A Multi-Actor Dynamic Integrated Assessment Model (MADIAM) of Induced Technological Change and Sustainable Economic Growth

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Abstract: Interactions between climate and the socioeconomic system are investigated with a Multi-Actor Dynamic Integrated Assessement Model (MADIAM) obtained by coupling a non-linear impulse response model of the climate sub-system (NICCS) to a multi-actor dynamic economic model (MADEM). 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 (or human capital) generated by endogeneous 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 determine 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.

In the reference 'moderate mitigation' scenario, business investments in energy and carbon efficiency, induced by government CO_2 taxes, yield the largest 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 energy and carbon efficiency, i.e. into induced technological change. The influence of consumer preferences, often neglected in integrated assessment analyses, can also be effective in guiding business investments. The chosen examples are intended as illustrations rather than to provide quantitative predictions.

Keywords: dynamic integrated assessment, induced technological change, socioeconomic modelling, climate change, multi-actor scenarios

1 Introduction

Integrated assessment (IA) models of the coupled climate-socioeconomic system provide an important tool for decision makers faced with the challenge of developing climate policies in response to the threat of anthropogenic climate change (cf. Dowlatabadi, 1995; Hasselmann et al., 1997; Morgan and Dowlatabadi, 1996; Parson, 1995; Rotmans and Dowlatabadi, 1998; Schneider, 1997; Weyant et al., 1996). However, in view of the great complexity of the complete coupled system, IA models are necessarily based on a large number of simplifying assumptions. No single model will ever succeed in capturing all the intricacies of the innumerable interactions characterizing the dynamics of the complete system. A satisfactory insight into the system dynamics and its response to external control measures will presumably evolve only through the development of an ensemble of models highlighting different aspects of the coupled system. In this paper, we apply systems-analysis methods to explore some of the principal processes governing the dynamics of the system. Our emphasis is on the roles of the principal actors (business, governments, consumers, wage-earners) which, in their varying responses to the challenge of climate change, jointly determine the evolution of the coupled climate-socioeconomic system. The dominant process governing economic growth in our model is endogeneous technological change, which is treated as synonymous to growth in human capital and labour productivity. In a multi-actor setting, technological change is the result of the multiple impacts of the principal actors controlling the system dynamics. In the context of climate change, these generally lead to accelerated (induced) technological change, which is the principal focus of our study.

The model MADIAM (Multi-actor Dynamic Integrated Assessment Model) used in our investigation is composed of two coupled modules: a climate module NICCS (a Nonlinear Impulse response model of the coupled Carbon-cycle-Climate System, Hooss et al., 2001) and a socioeconomic model MADEM (Multi-actor Dynamic Economic Model).

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 (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. Although IRF models are able to reproduce the space-time structures of all fields computed by the parent models against which the IRF models are calibrated, in this study we shall consider only the global mean near-surface temperature, with CO_2 emissions as external forcing.

Current impulse-response models do 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, 2001). 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 the changes in extreme events 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.

The economic module MADEM describes the growth of the socioeconomic system as driven by the efforts of business to increase profits by investing in physical and, in particular, human capital, thereby counteracting the erosion of profits by competition and the wage demands of labour. A prerequisite for business expansion through increased physical capital is investment in human capital (equivalent to labour productivity or technological change) which, besides increasing profitability, frees the additional labour required to operate the expanded physical facilities. Thus, endogeneous technological change represents the principal driving factor of economic growth. This is in accordance with the original concepts of Adam Smith (1776) and other classical treatises on economic growth, but contrasts with later neoclassical growth models, before being revived again in various forms in recent models of endogenous technological change (see Salvadori, 2003 for a historical discussion, and recent models of Grübler, 1998; Dowlatabadi, 1998; Popp, 2001; van der Zwaan et al.,2002, Kemfert, 2002, Edenhofer *et al*, 2004, and others). Governments can influence business choices between alternative forms of investments, including increased energy and emissions efficiencies, by taxes and subsidies (Induced Technological Change, ITC, cf. Buonanno et al., 2003; Goulder and Schneider, 1999; Goulder and Mathai, 2000; Nordhaus, 2002; Popp, 2000). In addition to business investment decisions, business competition, wage demands by labour and the regulatory action of governments, the economy is influenced also by consumer preferences, expressed by differences in the demands for climate-friendly (green) or non-climate-friendly (grey) goods.

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 (known, partially known or assumed) strategies of the other actors. In particular, we do not investigate the complex Nash equilibria that may or may not be established if all actors attempt to simultaneously optimize their strategies over time (this will be investigated in a later paper). 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 (see Barth, 2003, for an application of the model in the more traditonal single-actor cost/benefit mode, in which business maximizes the time-integral of discounted profits, given the control variables of the other actors).

Climate change is characterized by a wide spectrum of time scales, extending from years and decades into centuries, millenia and beyond. For anthropogenic climate change, the relevant time scale is governed by the long residence times of CO_2 in the atmosphere and the large thermal inertia of the oceans, extending to at least a few centuries (Hasselmann *et al*, 2003). Since human actions today affect climate and thus human living conditions on these time scales, they must be adequately represented in models of the socioeconomic system. However, the time scales clearly lie beyond the time horizon for which both reliable climate and realistic socioeconomic predictions are feasible. Thus, IA models must consider the impacts of uncertainty. These are represented in MADIAM in the form of stochastic processes, which are introduced into both the climate and socioeconomic modules. For space reasons this feature has not been activated in the model simulations presented in this paper, but a detailed discussion on the stochastic properties of MADIAM can be found in Weber (2004).

The paper is organized as follows: The core of the economic model MADEM is described, as yet without climate interactions, in Section 2. In Section 3, the core economic model is extended to the economic module MADEM used in the coupled climate-socioeconomic model MADIAM by introducing climate damages, finite fossil fuel resources, business investments in mitigation (energy and carbon efficiency) and government regulation measures. These are illustrated by simulation examples in Section 4. The control strategies assumed in these simulations and the calibration of the model are described in two appendices. The paper closes in Section 5 with a summary of principal conclusions, together with an outlook on further developments of the MADIAM model and a discussion of the relation of such developments to other types of IA models.

2 MADEM-core

To highlight the principal driving forces of the economic module MADEM we consider first a simpler core model (MADEM-core) in which 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 (e.g. Cass, 1965, Solow, 1956) and more recent endogenous growth models (e.g. Romer, 1986, Lucas, 1988), this leads to a system which is not in classical general equilibrium, allowing instead for (structural) unemployment and positive profits, both of which are well observed features of real-world economies.

The production function of MADEM-core depends on three pimary 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. (we distinguish *per capita* variables, e.g. $\hat{y}$, from the associated integral variables, y, by a circumflex). Formally, human capital h is defined as the time integral $\int i_h \, dt$ of human capital investments minus depreciation, but we shall use instead labour productivity $\hat{y}$ as equivalent state variable (eq.(8) below). We assume that the

technological level associated with 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 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. Our three primary production factors are thereby reduced in fact to only two independent production factors.

