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Kiel Working Paper No. 922

Modelling the Economic Impact of Global Warming in a General Equilibrium Framework

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April 1999

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by

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Key words: Climate Change, Impact Modelling, Damage Function, Computable General Equilibrium Model, Integrated Assessment Framework

JEL classification: D58, D8, Q1, Q2

Abstract. The issue of global warming has become a major topic in the international environmental debate. Alternative climate policy measures can be evaluated with the help of a simulation model that integrates economic and natural science considerations. A fully integrated assessment of the two-way relationship between the world economy and the climate system requires the incorporation of the repercussions of climate change on economic processes into the analysis. This paper seeks to review the contributions of the economic literature dealing with the modelling of climate change impacts. We look at the structure, assumptions, and results of impact studies to illustrate how climate change impacts can be incorporated into Computable General Equilibrium Models (CGEs). As a point of reference a generic general equilibrium model is established and extended to incorporate climate change impacts on the economy.

This paper has been produced as part of the research project on „Treibhauseffekt und wirtschaftliche Entwicklung: Ein disaggregiertes Klima-Ökonomie-Modell“ (‘Greenhouse Effect and Economic Development: A Disaggregated Climate-Economy-Model’). Funding by the Volkswagen Stiftung is gratefully acknowledged.

* We thank Gernot Klepper, Daniel Piazolo, Ulrich Wagner, and Manfred Wiebelt for helpful comments and suggestions. The usual disclaimer applies.

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1 Introduction

The issue of global warming has become the major topic in the international environmental debate. There is no doubt that the concentration of heat-trapping greenhouse gases (GHG) in the atmosphere has been rising in the past, in part due to human activity. There is also little doubt that over time this will alter the mean annual temperature, changing the climate in potentially damaging ways. However, the level at which GHG emissions become dangerous, and the effects that can be expected, are all a matter of dispute. This does not only undermine the political will to take action, as amply demonstrated at the international climate conferences in Rio de Janeiro, Berlin, Kyoto, and Buenos Aires, but also complicates economists' search for policy measures.

The identification of efficient emission reduction strategies requires the quantification of all abatement costs, but also calls for a quantification of all abatement benefits, i.e. the identification, quantification, and monetary evaluation of avoided global warming damages. Whereas the abatement costs of GHG emission reductions can be quantified relatively easily by means of economic simulation models, the identification and quantification of physical impacts of climate change, on the one hand, and their monetary evaluation, on the other, pose serious analytical and empirical problems since this presupposes an integration of economic and natural science considerations. An integrated framework which allows to model both, the generation of emissions by economic processes and the resulting impacts of climate change on economic processes simultaneously, provides a consistent basis for the assessment of the costs and benefits of climate policy measures. A fully integrated assessment of the two-way relationship between the world economy and the climate system requires to project the repercussions of climate change on economic processes and to incorporate them into the analytical framework.

However, the issue of climate impact modelling in a fully integrated framework has not been adequately addressed so far.[1] Only a few studies try to integrate both directions of the climate economy relationship. But none of the models used is *fully* integrated in the sense of a complete and consistent representation of the two-way interdependence between the economic and the climate system.[2]

Partly this may be due to the fact that the issue of climate change impacts has received by far less attention from economic modellers than the assessment of the costs of reducing GHG emissions. However, throughout the past decade a couple of economic studies dealing with climate impacts have been published.

This paper seeks to review the contributions of the economic literature dealing with the modelling of climate change impacts. However, it is not intended to give a comprehensive review of the state of the literature. Instead, we adopt a more 'pedagogical' approach, working through the structure, assumptions, and results of a couple of impact studies to illustrate how climate change impacts can be incorporated into computable general equilibrium (CGE) models. As a reference point we use a generic general equilibrium model against which the contributions of the literature are evaluated.

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1 A review of integrated assessment modelling of global climate change is given in Parson and Fisher-Vanden (1997). They define integrated assessment models as formal integrated representations of knowledge combined from multiple disciplines.

2 In a multi-disciplinary research project with the Max-Planck-Institute of Meteorology (Hamburg) the Institute of World Economics, Kiel (IfW) is linking a multi-regional, multi-sectoral CGE model with a climate model, hereby considering the climate change impacts on regional economies. The economic CGE model can be used to project economic activities, energy use and trade flows for each of the specified regions according to exogenous assumptions about the dynamics of the model (Springer (1998), Klepper and Springer (1999)). Anthropogenic carbon dioxide projections can be directly derived from the energy use projections made by the economic model. These emission projections are inputs to the climate model of the Max-Planck-Institute, and thereby form the first link in the integrated analysis of global climate change. The induced climate change derived from the climate model then serves as an input for the CGE model adapted to incorporate climate impacts on the economy.

The CGE framework is considered to be especially qualified for the modelling of climate change impacts because of its capacity to represent all relevant components of an economy and to model explicitly the interrelationships of these components. The change in climate variables as, for example, seasonal temperature, precipitation or extreme weather events may influence the factor endowment of economies, the productivity of factors, the parameters of production functions or final demand. A CGE model may incorporate these direct climate impacts on production sectors or final demand. The resulting indirect impacts for all other components of the economy, the so-called second order effects, can be derived via the interactions in the general equilibrium framework. Furthermore, the CGE framework avoids the use of questionable price tags on climate impacts because economic activities are modelled in terms of physical units.

Because the economic analysis of climate change presupposes an understanding of the underlying physical processes and of the impacts on the economy, these are outlined first. Chapter 2 presents an overview of the causes and consequences of global warming. In chapter 3 we give a critical survey on economic approaches for modelling climate change impacts, hereby pointing out their major shortcomings. On this basis the special qualification of the CGE framework for economic impact assessment is established.

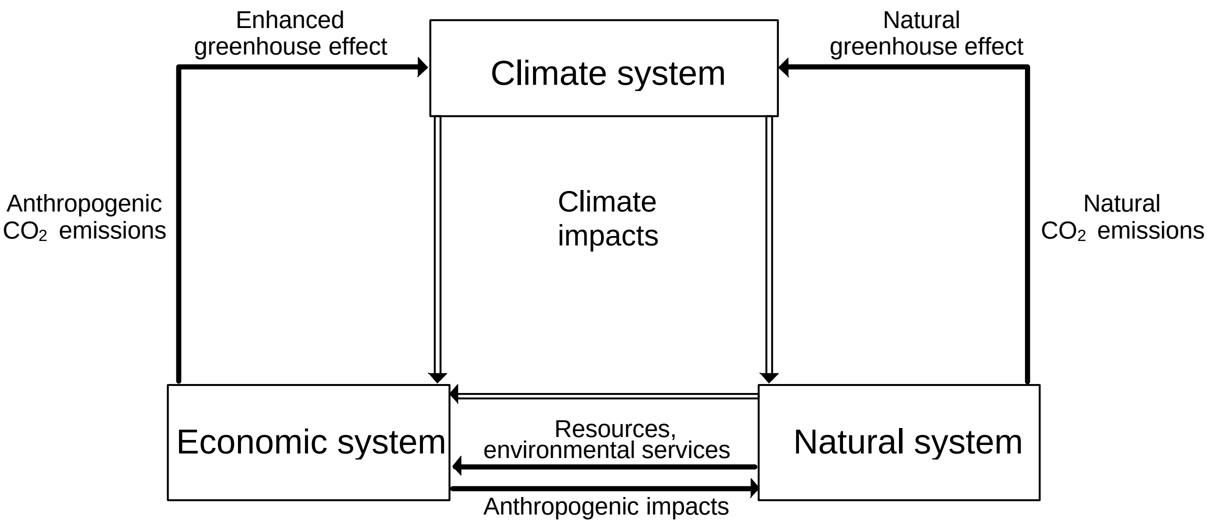
Chapter 4 provides an analytical framework for integrating the impacts of climate change into the economic analysis. It begins with the description of a generic general equilibrium model. The second part of this chapter shows how the generic model can be adapted to incorporate climate impacts on the economy. Against this analytical background, chapter 5 deals with the numerical implementation of the extended model. Empirical impact studies are surveyed and evaluated with regard to their compatibility with the general equilibrium framework. Impact studies dealing with the agricultural sector, the demand side, dynamics, and the incorporation of uncertainties and extreme weather events are analysed. Finally, in chapter 6, we draw some conclusions and suggest issues for further research.

2 Sources and Consequences of Global Warming

This chapter gives an introduction to the issue of global warming. First, the underlying physical processes are sketched. Then, the economic consequences of climate change are presented in more detail. Finally, the three basic options society has in order to cope with the problem are outlined.

The problem of global warming is a complex issue resulting from the interactions of the climate system, the natural system and the economic system. A simplified representation of these interactions is given in Figure 1.[3]

Figure 1: **The Global Warming Problem**



The concentration of GHGs in the atmosphere influences the energy balance of the Earth: The Earth receives short-wave radiation from the sun, two thirds of which are absorbed by the

3 A detailed description of the sources and consequences of global warming from the natural science perspective is given in IPCC (1996a).

atmosphere. This inflow of energy is balanced by outgoing long-wave infra-red energy. Whereas short-wave radiation easily passes through the atmosphere, the long-wave terrestrial radiation is partially absorbed by heat-trapping GHGs in the atmosphere. Part of these GHGs are of natural origin and sustain the *natural greenhouse effect* without which the atmosphere were about 33°C cooler than it actually is (Mabey et al. (1997)). However, the subject of the global warming debate are those emissions of GHGs that are by-products of economic activity. These so-called *anthropogenic GHG emissions* are assumed to enhance the natural greenhouse effect beyond its natural equilibrium, thereby inducing changes of the climate system that are summarised under the notions of ‘global warming’ or ‘climate change’.[4]

The major source of the anthropogenic greenhouse effect are carbon dioxide (CO_2) emissions. They contributed 55% to the increase in radiative forcing that occured between 1980 and 1990 and have their predominant origin in the combustion of fossil fuels and in deforestation. Emissions of methane, the second-most important greenhouse gas, are by-products of certain agricultural activities such as the cultivation of rice and the breeding of cattle as well as of coal, oil and gas extraction. Other gases that influence the greenhouse effect are water vapour, nitrous oxides, chlorofluorocarbons and ozone (Mendelsohn and Rosenberg (1994)).

Changes in the atmospheric concentration of greenhouse gases affect the *climate system.* Most climate change forecasts refer to an equilibrium climate which is reached after the climate system has adjusted to the increased atmospheric concentration of greenhouse gases.[5] Usually

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[4] Throughout this paper both terms ‘global warming’ and ‘climate change’ are used interchangeably. The first term is used as a catchwork in public debate. ‘Climate change’ is more precise, taking into consideration that an enhanced greenhouse effect would result in changes of several climate variables. There would also be regionally different changes in climate variables that cannot be subsumed under ‘global warming’.

[5] In order to forecast how the changing atmospheric concentration of greenhouse gases affects the climate, Coupled Atmosphere-Ocean General Circulation Models (CGCMs) are applied. These models are based on

these forecasts assume that a doubling of CO_2 concentration relative to the pre-industrial level would be reached by the end of the 21st century if the current levels of CO_2 emissions were maintained (IPCC (1996a, p. 25)).[6] Yet, the choice of a doubling-of-CO_2-'benchmark case' seems somewhat arbitrary: Climate is influenced by an increased GHG concentration before and after the doubling of CO_2. The extrapolation of the results of 2xCO_2 simulations does not necessarily supply information on the long-term implications of GHG emissions. The existence of thresholds of emission concentration, for instance, beyond which the reaction of the climate system changes abruptly, would call in question the assumption of a continuous relationship between emissions and climate change.

More appropriate for long-term forecasting are so-called transient experiments. They simulate the temporal evolution of the climate system, taking into account the accumulation of GHGs in the atmosphere (IPCC (1996a, p. 31)). This leads to predictions of the relationship between emissions and climate change that are more precise than those obtained from equilibrium climate models which capture only one single concentration level assumed to exist at a certain point of time. Moreover, transient models, by capturing the entire process of climate change, allow to forecast climate development before and after the doubling of CO_2 concentration (Bryan et al. (1982), Cubasch et al. (1992), Voss et al. (1998)).

Climatic changes have repercussions on *the natural system* and on *the economic system*. Changes of the level and the variability of climate variables, as for instance temperature and precipitation, disturb the balances these systems have established by adaptation. The systems either adapt to the new conditions or they disappear.

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data from the spaces of a three-dimensional grid which covers the entire globe and extends to about 35 km over the Earth's surface (IPCC (1996a)).

6 Most equilibrium simulations refer to a doubling of *equivalent* CO_2 concentration which is the concentration of CO_2 that would cause the same amount of radiative forcing as the given mixture of CO_2 and other greenhouse gases (IPCC (1996a, p. 48)).

The economic system is adapted to the prevailing climatic conditions which influence both, production processes as well as the natural resources and environmental services used in production and consumption. The impacts of climate change on the economic system may be damaging or beneficial; in any case they induce welfare changes. The notion of ‘climate change damages’ which is frequently used in global warming economics refers to the fact that adaptation is costly. Moreover, ecosystems, for instance, are cherished for the way they function under current climatic conditions. If the composition of and the interactions within ecosystems change due to adaptation, their current way of functioning disappears. This result of adaptation can be perceived as welfare loss by society, even though the ecosystems themselves survive.[7]

There exist several classifications of climate change impacts which differ according to the objective of the analysis. The Intergovernmental Panel of Climate Change (IPCC (1996b)), for instance, uses a natural science classification for its survey of impacts on different ecosystems such as forests, deserts, oceans etc. However, for economic impact assessment the results from natural science have to be related to economic categories such as production and consumption. For that purpose the IPCC (1996b) distinguishes activities with climate-sensitive markets, activities which are sensitive to climate themselves and activities which depend on climate-sensitive resources.[8] In global warming economics damages are often classified according to the categories shown in Figure 2.

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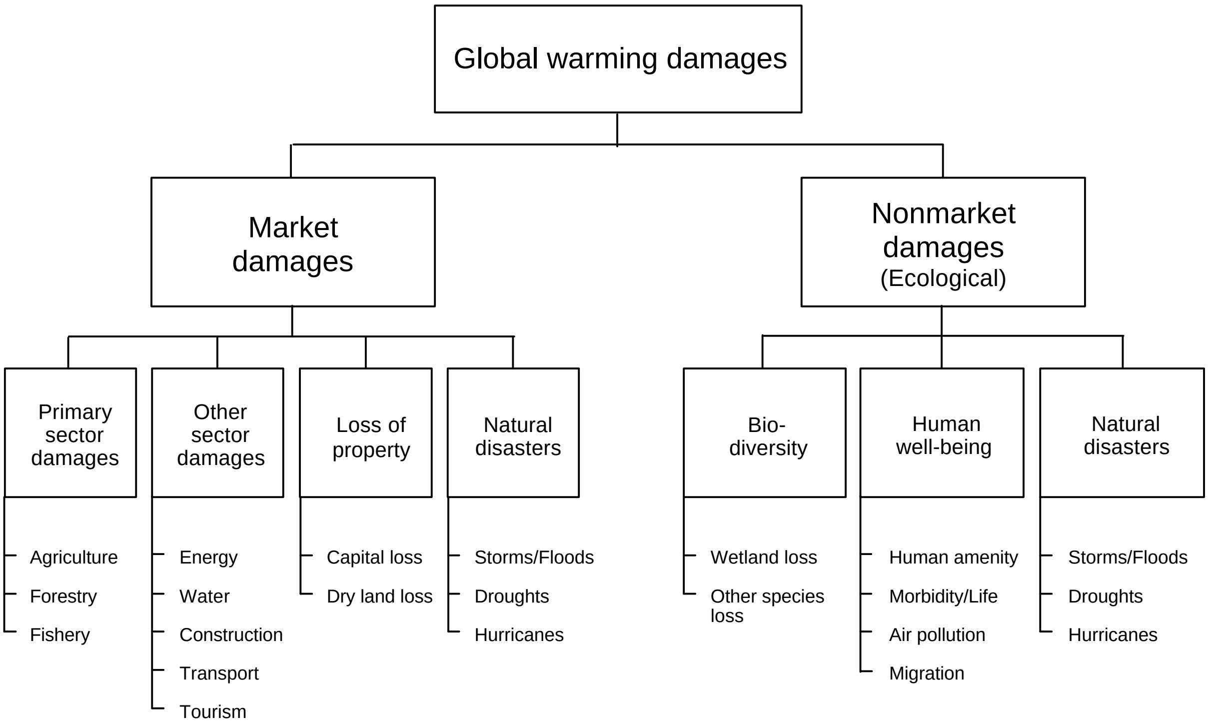
[7] In this paper both notions ‘impacts’ and ‘damages’ are used. In certain cases climate change impacts may turn out to be beneficial, as, for instance, higher winter temperatures in northern latitudes which allow a longer shipping season. The notion of ‘damages’ implies that impacts are associated to welfare losses which is an a priori evaluation. The notion of ‘impacts’, in contrast, is a neutral formulation which is often used in association with the physical impacts of climate change. For the sake of correctness the notion of ‘impacts’ should be used until an economic evaluation in terms of benefits or losses is specified.

