# The actor-driven dynamics of decarbonization

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## Introduction

Climate change represents an unprecedented challenge in the history of humankind. It requires not only a transformation of the present fossil-fueled global economic system to a sustainable system based on renewable energy, but, equally important, a reorientation of the relations between nations from the present system of individual competition to a global cooperative network of interdependent entities striving to preserve a common habitable planet. Science can facilitate these transitions by analyzing the conflicts of interest and inherent rigidity of perceptions that are presently hindering progress in both areas of transformation. But scientists should investigate not only the difficulties, but should also identify and highlight the most promising paths for overcoming the analyzed hindrances. This is an essential pre-condition for creating the necessary incentives for effective social, economic and political actions.

It is widely believed by climate scientists and environmentalists that the basic technology to achieve a successful transition to a sustainable future is available today, and that it can be further developed and implemented at an acceptable level of socio-economic adjustment cost, ultimately bringing advantages to all. However, while the reality of anthropogenic climate change is now generally accepted, the view that the problem is solvable without large-scale painful disruptions of present socio-economic systems and attendant life styles is not shared by large sectors of the public and many policy-makers. This has hindered the purposeful implementation of the needed climate change mitigation policies. It should be the task of environmental scientists to overcome the self-defeating, wide-spread pessimistic assessment of the climate mitigation task by presenting analyses demonstrating the many win-win impacts of enlightened climate policies.

However, transforming perceptions requires a new actor-oriented scientific approach. The prevalent view of climate policy, following the disappointing outcomes of the Copenhagen (2009) and Cancun (2010) climate conferences, is that we are trapped in a typical “prisoners dilemma” or “tragedy of the commons” deadlock: all countries expect to suffer in various degrees from climate change, but every country strives to shift the perceived burden of mitigating dangerous future climate change to other countries. The result is inaction or delay, which - through the inexorable dynamics of climate change - we cannot afford.

It is well-known from the many theoretical and empirical analyses of different variants of the prisoners dilemma game that the key factor determining the outcome of the game - if we can refer to the survival of today’s human civilization as a “game” - is the players’ understanding not only of the overall structure of the game, but, more importantly, of the different perceptions and motivations of the individual players. This understanding includes, in particular, the feedback interactions between the players that can lead to a change of the individual players’ perceptions and motivations. The ability of each player to understand and respond to the actions of other players is ultimately the key to resolving the prisoners’ dilemma problem.

Thus, we argue that an improved common understanding of the principal drivers of the individual participants in climate policy negotiations is a necessary condition for overcoming the present climate policy deadlock. An important component of this common understanding is the identification of win-win strategies that will bring an advantage to all participants. Once these are recognized, and the necessary trade-offs and transfers invariably required to achieve an equitable solution for all participants have been quantified and negotiated, a common climate policy can be agreed upon and implemented. The joint efforts involved in achieving a common understanding will also contribute to generating a higher level of mutual trust, an important factor in overcoming the present prisoners' dilemma deadlock, which is largely based on misunderstanding and mistrust.

A contributing factor to the present climate policy deadlock is the mismatch of scales (in time and space) between the components of the natural climate system and the political and socio-economic factors relevant for climate policy. While the characteristic time scale of the natural climate system is of the order of decades to centuries, the time horizons of political decisions are strongly dependent on election cycles of typically four years. It is often remarked that political decisions therefore tend to be driven by the needs of today without sufficient regard to longer-term issues. However, this view presupposes that politicians are restrained by the shorter term views of the electorate on which they depend. If, in contrast, the electorate has a more progressive longer term view than their currently elected representatives, the flexibility afforded by short election cycles enables, in fact, a more rapid response of the political system to the longer term demands of a planet in stress. Thus, the key for a successful long term climate policy is ultimately the education of the public via science, civil society organizations and the media.

We must also recognize that political decisions are necessarily directly governed by the prevailing value system. We decide on policies and take action under the values that are accepted today, extending them into the future, even though future generations may be far more concerned about things that are of less importance for us today. The inter-temporal mismatch in value systems is directly linked to an important economic parameter, the rate of discounting that we apply in our models. With discounting we assume that $1 today costs more than $1 a year later. The logic is that if properly invested, the $1 today can generate $10 in 10 years. Therefore it is more important to have the money now, than later. The chosen discount rate tells us how much more important. However, this simplified view needs to be differentiated with respect to the use made of the one dollar. Thus, it has been argued that in order to reconcile sustainability with inter-temporal discounting, discount rates should depend on the spatial, temporal and structural scale of the system being analyzed.

In addition to the different values attached by present and future generations to the same object (for example, the future environment) the present generation also applies different discount factors to different objects. Thus investors typically apply high discount rates in the development of companies (e.g. Bill Gates in the case of Microsoft) but often support government or private investments at low or zero discount rates in the pursuit of public goals (e.g. the Belinda and Bill Gates Foundation).