Specifically, we assume 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 in three alternative forms with respect to the three production factors:

$$y = \nu k = \nu^* h = \hat{y} l, \tag{1}$$

where the factors ν (constant), 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. We shall use the term productivity throughout only in the sense of mean labour productivity, from now on dropping the adjective ”labour”.

Given the available labour pool $l_{\max}(t)$, the levels of productivity and physical capital determine then the employment level

$$q = \frac{l}{l_{\max}} = \frac{\nu\, k}{\hat{y}\, l_{max}} < 1. \tag{2}$$

A variable employment level q, depending on investments in physical and human capital, is an important feature of our model. This 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 a constant level of employed labour. Employment levels below unity arise naturally in our model through investments in human capital (productivity), which reduce the number of employed labour unless accompanied by investments in physical capital. Thus, structural unemployment arises under conditions in which it is more profitable for business to invest in productivity than in physical capital. The complementary case of idle capital does not arise in the present application of our model, as we have not considered (conceivable) actor control algorithms that lead to recessions and business cycles.

We sub-divide total annual production y 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.1a),

$$y = i_k + i_h + r_g. \tag{3}$$

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].

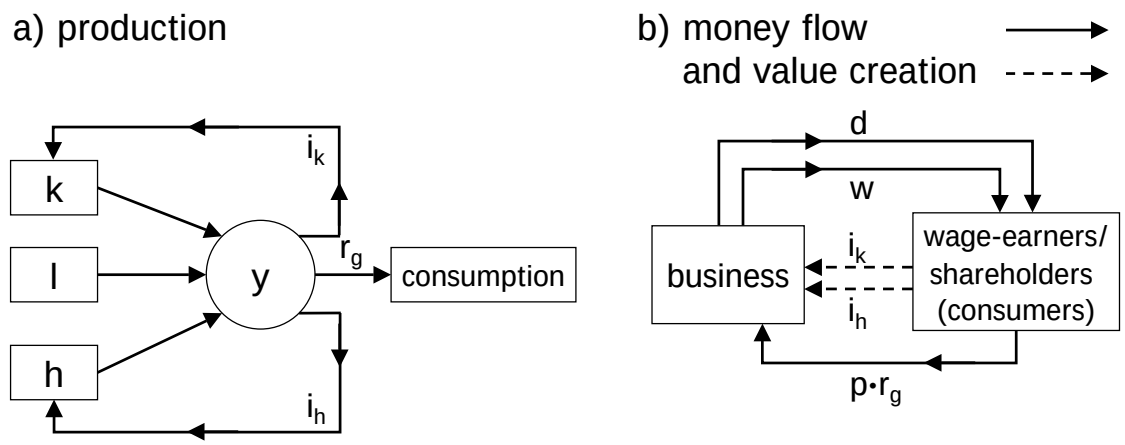

Figure 1: *Production factors and products (panel a, left, eq.(3)) and money flows and value creation (panel b, right, eq.(4)) for the MADEM-core model. In contrast to the full arrows representing the closed money flow via consumption in panel b, the dashed arrows represent added value created through 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.(4).*

The production rates can be related to the expenses x of production, measured in monetary units [$/yr]. Both the present core model and the extended economic model MADEM considered in the next section contain no vertical stratification of production sectors, involving intermediate inputs and outputs. Thus, 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; interests on credits are considered later in the full MADIAM model. The production expenses flow back to business as revenues from the sale of consumption goods. Thus

$$x = w + d = p \cdot r_g, \tag{4}$$

where $p[\$/G]$ is the price of the consumer goods (cf. Fig.1b).

The outputs of production, eq.(3), can be expressed also in currency units by multiplying all terms of eq.(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.(4) into eq.(3), we obtain then with this choice of numeraire

$$y[\$/yr] = i_k + i_h + w + d. \tag{5}$$

Net business profits after wage costs are given by

$$x'[\$/yr] = p - w = i_k + i_h + d. \tag{6}$$

Economic growth depends then on the way business chooses to partition its profits between investments in physical or human capital or distribution to shareholders as dividends. To focus

on essentials, we defer until the next section the consideration of growth generated by consumer savings, which flow back to business as credits, or by the purchase of shares by consumers.

We distinguish here, as usual, 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 section), 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 1b. Similarly, we have not used the traditional term ”firm” in Figure 1b, but rather the term ”business”, to emphasize that this box represents only a management unit, the *de facto* owners of the firm's physical capital being the shareholders.

Equations (3) - (5) summarize the alternative representations of the product-output and cost balances of production. Unless stated otherwise, all variables in the following refer to monetary rather than physical-goods units. We discuss these relations in more detail in the context of the full MADIAM model in the next section, where further processes are introduced representing the impacts of climate change.

In accordance with these concepts, 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 $\hat{w}$:

$$\dot{k} = i_k - \lambda_k k, \tag{7}$$

$$\dot{\hat{y}} = \mu_h \frac{i_h}{l} - \lambda_h \hat{y}, \tag{8}$$

$$\dot{\hat{w}} = \lambda_w (\hat{w}^0 - \hat{w}). \tag{9}$$

Equation (7) 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 balance equation (8) applies for the growth in productivity (representing human capital). Depreciation $\lambda_h \hat{y}$ of human capital arises through the retirement of skilled personnel, who must be replaced by new employees with initially less skill. Also included in this term is 'negative depreciation', due to the exogenous increase in productivity through advances in technology (at a rate assumed to be proportional to the already existing technology), or improvements in technology through 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, $\hat{w}$, eq. (9) expresses the profit-eroding impact of business competition and the wage demands of labour. Within an aggregated macro-economic model, the two effects cannot be distinguished. Successful business executives strive to expand their market share by lowering the market prices of their goods and by attracting labour through higher

