income (income effect).

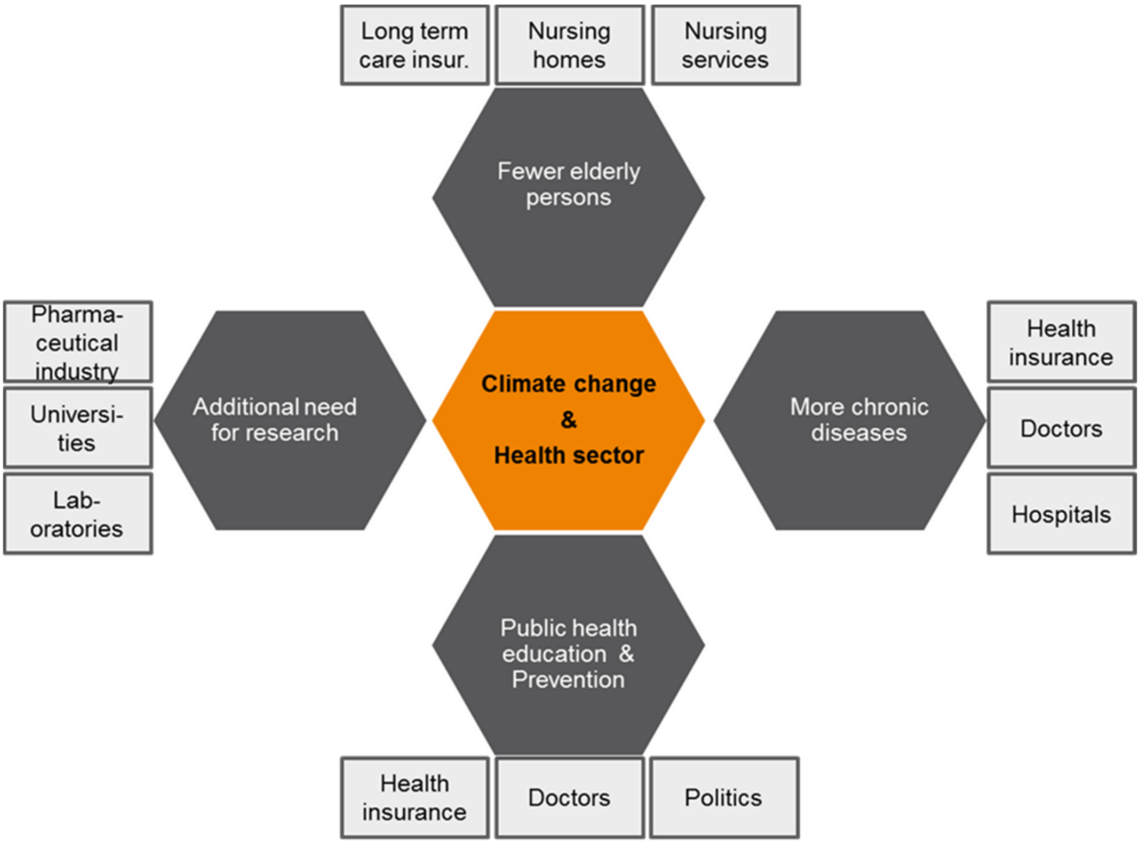

Figure 12 Functional chains between climate change, human health and the health sector (own figure)

Heat-waves (extreme weather events) lead to a higher number of deaths in the high risk groups, including people of age 80+. This age group show a high needs for care activities. If the number of people in the need of care decreases, the economic activity "87 Residential care activities" is directly confronted with less demand and hence negatively affected. Less nursing homes might be needed having a negative impact on investment in construction and the production of medical and care supplies. At the same time the long-term care insurance would be relieved offering the possibility of lower social security contributions or taxes. The disposable income of private households would be directly (no co-payment for long-term care) and indirectly (less tax/social security contributions to long-term care insurance) higher. Demand patterns will shift towards consumption purposes such as retail trade, hotels and restaurants, household related services, etc.

More diseases and allergies imply a higher number of patients and in the end more consultations. Physicians and hospitals would benefit. On the other hand, the expense situation of the statutory and private health insurances gets worse leading to increasing contributions for private households. The disposable income is lower and most probably consumption expenses would be as well. On the production side the increasing number of cases of employees becoming ill could result in a loss of production.

New pathogenic germs involve new disease patterns that require alterations in the medicaments and/or additional research. Laboratories, universities and other research institutions would be positively affected. The pharmaceutical industry could generate extra sales.

The higher number of patients and the rising health costs could evoke public health programmes aiming at awareness raising, protection or education. While in the short run the cost for the public health system would be higher, in the long run the health costs could be lower. At the same time different kinds of economic activities (advertising industry, services for health courses, and pharmaceuticals for immunisations) would benefit.

A First Approach to Quantify the Impact on the Health Sector

One challenge is to identify the functional relations between different impacts of climate change (see above) and the health sector. Once determined the consequences for health can be included in more complex models. Hence, model results depend on the quality of identified relations and assumptions of how to be implemented in the models.

Simply assuming an increase in health costs by 10 per cent each year from 2013 onwards through climate change in the PANTA RHEI model (see Figure 2), would imply positive effects on government consumption (+5.2 per cent in 2050) and negative effects on private consumption (-1.6 per cent), investment (-0.1 per cent) and exports (-0.3 per cent). Overall, GDP would be 0.2 per cent lower. The production output will be slightly lower than before due to adverse effects on economic activities. The consequences for the health sector are ambiguous as well.