The intergenerational aspect becomes especially acute when deciding on the role that different countries should play in climate mitigation. For example accounting for cumulative emissions instead of current emissions of CO2 can change the relative impact that various countries have played in creating the current climatic situation (Hansen, 2011). Should the present generations be responsible for the impact that previous generations have had on our climate? Should these long-term considerations be part of the current debate about CO2 quotas?

These distinctions are not reproduced in most economic analysis, where inter-temporal costs and benefits are simply weighted by a (usually relatively high) constant discount factor. If we use conventional exponential discount rates, even very low ones, catastrophic events that occur far enough in the future are essentially irrelevant today. Some economic analyses of global warming discount the future at rates as high as 6% (IPCC, 1996). At such rates, we would not spend $2500 today to prevent a $30 trillion dollar loss (the approximate gross global product today) in 400 years (Voinov and Farley, 2007) [1]. In most cases, developing appropriate policies can be directly linked to changing the preferences and prevailing value systems, in which case unpopular and inconvenient solutions suddenly turn out to be acceptable and even beneficial.

As pointed out, if scientists are to support efforts towards an improved common understanding, a new approach to the modeling of the coupled climate-socio-economic system is called for. Required are models that, firstly, focus on the dynamics of complex systems controlled by the strategies of individual actors pursuing different, often conflicting, goals, and, secondly, apply realistic representations of the different value systems and perceptions underlying the strategies of the individual actors.

The first point requires replacing the main-stream computable general equilibrium (CGE) models that have been used in traditional integrated assessments (IA) of climate change policies by system-dynamic, multi-actor models. The efficient-market paradigm underlying the CGE models assumes that the evolution of the economy is governed by a benevolent “invisible hand” that simulates the net effect of market forces. The invisible hand automatically ensures an optimal economic growth path that maximizes an abstract inter-temporal global utility function. In contrast, multi-actor models simulate the dynamical evolution of an economic system governed by the different strategies of individual actors striving to maximize individual “utility” functions that are often in direct conflict. The individual actor strategies depend, in turn, on the assumed strategies of the other actors. This can lead to very different evolution paths, including bifurcations, periodic fluctuations, instabilities, and various forms of breakdowns and crises, but also periods of stable growth, or steady state depending on the assumed goals, strategies and interactions of the actors.

Multi-actor models thus belong to the general class of system dynamic or evolutionary socio-economic models (cf. Meadows et al, 2004, Beinhocker, 2006), which focus on a set of possible trajectories of the system, rather than on an assumed optimal growth path or equilibrium state. The dynamics in such systems are normally described by a set of coupled ordinary differential (or difference) equations dependent on a number of system parameters. Essential for a closed description of the system dynamics is then the definition of the strategies of the various economic actors that govern the production and distribution of the outputs of the economy. While in system dynamic models these strategies are usually assumed and fixed in form of scenarios, the emphasis of actor-based models is on the dependence of the system dynamics on the assumed actor strategies. How do changes in actor behavior or priorities translate into the dynamics of the system? Which actors have an important role and which have less impact on the system output? What are the limits of system resilience, how far can we push the system without causing its collapse or run-away? These analyses determine the *structural sensitivity* of the model (cf. Section 6 below), as opposed to the *parameter sensitivity* considered in standard model analyses.

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[1] Despite longstanding criticisms of the application of constant discount factors in evaluating future climate damage (cf. Hasselmann et al,1997, the subsequent editorial comments of Nordhaus , 1997, Brown 1997, Heal ,1997 and the reply by Hasselmann , 1999) main-stream economists (e.g. Tol, 2007, Nordhaus , 2007, have recently invoked high constant discount rates to criticize Stern’s (2007) estimate (using a low discount rate of 1.4%) of the high costs of long-term climate damages.

We note in this context that we use the terms “multi-actor” or “actor-based” in the sense of Weber et al (2005) and Hasselmann and Kovalevskly (2011) to apply to a relatively small number of key decision-makers, such as governments, firms, consumers, the media, the voting public, etc. The concept “actor”, representing a human economic participant, should be distinguished from the more general term “agent” as used in “multi-agent” or “agent-based” models, which normally refers to a large number of agents - typically several hundred or thousand - of a given type, and which can represent any element of a model, human or otherwise, interacting with other elements via some well defined algorithm (Pahl-Wostl, 2005, Tesfatsion, 2006, Janssen and Ostrom, 2006, Farmer and Foley, 2009) . We do not address the interesting question of whether the predictions of multi-agent models can be expected to confirm the predictions of simpler actor-based models, or whether they will yield “emergent properties” that differ significantly from a straightforward replacement of the averaged impact of an ensemble of agents by the impact of an averaged agent (Beinhocker, 2006). This is related to the question of the structural sensitivity of a suite of models (cf. next section).