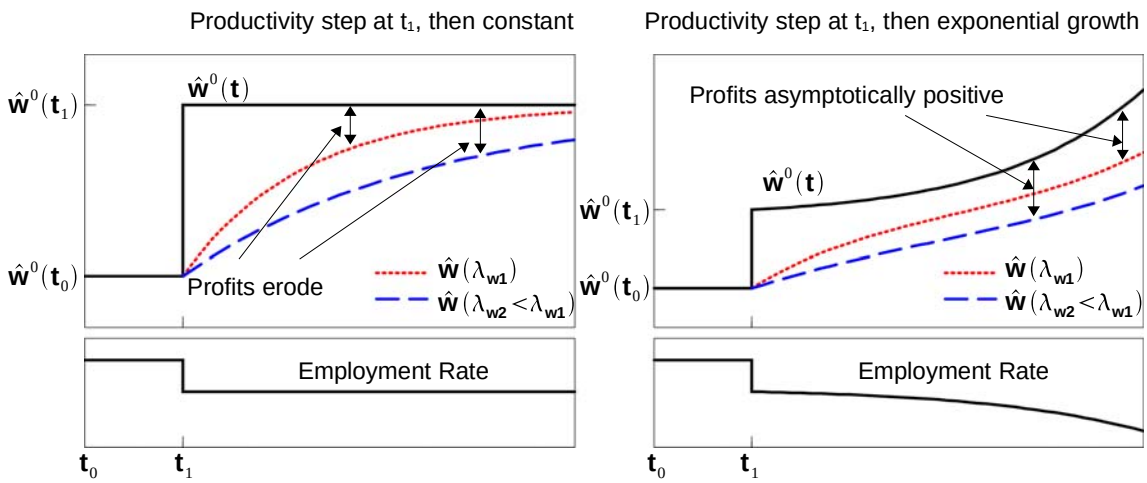

Figure 2: *Dynamic adjustment of wage rates, profits and employment level. Left: A step-function increase in productivity immediately raises the target wage $\hat{w}^0$ (proportional to $\hat{y}$) and depresses the employment level $q = l/l_{max}$. The wage rate $\hat{w}$ then adjusts with a time lag 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). Right: 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. Note that y-axes are scaled differently.*

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.(4)) to shareholders (for a given level of investments).

It is assumed in eq.(9) 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,

$$\widehat{w}^0 = a_w \hat{y}, \tag{10}$$

at the adjustment rate $\lambda_w(\widehat{w}^0 - \widehat{w})$. Thus the target-wage coefficient a_w and 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.(4), (7), (8)), we find for the limiting zero-profit-rate, zero-growth target-wage coefficient

$$a_w^{max} = (1 - \frac{\lambda_k}{\nu} - \frac{\lambda_h}{\mu_h}). \tag{11}$$

In summary, the control strategies available to wage-earners (as proxy also for competition) and business are the following:

The goal of wage-earners is 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 (cf. Appendix 1, eq.(41)).

Business 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. (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). 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 Appendix 1: Control Strategies)

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. 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 (considered further in the following section), have similar goals to wage-earners: to maximize their time-integrated, appropriately discounted income. The main distinctions between wage-earners and shareholders presumably lies 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.

Independent of these details, however, the principal driver of economic growth is investments in productivity and the technological change with which these are associated. For simplicity, we have assumed in the core model that growth from increased productivity is fueled 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. We shall discuss the impacts of these processes on economic growth in relation to endogeneous and induced technological change in the following discussion of the full model MADIAM.

3 MADIAM

The economic model MADEM required for the coupled climate-socioeconomic model MADIAM is obtained by extending MADEM-core through the incorporation of a number of additional features relevant for climate change: climate damages, carbon taxes (in the present aggregated model without trade, the alternative instrument of tradeable emissions would correspond simply to an emissions cap and therefore cannot be represented realistically), investments in energy and carbon efficiency, finite fossil fuel resources, two types of goods (green: climate-friendly and grey: non-climate-friendly), consumer preferences (including savings) and stochastic variability. However, we limit the analysis, as before, to a single (global) region.

We first distinguish, 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 (3) and (4) become for the extended model

$$y[G/yr] = \delta + \sum_{i=1}^{2} r_{gi} + \sum_{i=1}^{3}(i_{ki} + i_{ci} + i_{ei} + v_i) + i_h \quad \text{(products)}, \tag{12}$$

$$\begin{aligned} x[\$/yr] &= \sum_{i=1}^{3} \tau_i + w + d + z \cdot s \quad \text{(costs)} \\ &= \sum_{i=1}^{2} p_i r_{gi} + \kappa + \tau_{cycl} \quad \text{(net business income)} \end{aligned} \tag{13}$$

where δ denotes (tangible) climate damages (generally a negative good or ”bad”); 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); the third index value $i = 3$ refers to physical capital investments in the remaining economic sectors, which are aggregated to a single sector; i_{ci} and i_{ei} represent investments in carbon and energy efficiency, respectively; v_i denotes the energy production and τ_i the taxes imposed on the emissions generated in the three production sectors; w represents the total wage costs, $z \cdot s$ 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; κ is the rate of credit uptake of business, and τ_{cycl} the recycled carbon taxes.

Carbon taxes are assumed to be completely recycled, $\tau_{cycl} = \sum_{i=1}^{3} \tau_i$, so that their contributions in the costs-income balance equation (13) cancel. They will reappear later in the evolution equations.

To express eq.(12) in monetary units, in analogy with eq.(5), we multiply the equation throughout by a reference goods price p[\$/G]. It is convenient to define p as the average consumer goods price

$$p = \frac{\sum_{i=1}^{2} p_i \cdot r_{gi}}{\sum_{i=1}^{2} r_{gi}}. \tag{14}$$

It is shown below 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 choose, as before, $p = 1$ [\$/G] as numeraire.

Eliminating the consumer goods term in the resultant monetarized equation by applying eqs.(13), (14), we obtain then, in analogy with eq.(5),

$$y[\$/yr] = \delta + \sum_{i=1}^{3}(i_{ki} + i_{ci} + i_{ei} + v_i) + i_h + w + z \cdot s - \kappa + d. \tag{15}$$

Subtracting the costs for climate damages, energy, wages and interest from the total production plus credit uptake, eq.(15) yields then for the net business income (profits plus credit uptake)

$$x'[\$/yr] = \sum_{i=1}^{3}(i_{ki} + i_{ci} + i_{ei}) + i_h + d. \tag{16}$$

Business can choose to partition its net income between investments in physical capital, human capital, energy efficiency and carbon efficiency, and dividends to shareholders.

We ignore 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.(13) may be rewritten as

$$\epsilon = (w + d + z \cdot s)(1 - \eta) = \sum_{i=1}^{2} p_i r_{gi} \tag{17}$$

where ϵ represents the consumers' expenditure on consumer goods and η denotes the fraction of the total consumers income that is saved, $(w + d + z \cdot s) \cdot \eta = \kappa$. We treat the savings coefficient η and the interest rate z in the present applications as prescribed exogeneous variables, ignoring variations of savings and credit rates induced by changes in the interest rate set by central banks.

Not included explicitly in the cost balance is 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.

In order to derive the evolution equations of the MADIAM model, we need to consider the individual product and cost items appearing in eqs. (12) and (13) (cf. Figure 3). The investments $i_{ki},\ i = 1 - 3$ in physical capital and productivity $\hat{y}$ determine via the system evolution equations (presented below) the stocks of physical capital and the level of productivity (the latter is assumed, for simplicity, to be the same in all production sectors). The investments in carbon and energy efficiency determine further the associated energy requirements and the CO_2 emission levels, and thus the carbon taxes. The relative prices of green and grey consumer goods $p_i,\ i = 1, 2$ follow finally from the production levels and the consumer preferences.

