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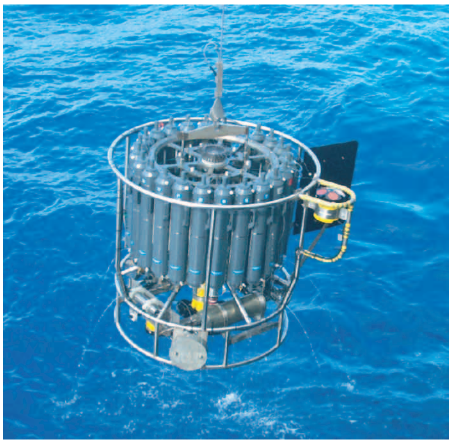
A Multi-Actor Dynamic Integrated Assessment Model (MADIAM)

Michael Weber



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A Multi-Actor Dynamic Integrated Assessment Model (MADIAM)

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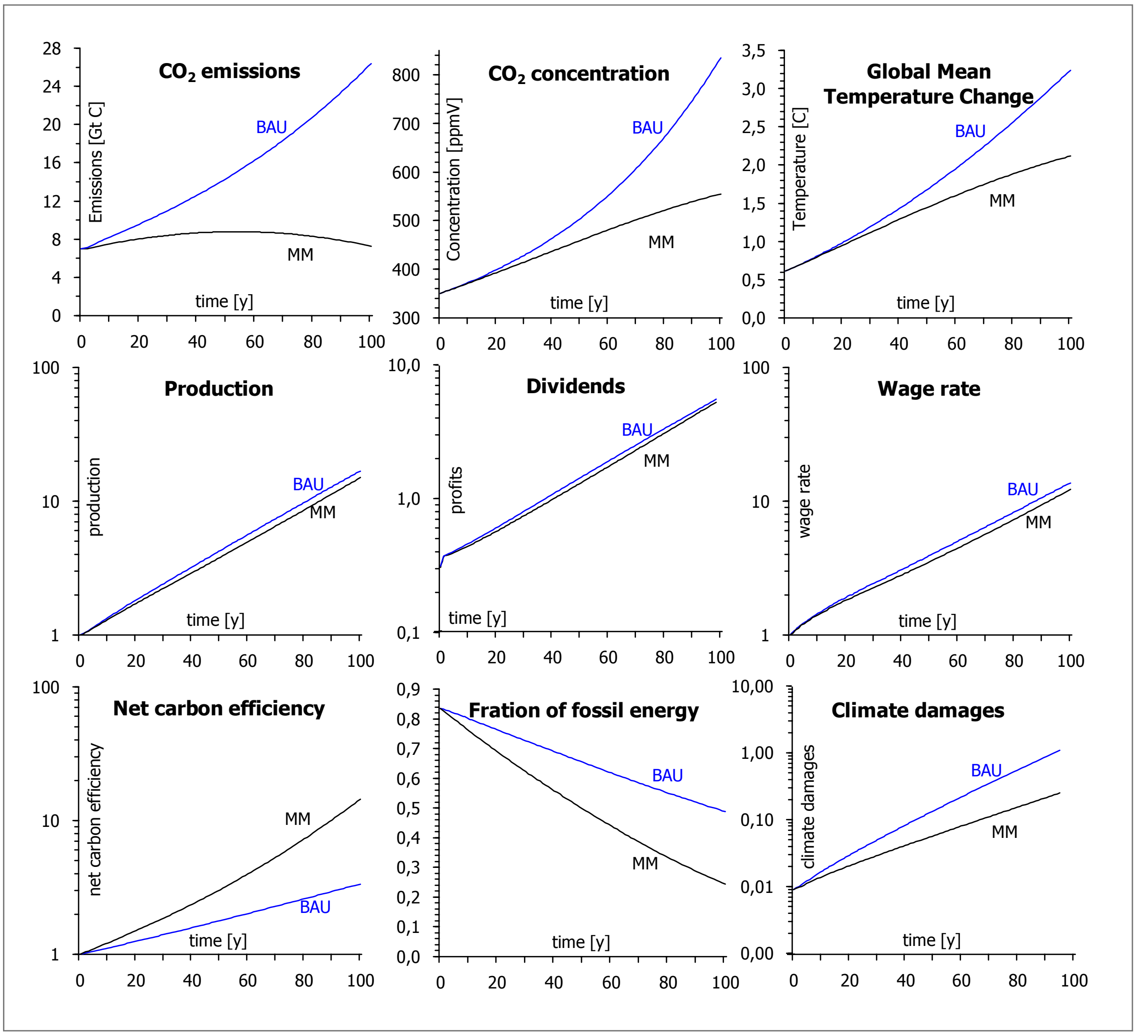

Michael Weber

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Zusammenfassung

Das Zusammenspiel von Klima- und sozioökonomischen Systemen wird in dieser Promotionsarbeit mit Hilfe eines dynamischen Mehr-Akteurs Modell zur integrierten Bewertung des Klimawandels ('Multi-Actor Dynamic Integrated Assessment Model (MADIAM)') untersucht. Zu diesem Zweck werden ein nichtlineares Impulse-Response Modell des Klimasystems (NICCS) und ein dynamisches Mehr-Akteurs Wirtschaftsmodell (MADEM) gekoppelt. Das Modell MADIAM stellt den ersten Entwicklungsschritt im Rahmen einer Modellumgebung dar, mit deren Hilfe die Dynamik des gekoppelten klima-sozioökonomischen Systems - einschliesslich endogenen technologischen Wandels - in einer Nicht-Gleichgewichtssituation untersucht werden soll. Dieser Ansatz erlaubt es, eine Reihe von Beschränkungen üblicher Ansätze der volkswirtschaftlichen Modellierung zu umgehen und aufzulösen.

Das Modul MADEM beschreibt eine Volkswirtschaft, welche einerseits durch Profitstreben (in Folge von Investitionen in Human- und physikalisches Kapital) und andererseits durch Erosion der Profite aufgrund wirtschaftlicher Konkurrenzsituation (zusätzlich verstärkt durch Anpassungen der Löhne) geprägt ist. Der grundsätzliche Antrieb des Wirtschaftswachstums ist der Anstieg der Arbeitsproduktivität (Humankapital), welcher durch Investitionen in technologischen Wandel erreicht wird. Diese Investitionen werden ergänzt durch (a) Steuern auf CO_2 Emissionen, welche die Regierung erhebt und in Form von Subventionen wieder in die Wirtschaft zurückführt, (b) Konsumentenpräferenzen, die sich entsprechend der Klimaänderungen einstellen und (c) modifizierten Investitionsentscheidungen der Wirtschaft in Folge der Aktivitäten der anderen Akteure.

Die Kombination der unterschiedlichen Strategien der einzelnen Akteure bestimmen Form und Intensität des induzierten technologischen Wandels. Dieser wiederum legt die Entwicklung des Klima-sozioökonomischen Systems fest. Bei dem Modell MADIAM handelt es sich um einen system-analytischen Ansatz, d.h. das primäre Ziel dieses Modells ist es, die grundsätzlichen, individuellen Einflussmöglichkeiten der Akteure herauszuarbeiten und zu verdeutlichen. Die Kontrollalgorithmen der einzelnen Akteure sind dabei weitgehend festgeschrieben. Dies steht im Gegensatz zu klassischen Kosten/Nutzen Optimierungen für einen einzelnen Akteur.

Die Ergebnisse der Szenariosimulationen sind die folgenden: Investitionen der Wirtschaft in Energie- und Emissionseffizienz, welche durch CO_2 Steuern der Regierung induziert werden, haben einen starken Einfluss auf die Reduktion der Emissionen. Es zeigt sich,

dass die Erhebung von Steuern besonders dann effektiv ist (im Hinblick auf Emissionsreduktion, aber auch nachhaltiges Wirtschaftswachstum), wenn ein signifikanter Anteil der eingenommenen Steuern wieder in Energie- und Emissionseffizienz zurückgeführt wird. Der Einfluss der Konsumentenpräferenz, welcher in anderen Untersuchungen oft vernachlässigt wird, hat ebenfalls einen starken Einfluss auf die Investitionsentscheidungen der Wirtschaft und kann zu positiven Effekten sowohl auf das Klima als auch auf das Wirtschaftswachstum führen.

Die Simulation von kombinierten, parallelen Kontrollstrategien, bei denen mindestens zwei Akteure gleichzeitig ihre jeweiligen Kontrollvariablen in derselben Weise variieren, zeigt, dass die Akteure eindeutig motiviert sind, zu kooperieren. Im Bezug auf die jeweiligen Wohlfahrtsziele der Akteure und im Vergleich mit dem individuellen Einfluss der Kontrollentscheidungen gibt es in jedem Fall kombinierte Strategien, welche für den Akteur effektiver und vorteilhafter sind. Die in dieser Arbeit gezeigten Beispiele sollen keine quantitativen Aussagen treffen, sondern vielmehr qualitative Zusammenhänge illustrieren.

Zusammfassend zeigen die Ergebnisse, dass einerseits alle Akteure einen deutlichen Einfluss auf technologischen Wandel haben sowie erhebliches Potential besitzen, globale Klimaerwärmung zu vermeiden, bzw. zu reduzieren, andererseits jedoch das Wirtschaftswachstum dabei kaum beeinträchtigen. Die Verlangsamung des Wirtschaftswachstums über die nächsten hundert Jahre beträgt lediglich ein bis zwei Jahre. Diese Ergebnisse sind unabhängig von der Kalibrierung des Modells.

Abstract

The interactions between climate and the socio-economic system are investigated with a Multi-Actor Dynamic Integrated Assessment Model (MADIAM) obtained by coupling a nonlinear impulse response model of the climate sub-system (NICCS) to a multi-actor dynamic economic model (MADEM). The main goal is to initiate a model development that is able to treat the dynamics of the coupled climate socio-economic system, including endogenous technological change, in a non-equilibrium situation, thereby overcoming some of the limitations of standard economic modelling approaches.

The core of MADEM describes an economy driven by the opposing forces of business, striving to increase profits by investments in human and physical capital, and the erosion of profits through business competition, enhanced by labour wage pressure. The principal driver of economic growth is the increase in labour productivity (human capital) generated by endogenous technological change. In the presence of climate change, these basic interactions are modified by government taxes on CO_2 emissions, which are recycled into the economy as various subsidies, by climate-related changes in consumer preferences, and by modified business investment decisions in response to these actions.

The combined effect of the climate-response strategies of the different actors determines the form of the induced technological change that ultimately governs the evolution of the coupled climate-socioeconomic system. To clarify the individual roles of the actors, the model is set up in a systems-analytical way, with prescribed control algorithms for the different actors, rather than in the traditional single-actor cost/benefit optimization mode.

The results of the scenario simulations are the following. Business investments in energy and carbon efficiency, induced by government CO_2 taxes, yield a significant contribution to emissions reduction. Direct government mitigation actions through carbon taxes are more effective with regard to both emission reductions and economic growth if a significant fraction of carbon taxes are recycled into investments in net carbon efficiency, i.e. into induced technological change. The influence of consumer preferences, often neglected in integrated assessment analyses, is also shown to be very effective in guiding business investments, thereby positively affecting both climate and economic growth.

The simulations of combined parallel control strategies, in which at least two actors simultaneously change their control variables in the same (climate friendly) direction, show that the actors are clearly motivated to cooperate. In relation to the different welfare goals of the actors and in comparison to the impacts of the individual control decisions, there are always combined strategies, which offer a more effective and reasonable choice than achieved with individual control decisions. The chosen examples are intended as illustrations rather than to provide quantitative predictions.

While all actors are found to exert a significant influence on technological change and the mitigation of global greenhouse warming, their impact on long-term economic growth in all cases is small. The delay in GDP growth incurred over a one-hundred-year period is typically of the order of only one or two years. This result is independent of the details of the (necessarily uncertain) calibration of our model.

The difficulty lies not with the new ideas,
but in escaping the old ones

(John Maynard Keynes)

Chapter 1

Introduction

1.1 General framework

Human activities have always modified the natural environment. However, the intensity and scale of these modifications, predicted and observed in recent years and decades with a high degree of scientific confidence, is new in the history of man.

One of the most important environmental issues facing society worldwide is human-induced climate change. The atmospheric concentrations of greenhouse gases and anthropogenic aerosols have increased dramatically due to human activities and are higher than they have ever been during the past 420.000 years (and most likely during the past 20 million years) [Petit et al., 1999]. It is no longer seriously questioned that these human activities are changing the earth's climate (especially the release of CO_2 from the burning of fossil fuels, which accounts for appropriately 60% of current greenhouse gas emissions), with potentially serious consequences for life-sustaining systems [IDAG, 2001; IPCC, 2001a].

The overwhelming majority of scientific experts and governments acknowledge that the full impacts of climate change will only gradually appear and further human-induced climate change is inevitable and should be addressed [IPCC, 2001a,b; UNCED, 1992]. Despite the scientific consensus, climate policy remains the subject of hot debate. Controversies arise, at least to some extent, through the mismatch between the typical time scales of the socio-political planning horizon and the century-time scale of the relevant climatological processes [Hasselmann et al., 2003; Watson, 2003].

The large inertia of climate change is mainly due to the large heat capacity of the world ocean, but also to the long residence times of some greenhouse gases, particularly CO_2, in the atmosphere as well as to other 'slow' components of the climate system, such as glaciers and ice sheets. In addition to this inertia is the known potential of the climate system for rapid and abrupt changes through instabilities. This includes the ocean thermohaline circulation system, the terrestrial carbon cycle, modes of atmospheric circulation leading to changes in extreme events, and thresholds for impacts on the biosphere.

These impacts of climate change can be averted or reduced only if action to reduce greenhouse gas (GHG) emissions begins without delay and is sustained over the long term [Hasselmann, 2003; Pew Center, 2003]. This requires transformations, which strongly affect the socio-economic system: the way energy is produced and consumed, goods and people are transported, and the infrastructure is built and used. These systems are characterized by long life cycles. Among technical, cultural and other aspects, the long time horizons, and the related uncertainties they present, pose special difficulties for political systems geared to more immediate concerns, and hence, for any effort to mobilize international action against climate change.

International climate negotiations are strongly influenced by the potential impacts of climate change, climate policy and the actions of socio-economic actors on business cycles, economic growth, unemployment, technological development, international competitively, gradients in welfare, political stability, conflicts, and other critical processes associated with the evolving global economic system. Many of these issues are related to short-to-medium term processes, which tend to be ignored in assessments of long-term economic change. However the implications of regulation policies designed to address long-term climate change are invariably judged also in relation to their impacts on the short-to-medium term economy. In fact, these often dominate the debate. It is therefore important to address the socio-economic impacts of climate policy instruments both in the long and the short-to-medium term.

Due to the exceptionally long time scales involved, current decisions about which pathways to follow in the next decades will be of crucial importance for the well-being of the next generations. Humankind is becoming more and more aware, on the one hand, of the limited understanding of the global system, and, on the other hand, of the interdependence of the various activities and consequences in time, place and scale. The awareness of the rapidly increasing complexity, the various types and sources of uncertainty and the insight that methods which consider only parts of global change in isolation have not been successful, have created a growing interest in an integrated approach to global (climate) change [Rotmans and Dowlatabadi, 1997].

1.2 Integrated assessment modeling approaches

Integrated Assessment (IA) of environmental problems can be defined as an interdisciplinary process of combining, interpreting and communicating knowledge from diverse disciplines in such a way that a given issue can be evaluated from a synoptic perspective. Two targets characterize this process: ”(1) it should add value compared to a single disciplinary oriented assessment; (2) it should provide useful information to decision-makers to develop a coherent framework for consideration of multiple objectives of decision-making.” [Rotmans and Dowlatabadi, 1997].

While there are different methods of integrated assessment, including expert panels, policy exercises and others [Kasemir et al., 2002], a key method consists in developing computer-based integrated assessment models (IAMs).[1] Decision makers use the support of reasonably realistic IAMs of the coupled climate-socio-economic system in order to provide information on the likely short, medium, and long term impacts of alternative climate policies (e.g. the Kyoto Protocol).

The challenging aspect of developing IAMs is to find the right balance between simplicity and complexity, aggregation and resolution, stochastic and deterministic elements, quantitative and qualitative linkages, transparency and uncertainty [Rotmans and Dowlatabadi, 1997]. Additionally it is important to face the limitations of the model and to be aware of the issues that cannot be addressed by the model

Aggregation versus disaggregation is one of the critical issues of IAMs. The level of aggregation within a model framework refers to the formulation of the dynamics in the model in terms of complexity, which is closely related to the spatial and especially the temporal resolution [Rotmans and Dowlatabadi, 1997]. The problem is that the models consist of a variety of submodels, which have different aggregation levels. These submodels are generally only linked, but not integrated.

A number of different approaches to integrated assessment modelling exist. They can roughly be categorized in policy optimization and policy evaluation IA models [Hisschemöller et al., 2001, Weyant et al., 1996]. Policy optimization IA models use techniques to choose the best decision from a set of clearly defined alternatives. Therefore some intertemporal objective function is optimized.[2] Policy evaluation IAMs analyse the outcomes of proposed policy strategies. These models calculate the future development from a given initial state and rules about the evolution of the states.[3] Subgroups of the policy evaluation models are system-analysis model approaches, which focus on the evaluation of long-term climate strategies and study the dynamic behaviour of the socio-economic system. Another group of models place uncertainty in the core of their endeavour, trying to capture the range of possible directions in which the underlying system may develop. The parameters are described by a probability density function. Variants of the model are used to analyse uncertainty about functional relationships between variables.[4] Due to the fact that climate and economic predictions are generally characterized by strong uncertainty, the consideration of the impacts of uncertainty is nevertheless of crucial importance

[1]General overviews of IAMs are given, for example, in Dowlatabadi [1995]; Hasselmann et al. [1997]; Morgan and Dowlatabadi [1996]; Parson [1995]; Rotmans and v. Asselt [1996]; Rotmans and Dowlatabadi [1997]; Schneider [1997]; Weyant et al. [1996].

[2]Examples of policy optimization models for climate change include DICE [Nordhaus, 1993], RICE [Nordhaus and Yang, 1996], MERGE [Manne et al., 1995], CETA [Peck and Teisberg, 1991, 1993], and FUND [Tol, 1997].

[3]Examples of policy evaluation models for climate change are IMAGE1 [Rotmans, 1990], ESCAPE [Rotmans et al., 1994], IMAGE2 [Alcamo, 1994], GCAM [Edmonds et al., 1994], and SIAM [Hasselmann et al., 1997].

[4]Examples of such models for climate change are ICAM [Dowlatabadi and Morgan, 1993], PAGE [Plambeck et al., 1997].

for all types of IA models of climate change. An inadequate treatment of uncertainty and the absence of stochastic behaviour limit their usefulness significantly.

The following subsections present a brief overview of the different model perspectives of climate change and economic models embodied in IA models.

Climate modules of integrated assessment models

In order to provide detailed estimates of the climate system within integrated assessment models, sophisticate climate models are required. Coupled atmosphere-ocean general circulation models (AOGCM) are the most reliable instruments currently available for the estimation of anthropogenic climate change. They involve coupling comprehensive three-dimensional atmospheric general circulation models with ocean general circulation models, with sea-ice models, and with models of land-surface processes [IPCC 2001a]. AOGCMs process a huge amount of data of the three-dimensional ocean-atmosphere system. However, they are computational expensive and typically need several months of completion time for climate change scenarios of a few hundred years even in relative coarse-resolution experiments.

Integrated assessment of anthropogenic climate change requires cost-efficient models of the carbon cycle and the atmosphere-ocean climate system that approach nevertheless the reliability and credibility of complex, state of the art AOGCMs. Conceptual models of the climate system and earth-system models of intermediate complexity (EMICs) are reduced resolution models and have been proposed to describe most of the processes implicit in comprehensive models, albeit in a reduced, i.e. a more parameterized form [Claussen, 2002]. Another class of models, the impulse-response function (IRF) models, is designed for applications requiring a large number of climate simulations. Although highly efficient, IRF models are nonetheless capable of reproducing the full set of climate-change information generated by the AOGCM against which they are calibrated [Hooss et al., 2001].[5]

Economic modules of integrated assessment models

Most integrated assessment models embody economic modules that are essentially standard neoclassical growth models [Hisschemoeller et al., 2001]. The neoclassical growth theory is grounded on the work by Solow [1956], who in direct response on the instability of the macroeconomic model by Harrod [1939] and Domar [1946] (who developed "the first macroeconomic model to formally analyse the problem of growth" [Salvadori, 2003]) introduced possibilities of substitution of physical capital and labour in the production function. On a (now balanced) 'steady state' growth path investments exactly outweigh increase in other factors of production. The rate of saving and the technological

[5] Details about the IRF model NICCS [Hooss et al., 2001], used for MADIAM, are given in Section 2.

progress are treated as exogenous factors. Inspired by the work of Ramsey [1928] a number of growth models, for example the model by Cass [1965] and Koopmans [1965], have been designed to improve Solow's model by introducing an endogenous rate of saving. These types of (Ramsey-) models assumed the usual neoclassical production function, but introduced a single agent, the planner, who is endowed with a separate and stationary utility function (and a constant discount rate) in order to control both production and saving decisions [Barro and Sala-i-Martin, 1995]. Due to the fact that in these models the technological progress is set exogenously (i.e. the source of growth is external to the model), all have a basic shortcoming: They basically assume what they should explain.

The endogenous growth models, introduced in the 1980s and 90s by Romer [1986] and Lucas [1988], aimed to overcome this shortcoming by making growth an endogenous variable. The different model approaches focus mainly on the introduction of human capital as a ”fully reproducible resource” (Salvadori [2003]) and on endogenous investment decisions yielding technological progress. This 'new growth' (or 'endogenous growth') theory[6] builds on the recognition that to a large extent this technological progress arises from the efforts of (profit-seeking) actors within the economy.

In recent years computable general equilibrium models (CGEs), originally introduced as tools of empirical economic analysis, are used for integrated assessment modelling. CGEs, which are based on a neoclassical core, are particularly designed to capture linkages and interactions within the economy and simulate its mode of functioning under alternative development options or scenarios [Robinson, 1991]. In principle, a CGE model is composed of a (within-period) static part and a (inter-period) dynamic part. The static part generates a general equilibrium solution at a specific point of time whereas the inter-period part reflects the dynamic relation between two equilibrium points. The equilibrium solution depends on resource endowment, selected policy variable and external conditions. These variables define conditions considered fixed within one period, but may vary between periods. To ensure the path from one equilibrium point to another, a complete set of dynamic relations or an inter-period model is therefore required. A CGE model works generally by using data to describe the economy in a benchmark year, and by varying one or more elements so as to disturb the economy and change values of data items.

1.3 Limitations of integrated assessment models

The majority of the integrated assessment approaches currently used face some fundamental limitations:

- Although there is a growing agreement that technological change is a key to address

[6] For details, see also Romer [1990], Aghion and Howitt [1992, 1998], Grossmann and Helpman [1991]

integrated assessments of climate change[7], almost all economic models applied to integrated assessment of climate change have embodied the conventional treatment of technological change, derived from standard neoclassical growth models. In particular, they assume that technological progress results from factors that are exogenous to the workings of the economy.

The assumption of exogenous technological change is a limitation in two respects: First, it is simply not clear what an appropriate exogenous rate of this scaling factor should be. This is important, especially for long-term projections, which are very sensitive to differences in assumed rates. Second, market-based innovation and the entrepreneurial pursuit of technological progress are not only undoubtedly endogenous economic processes but indeed are hallmarks of modern economies and should therefore be modelled endogenously [Pew Center, 2000].

- In almost all IA models using a neoclassical approach the economic growth is determined by control decisions of only one single decision maker, the 'social planner', who maximizes social and economic welfare by optimizing one single welfare function for the whole socio-economic system.

  The concept of a single planner for the entire socio-economic system mixes the completely different welfare criteria of the different actor groups of economy and society. Entrepreneurs, wage earners and political decision makers have undoubtedly divergent welfare goals. Although sustained economic growth is a key feature for all actors, additional focus is on personal benefits, like profits or earnings. In addition, there are completely different welfare criteria in different regions of the world. Thus, the conception of a single planner is to a large extent inadequate for integrated assessments of real-world economies.

- General-equilibrium models of long-term economic change tend to ignore short-to-medium term socio-economic processes such as business cycles, economic growth, and other critical processes associated with the evolving global economic system.

  Interactions between the principal economic actors can lead to instabilities and mean growth paths of the economy, which are far removed from the theoretical solutions of the general-equilibrium models. It is therefore important that integrated assessment models address the socio-economic impacts of climate policy both in the long and the short-to-medium term.

1.4 Objectives of this Study

The present study addresses the above-mentioned limitations of current IA models by introducing a new integrated assessment model approach, MADIAM (Multi-Actor Dy-

[7] Assessments about the role of technological change can be found, for example, in Dowlatabadi [1998], Edenhofer et al. [2004], Edmonds et al. [1997], Grübler [1998], , Kemfert [2002], Popp [2001], and van der Zwaan [2002].

namic Integrated Assessment Model). This has been developed in order to apply systems-analysis methods to explore some of the principal processes governing the multi-actor dynamics of the coupled climate-socioeconomic system. The following key features characterize this model approach:

- In MADIAM, economic growth is described as the result of the decisions of multiple actors (business, governments, consumers, wage-earners). The emphasis of the model is on the principal roles and influences of these actors in jointly determining the evolution of the coupled climate-socioeconomic system. The actors, in their varying and interacting responses to the challenge of climate change, influence the economic system by business investment decisions, business competition, wage demands by labour, regulatory action of governments, and consumer preferences, expressed by differences in the demands for different consumer goods.

- The dominant process governing economic growth in MADIAM is endogenous technological change, which is treated as synonymous to growth in human capital and labour productivity. Technological change is the result of the multiple impacts of the principal actors controlling the system dynamics. In particular technological progress in MADIAM is described not only through endogenous investments in labour productivity, but also through 'induced' technological change (ITC)[8] that is stimulated by climate policy (e.g. environmental taxes, regulation, and restrictions), and additionally through small exogenous contributions.

- The economic module of MADIAM, in contrast to almost all other economic models used for integrated assessment studies, is not a classical general equilibrium model, allowing instead for unemployment and positive profits, both of which are observed essential characteristics of real-world economies.

- Although the evolution of the coupled climate-socioeconomic system is determined by the actions of the actors pursuing divergent goals, MADIAM is not an optimization model approach. There is no attempt in the present study to determine the possible optimized strategies that the individual actors may adopt in response to the (known, partially known or assumed) strategies of the other actors. Instead, it is assumed here that each actor, in ignorance of the details of the other actors' strategies, simply follows some given individual strategy dependent only on the present system state and the actor's implicit personal anticipation of the future evolution of the system.[9]

The primary focus of this study is twofold. First, the individual as well as combined impacts of the decisions and control strategies of the principal actors on the socio-economic

[8] For publications about ITC see, for example Buonanno et al. [2003], Edenhofer et al. [2003], Goulder and Schneider [1999], Goulder and Mathai [2000], Nordhaus [2002], Popp [2000], and Weyant and Olavson [1999].