Directly coupled to the question of the value systems mentioned above is the choice of metrics used to evaluate the performance of a socio-economic system. The prevailing main-stream value systems typically favor the use of GDP (Global Domestic Product) as a single measure of economic output. GDP measures the total market value of all final goods and services produced within a country in a given period. It is an indicator of economic activity. However, it has been shown in numerous studies that GDP is not a good indicator of actual welfare or life quality and that the introduction of more realistic socio-economic variables that are able to capture the true value of economic output with respect to the well being of people (Daly and Cobb, 1989; Stiglitz et al., 2008; Berik and Gaddis, 2011) can entirely change the policy-making landscape. Although this question has received considerable attention in the socio-economic literature, in particular in relation to environmental and social issues, it has not, in our view, been adequately addressed in the context of the integrated assessment of climate change. Thus many of the misconceptions mentioned above regarding the costs of climate change mitigation stem from cost-benefit analyses based on an uncritical application of GDP in measuring both costs and benefits.

We develop our analysis in Section 3 by first introducing multi-actor models based on standard stable-growth paradigms. These are then subsequently replaced by more realistic formalizations, including actor-based instabilities and the dynamics of information-transfer processes. In Section 4 we turn then to the impact of more general welfare measures. However, as background, we first offer a few general comments on our approach to modeling complex systems.

## Model families

The transformation of the present fossil-based global socio-economic system into a sustainable low-carbon system, although widely seen as the greatest challenge facing humankind today (IPCC, 2007; Stern, 2007), is not the only major global problem societies are struggling to resolve. Most of these are strongly interconnected. Thus climate change is inseparably intertwined, for example, with the problems of biodiversity, worldwide poverty, north-south inequalities, food availability, shortages of water and other resources, migration pressures, and the potential of armed conflicts on regional or even larger scale. It is clearly impossible to develop a realistic world model that encompasses all of these interacting processes. Thus any model must be based on major simplifications. The model must specify the subset of processes that are included within the model, while defining the remaining processes that are prescribed as external boundary conditions, or are treated as still simpler sub-systems coupled to the main model.

Clearly, there exist a vast variety of such possible basic models. In view of the rather arbitrary nature of the choice of the processes included in the model, and the potential significance of the excluded processes, there appears to be little justification for representing the processes included in the model in great detail. Rather, it is more meaningful to start with a small set of particularly simple models. Once the dynamics and interrelations of the members of the model set are properly understood and, where possible, tested against data, one can successively introduce more complexity (Figure 1).

While it can be quite difficult to find appropriate quantitative data for testing aggregated models, the real power of these models is for studying the qualitative system dynamics, understanding the trends and learning what can be expected from the system under various control scenarios. Ideally, we expect to be able to maintain these qualitative features in the more complex models that we build further on, when we add more detail and realism into the system representation. However, this is rarely investigated, and in most cases each next level of complexity is treated independently and with no hierarchical connection to the previous levels of simpler models. Moreover, by changing the structure of the model we can very easily switch from one type of dynamics to another. This makes it all the more difficult to understand and track the evolution of model behavior through a complex tree of models (Voinov, 2008).

Ultimately, the degree of complexity that is still acceptable will be limited by the availability of data to test the models, or even - if one ignores the desirability of validating the models empirically - by the limited theoretical feasibility of critically testing the model concepts in the face of too many adjustable model parameters.