Conclusions

While the consequences of climate change on health are increasingly addressed and different transmission channels identified, little focus had been put on economic consequences. First reflections on potential economic impacts show that magnitude and direction of macroeconomic impacts are far from clear.

Nevertheless, the underlying structural changes could be immense and have considerable effects on single economic activities. A detailed scenario analysis of different transmission channels could provide the possibility to reveal adverse effects and show impacts of climate change on the health sector. Clearly, these simulations will build on crucial assumptions, which have to be substantiated with further research.

One must bear in mind that the economic results would depend on the underlying assumptions. Some initial effects cannot directly be quantified but have to be given by proxy, or remain as only rough estimates.

5. Feedback effects on the regional climate and outlook

In previous sections some examples to assess socio-economic effects of regional climate change and adaptation policies were provided. The whole local system is examined when applying spatial CGE approaches and suggestions are also made for approaches to analyse regional impacts of climate change on different sectors like tourism, energy, transport and health. These impact analyses follow a clear direction of causality – from climate change to the respective socio-economic system. An improvement in regional climate projections will raise the accuracy of these impact studies. However, regional climate also depends on local determinants, such as land use, that are subject to decisions of households, firms and politicians. Therefore, causality is less clear and may run in both directions. In the following, these interdependencies are central and some approaches to model these are proposed.

It is not the purpose to look at effects of regional economies on global climate change in this section. There are already many studies projecting greenhouse gas emissions arising from local activities and evaluating mitigation policies (e.g. Tscharaktschiew and Hirte 2010). If similar behaviour and policies can be found in many cities or regions this might explain changes in worldwide greenhouse gas emissions. The integrated assessment models discussed above provide a good enough aggregation of these socio-economic decisions. Feedback effects from the latter system to the global climate can be modelled in the IAMs with interdependent causality between socio-economic systems and global climate change.

Regional climate change projections usually use the output of world climate simulations as input and break it down to the region considering local variables such as land use patterns. Two examples are the COSMO-CLM and the STAR simulation model which are driven by the global climate model ECHAM5/MPI-OM under several global scenarios. These models provide projections of temperature, precipitation, relative humidity, air pressure, solar radiation, wind speed, water vapour, sunshine duration, cloud coverage and cloud liquid water (Keup-Thiel et al. 2012).

In particular, the focus is on the feedback effects of local decisions on local determinants of the regional climate. This has not been consistently assessed in a framework that considers socio-economic choices and policies yet. There are several modelling strategies suggested in the following. First, any change in the input variables may affect the projections of regional climate models. In this case an integrated regional climate and economic model might be required (regional IAM). Second, because the main input into the regional climate model is the global climate, it might be sufficient to build a model that uses regional climate projections as input and corrects them according to the expected changes in the input variables. This additional model could be an economic model with some climate features. Third, the impact of climate change on the regional socio-economic system depends on the "absorption" of the regional climate through idiosyncratic changes imposed by socio-economic decisions that affect local temperature or precipitation. Hence, considering the feedback effects is important to improve knowledge on the effects of climate change. For instance, if an increase in the temperature is expected, policy measures such as increasing the albedo or reducing aerosols may dampen the surface temperature below the projected level.

These are the reasons why the feedback effects of local activities on the regional climate are considered in the following. In particular, land use and pollution are discussed as channels through which local activities may affect local climate, in particular local temperature and precipitation. The literature distinguishes heat island effects arising from land use in cities and other anthropogenic heat fluxes, air pollution, and indirect effects. Figure 13 illustrates these interdependencies.