[8] The most comprehensive survey of climate change impacts on ecosystems and economic activities is given by the IPCC (1996b). In IPCC (1996b), chapters 1 to 10 are dedicated to ecosystems while chapters 11 to 17 refer to economic activities. Chapter 18 examines the impacts on human health. While broad in coverage the IPCC mostly restricts itself to the presentation of results which makes it impossible to judge the

Figure 2: Economic Classification of Global Warming Damages



Source: Manne et al. (1995, p. 25)

From an economic point of view market impacts and non-market impacts can be distinguished. Market impacts are those reflected in accounting.

Agriculture is the most climate-sensitive economic sector with both, the amount of arable land and its productivity directly depending on climate.[9] Since agriculture is important for domestic food security and as a foreign exchange earner mainly in developing countries these

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respective estimates. However, it is a source of extensive topic coverage and a starting point for literature search. An economically orientied survey on climate change impacts is given in Cline (1992).

9 Parry (1990) examines the consequences of climate change on world agriculture. Besides the derivation of empirical estimates and expected developments on the basis of regional studies he gives a survey on the results of natural science studies and reviews methodological issues of impact assessment. Sonka (1991) concentrates on methodological issues by comparing 19 agricultural impact studies. A compilation of contributions covering a wide range of issues is given in Reilly and Anderson (eds.) (1992). Contributions from natural science are compiled in Bazzaz and Sombroek (eds.) (1996).

might be affected most strongly by climate change.[10] The *energy* sector is influenced by climate change on both the supply and the demand side. On the supply side, electricity generation from water, wind and sun as well as the capacity of electricity transmission systems depend on climate. Yet, the major impacts on the energy sector have their origin on the demand side. Demand for space heating and cooling and the corresponding demand for electricity and fossil fuel are strongly influenced by climatic conditions (IPCC (1996b), chapter 11). The *construction* sector would be involved in a variety of adaptation measures such as coastal protection and urban planning. On the production side building materials and construction technology would have to be adapted. Other sectors which are influenced by climate are *transportation* and *tourism*. Moreover, all sectors of production may be subject to changes in the productivity of labour and physical capital, since workers and machinery equipment are adapted to or designed for prevailing climatic conditions.

Climate change can entail an increase in the probability and intensity of extreme events such as heat waves, droughts and resulting fires, tropical hurricanes, storms and floods (IPCC (1996a)). These events have considerable short- and long-term impacts on all economic activities of the regions in which they occur. The long-term consequences of natural catastrophes are difficult to assess. Whether nature and economy in a region hit by a catastrophe are able to recover depends on the severity of the catastrophe and on the specific characteristics of the natural and economic systems in that region. Immediate damages caused by natural catastrophes may be quantified in terms of the value of land or assets lost. In many cases these damages are covered by insurance. Within the last decades the insurance sector already had to react to an increasing demand for insurance of assets threatened by natural catastrophies (IPCC (1996b), chapter 17, Berz (1991), Berz (1992), Berz et al. (1996),

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[10] The issue of food security in connection with climate change has been analysed by Parry (1990) and Rosenzweig et al. (1993).

Dlugolecki (1992), Tucker (1997)). It is not clear whether this increase is indeed due to an increased frequency and intensity of natural catastrophes or rather to a higher propensity to insure. However, the reaction of the insurance industry is one of the few directly observable reactions of the economy to climate impacts.

While it may be difficult to trace changing prices or quantities of market commodities back to climate change impacts, market related impacts are still easier to record than *non-market impacts*.[11] Though the physical impacts on ecosystems or human health may be investigated by natural science, the absence or shortcomings of markets for these values make it difficult to evaluate these impacts economically. A concept frequently used for obtaining monetary values of non-market impacts is the willingness-to-pay concept. In some cases there are points of contact between such intangible values and markets. Changes in human health, for instance, are reflected in labour supply and labour productivity. Also the expenditures of the Public Health System might be an indicator.

Human society as a whole and the economic system in particular react to the threat of global warming. Basically, three *response options* may be distinguished: adaptation, abatement, and the enhancement of carbon sinks.

By *adaptation* society seeks to minimise the negative consequences of climate change impacts. It is, so to speak, the automatic response to climate change: Economic agents optimise their behaviour under given restrictions, with climate being one of these restrictions. If it changes, agents adapt their behaviour in order to reach a new optimum. Economic sectors which are affected by climate change adapt by altering input quantities, kinds of inputs,

[11] Dowlatabadi and Morgan (1993, p. 214) claim that if climate change has an impact on produced goods and services „... the market can be expected to lead to an adaptation to climate impacts, and reduction of losses due to changed climate through time." In contrast to welfare enhancing economic adaptation the adaptation of natural systems may constitute an irreversible loss, because „...many people place a value on natural systems as they are."

technologies or products. Whether explicit policy measures are involved in the adaptation of human society to global warming depends on the goods affected: Coastal protection from sea level rise, for instance, can be a public good provided by the government. As far as private goods are concerned, the market has the potential to react efficiently to climate change impacts. However, this clear-cut distinction cannot always be made: Impacts on human health, for instance, affect the Public Health System as well as labour supply. In this case, both the government as well as market agents are involved in adaptation.

The second response option, *abatement*, refers to the reduction of GHG emissions. It involves a trade-off between welfare-enhancing production and potential future damages of climate change impacts on the global level. Because of the global common character of the atmosphere the abatement option requires international co-operation and thus falls into the field of policy.[12] The derivation of globally optimal abatement targets is complicated by uncertainty and evaluation problems. Uncertainty prevails about the relations between GHG emissions, climate change and resulting impacts. These impacts are regionally different and they are differently evaluated by different negotiating parties. A further point of dispute is the choice of the rate at which future impacts are to be discounted. Still more difficult than the derivation of a global abatement target is its allocation to the respective negotiating parties.[13]

The third response option is the *enhancement of carbon sinks*. Here, the objective is to increase the capacity of the natural system to store carbon. This objective is most effectively achieved by afforestation: By the process of photosynthesis carbon dioxide is stored in biomass. Afforestation also contributes to the reduction of net emissions since deforestation and other land use changes are the second-largest source of carbon emissions after fossil energy-related activity (IPCC (1996c, p. 245)). Yet, in the long run afforestation is only a

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[12] For the appropriateness of interpreting the atmosphere as a global common see Heal (1991).

[13] For a discussion of international CO_2 agreements see Heister (1997).

temporary solution. While there is net carbon uptake (sequestration) as long as forests expand, the carbon contained in biomass will be released into the atmosphere when trees die.[14]

All three kinds of response options —adaptation to climate change impacts, emission abatement and the enhancement of carbon sinks — are costly. A socially optimal response is based on a trade-off: On the one hand there are costs of emission abatement and the enhancement of carbon sinks. On the other hand there are economic losses incurred by climate change impacts and adaptation costs. The realisation of an optimal response hinges on the interplay of the different agents involved: On the one hand economic agents adapt to climate change impacts in the course of their optimisation process. On the other hand governments make decisions on abatement policy and are responsible for certain adaptation measures. Furthermore the trade-off between abatement costs and damages and/or adaptation costs is an intertemporal one. The optimality of the response to climate change is conditional on the underlying evaluation of future benefits and costs which is expressed by the rate at which they are discounted.

The description of the global warming problem outlined so far suggests that the analysis of its sources and consequences requires the application of a model that accounts for both directions of the relationship between economy and climate: The influence of anthropogenic GHG emissions on climatic conditions on the one hand and the repercussions of changing climatic conditions on the economy on the other. Ideally, the representations of natural and economic processes ought to be connected in an integrated framework. Additionally, in order to derive optimal responses to climate change, a modelling framework should have the capacity to consider relevant response options. In any case adaptation and emission abatement should be compared. The benefits and costs attendant to each option have to be assigned to the

[14] For a more detailed discussion of forestry measures see Cline (1992) (chapter 5).

relevant economic or political agents who are characterised by optimisation behaviour. The issue of discounting has to be addressed.

For the specific problem of economic impact modelling, which is the focus of this paper, the following conclusions can be drawn:

First, whichever economic model is applied, one has to use the results from natural science analyses which describe the direct physical impacts on the relevant economic entities. Techniques have to be developed to integrate these results into economic models.

Second, empirical impact studies have to refer to a spatial dimension that is appropriate for the impacts under consideration: Climatic changes themselves have regionally different characteristics and thus different impacts. Moreover, the effects of a given impact depend on socio-economic characteristics which vary considerably among regions.

Third, in order to derive comprehensive welfare implications of climate change not only direct, but also indirect impacts have to be considered. Direct climate change impacts affect the restrictions of the economic agents, such as production sectors, owners of primary factors or consumers. The agents directly concerned react to the changing restrictions by reoptimising their behaviour, i.e. they adapt to the new conditions. Since all agents of the economy are interconnected, this induces indirect impacts on all other agents who also react by reoptimisation. If these indirect effects are not taken into consideration, impact assessment leads to over- or underestimation of the economic consequences of climate change.

3 Economic Impact Assessment: A Critical Review

Throughout the past two decades many contributions have been made to the economic analysis of the global warming problem.[15] Most advanced in empirical global warming economics is the assessment of abatement costs attendant to given targets. A wide range of models have been

15 A comprehensive survey on empirical approaches is given in Cline (1992).

developed which differ with respect to the underlying model type, the space and time horizon covered and the level of regional and sectoral disaggregation. The best-known abatement cost models fall under the category of resource allocation models. These are long-run equilibrium models where changes of relative prices are the driving force to reach the new equilibrium. Different specifications are possible: The Edmonds-Reilly-Barns Model (Edmonds and Reilly (1985), Edmonds and Barns (1990)) is a partial equilibrium model. The Jorgenson-Wilcoxen model (Jorgenson and Wilcoxen (1990), Jorgenson and Wilcoxen (1993)), GLOBAL 2100 (Manne and Richels (1991), Manne and Richels (1992), Manne and Richels (1994), the model by Whalley and Wigle (1991), the GREEN model by the OECD (Burniaux et al. (1992)) and CETA (Peck and Teisberg (1992), Peck and Teisberg (1993a), Peck and Teisberg (1993b), Peck and Teisberg (1998)), are general equilibrium models.[16]

However, optimal levels of emission abatement as a response to the global warming problem can only be derived if abatement costs are weighted against abatement benefits. These benefits consist in the prevented negative impacts of climate change and/or in saved adaptation costs. Thus, besides abatement costs also abatement benefits have to be analysed in empirical global warming economics.

Nordhaus was the first to apply an empirical optimisation approach where both costs and benefits of abatement are quantified. In his seminal paper (Nordhaus (1991)) he introduced the concept of a greenhouse damage function which describes the costs that accrue to society from climate change. This damage function incorporates, for example, the impacts of changing crop

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[16] The Stanford University's Energy Modeling Forum 12 (EMF 12) has compiled and compared 14 empirical models which are designed to analyse the economic impacts of alternative abatement options. A comparison of these models with emphasis on the modelling of energy supply and demand in the different modelling types is given in Beaver (1993). Another comparison is provided by Gaskins and Weyant (1993). Some of the EMF 12 models and further contributions are described and discussed in Cline (1992). A survey on models developed from 1983 to 1991, including macroeconomic and resource allocation models, is given in Boero et al. (1991). A more recent survey on applied general equilibrium models for energy studies is given by Bhattacharyya (1996).

yields or land lost to oceans. The damage function is the counterpart of the abatement cost function which describes the costs that are incurred to prevent or to slow down the greenhouse effect by emission abatement. On the basis of these functions optimal abatement strategies are derived, that maximise overall net economic welfare which comprises market and non-market goods and services as well as all externalities from economic activity (Nordhaus (1991, p. 923)).

Nordhaus' intitial model, the Dynamic Integrated Model of Climate and the Economy (DICE) (Nordhaus (1991)), a Ramsey type growth model, covers the United States. Damage estimates are based on a report by the U.S. Environmental Protection Agency. The damage function is derived under the assumption of a 3°C warming associated with an equilibrium doubling of equivalent CO_2 concentration. The monetary value of total damages is estimated to be about 0.25 % of U.S. income in 1981. This number does neither include non-market damages nor market damages where no estimates existed. To include these impacts Nordhaus assumes that total damages to the U.S. economy amount to about 1% of 1981 national income, with a range of 0.25-2%. He extrapolates his estimates to the entire world and concludes that total global damages are unlikely to exceed 2% of total world product.

To analyse different national strategies in international climate policy the DICE model was extended to a global model with regional disaggregation, the Regional Integrated model of Climate and the Economy (RICE) (Nordhaus and Yang (1996)). Furthermore, a probabilistic extension of the RICE model is applied to analyse the value of the resolution of uncertainties about impacts and costs (Nordhaus and Popp (1997)).

Nordhaus' approach represents a considerable achievement from a conceptual point of view: The climate-economy relationship relevant for impact assessment, namely the influence of climate on the economy, is represented in a function that relates results from natural science analyses to economic measures. This function represents abatement benefits which are opposed to abatement costs in order to derive optimal abatement levels.

The main problem of empirical impact modelling is the lack of reliable quantitative impact estimates. Nordhaus himself states that the representation of climate change impacts is the most uncertain part of the model (Nordhaus and Yang (1996, p. 743)). Nordhaus' approach is subject to substantial criticism yet for another reason, namely for the way his damage estimates were obtained (see e.g. Fisher and Hanemann (1993)).

A major point of criticism is that Nordhaus' damage function does not account for the linkages between the economic entities that are affected by climate change impacts: He obtains an aggregate damage estimate in terms of percentages of GDP by summing up impact estimates for different categories. This is called an 'enumerative approach' (Fankhauser (1995, p. 17)). Yet, the summation of estimates from partial equilibrium studies does not yield a consistent outcome. This results from the neglect of the economic processes that set in as direct physical impacts affect the different components of the economy. Through intersectoral linkages, primary factor markets, and final demand on regional, national and international scales direct impacts are propagated throughout the economy. Direct and indirect impacts induce adaptation, i.e. the economic agents concerned reoptimise their behaviour. These *second order effects* have to be taken into account in order to derive the eventual welfare implications of climate change impacts. They are not adequately captured by simply adding up direct impacts.

A related problem is the monetary evaluation of direct impacts. Besides the problems that arise with respect to the evaluation of non-market impacts, a source of over- or underestimation lies in the use of current prices: If an economy is affected by climate change, the scarcity of the goods affected changes which results in price changes. These price changes have to be taken into account in order to derive consistent welfare implications.[17]

Following Nordhaus, also Cline (1992), Fankhauser (1992), and Tol (1995) applied enumerative approaches in order to assess climate change impacts.[18]

A representative example for an enumerative approach is the damage function D(t), set up by Fankhauser (1995):

$$D(t) = k(t^*)\left(\frac{T(t)}{\Lambda}\right)^{\gamma}(1+\varphi)^{(t^*-t)}$$

D(t)	damages in period *t*, in terms of percentages of GNP
T(t)	change of average temperature in *t*, relative to pre-industrial level
k(t)*	damage in the benchmark period *t**, in terms of percentages of GNP
*t**	time at which benchmark warming occurs, assumed to be 2050
Λ	change of average temperature in the benchmark period *t**, relative to the pre-industrial level, occurring as a consequence of $2xCO_2$
γ	shape of the damage function
φ	parameter that relates speed of climate change with severity of impact, $\varphi > 0$

This damage function computes damages in terms of percentages of GNP in a given period t which occur due to a change of the average temperature of the upper layer of the oceans relative to its pre-industrial level, *T(t)*.

The monetary value of damages in period t is computed relative to the value of damages which are assumed to occur in a benchmark situation. This situation is assumed to arise in

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[17] The summation of losses evaluated at current prices is an appropriate method for the evaluation of the immediate damages resulting from natural catastrophies. The objective of climate change impact assessment, in contrast, is to provide information on the reaction of the economy to slowly evolving changes. Of course, as far as the increase of the frequency and intensity of natural disasters is part of these changes, also related potential damages have to be accounted for. Yet, for mid- to long-term projections immediate damages are only part of the net impact, since reconstruction activities and other reactions to the catastrophe have to be included.

[18] Comparisons of the most prominent estimates are given in Tol (1996) and Fankhauser (1995).

*t**=2050 as a consequence of a doubling of CO_2 concentration in the atmosphere and to be characterised by an increase of temperature of Λ=2.5°C. The value of damages in the benchmark period, *k(t*)*, is taken from enumerative approaches. Thus, if the time period t considered is the period *t**, where the benchmark situation is assumed to occur, *D(t)* is given by *k(t*)*.

Values for the damages in the periods before and after the assumed benchmark period are obtained by applying the damage function. The slope of the damage function, γ, determines how the value of damages evolves as temperature changes: A value of 1 implies that damages rise proportionally with temperature change. Most authors assume the damage function to be of a higher degree, which implies that damages increase more than proportionally with temperature change.[19] The term which contains the parameter φ captures the possibility of adaptation, which mitigates damages. Damages are higher if a given change in temperature occurs earlier, leaving less time for adaptation. For periods preceding the benchmark period *t** the term is bigger than one and the value of damages is — ceteris paribus — higher than in the benchmark period. For periods after the benchmark period the term is smaller than one and diminishes the value of damages compared to the benchmark situation.