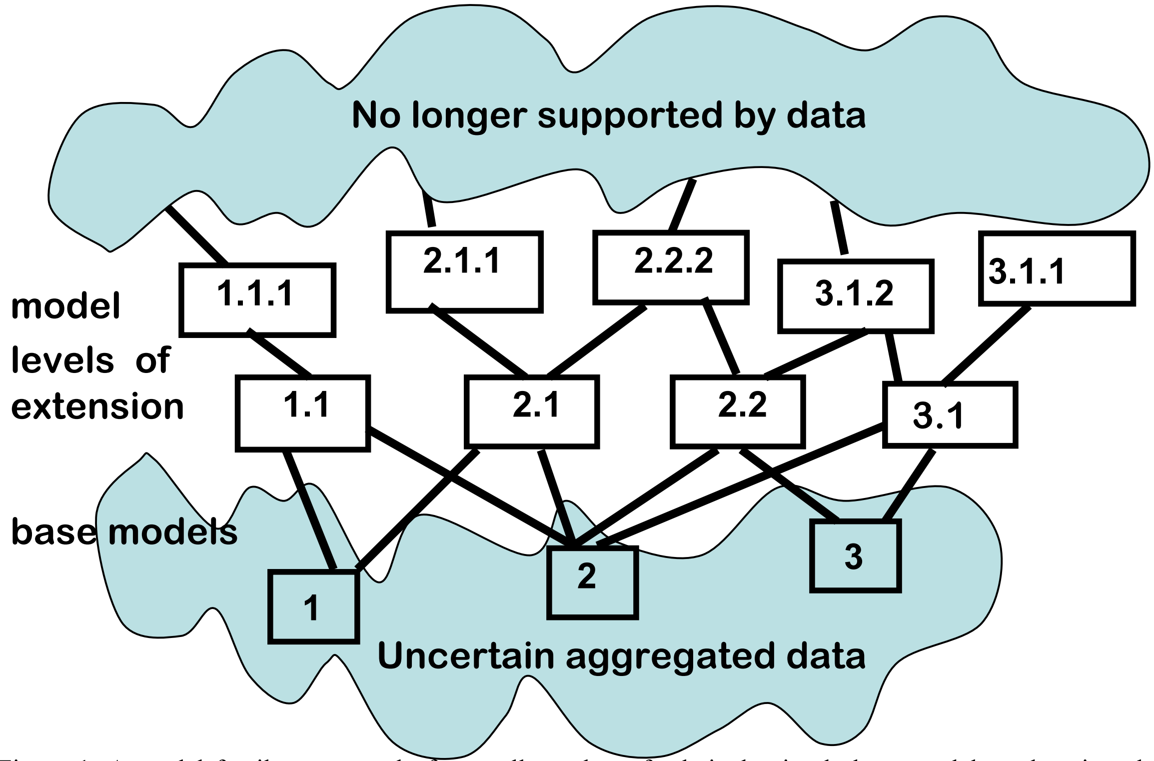

Figure 1. A model family composed of a small number of relatively simple base models and various levels of more complex extensions. On the high end, the acceptable level of complexity is ultimately limited by the data available to test the models and the number of model parameters and variables that we can keep track of to understand how the model

performs - and that can be tuned to reproduce the desired system dynamics. On the low end, data for testing aggregated system dynamics is also limited, so that here we usually have to stay on the level of qualitative trend analysis.

The development of a hierarchical family of models clearly offers the potential of providing a greatly broadened understanding of the dynamics of complex systems. However, it also requires the application of a more extensive sensitivity analysis than in the case of a single detailed model. In addition to the standard sensitivity test of the individual model members with respect to the model parameters, the complete model family, as an interconnected system, must be tested with respect to its overall structural sensitivity: Are the conclusions inferred from one member of the model consistent with the conclusions derived from other models of the family? And can the independent conclusions drawn from different members of the model family be meaningfully combined into a consistent overall picture?

In the following section we investigate a family of multi-actor models of varying complexity, in which the focus of the individual models is on the strategies of various combinations of actors governing the evolution of the coupled climate-socio-economic system. In the subsequent section we then apply a structural sensitivity analysis to the set of model outcomes. This leads to the identification of a number of key factors controlling the implementation of effective climate policies. It also emphasizes the need to evaluate integrated assessments of climate policies using more realistic multi-component measures of the real welfare value of economic output than the traditional use of GDP as single aggregate production variable. The changed perceptions resulting from a more realistic assessment of the multi-faceted impact of climate policies and a better understanding of the goals and motivations of the key economic actors and decision-makers involved in climate policy-making then lead to a clearer recognition of the many inherent win-win opportunities of far-sighted climate policies.

## Multi-Actor models

We consider three different versions of system-dynamic, multi-actor models of the coupled climate-socio-economic system. The dynamics of the various model versions are governed by the strategies of a number of key economic actors pursing different - generally competing - goals. In the first two models the economic actors consist of an average firm, an average household, a government, and a central bank. The models differ in the representation of the climate system coupled to the socio-economic system and in the assumed market dynamics. The third model includes, in addition to the economic actors of the first two models, further actors involved in the transmission of information: scientists, the media, the public and politicians. The motivation for the extensions of the third model was to investigate the role of the multiple time lags induced through the necessary communication from scientists to policymakers via the media, special interest groups and the public, and the additional time lags involved in formulating, negotiating and implementing climate policy. These multiple communication levels, with associated time delays, must be traversed before the scientific knowledge of climate change can be transformed into effective climate mitigation action.

All members of the model family are based on the same interaction structure of the three main constituents of the coupled climate socio-economic system (Figure 2): a climate module describing the climate change induced by human activities as well as the back-interaction of the changed climate on the socio-economic system, and a socio-economic module composed of a government component that establishes the framework under which the second component, the market economy operates.