[9] See Barth [2003] for an application of another model version in the more traditional single-actor cost/benefit mode.

system, estimated by MADIAM simulations, are identified. Second, the role and the impacts of different types and sources of technological change (e.g. endogenous investments in productivity, induced and exogenous technological change) are examined.

The main goals are to initiate a model development that (1) is able to treat the dynamics of the coupled climate socio-economic system, including endogenous technological change, in a non-equilibrium situation and thereby overcomes some of the limitations of standard economic model approaches and (2) represents a general approach to bridging the gap between growth models and computable general equilibrium models as currently applied in integrated assessment studies.

The Multi-Actor Integrated Assessment Model MADIAM is composed of two coupled modules: a climate module NICCS (a Nonlinear Impulse-response representation of the coupled Carbon cycle-Climate System [Hooss, 2001]), and a socio-economic model MADEM (Multi-Actor Dynamic Economic Model), which is based partly on the SDEM model by Barth [2003]. Both modules are described in detail in the following sections.

A simplified version of the MADIAM model, including three independent agents (business, government and consumers) and stochastic processes, has been implemented in an interactive climate computer game for a climate exhibition of the German Museum in Munich.

1.5 Outline

The paper is organized as follows. The core of the economic model MADEM is described, as yet without climate interactions, in Chapter 2, where we focus on the principal driving forces of the economic module.

In Chapter 3, the core economic model is extended to the economic module MADEM used in the coupled climate-socioeconomic model MADIAM by introducing the climate module NICCS as well as additional model features like climate damages, finite fossil fuel resources, business investments in mitigation and government regulation measures. Additionally the control strategies of the principal actors are defined and described in detail.

The impacts of these control strategies are illustrated by simulation examples in the following chapters. First, in Chapter 4 the basic initialization and calibration settings of the model are described shortly, the basic reference scenarios are presented and a number of sensitivity analysis are discussed. Second, the impact of individual actor strategies are examined in Chapter 5 and finally the impact of simultaneous parallel control decisions of two or three actors are explored in Chapter 6.

In Chapter 7 the basic stochastic behaviour of a number of critical parameters is presented (in addition to the sensitivity analysis in Chapter 4).

The study closes in Section 8 with a summary of the approach and the main findings, principal conclusions, and with an outlook on further developments of the MADIAM model. This Chapter includes a discussion of the relation of the current as well as future developments of MADIAM to other types of IA models.

The calibration constants, the initial values of variables, the initial settings of variable parameters, and the basic settings of the control parameters for the specific scenario are given in Appendix A.

The model scenarios presented in this study have all been explored for one single (global) region. Nevertheless the current version of MADIAM is coded in modular Fortran 90, using hierarchical variable structures designed to allow a straightforward extension to a second-generation model, which incorporates numerous additional features, like a larger number of regions, sectors and actors. This is demonstrated in Appendix B.

Chapter 2

The Multi-Actor Dynamic Economic Model (MADEM)

In order to stress the primary driving forces of the economic module MADEM, we present first a simpler core model (MADEM-core), which is based partly on the Structural Dynamic Economic Model (SDEM) by Barth [2003]. This core-model is highly aggregated and consists of only one region, with one sector producing one product output, which is subdivided into consumer goods and investment goods. Economic growth is described as the outcome of two opposing forces: business, striving to increase profits by investments in human and physical capital, and business competition, supported by labour wage demands, which erodes profits. In contrast to neoclassical growth models and more recent endogenous growth models (see Section 1), this leads to a system which is not in classical general equilibrium, allowing instead for unemployment and profits.

2.1 Production and Labour

The production function of MADEM-core depends on three primary production factors: physical capital k, human capital h and employed labour l, which together produce a total annual output y.

Human capital h is regarded as a proxy for all factors that contribute to labour productivity $\hat{y} = y/l$: training and education, technology, R&D, etc.[1] Formally, human capital h is defined as the time integral $\int i_h \, dt$ of human capital investments minus depreciation, but labour productivity $\hat{y}$ is used instead as equivalent state variable (eq. (2.7) below).

It is assumed that the technological level connected to a given level of labour productivity also uniquely determines the physical capital requirement per work place, $\hat{k} = k/l = f(\hat{y})$. Thus, in contrast to the usual neo-classical approach, physical capital and labour

[1] We distinguish *per capita* variables, e.g. $\hat{y}$, from the associated integral variables, y, by a circumflex.

are not regarded as instantaneously substitutable, but are coupled, as in Leontief [1941]. However, we do not assume a constant ratio of physical capital to labour, as in Leontief, but assume this to be a function $f(\hat{y})$ of labour productivity (human capital), where $\hat{y}$ can be changed through investments in human capital. The three primary production factors are thereby reduced in fact to only two independent production factors.

Specifically, it is assumed that the capital costs per workplace are proportional to labour productivity, $f(\hat{y}) = \hat{y}/\nu$, with constant ν. This is in accordance with the empirical findings from long time series of a constant production-to-capital ratio $\nu = y/k$ for industrialized countries [Maddison, 1982, 1995].

Thus the annual production rate can be expressed:

$$y = \nu k = \nu' h = \hat{y} l, \tag{2.1}$$

where the factors ν, ν' (variable, not used in the following and mentioned only for conceptual completeness) and $\hat{y}$ represent the mean output/input productivity ratios of production with respect to the primary production factors physical capital, human capital and labour, respectively. The term productivity is used throughout only in the sense of mean labour productivity, from now on the adjective 'labour' is dropped.

Given the available labour pool $l_{\max}(t)$, which is assumed to grow continuously and parallel to the world population[2], the levels of productivity and physical capital determine then the employment level

$$q = \frac{l}{l_{\max}} = \frac{\nu\, k}{\hat{y}\, l_{max}} < 1. \tag{2.2}$$

The variable employment level q, depending on physical and human capital (productivity), is a significant feature of the model approach and distinguishes MADEM from traditional AK models [Barro and Sala-i-Martin, 1995], which are also characterized by a constant production-to-capital ratio ν, but assume in addition a constant level of employed labour. According to eq. (2.2) unemployment arises naturally through an increase (i.e. investments) in human capital (productivity), which reduces the number of employed labour unless accompanied by investments in physical capital. Thus, structural unemployment occurs under conditions in which it is more profitable for business to invest in productivity than physical capital.

Total annual production y is sub-divided into three outputs: the annual production i_k, i_h of physical and human capital, $k,\ h$, respectively, and the annual production r_g of consumer goods and services g (cf. Fig.2.1a),

$$y = i_k + i_h + r_g. \tag{2.3}$$

[2]In accordance with recent world population studies [United Nations, 1998, 2003]. Details about the models initialization are given in Chapter 4 and Appendix A.

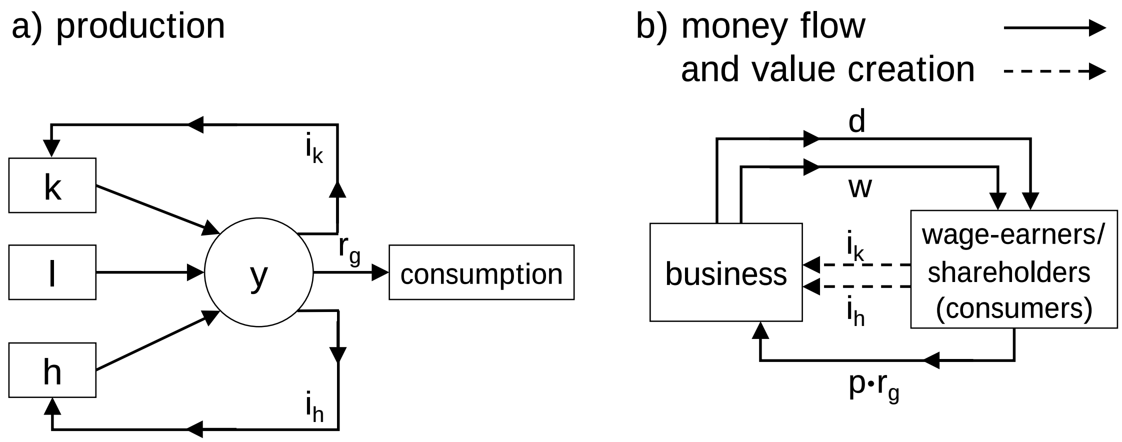

Figure 2.1: *Production factors and products (panel a, left, eq. (2.3)) and money flows and value creation (panel b, right, eq. (2.4)) for the MADEM-core model. In contrast to the full arrows representing the closed money flow via consumption in panel b, the dashed arrows represent added wealth created through investments. They result from the surplus production, in addition to the production of consumer goods, created by the actors owning the production factors labour, human capital and physical capital (i.e. by wage-earners and shareholders) and therefore do not appear in the closed money-flow balance of eq. (2.4).*

The variables k, h, g, although representing different physical entities, can be expressed in common units in terms of the labour workhours required for their production. For simplicity, the productivity in each of the three output sectors is assumed to be the same. We shall measure output products in units of consumer goods [G], and annual production in units [G/yr].

The production rates can be related to the expenses x of production, measured in monetary units [$/yr]. Since we assume that there is no vertical stratification of production sectors, involving intermediate inputs and outputs, all expenses of all production sectors reduce to payments to the owners of the production factors, i.e. to the annual wages $w[\$/yr]$ paid to workers (the 'owners' of human capital and labour) and the annual dividends $d[\$/yr]$ issued to the shareholders (who own the physical capital). We ignore in the core-model capital costs in the form of interests, assuming that the owners of capital are remunerated entirely through dividends. The production expenses flow back to business as revenues from the sale of consumption goods. Thus

$$x = w + d = p \cdot r_g, \tag{2.4}$$

where $p[\$/G]$ is the price of the consumer goods (cf. Fig.2.1b).

The outputs of production, eq. (2.3), can be expressed also in currency units by multiplying all terms of eq. (2.3) by the price p. We may choose currency units [$] or goods units [G] such that $p = 1$[$/G]. Substituting $p \cdot r_g$ from eq. (2.4) into eq. (2.3), we obtain then

$$y[\$/yr] = i_k + i_h + w + d. \tag{2.5}$$

Economic growth depends on the way business chooses to partition its net business profits after wage costs between investments in physical or human capital or distribution to shareholders as dividends. The consideration of growth generated by additional factors, for example consumer savings, which flow back to business as credits, is deferred until the next Chapter.

In order to understand the roles of the different actors, it is crucial to have in mind that we distinguish here between functions and persons. Thus, an individual can be both a wage earner and a shareholder. Similarly, a wage-earner acts both as a consumer, influencing the price of goods through consumer preferences (discussed in the following Chapter), and a wage-negotiator, while shareholders function both as consumers and as the recipients of dividends, driving business to increase profits. Traditionally, wage earners, shareholders and consumers are regarded as members of the category ’households’. However, we shall find it more useful to focus on the functions of different actors. We have therefore placed wage-earners and shareholders together in the function box ’consumers’ in Figure 2.1b. Similarly, we have not used the traditional term ’firm’, but rather the term ’business’, to emphasize that this box represents a management unit, the *de facto* owners of the firm’s physical capital being the shareholders.

2.2 Evolution Equations

The evolution of the core-model economy is described by the rates of change of the three state variables: physical capital, k, productivity $\hat{y}$ and the labour wage rate $\hat{w}$:

$$\dot{k} = i_k - \lambda_k k, \tag{2.6}$$

$$\dot{\hat{y}} = \mu_h \frac{i_h}{l} - (\lambda_{h1} - \lambda_{h2})\hat{y}, \tag{2.7}$$

$$\dot{\hat{w}} = \lambda_w(\widehat{w}^0 - \widehat{w}). \tag{2.8}$$

Equation (2.6) is the usual growth equation for physical capital, determined by the balance between investments i_k and depreciation, with a constant depreciation rate λ_k.

A similar evolution equation (2.7) applies for the growth in productivity (representing human capital). Depreciation $\lambda_{h1}\hat{y}$ of human capital arises through the retirement of skilled personnel, who must be replaced by new employees with initially less skill. ’Negative depreciation’ $\lambda_{h2}\hat{y}$ occurs due to the exogenous increase in productivity (at a rate assumed to be proportional to the already existing level) through improvements in technology caused, for example, by learning-by-doing. The parameter μ_h characterizes the effectiveness of investments in human capital (productivity $\hat{y}$) relative to investments in physical capital k. The factor $1/l$ enters because the investments refer to productivity, a *per capita* variable, and ensures that the economy is scale independent.

The evolution of the wage rate (eq. 2.8) is driven by the difference between a target wage rate $\widehat{w}^0$, which depends on productivity, and $\widehat{w}$. The time constant λ_w defined the relaxation rate of the dynamic wage formation process, which is described in the following subsection.

2.3 Wage Formation

The evolution of the wage rate, $\hat{w}$ expresses the profit-eroding impact of business competition and the wage demands of labour, both of which cannot be distinguished within an aggregated macro-economic model. Successful business executives strive to expand their market share by lowering the market prices of their goods and by attracting labour through higher wages. The latter effect is reinforced by the wage negotiations of organized labour. Thus a reduction of the sales prices for goods g and an increase in the wage level w both have the same effect of eroding the residual profits that business is able to issue as dividends $d = p \cdot r_g - w$ (eq. (2.4)) to shareholders (for a given level of investments).

It is assumed in eq. (2.8) that the net effect of business competition and the wage demands of labour is to drive wage rates towards a target wage rate $\hat{w}^0$ proportional to productivity,

$$\widehat{w}^0 = a_w \hat{y}, \tag{2.9}$$

at the adjustment rate $\lambda_w(\widehat{w}^0 - \widehat{w})$. Thus the target-wage coefficient a_w and the wage rate time parameter λ_w represent the effective net 'control variables' of businesses engaged in competition and wage earners negotiating wage increases. In their own interest, both will set the target-wage coefficient a_w lower than the maximal target-wage coefficient a_w^{max} that the economy is able to support in the limit of a zero profit rate, while still maintaining a constant level of physical and human capital stocks, $a_w < a_w^{max}$. From eqs. (2.1), (2.6), (2.7)), we find for the limiting zero-profit-rate, zero-growth target-wage coefficient

$$a_w^{max} = (1 - \frac{\lambda_k}{\nu} - \frac{\lambda_h}{\mu_h}). \tag{2.10}$$

2.4 Control Strategies

The evolution of the model system depends on the decisions of the basic actors. In the case of the MADEM-core model the principal driving forces are wage earners (as proxy also for competition) and business. Their control options are the following:[3]

[3]These strategies are discussed in more detail in the context of the full MADIAM model in the next Chapter.

- **Wage earners** seek to maximize wages, while at the same time maintaining a high employment level and a healthy growth of the economy. A higher target wage coefficient a_w leads to higher wages. This motivates business to invest more strongly in human than physical capital, thereby depressing the employment level. To counter this tendency, wage earners will lower the target wage if the employment level drops. Similarly, if the employment level is low, the equivalent target wage towards which business competition tends to drive wages is also reduced. Thus, the control parameter a_w is a variable that wage earners (and the invisible hand of business competition) set as a function of the employment level.

- **Business**[4] has the choice of spending its profits x' on dividends, or on investments in physical or human capital. The first option rewards shareholders in the short term at the cost of economic growth. The second option, investments in physical capital, increases production. However, increased physical capital translates into increased profits only to the extent that the current wage rate is sufficiently lower than the zero-profit wage-rate limit. Investments in physical capital are furthermore feasible only if full employment has not yet been attained; otherwise, capital investments must be accompanied by investments in human capital (productivity) in order to free workers for new jobs. The third option, investments in human capital for a fixed stock of physical capital, leads immediately to an increase in the profit rate through a reduction in the number of employed workers, while the production itself remains unchanged ($y = k\nu,\ \nu =$ const, eq. (2.1)). In general, continual investments in productivity (human capital), producing a depression of the employment level, are necessary to enhance profits and counter the erosion of profits through the pressures of business competition and wage demands (cf. Figure 2.2). However, to expand production, investments must be made also in physical capital. Optimal economic growth is achieved through an appropriate balance between these two forms of capital investment (see detailed description in Section 3.3).

Independent of these details, however, the principal driver of economic growth is investments in productivity and the technological change with which these are associated. In the core model it is assumed that growth from increased productivity is fuelled directly by increased profits, rather than by deferred consumption and an associated return flow to business through savings and the purchase of shares by consumers. The impacts of these processes on economic growth in relation to endogenous and induced technological change will be discussed in the following presentation of the full model MADIAM.

[4] Note that we have not distinguished in this discussion between the roles of business and shareholders. It has been assumed that the interests of shareholders are identical to those of business. Details about this assumption will be given in Section 3.3.2.

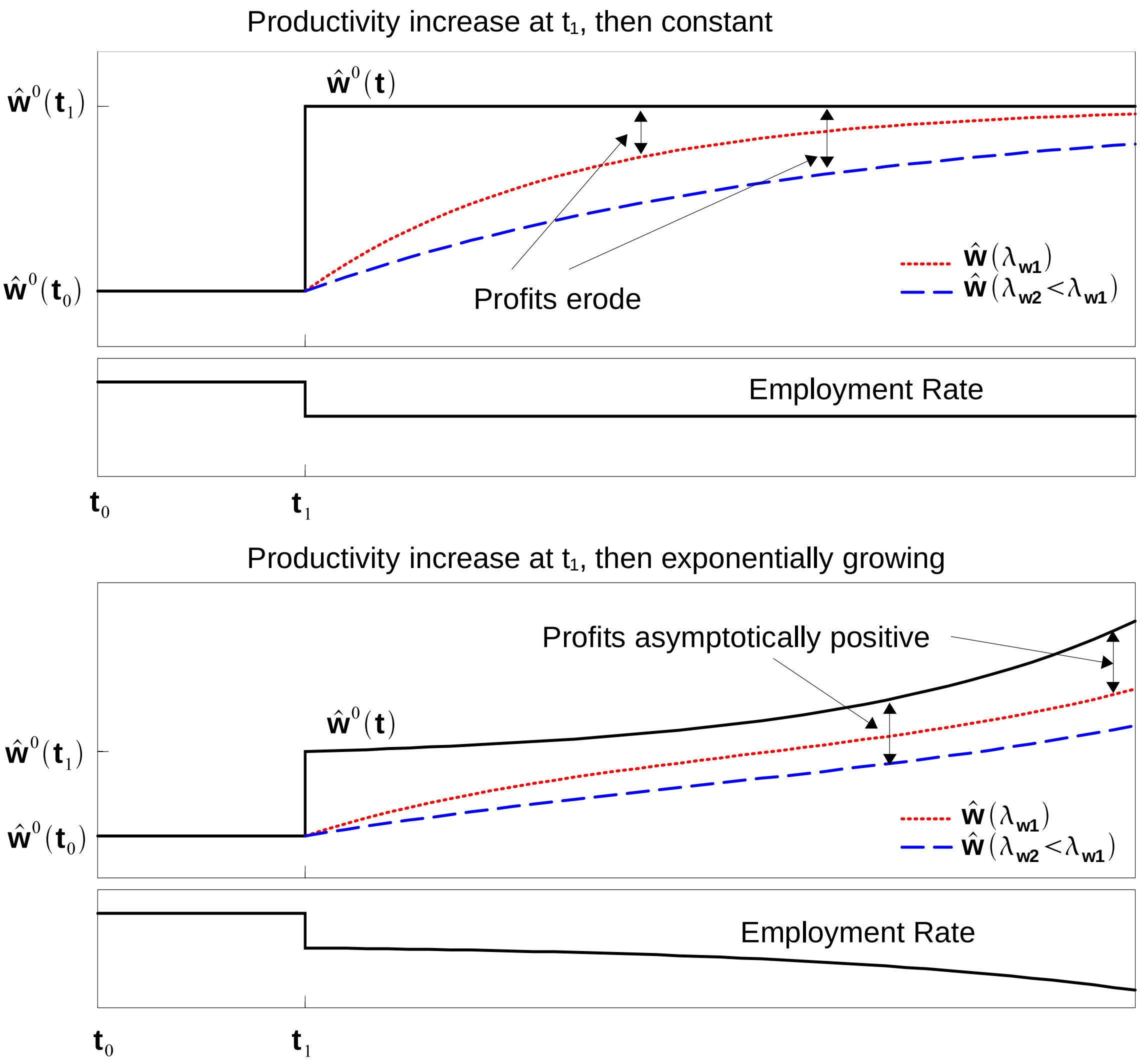

Figure 2.2: *Dynamic adjustment of wage rates, profits and employment level. Top: A step-function increase in productivity immediately raises the target wage $\hat{w}^0$ (proportional to $\hat{y}$) and depresses the employment level $q = l/l_{max}$. The wage rate $\hat{w}$ then adjusts with a time lag determined by the time constant λ_w, so that the profit rate (determined by the difference $\hat{w}^0 - \hat{w}$) gradually erodes. The employment rate remains at its depressed level (assuming physical capital investments are fixed at a rate balancing depreciation). Bottom: If productivity grows at a constant rate, the difference $\hat{w}^0 - \hat{w}$ no longer tends to zero, allowing a positive profit rate to be maintained. Increasing productivity lowers the demand for labour, and the employment level declines. (Figure according to Barth [2003].)*

Chapter 3

The Multi-Actor Dynamic Integrated Assessment Model (MADIAM)

The climate-socioeconomic model MADIAM is obtained by extending MADEM-core through the incorporation of a number of additional features and the integration of the climate module NICCS. The new features include climate damages, carbon taxes, investments in energy and carbon efficiency, finite fossil fuel resources, two types of consumer goods (green: climate-friendly and grey: non-climate-friendly), consumer preferences (including savings), interests on credits, and stochastic variability.

The outline of this Chapter is the following. In Section 3.1 the climate module NICCS by Hooss et al. [2001] is presented. This is followed in Section 3.2 by a detailed description of the MADIAM setup. Section 3.3 finally explains the different control strategies of the principal actors.

3.1 The climate module NICCS

The NICCS model is based on the technique of linear impulse response functions (IRFs) to simulate the response of the climate system to external forcing as computed with state-of-the-art 3D models of the carbon cycle and the general ocean-atmosphere circulation system (AOGCMs) [Hooss et al., 2001]. The response of the full 3D model to a sufficiently small and short (δ-function) impulse of a given input variable can be represented by an IRF (Green's function). Given an arbitrary time-dependent forcing of this variable, the response can then be represented as a superposition of the responses to a continuous sequence of such δ-function inputs. The resultant convolution of the IRF with the time-dependent forcing function reproduces the complex model result with high accuracy, and at a greatly reduced computational cost.

The IRF method is applicable whenever the climate response can be linearized, in practice, for global warming smaller than about 3 ° C (cf. Maier-Reimer and Hasselmann [1987]). The linearity restriction is partly overcome in the NICCS model by explicitly including some of the major nonlinearities of the climate system and the carbon cycle. IRF models are generally able to reproduce the space-time structures of all fields computed by the parent models against which the IRF models are calibrated.

The NICCS model is specifically developed to reproduce the space-time structure of the change in the annual and global near-surface temperature, cloud coverage, precipitation, and sea level. In MADIAM only the globally averaged temperature change is used as a proxy for climate change. The annual CO_2 emissions, which depends on the production and the net carbon efficiency (see Section 3.2.5 below) are used as extrenal forcing. Historical emissions are approximated by an exponential growth function for the period 1800 to t_0.

The model does not yet include changes in the statistics of extreme events or the possible occurrence of instabilities of the climate system, such as a shut-down of the oceanic thermohaline circulation (THC [Rahmstorf, 2000]), a break-off of the West-Antarctic ice sheet [Oppenheimer, 1998] or a release through global warming of large quantities of methane stored in permafrost regions or in methane clathrates in the deep ocean [IPCC, 2001a,b]. To the extent that they can be linearized, changes in the statistics of extreme events can be expressed using the same impulse-response formulation as applied to mean climate variables, calibrated in this case against these changes predicted by state-of-the-art climate models. However, instabilities of the climate system represent strongly nonlinear processes, which are not directly amenable to such techniques. They can nevertheless be included also in impulse response models by representing their occurrence as functions of the critical climate parameters on which they are found (or expected) to depend in state-of-the-art climate models, and which are represented also in IRF models. The inclusion of these features is planned for a later extension of the NICCS model.

3.2 MADIAM setup

This Section explains the setup of the complete MADIAM model. The first subsection presents the production and costs equations and describes the expansion of the model through additional features. These additional features are defined in the subsections afterwards.

3.2.1 Production and costs equations

We distinguish again, as in the core model, between the relative values of output products, related, for example, to workhour units, and the costs of production. The output and cost expressions corresponding to (2.3) and (2.4) become for the extended model

$$
\begin{aligned}
y[G/yr] &= \delta + \sum_{i=1}^{2} r_{gi} + \sum_{i=1}^{3}(i_{ki} + i_{ci} + i_{ei} + v_i) + i_h \quad \text{(products)}, \qquad (3.1) \\
x[\$/yr] &= \sum_{i=1}^{3} \tau_i + w + d + z \cdot s \quad \text{(costs)} \\
&= \sum_{i=1}^{2} p_i r_{gi} + \kappa + \tau_{cycl} \quad \text{(business income + credit uptake)} \qquad (3.2)
\end{aligned}
$$

where, in addition to the investments in physical and human capital, i_k and i_h, the wage costs w, and the dividends d, which have already been presented in Chapter 2,

- δ denotes (tangible) climate damages (generally a negative good or "bad"),
- i_{ci} and i_{ei} represent investments in carbon and energy efficiency, respectively
- v_i denotes the energy production,
- τ_i are the taxes imposed on the emissions generated in the three production sectors,
- τ_{cycl} are the recycled carbon taxes,
- $z \cdot s$ is the interest on business debts, where z is the interest rate and s the business debt,
- p_i denote the prices of consumer goods,
- and κ is the rate of credit uptake of business.

The indices $i = 1, 2$ refer to the production of consumer goods r_{gi} and associated investments i_{ki} in physical capital in the two consumer goods sectors $i = 1$ (green) and $i = 2$ (grey) and the third index value $i = 3$ refers to physical capital investments in the remaining economic sectors, which are aggregated to a single sector. The individual product and cost items appearing in eqs. (3.1) and (3.2) are described in the following sections. Figure 3.1 presents an overview of the production factors and products (Figure 3.1a) and money flows and value creation (Figure 3.1b).

Carbon taxes are assumed to be completely recycled into energy and carbon efficiency as well as physical and human capital (productivity), $\tau_{cycl} = \sum_{i=1}^{3} \tau_i$, so that their contributions in the costs-income balance equation (3.2) cancel. They will reappear later in the evolution equations.

In order to express eq. (3.1) in monetary units, in analogy with eq. (2.5), we multiply the equation throughout by a reference goods price p[\$/G]. p is chosen as the average consumer goods price

$$
p = \frac{\sum_{i=1}^{2} p_i r_{gi}}{\sum_{i=1}^{2} r_{gi}}. \qquad (3.3)
$$

It will be shown in Section 3.2.7 that the prices for consumer goods tend to equalize, so that the average goods price p reduces in this limit to the single goods price introduced in the previous Section. We set, as before, $p = 1$ [$/G] as numeraire.