Fankhauser (1995) refines the damage function *D(t)* by decomposing the value of benchmark damages *k(t*)* into market damages and non-market damages. Furthermore *k(t*)* is adjusted for population growth and economic development which take place over time. For each parameter and exogenous variable used in the model three values — mean, upper and lower bound — are used in order to account for the uncertainties prevailing about economic development, climate change and climate change impacts.

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[19] Peck and Teisberg (1993b) analyse the sensitivity of optimal emission paths with respect to the shape of the damage function.

Fankhauser's concept of a damage function integrates climatic and economic variables in order to compute the welfare implications of climate change over time. However, the results obtained with his specification will necessarily give wrong estimates of the welfare implications to be actually expected. To a large extent this results from the construction of the function around a 2xCO_2 benchmark estimate, *k(t*)*, which is derived with an enumerative approach. The damages for all other time periods are obtained by applying a function which relates damages to the level and speed of temperature change to this benchmark estimate. As a consequence the conceptual mistake of the enumerative approach is propagated to the entire range of results.

The shape of the function, characterised by the parameters γ and φ, is not obtained on the basis of microeconomic foundations. Instead, the implicit assumption is made that damages develop continuously with temperature change. Furthermore, adaptation is assumed to depend solely on time. Thus, the damage function *D(t)* is merely a scaling of the damages assumed to occur in the benchmark period.

In spite of their shortcomings, enumerative approaches and damage functions, as the one by Fankhauser (1995), are the basis of many damage modules included in empirical global warming analyses. Highly aggregated impact estimates for doubling-of-CO_2-scenarios are widely used to calibrate damage functions that connect changes of climate variables with percentage changes of GDP (see e.g. Peck and Teisberg (1993a), Manne et al. (1995), Dowlatabadi and Morgan (1993), Hope et al. (1993)).

The integration of results from natural science analyses of climate change impacts into economic models and the derivation of comprehensive measures of welfare changes on the basis of these results is a considerable challenge to empirical economic modelling.

However, what can be achieved is an appropriate representation of the economic consequences of potential climate change impacts. For that purpose climate change impacts have to be integrated into a framework which accounts for the economic processes that are induced by the occurrence of direct climate change impacts. Hereby, as argued above, regional differences of climate change impacts and their economic consequences have to be taken into consideration by choosing appropriate levels of regional disaggregation.

Computable general equilibrium models (CGEs) are appropriate tools for this purpose. The attractiveness of general equilibrium frameworks for climate change impact modelling lies in their capacity of representing the behaviour of all economic agents considered to be relevant for the problem at hand. Moreover, the interactions of these agents are explicitly modelled. The CGE framework allows to incorporate direct climate change impacts on any sector or component of final demand and to analyse the resulting indirect impacts for all other components of the economy. The explicit representation of the behaviour of the economic agents allows to model adaptation which takes place as the agents respond to changing restrictions by reoptimisation. In contrast to enumerative approaches, where direct impacts are merely summed up, the consideration of adaptation in the CGE framework allows to derive welfare measures such as percentage changes of GDP that reflect the economic evaluation of climate change impacts; the latter being indicated by changes of relative prices.

Furthermore, CGEs can be calibrated to regional data bases which allows the choice of an appropriate regional dimension of climate change impact analyses.

Since CGEs have also been used for the assessment of abatement costs, their use for impact assessment opens the opportunity to integrate cost and benefit analysis in the same modelling framework to obtain consistent results.

CGE models that are applied for climate change impact analysis include Kokoski (1984), Kokoski and Smith (1987), Godden and Adams (1992), Scheraga et al. (1993), Darwin et al. (1996) and Tsigas et al. (1997).

In the remainder of the paper we narrow down our survey of impact assessment to the general equilibrium framework.

4 Modelling Climate Impacts in a General Equilibrium Framework

As a point of reference for the discussion of climate change impact assessment we first set up a ‘generic’ analytical general equilibrium model. While most actual models used to assess climate policy measures are much larger, this ‘generic’ model captures the salient characteristics and mechanisms of those larger models. The second section of this chapter shows how the generic model can be adapted to incorporate climate impacts on the economy.

4.1 A Generic Model

A general equilibrium model has to incorporate the following components:[20] First, one has to specify the economic actors or agents whose behaviour is to be analysed. A simple Walrasian model includes only households and producers. In the climate context normally the government and trade partners, often modelled by an aggregate called ‘Rest of the World’, are added. Second, behaviour rules must be specified for these actors. Thus, producers are typically assumed to maximise profits subject to technological constraints and households to maximise utility subject to income constraints. Third, agents decide according to signals they observe. In a Walrasian model prices are the only signals agents need to know. Fourth, one must specify the institutional structure of the economy, i.e. the “rules of the game“ according to which agents interact. In most models dealing with the climate policy issue perfect competition is assumed.

[20] This desciption draws on Robinson (1989, pp. 907).

To complete a general equilibrium model one must also define „equilibrium conditions“ which are „system constraints“ that must be satisfied, but that are not taken into account by any agent in making his decision. Formally, an equilibrium can be defined as a set of signals such that the resulting decisions of all agents jointly satisfy the system constraints. For example, a market equilibrium in a competitive model is defined as a set of prices and associated quantities such that excess demand on all markets is zero (Robinson (1989, p. 907)). Computable general equilibrium models produce numerical results. In particular CGE models use actual data for countries or regions and produce numerical results relating to specific real world situations.

For the purpose of climate impact modelling the CGE model should cover multi-regional and multi-sectoral details as well as dynamic features. Regional detail enables the model user to consider regional differences in climate vulnerability and adaptation levels when implementing the feedback of the climate system on the economic system. Sectoral disaggregation allows the analysis of structural change as a consequence of climate change and climate policies. Dynamic features[21] allow to cover dynamic economic effects and the time dependent effects of greenhouse gas emissions and accumulation in the atmosphere, and the resulting climate change impacts.

A further distinguishing feature of CGE models dealing with climate change issues is the explicit modelling of the energy sector, i.e. the production and use of fossil fuels like crude oil, natural gas, coal and their substitution possibilities in intermediate and final demand. Energy use in production and consumption generates varying amounts of greenhouse gases depending on the fossil source and the policies assumed to be in place. Most CGE models base their specification of the energy sector on the ETA-MACRO model by Manne and Richels (1992) or the GREEN model by the OECD (Burniaux et al. (1992)). The implementation of the energy

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[21] Here, the term ‘dynamic’ refers to a multi-period setting.

sector allows to model consistently the energy use with the attendant emissions of greenhouse gases, the resulting climate change and the induced climate impacts on the economies.

In multi-regional models regions are linked by bilateral trade flows. Each region is fully specified and has a production structure described by industry production functions which include both primary factors and intermediate products as inputs. The endowments of primary factors are given exogenously. Each region has a system of market demand functions and a set of tariffs and domestic taxes.

Commodities are treated as heterogeneous across regions, i.e. the Armington assumption (Armington (1969)) is applied (see below equation (4)). This allows the modelling of intra-industry trade among regions. Market demand within any region satisfies Walras' law; that is, the value of demand by any region equals the value of income accruing to this region. This condition holds at any set of commodity and factor prices which implies that global demands (summed across regions) also satisfy Walras' law globally. No transport costs are considered in this basic model. Perfect competition is assumed. Thus, equilibrium is given by a set of goods and factor prices for each region, so that demands equal supplies for all goods and factors, no industry makes positive profit, and each region is in external-sector balance.

There are two main approaches to incorporate dynamic aspects into CGE models: the dynamic sequencing of static equilibria, i.e. the recursive dynamic approach, and the completely dynamic approach. Completely dynamic models rely on intertemporal optimisation, i.e. intertemporal substitution possibilities are incorporated. For the generic model the recursive dynamic approach is used. A recursive dynamic CGE model solves for a sequence of static equilibria which are connected to each other through capital accumulation. Hence, capital stocks available for use in year $t+1$ are determined by investment which takes place before year $t+1$. Because of the in principle static nature of this approach, the generic model is described by the single period equilibrium and the accumulation equations for the endowments, here capital and labour. For simplicity, the time subscript is omitted.

The generic CGE model for one time period can now be described algebraically as follows: There are N sectors producing one good i each, two factors, capital K and labour L, fossil fuels indexed by $k=1,....,K$, and a representative household in each of R regions, where the superscript r[22] denotes the rth region.[23] The world consists of NxR goods, 2xR factors, and R agents. Factors are owned by the representative household of each region.[24] Capital and labour are mobile across industry sectors but internationally immobile.

Sectoral Production

The behaviour of the firms is described by *sectorally aggregated production functions*. Production functions for each good specify input requirements of primary factors and intermediate goods. A requirement of fixed input per unit of production is assumed for a composite of primary factors and energy and a composite of intermediate goods. That means, here we assume a Leontief relation between intermediate goods and the composite bundle of value added and energy, as most models do. Nevertheless, any other functional form could be applied. Furthermore, a nested, i.e. hierarchical production structure is assumed by defining an value added - energy composite. This nesting structure is based on the ETA-MACRO model by Manne and Richels (1992, pp. 130). The producer i maximises profit, Π_i^r, or minimises production costs, respectively, and the primal sectoral production decision can be written as:

(1) $\max \Pi_i^r(Y)$

s.t.

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[22] Hereafter, indices r and s are used as aliases.

[23] The model formulation draws on Shoven and Whalley (1992, pp. 199).

[24] One can also implement different household types for every region if distributional issues are in the centre of interest. Furthermore, the government as a seperate agent is ignored in this generic model.

$$Y_i^r = Y_i^r\left(FE_i^r, H_{1i}^r, \ldots, H_{ji}^r, \ldots, H_{Ni}^r\right) = min\left(\frac{FE_i^r}{a_{VAEi}^r}, \frac{H_{1i}^r}{a_{1i}^r}, \ldots, \frac{H_{ji}^r}{a_{ji}^r}, \ldots, \frac{H_{Ni}^r}{a_{Ni}^r}\right),$$

where

Y_i^r is the output of good *i* in region *r*,

FE_i^r is the value added-energy composite used in producing good *i* in region *r*,

H_{ji}^r is the use of the composite good *j* in producing good *i* in region *r*,

a_{VAEi}^r is the fixed value added - energy composite requirement per unit of output of good *i*,

a_{ji}^r is the fixed requirement of the composite intermediate good *j* in region *r* per unit of production of good *i*.

The *substitution possibilities* between primary factors and energy within the composite FE_i^r are represented by the equation:

(2) $$FE_i^r = FE_i^r\left(K_i^r, L_i^r, E_i^r\right),$$

where

K_i^r denotes the amount of capital used in production of good *i* in region *r*,

L_i^r is the amount of labour used in production of good *i* in region *r,*

E_i^r is the energy composite used for the production of good *i* in region *r*.

The *energy composite*, E_i^r, describes the substitution possibilities among all primary energy inputs for producing good *i* in region *r*:

(3) $$E_i^r = E_i^r\left(FF_{1i}^r, \ldots, FF_{ki}^r, \ldots, FF_{Ki}^r, NFF_i^r, ELEC_i^r\right)$$

where

FF_{ki}^r is the fossil fuel *k* used for producing a unit of good *i* in region *r* (altogether, *K* fossil fuels are distinguished, e.g. coal, natural gas, crude oil),

NFF_i^r is the non-fossil fuel source used as energy input for producing good *i* in region *r*,

$ELEC_i^r$ is the electricity input for producing good *i* in region *r*.

The energy composite, E_i^r, is also an intermediate input to the production process and could be written likewise as H_{ei}^r, i.e. the amount of the composite energy good *e* used to produce good *i* in region *r*. Only because of the special importance of the substitution possibilities between fossil and non-fossil energy inputs for the amount of greenhouse gases emitted, and, therefore, for the influence on the climate system, the energy input nest is modeled explicitly. The inputs for the energy composite, FF_{ki}^r, NFF_i^r, $ELEC_i^r$, are produced like any other good Y_i^r using intermediate and factor inputs. One difference in the production structure of fossil fuels lays in the use of non-renewable natural resources. Therefore, one needs a resource extraction sector to model the supply of fossil fuels properly. For the sake of simplicity, we omit the natural resource input and emphasise only the special substitution possibilities between the primary energy inputs. The energy composite or the primary energy inputs respectively are tradable. Hence, the following equation (4) also applies to these inputs.

Intermediate input requirements are represented by functions specifying substitution possibilities between supply sources, i.e. the substitution possibility between domestically produced and imported goods:

(4) $$H_{ji}^r = H_{ji}^r\left(H_{ji_r}^1, \ldots, H_{ji_r}^s, \ldots, H_{ji_r}^R\right), \text{ where}$$

$H_{ji_r}^s$ is the amount of good *j*, supplied by region *s*=1,....,*R*, used to produce good *i* in region *r*.

This specification is also called ‘Armington specification’, which is based on the proposition by Armington (1969) that domestic and foreign goods are imperfect substitutes, and distinguished by country of origin. This allows the modelling of cross-country trade flows in a simple way.

The substitution possibilities within the composite inputs of production (intermediate composite, value added - energy composite) can be modelled by different types of functions. The most widely used functional forms are constant elasticity of substitution (CES) functions or nested, i.e. hierarchical, CES functions including the Cobb-Douglas and the Leontief function.

Investment good production can be modelled in a similar way as sectoral production. Because of the lack of data, most CGE models assume that investment goods are produced without primary factors. We also assume that regional gross investment demand is covered by one investment good *Z* which is a fixed coefficient linear combination of the other production goods and energy. This gives the following investment good production function:

(5) $$Z^r = Z^r\left(H^1_{1Z_r},\ldots,H^s_{iZ_r},\ldots.,H^R_{NZ_r},E^1_{Z_r},\ldots.,E^s_{Z_r},\ldots,E^R_{Z_r}\right)$$

where

Z^r is the investment good produced in region r

$H^s_{iZ_r}$ is the intermediate input of good i provided by region s=1,...,R which is used by the investment good production sector Z in region r,

$E^s_{Z_r}$ is the energy composite input provided by region s=1,...,R used for producing the investment good Z in region r.

The primary factor demand, the demand for intermediate goods and the demand for energy by the industry sectors, the profit maximising sectoral output and the supply of investment goods can be derived from the production functions described above.

Final Demand

The behaviour of the representative household in region *r* is described by a final demand function[25] which is derived from *utility maximisation*:

(6) $$\max U^r\left(C_{11}^r,\ldots,C_{is}^r,\ldots,C_{Es}^r,\ldots,C_{NS}^r,S^r\right),\quad i=1,\ldots,E,\ldots,N \quad s=1,\ldots,S$$

s.t. $$\sum_{s=1}^{S}\sum_{i=1}^{N}\left(P_{is}^r\cdot C_{is}^r\right)+S^r=I^r,$$

where

U^r	denotes the utility index of the representative household in region *r*,
C_{is}^r	is the amount of final good *i* from region *s* consumed by the household in region *r*,
C_{Es}^r	is the amount of the energy composite supplied by region *s* and consumed in region *r*, where *E* is a subset of the index *i*,
P_{is}^r	is the price paid by the household in region *r* for good *i* from region *s*,
I^r	is the income of the representative household in region *r*,
S^r	is the amount of savings of the representative household in region *r*.

As the income constraint shows the household in region *r* uses its income for consumption of goods and for savings, respectively investment. The utility of the representative household in region *r* can be modelled by various functional forms, e.g. nested CES and (Extended) Linear Expenditure System ((E)LES) functions.

The income of the household in region *r*, I^r, is defined as income from ownership of factors, plus transfers, less direct tax payments:

25 Note that the household in region *r* demands final goods whereas the industry sector i demands intermediate goods supplied by other sectors.

(7) $$I^r = Pk_r \overline{K}_r + Pl_r \overline{L}_r + R_r - T_r,$$

where

Pk_r	denotes the selling price of factor capital in region *r*
Pl_r	is the selling price of factor labour in region *r*
$\overline{K}_r$	is the exogenously given amount of capital services used in region *r*,
$\overline{L}_r$	is the exogenously given amount of labour used in region *r*,
R_r	are transfers received by the household in region *r*
T_r	are taxes paid by the household in region *r*.

The final demand for consumption goods and the investment demand are derived from the utility maximisation problem.

Equilibrium Conditions

If P_{ir} denotes the international price of good *i* produced in region *r*, then P_{is}^r differs from P_{ir} by taxes, tariffs, and other deviations from the world prices due to the trade policies captured by the model. Now for simplicity, we ignore tariffs, taxes, and transfers from the government in this system, then P_{is}^r becomes equal to P_{ir} for all regions *r,* and R_r and T_r are zero.

A general equilibrium for the international economy is given by a set of goods and factors prices such that demands equal supplies in all goods and factors markets, i.e. the following system constraints are fulfilled.