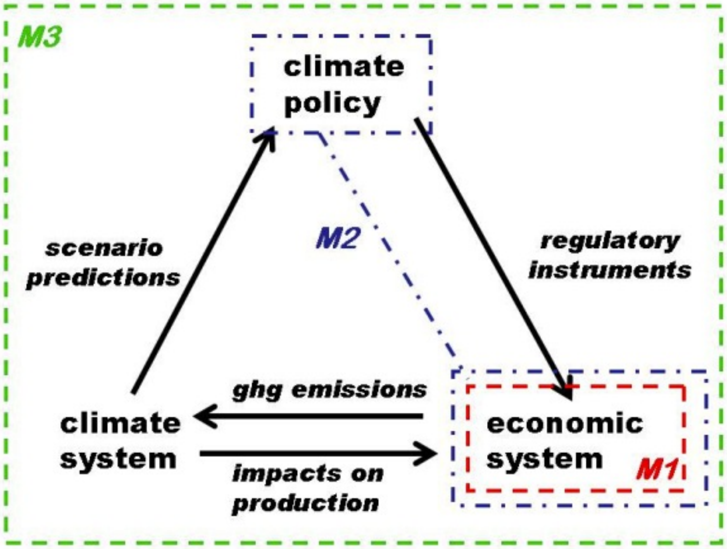

Figure 2. Basic interaction structure of the three members of the model family. In the notation of Figure 1, the base model is an economic module M1, which is extended at the next model level M2 to include role of governments and at the next higher model level M3 to include interactions with the climate system. The first two members of the model family belong to the model system MADIAMS and are based on similar representations of the base model M1, while the third model system is built on a generalized base model M1 emphasizing the role of information transfer.

The first two models belong to the model system MADIAMS (Multi-Actor Dynamic Integrated Assessment Model System), described in detail in Hooss et al (2001), Weber et al (2005) and Hasselmann and Kovalevsky (2011). Emphasis in these models is on the dynamics of the economic market. While the first model embraces the conventional economic paradigms and indicators of stable growth, the second model introduces instabilities arising from different forms of non-equilibrium actor behavior. The third model starts from a somewhat different base model emphasizing the role of the various actors involved in the communication of information, while the representation of the economic system and its interaction with the climate system is appropriately simplified. An aggregated view of the different perspectives offered by the three model versions will be developed in Section 6, after presentation of the simulation results of the three models in the following two sections..

## The Multi-Actor Dynamic Integrated Assessment Model System (MADIAMS).

The base model M1 of MADIAMS consists of an economic-market model characterized by two circulation systems (Figure 3): a goods circulation system and a money circulation system.

The goods circulation describes the production, distribution and depreciation or consumption of three types of goods: physical capital, human capital and consumer goods and services. A Leontief (1941) production function is assumed, in which the level of human capital determines both the amount of physical capital and the amount of labor needed to produce a unit of output. Human capital summarizes the net effects of technological know-how, education and training, social institutions, culture, etc on productivity. For a Leontief production function, in which physical capital and labor are not substitutable, human capital can be simply equated with labor productivity, or, equivalently, with physical capital productivity. Human capital is the single parameter that determines the efficiency of the economy, both with respect to labor and capital. Thus, for stable growth, characterized by full labor employment and full capital deployment, investments in human and physical capital must be appropriately matched.

With the exception of fossil-fuel reserves, natural resources, the fourth basic input of a realistic economic growth model, are not included in the model. Thus aspects of "limits to growth" associated with finite non-fossil natural resources (Meadows et al, 1979) are not considered. We remain here within the conventional economic growth paradigm, the model focusing on the impacts of climate policy on the energy sector.

The goods circulation system is accompanied by a parallel money circulation system. In contrast to the goods circulation system, this is source-and-sink-free, with the exception of the creation of money by the central bank, which strives to match the level of money in circulation to the increasing level of physical goods production.