Eliminating the consumer goods term in the resultant monetarized equation by applying eqs. (3.2), (3.3), we obtain then, in analogy with eq. (2.5),

$$y[\$/yr] = \delta + \sum_{i=1}^{3}(i_{ki} + i_{ci} + i_{ei} + v_i) + i_h + w + z \cdot s - \kappa + d. \tag{3.4}$$

Subtracting the costs for climate damages, energy, wages and interest from the total production plus credit uptake, eq. (3.4) yields then for the net disposable business resources (profits plus credit uptake)

$$x'[\$/yr] = \sum_{i=1}^{3}(i_{ki} + i_{ci} + i_{ei}) + i_h + d. \tag{3.5}$$

Business can choose to partition its disposable resources between investments in physical capital, human capital, energy efficiency and carbon efficiency, and dividends to shareholders. The control strategies will be presented in detail in Section 3.3.

Note, that we have not included explicitly in the cost balance the purchase of shares by consumers. This represents a transfer of a fraction of the consumer income to investments in physical capital. Since this is equivalent to a reduction of the wages and dividends paid by business, with a balancing increase in business physical capital investments, it can be represented simply by an appropriate modification of the relevant model parameters.

3.2.2 Savings and credit uptake

We ignore changes in the assets of banks and bank earnings, assuming that the accumulated savings s of consumers are transferred directly as loans s to business. The rate of business credit uptake κ is therefore equal to the rate of savings by consumers, so that eq. (3.2) may be rewritten as

$$\epsilon = (w + d + z \cdot s)(1 - \eta) = \sum_{i=1}^{2} p_i r_{gi} \tag{3.6}$$

where ϵ represents the consumers' expenditure on consumer goods and η denotes the fraction of the total consumers income that is saved,

$$\kappa = (w + d + z \cdot s) \cdot \eta. \tag{3.7}$$

We treat the savings coefficient η and the interest rate z in the present applications as prescribed exogenous variables, ignoring variations of savings and credit rates induced by changes in the interest rate set by central banks.

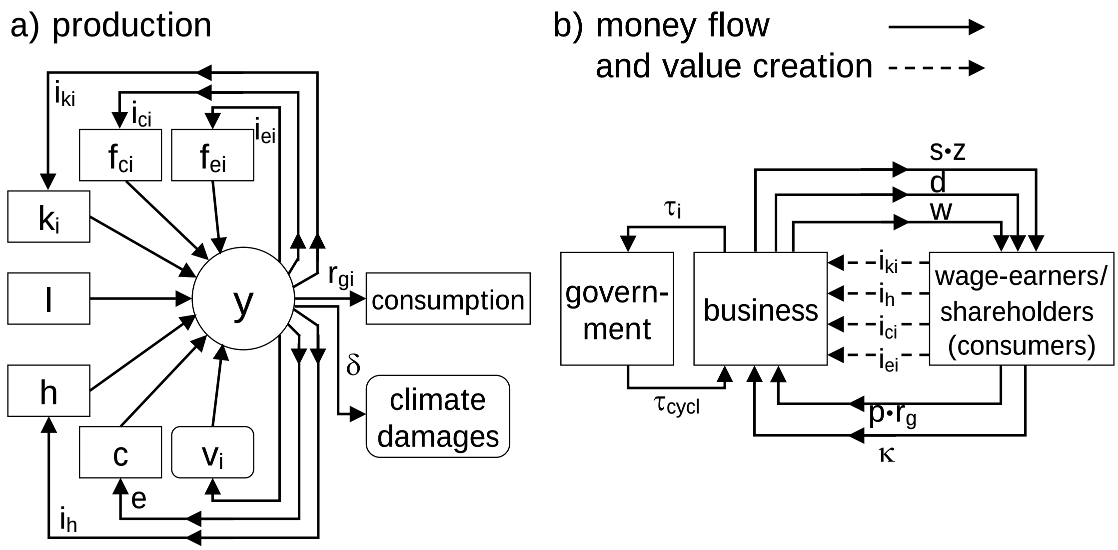

Figure 3.1: *Production factors and products (left, panel a, eq. (3.1)) and money flows and value creation (right, panel b, eq. (3.2)) for the model MADIAM. The dashed arrows in panel b represent surplus production: the additional wealth created through investments by the actors owning the production factors labour, human capital and physical capital (i.e. by wage-earners and shareholders). They therefore do not appear in the closed money-flow balance equation (3.2).*

Government assets are also not considered in the present model level. It is assumed that the government budget is balanced: subsidies for mitigation investments are derived from carbon tax revenues, which are completely recycled; other taxes or subsidies are not considered.

3.2.3 Climate damages

Critical aspects of IA models are the expressions assumed for the damages imposed by climate change. Climate change affects and modifies the natural environment significantly. Some of these modifications can be beneficial but most of them are detrimental for human living conditions.

In order to include climate damages in production and cost functions, the impacts of climate change have to be expressed in the same units as production and costs factors. In MADIAM, climate damages are represented as the sum

$$\delta = \bar{\delta} + \delta' \tag{3.8}$$

of continual climate damages $\bar{\delta}$ and stochastic climate damages δ'. Continual climate damages refer for example, to the costs of higher dykes through sea level rise, adaptation of agriculture to a modified mean climate, changing patterns of recreation and tourism, and changing costs for energy, buildings, construction, etc. Stochastic climate damages represent the costs of unpredictable extreme events, such as the increased frequencies of hurricanes and severe storms, exceptional storm surges and severe flooding, long drought periods, etc.

Continual climate damages are expressed in terms of the changes ΔT of global mean temperature computed from the CO_2 emissions using the NICCS model (see Section 3.1). We assume a simple quadratic dependence on the change and rate of change of temperature in accordance with Hasselmann et al. [1997]:

$$\bar{\delta} = D\, y \left\{ \left(\frac{\Delta T}{T_b} \right)^2 + \left(\frac{d\Delta T/dt}{dT_b/dt} \right)^2 \right\}, \tag{3.9}$$

where T_b is a constant benchmark temperature, dT_b/dt a benchmark rate of change of temperature and D a constant coefficient relating mean (tangible) climate damages to GDP. The damages depend both on the absolute level of climate change, expressed through ΔT, and the rate of climate change, expressed through dT/dt. The relation (3.9) reflects only general views on the (poorly known) global impact of climate change but is believed to represent the magnitude as well as the principal mechanisms adequately [Barth, 2003]. In spite of the fact that the valuation of climate impacts is highly controversial, we assume (in combination with the stochastic climate damages below) a rather large damage estimate of 2% of GDP. Therefore we set the benchmark temperature to 2 $^\circ C$ and the benchmark rate of change of temperature to 0.02 $^\circ C/yr$.

The stochastic climate damages are related to continual climate damages through the simple expression

$$\delta' = \xi_\delta(t)\bar{\delta} \tag{3.10}$$

where ξ_δ is a positive stochastic variable representing a Poisson process with a probability m_1 of occurrence per unit time and a Rayleigh amplitude distribution per occurrence with a mean value m_2. Thus the average climate damages per unit time due to stochastic events is proportional to the continual climate damage level, $< \delta' >= m_1 m_2 \bar{\delta}$. In trial Monte Carlo runs, we assumed that the stochastic and continual climate damages are of comparable magnitude, $m_1\, m_2 \approx 1$. The impact of the additional stochastic part is investigated in Chapter 7.

3.2.4 Energy and Emissions

The production of consumer and investment goods and services requires energy. Most of the energy comes from fossil fuels, the origin of the principal greenhouse gas CO_2. Coal, oil, and natural gas supply about 83 % of the world primary energy consumption. In this study, we limit the view on CO_2, the only climate relevant output generated by the use of fossil fuels, that accounts for appropriately 60% of current greenhouse gas emissions.

Fossil fuels are not the only source of energy. Renewable energy sources like wind, solar, geothermal, hydrogen and biomass play a more and more important role. These sources are 'renewable' because they are naturally replenished, because they can be managed so that they last 'forever', or because their supply is sufficiently large that humans can never meaningfully deplete them. Renewable energy sources have much smaller environmental impacts than fossil fuels.

In MADIAM individual carbon dioxide emissions e_i are related to total energy use E_i (fossil and renewable energy) through the energy-carbon (for short: *carbon*) efficiency f_{ci},

$$e_i = \frac{E_i}{f_{ci}}. \tag{3.11}$$

E_i is measured in equivalent carbon units, i.e. in terms of the emissions that would result if the energy were produced entirely by fossil fuels ($f_{ci} = 1$ for a pure fossil-based economy).

Energy use E_i is related to production y_i in the relevant sector through the production-energy (*energy*) efficiency f_{ei},

$$E_i = \frac{y_i}{f_{ei}}. \tag{3.12}$$

Assuming the same production-to-physical-capital ratio ν in all physical-capital sectors, the production y_i in sector i is given by the product of the total production y and the ratio of physical capital k_i in sector i to the total physical capital (eq. (2.1)):

$$y_i = \frac{y k_i}{\sum_{i=1}^{3} k_i} \tag{3.13}$$

The net production output-carbon (*net carbon*) efficiency (inverse carbon intensity) is given by the product of the production output-energy and energy-carbon efficiencies,

$$f_i = f_{ei} f_{ci}, \tag{3.14}$$

and relates then production outputs to emissions

$$e_i = \frac{y_i}{f_I}. \tag{3.15}$$

The efficiencies are treated as endogenous variables governed by investments in technology. Starting from initial values that are consistent with current (year 2000) energy assessments [IEA, 2003] the energy-carbon and production-energy efficiencies are changed through business investments from profits and taxes recycled from government. The evolution equations are presented in Section 3.2.8 and the initialization of the model is described in detail in relation to the MADIAM simulations (Chapter 4) in Appendix A, in which all initialization and calibration settings and summarized.

3.2.5 Carbon taxes

Government is an important actor of MADIAM. The control options of government are the setting of the carbon tax rate and the recycling of these taxes. Taxes on CO_2 emissions in a given production sector $i = 1 - 3$ are set proportional to the emissions of that sector and total production,

$$\tau_i = c_\tau \frac{y}{y^0}\, e_i \tag{3.16}$$

where c_τ is a constant tax coefficient and y^0 the initial production at time $t = 0$. The factor y/y^0 corresponds to the assumption that the non-market ”value of climate”, expressed in terms of willingness-to-pay, can be represented as a time-independent constant fraction of total production. This is consistent with the differential treatment of discount factors for climate damage and abatement costs introduced in the intertemporal optimization of greenhouse gas emissions in Hasselmann et al. [1997][1].

Expressed in terms of the net carbon efficiency (see Section 3.2.4) and overall production, the emission taxes may also be written as

$$\tau_i = c_\tau \frac{y}{y^0} \frac{y_i}{f_i}. \tag{3.17}$$

Government bank assets are not considered in MADIAM and the carbon taxes are assumed to be completely recycled. The recycling of CO_2 taxes into energy and carbon efficiency as well as productivity and the physical capital of the ’green’ good is described through the evolution equations (Section 3.2.8 below) and the settings of the recycling fraction, which is a control option of government, described in more detail in Section 3.3.

There is no emission trading implemented in MADIAM. The alternative instrument of tradeable emissions would correspond to an emissions cap and therefore cannot be represented realistically.

3.2.6 Energy costs

The costs of energy include many components: costs for establishing and maintaining the production, conversion, transport and distribution, levies, and profit margins [Nakicenovic et al., 1998]. The long-term behaviour of energy prices is difficult to predict. Therefore, the assessment of the costs of fossil and renewable energy in this study must be viewed only as a plausible assumption in the spirit of a general systems-analysis approach.

Energy costs v_i appears in the products equation (3.1) as energy production and later in the monetarized production equation (3.4) as costs (Section 3.2.1 described the different usage of energy costs in units of consumer goods [G] and in monetary units [$] in detail.). In this Section the term ’costs’ is used.

[1] See also discussions by Brown [1997], Heal [1997], Nordhaus [1997], and Hasselmann [1999]

To determine the value of energy costs v_i in eq. (3.1), we consider the separate contributions

$$v_i = v_{fi} + v_{ri} \tag{3.18}$$

for fossil fuel, v_{fi}, and renewable energy, v_{ri}. These are determined by the individual energy prices $p_f,\ p_r$ (costs per unit energy) and the amounts $\alpha_{fi}E_i,\ (1-\alpha_{fi})E_i$ of energy used for fossil and renewable energies, respectively:

$$v_{fi} = p_f\ \alpha_{fi}E_i \tag{3.19}$$

$$v_{ri} = p_r\ (1-\alpha_{fi})E_i, \tag{3.20}$$

where α_{fi} is defined as

$$\alpha_{fi} = \frac{1}{f_{ci}}. \tag{3.21}$$

Following Barth [2003], based on Rogner's [1997] extraction-cost estimates, the prices of fossil fuels are assumed to increase with the inverse square of the available resources,

$$p_f \sim \frac{1}{c^2} \tag{3.22}$$

The fossil-resource estimates of Rogner [1997] assume a fossil energy resource base of about 5,000 GtC for the year 2000 but these estimates increase significantly if gas hydrates and other uncertain occurrences are included [IPCC, 2001b]. The assessment of the resource base is a question of hot debate. It is assumed that some additional (so called 'exotic') fossil resources can be utilized and the initial value is set to $c(t_0)$ = 10,000 GtC. The model sensitivity to variations of this setting is explored in Section 4.3.

The medium to long-term development of renewable energy prices is also difficult to predict. A significant learning-by-doing effect on the prices of renewable energy is assumed. Following the historical technology learning curves for renewable energy sources [Nakicenovic et al., 1998], and allowing for further energy-costs reduction through learning-by-using [IPCC, 2000; Pew Center, 2003] it is assumed that the prices decreases as the use of renewable energy increases,

$$p_r \sim \frac{1}{(1-\alpha_f)E}, \tag{3.23}$$

Using these assumptions the cost equations (3.19) and (3.20) can then be expressed as

$$v_{fi} = \frac{\alpha_{fi}}{\alpha_{fi}^0}\frac{E_i}{E_i^0}\left(\frac{c^0}{c}\right)^2 \cdot v_{fi}^0 \tag{3.24}$$

$$v_{ri} = \frac{(1-\alpha_{fi}^0)E_i^0}{(1-\alpha_{fi})E_i} \cdot \frac{(1-\alpha_{fi})E_i}{(1-\alpha_{fi}^0)E_I^0} \cdot v_{ri}^0 = v_{ri}^0, \tag{3.25}$$

where the upper index 0 refers to the initial values at time $t=0$.

3.2.7 Prices of consumer goods

We introduce two types of consumer goods, a climate-friendly 'green' good (i=1) and a non-climate-friendly 'grey' good (i=2) and assume that the goods market is cleared. The prices p_i (eq. (3.6)) for consumer goods depend on consumer preferences. Goods prices provide investment signals for business, so that changes in consumer preferences due to climate change produce changes in business investments.

We assume that both groups of consumers, wage earners and shareholders, exhibit the same preferences with respect to the purchase of green or grey goods. They may therefore be treated as a single homogeneous group. Consumer preferences for green or grey goods can be expressed by utility functions u_i, which we take to be of the usual logarithmic form

$$u_i = A_i \ln \frac{g_i}{g_i^c}, \quad (i = 1, 2) \tag{3.26}$$

where g_i is the amount of good purchased (prescribed in our case by the supply), A_i is the demand coefficient, and g_i^c a scale coefficient. A_i and g_i^c can change slowly with time, but are regarded as constant on the short time scale relevant for the clearing of the goods market. The demand coefficients A_i are the control variables through which consumers express their relative preferences for the two options of consumer goods.

Prices adjust to the consumers' goods preferences such that the marginal increase of utility with respect to a marginal expenditure increase is the same for both goods:

$$\frac{du_i}{d\epsilon_i} = \frac{A_i}{p_i g_i} = B = \text{const}, \tag{3.27}$$

where $\epsilon_i = p_i g_i$ is the expenditure of consumers on good g_i. The constant B is determined by the consumers' total goods expenditure

$$\epsilon = \epsilon_1 + \epsilon_2 = \frac{A_1}{B} + \frac{A_2}{B}, \tag{3.28}$$

or

$$B = \frac{A_1 + A_2}{\epsilon}. \tag{3.29}$$

Thus, we obtain for the price of goods:

$$p_i = \frac{\epsilon}{g_i} \frac{A_i}{A_1 + A_2} \tag{3.30}$$

where $g_i = r_{gi}$ is the annual production of good g_i.

To maximize profits, business will invest preferentially in the consumer good with the higher price until the prices for both goods are equalized, $p_1 = p_2$ (in accordance with classical economical theory; details about the price mechanism are presented in Section 3.3). This implies an equilibrium goods production ratio (eq. (3.30)),

$$\frac{r_{g1}}{r_{g2}} = \frac{A_1}{A_2}. \tag{3.31}$$

For logarithmic utility functions, this ratio maximizes also the consumers' total utility $u_1 + u_2$ for a given total amount of goods $g_1 + g_2$.

3.2.8 The evolution equations

Given the various product and cost expressions, we can now write down the extension of the evolution equations (2.6)-(2.8) of the MADEM-core system required for the complete economic module MADEM of the coupled climate-socioeconomic system MADIAM (cf. Figure 3.1):

$$\dot{k}_i = i_{ki} + \sigma_{ki}\tau - \lambda_k k_i \quad (i = 1, 2, 3) \tag{3.32}$$

$$\dot{\hat{y}} = \frac{\mu_h}{l}(i_h + \sigma_h \tau) - (\lambda_{h1} - \lambda_{h2})\hat{y} \tag{3.33}$$

$$\dot{\widehat{w}} = \lambda_w(\widehat{w}^0 - \widehat{w}) \tag{3.34}$$

$$\dot{f}_{ci} = \mu_c(i_{ci} + \sigma_{ci}\tau) + \lambda_c f_c \quad (i = 1, 2, 3) \tag{3.35}$$

$$\dot{f}_{ei} = \mu_e(i_{ei} + \sigma_{ei}\tau) + \lambda_e f_{ei} \quad (i = 1, 2, 3) \tag{3.36}$$

$$\dot{c} = -e \tag{3.37}$$

$$\dot{s} = r \tag{3.38}$$

Equations (3.32) - (3.34) are identical to the core-system equations (2.6) - (2.8), except for the additional index i in eq. (3.32), which runs over the two consumer goods sectors $i = 1, 2$ and the residual goods sector $i = 3$ (we distinguish between different capital stocks for the three goods sectors, but assume, for simplicity, that productivity is independent of the good produced) and the fractions σ_{ki} and σ_h of carbon taxes τ (=$\sum_{i=1}^{3} \tau_i$) that are recycled into physical capital and productivity, respectively.

Equations (3.35), (3.36) are analogous to the physical and human capital investment equations, where i_{ci} and i_{ei} denote business investments in energy-carbon and production-energy efficiency, respectively, μ_c and μ_e the associated net investment efficiency coefficients (independent of the good produced), λ_c and λ_e the associated growth-rate coefficients in carbon and energy efficiency through exogenous technological improvement (also independent of the good produced), and σ_{ci}, σ_{ei} the associated fractions of government CO_2 taxes τ that are recycled into non-fossil emission reduction and energy-efficiency technologies. The recycled tax fractions sum to unity: $\sum_{i=1}^{3}(\sigma_{ki} + \sigma_{ci} + \sigma_{ei}) + \sigma_h = 1$.

The decrease in fossil resources c due to CO_2 emissions e (=$\sum_{i=1}^{3} e_i$) is described by eq. (3.37), while the last equation (3.38) represents the rates of change of the savings s of consumers (equal to the loans of business).

Stochastic components

In analogy with the stochastic component introduced into the expression for climate damages (eq. (3.10)), we introduce stochasticity into the evolution equations for human capital, carbon efficiency and emission efficiency by splitting the investment coefficients μ_h, μ_{ci} and μ_{ei} into a continual and stochastic part

$$\mu = \bar{\mu} + \mu', \tag{3.39}$$

where

$$\mu' = \xi_\mu(t)\bar{\mu} \tag{3.40}$$

and $\xi_\mu(t)$ represents a Poisson processes with given probabilities of occurrence per year and Rayleigh amplitude distributions. The random components μ' represent the impact of unpredictable advances through significant inventions, technological breakthroughs, etc. The parameters of the stochastic processes can be chosen individually for each of the three state variables. The impact of the additional stochastic part is investigated in Chapter 7.

3.2.9 Wage costs

The MADEM-core evolution equation (2.8) for the wage rate $\hat{w}$ remains unchanged in the complete MADIAM model, but the expression (2.10) for the limiting zero-growth, zero-dividend target-wage coefficient now becomes, allowing for the expenses before profits listed in (3.4),

$$a_w^{max} = 1 - \frac{\lambda_k}{\nu} - \frac{\lambda_h}{\mu_h} - \frac{1}{y}\left\{\delta + \sum_{i=1}^{3}(i_{ci} + i_{ei} + v_i) + z \cdot s\right\} \tag{3.41}$$

3.3 Control strategies

The evolution of the system in accordance with eqs. (3.32)-(3.38) depends on the control strategies of the basic economic actors (wage-earners, shareholders, consumers, business and governments) in response to the various costs, consumer preferences and prices summarized in Section 3.2. Rather than addressing the general game-theoretical problem of determining the solution, or set of possible solutions, that evolves if each actor optimizes his or her control strategy in response to the observed or anticipated strategies of the other actors, we have simply postulated plausible control strategies of the individual actors, anticipating only obvious control strategies of the other actors. The associated control parameters are listed in Appendix A.

3.3.1 Wage earners

Wage earners (as proxy also for business competition) strive to adjust the dynamic wage-adjustment parameters a_w and λ_w to maximize wages and maintain a high employment level as well as a healthy economic growth. As mentioned before, a high target-wage rate close to $a_w = a_w^{max}$ can be expected to lead to low employment levels, as the response of business to high wages is to invest in human capital, with an associated reduction of the workforce, rather than in physical capital. We have therefore assumed that wage earners adjust the target wage in response to the employment level in accordance with the simple power-law relation

$$a_w = a_w^{min} + \left(a_w^{max} - a_w^{min}\right) q^{\alpha_q} \tag{3.42}$$

where a_w^{min}, α_q are constant parameters.

3.3.2 Shareholders

Shareholders are represented in our model as independent actors only in their role of consumers. In this function they are assumed to exhibit the same consumer-goods preferences as wage earners. It has been assumed that the interests of shareholders are identical to those of business. This must be viewed as an approximation: business will generally have corporate goals that are not necessarily identical to those of shareholders. Moreover, shareholders, in their roles as consumers, have similar goals to wage earners: to maximize their time-integrated, appropriately discounted income. The main distinctions between wage earners and shareholders presumably lie in the application of different effective discount factors (shareholders normally taking a longer-term view) and in different bargaining positions with respect to business management. We have suggested here only a simple approximate model of the dynamics of the three-way bargaining process between business, wage earners and shareholders.

3.3.3 Consumers

Consumers modify the ratio of their demand coefficients A_i for the two types of consumer goods in response to the projected climate change. We assume a linear dependency of the ratio A_1/A_2 on the level of climate damages δ, normalized by GDP (y),

$$\frac{A_1}{A_2} = \frac{A_1^0}{A_2^0}\frac{\delta}{\delta^0}\frac{y^0}{y}, \tag{3.43}$$

where A_1^0 and A_2^0 are the initial preference values. The ratio A_1/A_2 determines the goods prices, given the production ratios r_{g1}/r_{g2} (Section 3). Different prices imply different profitabilities in the production of different goods, in response to which business then adjusts its physical capital investments (see Section 3.3.4 below).

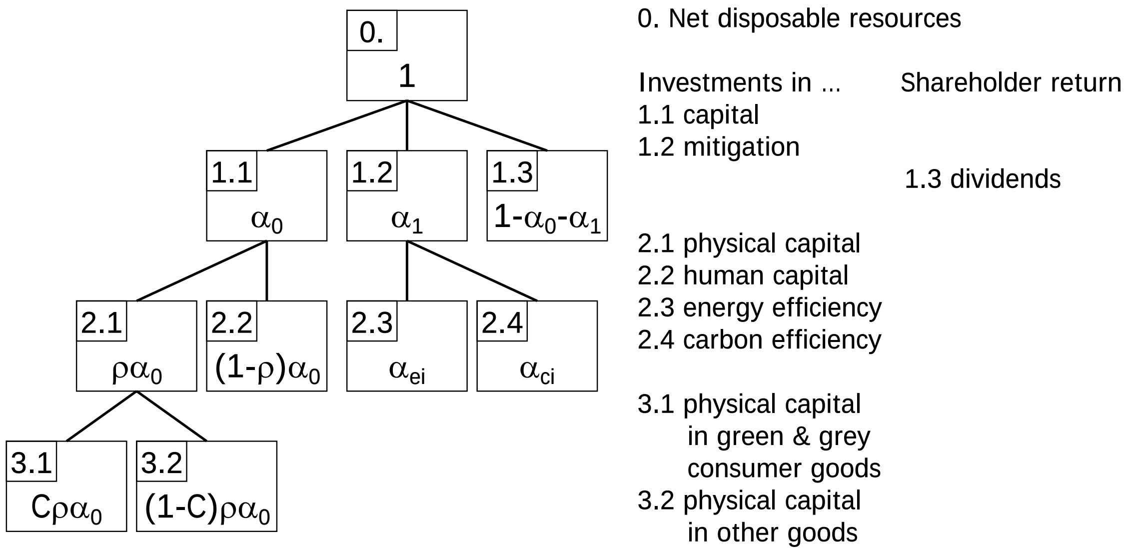

Figure 3.2: *Fractions of net disposable resources x' of business (profits plus credit uptake) distributed between various investment options (left and middle branches) and dividends (right branch).*

3.3.4 Business

Business has the choice of using its net disposable resources x' (profits plus credit uptake, eq. (3.5)) for investments in physical or human capital, i_{ki} , i_h, investments in energy or carbon efficiency, i_{ei} , i_{ci}, or dividends for shareholders. Rather than attempting to carry out a detailed cost/benefit analysis of present and discounted future costs, business adopts a simple successive partitioning strategy (Figure 3.2).

- **In the first partitioning level 1**, business decides on the fractions α_0, α_1 and $1 - \alpha_0 - \alpha_1$ of the net disposable income x' to be used for capital (physical and human) investments, mitigation measures (energy and carbon efficiency) or dividends, respectively. The decision is guided by two considerations: the results of cost/benefit analyses [Barth, 2003], and the carbon tax level. Cost-benefit analyses indicate that in order to maximize the discounted time-integral of dividends (the basic goal of business representing shareholder interests), dividends should represent an approximately constant fraction of capital investments. The impact of the carbon tax level is also represented by a constant factor α_1. We have not included a feedback of the carbon tax coefficient set by government on the factor α_1, in keeping with our approach of investigating first the impact of the individual actor control parameters before considering interactions between actors.