The market clearance condition for the market of good *i* in region *r* is then given by:

(8) $$Y_i^r = \sum_{s=1}^{R} \sum_{j=1}^{N} H_{ij_s}^r + \sum_{s=1}^{R} H_{iZ_s}^r + \sum_{s=1}^{R} C_{ir}^s \qquad \text{(i=1,....,N; r=1,....,R)}$$

where the gross output of good *i* in region *r*, Y_i^r, is equal to the sum of total intermediate demand of all other sectors *j* and the investment good sector *Z* for that good *i* and the total final demand for good *i*.

The market for energy goods is similar to the other goods market (cf. equation 8). So the market clearance condition for the composite energy good *E* in region *r* is given by:

(9) $$E^r = \sum_{s=1}^{R}\sum_{i=1}^{N} E_{i_s}^r + \sum_{s=1}^{R} E_{Z_s}^r + \sum_{s=1}^{R} C_{Er}^s, \qquad (r=1,......,R)$$

where the first sum describes the energy demand of all industry sectors *i* in all *R* regions, the second sum comprises the energy demand for the investment good production, *Z,* in all regions, and the last term on the right hand side of the equation denotes the final demand for energy produced in region *r*.

For the investment good, *Z,* the market clearance is written as:

(10) $$Z^r = \sum_{i=1}^{N} Z_i^r \qquad (r=1,......,R)$$

where the whole regional investment is demanded by the *N* sectors. The investment good *Z* is nontradable.

Note that the primary factors capital and labour are mobile across sectors but internationally immobile. The market clearance condition for the factor capital in region *r* is given by:

(11) $$\overline{K}_r = \sum_{i=1}^{N} K_i^r \qquad (r=1,......,R),$$

and for the labour market:

(12) $$\overline{L}_r = \sum_{i=1}^{N} L_i^r \qquad (r=1,......,R),$$

where the left hand side denotes the exogenously given factor supply in region *r* and the right hand side the factor use by industry in region *r*.

Assuming perfect competition, all industries in all regions earn zero profit in equilibrium. The zero profit condition for industry *i* in region *r* is:

(13) $$P_{ir}Y_i^r = \sum_{j=1}^{N}\sum_{s=1}^{R} P_{js}H_{ji_r}^s + \sum_{s=1}^{R} Pe_s E_{i_r}^s + Pk_r K_i^r + Pl_r L_i^r \qquad (i=1,....,N;\ r=1,....R)$$

where the value of sales of good *i* produced in region *r* , i.e. the left hand side of the equation, equals the total costs of producing this good, that is the sum of the intermediate costs, the cost for the energy composite, and the factor costs for capital and labour.

In this simple model, the macroeconomic equilibria are described by a balanced current account, and the savings-investment-equality. Hence, by assumption no trade deficit or surplus occurs and the the *external sector balance* of region *r* is given by:

(14) $$\sum_{i=1}^{N}\sum_{s\neq r} M_{is}^r - \sum_{i=1}^{N} X_{ir} = 0 \qquad (r=1,....R)$$

where the export of good *i*[26] by region *r*, X_{ir}, is given by:

(15) $$X_{ir} = \sum_{s\neq r}\sum_{j=1}^{N} P_{ir}H_{ij_s}^r + \sum_{s\neq r} P_{ir}C_{ir}^s .$$

The import of good *i* from region *s* into region *r*, M_{is}^r, is given by:

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[26] Note that the energy composite *E* is an element of the index *i*=1,..,*N*.

(16) $$M_{is}^{r} = \sum_{j=1}^{N} P_{is} H_{ij_r}^{s} + P_{is} C_{is}^{r} .$$

Equation (14) postulates the first macroeconomic constraint, i.e. a balanced current account for each region *r*. Hence, the *global trade equilibrium* is also satisfied, meaning that the sum over all regional trade deficits and surpluses has to be zero.

The second macroeconomic constraint incorporates the ex-post *identity between investment and savings* in each region *r*; that is:

(17) $$Z^{r} = S^{r} .$$

If trade policies and government activity are incorporated the representation of an equilibrium is more complex, but the same equilibrium conditions (augmented by taxes) will still apply. Additionally, the government budget balance will hold in each region because of Walras' law and the external sector balance. Walras' law, i.e. the sum of the excess demands over all markets is zero, implies that the equilibrium conditions are not independent of each other. Hence, the budget balance is implied by the trade balance and vice versa.

Because of the dynamic nature of the economy also a static model has to reflect the possibility for agents to save or dissave. In order to solve a general equilibrium model which is not based on an explicite intertemporal optimisation framework, one of the constraints of the model has to be dropped because the system of equations is overdetermined (cf. Dewatripont and Michel (1987)). This requires to choose closure rules which determine the exogenous and endogenous variables in the macroeconomic equilibrium conditions of the model. The choice of macroeconomic closure rules follows from the impossibility to warrant the ex-post identity between savings and investment although all markets are in equilibrium (Conrad (1997, p. 21)). Hence, closure rules for the foreign trade activity, for the government activity and for the ex-post savings and investment identity have to be added.[27] The choice of the exogenous parameters in the model determines the adaptation of the economic system to exogenous shocks.

Dynamics

Having described the economic behaviour of the agents for one time period, the dynamics are introduced through equations which describe how the endowments of the primary factors evolve over time, i.e. the factor accumulation equations for each region.

Exogenous labour supply $\overline{L}$ in region *r* at the beginning of time period *t*+1 is given by:

(18) $$\overline{L}_{r,t+1} = \overline{L}_{r,t} \cdot \left(1 + g_{r,t}\right).$$

Effective labour $\overline{L}$ increases by the growth rate $g_{r,t}$ in every time step. The growth rate may incorporate growth of the human capital accumulated per physical unit of labour, population growth, and / or total factor productivity improvement.

Investment in the current period augments the capital stock in the next period. The aggregated regional capital stock, *Kst,* is updated in each time period *t* by an accumulation function equating the capital stock available in the next period, Kst_{t+1}, to the sum of the depreciated capital stock of the current period and the current period real gross investment, Z_t^r. In each time period gross investment is determined by equation (17). The equation of motion for the capital stock $Kst_{r,t+1}$, used in region *r,*[28] is given by:

(19) $$Kst_{r,t+1} = \left(1 - \delta_t\right) Kst_{r,t} + Z_t^r$$

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[27] For different types of closure rules see Conrad (1997). We omit an exact specification of the closures for the generic model because they are less important for the direct incorporation of climate impacts into the model.

[28] The corresponding capital service is denoted by the variable K_r in the generic model above.

where d_t denotes the exogenously given depreciation rate in period *t.* The allocation of capital among sectors follows from the intra-period optimisation of the firms.

4.2 Analytical Extensions for Modelling Climate Impacts

After having presented a generic CGE model for climate policy evaluation we now extend the model in order to incorporate climate impacts on the economy. Climate variables have direct and indirect impacts on economic sectors and agents. These climate impacts can be introduced into the CGE framework by altering exogenously certain parameters according to climate change. Climate variables may influence the behaviour of all economic agents and the system constraints of the general equilibrium model. Therefore, the CGE model components like production, final demand, and the update of factor endowments are looked at with regard to the possibility of implementing climate impacts.

As mentioned in chapter 3, the CGE framework is capable of incorporating direct climate impacts on production sectors or final demand. The resulting indirect impacts for all other components of the economy can be derived through the interactions in the general equilibrium framework. The behaviour of all economic agents in the economy is explicitly described by objective functions and restrictions. Hence, climate change has to be modelled in terms of physical impacts. This has the advantage of avoiding the use of questionable price tags on climate impacts in the CGE framework.

The climate change impacts outlined in chapter 2 can be classified as impacts on production, and private and government demand. For implementing climate change impacts into the generic model, we first look at the production side, then the final demand side, the model dynamics, and conclude with the second order effects.

4.2.1 Production

The linkage between changes in climatic variables and their impacts on production activities may be established by considering climate as an exogenously supplied commodity or input.[29] Since it is exogenously imposed at a zero price, it represents an implicit input into production of various goods and services. Thus, the production decision of the generic model may be extended to:

$$(20) \qquad Y_i^r = Y_i^r\left(FE_i^r, H_{1i}^r, \ldots, H_{ji}^r, \ldots, H_{Ni}^r, \omega^r\right),$$

where the ω denotes the quantity or quality of climate factors which are different for each region *r*.

In the generic model we have described the producers' behaviour in terms of profit maximisation with respect to the production function. For incorporating the climate impact we use now the principle of duality to represent the behaviour of agents in the model. The principle of duality says that any concept defined in terms of the properties of the production function has a dual definition in terms of the properties of the cost function and vice versa (Varian (1992, p. 81)). Therefore, the dual decision problem to profit maximisation is cost minimisation and can be represented by the cost function.

The cost function measures the minimum cost of producing a given level of output for some fixed factor prices. As such it summarises information about the technological choices available to the firms. We choose the dual representation of the behaviour for modelling the climate impact ω^r since it subsumes the behavioural assumptions in the functional specification. Therefore, the cost function allows to analyse the effects of the climate parameters already on

[29] Kokoski (1984) was among the first who has implemented climate factors into the CGE framework on the production side. This section draws mainly on Kokoski (1984).

the *optimal* decision. Hence, a technology can be completely specified by a parametric form of the cost function which is a continuous homogenous, monotonic and concave function of factor prices.

Since the climate impact ω^r is exogenous, the effect of a given change in ω^r on the sectoral output Y_i^r is tantamount to a parametric change in the cost function (Kokoski (1984, p. 166)). Hence, one has to consider specific functional forms of the cost functions such as the constant-elasticity-of-substitution (CES) function. The CES unit cost function[30] can be explicitly written as:

(21) $$\lambda_i(\pi) = \gamma \left[\sum_j \kappa_j \pi_j^{\;1-\sigma} \right]^{1/(1-\sigma)}$$

where

$\lambda_i(\pi)$	is the cost per unit of output *Y* of good *i*
π_j	is the price of input *j*[31],
σ	is the constant elasticity of substitution between the inputs,
κ_j	is the share parameter of input *j*,
γ	is the efficiency parameter.

The parametric role of the climate factor ω may now be represented by incorporating the climate factor ω into the CES unit cost function for producing good *i* (cf. Kokoski (1984, p. 166)):

(22) $$\lambda_i(\pi) = A_i(\omega) \cdot F_i\left[S_j^i(\omega), \sigma_i(\omega) \right]$$

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[30] The unit cost function gives the minimum costs per unit of output *Y*. Multiplying the unit cost function with total output *Y* gives the total cost function C(π).

[31] The subscript *j* stands for all intermediate inputs, represented by H_{ji} in the primal form, and for all factors, i.e. L and K in the primal form of the generic model (cf. section 4.1), hence, for all inputs of the production process of good *i*.

where

$\lambda_i(\pi)$	denotes the cost per unit of output Y of good *i* as a function of input prices π
$A_i(\omega)$	is a scaling factor or total productivity index,
$F_i[.]$	denotes the CES cost function type for good *i*
$S_j^i(\omega)$	represents the cost shares (or coefficients at given price vectors) of input *j* in producing good *i*,[32]
$\sigma_i(\omega)$	is a vector of elasticities of substitution between inputs *j* for producing good *i*.

Here, the climate impact ω affects the nature of the production process by changing the parameters which define the technical relationship between inputs and outputs. Therefore, the influence of changing climate works through the productivity effect, the endowment effect, the variation of input shares, and the elasticity of substitution.

Productivity

Climate change may influence total factor productivity as well as the productivity of individual factors. In the first case, a change in ω would reduce (or increase) the quantity of output at given input quantities, i.e. the production isoquant shifts in a parallel fashion according to the change in the productivity index $A_i(\omega)$. An example would be a farmer applying given amounts of labour, land, and fertiliser to crop production with yields depending upon rainfall conditions described by ω_0 or ω_1. Such a change in the total factor productivity can be modelled as an exogenous change of the scaling factor of the unit cost function from $A_i(\omega_0)$ to $A_i(\omega_1)$.

[32] The cost share $S_j^i(.)$ represents a function whose explicit form depends on the underlying CES function $F_i[.]$. If we consider a single level CES function $S_j^i(.)$ is equal to the share parameter κ in equation (21). If we consider nested (hierarchical) CES functions, which are mostly used in CGE models, $S_j^i(.)$ becomes rather complicated. See Chung (1994, p. 135) for a two-level nested CES cost function. As it can be seen from the example of a two level-nested CES function, the share parameters depend on the elasticity of substitution, σ, but the elasticity of substitution is independent of the share parameters (cf. Chung (1994, p. 135)).

The second case assumes that producers react to climate change by changing their production process. The production technology which minimises cost under climatic condition ω_0 may be suboptimal compared to an available alternative technology under changed climate conditions ω_1. This reaction can be modelled in several ways in a CGE framework. One way to implement changes in production technologies resulting from climate change would be to vary factor specific productivity indices (see e.g. Tsigas et al. (1997) or Godden and Adams (1992)). Another way to model these changes in production technology is via exogenous changes in the share parameters of the unit cost function which is described in more detail below.

Tsigas et al. (1997, p. 283) use the following production function for agricultural sectors, here presented for the two factor case:

(23) $$\frac{Y}{A_0(\omega)} = f\left(x_1 \cdot A_1(\omega), x_2 \cdot A_2(\omega)\right),$$

where the parameter A_0 describes the climate dependent total factor productivity index and A_1 and A_2 are factor specific productivity indices. The productivity of land for instance is highly dependent on climatic conditions. But also capital and labour perform differently under different climatic conditions.

Primary Factor Supply

Besides its impact on productivity, climate change may directly affect the supply of primary factors. For example, valuable land may disappear in the case of sea level rise, labour supply may be reduced as a result of migration or human health deterioration, and physical capital may be destroyed by catastrophic events such as storms or floods.

Furthermore, it can be assumed that climate factors are an inseparable part of the region's endowments, i.e. the quantities of endowments subsume quality aspects which may be affected by climate (Kokoski (1984, p. 152)). Therefore, the physical impacts of climate change influencing the quality of inputs may also be translated into a change in the quantity of the respective factor inputs.

Arable land is not homogenous but has to be differentiated according to quality attributes such as soil fertility, slope, and the amount of sunshine, heat and precipitation it receives (Kokoski (1984, p. 168)). A decrease in precipitation may reduce its productivity which is equivalent to a decrease in the endowed quantity of land. This also implies that cropping patterns may have to be changed in response to climate change.

Land differentiation can be incorporated into the CGE framework by dividing the whole regional endowment of land into various land classes which can only be used by specific sectors and where climate influences the supply of land classes differently (see section 5.1.2). The labour endowment may also subsume different quality aspects. Hence, the effects of climate factors on human health and physical productivity of labour can be likewise specified by altering the endowment quantity of the factor labour.

Summarising the impacts of climate change on factor supply, the „endowment effect“ may be represented in a CGE model by expanding equations (11) and (12) in the generic model with $\overline{K} + \Delta_K(\omega_1)$ and $\overline{L} + \Delta_L(\omega_1)$ where $\overline{K}$ and $\overline{L}$ denote the base case quantity endowment of the primary factors capital and labour. Δ gives the percentage change in the endowment as a function of the change in the climate factor ω from ω_0 to ω_1. Under this type of „endowment“ scenario, the impacts of climate change affect all sectors using the input concerned. The results of modelling climate change impacts via the „endowment effect“ or via the specific-input productivity change are the same. The nature and magnitude of the impact on a given sector depend on its cost functions parameters such as the nesting structure of the cost function and the elasticity of substitution among primary factors (Kokoski (1984, p. 169)).

Elasticities of Substitution

Climate change may influence the production technology not only by affecting the location of the isoquants through productivity changes or changes in the primary factor supply, but also by reducing or increasing the elasticities of substitution between the inputs used, i.e. changing the curvature of the isoquants. The elasticity of substitution among inputs reflects the flexibility of producers to respond to changes in input prices. Hence, if the elasticity of substitution increases (decreases) due to a change in climate factors from $\sigma_i(\omega_0)$ to $\sigma_i(\omega_1)$ the production technology would become more (less) responsive to changes in input prices. That means if the employment of one input becomes less suitable under new climatic conditions, say for instance heavier machinery on wetter soil conditions due to increased amount of rainfalls, its substitutability for other inputs decreases. This can be modelled by changing exogenously the elasticities of substitution among these climate affected inputs (cf. Godden and Adams (1992)).

Variation of Input Shares

As mentioned above, a plausible reaction to climate change induced productivity changes is the variation of input shares from $S_j^i(\omega_0)$ to $S_j^i(\omega_1)$ as proposed by Kokoski (1984). The share parameters of the unit cost functions may alter because agents adjust their behaviour to mitigate the impacts of the climate change. An example would be a farmer who employs greater proportions of capital and energy per given expenditure on inputs when the amount of precipitation diminishes.