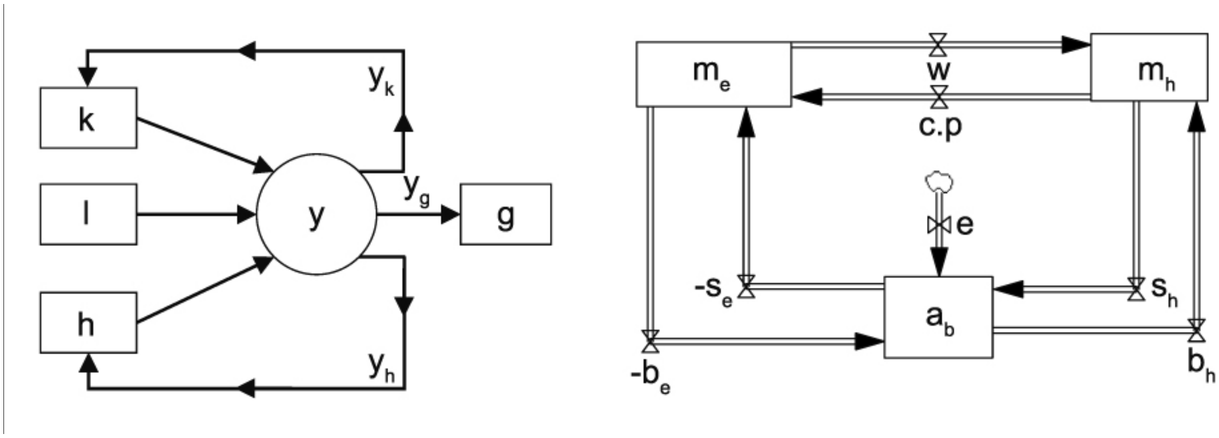

Figure 3. The circulation systems for goods (left panel) and money (right panel) for the base model M1 of the MADIAMS model family. The total production y (left panel) depends on the availability of physical capital k, human capital h and labor l. The physical output is divided into investments in physical and human capital ($y_k$ and $y_h$) and the production of consumer goods and services ($y_g$). The right panel shows the flows of money as wages (w), saving rates ($s_e$, $s_h$ ), interest ($b_e$, $b_h$), consumption (c.p) and money creation e by the central bank, that together determine the money reserves of enterprises ($m_e$, representing firms or governments), households ($m_h$ ) and the central bank ($a_b$). Details are given in Weber et al. (2005).

The evolution of the economy is governed on the one hand by the decisions of firms regarding the distribution of the net output of production between physical capital, human capital and consumer goods and services (modified by decisions on how much to borrow from banks, save or distribute as dividends). On the other hand, it depends also on the consumption and saving behavior of households. The decisions of both types of actors depend, in turn, also on the wage levels negotiated between firms and wage earners (households). Simulations with the MADIAMS model M1 (cf. Hasselmann and Kovalevsky, 2011) illustrate the pronounced sensitivity of the economic evolution with respect to the assumed strategies of the actors with respect to these various decision options (which cannot be simply subsumed in the global power of the invisible hand).

In the extended versions M2 and M3 of MADIAMS, the basic economic model M1 is augmented through the inclusion of the climate system and, as an additional actor, governments. The climate system is computed using a so-called nonlinear impulse response model that can be run on a personal computer (Hooss et al, 2001). The model is calibrated against the computed response (using a super-computer) of a state-of-the-art three-dimensional coupled ocean-atmosphere-carbon-cycle climate model to increased greenhouse gases. For the small climate changes (relative to the mean state) relevant for anthropogenic global warming, the impulse-response model is able to capture the same level of detail as the full climate model.

The extended model includes a broader choice of options for the actors. Thus governments must decide on the regulatory framework for climate change mitigation (the carbon price and subsidies for renewable energy technologies), while business can choose between the investment of physical capital in renewable or conventional energy technology. Similarly, households can choose between buying (more expensive) low-carbon-footprint goods or high-carbon-footprint goods. This feeds back, in turn, on the prices and production rates set by firms for the two types of consumer goods.

Figure 4 shows as example the impact of three different levels of climate mitigation policies on the evolution of selected climate and economic variables. The simulations were based on a relatively low effective discount factor for future climate damages (comparable, for example, with the values assumed in Hasselmann et al, 1997, or Stern 2007) . However, since the actors did not carry out a formal inter-temporal optimization, this was reflected only indirectly in the instantaneous investment strategies of the actors.

Striking is the pronounced difference between the large impact of mitigation policies on the projected climate change and the relative minor impact on the growth of typical economic variables. The computations are consistent with similar estimates by other authors (e.g. Azur and Schneider, 2002; Stern, 2007 ), who conclude that effective climate mitigation policies that avoid dangerous climate change can be implemented at a cost of about 1% of GDP. This corresponds to a delay in economic growth over a period of 50 years of a few months to a year - clearly an acceptable insurance premium to avoid the risks of major climate change.

The explicit representation of the individual strategies of key economic actors enables a focus on the interactions between government policies and the differentiated responses of individual actors to climate policies. The multi-actor approach thereby overcomes one of the principal shortcomings of traditional CGE models, in which the differentiated response of several actors pursuing divergent goals is subsumed in the formal optimization of a single utility function dictated by the "invisible hand" of market forces. However, another limitation of CGE models was not removed in Weber et al (2005), namely the inability to reproduce the inherent instabilities that can arise in dynamical systems dependent on the behavior of several interdependent actors. This limitation of the main-stream efficient market paradigm became very evident in the non-predicted major global financial crisis of 2008 with the ensuing global recession.

The lack of instabilities in the economic growth curves in Figure 4 is due to the assumption of cleared markets for consumer goods and services in the original MADIAM model of Weber et al (2005) (the non-saturated exponential form of the growth curves is due, in turn, to the afore-mentioned assumption of unlimited non-fossil natural resources). By retaining this important assumption of CGE models, a number of potential instabilities associated with imbalances and feedbacks in supply and demand were suppressed. This restriction has been removed in an updated version (Hasselmann and Kovalevsky, 2011) of MADIAMS (an S, for “System”, has been added to the acronym to indicate that the various model versions represent members of a model family). In the updated economic module M2, imbalances in supply and demand are no longer cancelled instantaneously, but generate rates of change in supply (S), demand (D) and price (P) dependent on the actors’ response to the imbalances.