- **At the next level 2**, business decides on the further partitioning of the capital and mitigation investments. The distribution of capital investments between physical and human capital is again guided by cost/benefit analyses, supported by qualitative feedback considerations: If the employment level and wage rate are low compared with the full-employment level and zero-profit wage rate, respectively, it is more profitable to invest in physical capital than human capital. As these two limits are approached, however, it becomes more profitable to divert a higher fraction of investments from physical capital into human capital. The partitioning of the total capital investments into the physical and human capital investment branches (with $i_k = \sum_{i=1}^{3} i_{ki}$) is accordingly set as

$$i_k = \rho\alpha_0 x' \tag{3.44}$$
$$i_h = (1-\rho)\alpha_0 x'. \tag{3.45}$$

where the factor feedback factor ρ is represented as the product $\rho = \rho_q \rho_w$ of two factors $\rho_q,\ \rho_w$ describing the impact of the employment level and wage rate, respectively. In our simulations we set

$$\rho_q = \frac{(1-q)^2}{a_1 + (1-q)^2}, \tag{3.46}$$
$$\rho_w = \frac{(1-\hat{w}/\hat{w}^0)^2}{a_2 + (\hat{w}/\hat{w}^0)^2}, \tag{3.47}$$

with constant parameters a_1, a_2 (cf. Appendix A). The net effect of the two feedback factors $\rho_q,\ \rho_w$ is to stabilize growth at a given employment level, a given wage-to-productivity ratio and a given ratio of investments in human and physical capital.

The partioning of mitigation investments between energy and carbon efficiency is carried out in fixed proportions,

$$i_{ei} = \alpha_{ei} x' \tag{3.48}$$
$$i_{ci} = \alpha_{ci} x', \tag{3.49}$$

with constant α_{ei} , α_{ci} (cf. Appendix A) and

$$\sum_{i=1}^{3} (\alpha_{ei} + \alpha_{ci}) = \alpha_1. \tag{3.50}$$

The distribution of the mitigation investments, i_c (=$\sum_{i=1}^{3} i_{ci}$) and i_e (=$\sum_{i=1}^{3} i_{ei}$), between the different goods (i=1,2,3) is then determined by a business analysis of the net energy-related costs (energy costs, v_i plus carbon taxes, τ_i). Due to the fact that the energy and carbon efficiencies influence both of these costs, business invests 60% of the total mitigation investments in the goods sector with the highest costs and splits the residue into the remaining sectors. This mechanism is an option, which has recently been implemented in the model. The scenarios in the following simulation chapters are simulated with this option deactivated. Instead 1/3 of the mitigation investments are distributed in each good sector. However, the effect of this option is examined in a sensitivity analysis in Section 4.3.

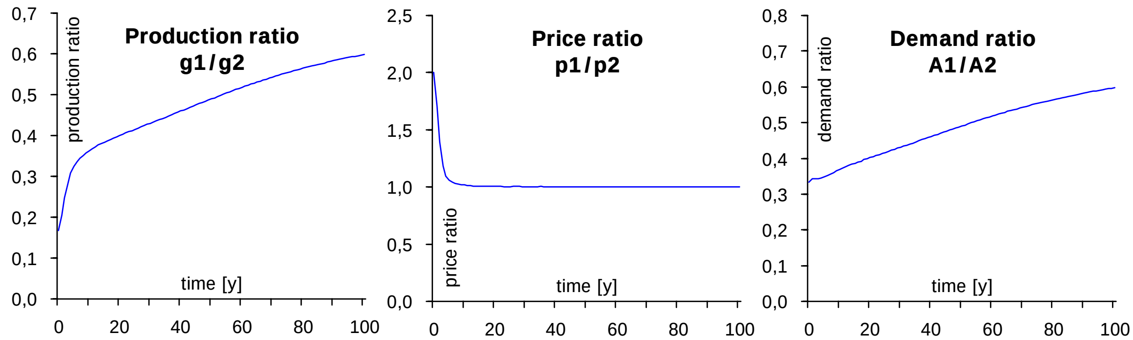

Figure 3.3: *Price mechanism for different initial ratios of consumer goods production and consumer demand. The initial ratio of the production is 1:6 and the initial demand ratio is 1:3. As a result the price of good 1 is twice as high as the price of good 2. Business invests its consumer goods fraction of physical capital entirely in the higher priced good until the price is balanced and the production ratio is equal to the demand ratio.*

- **Finally, in the third level**, business decides on the distribution of physical capital investments between green and grey consumer goods and the remaining goods sectors, in response to the price signals. We assume that business decides to invest a fraction Ci_k in consumer goods, and the remaining fraction $(1-C)i_k$ in the remaining goods sectors:

$$i_{k1} + i_{k2} = C\,i_k = C\,\rho\,\alpha_0\,x', \tag{3.51}$$
$$i_{k3} = (1-C)\,i_k = (1-C)\,\rho\,\alpha_0\,x'. \tag{3.52}$$

The fraction Ci_k is then further divided between green and grey goods. This is determined by the relative profitabilities of the two goods. At any point in time, business invests its consumer-goods fraction of physical capital entirely in the goods sector with the higher profitability. Once the profitabilities have equalized, the investments are distributed equally between the two sectors.

3.3.4.1 The price mechanism

To determine the relative profitability of green and grey consumer goods, consider an infinitesimal shift in physical capital from the first to second goods category. This will produce equal and opposite changes $\delta g_1 = -\delta g_2$ in the annual production of goods, with associated changes $\delta w_1 = -\delta w_2$ in the wage costs (note that the same productivity was assumed for both goods sectors). For given prices p_i, the resulting change in the profit rate, given by the change in revenues from the sale of the goods minus the change in wage costs (eq. (3.2)), is then: $\delta b = p_1\delta g_1 + p_2\delta g_2 - \delta w_1 - \delta w_2 = (p_1 - p_2)\delta g_1$. The marginal change in the profit rate therefore vanishes if $p_1 = p_2$, in accordance with the classical market equilibrium result for equal productivities, or (eq. (3.30))

$$\frac{g_1}{g_2} = \frac{A_1}{A_2}. \tag{3.53}$$

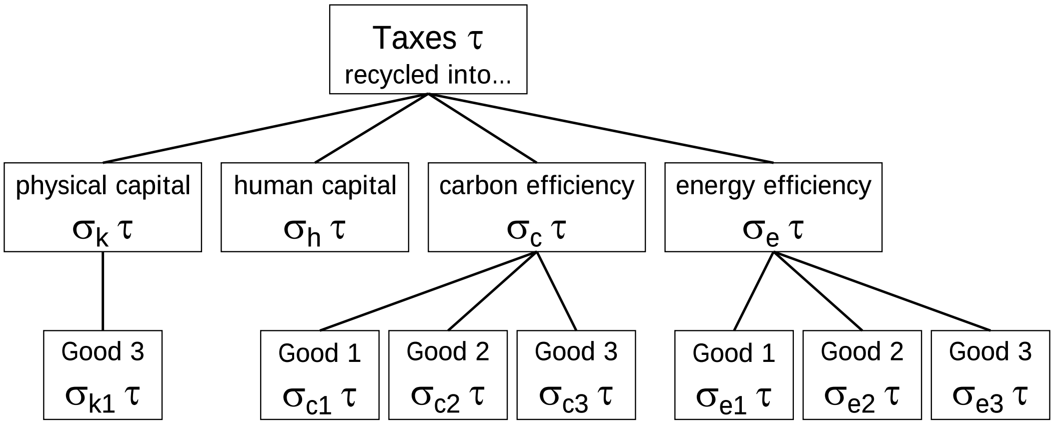

Figure 3.4: *Fractions of carbon taxes τ distributed between physical capital, human capital and energy and carbon efficiency.*

To maximize profits, business will therefore invest its consumer-goods fraction of physical capital investments entirely in the higher priced good until the goods balance (3.53), corresponding to equalized prices, is achieved. Figure 3.3 illustrates this mechanism.

The optimization argument implies that business acts as a price taker, ignoring the impact of an incremental change in production on the goods price. If business acts as a monopolist, rather than as an aggregated group of individual entrepreneurs exposed to competition, shifts in capital between green and grey goods have no impact on profits, as the price changes anticipated by the monopolist cancel the production changes: $\delta(p_1 g_1) = \delta(p_2 g_2) = 0$, cf. eq. (3.30). The monopolist has no motivation to change the consumer-goods production ratio: Given the total wages for goods production, equal production costs for both kinds of goods and the dividends he or she has decided to allocate, he or she is assured *a priori* that all goods will be sold and the costs expended for wages and dividends thereby returned as revenues on sales, independent of the production ratio.

3.3.5 Governments

Governments set carbon taxes and recycle tax revenues into the economy with the goal of maximizing public welfare, defined in terms of suitably discounted time-integrated consumption minus the public costs of climate change (including not only the tangible damage costs to business, but also the intangible costs of the loss of species, health, migratory pressures, etc.). Specifically, government controls the tax rate coefficient c_τ, the fractions σ_c and σ_e of the CO_2 taxes τ that are recycled into non-fossil emission reduction and energy-efficiency technologies, respectively, the fraction σ_h that is recycled into human capital and the residual fraction σ_{k1} that is recycled into investments in physical capital in the green goods sector ($\sigma_{ki} = 0$ for the grey goods sector (i=2) and the remaining goods sector (i=3)). Figure 3.4 illustrates the portioning between the different options.

There are two (model) options for government to distribute the fractions σ_c (=$\sum_{i=1}^{3} \sigma_{ci}$) and σ_e (=$\sum_{i=1}^{3} \sigma_{ei}$) between the different goods (i=1,2,3). First, government recycles exact the same amount in each goods sector. Second, the distribution is determined by the specific efficiencies, f_{ci} and f_{ei}. In order to support renewable energy and reduce the total energy use, government recycles 60% in the goods sector with the lowest efficiency and splits the residue into the remaining sectors. As with the distribution of the mitigation investments in the different goods sectors by business (3.3.4) this mechanism is an option, which has been implemented in the model recently. This option is not activated for the scenarios presented in the following chapters but the impact is discussed in Section 4.3.

Chapter 4

MADIAM initialization and basic scenarios

Having presented and discussed the model setup in the previous chapters, the following sections and chapters show examples of simulation experiments with the complete MADIAM model. In accordance with the main goal of this study, the examples have been chosen to illustrate different aspects of the socio-economic system as controlled by multi-actor dynamics:

- the impact of individual control strategies,
- the superposition and synergy effects of parallel actor strategies,
- the role of different types of technological change,
- the influence of stochasticity, and
- multi-regional aspects (in a non-interacting form).

Relevant for the following discussion of the individual (Section 5) and parallel (Section 6) control strategies of the principal actors are not the detailed parametrical forms of the control algorithms presented in Section 3.3, but rather (in the spirit of neural networks) the general structure of the assumed feedbacks. The purpose of the simulations is to investigate the impact of the various properties of the control algorithm feedbacks on the overall evolution of the coupled climate-socioeconomic system, rather than to provide quantitative predictions.

These examples of the impact of the control variables include different sources of technological change, such as endogenous technological change through business investment decisions in productivity, carbon and energy efficiency. Additionally, government, which sets carbon taxes and recycles tax revenues into the economy, stimulates induced technological change.

In the following Section a general overview of the model initialization and calibration is given. This is followed by the presentation of the basic reference scenarios BAU ('Business As Usual') and MM ('Moderate Mitigation'). In the last Section of this Chapter sensitivity analysis of some crucial parameters are presented.

The impact of the individual control strategies is discussed in the following Chapter 5 while the impact of parallel actor strategies is demonstrated in Chapter 6. The role of stochasticity is not considered in chapters 5 and 6. This aspect is discussed in Chapter 7.

4.1 Model initialization

The start year of the model scenarios is set to t_0=2000 and the evaluation is performed over 100 years. The model is integrated using a second-order predictor-corrector method (Abramowitz and Stegun, 1965) with a time-step of one year, which was sufficiently fine to remove graphically detectable discretization errors.

The model has been calibrated to reproduce the basic stylized growth parameters of Kaldor [1963] (and suggested modifications and adjustments of these facts by Edenhofer [2004]):

- Labour productivity (y/l) and energy productivity (y/E) increases steadily over time and the growth rate of labour productivity exceeds the growth rate of energy productivity.
- Capital intensity (k/l) grows roughly with the growth rate of labour productivity.
- The ratio of capital to output (k/y) is constant.
- The interest rate is constant.

All results presented in the following chapters fit in this calibration framework. The ratio of capital to output is constant and set to 0.4, in accordance to eq. (2.1), which is one of the principal assumptions of MADIAM. As a consequence, the capital intensity grows with the the growth rate of labour productivity (see eq. (2.1)). The interest rate is introduced as a constant parameter (z=0.02). The simulation results of the following sections and chapters will demonstrate that the first property is also reproduced. The production growth rates of the simulations match the characteristic data of the aggregate world economy provided by Maddison [1995]: production grows at about 2.6-3.0% p.a.

The available labour pool is assumed to grow continuously and parallel to the world population, in accordance with recent population studies [United Nations, 1998, 2003]. It is assumed that half of the current world population of 6.6 billion people is employable and the initial employment rate is set to 0.91 (i.e. l_0=3.0 billion people are initially employed and the available labour pool is set to l_0^{max} = 3.3 billion people).

In addition to the economic calibration energy-related initialization settings are as follows.

$c(t_0)$	10^4	fossil fuel resources $[GtC]$ [IPCC, 2001b; Rogner, 1997]
$e(t_0)$	7.0	CO_2 emissions $[GtC/yr]$ [IPCC, 2000, 2001a,b)
$\alpha_f(t_0)$	0.83	fraction of fossil energy [IEA, 2003]
$v(t_0)$	$0.1 \cdot$ y	energy costs $[\$/yr]$ [DoE/EIA, 2003]

The settings of the constant parameters appearing in the evolutions equations 3.35 and 3.36 are presented in the following overview.

λ_k	0.04	depreciation rate of physical capital [1/yr]
λ_{h1}	0.015	depreciation rate of human capital
λ_{h2}	0.005	exogenous growth rate coefficient of human capital (productivity)
λ_c	0.005	exogenous growth rate coefficient of carbon efficiency
λ_e	0.005	exogenous growth rate coefficient of energy efficiency
μ_h	0.4	efficiency coefficient for investments in human capital
μ_c	0.0003	efficiency coefficient for investments in carbon efficiency $[yr/G]$
μ_e	0.2	efficiency coefficient for investments in carbon efficiency $[yr/GtC]$

It is assumed that the initial consumer good ratio of green to grey goods is 1:6 for all scenarios. The setting of the control parameters of the different actors is presented in the specific sections below. A complete overview of the initialization assumption of the system state and derived variables and the MADIAM constants is given in Appendix A. Additionally, the control parameters settings for all scenarios illustrated in this study are also presented in this Appendix.

4.2 The basic scenarios BAU and MM

The scenarios in this Section are discussed in relation to two basic scenarios, a 'Business As Usual' scenario BAU and a reference 'Moderate Mitigation' scenario MM (Figure 4.1). The BAU scenario corresponds to a case without a specific climate policy. The CO_2 tax rate is set to zero and there are no business investments in energy and carbon efficiency. The CO_2 emissions increase significantly from 7.0 GtC/year in 2000 to 26.4 GtC by the year 2100 and as a result the CO_2 concentrations more than double. The model simulates a global mean temperature increase of more than 3 °C for the end of the century. These results lie roughly in the middle of the ensemble of BAU scenarios considered by IPCC [2000, 2001b].

In the MM scenario, government introduces a carbon tax of 0.5% of GDP at current carbon efficiency levels (corresponding to c_τ=4.3, cf. eq. (3.17)) and uses 10% of these taxes to improve energy and carbon efficiency, 15% being recycled into the economy as subsidies in the physical capital of the 'green' consumer good, and the remaining 75% being recycled as investment subsidies in human capital (see Section 3.3.5 and Figure 3.4 for details). Business invests 1.5% of production in emission and energy efficiency. The

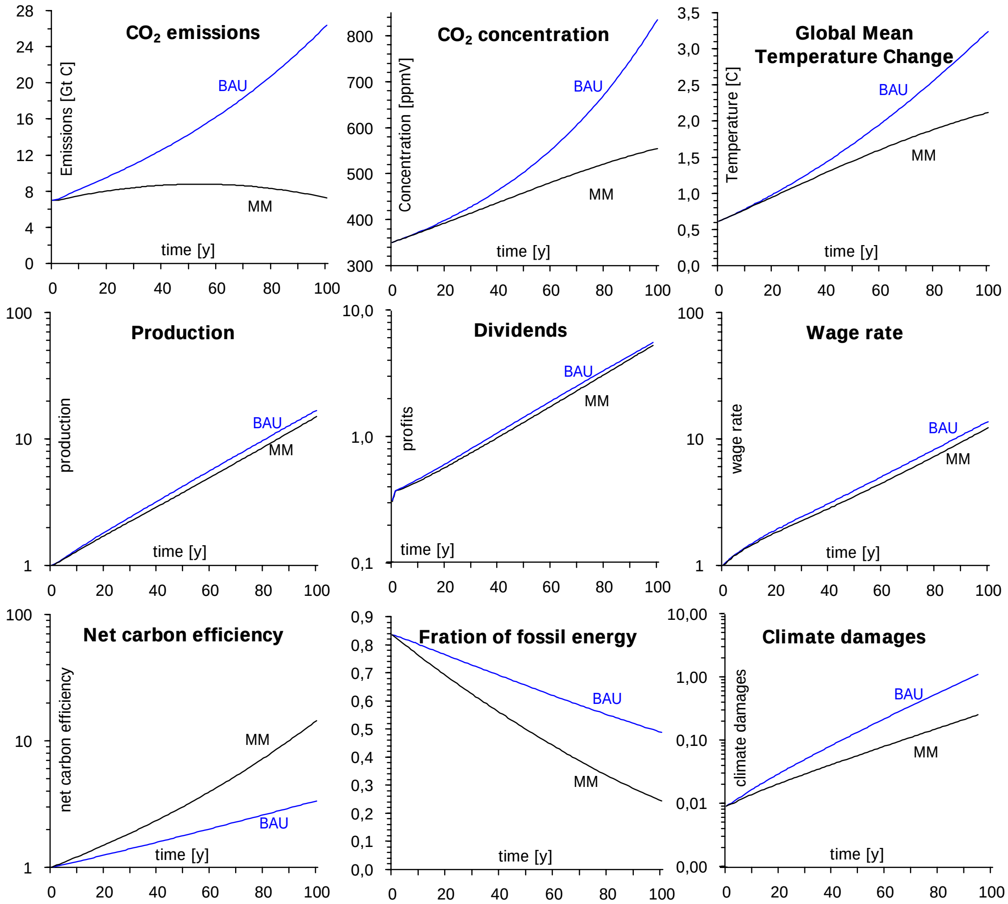

Figure 4.1: *'Business As Usual' (BAU) and 'Moderate Mitigation' (MM) scenario. Top: global CO_2 emissions, CO_2 concentrations and global mean temperature. Center: production, dividends (both normalized on $y(t_0)$=1) and normalized wage rates. Bottom: normalized net carbon efficiency, fraction of fossil energy, climate damages (normalized on $y(t_0)$=1).*

consumers preference ratio (A1:A2) of green to grey goods is initially 1:6, which, given initial production rates of 1:6 for green to grey goods, results in equal prices for both consumer goods (see Section 3.3.4 and Figure 3.3 for details of the price mechanism).

This 'moderate' mitigation has a marked effect on the climate parameters. CO_2 emissions increase to 8.7 GtC/year in 2060 and then fall to 7.3 GtC/year by the end of the century. Because of the large inertia of the climate system, this significant reduction in CO_2 emissions relative to the BAU scenario achieved in the MM scenario pays off mainly in the next centuries. Nevertheless, the carbon dioxide concentrations expand to only about 550 ppm in 2100, which is a reduction of more than 250 ppm in the year 2100 compared to the BAU scenario. A similar downtrend is shown for the global mean temperature.

There are also significant changes in the net carbon efficiency, the fossil fuel fraction and the climate damages, presented in the bottom panels of Figure 4.1. In the BAU scenario the increase of the net carbon efficiency and the decrease in the fraction of fossil energy is only due to exogenous technological improvement (eq. (3.35) and (3.36)). The additional business investments and the tax recycling in energy and carbon efficiency raise the growth rate of the net carbon efficiency significantly from 1.2% p.a. (BAU) to 2.7% p.a. (MM). The fraction of fossil energy decreases to 25% in the year 2100 for the MM scenario (BAU: 50%). The growth rate of the climate damages falls from almost 5% p.a. (BAU) to 3.3% p.a. (MM). in accordance with the decrease of emissions and projected global mean temperature change (eq. (3.9)).

Despite the significant influence of moderate mitigation on climate already in this century, the changes in economic growth are exceptionally weak: the average annual growth rates falls from 2.85% to 2.75% p.a. for production, from 2.91% to 2.88% p.a. for dividends, and from 2.63% to 2.54% for the wage rates. In summary, significant mitigation of climate change is achieved at a very low economic cost, resulting in a delay in economic growth of only two or three years over a period of 100 years (see also Azar and Schneider, 2002).

4.3 Sensitivity analysis

To explore the dynamic behaviour of MADIAM in more detail, in this Section the effect of slight variations of selected crucial parameters and the impact of alternative mechanisms for the partitioning mechanisms of business and government (as described in the Section 3.3) on the socio-economic system is examined and compared to the MM scenario results. Additionally in Chapter 7 stochastic uncertainty in different investment coefficients and in climate damages is investigated.

4.3.1 Fossil energy resources

In Figure 4.2 the sensitivities of the model to changes in the initial (i.e. year 2000) fossil fuel resources are explored. As discussed in Section 3.2.6, estimates about available fossil energy resources differ between 5,000 GtC and 15,000 - 20,000 GtC, when gas hydrates (clathrates) are included [IPCC, 2001b; Rogner, 1997]. The amount of clathrates and the degree to which they can be utilized are highly uncertain. In Figure 4.2 the available resources c are set to 5,000 GtC ('RES-' scenario) and 15,000 GtC ('RES+' scenario), respectively and the results are compared to the MM scenario (with $c(0)$=10,000 GtC).

The simulation results show that the effect of higher initial fossil fuel resources ('RES+' scenario) is very weak. There are nearly no changes in the economic growth rates and in the net carbon efficiency. The fossil energy costs (bottom right panel), which depend directly on the resources (see eq. (3.22)) are reduced only slightly. The influence on CO_2 emissions and the corresponding climate parameters is negligible and therefore there is

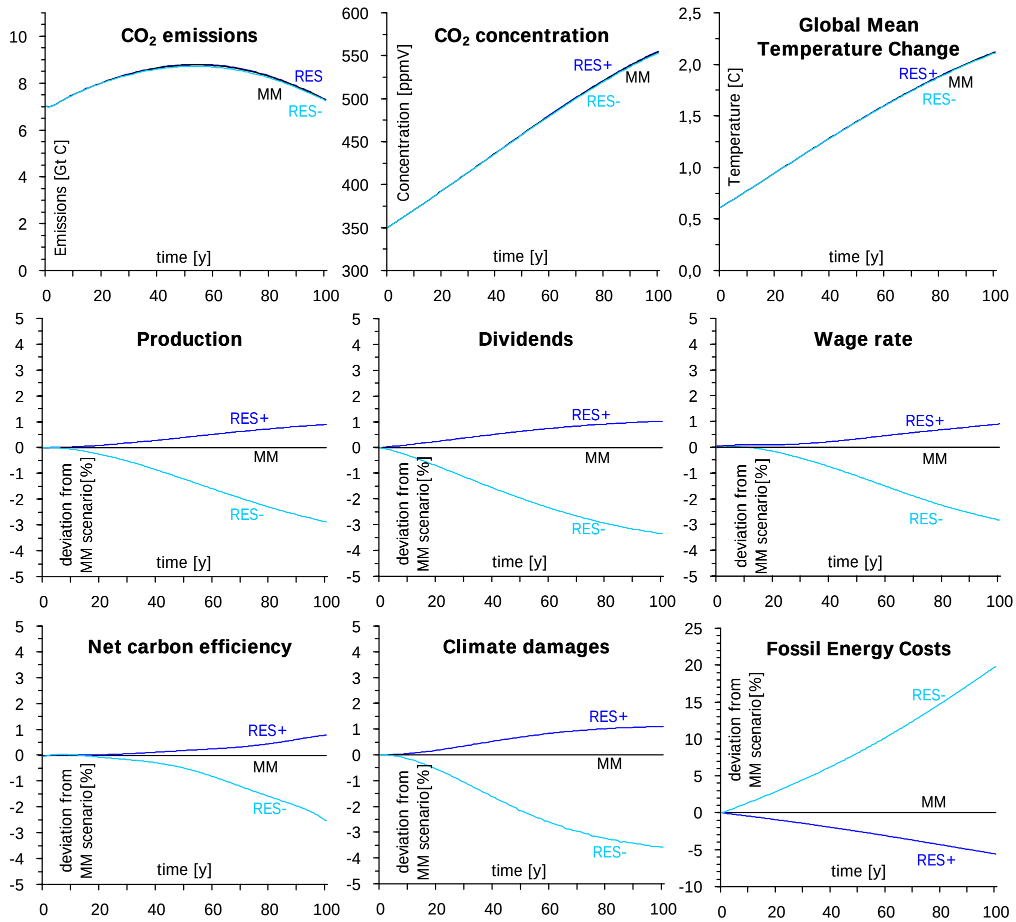

Figure 4.2: *Sensitivities to changes of the initial (i.e. year 2000) fossil fuel resources* c *(RES-: 5,000 GtC, MM: 10,000 GtC, RES+: 15,000 GtC). Top:* CO_2 *emissions,* CO_2 *concentrations and global mean temperature. Center: production, dividends, and wage rates, in percentage changes relative to initial MM levels. Bottom: net carbon efficiency, climate damages, and savings, in percentage changes relative to initial MM levels.*

only a weak decrease in the climate damage growth rate. The increase in production is compensated through the parallel increase in the net carbon efficiency.

In contrast, a reduction of the initial fossil fuel resource to 5,000 GtC ('RES-' scenario) affects the growth rates of production, dividends and wage rate much stronger than the increase to 15,000 GtC. As a result of a significant increase in the fossil energy costs, the economic growth rates and consequently the net carbon efficiency are reduced significantly. However, there is again no influence on the climate parameters. As in the 'RES+' scenario the 'parallel behaviour' of production and net carbon efficiency results in (nearly) unchanged CO_2 emissions (in accordance to eq. (3.15)).

In summary, the variations of $c(0)$ by +/- 50% compared to the MM scenario have only a small impact on the model behaviour. This is due to the fact that the 'importance' of the energy costs is reduced as the (model) years go by. The initial (year 2000) total energy costs are set to $0.1 \cdot y$ (i.e. 10% of the overall production, see Section 4.1). The evolution of the energy costs depends mainly on the fossil energy use (renewable energy costs are assumed to be constant, see Section 3.2.6). Due to the introduced mitigation strategies, the growth rate of energy use is much slower than the growth rate of production. Therefore, the share of energy costs in the overall production costs lowers significantly over time.

The reduction of $c(0)$ has a much higher impact on economy than the increase. This is mainly due to the fact that the fossil fuel resources in the 'RES-' scenario are reduced by 16.6% (1,816 GtC accumulated fossil energy use for 100 model years), but there is only a 5.5% the reduction in the 'RES+' scenario (MM scenario: 8.3% reduction). Thus, the relative reduction in the 'RES-' case is exceptionally higher and influences the energy costs much stronger, compared to the MM scenario (in accordance with eq. (3.24)).

Despite the fact that the effect of the variations of the initial fossil fuel resources on the system is small, it is unclear if the assumption that the prices of fossil fuels increase with the inverse square of the available resources is appropriate. The feedback of reduced resources on the socio-economic system is as uncertain as the resource base itself.