This exogenous alteration of the share parameter from $S_j^i(\omega_0)$ to $S_j^i(\omega_1)$ must not be confounded with the endogenous change of the input shares resulting from changes in relative prices. These endogenous quantity reactions of inputs to price changes are determined by the elasticities of substitution in place. As can be seen in the example of the two-level nested CES function (cf. Chung (1994, pp. 135)), the share parameters depend on the elasticity of substitution but the elasticity of substitution is independent of the share parameters, and therefore, does not change if share parameters $S_j^i(\omega_0)$ are altered.

4.2.2 Final Demand

In the generic equilibrium model final demand is derived from the utility maximisation problem of the representative household in region r.[33] The consumption and savings behaviour of the representative household is described by specific functional forms. Hence, climate change may be implemented as a parametric change of the expenditure function of the household similar to the production activities. Also the government behaviour can be described by a climate-dependend expenditure function.

Private and Public Expenditures

The utility maximisation problem of the representative agent (cf. equation (6) in the generic model) may be represented by the dual minimisation problem, where the agent q[34] wants to maintain a certain utility level while minimising the expenditures. Hence, the behaviour of the agent q can be described by an unit expenditure function ε, which gives the expenditure for the 'production' of one unit of utility. Assuming a special functional form, e.g. a CES function, the unit expenditure function of agent q, $\varepsilon_q(\pi_i)$, including the climate factor ω is given in analogy to the unit cost function (cf. equation (22)) by:

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[33] Investment good demand by industry sectors is similar to the intermediate good demand of these sectors. Total investment demand by region r is equal to domestic savings (cf. equation (17)). The derived regional investment depends on the savings-investment closure rule chosen. i.e. whether regional investment or savings is exogenously specified.

[34] In the generic model q corresponds with index r. We use the index q because q may also comprise the government besides the private household in each region r.

(24) $$\varepsilon_q(\pi_i) = A_q(\omega) \cdot F_q\left[S_i^q(\omega), \sigma_q(\omega)\right]$$

where,

$A_q(\omega)$ is the climate dependent scaling factor of expenditure of agent *q*,

$S_i^q(\omega)$ is the expenditure share of consumption good i in 'producing' a certain level of consumption (or utility) for agent *q*,

$\sigma_q(\omega)$ is a vector of elasticities of substitution among the inputs for 'producing' a certain consumption level demanded by agent *q*.

The scaling factor $A_q(\omega)$ relates the minimum amount of income or expenditure necessary for achieving one unit of utility for agent *q*. That means, a change in the climate factor ω would increase (or reduce) the minimum cost of achieving a fixed level of utility or would alter the utility level achievable with a fixed amount of income. Hence, the non-market climate impacts influencing the utility of agent *q* may be subsumed under the scaling factor $A_q(\omega)$. But this is a rather vague concept because the impact can be hardly quantified.

More realistic seems the exogenous alteration of agent *q*'s expenditure share for good i, $S_i^q(\omega)$, due to climate change. For example, private households increase their demand for air condition in Europe in response to a rise in temperature. This means that the share of air condition products will increase in the expenditure function of households in response to an exogenous change in climate factors. Another example is, that the government may increase its expenditure share for climate adaptation measures, e.g. coastal protection, in the public budget. Moreover, the share between consumption and savings, or investment respectively, may exogenously alter due to a shift in climate factors.

Furthermore, a change in climate factors may influence the responsiveness of agents in adjusting their expenditures to a change in relative prices. This can be modelled by altering the elasticity of substitution, $\sigma_q(\omega)$, in the expenditure function of agent *q*. However, this approach seems rather artificial.

In general, modelling climate change impacts on the demand side is possible but rather hypothetical, except for the climate induced changes in expenditure shares. It may be preferable to model the climate impact through the production side which influences the demand side through second order effects, i.e. changes in relative prices of consumption goods, changes in factor income, or changes in the relative prices between consumption and investment, because better data and more sophisticated impact studies are available for the supply side (cf. chapter 5).

Trade Relations

The intermediate and final goods demanded by agents are Armington goods, i.e. composite goods consisting of imported and domestically produced goods (cf. equation (4) in the generic model). Hence, goods are differentiated by regions of origin, and regions are linked through endogenous bilateral trade flows.

The multi-regional perspective and the modelling of trade relations is very important for analysing the economic impact of climate change. As Kokoski (1984) has shown in her stylised simulations, interregional spillovers of direct impacts as well as regionally different changes in climate variables significantly influence the welfare costs (and/or benefits) of climate change. Furthermore, the regional distribution of changes in welfare among consumers differed widely from the average welfare change of climate impacts given by the aggregated single-regional models (Kokoski (1984, p. 366)). Thus, in assessing costs and benefits of climate impacts from the multiregional perspective, the *nature* of interregional economic relationships is an important factor:

The modelling of international trade (cf. equation (4)), i.e. the Armington specification with regionally differentiated goods versus the Heckscher-Ohlin specification with regionally homogenous goods, strongly influences the international spillovers of climate change obtained with the model. If the Armington elasticity of substitution is very high, i.e. goods originating from different regions are almost homogenous, the interregional spillovers from direct climate impacts are also high and vice versa.

Climate change may also influence trade flows through changes in transport costs[35]. For example, an increase in the intensity and frequency of storms may lead to an increase in transport costs. A rise in transport costs changes the relative price between domestically produced and imported goods, and thus, influences the allocation between imports and domestic products. Furthermore, bilateral trade flows may be affected differently which leads to a change in relative prices between the imported goods stemming from different regions and thus to a change in the import structure. These trade effects of climate change may be modelled by climate dependent bilateral international transport costs, $TC_{i_r}^{s}(\omega)$, which have to be incorporated into equation (4), the Armington specification in the generic model.

4.2.3 Dynamics

As mentioned in chapter 2, climate change may also lead to an increase in the probability and intensity of extreme events such as heat waves, tropical hurricans, storms and floods. Immediate impacts of such natural catastrophes may be quantified in terms of losses in endowments like capital or useable land area. This would influence the dynamics of the generic CGE model.[36]

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35 International transport costs may be represented by the price wedge between the bilateral export and import price of good *i*.

36 Also the investment behaviour may alter because of climate change. Investors may, for example, be more reluctant to invest in climate sensitive sectors such as forestry. Modelling the climate impact on the

The endowment loss due to extreme weather events may be depicted by a climate dependend depreciation parameter, $\delta_t(\omega)$, in the update equation for the endowments (cf. equations (18) and (19)). Considering, for instance, climate change impacts on capital accumulation, equation (19) becomes:

$$Kst_{r,t+1} = (1 - \delta_t(\omega))Kst_{r,t} + Z_t^r \tag{25}$$

where Kst stands for all types of endowment. An increase, for instance, in the frequency of storms, i.e. ω_0 shifts to ω_1, would cause a greater destruction of capital compared to the case without changes in the climate variable. This can be modelled by increasing the climate dependent depreciation rate from $\delta_t(\omega_0)$ to $\delta_t(\omega_1)$. The same method can be applied to model land losses resulting from a higher intensity and/or probability of floods, and changing labour supply due to cliamte induced mitigation or impacts on health.

4.2.4 Second Order Effects of Climate Impacts

The aggregate net cost or benefit of climate impacts to the economy do not only depend upon their direct impacts on affected sectors, but also upon the repercussions of these direct effects. For modelling climate change impacts the CGE framework is attractive because of its capacity to represent all relevant components of an economy and to model explicitly the interrelationships of these components.

As shown above, the change in climate variables as, for example, seasonal temperature, precipitation or extreme weather events may influence the factor endowment of economies, the productivity of factors, the parameters of production functions and the final demand. A CGE model may incorporate these direct climate impacts on production sectors and final demand.

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investment decision would require to specify explicitly the investment decision intertemporally. However, the generic model is recursively dynamic and considers only myopic agents. Therefore, the influence of climate on the investment decision is not considered in this paper.

The indirect impacts for all other components of the economy result from the transmission mechanism in the model. The propagation of the direct climate impact throughout the model depends on the behavioural rules specified for the agents, the signals they observe, the market structure, and the closure rules assumed in the model.

In the generic model, a direct climate impact on, e.g., capital endowment would lead to a change in the relative price for capital. Assuming perfect competition with flexible prices and agents as price takers, all factor and good markets adjust according to this changed price signal until a new equilibrium is reached. Here, the macroeconomic closures chosen may influence the outcome of the model because they determine the way how the economic system adapts to climate impacts.

Therefore, even a single detrimental climate impact, such as an increase in the cost per unit of agricultural products, $\lambda_{Agric}(\pi)$, may cause welfare gains to certain agents through increased returns to factor resources. The magnitude and distribution of the welfare gains and losses depend upon the distribution of factor endowments, the behavioural rules, and market interrelationships in a complex fashion (Kokoski (1984, p. 371)).

In contrast to that stands the partial equilibrium approach which neglects indirect impacts and interrelationships within and among economies. Kokoski and Smith (1987) and Tsigas et al. (1997) compare the performance of partial and general equilibrium welfare measures. They find out that the structural attributes of the economy under concern are an important factor.

5 Numerical Implementation

The general equilibrium framework is well suited for modelling the economic impacts of global warming. However, to compute the costs and benefits of climate change, the theoretical structure has to be combined with empirical evidence of climatic effects.

In this context a problem of consistency may arise: The empirical quantification of impacts and adaptational responses has to be made on the basis of physical impact studies. Yet, most physical impact studies that connect natural science models with economic models refer to small economic entities such as individuals, households or firms. Thus, the results in terms of firm-level or household estimates have to be translated consistently into changes of sectoral production functions and aggregate final demand functions.

This chapter focuses on the derivation of numerical values for the quantification of the climate dependent parameters and variables of sectoral production functions. This will be done by surveying contributions from the literature that deal with climate change impacts on agricultural production.

The concentration on agriculture in section 5.1 reflects the state of the literature where few contributions exist that deal with climate change impacts on other sectors. The fact that agriculture is highly dependent on weather and climatic conditions suggests that important impacts are to be expected within that sector. Moreover, considerable macroeconomic impacts are to be expected in regions where agriculture plays an important role in income generation. Even though the focus is on agriculture, general methodological insights may be derived from this literature that are useful for impact modelling in CGE frameworks.

In section 5.2 examples are given for modelling demand side impacts in CGE models. Furthermore an approach is presented that integrates non-market related impacts into a CGE model.

5.1 Lessons from Agricultural Impact Studies

The first part of this section discusses agricultural impact studies of different levels of aggregation. These studies start from agricultural production functions and are based on the examination of climate change impacts on yield changes. From the discussion of these 'production-function-approaches' (Mendelsohn et al. (1993)) conclusions are drawn for CGE modelling and two examples of application are presented.

The second part of the section deals with alternative approaches of examining climate change impacts on agriculture. The first contribution is the so-called 'Ricardian Approach' (Mendelsohn et al. (1993))[37] which directly examines the influence of climate on economic variables, instead of investigating production functions. The second contribution examines climate change impacts on land endowment in a CGE framework.

5.1.1 The Conventional Approach: Yield Changes

The majority of agricultural impact studies start from climate change impacts on crop growth and examine attendant yield changes. In order to derive resulting output changes, these yield changes are combined with economic representations of agricultural production.

The response of yields to changing climatic conditions is most frequently derived with crop growth simulation models (Parry (1990)). These models simulate the growth process of a given plant throughout the growing season. They explicitly represent the biophysical processes that underlie the interactions of plant growth, soil and climate. This makes them universally applicable. In order to obtain region-specific yield changes, data from the region under consideration are fed into these models. Examples of growth simulation models are CERES-Maize (Ritchie et al. (1989)), CERES-Wheat (Ritchie and Otter (1985)) and SOYGRO (Jones et al. (1989)) which are frequently used in agricultural impact studies (Adams (1989), Adams et al. (1990), Adams et al. (1995), Rosenzweig et al. (1993), Rosenzweig et al. (1998)).

In order to analyse the economic responses to climate change induced yield changes the results obtained with crop growth simulation models are combined with economic models of agricultural production. The problem that arises at this step of the analysis are the different

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[37] The approach is called 'Ricardian' after Ricardo who analysed the economic determination of land rents.

temporal and spatial dimensions of biophysical and economic models. The former use daily time steps and describe the reaction of a single plant while economic processes are modelled in annual time steps and refer to farm, regional, or national agricultural spaces (Johnson (1991)). Given this problem, the most appropriate economic model is one that explicitly describes the objective function and restrictions of the smallest agroeconomic unit, i.e. the farm. In such a microeconomic framework the interdependencies between environmental conditions and economic decisions can be adequately represented.

In the following three agricultural impact studies are discussed. The first models economic activity on the farm level, the second models a national agricultural sector, and the third covers global agricultural markets.

In their *farm-level* study Kaiser et al. (1992) model a hypothetical cash-grain farmer who is representative for the region under consideration. The farmer faces environmental constraints which depend on climate. These include crop yields, crop moisture content and field time availability. Economic constraints include primary factor availability and output prices. Some of the constraints vary stochastically with climate dependent states of nature. The farmer maximises expected annual net revenues by deciding upon the timing of field operations and the crop species to grow. Decisions on annual farming activities take place in two steps: In spring decisons are made on crop choice and on the timing of field operations. These decisions partly determine the harvest options the farmer has to decide upon in autumn.

The microeconomic framework applied by Kaiser et al. (1992) allows the detailed modelling of the farmer’s decision process and the integration of climate dependent constraints. Changes in agricultural output are then obtained as a result of the responses of the farmer to the direct climate change impacts on the environmental constraints he faces. This specification allows a consistent derivation of the consequences of climate change impacts on the farm level. However, farm-level models cannot derive regional supply changes of agricultural commodities or interregional production shifts resulting from climate change. Nor can they derive such welfare measures as consumers' and producers' surplus. The analysis of these larger scale effects and welfare implications requires the application of sectoral models.

The *sectoral model* by Adams (1989) and Adams et al. (1990), Adams et al. (1995)) is a partial equilibrium model of the national agricultural sector of the U.S. where the empirical values for sectoral supply shifts are obtained from a regionally disaggregated analysis.

Agricultural production in each region is characterised by a series of technical coefficients. The coefficients describe producers' behaviour and regional endowments of primary factors of production. Simulated yield changes are then combined with these representations of regional agricultural production in order to obtain regional supply changes. Hereby, adaptational responses in the form of substitution among input factors and substitution of crops are considered. This method can be compared to the modelling of representative farms as applied by Kaiser et al. (1992).

Regional supply changes are linked to national demand in an aggregated sectoral model. The analytical framework underlying the aggregation of heterogeneous firms — heterogeneous regions in the model by Adams (1989) and Adams et al. (1990), Adams et al. (1995) — into a sectoral supply function is explicitly described in McCarl and Spreen (1980), Önal and McCarl (1989), and Önal and McCarl (1991).

In order to derive the welfare implications of climate induced yield changes Adams (1989), Adams et al. (1990), and Adams et al. (1995) assume perfect competition in supply and demand. This enables them to derive annual net income gained or lost in terms of changes of net economic surplus. For each agricultural commodity market net surplus is the sum of consumers' and producers' surplus, and net agricultural surplus is the sum of net surpluses on all agricultural commodity markets.

Adams (1989), Adams et al. (1990), and Adams et al. (1995) demonstrate that a consistent assessment of climate change impacts is possible in a sectoral model if sectoral responses to climate change impacts are based on microeconomic foundations and if a theoretically sound aggregation procedure is used.

Kane et al. (1992) and Reilly and Hohmann (1993) examine climate change impacts on *world markets* for agricultural commodities. The consideration of world markets is important for impact assessment because they can transmit the consequences of climate change impacts occurring in one region to other regions. The net welfare effect of climate change impacts on a country depends on its net trading position: Suppose a large net exporter of an agricultural commodity is subject to climate change induced yield decline. This leads to a decline in export supply, the world price increases. The rise in world price induces an increase in producers' surplus which may dominate the loss of producers' surplus due to yield decline and the loss in consumers' surplus due to the higher price for the agricultural commodity. The net welfare position of the country improves. A large net importer, in contrast, may experience net welfare losses: If yield declines result in a higher demand for imports and an increase of the world market price, the loss of consumers' surplus due to the higher world market price and the loss of producers' surplus due to yield declines may be too large to be outweighed by the higher producers' surplus due to the price increase.

Kane et al. (1992) and Reilly and Hohmann (1993) examine climate change impacts on world food markets using the Static World Policy Simulation (SWOPSIM) model. Each region is represented by a demand and supply function for each agricultural commodity it produces or consumes. The regions are connected by trade in these commodities. In equilibrium world supply of a commodity equals world demand. Yield changes are introduced as parametric shifts of the regional commodity supply functions. Then the model is solved for a new equilibrium which allows for an analysis of welfare changes by means of comparative statics.

In contrast to the other two models discussed above, the quantification of the shifts of the regional supply functions is based on different sources of the literature. This seems to be reasonable in the presence of the broad regional scope of the analysis. The introduction of results from different sources into the model requires a careful analysis of the assumptions and methods underlying these studies. It is likely that the assumptions on climate change as well as on biophysical and economic responses do not match exactly. Also the regional dimensions may not fully coincide.