Climate damages

Climate damages are expressed in terms of the changes ΔT of global mean temperature computed from the CO_2 emissions using the NICCS model. These damages refer to the costs of

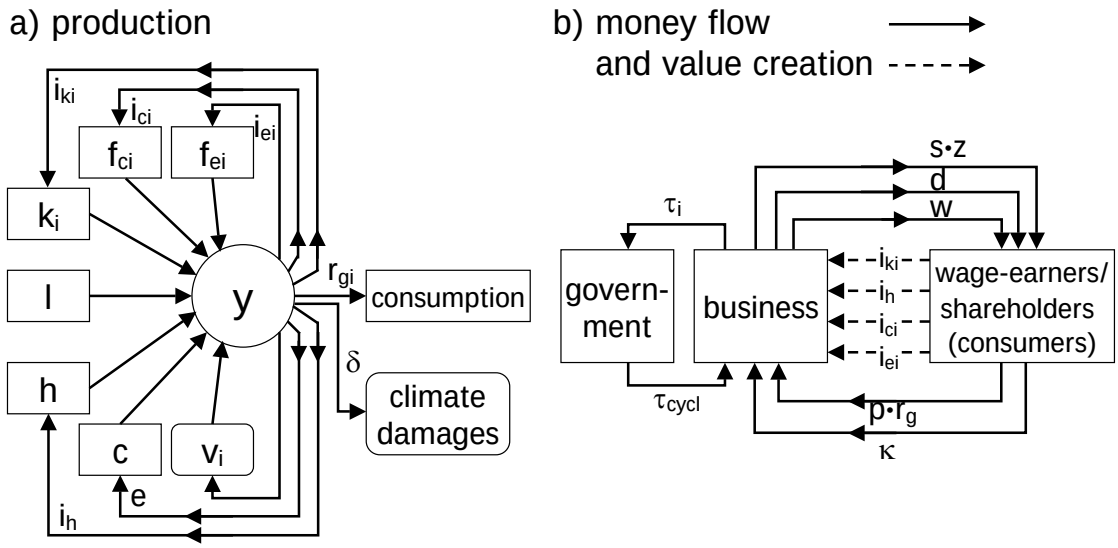

Figure 3: *Production factors and products (left, panel a, eq.(12)) and money flows and value creation (right, panel b, eq.(13)) for the model MADIAM. The dashed arrows in panel b represent surplus production: the additional value created through investments by the actors owning the production factors labour, human capital and physical capital (i.e. by wage-earners and shareholders). They therefore do not appear in the closed money-flow balance eqation (13).*

higher dykes through sea level rise, adaptation of agriculture to a modified mean climate, modified patterns of recreation and tourism, and changing costs for energy, buildings, construction, etc. We assume a simple quadratic dependence on the change and rate of change of temperature in accordance with Hasselmann *et al.* (1997):

$$\bar{\delta} = D\, y \left\{ \left(\frac{\Delta T}{T_b} \right)^2 + \left(\frac{d\Delta T/dt}{dT_b/dt} \right)^2 \right\}, \tag{18}$$

where T_b is a benchmark temperature, dT_b/dt a benchmark rate of change of temperature and D a benchmark coefficient relating mean (tangible) climate damages to GDP. The relation (18) reflects general views on the (poorly known) global impact of changes and rates of change of global mean temperature and is consistent (in combination with the stochastic climate damages below) with the range of estimates of climate change damages, of order of 2% of GDP, reported in IPCC (2001a).

Carbon taxes and investments in carbon and energy efficiency

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,

$$\tau_i = c_\tau \frac{y}{y^0}\, e_i \tag{19}$$

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) (see also discussions by Brown, 1997, Heal, 1997, Nordhaus, 1997, and Hasselmann, 1999).

Individual emissions e_i are related to energy use E_i through the energy-carbon (for short: *carbon*) efficiency f_{ci},

$$e_i = \frac{E_i}{f_{ci}}. \tag{20}$$

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},

$$E_i = \frac{y_i}{f_{ei}}. \tag{21}$$

Assuming the same production-to-physical-capital ratio ν in all physical-capital sectors, the production y_i in sector i is given by product of the total production y and the ratio of physical capital k_i in sector i to the total physical capital (eq.(1)):

$$y_i = \frac{yk_i}{\sum_{i=1}^{3} k_i} \tag{22}$$

The net production output-carbon (*net carbon*) efficiency $f_i = x_i/e_i$, relating production outputs to emissions, is then given by the product of the production output-energy and energy-carbon efficiencies,

$$f_i = f_{ei} f_{ci}. \tag{23}$$

Expressed in terms of the net carbon efficiency (inverse carbon intensity) and overall production, the emission taxes, eq. (19), may also be written as

$$\tau_i = c_\tau \frac{y}{y^0} \frac{y_i}{f_i}. \tag{24}$$

Energy production

To determine the value of energy production v_i in eq.(12), we consider the separate contributions $v_i = v_{fi} + v_{ri}$ 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:

$$v_{fi} = p_f\ \alpha_{fi} E_i \tag{25}$$

$$v_{ri} = p_r\ (1-\alpha_{fi}) E_i. \tag{26}$$

The prices of fossil fuels are assumed to increase with the inverse square of the available resources, $p_f \sim c^{-2}$ (Barth, 2003, on the basis of Rogner's, 1997, extraction-cost estimates and

the fossil-resource estimates of IPCC, 2001b, and Rogner, 1997). The price of renewable energy decreases as the use of renewable energy increases, $p_r \sim \{(1-\alpha_f)E\}^{-2}$, 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). Thus, the energy costs in sector i are given by

$$v_{fi} = \frac{\alpha_{fi}}{\alpha_{fi}^0}\frac{E_i}{E_i^0}\left(\frac{c^0}{c}\right)^2 v_{fi}^0 \tag{27}$$

$$v_{ri} = \frac{(1-\alpha_{fi}^0)E_i^0}{(1-\alpha_{fi})E_i} v_{ri}^0, \tag{28}$$

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

Prices of consumer goods

The prices p_i for consumer goods in eq.(17) depend on consumer preferences. We assume that the goods market is cleared. Given the consumer preferences, this defines the goods prices. 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

$$u_i = A_i \ln(g_i/g_i^c), \quad (i = 1, 2) \tag{29}$$

where g_i is the amount of good purchased (prescribed in our case by the supply), A_i is a demand coefficient, and g_i^c a scale coefficient. A_i and g_i^c can change slowly with time, but may be 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 adapt 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:

$$\frac{du_i}{d\epsilon_i} = \frac{A_i}{p_i g_i} = B = \text{const}, \tag{30}$$

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 $\epsilon = \epsilon_1 + \epsilon_2 = A_1/B + A_2/B$, or $B = (A_1 + A_2)/\epsilon$. Thus, we obtain for the price of goods:

$$p_i = \frac{\epsilon}{g_i}\frac{A_i}{A_1 + A_2} \tag{31}$$

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, cf. Appendix 1). This implies an equilibrium goods production ratio (eq.(31)),

$$\frac{r_{g1}}{r_{g2}} = \frac{A_1}{A_2}. \tag{32}$$

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

Wage costs

The evolution equation (9) for the wage rate $\hat{w}$ remains unchanged, but the expression (11) for the limiting zero-growth, zero-dividend target-wage coefficient now becomes, allowing for the expenses before profits listed in (15),

$$a_w^{max} = 1 - \frac{\lambda_k}{\nu} - \frac{\lambda_h}{\mu_h} - \frac{1}{y}\left\{\delta + \sum_{i=1}^{3}(i_{ci} + i_{ei} + v_i) + z \cdot s\right\} \tag{33}$$