4.3.2 Exogenous technological change

Figure 4.3 shows the sensitivity of changes of the exogenous improvement coefficients λ_e and λ_c on the socio-economic system. These exogenous technological changes of the energy and carbon efficiency are introduced in order to include all kinds and sources of technological change in the model (in addition to endogenous technological change and specifically 'induced' technological change, both of which are described in Section 6). In the reference scenario MM the exogenous improvement coefficients are set to λ_e = λ_c = 0.006 yr^{-1} (Section 4.1). In order to explore the sensitivities of these parameters on the system, the coefficients are set to 0.005 yr^{-1} ('EX-' scenario) and 0.007 yr^{-1} ('EX+' scenario).

The simulation results show that the system is very sensitive to the setting of this exogenous technological change parameter. The slight variations of λ_e and λ_c cause large changes in some parts of the system and have moderate impacts on other parameters. The direct and significant impact on the growth rate of the net carbon efficiency (compared to the MM scenario) is clearly visible in Figure 4.3. The changes in the economic growth rates of production, dividends, wage rate and savings, however, are relatively moderate. As a consequence CO_2 emissions change by 9 - 10% (in the year 2100).

As discussed in the introduction it is problematic to include exogenous technical change in IA models, especially if this is the only source of technological change. The problems are that it is simply not clear what an appropriate setting of this scaling factor should be and that it is an unrealistic assumption in terms of 'real world' economics. Despite the fact that in this model the exogenous technological improvements are used only in addition

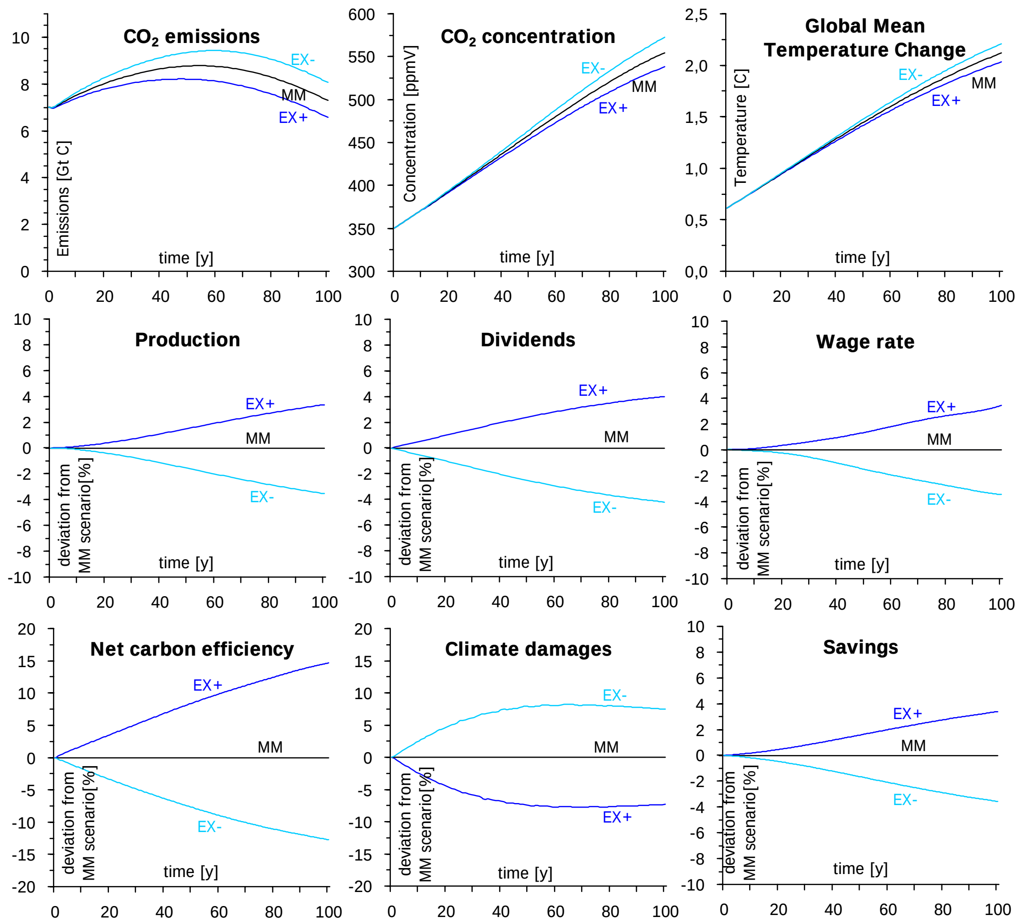

Figure 4.3: *Sensitivity to changes of the exogenous improvement coefficients λ_e and λ_c of the net carbon efficiency. Top: global CO_2 emissions, CO_2 concentrations and global mean temperature. Center: production, dividends, and wage rates, in percentage changes relative to initial MM levels. Bottom: net carbon efficiency, climate damages, and savings, in percentage changes relative to initial MM levels.*

to the dominant endogenous technological change, the results of the sensitivity analysis show that there is a significant impact of variations of λ_e and λ_c on the socio-economic system.

4.3.3 Distribution of mitigation investments on the different goods

The successive partitioning strategy of business is introduced in Section 3.3.4. The specific distribution of the mitigation investments, i_c ($=\sum_{i=1}^{3} i_{ci}$) and i_e ($=\sum_{i=1}^{3} i_{ei}$), between the different goods sectors is determined through an optional mechanism. Business analyses the net energy-related costs (energy costs v_i plus carbon taxes τ_i) and invests 60% of the total mitigation investments in the goods sector with the highest costs and splits the residue into the remaining sectors. However, this mechanism is not activated in the MM scenario and the scenario simulations presented in the following sections 5 and 6. In this Section, the effect of this option is examined and compared to the 'standard' setting of the MM scenario (equal shares in all three sectors).

Figure 4.4 presents the effect of the optional investment distribution ('B2' scenario) in comparison to the MM scenario. The results show that the impact is significantly positive for both the economic growth rates and the climate parameters. The deviation of the economic growth rates from the MM scenario is about 6-8% (by the year 2100) and the CO_2 emissions drop down to 5.9 GtC at the end of the century (-1.4 GtC). These results are forced by a marked increase in the net carbon efficiency, which is remarkable in the sense that these results occur only through shifts in the distribution of the mitigation investments. The overall amount of the mitigation investments is unchanged (just as the amount of investments in physical and human capital).

The initial settings of the net carbon efficiency for the different goods sectors are different. The green consumer good (good 1) is characterized by the highest net carbon efficiency. This results from the higher carbon efficiency f_c (eq. (3.11)), which is the inverse of the fraction of fossil fuel used for the specific good (eq. (3.21), see also Section 4.1 and Appendix A). The initial energy efficiency f_e, eq. (3.12), is set equal for all goods. As mentioned before the initial production ratio of the green and grey consumer goods is 1:6. Thus, the grey consumer goods sector is characterized by the highest production and the lowest net carbon efficiency. Consequently, the business analysis of the energy-related costs shows clearly that the highest net costs of energy and carbon taxes appear in the grey goods sector. These costs are illustrated in the bottom panels of Figure 4.4, which shows the net energy-related costs of the three goods sectors, normalized by the sum of these costs, for the standard MM and the optional 'B2' scenario. The costs of the grey goods sector are much higher than the costs of the other sectors, but in the 'B2' scenario the increase in the overall energy-related costs and specifically in the costs of the grey consumer goods is reduced significantly (while the green goods costs are only slightly increased).

In summary, the main fraction of the business mitigation investments is invested in the grey consumer goods sector and this increase in investments in the net carbon efficiency of the dominant consumer good (compared to the 'standard' mechanism) strongly increases the average net carbon efficiency. Therefore the energy-related costs decline (compared to the MM scenario, see Figure 4.4) and the impact on the economic growth rates is positive. The higher net carbon efficiency affects the climate parameters and the climate damages and despite the increase in production this impact is also significantly positive. Thus, CO_2 emissions (and correspondingly all other climate parameters) are reduced significantly.

The simulation results of Figure 4.4 show that an alternative, goal-oriented mitigation investments distribution strategy, which is based on a costs analysis presented in Section 3.3.4, has a marked positive impact on the socio-economic system.

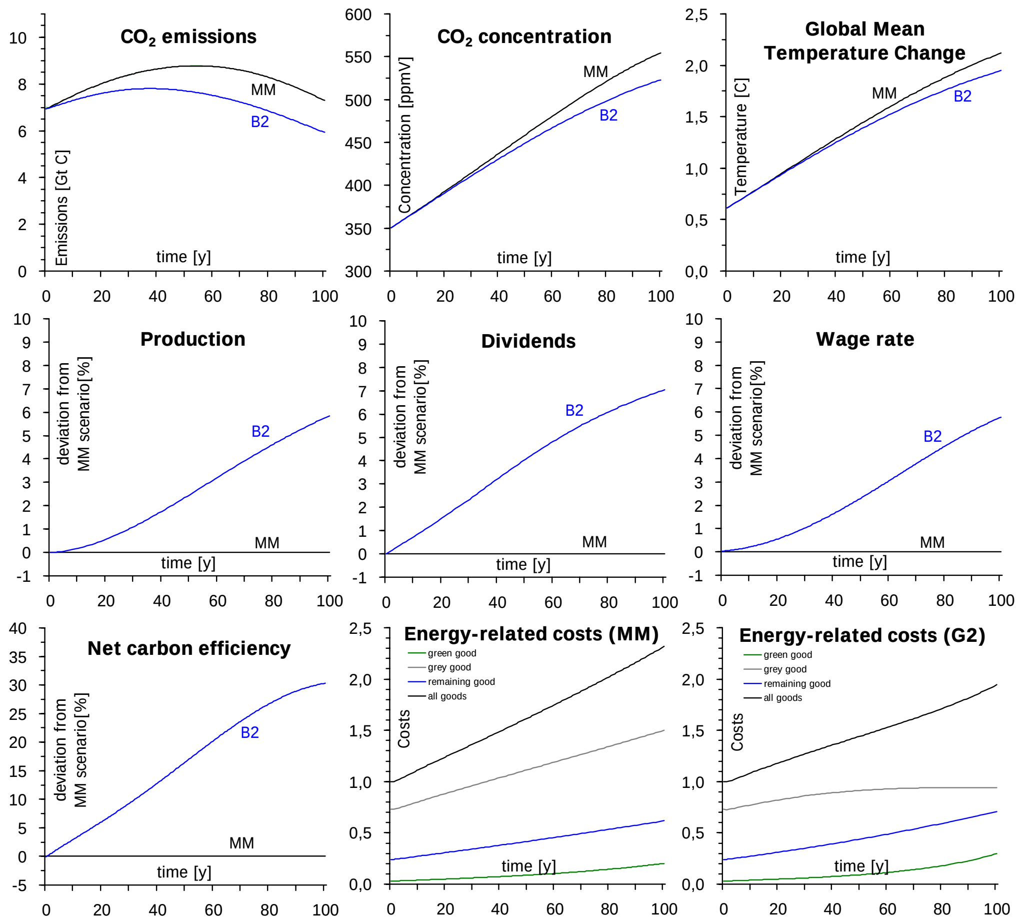

Figure 4.4: *Comparison of different distributions mechanisms of the business mitigation investments in the different goods sectors. Top: CO_2 emissions, CO_2 concentrations and global mean temperature. Center: production, dividends, and wage rates, in percentage changes relative to initial MM levels. Bottom: net carbon efficiency in percentage changes relative to initial MM levels, energy-related costs of MM and 'B2' scenario.*

4.3.4 Distribution of the tax revenues on the different goods

The partitioning strategy of government is introduced in Section 3.3.5. As an optional strategy to support renewable energy and reduce the total energy use, government recycles 60% in the goods sector with the lowest net carbon efficiency and splits the residue into the remaining sectors. As with the business mitigation investments in Section 4.3.3 this optional strategy is not activated in the following chapters.

Figure 4.5 presents the effect of the alternative tax revenue distribution mechanism ('G2' scenario) in comparison to the 'standard' MM scenario distribution. The results demonstrate that the impact is positive for both the economic growth rates and the climate parameters. The outcome is qualitatively similar to the outcome of the alternative business

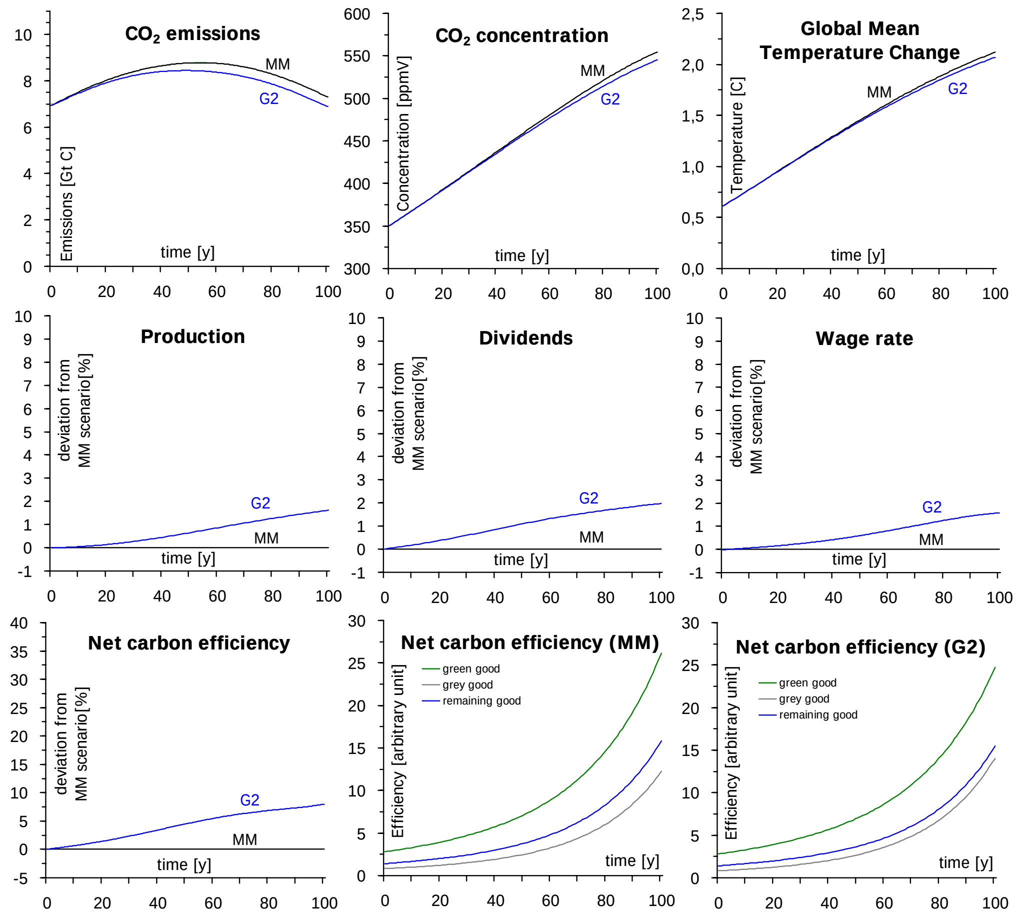

Figure 4.5: *Comparison of different distributions mechanisms of the carbon tax revenues in the different goods sectors. Top: global CO_2 emissions, CO_2 concentrations and global mean temperature. Center: production, dividends, and wage rates, in percentage changes relative to initial MM levels. Bottom: net carbon efficiency in percentage changes relative to initial MM levels, net carbon efficiency of MM and 'G2' scenario.*

mitigation investments distribution in the previous Section, but the impact of this government strategy is less effective (in order to demonstrate this, Figure 4.5 uses the same scale for the y-axes as Figure 4.4).

As mentioned above the initial settings of the net carbon efficiency for the three goods are different. This is illustrated in the bottom panels of Figure 4.5. The net carbon efficiency of the grey goods sector is much smaller than the efficiency of the green goods sector. Therefore, the main fraction of the tax revenues invested in mitigation is invested in the grey consumer goods sector and this increase in investments in the net carbon efficiency of the dominant consumer good (compared to the 'standard' distribution mechanism) strongly increases the average net carbon efficiency. Therefore, the energy-related costs decline and the impact on the economic growth rates is again positive, just as the impact on the climate parameters (the increase in the net carbon efficiency more than compensates the increase in production).

The simulation results of Figure 4.5 show clearly that this alternative distribution mechanism for the recycling of the tax revenues has a positive impact on the socio-economic system, compared to the standard stetting.

Chapter 5

The impact of individual actor strategies

The impact of the separate actors on the evolution of the coupled climate-socio-economic system is illustrated in the next sections, in which the control decisions of the individual actors (G: Government, B: Business, C: Consumer) are modified separately relative to the MM case, keeping the control values of the other actors fixed. In all scenarios, the control parameters of the individual actors are either decreased (climate hostile case, indicated by a suffix '-') or increased (climate friendly case, suffix '+'). More explanations are given within the subsections. A detailed overview of all presented scenarios setting is given in Appendix A.

Although unrealistic in terms of real world economics these simulations are useful in a system-analysis framework in order to consider the individual importance of the actors' control strategies and to compare the results with simulations results from parallel multi-actor controls strategies, which are presented in the following Chapter.

5.1 The impact of business

The impact of business on the evolution of the coupled climate-socioeconomic system is illustrated in Figure 5.1, which shows the effects of variations in net business investments in energy and emission efficiency (i_e, i_c, eqs. (3.35), (3.36)) between 1.0% (for a non-climate-friendly scenario 'B-') and 2.0% (for a climate-friendly scenario 'B+') of production, relative to the MM case of 1.5%.

The effect of these changes on the economic growth rates is small compared to the impact on climate. The higher investments in net carbon efficiency in the 'B+' case lead to a 25% decrease of CO_2 emissions by 2100 ($e(100)$=5.4 GtC) and a corresponding decrease in the CO_2 concentration and the global mean temperature change. The economic growth rates of production, wage rates and dividends, however, are reduced by only 4-5%, corresponding to a growth delay (cf. Figure 4.1) of the order of two years. The results of the 'B-' case show a similar behaviour of the system. The weaker investments in energy and carbon efficiency lead to an increase of about 40% of CO_2 emissions by 2100, but the economic parameters increase by only 5-6% over 100 years.

The net carbon efficiency grows in consequence of the improved investments in energy and carbon efficiency, which is in addition to the reduction of the economic growth rates responsible for the significant climate impact. The influence on the climate damages is dramatic. This is due to the simultaneous increase (decrease, respectively) of the temperature change and the production growth rate, both of which affect the climate damages (eq. (3.9)).

These model results show that business mitigation actions alone, independent of government regulation policies and consumer preferences, can have a strong impact on climate change, without significantly affecting long-term economic growth. The increase of mitigation investments reduces business costs for future energy, climate damages, and carbon tax and this compensates partly the slightly weaker investments in physical and human capital.

5.2 The impact of government

The impact of different carbon tax rates, set by government, is presented in Figure 5.2. The tax rate c_τ (eq. (3.17) is varied between 0.25% (for a non-climate-friendly scenario 'G-') and 0.75% (for a climate-friendly scenario 'G+') of production, relative to the MM case of 0.5% (corresponding to c_τ settings of 2.15 ('G-'), 4.3 (MM), and 6.45 ('G+'), cf. eq. (3.17)). Government uses 10% of these taxes to improve energy and carbon efficiency, 15% being recycled into the economy as investment subsidies in physical capital of consumer good 1 and the remaining 75% being recycled as investments in human capital. This recycling ratio, although a control variable of government, is kept fix in this first example. The impact of different recycling ratios in combination with different carbon tax rates is discussed afterwards.

The results in Figure 5.2 shows that the impact of government on the socio-economic system, varying only the carbon tax rate, is small compared to the impact of business (see Section 5.1 above). In terms of the climate parameters, this is due to the fact that the investments in the net carbon efficiency are significant smaller for the 'G+' scenario (0.75% of GDP) than for the 'B+' scenario (1.5% of GDP).

Nevertheless, the changes in the economic growth rates are again much weaker than the impact on the climate parameters. There is an 8% carbon dioxide emission reduction by the year 2100 for the 'G+' scenario and a 10% increase of emissions for the 'G-' scenario. This is a consequence of the higher carbon tax revenues that are (partly) used

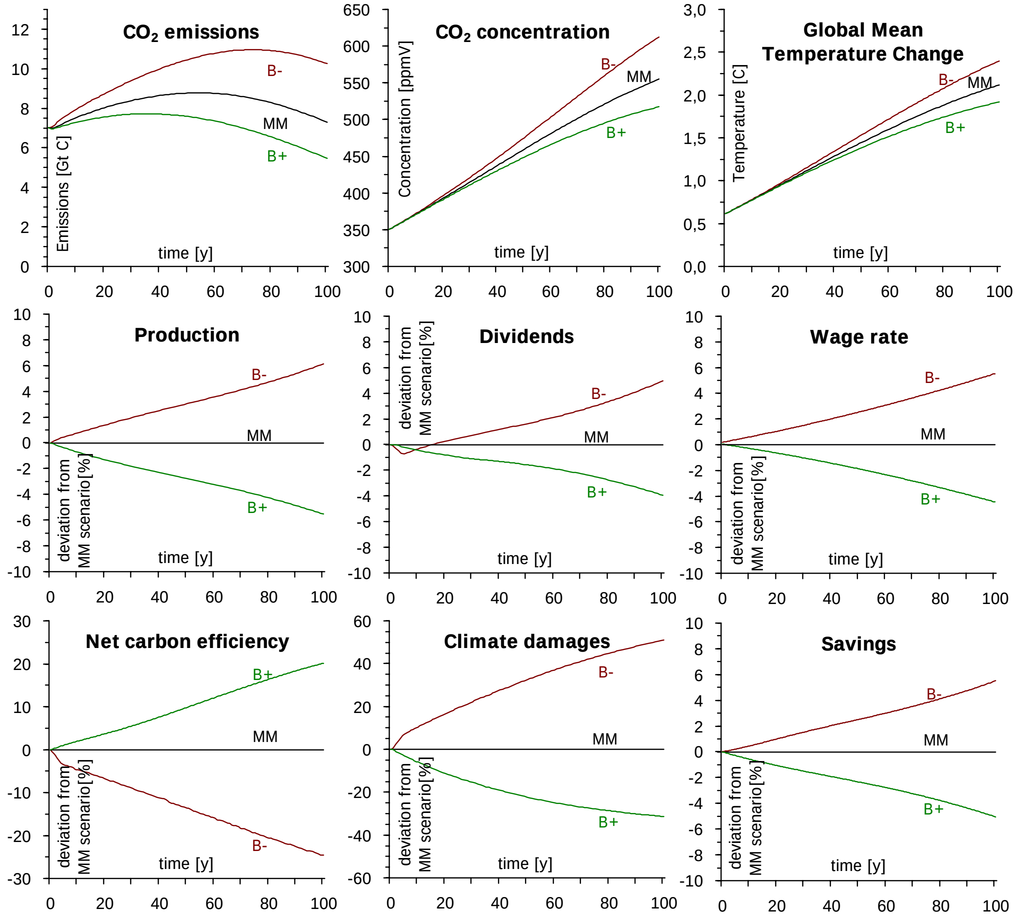

Figure 5.1: *Impact of business investment rates in net carbon efficiency (B-: 0.5%, MM: 1.0%, B+: 1.5% of GDP) on climate and economic growth. Top:* CO_2 *emissions,* CO_2 *concentrations and global mean temperature. Center: production, dividends and wage rates, in percentage changes relative to initial MM levels. Bottom: net carbon efficiency, climate damages, and savings, in percentage changes relative to initial MM levels.*

to improve the net carbon efficiency and the physical capital of the green consumer good. The economic growth rates, however, are about the same as for the MM scenario. There are only minimal changes of about 0.5%. This almost nonexistent influence of the carbon tax rate variation on the economic growth rates does not depend on the chosen value for c_τ. Even a much higher or significant reduced tax rate would lead to the same result(which is due to the complete recycling of the tax revenues into the economy, see discussion below). Climate damages, which depend on climate change and production, grow in accordance with the projected changes in the climate parameters (and the nonexistent changes in production), compared to the MM scenario.

In summary, a higher carbon tax rate supports climate by reducing the CO_2 emissions as a result of a higher net carbon efficiency. This moderate positive climate impact is achieved

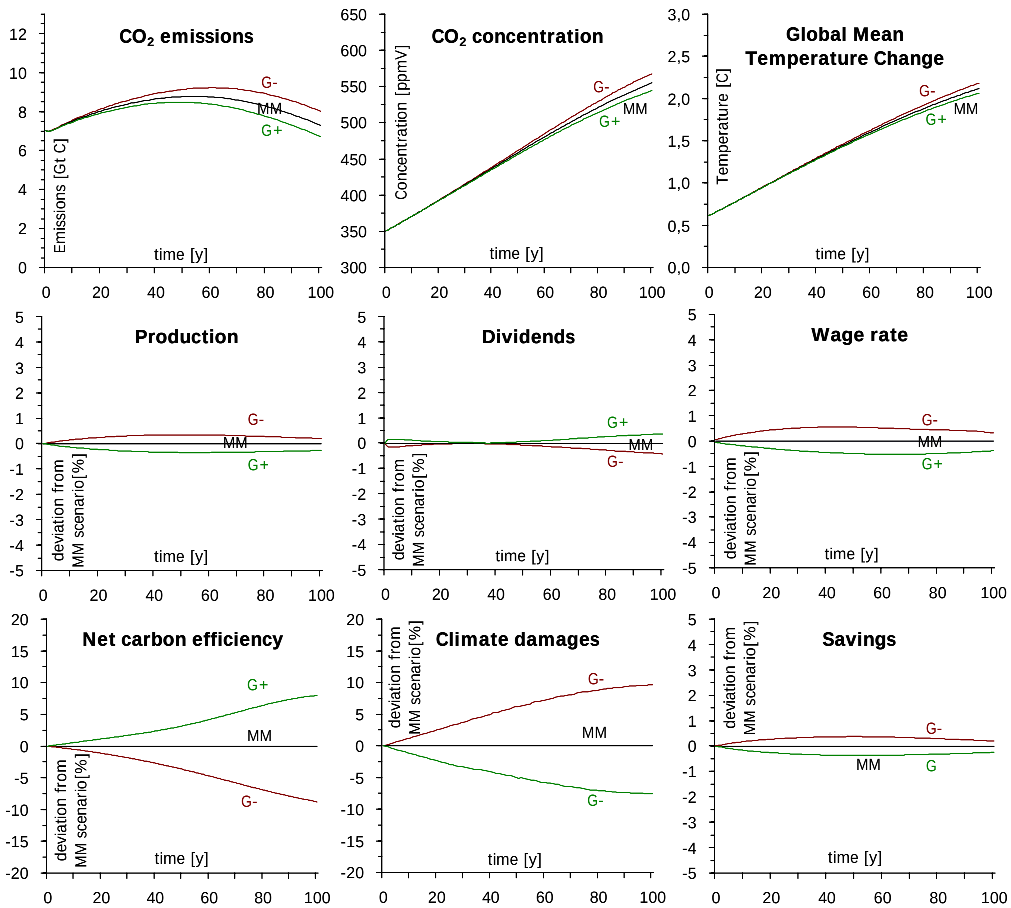

Figure 5.2: *Impact of government carbon tax rate settings (G-: 0.25%, MM: 0.5%, G+: 0.75% of GDP) on climate and economic growth. Top: global CO_2 emissions, CO_2 concentrations and global mean temperature. Center: production, dividends and wage rates, in percentage changes relative to initial MM levels. Bottom: net carbon efficiency, climate damages, and savings, in percentage changes relative to initial MM levels.*

at very low economic cost. One has to keep in mind that this is only due to the fact that the tax revenues are completely recycled into the economy (which is not necessarily a real world scenario) and that the recycling ratio is unchanged in this model simulation.