On the basis of the review of these three examples of agricultural impact studies a first conclusion may be drawn for the empirical quantification of the climate dependent parameters and variables of the sectoral production functions in CGE models.

The surveyed studies are compatible with the CGE context. Especially the farm-level and the national agricultural sector study can be used to quantify climate impacts by translating them into exogenous parametric changes for the CGE model. The results of the global scale studies by Kane et al. (1992) and Reilly and Hohmann (1993), however, cannot be used for the quantification of climate change impacts because they already include economic adaptation generated by the model. In CGE models adaptation in the form of changes in relative input or output quantities takes place endogenously via the optimisation process caused by changes in relative prices. Therefore, using the results of the global scale model would lead to a 'double counting' of economic adaptation. Nevertheless, the global approach shows how different sources of literature can be exploited for quantifying the climate dependent parameters in the model.

As argued in section 4.2.1 sectoral yield changes may be represented by changing the total productivity parameter $A_i(\omega)$, where i denotes the agricultural sector considered. Yield changes derived from farm level or national level studies have to be aggregated according to the sectoral definition of the CGE model. If a functional relationship between yield change and climate variables is established, these agricultural output changes are translated into inverse productivity changes. Thereby, it is assumed that the changed output is obtained by application of the same inputs, i.e. the other parameters of the production function such as $S_j^i(\omega)$ or $\sigma_i(\omega)$ remain constant. For example, a decrease of 20% in yield is represented by a 20 % increase in inputs per unit of output, i.e. the cost function for agriculture is scaled up by 20% via $A_i(\omega)$.

Alternatively, the behavioural response of agricultural producers to changed climate may be incorporated exogenously into the CGE model by altering the input share parameters $S_j^i(\omega)$ or the elasticites $\sigma_i(\omega)$ of the cost function. Information about behavioural changes due to climate impacts may be derived from farm-level studies such as Kaiser et al. (1992).

However, one has to distinguish carefully between exogenous behavioural responses to climate change implemented into the model and the model-inherent reoptimisation process. Exogenous changes of behavioural parameters alter the results of the reoptimisation process, capturing the fact that climate change impacts influence the options economic agents face in optimising their behaviour.

As demonstrated by the reviewed contributions a consistent quantification of the sectoral production function has to be based on the microeconomic foundation of firm-level responses. For that purpose, the integration of models of different levels of aggregation is an appropriate method (Johnson (1991)).

An example for this method is the study by Conner (1994) which analyses the socio-economic impacts of climate change on grazinglands. It starts with the choice of representative firms and ends at the regional level. At each level appropriate biophysical or socio-economic models are integrated. The augmenting levels of aggregation are consistently connected insofar as output data from the lower level model enter the model describing the subsequent level.

If it is not possible to connect models of different levels of aggregation, empirical values for adaptational responses and supply changes have to be taken from other sources. These sources have to be thoroughly checked with respect to the underlying assumptions on climate change, climate change impacts and economic responses. Furthermore, the spatial dimension of the source studies should coincide with the regional coverage of the main model.

Examples for modelling the economy-wide consequences of climate change impacts are the works by Easterling et al. (1993), Bowes and Crosson (1993) and Scheraga et al. (1993).[38] The contributions by Easterling et al. (1993) and Bowes and Crosson (1993) refer to a study that integrates biophysical and economic models in order to derive regional supply shifts of agricultural commodities. Scheraga et al. (1993), in contrast, refer to the results of other studies to quantify climate change impacts on production cost in the agricultural sector.

Easterling et al. (1993) and Bowes and Crosson (1993) use an input-output model (IOM) to examine overall climate change impacts on the Missouri-Iowa-Nebraska-Kansas (MINK) area.[39]

However, because of its fixed coefficients the IOM cannot be used to account for the adaptational responses of the agricultural sector to climate change induced yield declines.[40]

Therefore, Easterling et al. (1993) and Bowes and Crosson (1993) use the Erosion Productivity Impact Calculator (EPIC) to model adaptation. EPIC integrates biophysical processes and farm-level responses. Several representative farms are modelled that characterise

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[38] The economic model used by Bowes and Crosson (1993) is an input-output model (IOM). IOMs have to be distinguished from CGEs in several respects. Although not entirely closed, IOMs may be interpreted as component parts of CGEs insofar as they represent the intersectoral linkages of an economy. Compared to partial equilibrium sectoral models IOMs are a step into the direction of a comprehensive representation of the economy.

[39] A survey on the study is given in Rosenberg and Crosson (1991). A special issue of Climatic Change 24 (1-2), June 1993 is dedicated to the MINK study. Eight contributions, covering all aspects of the study, are presented there.

[40] For an introduction to and applications of input-output analysis see for instance Sohn (1986).

the agricultural systems existing in the MINK area. EPIC allows to simulate climate change impacts and to analyse the responses of the representative farms. Hereby, different assumptions about adaptation options are made. Adaptation options on the farm level include changing the planting date, changing crop species and the introduction of new technologies. Hence, with respect to farm-level responses different results can be obtained from EPIC simulations: Either yield changes that result from climate change impacts without farm-level adaptation or yield changes that result when adaptation measures are taken. The yield changes obtained with EPIC on the farm level are then aggregated to yield changes on a regional level.

The translation of *yield* changes into *output* changes is made under the assumption of a small open economy. This implies that crop prices cannot be influenced by supply changes in the MINK area. Decreasing yields increase marginal production costs. In the presence of fixed output prices, an increase in production costs leads to output declines. This decline is reached by two kinds of responses: Either the production of a given crop species is cut back until marginal costs equal the price again. Or unprofitable production is given up and a more profitable species is produced instead. The IOM cannot derive the magnitude of the output decline because it does not contain information on production costs. Therefore, the output decline is modelled as follows: If the response consists in production cut-backs, output changes are proportional to yield changes. If the response consists in shifting production, the output of the crops the production of which is extended under new conditions declines proportionally less than yields, while the output of the crops the production of which is partially abandoned declines more than in proportion to yields.

The MINK study consistently assesses farm-level responses to climate change induced yield changes. This is achieved by the application of a model that integrates biophysical and economic processes on the farm level. The translation of farm-level responses into sectoral aggregates is limited by the economic model, the IOM, used. Here the trade-off between desired model characteristics and data availability becomes obvious: Although it cannot represent sectoral behaviour the input-output model is chosen because of the favourable data situation. As a counter-move concessions are made as for the translation of yield changes into supply changes.

With respect to data requirements CGEs are more demanding than IOMs. Yet, they have the advantage to allow the modelling of adaptational responses, even in two respects: First, adaptation is automatically considered in the new equilibrium, as the agents reoptimise their behaviour in reaction to changing restrictions. Second, the description of the behaviour of the agents itself, viz. such parameters as elasticities and shares, can be changed exogenously by the modeller.

Scheraga et al. (1993) apply the CGE model of the U.S. by Jorgenson and Wilcoxen (Jorgenson and Wilcoxen (1990)) to examine the economic consequences of climate change impacts on agriculture, electricity supply and coastal protection. Direct climate change impacts on the agricultural sector are introduced into the model as an increase of unit cost. The increase of unit cost is simulated as an exogenous shift of the agricultural production technology that increases the factor requirements for a given level of output.

In terms of our generic CGE model this would correspond to an exogenous increase in unit cost $\lambda_i(\pi)$ for sector i, here agriculture, holding the productivity parameter $A_i(\omega)$ constant. The factor demand for producing one unit of output in sector i can easily be derived by using Shephard’s Lemma, i.e. the first-order derivative of the unit cost function with respect to the factor prices. For a well-behaved cost function the first-order derivative is positive. Hence, the factor requirements for sector i increase when the unit cost is raised exogenously.

Scheraga et al. (1993) base their quantification of the unit cost increase in the agricultural sector on the work by Adams (1989) and Adams et al. (1989). There, the results are given in terms of price increases for agricultural commodities. Scheraga et al. (1993) aggregate them in order to obtain a single price change for agricultural output. They use this price change as an estimate for the increase of unit cost in the agricultural sector. In terms of our generic CGE model, Scheraga et al. (1993) directly increase the aggregated unit cost $\lambda_i(\pi)$ instead of introducing the climate impact in the next lower level of the nested cost function where factor requirements are explicitely stated. Hence, they ignore the information incorporated in the cost function like substitution possibilities among inputs or input-specific productivity changes.

The procedure applied by Scheraga et al. (1993) illustrates the possibility of using the results of more detailed studies if climate change impacts are to be analysed in a highly aggregated model. It demonstrates that CGE approaches do not necessarily have to be integrated with biophysical and more disaggregated economic models as long as the results of other studies are given in suitable terms. Furthermore these studies have to refer to the same area and they have to be based on the same assumptions as the CGE model with respect to climate change, climate change impacts, and adaptational responses.

5.1.2 Alternative Approaches: Land Value and Land Endowment

As demonstrated in the previous section, the derivation of consistent empirical quantifications for parametric shifts of the sectoral production or cost function that capture climate change impacts and economic responses is analytically and empirically demanding. The lack of data or appropriate modelling techniques may prevent the derivation of consistent empirical results. Therefore, this section discusses two approaches that deviate from the production-function-approach. Both approaches start from the meaning of land as an essential factor of production which is influenced by climate.

In their ‘Ricardian Approach’ Mendelsohn et al. (1993, 1994) analyse the functional relationship between climate change and land values directly. They assume that the present economy is perfectly adapted to the prevailing climatic conditions and that the land market is perfectly competitive. In this case, land rents reflect the net yield of the highest and best use of the land under the prevailing conditions. If climate conditions change, the current land use is no longer optimal and adaptation takes place. The new land rents then reflect the new optimal uses. Land values are the expected present values of future rents.

Mendelsohn et al. (1993), Mendelsohn et al. (1994) do not consider the adaptational responses of the land owners — which include changes of crop variations, substitution of inputs and complete changes of land use — explicitly.

Instead, the influence of climate on land value is estimated statistically. Two data sets, from 1978 and 1982, for 3000 counties covering the lower states of the U.S., are used in the regression analysis. The underlying idea is to infer likely responses to changing climate from a comparison of farmer behaviour under different climatic conditions as they prevail across the U.S. Under the assumptions of perfect adaptation and perfect land markets, other things being equal, land rents should reflect these differences in climate. In order to control for differences other than climatic conditions, variables that represent soil and socio-economic characteristics are included as regressors. The same analysis as for farm land values is done for farm revenues.

The climate variables considered are temperature and precipitation for four months of the year in order to account for seasonal variations. These regressions yield the marginal influence of climate variables on farm value or farm revenue. These relationships, which are obtained from historical data, are then used to make projections of the influence of expected climate changes on land values or farm revenues.

As for all empirical work it has to be kept in mind that the results obtained from the analysis of data from one region and time span cannot be easily extrapolated to other regions or to the future. Using the estimates of marginal impacts of climate variables on farm value or farm revenue for predictions rests on the assumption that the biophysical and economic responses underlying the model are also valid in the future, when climatic changes are supposed to occur.

The Ricardian Approach represents an alternative to impact modelling in a CGE framework. Both approaches consider the influence of climate as an input to the production process and solve for prices which satisfy the optimality conditions. In the Ricardian Approach all information about climate impacts are contained in one single price, i.e. land value or land revenue, whereas the CGE framework considers the repercussions of changes in the agricultural sector on other economic sectors and activities and solves for a price vector in equilibrium which includes the economic evaluation of climate impacts. Therefore, the price information given by the Ricardian Approach cannot be used as an input information for the CGE model. Nevertheless, compared to the production-function-approach, the method applied by Mendelsohn et al. (1993), Mendelsohn et al. (1994) has the advantage of directly connecting climate variables to economic variables. This avoids a considerably amount of modelling effort.[41]

Also Darwin et al. (1996) deviate from the conventional examination of climate change impacts on yields. In their 'land-class-approach' they concentrate on land as a climate dependent factor of production. They include land into a CGE model as a heterogeneous primary factor which is essential to all sectors. This model is an aggregation and extension of the Global Trade Analysis Project (GTAP) model (Hertel (1997)).[42]

The heterogeneity of land is specified in terms of different productivities. There are two sources of productivity differences: one source is climate and the other source is the economic

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41 The results obtained by Mendelsohn et al. (1993), Mendelsohn et al. (1994) are criticised by Kaufmann (1998). He claims, that across the different models that are estimated, the coefficients obtained for the climate variables are not stable. Furthermore, the coefficients estimated with some of these models are not consistent with the physiology and economics of grain production. According to Kaufmann this completely undermines the credibility of the models applied for the regression.

42 Darwin et al. (1996) refer to an older version from 1993. Hertel (1997) gives a comprehensive description of the GTAP model and compiles a number of applications.

use of land. These two sources of productivity differences are captured by classifying each unit of land that is used in production according to these two criteria.

The first criterion captures productivity differences of land that are caused by climate. Climate influences the length of growing seasons which determines potential productivity. Six land classes which differ in the length of growing seasons are distinguished. Each unit of land used as input to production is assigned to one of these land classes. The second criterion captures productivity differences of land that accrue from different economic uses. Each unit of land is classified into one of the following land use categories: cropland, pasture, forest and other land. Thus, in the benchmark equilibrium each unit of land used in a given sector in a given region belongs to a *land class* that depends on climate and to a *land category* which indicates its economic use.

The economic use of land is further specified in the CGE: For each region eleven production sectors are defined, each of which uses land as an essential factor of production. Cropland is used in the crop sector, pasture in the livestock sector, forest in the forest sector, and other land in the manufacturing and service sectors.

Productivity differences exist between land classes because of climatic differences and within land classes, and thus between land categories, because of different economic uses.

Climate change impacts on land endowment are introduced into this framework as changing distributions of land across land classes. These changes are derived with a Geographical Information System which connects changes of climate variables and length of growing seasons. Changes of the length of growing seasons change the natural productivity of (economic) land categories. This is shown by the new land class classification of the land categories concerned.

If the natural productivity of land changes, a given unit of land used in a given sector is less productive than before the change. The economy adjusts to these exogenous changes of productivity by shifting the use of land towards the use where it is economically most productive given its new natural productivity.

The economic model solves for a new equilibrium with new quantities and prices which result from the adjustment process. With respect to land use this adjustment process is modelled by specifying several elasticities of substitution and by making further assumptions:

Factor substitution elasticities are relatively low in the land-intensive sectors while they are highest in the service sector which is the least land-intensive. Primary factors, which include land, are Leontief-connected to intermediate inputs which precludes substitution between primary and intermediate inputs. In each region the total endowment of land is fixed and exogenously given. Land is immobile across regions. This implies that the expansion of one kind of land use restricts other uses. Together with the assumption that land is essential to all production sectors this model specification reflects competition for the heterogeneous production factor land within a region.

The new equilibrium is characterised by new economic uses of the land, i.e. structural change has taken place.

The land-class-approach is conceptually consistent with the CGE framework and can therefore be applied to introduce one kind of physical impacts of climate change, namely changing land quality, into the economic model.

The application of the concept of land classes in a CGE framework requires the introduction of land as a factor of production in all sectors. In order to account for the heterogeneity of land with respect to potential productivity climate dependent characteristics of land have to be analysed and formalised. Furthermore it has to be determined how the economy adjusts to changing land endowment. This is done by choosing appropriate elasticities of substitution.

In terms of our generic general equilibrium model this means to implement the additional factor land supplied in region r, $\overline{B}_r$, which is subdivided into M different land classes, with *m=1...M,* distinguished by climate characteristics. Here, several climate variables as temperature, moisture, precipitation etc. are transformed into a one-dimensional variable like growing season. Furthermore, a lower nesting level has to be implemented into the sectoral cost function $\lambda_i(\pi)$ where the different land classes B_r^m are substitutable at a certain elasticity of substitution, σ^m. The influence of a changing climate now comes in either through the endowment effect, i.e. extending or reducing the supplied amount of land class *m* in region *r,* $B_r^m + \Delta_B(\varpi)$ (see section 4.2.1), or through the factor specific productivity improvement or reduction, $A_{B_r^m}(\omega)$ (see equation (23).

Unlike the Ricardian Approach, which is a conceptional, yet partial equilibrium, alternative to the CGE approach, the land class approach connected to the CGE framework allows to derive information on the structural changes which result from climate change impacts. Both, new land prices as well as shifts in land uses, are obtained.

5.2 Final Demand

There exist by far less analyses of climate change impacts on final demand than on the production side of the economy.

An exception is the *demand for energy and electricity*.[43] Scheraga et al. (1993), for instance, introduce demand side impacts on the electricity service sector into their CGE framework using the results by Linder and Inglis (1989). Increasing inter-industry and final demand for electricity which is due to climate change is simulated in the model as an increase in the quantity of electricity input needed to produce a unit of electricity service. This increase in input requirements is assumed to cause an equal percentage rise in unit costs in the electricity service sector.

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[43] A survey on climate change impacts on energy demand is given in IPCC (1996b) (chapter 11).

Besides changes of private household demand the analysis of other components of final demand such as investment, public demand and export demand is relevant for the assessment of climate change impacts.