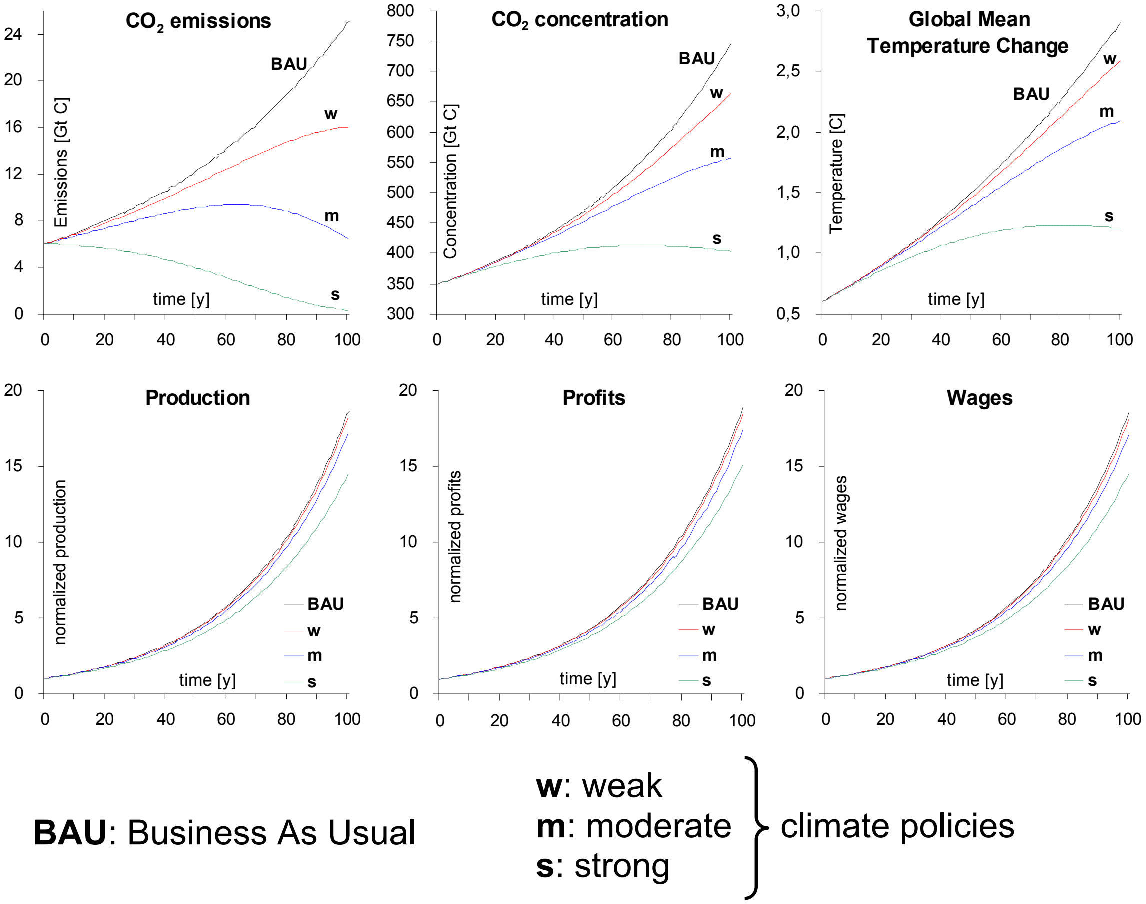

Figure 4. Computed climate variables (top panels) and typical associated economic variables (lower panels) for weak, moderate and strong climate mitigation policies, computed with the M3 model of MADIAMS (from Weber et al, 2005). Note the strong discrepancy between the major impact of climate policies on climate change and the relative weak impact on economic evolution compared with the business-as-usual (BAU) case in which climate damages are ignored. (We argue later in Section 6, however, that the more relevant view, using more appropriate measures of net socio-economic welfare than the variables GDP, profits and wages shown here, is not the low economic *cost* of climate change mitigation relative to the BAU case, but rather the high *gain* in socio-economic welfare.).

The resulting set of three coupled dynamical equations for the variables S, D and P can yield solutions representing a relaxation to a stable equilibrium, as described in standard economic textbooks, but also, depending on actor behavior, to solutions representing periodic business cycles (Figure 5), or a sequence of strongly nonlinear boom-and bust events (Figure 6). Details of the dynamics are described in Hasselmann and Kovalevsky (2011).