The evolution equations

Given the various product and cost expressions, we can now write down the extension of the evolution equations (7)-(9) of the MADEM-core system required for the economic module MADEM of the coupled climate-socioeconomic system MADIAM (cf. Figure 3):

$$\begin{aligned}
\dot{k}_i &= i_{ki} + \sigma_{ki}\tau - \lambda_k k_i \quad (i = 1, 2, 3) && (34)\\
\dot{\hat{y}} &= \frac{\mu_h}{l}(i_h + \sigma_h \tau) - \lambda_h \hat{y} && (35)\\
\dot{\hat{w}} &= \lambda_w(\hat{w}^0 - \hat{w}) && (36)\\
\dot{f}_{ci} &= \mu_c(i_{ci} + \sigma_{ci}\tau) + \lambda_c f_c \quad (i = 1, 2, 3) && (37)\\
\dot{f}_{ei} &= \mu_e(i_{ei} + \sigma_{ei}\tau) + \lambda_e f_{ei} \quad (i = 1, 2, 3) && (38)\\
\dot{c} &= -e && (39)\\
\dot{s} &= r && (40)
\end{aligned}$$

Equations (34) - (36) are identical to the core-system equations (7) - (9), except for the additional index i in eq. (34), 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 (37), (38) are analogous to the preceding 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 exogeneous technological improvement (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.(39), while the last equation (40) represents the rates of change of the savings s of consumers (equal to the loans of business).

4 MADIAM simulations

The following simulations illustrate the impacts of the control strategies of the principal MADIAM actors on climate change and economic growth. The assumed control algorithms of the different actors are described in Appendix 1 and Weber (2004). The model has been calibrated to reproduce the basic stylized growth parameters of Kaldor (1963), see also Edenhofer et. al (2004). The calibration constants are listed in Appendix 2. The model was 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.

Relevant for the following discussion are not the detailed parametrical forms of the control algorithms, but rather - in the spirit of neural networks - the general structure of the assumed feedbacks. Thus wage-earners, acting as proxy also for business competition, vary the target-wage rate coefficient a_w from a minimal value for low employment levels up to a maximum value given by the zero-profit limit a_w^{max} as full employment is approached. The ratio of the consumer demand coefficients for green and grey goods is assumed to vary linearly with the climate damages. Business applies a successive partitioning algorithm dependent on the employment level, wages, emissions, carbon taxes and the prices of green and grey goods to distribute its net disposable income, after subtraction of damage costs, wages, energy costs and interest payments, between investments in energy and carbon efficiencies, human and physical capital (divided into green and grey consumer-goods sectors) and dividends. Government, finally, imposes and recycles carbon taxes as defined by the coefficients in the system evolution equations (34), (35), (37), (38). 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.

For space reasons we have not been able to demonstrate all features of the model. We have not been able to present some of the interesting synergy and feedback effects arising from alternative, more sophisticated responses of individual actors to the observed or anticipated actions of other actors. Our examples are limited rather to basic cases illustrating the separate first-order impacts of the different actors.

The scenarios are discussed in relation to two basic scenarios, a ‘Business As Usual’ scenario BAU and a reference ’Moderate Mitigation’ scenario MM (Figure 4). The BAU scenario corresponds to a case without a specific climate policy, in which CO_2 emissions increase from 7.0 GtC/year in 2000 to 23.7 GtC by the year 2100. This lies roughly in the middle of the ensem-

ble 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 $c_\tau = 0.005\times$ GDP$_{Europe}$/ GtC for Europe, for example, cf. eq. (24)) and uses 10% of these taxes to improve carbon efficiency, the remaining 90% being recycled into the economy as investment subsidies in human and physical capital. Firms invest 1.0% of production in emission and energy efficiency. Consumers preference ratios of green to grey goods are initially 1:6. CO_2 emissions increase in the MM scenario to 8.3 GtC/year in 2060 and then fall to 7.1 GtC/year by the end of the century. Because of the large inertia of the climate system, the significant reduction in CO_2 emissions relative to the BAU scenario achieved in the MM scenario pays off mainly in the next centuries (not shown).

Despite the significant influence of moderate mitigation on climate already in this century, the changes in economic growth rates are exceptionally weak: the average annual growth rates falls from 2.85% to 2.82% p.a. for GDP, from 2.63% to 2.54% p.a. for dividends, and from 2.80% to 2.76% for the wage rates. The net carbon efficiency, which grows for the BAU scenario only through exogenous technological improvement (eqs. (38), (39)) increases significantly in the MM scenario; the climate damages decrease in accordance with the decrease of emissions and projected global mean temperature change (eq. (18)), and the savings decrease slightly in accordance with the weaker wage and dividend rates (eq. (17)). In summary, significant mitigation of climate change is achieved at a very low economic cost, resulting in a delay in economic growth of only one or two years over a period of 100 years (see also Azar and Schneider, 2002).

As example of the impact of business on the evolution of the coupled climate-socioeconomic system, Figure 5 shows the effects of variations in net business investments in energy and emission efficiency between 0.5% (for a non-climate-friendly scenario 'B-') and 1.5% (for a climate-friendly scenario 'B+') of production, relative to the MM case of 1.0 %. The effect of these changes on the economic growth rates is again weak compared to the impact on climate. The higher investments in net carbon efficiency in the B+ case leads to a halving of CO_2 emissions by 2100, while production, wage rates and profits are reduced by only 3%, corresponding to a growth delay (cf. Figure 4) of the order of a year. Thus, 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.

Figure 6 demonstrates the impact of shifting recycled carbon taxes more strongly into investments in net carbon efficiency. The enhanced mitigation scenario ITC is compared against the reference scenarios BAU and MM. In the ITC scenario, the ratio of recycled taxes invested in net carbon efficiency compared with investments in physical and human capital is set at 50:50, as compared with 10:90 in the MM scenario. The carbon tax rate and all other control parameters remain unchanged at their MM values. Surprisingly, the ITC scenario exhibits not only a positive impact on climate, but also on economic growth: the shift of recycled taxes towards enhanced net carbon efficiency improves the growth rates of GDP, the business profit rate and the wage rate by 2-3%, while reducing CO_2 emissions by 25%. It appears that the 40% enhancement of net carbon efficiency resulting from the increased investments of recycled taxes into net carbon efficiency results in strongly reduced business costs for future energy and carbon taxes, which more than compensates for the reduced investments of recycled taxes into physical and human capital.