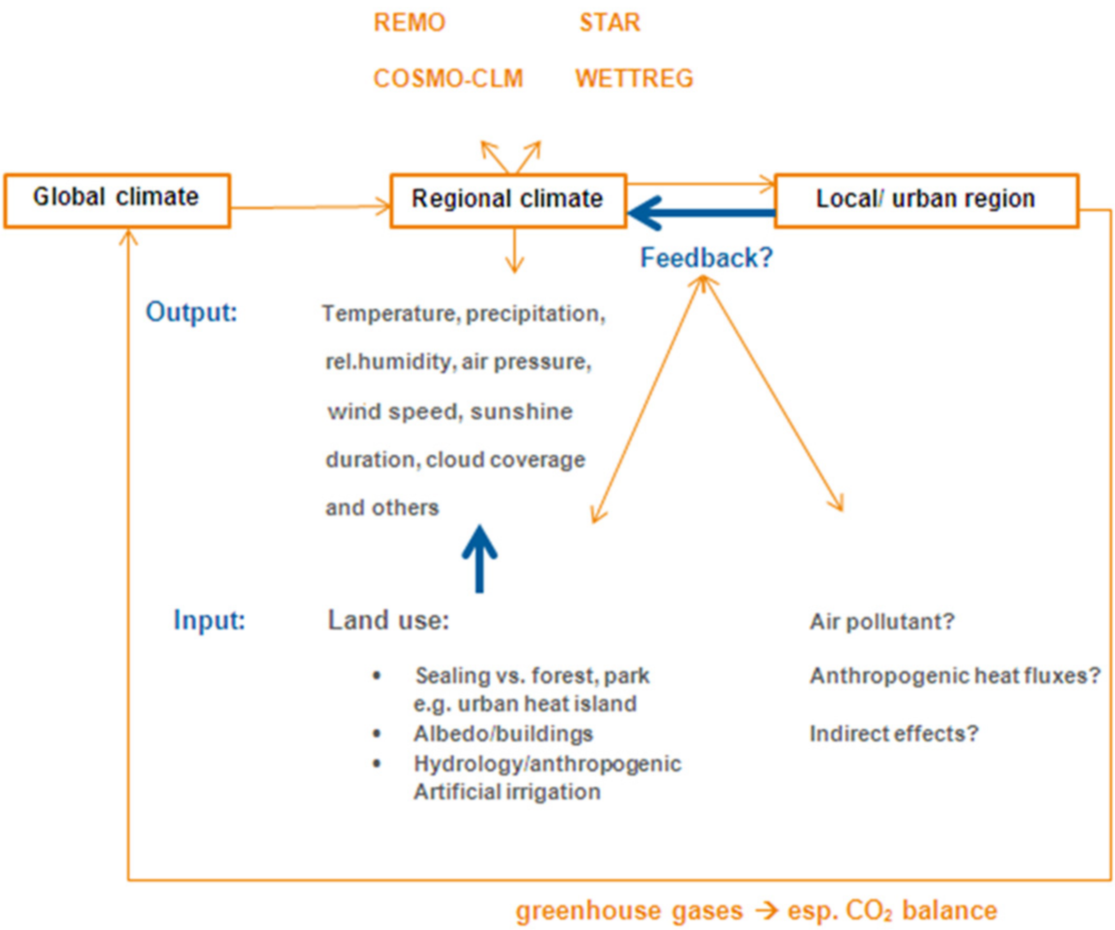

Figure 13 Interdependences among climate and the socio-economic system (own figure)

There are some important feedback to take into account, like urban land use which among others, depend on economics factors, such as relative land, housing and office prices, and preferences for housing and office quality, as well as on factors such as land use planning, infrastructure planning, building regulations and taxes such as property taxes. Whether and how land use does affect the regional climate is, thus, an important issue to decide on for a modelling strategy.

Additionally, in the literature land use is often discussed in connection to the urban heat island (UHI) effect. The UHI effect is defined as the significantly higher air temperature within urban areas than that in the surrounding rural areas. It is caused by hot surfaces and anthropogenic heat released from industry and human activities. Typically urban heat islands occur in areas where soil sealing through non-porous surfaces or pavements is present on substantial scales such as in cities. It is also related to an anthropogenic heat fluxes (Ca Vu et al. 1998), high population size, and density of a city (Chang et al. 2007) and the structure of buildings (Perini and Magliocco 2014).

Another important determinant of the effect of buildings and land on the local temperature is their albedo. Albedo is the reflection coefficient or reflecting power of a surface. Buildings have different albedo depending on their surface. High albedo reduces the surface temperature due to the reduction of long-wave radiation. Therefore the local ambient air temperatures in surroundings with high albedo are smaller due to smaller heat fluxes (Taha 1997). In general, the higher the albedo (especially high for white surface), the lower the temperature. For instance, parks tend to have a relatively lower albedo in the natural canopies as compared with urban fabric (Jauregui 1990).

Other effects, like soil sealing and green areas can be taken into account because they generate higher average air temperatures even though relative temperatures can vary greatly depending on the nature of vegetation, the density of plants related to shading and the moisture content of soil (Anthes 1984). If a vegetated area is big enough precipitation may increase. Nonetheless, results found in the literature are ambiguous (Anthes 1984). There are a lot of studies examining the ability of parks and green roofs to lower the UHI effect. They examine differences in the temperature in parks and non-green city sites and ask whether there is a local spill over of the cooling effect of parks.

Regarding soil sealing, buildings may affect regional climate determinants through a reduction of the wind speed and air circulation. The density and height of buildings in a city area influence potential temperatures and mean radiant temperatures. High density of buildings and urban structures absorb more solar radiation. Also the materials used for buildings can be a crucial factor for solar radiation and thus, the ambient air and rooftop temperature (Perini and Magliocco 2014). Materials with high albedo and emittance attain lower temperatures when reducing the transference of heat to environmental air. Such feedbacks representation in models can be very interesting and of high relevance for local climate changes. This has been studied by, for instance, Perini and Magliocco (2014). They find that higher density causes higher potential temperatures in Italian cities. They measured a difference of 3.68°C on the street level at noon. Another example is Taha (1997) who finds for a couple of US cities that a white surface with an albedo of 0.61 was only 5°C warmer than ambient air whereas conventional gravel with an albedo of 0.09 was 30°C warmer than the air. Furthermore, afternoon air temperatures on summer days can be lowered by as much as 4°C by changing the surface albedo from 0.25 to 0.40 in a typical mid-latitude warm climate.

The literature provides strong evidence that land use, the structure of buildings, the material and colour used for buildings, the anthropogenic flux from heating, energy use, transportation, as well as the vegetation are important determinants of the local temperature. Therefore, Chang et al. (2007) suggest the following strategies to mitigate the UHI effects: (1) modification of urban geometry, (2) use of light-coloured surfaces, (3) policies and measures to increase energy efficiency, (4) management of traffic and better transportation system design, (5) use of permeable surfaces, and (6) use of vegetated surfaces.