Figure 5.3 shows the impact of shifting recycled carbon taxes more strongly into investments in net carbon efficiency and the physical capital of the green consumer good demonstrating the effect of induced technological change. The enhanced mitigation scenario ITC is again compared to the reference scenario MM. In the ITC scenario, the ratio of recycled taxes invested in net carbon efficiency and physical capital of consumer good 1 compared with investments in human capital is set at 75:25 (as compared with 25:75 in the MM scenario, see above), of which 25% are used to improve energy and carbon efficiency, 50% being recycled as investments in the physical capital of the green consumer good and 25% being recycled as investments in human capital (productivity). The carbon tax

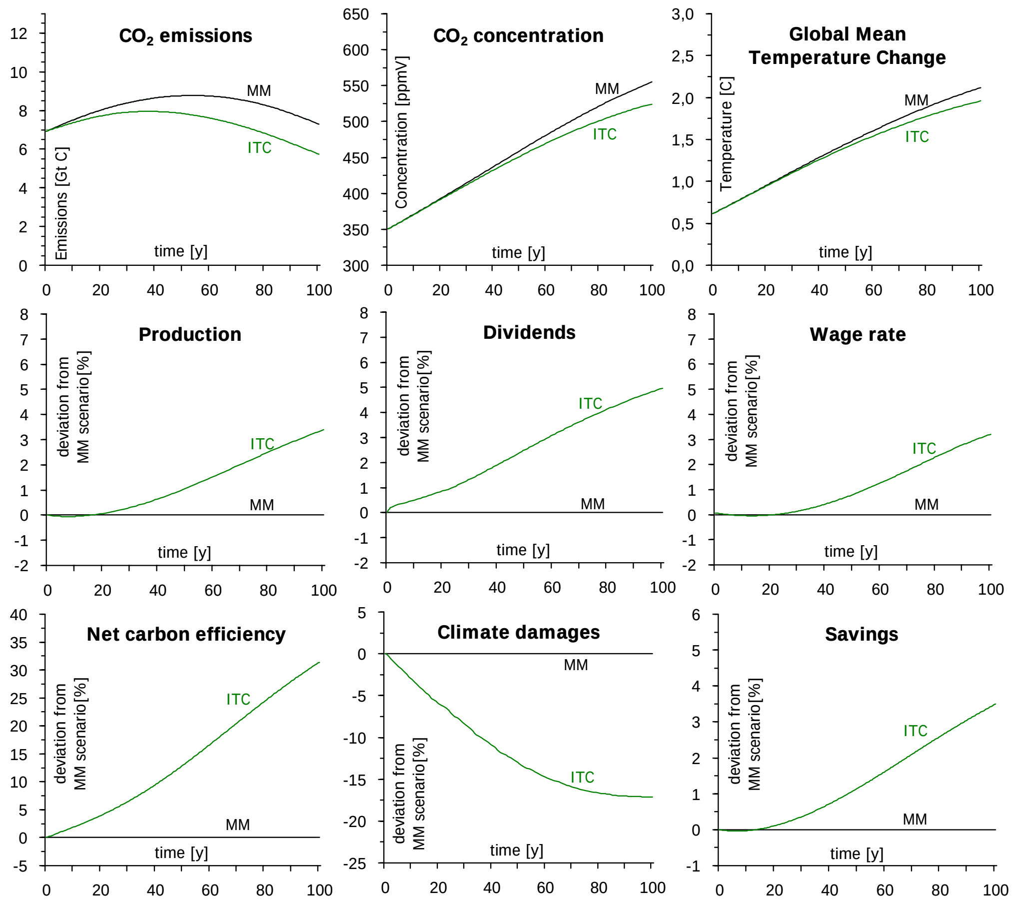

Figure 5.3: *Impact of different ratios of taxes recycled into investments in net carbon efficiency and human/physical capital (MM: 25:75; ITC: 75:25). Top: CO_2 emissions, concentrations and global mean temperature. Center: production, dividends and wage rates, in percentage changes relative to initial MM levels. Bottom: net carbon efficiency, climate damages, and savings, in percentage changes relative to initial MM levels.*

rate is set as in the 'G+' scenario. This example is restricted to a climate friendly control strategy.

The impact of the ITC scenario on climate is clearly positive. The CO_2 emission reduction is much more significant than for the 'G+' scenario. The changed recycling ratio leads to a 21% emission reduction by the year 2100 and a corresponding decrease in the CO_2 concentration and the global mean surface temperature change.

The induced technological change scenario ITC exhibits not only a positive impact on climate, but also on economic growth: the shift of recycled (increased) taxes towards enhanced net carbon efficiency and subsidies for the green consumer good improves the growth rates of GDP in the long term. There is almost no effect on the economic growth rate of production at the beginning of the century, as in the 'G+' scenario. In the long term, the economic growth rate increases by 3-5%, relative to the MM case. The increase of the growth rate of the net carbon efficiency is more significant in the ITC case than in the 'G+' scenario and the climate damages are markedly reduced but the reduction is slowed down in consequence of the increasing production at the end of the century.

It appears that the enhancement of net carbon efficiency and physical capital of good 1 resulting from the increased investments of recycled taxes results in strongly reduced business costs for future energy and carbon taxes, which more than compensates for the reduced investments of recycled taxes into human capital. In comparison to the 'G+' scenario, the ITC scenario is clearly the more reasonable and plausible choice in terms of both climate change and economic growth.

5.3 The impact of consumers

The influence of consumer preferences on climate and economy is illustrated in Figure 5.4. Shown is the impact of the initial demand coefficient ratio A_1^0/A_2^0 for three settings: $A_1^0/A_2^0 = 1/6$ (MM scenario), $1/3$ ('C+' scenario) and 1 ('C++' scenario). In all cases, the initial goods production ratio is set at $g_1^0/g_2^0 = 1/6$. There is no 'C-' scenario because a further decrease of the initial demand ratio indicates that the price of the green good is lower than the price of the grey good, which is assumed unrealistic (for details about the price mechanism see below and Section 3.3).

The impact of consumer preferences on the evolution of climate is clearly visible. The CO_2 emissions are reduced by 5% ('C+') and 13% ('C++') by the year 2100 and the CO_2 concentrations and the global mean temperature change decrease correspondingly. In addition to the positive influence on climate, there is also a positive impact on economic growth: the average growth rate of GDP rises with increasing demand in consumer good 1 from 2.85% p.a. to 2.89% p.a. (for 'C+' scenario) and to 2.93% p.a. (for 'C++' scenario), respectively. The growth rates of the profits/dividends and the wage rate have a similar behaviour (shown in Figure 5.4 are the deviations of the 'C+' and 'C++' scenarios from the reference 'MM' scenario, rather than the growth rates).

The positive impact on economic growth is mainly a consequence of the initial prices of the green and grey consumer goods in the 'C+' and 'C++' scenario. Business is striving to equalize the prices using the price mechanism, presented in Section 3.3.4. Figure 5.5, which shows the ratio of the consumer goods production g_1/g_2 (green/grey good), the price ratio p_1/p_2 and the demand coefficient ratio A_1/A_2, illustrates this mechanism. In the MM scenario, the initial ratios of demand and the amount of goods produced and purchased (prescribed in this model by the supply) are equal (1:6). Following eq. (3.30) the initial price ratio is 1 and since the prices tend to equalize the ratio stays fixed. The ratio A_1/A_2 of the consumers' demand for green or grey goods increases at a rate proportional to the level of climate damages δ, normalized by the production level (eq. (3.43)).

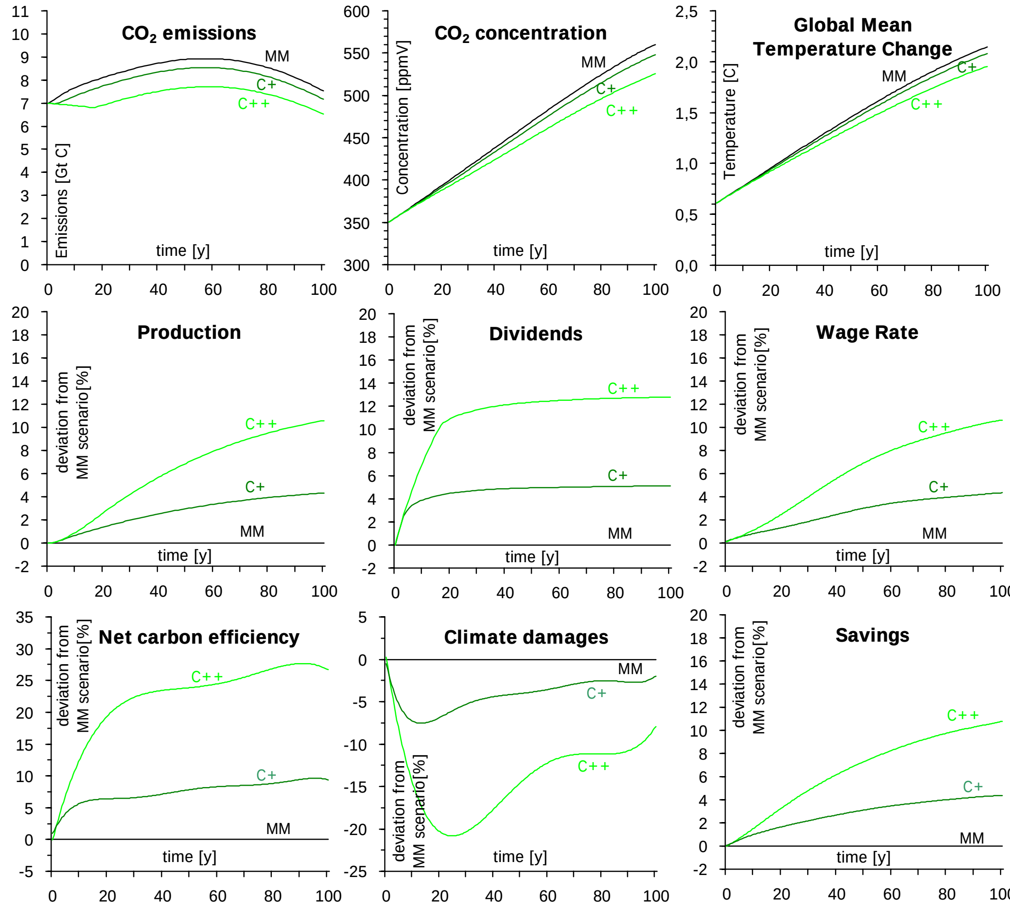

Figure 5.4: *Impact of different initial consumer goods demand ratios A_1^0/A_2^0 (MM: 1/6, 'C+': 1/3, 'C++': 1). Top: global CO_2 emissions, CO_2 concentrations and global mean temperature. Center: production, dividends, and wage rates, in percentage changes relative to initial MM levels. Bottom: net carbon efficiency, climate damages, and savings, in percentage changes relative to initial MM levels.*

The initial preference ratios are 1/3 in the 'C+' scenario and 1 in the 'C++' scenario. Thus, the initial price ratios are 2 and 6, respectively (eq. (3.30)). Different prices imply different profitabilities in the production of different goods, in response to which business then adjusts its physical capital investments. The consumer goods fraction of physical capital is entirely invested in the good with the higher profitability (price).[1] Figure 5.5 illustrates the rapid increase in the production ratio g_1/g_2 and the parallel decrease in the price ratio p_1/p_2 in the 'C+' and 'C++' scenarios. Once prices have adjusted such that the two sectors exhibit equal prices, the investments are distributed equally between the two sectors. The production ratio then adapts to the demand coefficient ratio A_1/A_2.

[1] To avoid numerical jitter, the adjustment to the equi-profitability point can be achieved by a strong but continuous stabilizing fix point algorithm.

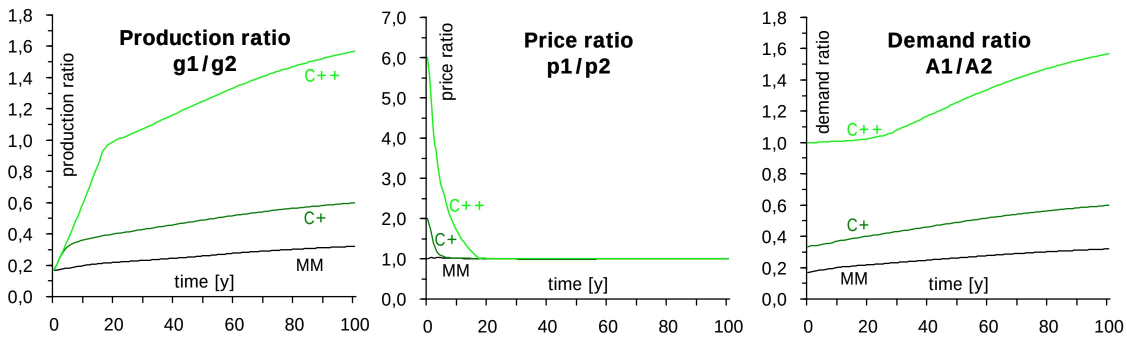

Figure 5.5: *Impact of different initial consumer goods demand ratios* A_1^0/A_2^0*: Ratios of production* g_1/g_2*, prices* p_1/p_2*, and demand* A_1/A_2*.*

The dramatic decrease of the climate damages and the increase of the net carbon efficiency (Figure 5.4) at the beginning of the century (compared to the MM scenario) are consequences of the strong support for the green consumer goods. The weak increase of production and the heavily reduced increase of temperature change (as a consequence of CO_2 emission reduction) result in a significant decrease of climate damages (compared to the MM scenario). The net carbon efficiency grows in the 'C+' and 'C++' scenarios with a much stronger rate because the investments in the green consumer good change the energy mix of the economy and therefore the average emission efficiency of the overall production. At the point in time when the price ratio of the specific scenario is equal to 1, the strong business investment support for the green good ends. The production ratio g_1/g_2 is then equal to the preference ratio A_1/A_2.

The results of this model simulation show that consumers have a significant influence on the socio-economic system. A significant increase in the preference for green products leads to a positive impacts on climate change as well as on the economic growth. This is due to the fact that the shift from grey to green goods reduces the climate damages and the energy costs without otherwise affecting production costs. There is also a reduction in carbon taxes, but this has little net effect on growth, as these are completely recycled into the economy (see Section 5.2).

Another control option of consumers on the economy is the savings rate. Consumer savings are returned to business as loans, thereby increasing the net disposable resources available to business, after payment of wages and other expenses (eq. (3.5)). This is available for various forms of investments, and the provision of dividends. Economic growth can be fuelled either directly by retained business profits, which are reinvested by business, or by the return flow to business of consumer savings. The ratio of these two contributions can vary widely; historical precedents can be found for the dominance of either contribution. However, regardless of the source of income, the motivation of business is always to increase profits, which is best achieved by optimally balancing the investments in human and physical capital (see Section 3.3).

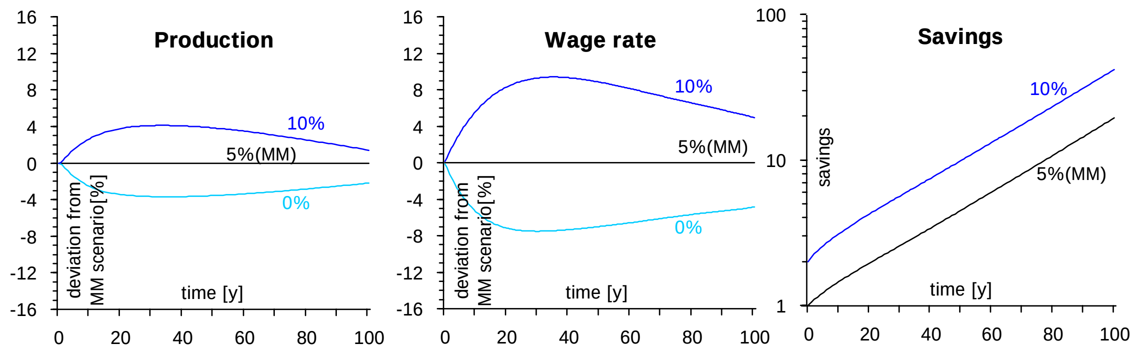

Figure 5.6: *Impact of different consumers' savings rates (0%, 5%, 10%) with parallel adjustment of the wage rate coefficient on production and wage rates, in percentage changes relative to initial MM levels, and savings.*

To illustrate the qualitative differences between growth generated by business earnings and consumer savings, Figure 5.6 shows three simulations with different savings rates, 0%, 5% and 10%. The net disposable business resources were adjusted to approximately the same level in the three cases by adjusting the wage rate coefficient a_w: a higher savings rate is assumed to be correlated with a higher wage rate. The minimum wage adjustment parameter a_w^{min} is varied between 0.6 (for the 0% savings rate scenario) and 0.72 (for the 10% scenario). In the MM scenario a_w^{min} is set to 0.66. These variations change the wage rate coefficient a_w, in accordance with eq. (3.42). More details of the wage earners control strategies and the dynamic wage formation are given in Sections 2.3 and 3.3.1.

As expected, there is no significant change in the production growth rate and no change in the dividends growth rate (not shown). In the early years the growth rate of the wage rate rises for the 10% savings rate stronger (and for the 0% savings rate correspondingly weaker) than in the MM scenario but this deviation becomes weaker at the end of the century. Significant differences are found only in the savings assets of the consumers, which slowly enhance the consumers' income through interests. These results show that the impact of the savings rate is compensated by a parallel moderate increase in wage rate.

The question whether economic growth is driven directly by re-invested business profits or indirectly by investments fuelled by consumer savings is not a key issue for the present modelling exercise and therefore we skip the discussion of these issue at this point. Nevertheless, a deeper evaluation of the problem is of crucial interest and should be the focus of another study.

Chapter 6

The impact of combined control strategies

The results of the simulated individual actor control strategies on the socio-economic system has been presented in Section 5. The scenarios have shown that (in relation to climate friendly control decisions) the positive impact on the climate parameters is not necessarily connected to a strong negative impact on the economic parameters. A significant negative impact on economic growth is simulated only for the 'B+' scenario, but this effect is weak compared to the impact in climate.

There is a very small influence of government on the economic growth rates ('G+' and 'G-' scenario), which means that a moderate emission reduction is achieved without any change in economic growth. In the ITC scenario, in which government not only varies the carbon tax rate but also changes the recycling ratio of the tax revenues into the economy, it is shown that a specific climate policy potentially leads to strong positive influence on both the climate parameters and the economic growth rates (at least in the long-term). A similar result is obtained from the 'C+' scenario. An increase in the consumer goods preference ratio between the climate friendly green and the climate adverse grey good has a positive climate and economic feedback.

The following sections will present the impact of parallel control decisions of the principal actors. First, it is assumed that two actors change their control variables in the same (climate friendly, indicated by '+') direction, while the control variables of the third actor are left unchanged ('BG+', 'GC+', and 'CB+' scenario). This is followed by a simulation of the impacts of all actors simultaneously changing their control variables in the same (climate positive) direction ('GBC+' scenario). For simplicity and clearness, the scenarios are reduced to the climate friendly control strategies. Finally, in the last section of this chapter the anti-parallel control strategies of government and business are simulated, that is the actors change their control variables in opposite directions ('G-B+' and 'G+B-' scenario). The settings of the specific control parameters of the different actors in these scenarios are identical to the settings of the individual strategies presented in Chapter 5.

6.1 The impact of parallel control strategies

In this section, the impacts of parallel climate friendly control decisions on the socio-economic system are presented. The results of the scenarios 'BG+', 'CB+' and 'GC+' are illustrated in Figure 6.1.

The simulation results of the scenario 'BG+' (for the settings of the control parameters see Chapter 5 and Appendix A) show that the characteristic economic parameters decrease by 5-6% (by the year 2100), compared to the MM scenario. The climate impact is significantly positive. The combined action reduces the CO_2 emissions by 30% (in 2100) and correspondingly reduces the CO_2 concentration and the global mean temperature change. The climate damages are also markedly reduced and the improved business investments in energy and emission efficiency raise the net carbon efficiency (compared to the MM scenario). This increase and the weaker production are responsible for the emission reduction. A comparison with Figures 5.1 ('B+' scenario) and 5.2 ('G+' scenario) indicates that these results can largely be explained by straightforward superposition.

The simulation scenario 'GC+' shows that the increase of the economic growth rates is of the same order as the increase in the 'BG+' scenario. The climate impact is slightly positive. At the end of the century the CO_2 emissions are reduced by 12%. These results as well as the simulated evolution of the climate damages and the net carbon efficiency, indicate that the results can also largely be explained by straightforward superposition of the results of the individual actions, shown in Figures 5.1 and 5.2. The significant reduction of the climate damages and the increase of the net carbon efficiency (relative to the MM scenario) at the beginning of the century are due to the price mechanism, which is presented in Section 3.3.4. Business improves the investments in the physical capital of the green consumer good and thereby raises the net carbon efficiency significantly. This mechanism has been described in more detail in Section 5.3.

The impact of government on the economic growth rates in the parallel scenario 'BG+' and 'GC+' is almost irrelevant (as in the individual scenario 'G+'). As mentioned in Chapter 5 this is mainly due to the fact that tax revenues are completely recycled into the economy. The economic impact of the scenarios 'BG+' and 'GC+' is therefore equivalent to the scenarios 'B+' and 'C+'. Nevertheless, the results show that government decisions influence the climate parameters substantially and therefore combined actions of two actors reduce the emissions much stronger than individual actions.

A combined parallel action of government and consumers is shown in the 'CB+' scenario. Figure 5.4 shows that the impact on economy is very weak in this scenario. The economic rates of production, dividends and wage rate are more or less the same as in the MM scenario, which is obviously a superposition of the negative impact in the 'B+' scenario and the positive impact in the 'C+' scenario, presented in Chapter 5. The impact on the CO_2 emissions is clearly positive and of the same order of magnitude as the reduction in the 'BG+' scenario. The evolution of the net carbon efficiency and the climate damages

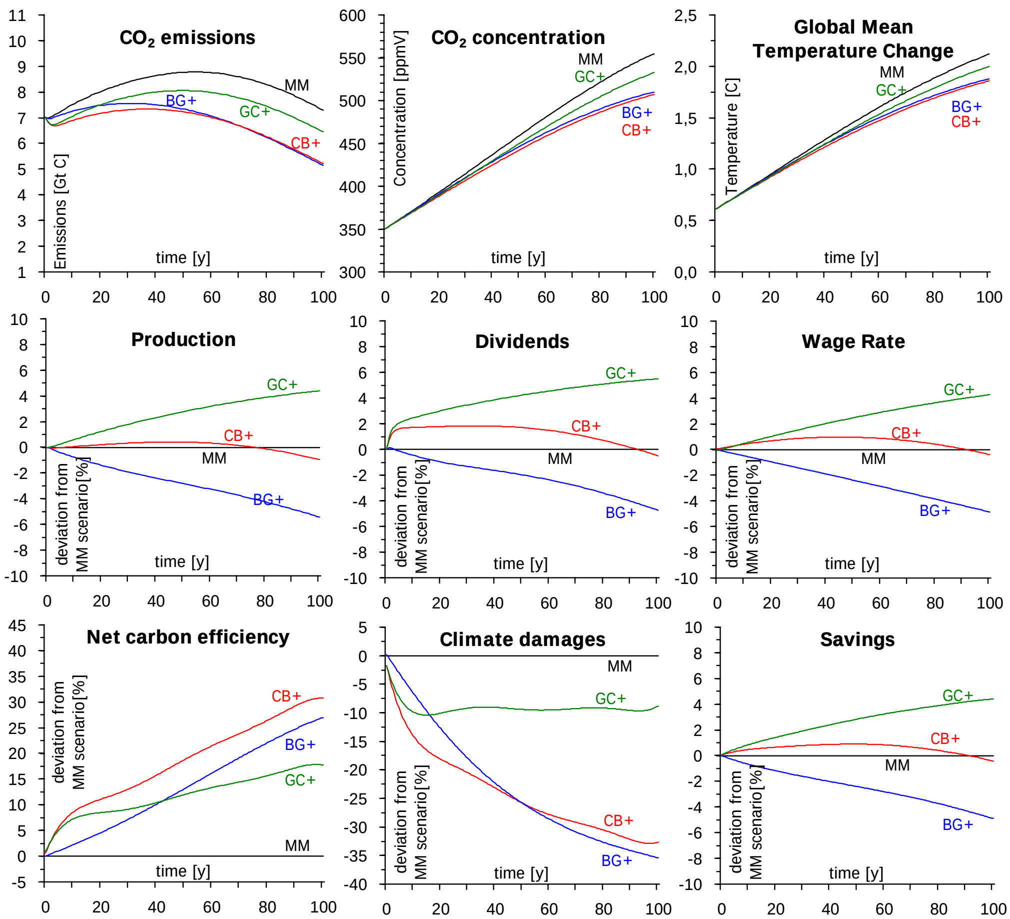

Figure 6.1: *Impact of simultaneous parallel changes of the actors' control variables on climate and economic growth ('GC+', 'CB+', 'BG+'). Top: global CO_2 emissions, CO_2 concentrations and global mean temperature. Center: production, dividends, and wage rates, in percentage changes relative to initial MM levels. Bottom: net carbon efficiency, climate damages, and savings, in percentage changes relative to initial MM levels.*

is also similar to the results of the combined action of business and government ('BG+').

In summary, the results of the combined actions can largely be explained by straightforward superposition; synergy effects obviously do not play a significant role. In terms of sustainable economic growth, the combined control strategies of consumers and government lead to the 'most successful' result. In addition to a positive feedback on the climate parameters, the economic growth rates are increased, relative to the MM scenario. However, the CO_2 reduction is significantly smaller than for the combined strategies of government/business ('GB+') and consumers/business ('CB+'). The 'CB+' scenario has no significant economic impact (in contrast to the negative impact of the 'GB+' scenario), but a strong (positive) influence on the climate parameters and is therefore the most reasonable scenario in terms of climate change.