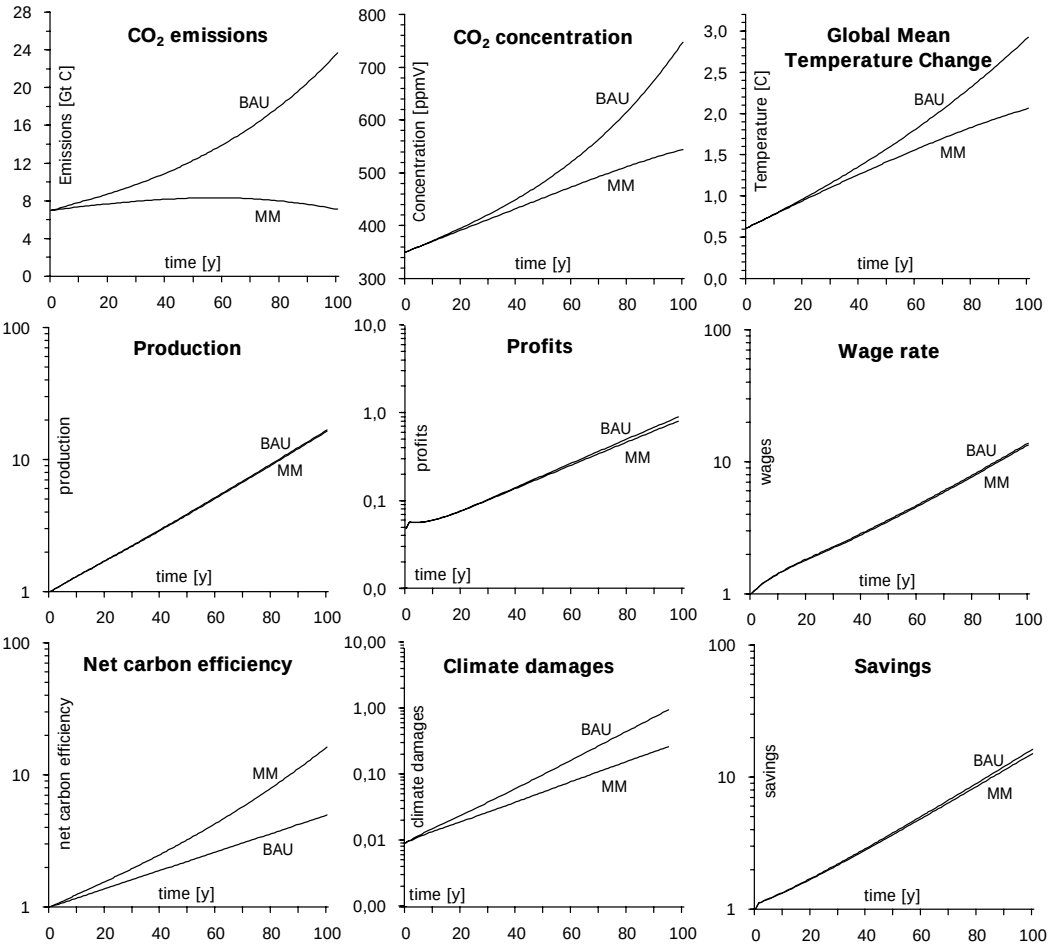

Figure 4: *'Business As Usual' (BAU) and 'Moderate Mitigation' (MM) scenario. Top: global CO_2 emissions, CO_2 concentrations and global mean temperature. Center: production, profits (both normalized on y^0=1) and normalized wage rates. Bottom: normalized net carbon efficiency, climate damages, and savings.*

The influence of consumer preferences is illustrated in Figure 7. The ratio A_1/A_2 of the consumers' demand coefficients for green or grey goods is assumed to be proportional to an initial preference ratio A_1^0/A_2^0, increasing thereafter at a rate proportional to the level of climate damages δ, normalized by the production level (eq. (42), Appendix 1). Shown is the impact of the initial preference ratio A_1^0/A_2^0 for three ratios $A_1^0/A_2^0 = 1/6, 1/3$ and 1. In all cases, the initial goods production ratio was set at $g_1^0/g_2^0 = 1/6$. The impact of consumer preferences on the evolution of climate is clearly visible. There is also a small positive impact on economic growth: the growth rate of GDP rises with increasing demand in good 1 from 2.83% p.a. to 2.93% p.a. This is because a shift from grey to green goods reduces the climate damages without otherwise affecting production costs (there is also a reduction in carbon taxes, but this has little net effect on growth, as these are recycled into the economy).

Another impact of consumers on the economy is the savings rate. Consumer savings are returned

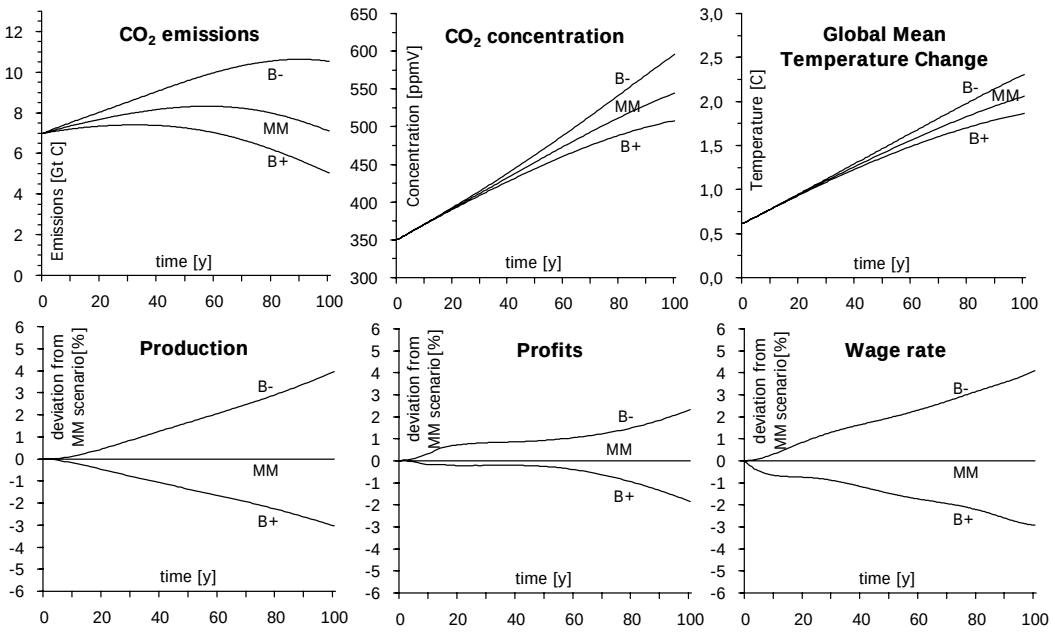

Figure 5: *Impact of different business investment rates in net carbon efficiency (B-: 0.5%, MM: 1.0%, B+: 1.5% of GDP) on climate and economic growth. Top: global CO_2 emissions, CO_2 concentrations and global mean temperature. Bottom: production, profits and wage rates, in percentage changes relative to initial MM levels.*

to business as loans, thereby increasing the net disposable resources available to business, after payment of wages and other expenses (eq. (16)). This is available for various forms of investments, and the provision of dividends. Economic growth can be fueled either directly by retained business profits, which are reinvested by business, or by the return flow to business of consumer savings (and also by the purchase of shares by consumers, but as was pointed out above, this can be absorbed in a renormalization of model parameters). 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 Appendix 1).