Climate change and human activities are also the leading factors affecting the change of catchment hydrology. Alterations in regional hydrological cycles are associated. Human activities could be river regulation, irrigation, deforestation, agriculture intensification and infrastructure construction. These activities change, for example, the flow regime and especially affect large scale changes of land cover. It impacts the runoff and reduces the stream flow due to conservation practices and increased water utilisation. Land use and land cover changes (LULC) are linked to heat fluxes, evapotranspiration and the exchange of greenhouse gases from plants and soil. Of course, non-anthropogenic impacts can also alter weather patterns, such as the Indian monsoon, which dramatically affect water resources (Kharol et al. 2013).

Alterations in hydrology and anthropogenic irrigation may affect regional climate determinants since they cause negative trends in humidity, vapour pressure, wind speed, sunshine duration, and decreasing potential for evapotranspiration (Ye et al. 2013). It could further increase soil moisture and latent heat flux due to larger availability of water vapour in the atmosphere. It remains uncertain if the land cover change affects precipitation and the hydrological cycle through the partitioning of the incoming solar radiation into turbulent heat fluxes (Kharol et al. 2013).

However, it is not yet clear whether these effects can be influenced in cities or small regions. Most examples studied in the literature concern large projects that are not typical for most regions in the developed world.

For instance, Ye et al. (2013) mention that a large amount of water demand decreases the catchment discharges to Poyang Lake and amplifies droughts as well as water scarcity in the lake area. As a consequence, temperature and precipitation (+200mm) significantly increased and evapotranspiration decreased (-100mm) from 1960-2007. Another example is Kharol et al. (2013) who investigate the influence of LULC changes in the Indian region of Rajasthan caused by the construction of the Indira Gandhi canal project. The sensible heat showed a decreasing trend (-27 per cent) associated with a decrease in soil temperature due to an increase in vegetation areas. Specific humidity increased by 15 per cent from 1979-2007.

The rapid growth of industrialisation and urbanisation has led to a significant increase in fossil fuel usage and, thus, to significant higher emission of aerosol particles. Aerosol particles are mainly comprised of sulphate, black carbon (soot), mineral dust and organic carbon. Anthropogenic aerosols alter the Earth’s energy budget by scattering and absorbing the solar radiation that energises the formation of clouds, in addition the reflectivity of clouds is modified. The effects of aerosols on the atmospheric radiation budget are uncertain. In contrast radiative and microphysical impacts of aerosols are related to cloud composition, precipitation, the hydrological cycle and atmospheric circulation systems.

Effects of air pollutants on regional climate determinants can be described as follows. Aerosol loading can suppress convective precipitation and light rain but enhance heavy rain (Yang et al. 2013). Anthropogenic aerosol particles and their precursor gases (AAPPG) increase the aerosol optical depth, cloud optical depth and decrease near-surface air temperatures.

AAPPG also reduce precipitation by lowering wind speeds, which in turn reduces near-surface water vapour. This reduces the turbulent kinetic energy and the vertical transport of horizontal properties (Jacobson and Kaufman 2006), but air pollution incites storms in areas with large vertical instability (Bell et al. 2008). In addition, the aerosol's negative radiative forcing stabilises the lowest troposphere which leads to less vertical exchange of air. This causes a reduction in lowland surface winds and an increase in highland wind speeds (Yang et al. 2013). The large reduction of precipitation is correlated to high concentrations of aerosols (Zhao et al. 2006). Aerosols absorb and reflect solar radiation and decrease daily maximum temperatures. Surface heating in contrast decreases, due to aerosols radiative cooling (Yang et al. 2013). AAPPG decreases the amount of solar radiation that reaches the land surface, and therefore causes less heat to be available for evaporating water and convective rain clouds (Rosenfeld et al. 2008). Soot emissions enhance solar heating, increase atmospheric temperatures, and lower relative humidity (Ackerman et al. 2000).

There are also indirect effects that result from the interaction of regional climate with urban land use. They are indirect effects because the connection to changes in regional climates is not obvious. For example, the adaptation to higher temperatures from an urban heat island effect could increase the energy demand for air conditioning in buildings and photochemistry effects and therefore increase atmospheric pollution (Perini and Magliocco 2014). Besides technical innovations, the adaption of infrastructure towards a higher albedo is a potential effect, too. For instance, a drop in temperature due to a higher albedo of the above mentioned magnitude reduces the electricity load from air conditioning by 10 per cent and from smog by up to 20 per cent during a summer day (Taha 1997).

Another example is provided by Doron (2005) presenting evidence that a one dollar investment in a food-growing project in the urban area yields six dollars of production value. It saves shipping to the city and reduces the use of pesticides and fertilizers. Hence, it prevents the emission of CO_2 and air pollutants and, thus, reduces negative health effects.

Wong (2002) finds that a decline of the temperature in Tokyo by 0.8°C implies electric bill savings, equivalent to approximately 1.6 million dollars per day. This is an energy consumption reduction of one percentage, with a 0.5 per cent reduction from heating and 6 per cent reduction from cooling. Further, environmental impacts can be reduced by 1-5.3 per cent, and energy savings for cooling can reach up to 25 per cent (Saiz et al. 2006). Ca Vu et al. (1998) find that a 1-2°C reduction in air temperature leads to a decrease of up to 10 per cent in peak energy demand. This in turn corresponds to a net saving in the order of 10-35 dollars per 100 m2 of roof area. Figure 14 shows possible indirect effects and their interaction.