Investment and public demand, for instance, are important channels of adaptation. If producing sectors change their technology in response to climate change this is done by investment. Compared to a situation without climate change investment may take place earlier or involve higher expenditures. An example for an adaptive measure that can be provided by the government is coastal protection. Scheraga et al. (1993) introduce it into their model as an increase of government purchases from the construction sector which is financed by raising average taxes on labour income to keep the budget balance.

In our generic model an increase in the public expenditure for certain goods *i* due to climate change can be implemented by altering exogenously the share parameter, $S_i^q(\omega)$, in the expenditure function of the government, $\varepsilon_q(\pi_i)$, where q stands for the government.

Export demand can change exogenously, i.e. independently of export price changes, if foreign countries are subject to climate change impacts or if they introduce greenhouse policy measures. The latter case is considered by Godden and Adams (1992) who examine climate change impacts on the Australian economy with the ORANI general equilibrium model. As part of the analysis they introduce an exogenous decline in export demand for Australian coal. This decline is motivated by emission policy abroad which is supposed to induce substitution away from emission intensive energy generation on coal basis.[44] Declining export demand can also be motivated by climate change impacts on the exporting region itself. An example is the decline of the attractiveness of a region for tourism which can occur as a consequence of climate change.

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[44] In contrast to a single region model as ORANI a multi-regional model as outlined in chapter 4 allows for an endogenous change of export demand motivated by unilateral climate policy.

The quantification of climate change impacts on final demand is subject to the same difficulties as the quantification of impacts on production, i.e. the consistent numerical implementation of physical impacts into economic models. Additional complications occur if climate change impacts on utility have to be analysed, because many goods that contribute to utility are non-market goods (cf. chapter 2). Impacts on such goods as, for instance, intrinsic values of ecosystems are difficult to analyse in CGE models because these goods are not considered in national accounting.[45]

Perroni and Wigle (1997) have suggested a possibility to introduce *non-market values* into a CGE framework. In particular, they have modified and extended the GTAP model (Hertel (1997)) in order to derive the net welfare implications of an introduction of emission fees. These welfare implications include the improvement of environmental quality, a non-market good which contributes to utility.

They specify a CES utility function with an elasticity of substitution between conventional consumption goods and environmental quality. Environmental quality is defined as the difference between the initial endowment of environmental quality and emission damages. Emission quantities are obtained from the production part of the model. It is assumed that the marginal damages from these emissions are constant. The initial endowment of environmental quality cannot be quantified. In order to be able to compute the model at all, the authors assume that the ratio between damages and environmental endowment in the benchmark case is 0.25. Then, total utility, including environmental quality, depends on consumption goods and on emission damages which are determined within the model. The elasticity of substitution between the two components of total utility, namely between consumption goods and environmental quality, is assumed to be 0.5.

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[45] A revision of the System of National Accounts of the United Nations is in progress in order to introduce environmental and resource components into the system. Lutz (1993) gives a survey on conceptual and empirical issues.

This specification allows to compute the share of environmental quality in total utility. On the basis of this share the welfare effects of the introduction of emission fees can be adjusted to reflect the benefits of improved environmental quality.[46]

In the dual representation of the generic model such an approach requires to introduce into the expenditure equation of agent *q*, $\varepsilon_q(\pi_i)$ (cf. equation (24)), an additional 'good', environmental quality (i=env) and an expenditure share for environmental quality which depends on climate, $S^q_{env}(\omega)$. Furthermore, another nesting level has to be added to equation (24) where at the top-level the „good" environmental quality substitutes for the consumer good bundle at the elasticity of substitution, $\sigma_q(\omega)$, for which Perroni and Wigle (1997) suggest the value of 0.5.

While not directly concerned with the analysis of climate change impacts on final demand the contribution by Perroni and Wigle (1997) is relevant for impact analysis in CGE models. It demonstrates the analytical introduction of non-market impacts in a way that allows their connection with market related impacts. This reflects an essential feature of real consumer behaviour.[47] Yet, the results will remain only illustrative as long as quantitative values for environmental quality and the relevant elasticities cannot be based on solid empirical foundations.

5.3 Dynamics and Uncertainty

So far this chapter dealt with the introduction of climate change impacts into the static CGE framework. This section deals with the dynamics and uncertainties that characterise the climate change problem and discusses how they can be incorporated into CGE models.

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[46] For details of the calibration see Perroni and Wigle (1994).

[47] On the interactions between non-market and market values in the context of the emission abatement issue see Perroni and Wigle (1994), Perroni and Wigle (1997).

Climate change is a mid- to long-term phenomenon that evolves over time. Climatologists speak of a ‘climate memory’ which lasts up to 300 to 400 years. This is due to the thermal inertia of the ocean-atmosphere climate system and the slow decay of the atmospheric concentration of CO_2 which takes place through transfers of CO_2 from the atmosphere to other components of the carbon cycle (Hasselmann et al. (1996)).

Large time lags in climate change imply that also potential impacts on natural and economic systems will occur in the mid- to long-term future. Thus, the analysis of potential climate change impacts in models that describe the present economy leads to wrong estimates of the resulting welfare implications. The appropriate assessment of future climate change impacts requires economic models that represent the future economy. In the presence of a time lag of over a century such models are difficult to establish: The development of socio-economic conditions even over a few decades is hard to predict. Given the different time horizons of climatic and economic processes it seems nearly impossible to build fully closed climate-economy models for the analysis of the global warming problem.

Apart from these systematic problems the representation of a future economy is also challenging from the perspective of modelling technique. Bowes and Crosson (1993), for instance, face the problem of modelling a future economy on the basis of an IOM of the present MINK economy. Projections are made of the future MINK economy with respect to population, real personal income, the shares of farm income in total regional income, agricultural production, and the situation on world markets. Instead of making guesses on future intersectoral relationships the authors proceed as follows. First they introduce climate change impacts into the IOM of the present economy. In a second step they ask by how much future multipliers would have to deviate from present ones in order for impact values to differ significantly between present and future scenarios. The results obtained by this methodology are then given conditional on assumptions about future multipliers. This allows to assess whether climate change impacts on a future economy are likely to be severe, given assumptions on how this future economy could look like.

Dynamic CGE models, in contrast, allow an endogenous derivation of the future economy. The CGE model of the U.S. applied by Scheraga et al. (1993) covers the period from 1992 to 2060 with a fully dynamic specification. The model solves for an equilibrium path which results in a steady state. As described in sections 5.1 and 5.2 climate change impacts are introduced into the model as percentage changes of the unit cost of the agricultural and electricity service sectors and as governmental expenditures for coastal protection. Yet, the authors use impact estimates which refer to an equilibrium climate assumed to prevail in 2060 as a result of the doubling of CO_2 concentration. In order to operate in a dynamic framework on the basis of these estimates, simplifying assumptions are made: The authors assume that the projected rise in temperature occurs gradually between 1992 and 2060 and that the increases of unit costs and coastal protection expenditures are linear functions of the projected annual temperature changes.

In the generic notation of the generic model this would correspond to $\lambda_i(\pi)$ and $\varepsilon_q(\pi_i)$ being linear functions of ω, here annual temperature changes, (cf. the unit cost equation (22) and the expenditure function (25)).

The procedure applied by Scheraga et al. (1993) illustrates the problem of consistency that arises if equilibrium climate simulations and impact estimates are used for the quantification of climate change impacts in a dynamic economic model.[48] Sequential shocks in dynamic CGEs can be consistently quantified only on the basis of transient climate projections and the corresponding development of physical impacts.

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48 The authors themselves emphasise that the assumptions are substantial simplifications of the actual development of climate change and the resulting impacts, and that the results of the model are not to be taken as projections. Rather, their approach should be understood as an effort to bound the problem and as a suggestion of modelling techniques.

Controversial projections of climate change and resulting physical impacts result from the fact that the underlying natural processes are not yet fully understood. Moreover, the projections of future socio-economic development and response options to climate change impacts are uncertain. Although it is more or less possible to make projections on population growth, technical progress and economic growth, these are only valid if no unforeseen shocks occur. If they occur, the economy may depart from the initial path for which the projections were made. This problem is aggravated the longer the time horizon for which projections are made.[49]

In CGE approaches the issue of uncertainty is not explicitly addressed through stochastic formulations. Rather, different scenarios of climate change, impact quantity and future economic conditions are developed. Sensitivity analyses are conducted in order to analyse the influence of uncertain exogenous parameters and variables on relevant endogenous variables. The scenario approach to the issue of uncertainty is technically easy to apply. Once a model is established, simulations may be conducted for any variations of the exogenous parameters and variables.

The concept of probability distributions of uncertain parameters has been applied to the enumerative damage functions introduced in chapter 3. These functions relate changes of climate variables to decreases in GDP. In some approaches probability distributions of damages are derived on the basis of probability distributions of uncertain parameters (Fankhauser (1995), Dowlatabadi and Morgan (1993), Hope et al. (1993)). This opens the opportunity to consider the entire range of potential impacts, including mode (best guesses), median (expected damages) as well as lower and upper bounds, the latter being associated with so-called low probability-high impact events (disastrous outcomes).

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[49] A detailed discussion of the assumptions and growth projections used for the dynamic benchmarking of a recursive-dynamic multi-regional CGE model is given in Klepper and Springer (1999).

Apart from the fundamental mistake which is made with the empirical implementation of most damage functions (cf. chapter 3) the application of probability functions may lead to additional insight, in particular with respect to extreme outcomes. This is of special relevance for policy analysis — an option which is judged to be optimal under expected conditions may turn out inferior if the worst case occurs.[50]

The useful approach of probability distributions of impacts could be applied to impact modelling in CGE frameworks in order to generate a probability distribution of consistently derived welfare implications: Instead of falling back upon damage estimates derived by summation and non-transparent aggregation methods, CGE simulations can be conducted systematically for parametric values of different probabilities. The results can then be given in terms of highly aggregated welfare indicators such as GDP which are assigned probabilities on the basis of the probabilities of the exogenous variables applied.

Jacoby et al. (1996), for instance, use a recursive-dynamic CGE model to project future CO_2 emissions. They subject uncertain parameters, such as the rate of labour productivity growth, the rate of non-price induced improvement in energy efficiency and the relative costs of the backstop technologies to an uncertainty analysis. This allows to make the projections in terms of probability densities and hence to distinguish scenarios of reference and of high and low probability.

Whereas the problem of uncertainty in climate change analysis is raised in a number of publications, very few deal with the impacts of catastrophic events on economies.[51] Yin and

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[50] Lempert et al. (1996) derive adaptive policy strategies which, in comparison to optimal and best-estimate policies, react to changing probabilities which are observed over time. A three dimensional probability space is established which represents the uncertainties that are crucial for the evaluation of a policy strategy.

[51] In this context it is important to remember that, besides changes in the average level of climatic variables such as temperature and precipitation, climate change also implies changes in the variability of these variables. It is this variability that is associated to the occurence of extreme events such as heat waves or floods. For the relationship between changes in the variability and changes in the probability of extreme values of climate variables see Katz and Brown (1992).

Newman (1996), for instance, analyse the effect of catastrophic risk on forest investment decisions. They use numerical simulations for their analysis, and conclude that the presence of catastrophic risk always results in a reduced production value but an increased investment threshold for a forestry project.

For the generic model this would imply to implement the climate impact of catastrophic events via the investment decision (see footnote 36) and/or through an exogenously given climate dependent depreciation rate $\delta_t(\omega)$ which allows to depreciate the returns of forest projects due to extreme weather events (cf. section 4.2.3). The unsolved problem lays now in the quantification of the depreciation rate $\delta_t(\omega)$. However, some emipircal evidence for quantifying losses of factor endowments due to catastrophic events can be supplied by the insurance industry (see, e.g., Berz and Klaus (1994), Flavin (1994), Legett (1993), Legett (1994), Swiss Re (1995), Tucker (1997)).

6 Conclusion

The purpose of this paper was to review the existing economic literature on climate change impact assessment and to incorporate decisive elements into a General Equilibrium Framework.

The CGE framework appears to be especially qualified for the purpose of a consistent assessment of the consequences of climate change on the regional, national and world economy, because of its capacity to represent the behaviour and interrelationships of all relevant agents in an economy. This is important for impact modelling in two respects: First, climate change more or less affects the behaviour and the restrictions of all economic agents. In order to derive the resulting impact on the scale of the entire economy all these impacts have to be considered simultaneously. Second, direct climate change impacts that affect a given agent are propagated throughout the economy because of the relationships this agent has with all other agents of the economy. This results in second order effects which must be taken into consideration if the impacts of climate change are to be assessed correctly.

We have demonstrated how climate impacts can be incorporated into a generic model which exhibits the crucial characteristics necessary for the modelling of climate policy. Furthermore we have shown how to derive the empirical values which are needed for the quantification of climate change impacts in this extended CGE framework.

From this exercise the following conclusion can be drawn:

Modelling the consequences of climate change for the economy requires the introduction of empirical results from natural science analyses into economic models. In the CGE framework this connection cannot be easily established, because of the high aggregation level at which it represents the economy. In order to obtain consistent values for the empirical quantification of climate change impacts on high levels of aggregation it is necessary to use results from partial equilibrium studies. These concentrate on a single component of the economy such as a type of final demand or a producing sector and therefore allow a more detailed analysis of the microeconomic foundations of the behaviour of the respective agents. At this level of aggregation the introduction of results from natural science models into economic models is easier to accomplish than in larger scale CGEs. Therefore, partial equilibrium studies produce important information that can be used as input in CGEs.[52]

For an actual modelling project one has to decide whether to build up a sequence of models with increasing levels of aggregation or to use results from other studies which are compatible with the CGE model's level of aggregation. The decision depends upon several aspects, such as the sectoral and regional coverage of the CGE model, the possibility of coordinating models

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[52] Depending on the region and kind of impact to be analysed, it is possible that the agent or sector which experiences a direct impact, has very few interrelationships with the rest of the economy. In this case the application of a CGE framework does not yield additional insight.

from different fields of science and data availability. If results from other studies are used, it is important to ensure that they are based on the same assumptions as the CGE model with respect to climate change, biophysical and economic responses; and that they refer to the same region.

The specification of the analytical premises for the incorporation of climate change impacts in general equilibrium models is only the first step on the way to consistent impact modelling. The next step would be to transform the climate dependent variables and parameters into operationable functions or consistent scenarios which can be used in an integrated CGE-climate modelling framework. Further important issues to be addressed are (i) the handling of uncertainty and of (ii) dynamics, and (iii) the consideration of extreme weather events.

First, the issue of uncertainty can be addressed in CGE models by running a given model for different empirical values of the climate dependent variables and parameters. The welfare implications resulting from each scenario can than be compiled in the form of a probability distribution function which connects them to the probabilities assigned to the respective values of the climate dependent parameters and variables.

Second, no satisfactory method of connecting the dynamics of the climate system and the economic system has been applied so far. One reason are the widely differing time horizons of climatic and economic processes. Another difficulty lies in the derivation of what could be called ‘physical impact functions’ which connect changes in climatic variables to physical impacts more systematically than it is done with scenario approaches.

Third, the consequences of changes in the variability of climate variables and the associated increases in the frequency and intensity of extreme events should be examined. This would allow to consider other than expected or best guess scenarios in general equilibrium frameworks.

Despite these challenges for further research, the incorporation of climate change impacts in the CGE framework appears to be feasible in the near future. This integrated approach will yield new and useful insights for decision-makers on issues of global warming. It allows a consistent evaluation of the costs and benefits of climate change policy measures for different regions, and facilitates economists’ search for efficient policy measures.

References

Adams, R. M. (1989). Global Climate Change and Agriculture: An Economic Perspective. *American Journal of Agricultural Economics* 71 (5): 1272-1279.

Adams, R. M., R. A. Fleming, C.-C. Chang, B. A. McCarl, and C. Rosenzweig (1995). A Reassessment of the Economic Effects of Global Climate Change on U.S. Agriculture. *Climatic Change* 30: 147-167.

Adams, R. M., J. D. Glyder, and B. A. McCarl (1989). The Economic Effects of Climate Change on U. S. Agriculture: A Preliminary Assessment. In J. B. Smith and D. Tirpak (eds.), *The Potential Effects of Global Climate Change on the United States* . Washington, D. C.

Adams, R. M., C. Rosenzweig, R. M. Peart, J. T. Ritchie, B. A. McCarl, J. D. Glyer, R. B. Curry, J. W. Jones, K. J. Boote, and L. H. Jr. Allen (1990). Global Climate Change and US Agriculture. *Nature* (345): 219-224.

Armington, P. (1969). A Theory of Demand for Products Distinguished by Place of Production. *IMF Staff Papers* 16: 159-178.

Bazzaz, F., and W. Sombroek (eds.) (1996). *Global Climate Change and Agricultural Production*. Chichester

Beaver, R. (1993). Structural Comparison of the Models in EMF 12. *Energy Policy* 21 (3): 238-248.

Berz, G. (1991). Klimaänderung und ihre Folgen für die Versicherungswirtschaft. *Die Versicherungsrundschau* 46 (7/8): 209-217.