5 Conclusions and outlook

From the simulation results of a first version of the multi-actor dynamic integrated assessment model MADIAM presented in this paper, we can draw the following general conclusions:

While all actors are found to exert a significant influence on induced 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

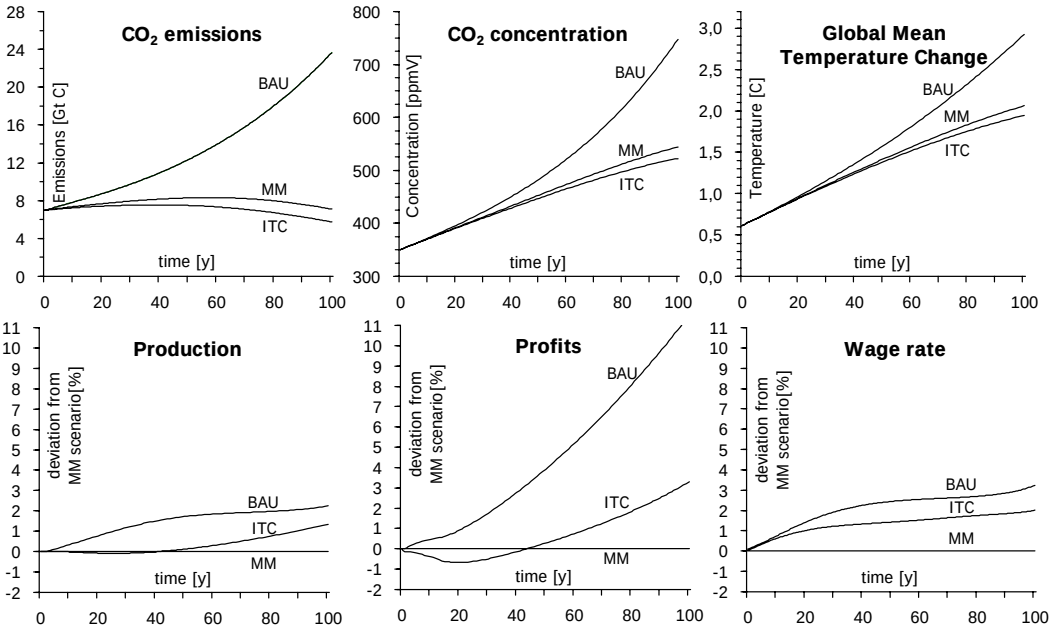

Figure 6: *Impact of different ratios of taxes recycled into investments in net carbon efficiency and human/physical capital (MM: 10:90; ITC: 50:50). Top: global CO_2 emissions, CO_2 concentrations and global mean temperature. Bottom: production, profits and wage rates, in percentage changes relative to initial MM levels.*

uncertain) calibration of our model, and is found also in other studies, e.g. Azar and Schneider (2002) and Edenhofer et al., (2004).

The strongest impact on climate-change is obtained, as expected, from investments of business in increased energy and carbon efficiency. This cannot be separated, however, from government regulation policies in the form of carbon taxes, which have a direct influence on business investment decisions. The manner in which carbon taxes are recycled into the economy is also important. Thus, increasing the fraction of carbon taxes recycled into subsidizing investments in mitigation technologies not only reduces global warming, but also enhances economic growth by freeing business resources, which are then available for investments in human and physical capital. Consumer preferences can also have a significant impact by shifting business investments into green as opposed to grey consumer goods. Not discussed in the present simulations for lack of space were the impacts of stochastic variations, both in climate and technological development, and the synergies and feedbacks arising from various possible responses of the actors to the observed or anticipated control strategies of the other actors. These will be investigated in further studies.

The details of the model response depend on a number of calibration parameters of the basic model dynamics and the actor control algorithms. These include, for example, the response of business to carbon taxes, the learning coefficients of technological change, and the sensitivity of consumer preferences to climate change. In many cases, these are not yet well established. However, the purpose of our simulation exercise was not to provide reliable predictions, but

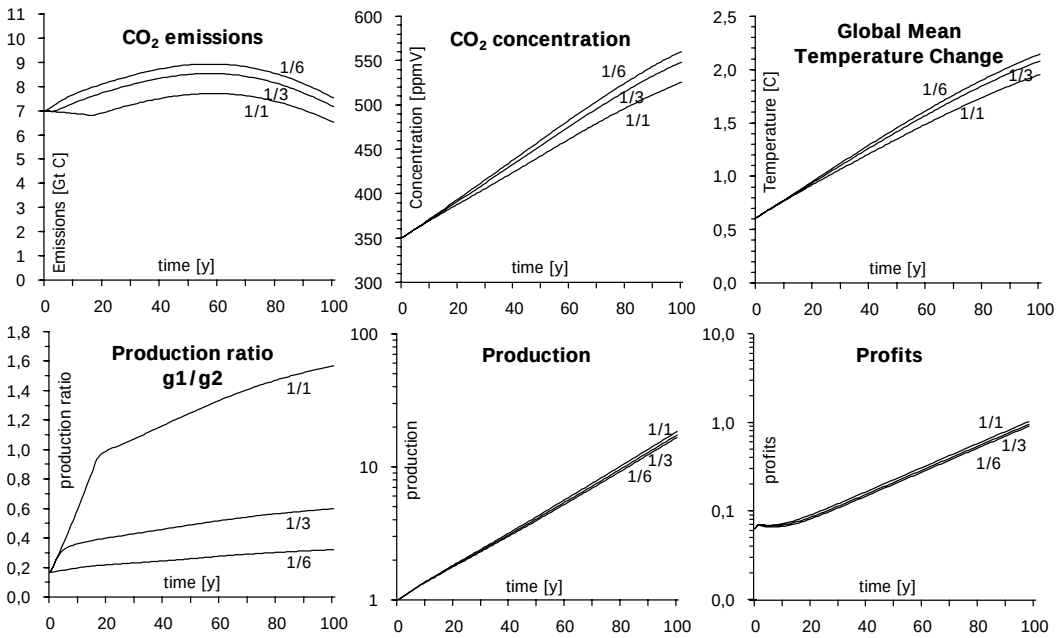

Figure 7: *Impact of different initial consumer goods demand ratios* A_1^0/A_2^0. *Top: global* CO_2 *emissions,* CO_2 *concentrations and global mean temperature. Bottom: ratios of production* $g1/g2$, *overall production, profits, both normalized on* y^0*=1.*

rather to identify the relevant processes and associated parameters of the system which need to be more closely investigated.