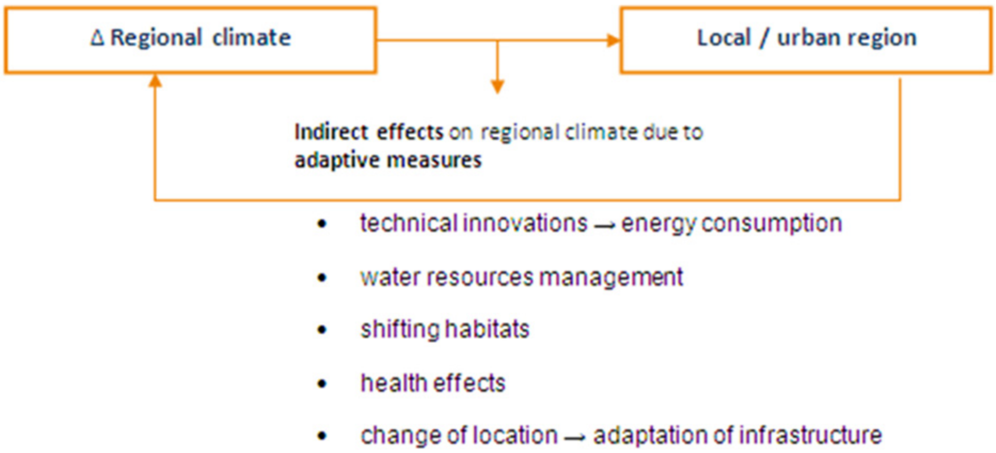

Figure 14 Indirect effect of the socio-economic system on the regional climate (own figure)

5.1. Desirable features of a coupled regional and climate model

As shown above, local temperatures and even precipitation or local winds can be affected by socio-economic decisions on land-use, travelling, heating, etc. In particular, effects on heat and humidity are very strong. Further, it has been shown that planning and policy decisions and regulations are important determinants of that link between individual decisions and the "immission" of the regional climate on the local level. For this reason, modelling these interdependencies is an important issue not yet done. One of the following modelling strategies is suggested:

a. Build a weakly integrated regional climate and economic model (regional IAM) where regional climate projections are used as inputs into the regional economy model that evaluates the socio-economic impact of regional climate changes as well as effects of economic decisions on soil sealing, albedo and aerosol emissions. These are used to correct the inputs into the regional climate model. There are several ways to consider these interdependencies in a single approach. Differences in the spatial and temporal resolution of the different model components are a major challenge. This might imply that both model parts are solved independently, exchange information and are solved again until a stable solution is achieved.

b. Build an additional tool for the regional climate model that translates regional climate projections to a model of climate "immission" meaning that there are local factors requiring the adjustment of regional projections due to local idiosyncratic conditions that are changed through decisions of individuals, firms or politicians. This additional tool should be weakly integrated with an economic model as described in what we call a) a "regional climate immission and economic impact model".

c. Build a climate adjusted regional economic model, where the "immission" of the regional climate projections on the specific regional economy is integrated in the economic model. For instance, the share of green land or parks is used to downgrade the projected temperature in that zone of the model by a factor used from the literature. Then the economic model is solved including adjustment to the size of green land or the structure of buildings. This enables us to evaluate policies aiming at, for instance, reducing the urban heat island effect either by increasing the size of parks, regulating use of green roofs, providing incentives to lower emission of aerosols, etc.

None of the three approaches has been followed yet, though they are able to improve the knowledge on the effects of adaptation measures to climate change and may enable the analysis and comparison of a much larger set of policies than considered in other adaptation studies before. However, considering the discussion on the IAMs in chapter 4, modelling strategy a) will also be subject to many restrictions. Therefore strategies b) and c) should be preferred.

5.2. Summarising and looking at knowledge and gaps

From the previous chapters, two main research lines in the context of regional climate economic modelling can be identified. First, it is still necessary to identify the economically important impact channels of climate change on a regional scale and to develop more accurate estimates of their magnitude. Second, once the first question has been answered, it is desirable to include the feedback effects discussed in chapter 6 into the modelling framework.

Regarding the potential structure of the economic model, the two most relevant types, IO/IOE and CGE models, have been discussed in chapter 3. Additionally System Dynamics is starting to play an important role in providing the basis for connecting regional economic models with climate and other bio-physical models.

The present capabilities of IO/IOE-type models to represent climate change are given through the inclusion of climate parameters into econometric equations determining the demand for the goods/services of certain economic sectors. For example, current applications of the (national) IOE-type model PANTA RHEI include heating degree days as such a variable. The regionalised version, PANTA RHEI REGIO provides an opportunity to consider corresponding effects on the regional scale.

In general, necessary climate inputs to this model class would have to be regional climate variables which are closely related to the demand for certain goods or services of certain sectors. Relevant climate-sensitive sectors have been discussed in chapter 5.

The effects of climate on the health sector seem to be ambiguous. On the one hand, an expected increase in the number of extreme weather situations causes health stress which affects the society negatively. On the other hand, if the health sector is interpreted as part of the value chain, the related increase in demand for goods and services from the health sector might increase economic output. Regarding the impact of climate change on the regional demand for tourism, an attempt to quantify these impacts is presented in Zimmermann et al. (2013). Unsurprisingly, there is a rather strong dependence between the results and the scenarios considered. For the transport sector, destruction of infrastructure through extreme weather events is identified as a main impact of climate (change).