— (1992). Greenhouse Effects on Natural Catastrophes and Insurance. *The Geneva Papers on Risk and Insurance* 17 (64): 386-392.

Berz, G., and C. Klaus (1994). The mounting windstorm risk and consequences for the insurance industry. *Ecodecision* 12: 65-68.

Berz, G., R. Voigtländer, and H. Frhr. von Lersner (1996). Klimaveränderungen und Umweltriskmanagement. In H. Baumann, H. Schirmer, and W. Zschockelt (eds.), *Versicherungswissenschaft in Berlin, Heft 12*

Bhattacharyya, S. C. (1996). Applied General Equilibrium Models for Energy Studies: A Survey. *Energy Economics* 18 (3): 145-164.

Boero, G., R. Clarke, and L. A. Winters (1991). *The Macroeconomic Consequences of Controlling Greenhouse Gases: A Survey*. London

Bowes, M. D., and P. R. Crosson (1993). Consequences of Climate Change for the MINK Economy: Impacts and Responses. *Climatic Change* 24: 131-158.

Bryan, K., F. G. Komro, S. Manabe, and M. J. Spelman (1982). Transient Climate Response to Increasing Atmospheric Carbon Dioxide. *Science* (215): 56-58.

Burniaux, J.-M., J. P. Martin, G. Nicoletti, and J. O. Martins (1992). GREEN - A Multi-Sector, Multi-Region General Equilibrium Model for Quantifying the Cost of Curbing CO_2 Emissions: A Technical Manual. *Economics Department Working Papers No. 116*. OECD, Paris.

Chung, J. W. (1994). *Utility and Production Functions: Theory and Applications*. Cambridge, MA

Cline, W. R. (1992). The Economics of Global Warming. Institute for International Economics, Washington, DC.

Conner, R. J. (1994). Assessing the Socioeconomic Impacts of Climate Change on Grazinglands. In K. D. Frederick and N. J. Rosenberg (eds.), *Assessing the Impacts of Climate Change on Natural Resource Systems* . Dordrecht

Conrad, K. (1997). Computable General Equilibrium Models for Environmental Economics and Policy Analysis. *Discussion Paper 556-97*. Mannheim University, Mannheim.

Cubasch, U., K. Hasselmann, H. Hoeck, E. Maier-Reimer, U. Mikolajewicz, B. D. Santer, and R. Sausen (1992). Time-dependent Greenhouse Warming Computations with a Coupled Ocean-Atmospheric Model. *Climate Dynamics* 8: 55-69.

Darwin, R., M. Tsigas, J. Lewandrowski, and A. Raneses (1996). Land Use and Cover in Ecological Economics. *Ecological Economics* 17: 157-181.

Dewatripont, M., and G. Michel (1987). On Closure Rules, Homogeneity and Dynamics in AGE models. *Journal of Development Economics* 26: 65-76.

Dlugolecki, A. F. (1992). Insurance Implications of Climatic Change. *The Geneva Papers on Risk and Insurance* 17 (6): 393-405.

Dowlatabadi, H., and M. G. Morgan (1993). A Model Framework for Integrated Studies of the Climate Problem. *Energy Policy* 21 (3): 209-221.

Easterling, W. E., P. R. Crosson, N. J. Rosenberg, M. S. McKenney, L. A. Katz, and K. M. Lemon (1993). Agricultural Impacts of and Responses to Climate Change in the Missouri-Iowa-Nebraska-Kansas Region. *Climatic Change* 24: 23-61.

Edmonds, J. A., and J. M. Reilly (1985). *Global Energy: Assessing the Future*. New York

Edmonds, J., and D. W. Barns (1990). Estimating the Marginal Cost of Reducing Global Fossil Fuel CO_2 Emissions. *PNL-SA-18361*. Pacific Northwest Laboratory, Washington DC.

Fankhauser, S. (1992). Global Warming Damage Costs: Some Monetary Estimates. *CSERGE GEC Working Paper 92-29*. CSERGE, Norwich.

— (1995). *Valuing Climate Change: The Economics of the Greenhouse*. London

Fisher, A. C., and W. H. Hanemann (1993). Assessing Climate Change Risks: Valuation of Effects. In J. Darmstadter and M. A. Toman (eds.), *Assessing Surprises and Nonlinearities in Greenhouse Warming. Proceedings of an Interdisciplinary Workshop* . Washington DC

Flavin, C. (1994). Storm warnings: climate change hits the insurance industry. *World Watch* 7 (10): 11-20.

Gaskins, Jr. D. W., and J. P. Weyant (1993). Model Comparisons of the Costs of Reducing CO_2 Emissions. *American Economic Review* 83 (2): 318-323.

Godden, D., and P. D. Adams (1992). The enhanced Greenhouse Effect and Australian Agriculture. In J. M. Reilly and M. Anderson (eds.), *Economic Issues in Global Climate Change* . Boulder

Hasselmann, K., S. Hasselmann, R. Giering, V. Ocaña, and H. von Storch (1996). Optimization of CO_2 Emissions Using Coupled Integral Climate Response and Simplified Cost Modes. A Sensivity Study. *Report No. 192*. Max-Planck-Institut für Meteorologie, Hamburg.

Heal, G. (1991). Economy and Climate: A Preliminary Framework for Microeconomic Analysis. In R. E. Just and N. Bockstael (eds.), *Commodity and Resource Policies in Agricultural Systems* . Berlin

Heister, J. (1997). *Der Internationale CO_2* Vertrag. Strategien zur Stabilisierung multilateraler Kooperation zwischen souveränen Staaten. Tübingen

Hertel, T. W. ed. (1997). *Global Trade Analysis. Modeling and Applications*. Cambridge, MA

Hope, C., J. Anderson, and P. Wenman (1993). Policy Analysis of the Greenhouse Effect. An Application of the PAGE Model. *Energy Policy* 21 (3): 327-338.

IPCC (1996a). *Climate Change 1995. The Science of Climate Change*. Cambridge, MA

— (1996b). *Climate Change 1995. Impacts, Adaptiations and Mitigation of Climate Change: Scientific-Technical Analyses*. Cambridge, MA

— (1996c). *Climate Change 1995. Economic and Social Dimensions of Climate Change*. Cambridge, MA

Jacoby, H. D., R. S. Eckaus, A. D. Ellerman, R. G. Prinn, D. M. Reiner, and Z. Yang (1996). *QELRO Impacs: Domestic Markets, Trade and Distribution of Burdens, and Climate Change.* Report No. 9. Cambridge, MA

Johnson, S. R. (1991). Modelling the Economic Impacts of Global Climate Change for Agriculture and Trade. In OECD (ed.), *Climate Change. Evaluating the Socio-Economic Impacts* . Paris

Jones, J. W., K. J. Boote, G. Hoogenboom, S. S. Jagtap, and G. G. Wilkerson (1989). SOYGRO V5.42: Soybean Crop Growth Simulation Model. Users' Agronomy. Department of Agricultural Engineering and Department of Agronomy. University of Florida, Gainsville.

Jorgenson, D. W., and P. J. Wilcoxen (1990). Intertemporal General Equilibrium Modeling of U. W. Environmental Regulation. *Journal of Policy Modeling* 12: 715-744.

Jorgenson, D. W., and P. J. Wilcoxen (1993). Reducing US Carbon Emissions: An Econometric General Equilibrium Assessment. *Resource and Energy Economics* 15 (1): 7-25.

Kaiser, H. M., S. J. Riha, D. G. Rossiter, and D. S. Wilks (1992). Agronomic and Economic Impacts of Gradual Global Warming: A Preliminary Analysis of Midwestern Crop Farming. In J. M. Reilly and M. Anderson (eds.), *Economic Issues in Global Climate Change* . Boulder

Kane, S., J. Reilly, and J. Tobey (1992). An Empirical Study of the Economic Effects of Climate Change on World Agriculture. *Climatic Change* 21: 17-35.

Katz, R. W., and B. G. Brown (1992). Extreme events in a changing climate: variability is more important than averages. *Climatic Change* 21: 289-302.

Kaufmann, R. K. (1998). The Impact of Climate Change on U.S. Agriculture: A Response to Mendelsohn et al. *Ecological Economics* 26: 113-119.

Klepper, G., and K. Springer (1999). Benchmarking the Future - Calibrating a long-run, multi-regional, multi-sectoral CGE model. *mimeo*

Kokoski, M. F. (1984). *A General Equilibrium Analysis of the Measurement of the Economic Impacts of Climatic Changes*. Chapel Hill, North Carolina

Kokoski, M. F., and V. K. Smith (1987). A General Equilibrium Analysis of Partial-Equilibrium Welfare Measures: The Case of Climate Change. *American Economic Review* 77 (3): 331-341.

Legett, J. (1993). Climate change and the insurance industry. *European Environment* 3 (3): 3-8.

— (1994). The emerging response of the insurance industry to the threat of climate change. *UNEP Industry and the Environment Report*

Lempert, R. J., M. E. Schlesinger, and S. C. Bankes (1996). When We Don't Know the Costs or the Benefits: Adaptive Strategies for Abating Climate Change. *Climate Change* 33: 235-274.

Linder, K. P., and M. R. Inglis (1989). The Potential Effects of Climate Change on Regional and National Demands for Electricity. In J. B. Smith and D. Tirpak (eds.), *The Potential Effects of Global Climate Change on the United States* . Washington, D.C.

Lutz, E. ed. (1993). *Toward Improved Accounting for the Environment. An UNSTAT-World Bank Symposium*. Washington, D.C.

Mabey, N., S. Hall, C. Smith, and S. Gupta (1997). *Argument in the Greenhouse. The International Economics of Controlling Global Warming*. London

Manne, A. S., R. Mendelsohn, and R. Richels (1995). MERGE. A Model for Evaluating Regional and Global Effects of GHG Reduction Policies. *Energy Policy* 23 (1): 17-34.

Manne, A. S., and R. G. Richels (1991). Global CO_2 Emission Reductions - The Impacts of Rising Energy Costs. *The Energy Journal* 12 (1): 87-107.

— (1992). *Buying Greenhouse Insurance: The Economic Cost of CO_2* Emission Limits. Cambridge, MA

— (1994). The Cost of Stabilizing Global CO_2 Emission: A Probabilistic Analysis Based on Expert Judgements. *The Energy Journal* 15 (1): 31-56.

McCarl, B. A., and T. H. Spreen (1980). Price Endogenous Mathematical Programming as a Tool for Sector Analysis. *American Journal of Agricultural Economics* 62 (1): 87-102.

Mendelsohn, R., W. D. Nordhaus, and D. Shaw (1993). The Impact of Climate on Agriculture: A Ricardian Approach. In Y. Kaya (ed.), *Costs, Impacts, and Benefits of CO_2* Mitigation . Laxenburg

— (1994). The Impact of Climate on Agriculture: A Ricardian Analysis. *American Economic Review* 84 (4): 753-771.

Mendelsohn, R., and N. J. Rosenberg (1994). Framework for Integrated Assessment of Global Warming Impacts. In K. D. Frederick and N. J. Rosenberg (eds.), *Assessing the Impacts of Climate Change on Natural Resource Systems* . Dordrecht

Nordhaus, W. D. (1991). To Slow or not to Slow: The Economics of the Greenhouse Effect. *The Economic Journal* 101: 920-937.

Nordhaus, W. D., and D. Popp (1997). What is the Value of Scientific Kowledge? An application to Global Warming Using the PRICE Model. *The Energy Journal* 18 (1): 1-45.

Nordhaus, W. D., and Z. Yang (1996). A Regional Dynamic General Equilibrium Model of Alternative Climate-Change Strategies. *American Economic Review* 86 (4): 741-765.

Önal, H., and B. A. McCarl (1989). Aggregation of Heterogeneous Firms in Mathematical Programming Models. *European Review of Agricultural Economics* 16 (4): 499-513.

— (1991). Exact Aggregation in Mathematical Programming Sector Models. *Canadian Journal of Agricultural Economics* 39 (2): 319-334.

Parry, M. (1990). *Climate Change and World Agriculture*. London

Parson, E. A., and K. Fisher-Vanden (1997). Integrated Assessment Models of Global Climate Change. *Annual Review of Energy and the Environment* 22: 589-628.

Peck, S. C., and T. J. Teisberg (1992). CETA: A Model for Carbon Emissions Trajectory Assessment. *The Energy Journal* 13 (1): 55-77.

— (1993a). CO_2 Emissions Control. Comparing Policy Instruments. *Energy Policy* 21 (3): 222-229.

— (1993b). The Importance of Nonlinearities in Global Warming Damage Costs. *Assessing Surprises and Nonlinearities in Greenhouse Warming* . Washington, D.C.

— (1998). CO_2 Concentration Limits, the Costs and Benefits of Control, and the Potential for International Agreement. *Nota di lavoro 6.98*. Fondazione Eni Enrico Mattei, Milano.

Perroni, C., and R. Wigle (1994). International Trade and Environmental Quality: How Important Are the Linkages. *Canadian Journal of Economics* XXVII (3): 551-567.

— (1997). Environmental Policy Modeling . In T. W. Hertel (ed.), *Global Trade Analysis. Modeling and Applications* . Cambridge, MA

Reilly, J. M., and M. Anderson (eds.) (1992). *Economic Issues in Global Climate Change. Agriculture, Forestry, and Natural Resources*. Boulder

Reilly, J., and N. Hohmann (1993). Climate Change and Agriculture: The Role of International Trade. *American Economic Review* 83 (2): 306-312.

Ritchie, J. T., and S. Otter (1985). Description and Performance of CERES-Wheat: A User-Oriented Wheat Yield Model. In W. O. Willis (ed.), *ARS Wheat Yield Project* . Washington, D.C.

Ritchie, J. T., U. Singh, D. Godwin, and L. Hunt (1989). *A User's Guide to CERES-Maize V2.10* . Muscle Shoals

Robinson, S. (1989). Multisectoral Models. In H. Chenery and T. N. Srinivasan (eds.), *Handbook of Development Economics* Vol. II. Amsterdam

Rosenberg, N. J., and P. R. Crosson (1991). The MINK Project: A New Methodology for Identifying Regional Influences of, and Responses to, Increasing Atmospheric CO_2 and Climate Change. *Environmental Conservation* 18 (4): 313-322.

Rosenzweig, C., A. Iglesias, G. Fischer, Y. Liu, W. Baethgen, and J. W. Jones (1998). Wheat Yield Functions for Analysis of Land-Use Change in China. *IIASA Report IR-98-069*. IIASA, Laxenburg.

Rosenzweig, C., M. L. Parry, G. Fischer, and K. Frohberg (1993). Climate Change and World Food Supply. *Research Reports from the Environmental Change Unit Report No. 3* Oxford.

Scheraga, J. D., R. J. Goettle, D. W. Jorgenson, and P. J. Wilcoxen (1993). Macroeconomic Modeling and the Assessment of Climate Change Impacts. In Kaya (ed.), *Costs, Impacts, and Benefits of CO_2* Mititgation . Laxenburg

Shoven, J. B., and J. Whalley (1992). *Applying general equilibrium*. New York

Sohn, I. ed. (1986). *Readings in Input-Output-Analysis. Theory and Applications*. New York

Sonka, S. T. (1991). Evaluating Socioeconomic Assessments of the Effect of Climate Change on Agriculture. In M. Anderson and J. M. Reilly (eds.), *Economic Issues in Global Climate Change. Agriculture, Forestry, and Natural Resources* . Boulder

Springer, K. (1998). The DART General Equilibrium Model: A Technical Description. *Kiel Working Papers No. 883*. The Kiel Institute of World Economics, Kiel.

Swiss Re (1995). *Global Warming: Element of Risk*. Zürich

Tol, R. S. J. (1995). The Damage Costs of Climate Change Toward More Comprehensive Calculations. *Environmental and Resource Economics* 5 (4): 353-374.

— (1996). The Damage Costs of Climate Change. Towards a Dynamic Representation. *Ecological Economics* 19 (1): 67-90.

Tsigas, M. E., G. B. Frisvold, and B. Kuhn (1997). Global Climate Change and Agriculture. In T. W. Hertel (ed.), *Global Trade Analysis. Modeling and Applications* . Cambridge, MA

Tucker, M. (1997). Climate Change and the Insurance Industry: The Cost of Increased Risk and the Impetus for Action. *Ecological Economics* 22: 85-96.

Varian, H. R. (1992). *Microeconomic Analysis*. New York

Voss, R., R. Sausen, and U. Cubasch (1998). Periodically Synchronously Coupled Integrations with the Atmosphere-Ocean General Circulation Model ECHAM3/LSG. *Climate Dynamics* 14: 249-266.

Whalley, J., and R. Wigle (1991). The International Incidence of Carbon Taxes. In R. Dornbusch and J. M. Poterba (eds.), *Global Warming: Economic Policy Responses* . Cambridge, MA

Yin, R., and D. H. Newman (1996). The Effect of Catastrophic Risk on Forest Investment Decisions. *Journal of Environmental Economics and Management* 31 (2): 186-197.