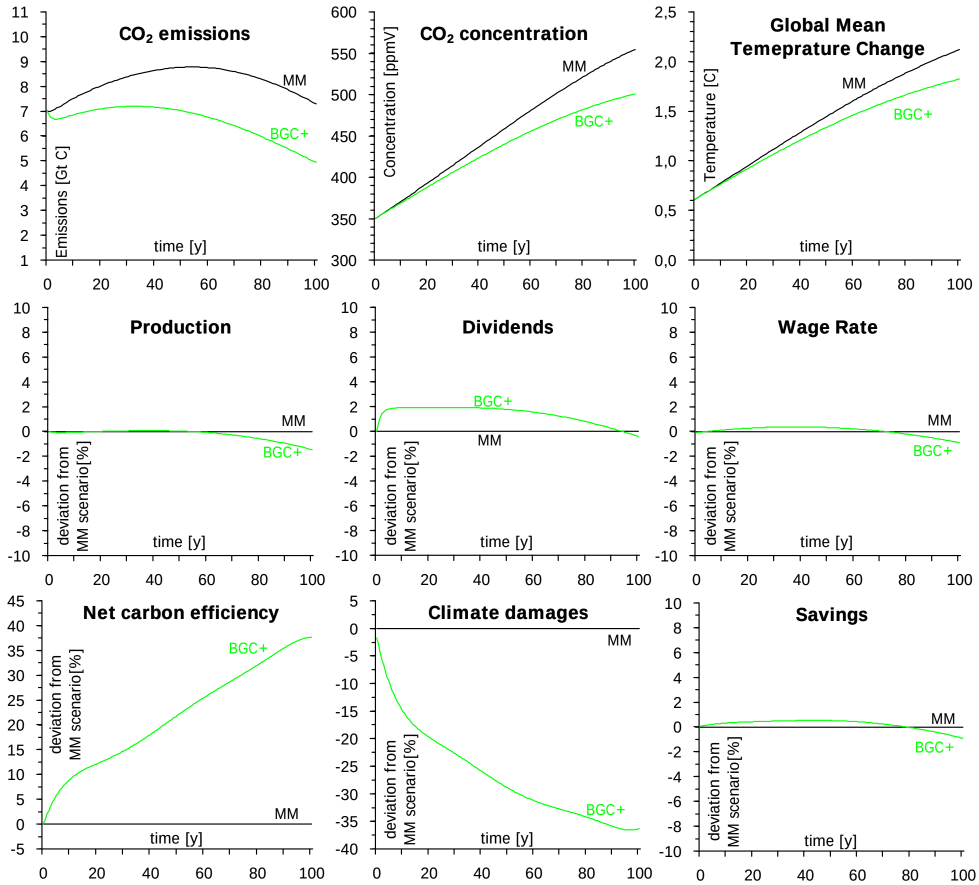

Figure 6.2: *Impact of simultaneous parallel changes of the actors' control variables on climate and economic growth ('BGC+'). Top: global CO_2 emissions, CO_2 concentrations and global mean temperature. Center: production, dividends, and wage rates, in percentage changes relative to initial MM levels. Bottom: net carbon efficiency, climate damages, and savings, in percentage changes relative to initial MM levels.*

6.1.0.1 The impact of parallel control strategies of all actors

Figure 6.3 presents the results of the scenario 'GBC+'. The combined control strategies of all actors in the same (climate friendly) direction is to a large extent a superposition of the combined parallel scenarios presented above (Figure 6.1). There is a strong positive climate impact. The CO_2 emissions are reduced to 4.9 GtC (-32%) by the end of the century. Although the climate impact is positive, there is no negative impact in economy. The economic growth rates are similar to the rates in the 'CB+' scenario (and therefore also similar to the economic growth rates in the MM scenario). Since the government control decision is quasi irrelevant for the economic growth rates but supports emission reduction, the 'GBC+' scenario is found to achieve the most significant CO_2 emission reduction and is neutral (thereby balancing the positive consumer and the negative business feedback) to changes in economic growth (relative to the MM scenario).

In summary, although synergy effects are small, actors are generally motivated to cooperate (under the condition of climate friendly decisions). In relation to the global (reduction of climate change) and personal (growth in GDP, dividends and wage rate) welfare goals of the actors, and in comparison to the impacts of the individual control decisions, there is always at least one combined scenario which offers a more effective and reasonable choice for all of the actors than achieved with individual control decisions. In addition, the combined parallel control strategies could achieve an even more positive impact on climate, and the economy if government changes the recycling ratio of the tax revenues, as in the ITC scenario (Section 5.2).

6.2 The impact of antiparallel control strategies

Figure 6.3 presents the results of the 'B+G-' and 'B-G+' scenarios in which the antiparallel control strategies of government and business are simulated, in other words the actors change their control variables in opposite directions. These simulations should reflect the ('real world') situation of business reacting on government decision to increase or reduce the carbon tax rate. In the scenario 'B-G+' the business investments are reduced, while the carbon tax rate is increased and in the 'B+G-' scenario inversely.

The results of the 'B+G-' scenario seem to be a straightforward superposition of the 'B+' (Figure 5.1) and 'G-' (Figure 5.2) scenario with respect to the economic growth rates of production, dividend and wage rate (and the savings), which are slightly increased in the 'B+G-' scenario (compared to the 'B+' scenario). In comparison to the 'B+' scenario there is almost no impact on the climate parameters through the reduced tax rate of the additional 'G-' scenario. Although the 'G-' scenario settings have been intensified CO_2 emissions by 0.8 GtC to 8.07 GtC by the year 2100 (compared to the MM scenario, Figure 5.2), the positive effect on the CO_2 emissions in the 'B+G-' scenario is only 0.35 GtC (to 5.82 GtC), compared to the 'B+' scenario (5.47 GtC). The climate adverse decision of government is therefore of secondary importance in the 'B+G-' scenario, with respect to both economic and climate parameters. This very weak impact of the lower carbon tax rate can be explained partly due to the increase in investments in the net carbon efficiency, which reduced the CO_2 emissions in the 'B+' scenario significantly. Therefore, the tax revenues and consequently the importance of the tax recycling mechanisms are reduced.

In contrast, in the opposite scenario, 'B-G+', the climate friendly decision of government is of significant importance and this holds for the economic as well as climate parameters. The deviation of the production rate from the MM reference growth rate is -0.27% for the 'G+' scenario (Figure 5.2) and +6.1% for the 'B-' scenario (Figure 5.1). The antiparallel scenario 'B-G+', however, deviates only 3.3% from the MM scenario. There is a similar outcome for CO_2 emissions. In the 'G+' scenario, the emissions are reduced by 0.57 GtC by the year 2100 (compared to the MM scenario) and in the 'B-' the emissions grow by

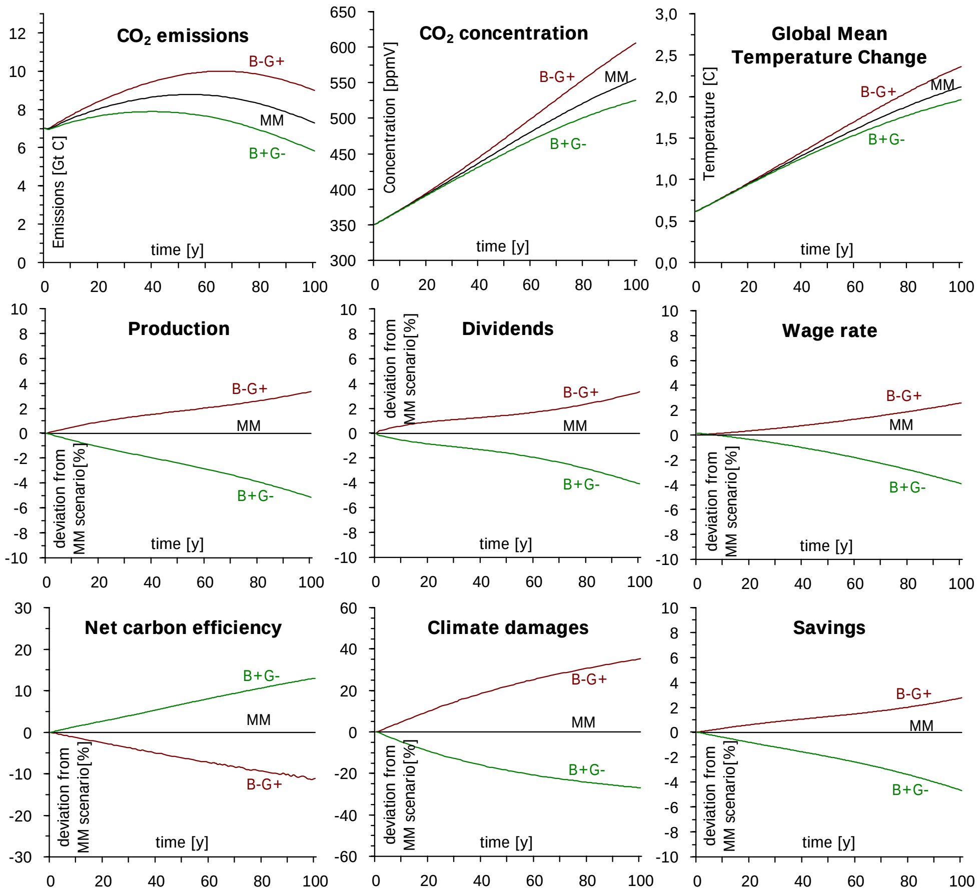

Figure 6.3: *Impact of simultaneous antiparallel changes of the actors' control variables on climate and economic growth ('B-G+', 'B+G-'). Top: CO_2 emissions, concentrations and global mean temperature. Center: production, dividends, and wage rates, in percentage changes relative to initial MM levels. Bottom: net carbon efficiency, climate damages, and savings, in percentage changes relative to initial MM levels.*

3.0 GtC (10.26 GtC in 2100). Figure 6.3 demonstrates that in the 'B-G+' scenario the increase in CO_2 emissions is only 1.7 GtC. The 'climate friendly' decision of government is therefore of great consequence in the 'B-G+' scenario. The influence on the economic as well as climate parameters is significantly stronger than expected with respect to the results of the 'G+' scenario. The effect of the higher tax rate is mainly because the reduction of business investments in the net carbon efficiency leads to higher emissions and therefore the tax revenues are increased in two ways.

The results of the 'B+G-' and 'B-G+' scenario presented in Figure 6.3 indicate that in contrast to the parallel control strategies (Section 6.1) the antiparallel decisions of government and business cannot be explained only by straightforward superposition of the individual simulations results; synergy effects obviously do play a certain role.

Chapter 7

Stochastic behaviour

In addition to the sensitivity analysis performed in Section 4.3, MADIAM includes stochastic uncertainty in some parameters. As mentioned in Section 3.2.8, stochasticity is introduced into the evolution equations for human capital, carbon efficiency and emission efficiency (eqs. (3.33), (3.35), (3.36)) by splitting the investment coefficients μ_h, μ_{ci} and μ_{ei} into a continual and a stochastic part $\mu = \bar{\mu} + \mu'$. The random components μ' represent the impact of unpredictable advances through significant inventions, technological breakthroughs, etc. The stochastic part is related to the continual part through the expression

$$\mu' = \xi_\mu(t)\bar{\mu} \tag{7.1}$$

and $\xi_\mu(t)$ represents a Poisson processes with given probabilities $m_{\mu 1}$ of occurrence per year and Rayleigh amplitude distributions $m_{\mu 2}$. The average investment coefficient due to stochastic events is proportional to the continual climate coefficient,

$$< \mu' >= m_{\mu 1} m_{\mu 2}\, \bar{\mu}. \tag{7.2}$$

In analogy with the stochastic component introduced into the investment coefficients (and as described in Section 3.2.3) climate damages are represented as the sum $\delta = \bar{\delta} + \delta'$ of continual climate damages $\bar{\delta}$ and stochastic climate damages δ'. Stochastic climate damages represent the costs of unpredictable extreme events, such as the increased frequencies of hurricanes and severe storms, exceptional storm surges and severe flooding, long drought periods, etc. The stochastic climate damages are related to continual climate damages through the expression

$$\delta' = \xi_\delta(t)\bar{\delta} \tag{7.3}$$

where ξ_δ is a positive stochastic variable representing a Poisson process with a probability $m_{\delta 1}$ of occurrence per unit time and a Rayleigh amplitude distribution per occurrence with a mean value $m_{\delta 2}$. Thus the average climate damages per unit time due to stochastic events is proportional to the continual climate damage level,

$$< \delta' >= m_{\delta 1} m_{\delta 2}\, \bar{\delta}. \tag{7.4}$$

In the following three sections the stochastic uncertainty in the investment coefficients of human capital (Section 7.1), in the investment coefficients of carbon and energy efficiency (Section 7.2) and in climate damages (Section 7.3) are investigated. In all three cases it is assumed that assumed that the stochastic and continual climate damages are of comparable magnitude ($m_{\delta 1}\, m_{\delta 2} \approx 1$; $m_{\mu 1}\, m_{\mu 2} \approx 1$), but these parameters are chosen individually for all of the coefficients (the settings are given within the following sections).

7.1 Stochastic uncertainty in human capital

This Section presents the results of 100 Monte Carlo simulation model runs with uncertain investment coefficient μ_h (eq. (3.33)) of human capital. This coefficient has been split into a continual and stochastic part and the average investment coefficient due to stochastic events is proportional to the continual part of the coefficient, according to eq. (7.2). The mean value of the probability is set to $< m_{\mu 1} >= 0.5$, and the mean amplitude is set to $< m_{\mu 2} >= 2.0$.

Figure 7.1 shows the effect of these additional stochastic parts by presenting the mean value of 100 model runs, the minimum and maximum value, the standard deviation, and the MM scenario curve of CO_2 emissions, the overall as well as green and grey consumer goods production, the net carbon efficiency and the climate damages.

The range of results of the model runs is remarkably wide for all parameters. The spectrum of CO_2 emissions ranges from 4.9 to 8.6 GtC in the year 2100. The mean value and the MM scenario emissions are nearly equal (as for all parameters presented in this Section) and the standard deviation is about 0.65 GtC. The minimum and maximum values of the production growth rate are 1.7% p.a. and 3.4% p.a., respectively (2.75% p.a. is the MM and mean growth rate). The variance is even greater for the green consumer good. The spectrum of growth rates ranges from 1.9% p.a. to 4.1% p.a. (3.25% p.a. is the MM and mean growth rate). Due to the initial production ratio of green and grey goods (1:6) changes in the partitioning of the business investments, which are a consequence of varied 'efficiency' of investments in human capital, have a much stronger impact on the physical capital of the green good than on the (initially much higher) physical capital of the grey good.

The range of the results is extremely wide also for the net carbon efficiency and the climate damages. The minimum growth rates are 1.1% (for the net carbon efficiency) and 2.0% p.a. (for the climate damages); the corresponding maxima are 3.9% and 4.2% p.a., while the mean values (which again fit to the MM scenario values) are 2.7 and 3.4% p.a., respectively.

The results show that the model is highly sensitive to variations in the investments coefficient of human capital. The additional stochastic part of this coefficient with a probability of occurrence per unit time of $< m_{\mu 1} >= 0.5$ and a mean amplitude of $< m_{\mu 2} >= 2.0$

causes a wide range of possible outcomes and this holds for both economic and climate parameters.

7.2 Stochastic uncertainty in carbon & energy efficiency

In analogy to the stochastic uncertainty in the investment coefficient of human capital, this Section presents the results of 100 Monte Carlo simulation runs with uncertain investment coefficients in carbon and energy efficiency, μ_c and μ_e (eqs. (3.35), (3.36)). The mean values of the probabilities of both coefficients are set to $< m_{\mu 1} >= 0.5$, and the mean amplitudes are set to $< m_{\mu 2} >= 2.0$ (as for the investment coefficient of human capital).

Figure 7.2 shows the effect of this additional stochastic part by presenting again the mean value of 100 model runs, the minimum and maximum value, the standard deviation, and the MM scenario curve of CO_2 emissions, the overall as well as green and grey consumer goods production, the net carbon efficiency and the climate damages.

The range of values of the 100 model runs is significantly smaller than in the previous Section, especially for the economic parameters. The strongest variability occurs for the CO_2 emissions. At the end of the century the CO_2 emissions range from a minimum value of 6.3 GtC to a maximum value of 8.3 GtC. The standard deviation is 0.42 GtC. The range of values of the production growth rates is relatively small. The growth rates of the overall production are between 2.7 and 2.8% p.a. As with the stochastic uncertainty in human capital, the growth rate of the green consumer good differs more than the growth rate of the overall production (with a very small variance) and the grey good and ranges from 3.18 to 3.34% p.a. The variance of the distribution of the growth rates of net carbon efficiency and climate damages is also relatively small and in the order of magnitude of the variance in the production growth rate of the green consumer good.

The results show that the response of the model system to variations in the investment coefficients of carbon and energy efficiency is weak (and much weaker than the response to variations in the investment coefficients of human capital). The additional stochastic part of this causes a significant variance in CO_2 emissions, but the range of values of the economic growth rates is rather small; surprisingly this applies also for the growth rate of the net carbon efficiency. A reason for this might be the relativly strong impact of the exogenous improvements factors λ_c and λ_e. The sensitivity of the system on variations of these factors is discussed in the Section 4.3.2.

7.3 Stochastic uncertainty in climate damages

This section presents the results of 100 model runs with uncertain climate damage coefficient (eq. (3.9)). In this case the mean values of the probability is set to $< m_{\delta 1} >= 0.1$, and the mean amplitude is set to $< m_{\delta 2} >= 10.0$. This setting intends to reflect the assumption of unpredictable extreme climate events once per decade.

Figure 7.2 shows the effect of this additional stochastic part of the climate damages on CO_2 emissions, the overall as well as green and grey consumer goods production, the net carbon efficiency and on the climate damages. As a straightforward consequence of the probability of climate events with extreme amplitude ($m_{\delta 2}$), the range of values of the climate damages increases significantly, starting immediately in the year 2000. This wide range of climate damages affects the growth rate of the green consumer good through the demand ratio (eq. (3.53), which depends on the climate damages (eq. (3.43)). This feedback varies the investments rates of the physical capital in the consumer goods. Due to the fact that the production ratio of the green and grey consumer good is initially 1:6, the investment decisions affect the physical capital and correspondingly the production of the green good much more strongly than the grey good (for details about the price mechanism, see Section 3.3.4.1).

The overall production is (as in the previous sections) only slightly affected by the stochastic uncertainty of the climate damages. The relative small impact of the additional stochastic part on the CO_2 emissions seems to be unusual, but this is an effect of the strong shift in the production ratio, which balances the overall production and therefore the variance of the emissions. The minima and maxima of the range of values of emissions differ from the mean value (again nearly equal to the MM scenario) by 1 GtC and the standard deviation is about 0.25 GtC.

The results show that the simulation of extreme climate events through the introduction of uncertainty in the climate damages affects the production of the green consumer good significantly. This strong feedback mechanism of the MADIAM model balances the impact on the growth rate of the overall production (and other economic growth rates not shown here).

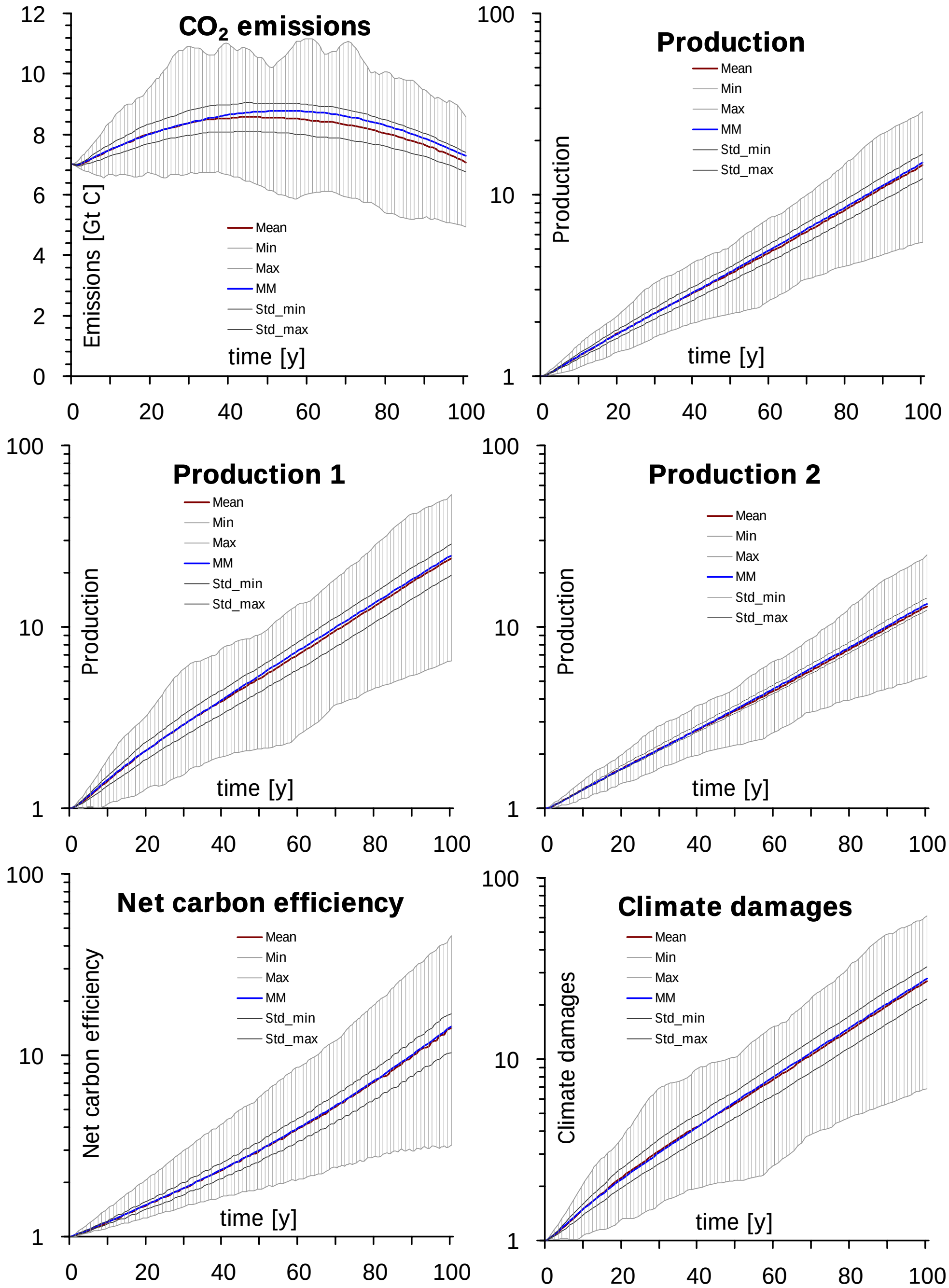

Figure 7.1: *Stochastic uncertainty in human capital. Shown is the mean value of 100 Monte Carlo simulation model runs (dark red), the minimum and maximum (outer grey lines, the vertical lines indicate the range of the 100 runs), the standard deviation (inner dark grey lines), and the MM scenario value (blue line) of CO_2 emissions, overall as well as green and grey consumer goods production, net carbon efficiency and climate damages (all, except emissions, normalized to the initial values).*

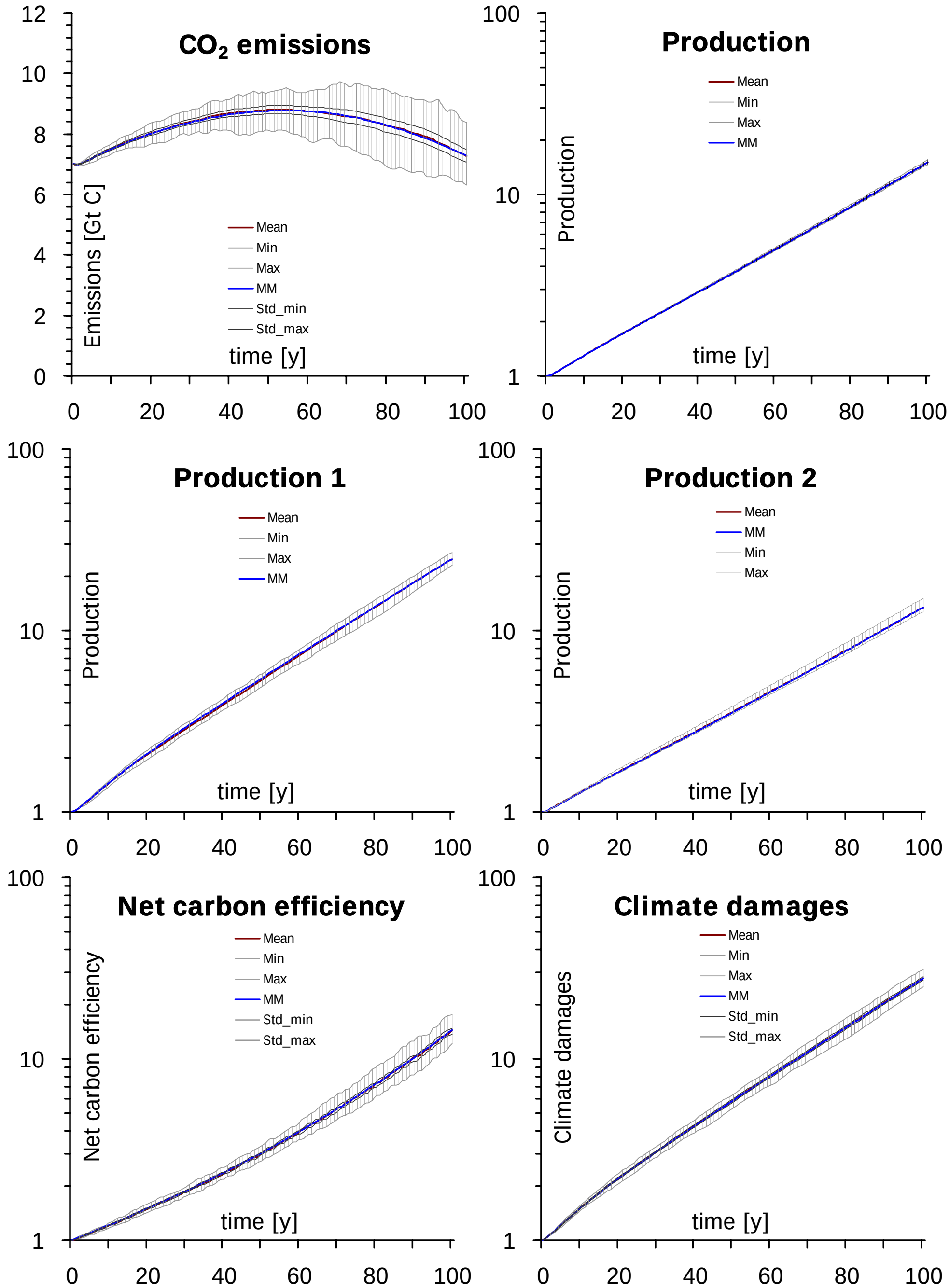

Figure 7.2: *Stochastic uncertainty in carbon and energy efficiency. Shown is the mean value of 100 Monte Carlo simulation model runs (dark red), the minimum and maximum (outer grey lines, the vertical lines indicate the range of the 100 runs), the standard deviation (inner dark grey lines, not presented for production), and the MM scenario value (blue line) of CO_2 emissions, overall as well as green and grey consumer goods production, net carbon efficiency and climate damages (all, except emissions, normalized to the initial values).*