Corresponding short and medium term effects can be studied within the IO or IOE framework, e.g. with the ARIO model (Hallegatte 2008). The effect of climate on the regional demand for energy has been studied with the PANTHA RHEI model and heating degree days and corresponding cooling degree days seem to be a suitable indicator that links climate to energy demand.

At this point, it makes sense to include CGE type models into the discussion. As mentioned in chapter 5, a major impact of climate change on the energy system could be a temporal lack of critical inputs like cooling water and a resulting lack of electricity for the economy. This issue has been studied in e.g., Rose and Liao (2005).

From chapter 3 it has become clear that – both in the IO/IOE and CGE model class - one approach to study regional climate change is to extend disaster impact models. However, the required regional projections of number and intensity of extreme weather events are subject to very large uncertainties.

In the CGE model class, in a recent study (Jahn 2014) a modelling approach is presented to include the effect of climate change induced flood events on a regional or local economy through (changing) probabilities of occurrence, thereby overcoming the problems of projecting single events. In another recent CGE study regularly occurring or regularly expected flood events are modelled as permanent or expected changes in quality of land (Hirte et al. 2014), where missing knowledge on probability of events, expected damages and technologies of adaptation has been dealt with by imposing a variety of different assumptions.

In chapter 6, feedback effects of the regional economy on the regional climate have been discussed. This adds another link between regional climate projections and the regional economic models. In addition to improved modelling of climate impacts on the regional economy with "conventional" models as described in the beginning of this chapter, it might be desirable to build climate adjusted regional economic models. This means to integrate the specific effect of the regional climate ("immission") - which may depend on characteristics of the regional economy - into the economic model. This allows evaluating adaptation policies including their effect on this "immission". For instance, building parks reduces the "immission" of the regional climate change because it lowers the urban heat island effect.

A recurring problem in the coupling of climate and economic models is the different temporal and spatial resolution on which they operate. Below (Table 6) the climate data requirements for the PESETA II project are shown.

Sector	Variables required	Time resolution	Spatial resolution
Agriculture	Max/min temperature	Monthly	50 x 50 km
	Precipitation	Monthly	50 x 50 km
	CO2-equivalent concentration	Annual	50 x 50 km
River floods	Temperature	Daily	12 x 12 km and 50 x 50 km
	Precipitation	Daily	12 x 12 km and 50 x 50 km
	Net (or downward) shortwave (solar) radiation	Daily	12 x 12 km and 50 x 50 km
	Net (or downward) longwave (solar) radiation	Daily	12 x 12 km and 50 x 50 km
	Humidity	Daily	12 x 12 km and 50 x 50 km
	Wind speed	Daily	12 x 12 km and 50 x 50 km
	For comparison purposes: evaporation, snow, and runoff	Daily	12 x 12 km and 50 x 50 km
Coastal systems	Regional surfaces of sea-level rise	Annual	-
Tourism	Maximum/average temperature	Monthly	50 x 50 km
	Hours of sun or cloud cover	Monthly	50 x 50 km
	Wind speed	Monthly	50 x 50 km
	Relative humidity or vapor pressure	Monthly	50 x 50 km
Human health	Max/min/average temperature	Daily	50 x 50 km
	Relative humidity or vapor pressure	Daily	50 x 50 km

Table 6 Climate data requirements for sectoral economic modelling (Ciscar et al. 2014 - modified)

In general, both the temporal and spatial resolution of economic data is much lower than that of climate data. Economic models usually generate outcomes for variables like output and employment on an annual basis, whereas climate data often consider daily variables. Regarding the spatial resolution, it is due to the lack of precise regional economic data that it can be a challenging task to construct economic models on any sub-national scale. Again, climate models work with grid sizes of only several square kilometres.

Thus, the economic data, which usually comes on the level of administrative regions, has to be made compatible with gridded climate data.

5.3. Conclusion and outlook

Though projections of regional climate change are available, they are hardly used in economic models on costs of climate change and benefits of adaptation. However, there are such models on the global scale. If one links available regional economic models with some features of global models and uses inputs of regional climate projections, it will be possible to develop regional economic models suited to analyse costs of climate change as well as costs and benefits of adaptation. This is a gap in current research, in particular in Germany, despite the authors and others currently working on some closely related issues.

This study has shown that there are appropriate approaches available, so that such models and studies can be successfully realised in the near future. Of course, there are some conceptual issues to be solved. For instance, the time and space resolution of regional climate change projections is much higher than those possible and sensible in economic models. Further research is needed to clarify what resolution is necessary in a regional economic model to adequately address the problem at hand. Besides, how economic and policy decisions on adaptation and, for instance, land use or transport means, considered in regional economic models affect the impact of the regional climate on the regional economy must be explored. Further, there are non-economic impact studies of climate change, e.g. on urban heat depending on the microstructure of buildings and land-use. It is remains an open issue how these can be linked to regional economic models. Eventually, it will become clear how adequate regional economic models should look like and this will feed the creation of appropriate models either of the hybrid type, integrated type or pure regional economic type.