More importantly, 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-socioeconomic system in the typical non-equilibrium situation of finite profit rates and structural unemployment associated with investments in human capital (endogeneous technological change), and (2) ultimately 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 competitivity, 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.

Although the model dynamics and actor control algorithms assumed in the present paper suppressed short term cyclic or aperiodic variations, the 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. 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 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. The model can furthermore be readily extended to 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.

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, enabling the investigation of interregional trade, capital flow, technological transfer and regional differences in climate change impacts, welfare, etc. The model is coded in modular Fortran 90, using hierarchial variable structures designed to allow a straightforward extension to a second generation model MADIAM-2 incorporating these features. 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. 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 differ from a CGE in several important respects. Thus, MADEM is driven primarily by the profit motivation of business. This leads to a balance of investments in both productivity and physical capital (see Appendix 1; 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 fueled 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 endogeneous technological change, in combination with the profit motivation of business, represents always the basic driver of economic growth.

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 quantitave 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 provide useful quantitative policy advice.

Acknowledgments

We would like to thank Georg Hooss for providing the NICCS model and support in its application. We are also grateful to Carlo Jaeger and Claudia Kemfert for constructive criticisms and helpful comments.

Appendix 1: Control strategies

The evolution of the system in accordance with eqs.(34)-(40) 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. 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, based only on obvious anticipated control strategies of the other actors. The associated control parameters are listed in Appendix 2, Tables 2 and 3.

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 in Section 2, 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

$$a_w = a_w^{min} + \left(a_w^{max} - a_w^{min}\right) q^{\alpha_q} \tag{41}$$

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

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. The goal of shareholders to maximize time-integrated discounted dividends is assumed to be adequately represented by business (discussed below), which strives to maximize share-holder value by maximizing profits.

Consumers modify the ratio of their demand coefficients A_i for green and grey 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),

$$\frac{A_1}{A_2} = \frac{A_1^0}{A_2^0}\frac{\delta}{\delta^0}\frac{y^0}{y}, \tag{42}$$

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.

Business has the choice of using its net disposable income x' (profits plus credit uptake, eq.(16)) for investments in physical or human capital, i_{ki} , i_h, investments in energy or carbon efficiency, i_{ei} , i_{ci}, or dividends issued to shareholders. Rather than attempting to carry out a detailed cost/benefit analysis of present and discounted future costs, business adopts a simple three-level partitioning strategy.

In the first partioning level 1, business decides on the fractions of the net disposable income x' to be used for capital investments, mitigation measures and dividends, respectively. The decision is guided by two considerations: the results of cost/benefit analyses (Barth, 2003), and the carbon tax level. 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. 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 price signals. Detailed information about the partitioning strategy and the price mechanism can be found in Weber (2004)

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)). The parameters used in our simulations are listed in Appendix 2.

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. (21)
$\sum l_i$	3000.0	employed labour [L]	eq. (1), 3)
$\sum p_i$	3000.0	production [$\$/yr$]	eq. (1), 3)
e	7.0	emissions [GtC/yr]	(IPCC, 2000, 2001a,b)
E	8.4	energy use [GtC/yr]	eq. (20)
α_f	0.833	fraction of fossil energy	(IEA, 2003)
v	300.0	energy costs [$\$/yr$]	
l_{max}	3300.0	available labour pool [L]	1), 4)
q	0.91	employment rate	eq. (2)

1) Basic initialization assumptions (see text for details)
2) We assume an initial k_1:k_2 ratio of 1:6.
3) The initial settings for the individual goods are in accordance with the settings for phys. 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, 2003).

Table 1: Initial values of state (top) and derived (bottom) MADIAM variables.

Appendix 2: Model calibration

The MADIAM model has been calibrated to reproduce the basic stylized growth parameters of Kaldor (1963) (see also Edenhofer *et al.* (2004)). Table 1 lists the initial values of the state variables and other MADIAM variables derived from these 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 $p[\$/G] = (\sum_{i=1}^{2} p_i \cdot r_{gi})/(\sum_{i=1}^{2} r_{gi}) = 1$ for consumer goods (eq.(14)). 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, 2003) is employable. The initial productivity, $\hat{y}(0)$, 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 as well as the initial values of other variables that depend on these. The constants used in MADIAM are listed in Table 2, the basic settings of the control parameters for the MM scenario in Table 3. The changes introduced for the different scenario simulations are described in Section 4.

Parameter	*Value*	*Description*	*Equation*
ν	0.4	production-to-capital ratio [1/yr] (Maddison, 1995)	eq. (1)
z	0.02	interest rate [1/yr]	eq. (17)
D	0.004	climate damages benchmark factor	eq. (18)
T_b	2.0	climate damages benchmark temperature [$^\circ C$]	eq. (18)
dT_b/dt	0.02	climate damages benchmark rate of change of temperature [$^\circ C/yr$]	eq. (18)
λ_k	0.045	depreciation rate of physical capital [1/yr]	eq. (34)
λ_h	0.045	depreciation rate of human capital	eq. (35)
μ_h	0.5	efficiency coefficient for investments in human capital	eq. (35)
λ_c	0.005	exogeneous improvement of f_c	eq. (37)
μ_c	0.0007	efficiency coefficient for investments in f_c [yr/G]	eq. (37)
λ_e	0.005	exogeneous improvement of f_e	eq. (38)
μ_e	0.5	efficiency coefficient for investments in f_e [yr/GtC]	eq. (38)

Table 2: MADIAM constants

Actor	*Parameter*	*Value*	*Description*	*Equation*
Government	c_τ	0.5	tax coefficient [$\$/GtC$]	eq. (19)
	σ_{ki}	0.4	fraction of tax recycled in k_i (i=1)	eq. (34)
	σ_{ki}	0.0	fraction of tax recycled in k_i (i=2,3)	eq. (34)
	σ_h	0.4	fraction of tax recycled in h	eq. (35)
	$\sum_i \sigma_{ci}$	0.1	fraction of tax recycled in f_c	eq. (37)
	$\sum_i \sigma_{ei}$	0.1	fraction of tax recycled in f_e	eq. (38)
Consumers	η	0.05	savings rate [1/yr]	eq. (17)
	$A1$	0.1666	demand good 1 (initial value)	eq. (42)
	$A2$	1.0	demand good 2	eq. (42)
Wage-earners	α_w^{min}	0.66	wage-adjustment parameter	eq. (41)
	α_q	4	unemployment feedback exponent	eq. (41)
	λ_w	0.2	rate of wage adaptation[$1/yr$]	eq. (41)
Business	The business control parameters and algorithms are presented in Weber (2004)			

Table 3: MADIAM control parameters and initial values for the MM reference scenario

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