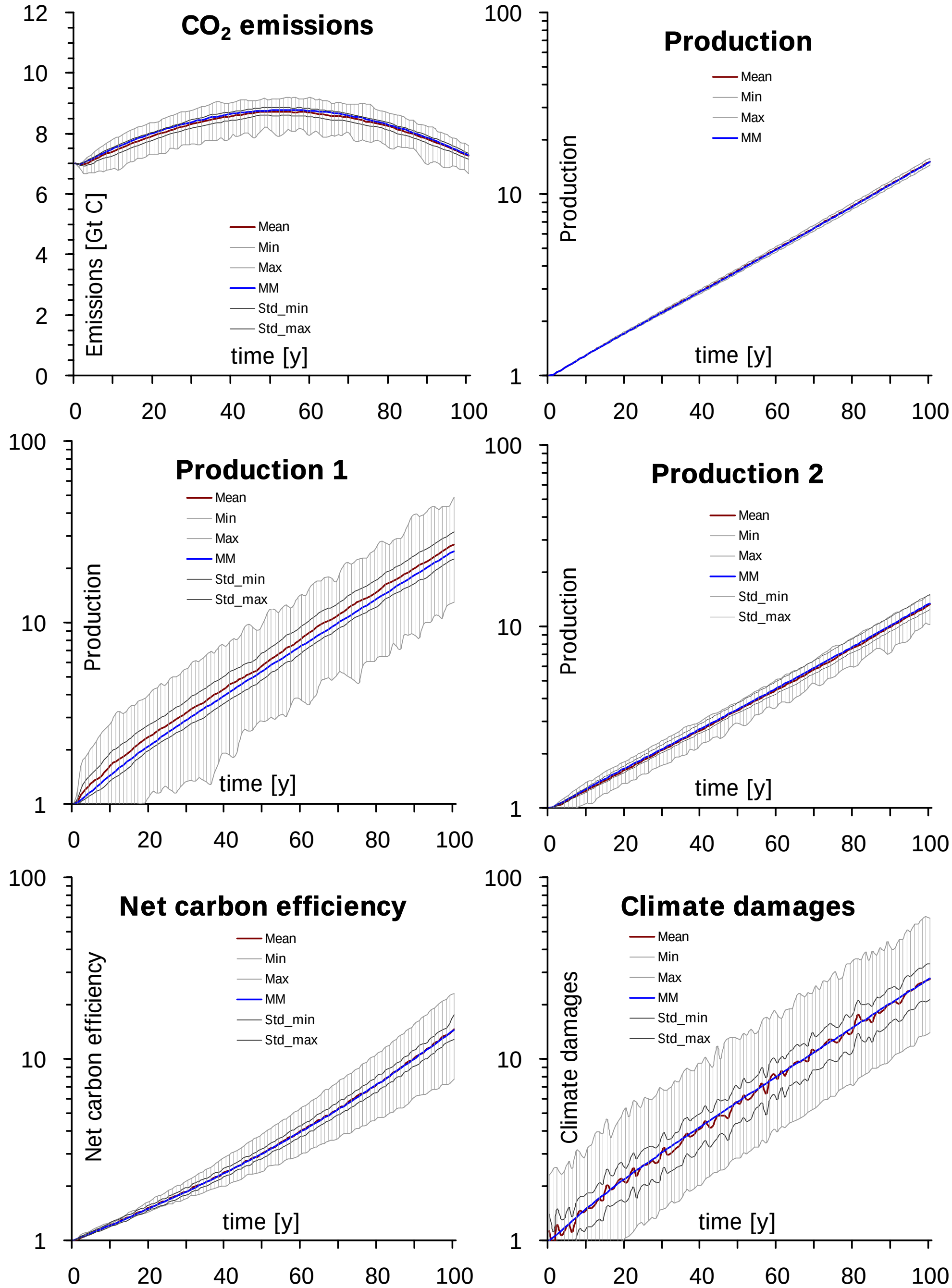

Figure 7.3: *Stochastic uncertainty in climate damages. Shown is the mean value of 100 Monte Carlo simulation model runs (dark red), the minimum and maximum (outer grey lines and the vertical lines indicate the range of the 100 runs), the standard deviation (inner dark grey lines), and the MM scenario value (blue line) of CO_2 emissions, overall as well as green and grey consumer goods production, net carbon efficiency and the climate damages (all, except emissions, normalized to the initial values).*

Chapter 8

Conclusions and outlook

8.1 Approach

In this study the Multi-Actor Dynamic Integrated Assessment Model (MADIAM) has been developed and applied in a systems-analysis mode in order to explore some of the principal processes governing the multi-actor dynamics of the coupled climate-socio-economic system, including endogenous technological change, in a non-equilibrium situation, thereby overcoming some of the limitations of standard economic equilibrium modelling approaches.

The model is composed of two coupled modules: a climate module NICCS (a Nonlinear Impulse-response representation of the coupled Carbon cycle-Climate System [Hooss, 2001]), and a socio-economic model MADEM (Multi-Actor Dynamic Economic Model). MADEM describes an economy driven by the opposing forces of business, striving to increase profits by investments in human and physical capital, and the erosion of profits through business competition, enhanced by labour wage pressure.

The principal driver of economic growth is the increase in labour productivity (human capital) generated by endogenous technological change. Technological change is the result of the multiple impacts of the principal actors controlling the system dynamics. The actors, in their varying and interacting responses to the challenge of climate change, modify the basic interactions by regulatory actions of government, in the form of taxes on CO_2 emissions, which are recycled into the economy as various subsidies, by climate-related changes in consumer preferences for different consumer goods, and by modified business investment decisions in response to these actions.

Thus, the evolution of the coupled climate-socioeconomic system is determined by the actions of a number of actors pursuing divergent goals. In contrast to the usual game-theoretical setting, however, we do not attempt in the present study to determine the possible optimized strategies that the individual actors may adopt in response to the strategies of the other actors. Instead, we assume here that each actor, in ignorance of the details of the other actors' strategies, simply follows some given individual strategy dependent only on the present system state and the actor's implicit personal anticipation of the future evolution of the system

8.2 Main findings

The impacts of various individual as well as combined control strategies of the principal actors of the socio-economic system (government, business, consumer) are simulated and compared with two reference scenarios: a 'business as usual' (BAU) scenario and a reference 'moderate mitigation' (MM) scenario, defined by calibrating the model against empirical economic data and medium to long-term climate predictions. The chosen examples are intended as illustrations rather than to provide quantitative predictions.

All actors are found to exert a significant impact on the mitigation of global climate warming. In contrast, the impact on long-term economic growth in all cases is small. The delay in GDP growth incurred over a one-hundred-year period is typically of the order of only one or two years. This result is independent of the details of the (necessarily uncertain) calibration of our model, and is found also in other studies, e.g. Azar and Schneider [2002] and Edenhofer et al. [2004]

Business investments in energy and carbon efficiency are able to reduce CO_2 emissions significantly. The regulatory actions of government mitigation actions through imposed and recycled carbon taxes are nearly neutral with respect to changes in the economic growth rates in the reference MM scenario, and there is also only a weak positive impact on climate. Government's actions are more effective with regard to emission reductions (and additionally to economic growth) if a significant fraction of the carbon taxes is recycled into investments in net carbon efficiency, i.e. into induced technological change. The influence of consumer preferences is also shown to be very effective in guiding business investments, thereby positively affecting both climate and economic growth. In general, the results demonstrate that a positive impact on climate change is not necessarily connected to a negative impact on economic growth.

Combined parallel control strategies are presented in which at least two actors simultaneously change their control variables in the same (climate friendly) direction. The results are compared to the outcome of the individual strategies. It is shown that the actors clearly have a motivation for negotiation and cooperation in the distribution of the climate policy load. In relation to the common global goal (reduction of climate change) and their personal welfare goals (growth in GDP, profits and wage rate), there is always at least one combined scenario which offers a more effective and reasonable choice for all of the actors than achieved with individual control decisions.

A sensitivity analysis has been applied to investigate the impact on the results of different model parameters and optional model features, such as stochastic uncertainty, which has been implemented in both the climate and socio-economic modules. The system was found to be highly sensitive to a number of parameters. Thus, the details of the model response depend strongly on a number of initialization and calibration parameters of the model dynamics and actor control algorithms, which in many cases are not yet well established. However, the purpose of our simulation exercise was not to provide reliable predictions, but rather to identify the relevant processes and associated parameters of the system, which need to be more closely investigated.

8.3 Conclusions

The main goals of the paper were to initiate a model development that would be able to (1) treat the dynamics of the coupled climate socio-economic system, including endogenous technological change, in a non-equilibrium situation and thereby overcomes some of the limitations of standard equilibrium economic modelling approaches, and (2) bridge the gap between growth models and computable general equilibrium (CGE) models as currently applied in integrated assessment studies.

The motivation for the first goal was the well-established empirical observation that interactions between the principal economic actors can lead to instabilities and mean growth paths of the economy which are far removed from the theoretical solutions of general-equilibrium models. International climate negotiations are strongly influenced by these concerns, in particular with respect to the potential impacts of climate change, climate policy and the actions of socioeconomic players on business cycles, GDP growth, structural and conjunctural unemployment, technological development, international competitively, gradients in welfare, political stability, conflicts, and other critical processes associated with the evolving global economic system.

Many of these issues are related to short-to-medium term processes, which tend to be ignored in models of long-term economic change. However, on the policy level, the implications of regulation policies designed to address long-term climate change are invariably judged also in relation to their impacts on the short-to-medium-term economy. In fact, these often dominate the debate. It is therefore important that integrated assessment models address the socioeconomic impacts of climate policy instruments both in the long and the short-to-medium term.

In order to achieve also the second objective of bridging the gap between the present generation of growth models and CGE models used in integrated assessment studies, MADIAM will need to be extended to include a larger number of regions, sectors and actors (see Outlook below). The economic module MADEM-2, once extended, will become comparable, with respect to the level of economic disaggregation, to a typical CGE model. However, as a dynamic non-equilibrium model, MADEM-2 will clearly differ from a CGE in several important respects. MADEM is driven primarily by the profit motivation of business. This leads to a balance of investments in both productivity and physical capital (see Section 3.3; this is independent of the degree to which the efforts to maximize profits are supported by savings and the purchase of shares by consumers).

In contrast, the growth of a traditional zero-profit CGE model is fuelled entirely by the savings of households, which (in the absence of a human-capital sector) is transferred into investments in physical capital. In the limit as the profit rate approaches zero (large productivity-depreciation rate $\lambda_h \rightarrow \infty$, and/or wage rates close to the limit set by the maximal target wage rate coefficient a_w^{max}), growth is maintained also in MADEM by consumer savings. However, the profit motive remains the principal source of economic growth. Essential for the realization of profits remains also in this limit the option of business to invest in productivity, which is normally accompanied by some level of structural unemployment. Thus endogenous technological change, in combination with the profit motivation of business, represents always the basic driver of economic growth.

8.4 Outlook

This study shows that MADIAM is a useful integrated-assessment tool, which can be used to investigate the dynamic interactions of the principal actors of the socio-economic system. Nevertheless, some general shortcomings and limitations exist, which are planned to be addressed in the future.

The model scenarios presented in this study have all been restricted to a single (global) region. In a forthcoming economic model version MADEM-2, numerous additional features like a larger number of regions, sectors and actors will be incorporated, enabling the investigation of interregional trade, capital flow, technological transfer and regional differences in climate change impacts, welfare, etc. These features are important in order to bridge the gap between the present generation of growth models and CGE models used in integrated assessment studies. The current version of MADIAM is coded in modular Fortran 90, using hierarchical variable structures designed to allow a straightforward extension to the second-generation model MADIAM-2 (see Section B).

The climate module NICCS already satisfies the regional requirements of MADIAM-2 by computing climate-change information at the spatial resolution provided by the state-of-the-art three-dimensional climate model against which NICCS was calibrated. However, the model does not yet include changes in the statistics of extreme events or the possible occurrence of instabilities of the climate system. Therefore, it is planned to generalize NICSS further to include extreme events and instabilities.

The model dynamics and actor control algorithms assumed in this study suppressed short-term cyclic or aperiodic variations of the economy. Examples are variable business and consumer confidence, business response to reduced consumer demand by reducing production (i.e. laying off workers and idling capital) rather than reducing prices, responses triggered by unpredictable, discontinuous technological innovations, and unstable feedbacks between the employment level, investments in human capital and the wage rate. The current model version also does not include further processes relevant for investigating possible transition pathways to sustainable development, such as the role of capital stock ageing [Jaeger, 2002, Edenhofer et al., 2004], technological locking-in, monopolistic concentrations resulting from increasing returns to scale, and the implications of climate risk for the insurance industry. However, the multi-actor dynamic structure of MADIAM is well suited for investigating the impacts of such short-to-medium term processes when superimposed on long-term climate regulation measures. These processes as well as various models of business cycles and short-to-medium term variability proposed in the literature (cf. Salvadori, 2003) can be readily incorporated in MADIAM by introducing appropriately modified system feedbacks and actor control algorithms.

In addition, forthcoming versions of MADIAM will include game-theoretical settings to determine the possible optimized strategies that the individual actors may adopt in response to the (known, partially known or assumed) strategies of the other actors. This included, in particular, the complex Nash equilibria that may or may not be established if all actors attempt to simultaneously optimize their strategies over time.

In parallel with basic model development, efforts need to be devoted also to collecting, processing and quality-checking a set of critical econometric time series needed for model testing and calibration. This is an essential prerequisite for providing a sound quantitative basis for the models, and establishing the necessary confidence to apply the models not only as tools for a better understanding of the coupled climate-socioeconomic system, but, ultimately, to produce useful quantitative policy advice.

Appendix A

Model calibration

The MADIAM model has been calibrated to reproduce the basic stylized growth parameters of Kaldor (1963) (see also Edenhofer et al. (2004)). The calibration constants, the initial values of variables, the initial settings of variable parameters, and the basic settings of the control parameters for the MM scenario are given in Tables A.1-A.6.

Table A.1 lists the initial values of the state variables and Table A.2 lists other MADIAM variables derived from the initial values or set exogenously. The model currency unit [$] represents a basically arbitrary monetary unit which must be matched, however, with the similarly arbitrary physical-products unit [G] to yield a unit average price $p[\$/G] = (\sum_{i=1}^{2} p_i r_{gi})(\sum_{i=1}^{2} r_{gi}) = 1$ for consumer goods (eq. (3.3)). The time unit (and model time step) is 1 year [yr], and the unit [L] represents 10^6 workers.

The initial values of the state variables are set as follows: We assume that half of the current world population of 6.6 billion people (United Nations, 1998, 2003) is imployable. The initial productivity, $\hat{p}(0)$, is set equal to 1 and the physical capital stock is set at 7500 [$]. These values (in addition to the production-to-capital ratio ν) generate all other initial state values and the initial values of other variables depend on these.

The constants used in MADIAM are listed in Table A.3. This is follwed by the settings of the control parameters for the MM scenario. In Table A.4 all control parameters are listed and described. In Table A.5 the values of the control parameters that has not been varied in the scenario simulations in chapters 4-6 ('passive' control variables) are presented. Finally in Table A.6 the values of the 'active' control parameters are given for each scenario. The names of the scenarios refer to the names used in the chapters 4-6.

Parameter	*Value*	*Description*	*Reference, Equation*
$\hat{p}$	1	productivity [$\$/yrL$]	$1)$
$\sum k_i$	7500.0	physical capital [$\$$]	$1)$
k_1	803.6	physical capital consumer good 1 [$\$$]	$1)$, $2)$
k_2	4821.4	physical capital consumer good 2 [$\$$]	$1)$, $2)$
k_3	1875.0	physical capital other goods [$\$$]	$1)$
$\hat{w}$	0.5	wage rate [$\$/yrL$]	$1)$
w	1500.0	wages [$\$/yr$]	$1)$
c	10000.0	fossil fuel resources [GtC]	(IPCC, 2001b; Rogner, 1997)
f_c	1.2	energy efficiency	(IEA, 2003)
f_e	357.1	emission efficiency [$\$/GtC$]	eq. (3.12)

$1)$ Basic initialization assumptions (see text for details)

$2)$ We assume an initial k_1:k_2 ratio of 1:6.

Table A.1: Initial values of state MADIAM variables.

Parameter	*Value*	*Description*	*Reference, Equation*
$\sum l_i$	3000.0	employed labour [L]	eq. (2.1), $3)$
$\sum p_i$	3000.0	production [$\$/yr$]	eq. (2.1), $3)$
e	7.0	emissions [GtC/yr]	(IPCC, 2000, 2001a,b)
E	8.4	energy use [GtC/yr]	eq. (3.11)
α_f	0.833	fraction of fossil energy	(IEA, 2003)
v	300.0	energy costs [$\$/yr$]	(DoE/EIA, 2003)
l_{max}	3300.0	available labour pool [L]	$1)$, $4)$
q	0.91	employment rate	eq. (2.2)

$3)$ The initial settings for the individual goods ($i = 1, 2, 3$) are in accordance with the settings for physical capital.

$4)$ The available labour pool is assumed to grow continuously and parallel to the world population, in accordance with recent world population studies (United Nations, 1998, 2003).

Table A.2: Initial values of derived MADIAM variables.

Parameter	*Value*	*Description*	*Equation*
ν	0.4	production-to-capital ratio [1/yr]	eq. (3.1)
z	0.02	interest rate [1/yr]	eq. (3.6)
D	0.004	climate damages benchmark factor	eq. (3.9)
T_b	2.0	climate damages benchmark temperature [$^\circ C$]	eq. (3.9)
dT_b/dt	0.02	climate damages benchmark rate of change of temperature [$^\circ C/yr$]	eq. (3.9)
λ_k	0.04	depreciation rate of physical capital [1/yr]	eq. (3.32)
λ_{h1}	0.015	depreciation rate of human capital	eq. (3.33)
λ_{h2}	0.005	exogenous growth rate coefficient of human capital (productivity)	eq. (3.33)
λ_c	0.006	exogenous growth rate coefficient of carbon efficiency	eq. (3.35)
λ_e	0.006	exogenous growth rate coefficient of energy efficiency	eq. (3.36)
μ_h	0.4	efficiency coefficient for investments in human capital	eq. (3.33)
μ_c	0.0003	efficiency coefficient for investments in f_c [yr/G]	eq. (3.35)
μ_e	0.2	efficiency coefficient for investments in f_e [yr/GtC]	eq. (3.36)

Table A.3: MADIAM constants

Actor	*Parameter*	*Description*	*Equation*
Government	c_τ	tax coefficient [$\$/GtC$]	eq. (3.16)
	σ_{ki}	fraction of tax recycled in k_i (i=1)	eq. (3.32)
	σ_{ki}	fraction of tax recycled in k_i (i=2,3)	eq. (3.32)
	σ_h	fraction of tax recycled in h	eq. (3.33)
	$\sum_i \sigma_{ci}$	fraction of tax recycled in f_c	eq. (3.35)
	$\sum_i \sigma_{ei}$	fraction of tax recycled in f_e	eq. (3.35)
Business	α_0	fraction of disposable income (x') invested in k & h	eq. (3.44)
	$\sum_i \alpha_{ei}$	fraction of x' invested in f_c	eq. (3.48)
	$\sum_i \alpha_{ci}$	fraction of x' invested in f_e	eq. (3.49)
	α_1	fraction of x' invested in mitigation	eq. (3.50)
	C	fraction of i_k invested in consumer goods	eq. (3.51)
	a_1	feedback constant	eq. (3.46)
	a_2	feedback constant	eq. (3.47)
Consumer	η	savings rate [1/yr]	eq. (3.6)
	A_1	demand good 1 (initial value)	eq. (3.43)
	A_2	demand good 2	eq. (3.43)
Wage earners	α_w^{min}	wage-adjustment parameter	eq. (3.42)
	α_q	unemployment feedback exponent	eq. (3.42)
	λ_w	rate of wage adaptation[$1/yr$]	eq. (3.42)

Table A.4: MADIAM control parameters and initial values for the MM reference scenario

Business				Consumer	Wage earner		
a_0	C	a_1	a_2	η	α_w^{min}	α_q	λ_w
0.7	0.75	0.005	0.005	0.05	0.66	4	0.2

Table A.5: MADIAM control parameters and initial values for the MM reference scenario

	Government					Business		Consumer	
Scenario	c_τ	σ_{k1}	σ_h	$\sum_i \sigma_{ci}$	$\sum_i \sigma_{ei}$	$\sum_i \alpha_{ei}$	$\sum_i \alpha_{ci}$	A_1	A_2
BAU	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.166	1.0
MM	4.3	0.15	0.75	0.05	0.05	0.0075	0.0075	0.166	1.0
B-	4.3	0.15	0.75	0.05	0.05	0.005	0.005	0.166	1.0
B+	4.3	0.15	0.75	0.05	0.05	0.01	0.01	0.166	1.0
G-	2.15	0.15	0.75	0.05	0.05	0.0075	0.0075	0.166	1.0
G+	6.45	0.15	0.75	0.05	0.05	0.0075	0.0075	0.166	1.0
ITC	6.45	0.5	0.25	0.125	0.125	0.0075	0.0075	0.166	1.0
C+	4.3	0.15	0.75	0.05	0.05	0.0075	0.0075	0.333	1.0
C++	4.3	0.15	0.75	0.05	0.05	0.0075	0.0075	1.0	1.0
BG+	6.45	0.15	0.75	0.05	0.05	0.01	0.01	0.166	1.0
GC+	6.45	0.15	0.75	0.05	0.05	0.0075	0.0075	0.333	1.0
CB+	4.3	0.15	0.75	0.05	0.05	0.01	0.01	0.333	1.0
GBC+	6.45	0.15	0.75	0.05	0.05	0.01	0.01	0.333	1.0
G-B+	2.15	0.15	0.75	0.05	0.05	0.01	0.01	0.166	1.0
G+B-	6.45	0.15	0.75	0.05	0.05	0.005	0.005	0.166	1.0

Table A.6: MADIAM control parameters and initial values for the MM reference scenario

Appendix B

The multi-region model struture

The model scenarios presented in this study have all been explored for one single (global) region. Nevertheless the current version of MADIAM is coded in modular Fortran 90, using hierarchical variable structures designed to allow a straightforward extension to a second-generation model MADIAM-2, which incorporates numerous additional features, like a larger number of regions, sectors and actors, enabling the investigation of interregional trade, capital flow, technological transfer and regional differences in climate change impacts, welfare, etc. These features are important in order to bridge the gap between the present generation of growth models and CGE models used in integrated assessment studies.

The climate module NICCS already satisfies the regional requirements of MADIAM-2 by computing climate-change information at the spatial resolution provided by the state-of-the-art three-dimensional climate model against which NICCS was calibrated. However, it is planned to generalize NICSS further to include extreme events and instabilities of the climate system.

Figure B.1 presents the Fortran 90 code of the MADIAM module 'mo_parameter', which shows that the basic settings for a multi-region model are already included in the model code. The number of regions can be increased to 4, but this maximum is only a temporary limitation and can easily be expanded. However, at the current model stage there are no interactions between these regions implemented.

In order to illustrate the principal ability of multi-region simulations with the current model version Figure B.2 presents the CO_2 emissions, the overall production and the net carbon efficiency for two exemplary regions. These regions are characterized by slightly different parameterizations. The settings of both regions are identical except for the initial values of the energy and carbon efficiency, the carbon tax rate and the initial business mitigation investments. All other settings correspond to the MM scenario settings. The energy and carbon efficiencies and the mitigation investments of region 1 (EU) are slightly higher than in the MM scenario. The CO_2 emissions are in the order of 0.9 GtC (roughly representing the European Union, in accordance with IPCC, 2000). The growth rate of

```
MODULE mo parameters
!-----------------------------------------------------------
!
!    PURPOSE:
!    --------
!    Definition of parameters
!
!    AUTHOR(S):
!    -------
!    Michael Weber, MPIMet, Hamburg, Germany (michael.weber@dkrz.de)
!    Klaus Hasselmann, MPIMet, Hamburg, Germany (klaus.hasselmann@dkrz.de)
!
!    CREATED: 17.07.03
!-----------------------------------------------------------
IMPLICIT NONE
!-----------------------------------------------------------
! Parameter Declaration
!-----------------------------------------------------------
!set flags
INTEGER, PARAMETER :: &
!
    n region = 1    ,&  ! number of Regions
    max_region = 4  ,&  ! max number of Regions
!
    n firm = 1      ,&  ! number of Firms
    max_firm = 1    ,&  ! max number of Firms
!
    n good = 3      ,&  ! number of Goods
    max_good = 3    ,&  ! max number of Goods
!
    n household = 1 ,&  ! number of Households
    max_household = 2 ,& ! max number of Households
!
    n agent = 3     ,&  ! number of agents
    n_round = 4     ,&  ! number of (decision) rounds
!
    n tax = 1       ,&  ! number of taxes
    n_subsidy = 2   ,&  ! number of subsidies
!
    n state =       & !number of state variables
   n region*(1 * n firm  + &      ! business assets
             1 * n household + &  ! household assets
             1 + &                ! fossil resources
             1 * n household + &  ! household wagerate
             3*n good*n region*n firm + &  ! energy eff, emission eff, physcap
             1)                   ! humcap

!-------------------------------------------------------------
END MODULE mo_parameters
```

Figure B.1: *Fortran 90 code of the MADIAM module 'mo_parameter'.*

GDP is 2.68% p.a., which is below the world average (MM scenario). In the second region (NA) the business mitigation investments and the carbon tax rate are significantly smaller and both the energy and the carbon efficiency slightly smaller than in the EU scenario. The initial carbon dioxide emissions are much higher than in the EU scenario (1.6 GtC, roughly representing North America) and the growth rate of GDP is above the global mean growth rate (2.87% p.a.).

In addition to the increase in the number of regions, the Fortran 90 code also allows for an increase in the number of firms and sectors, which is essential in order to implement inter-regional trade, capital flow, and technological transfer. The maximum numbers in Figure B.1 reflect the settings for the simulations presented in this study, but can be enlarged easily.

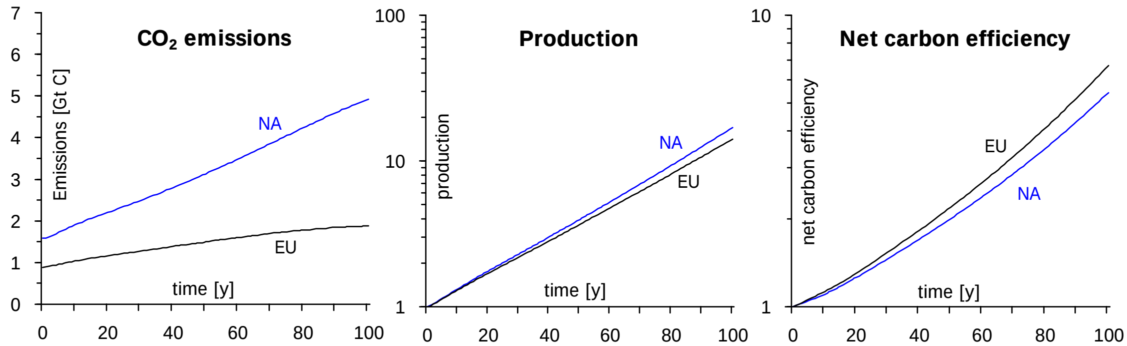

Figure B.2: *Example of simultaneous multi-region model simulations. Global CO_2 emissions, production, and net carbon efficiency for two exemplary regions.*

In summary, the model structure is already appropriate to implement additional features as well as a larger number of regions, sectors, and actors, but requires significant but manageable extensions in order to perform more sophisticated integrated assessments studies.

Appendix C

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