6. Appendix

6.1. Existing projects and modelling attempts

Name	Institute/University	Location	Duration	Website	Description	Acronym
Climate change predictions in Sub-Saharan Africa: impacts and adaptations	CMCC (coordinating organization) - various global partners (Germany: PIK)	Lecce (Italy) / Potsdam	10.2010 - 09.2014	http://www.cmcc.it/projects/climafrica-climate-change-predictions-in-sub-saharian-africa-impacts-and-adaptations	Developing improved climate predictions on seasonal to decadal climatic scales, especially relevant to SSA. Assessing climate impacts in key sectors of SSA livelihood and economy, especially water resources and agriculture. Evaluating the vulnerability of ecosystems and civil population to inter-annual variations and longer trends (10 years) in climate. Suggesting and analysing new suited adaptation strategies, focused on local needs. Developing a new cept of 10 years monitoring and forecasting warning system, useful for food security, risk management and civil protection in SSA and analysing the economic impacts of climate change on agriculture and water resources in SSA and the cost-effectiveness of potential adaptation measures. This objectives will be achieved by an integrated working approach that involves 9 European, 8 African and 1 International Organization.	FP7-ENVIRONMENT CLIMAFRICA
Einflüsse von Naturkatastrophen auf internationale Handelsströme und globale Wertschöpfungsketten	ZEW	Mannheim	01.07.2013 - 30.06.2014	http://www.zew.de/de/forschung/projekte.php3?action=detail&nr=1312&abt=urm	The objective of the “DISIMP”-project is the quantitative analysis of the effects of natural disasters in third world countries on international trade relations. The impacts on sectoral trade flows and the shock transmission on downstream value chains in import countries are analyzed in particular. Findings of the econometrical analysis are used for calibration of a computable general equilibrium (CGE) model in order to better analyze the effects of natural disasters on global value chains.	DISIMP
European and Russian Extreme events: Mechanisms, Variability and Future Climate Change	Helmholtz-Zentrum für Ozeanforschung (GEOMAR)	Kiel	12.2012 - 12.2014	http://www.geomar.de/forschen/aktuelle-projekte/detailansicht/prj/313954/	Aims to understand individual events such as the Russian heat wave 2010 (etc.) and the mechanisms underlying extremes in cyclone activity and marine storminess. Aims to determine the influence of external forcing and internal modes of decadal variability, in particular the Atlantic Multi-decadal Oscillation, on extreme events. Assessing the representation of extreme events in climate models, in particular as a function of model resolution, and on regional scales. Developing future scenarios of extreme events in Europe and Russia including the associated uncertainties. To address these questions, case study simulations, sensitivity integrations and future projections with global and very high-resolution regional climate models in different forcing and coupling settings will be carried out. These experiments and additional millennial-long control runs will be validated against observational data by means of modern statistical methods, in particular extreme value theory, vector-generalised regression models and cyclone tracking algorithms. The regional climate model projections will be bias-corrected with a special focus on correcting the magnitudes of extreme events.	EUREX

Name	Institute/University	Location	Duration	Website	Description	Acronym
Integrierte Bewertung der Instrumente und der fiskalischen und marktbasierten Anreize internationaler Klimapolitik und ihrer Auswirkungen	Ifo Institut	München	10.2011 - 09.2014	https://www.cesifo-group.de/de/ifoHome/research/Projects/Archive/Projects_EUR/2014/proj-eur-integrierte-bewertung.html	The structure of estimating equations out of theoretical modelling shall be derived and the estimated micro-founded connections shall be considered in corresponding CGE models in order to analyze climate policy frameworks, based on empirical methods to estimate suitable model parameters which enable the analyses of structural coherences of theoretical models. As a result a consistent integrated approach to improve climate policy consulting is created. In a second important step appropriate extensions of the FUND model are developed to allow for a theoretically founded structural estimation of the behavioral economic connections. In a final step, based on the extended model approach, findings regarding possible impacts and the efficiency of existing unilateral climate policy measures are evaluated.	IACCP
Klimapolitik und die Wachstumsmuster der Nationen	ZEW / PIK /HHL / Uni Bielefeld	Mannheim / Potsdam / Leipzig / Bielefeld	01.09.2011 - 31.08.2014	http://kooperationen.zew.de/de/clipon/startseite.html	CliPon analyzes the close interaction between climate policies and economic growths of various economies by means of theoretical models as well as empirical and numerical proceedings. The challenges of climate change in consideration of increasing international trade, i.e. growing international division of labor and increasing involvement of emerging countries are addressed. This project analyzes thereby the influencing factors of (endogenous) technological progress and structural change with respect to the challenges of global climate change on growth and development in various regions. The purpose of this project is to generate new insights regarding the impact of climate policies on international trade, environmental-related topics and growth in different regions and make this information publicly available.	CliPoN
Kooperative Ansätze zukünftiger Klimapolitik	FhG / KIT / IfW	München / Karlsruhe / Kiel	02.2012 - 01.2015	http://project-core.info/core-en/index.php	The main focus relies on theoretical and empirical analyses of future options of international climate policy under consideration of long term climate targets, various negotiation procedures, technological progress and uncertainties regarding the development of important mitigation technologies. A theoretical framework is created initially on the basis of cooperative game theory that depicts essential elements of international climate policy as well as technological uncertainties. To allow for analyses based on empirical data a CGE model is extended by development paths of mitigation technologies. In a further empirical analysis a field experiment is conducted with the stakeholder as well as a controlled experiment with students. Finally economical and ecological impacts of relevant policy options are analyzed based on the extended CGE model.	CORE

Name	Institute/University	Location	Duration	Website	Description	Acronym
Ökonomische Instrumente zur Erreichung klimapolitischer Ziele in Europa	ZEW	Mannheim	01.09.2012 - 31.08.2015	http://www.zew.de/de/forschung/projekte.php3?action=detail&nr=1219&abt=urm	This research project evaluates the climate policy portfplio of the EU and analyzes thereby the EU ETS and further policy instruments, energy efficiency standards, the support of renewable energies, taxation of CO_2 emissions , innovation policy and trade policy measures. ENTRACTE elaborates a deeper understanding of the interaction of climate policy policy instruments and other related policy measures. The real world and its imperfection are comprehensively considered as well as practical barriers (information asymmetry, uncertainties, political and statutory regulations, behavioral economic aspects). ENTRACTE integrates empirical findings out of ex-post-evaluations based on a wide spectrum of empirical data as well as ex-ante-analyses with simulation models and experimental approaches with theoretical insights, to optimize the policy mix.	ENTRACTE
Quantifying projected impacts under 2°C warming	HZG/ CSC / PIK	Geesthacht/ Hamburg/ Potsdam	10.2011 - 09.2015	http://www.hzg.de/mw/impact2c/	IMPACT2C utilises a range of models within a multi-disciplinary international expert team and assesses effects on water, energy, infrastructure, coasts, tourism, forestry, agriculture, ecosystems services, and health and air quality-climate interactions. First, harmonised socio-economic assumptions/scenarios will be used, to ensure that both individual and cross-sector assessments are aligned to the 2°C (1.5°C) scenario for both impacts and adaptation, e.g. in relation to land-use pressures between agriculture and forestry. Second, it has a core theme of uncertainty, and will develop a methodological framework integrating the uncertainties within and across the different sectors, in a consistent way. In so doing, analysis of adaptation responses under uncertainty will be enhanced. Finally, a cross-sectoral perspective is adopted to complement the sector analysis. A number of case studies will be developed for particularly vulnerable areas, subject to multiple impacts (e.g. the Mediterranean), with the focus being on cross-sectoral interactions (e.g. land use competition) and cross-cutting themes (e.g. cities). The project also assesses climate change impacts in some of the world's most vulnerable regions: Bangladesh, Africa (Nile and Niger basins) and the Maldives.	FP7-ENVIRONMENT IMPACT2C

Name	Institute/University	Location	Duration	Website	Description	Acronym
Raising the alert about critical feedbacks between climate and long-term land use change in the Amazon	Stichting Dienst Landboukwundig Onderzoek (coordinating organization) - various global partners (Germany: PIK)	Potsdam	09.2011 - 08.2014	http://cordis.europa.eu/projects/rcn/99921_en.html	AMAZALERT will enable raising the alert about critical feedbacks between climate, society, land-use change, vegetation change, water availability and policies in Amazonia. The project aims to: 1) analyze and improve coupled models of global climate and Amazon, land use, vegetation and socio-economic drivers to quantify anthropogenic and climate induced land-use and land cover change and non-linear, irreversible feedbacks among these components 2) assess the role of regional and global policies and societal responses in the Amazon region for altering the trajectory of land-use change in the face of climate change and other anthropogenic factors and finally 3) propose i) an Early Warning System for detecting any imminent irreversible loss of Amazon ecosystem services, ii) policy response strategies to prevent such loss.	FP7-ENVIRONMENT AMAZALERT
Regionale Klimaprojektionen	CSC / Uni Göttingen	Hamburg / Göttingen		http://www.kliff-niedersachsen.de.vweb5-test.gwdg.de/?page_id=97	The determining climate variables temperature and precipitation rate are forecasted for the region of Lower Saxony (Germany). The assumptions are made first and foremost possible greenhouse gas emissions for the future (middle run: until 2030; long run: until 2100). The focus of KLIFF relies on the so called A1B-scenario, but other developments (B1, A2 etc.) are considered as well. These scenarios are seen as the “drivers” of a global climate model which includes the entire globe (in a coarse grid) including the oceans and the atmosphere. These targets of the global model are in turn the “drivers” of a regional climate model which contains Lower Saxony in a finer grid.	KLIFF

6.2. Integrated Assessment Models

The following table lists a number of IAM's which were not addressed in the text but are nevertheless worth mentioning in this report. However, the table does not claim to be a complete overview but rather underscores the fact that a lot of IAM's are in place, but none is – to our knowledge – suitable for deriving guidelines for regional or even national policy.

Name	Author(s)	Classification
AIM	Yuzuru Matsuoka et al.	Policy Evaluation
CETA	Stephen C. Peck & Thomas J. Teisberg	Policy Optimization
CONNECTICUT	Gary Yohe & Rodney Wallace	Policy Optimization
CRAPS	James K. Hammitt	Policy Optimization
DICE	William D. Nordhaus	Policy Optimization
FUND	Richard S. J. Tol (& David Anthoff)	Policy Optimization
ICAM	Hadi Dowlatabadi	Policy Evaluation
IMAGE 2.4	Joseph Alcamo (ed.)	Policy Evaluation
MAGICC	Mike Hulme et al.	Policy Evaluation
MERGE	Alan Manne & Richard G. Richels	Policy Optimization
MESSAGE III	Manfred Strubegger & Sabine Messner	Policy Optimization
PAGE09	Chris W. Hope	Policy Evaluation
PEF	David Cohan & Robert K. Stafford	Policy Evaluation
WIAGEM	Claudia Kemfert	General Equilibrium

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