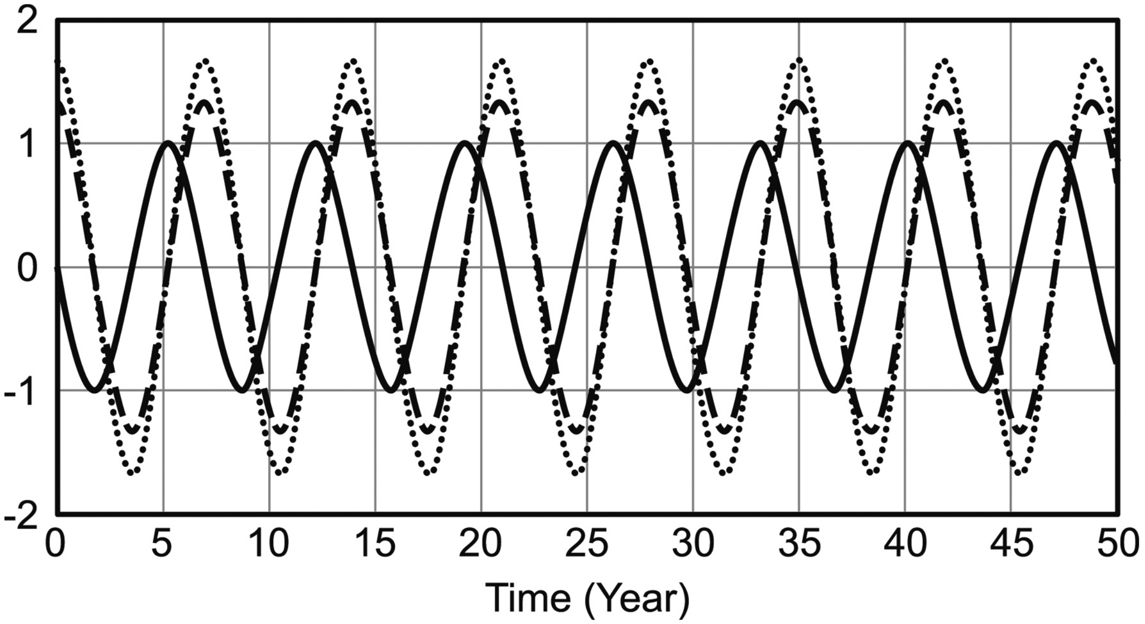

Figure 5. Periodic variations of the perturbations in supply (full line), demand (dashed) and price (dotted) in a typical linearized business cycle. (The perturbations represent deviations relative to the mean growth curves for the stable case of a cleared market for consumer goods and services.)

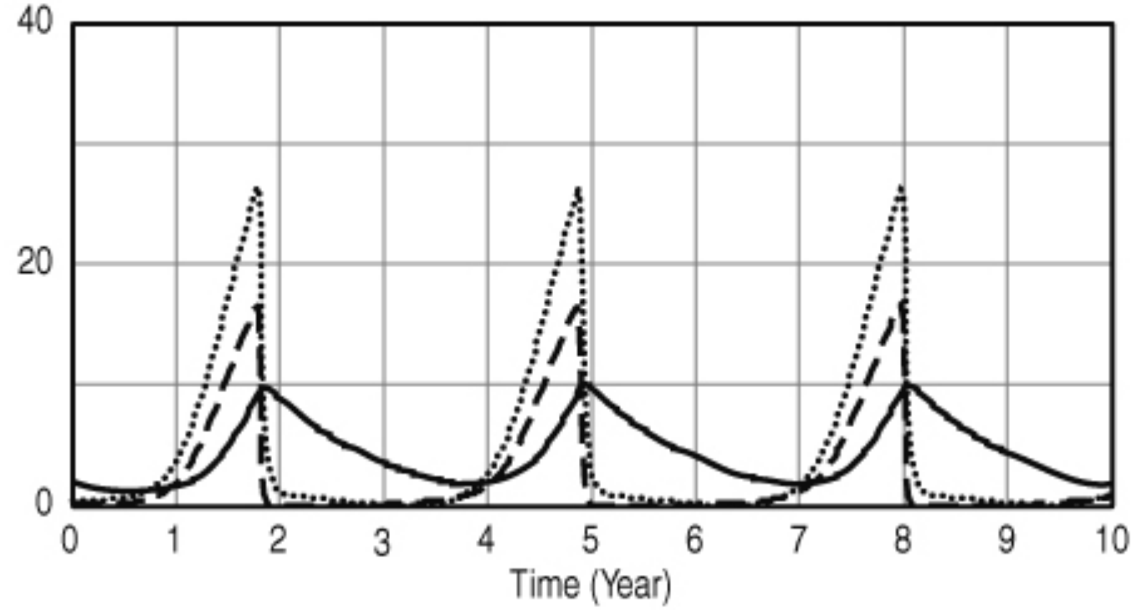

Figure 6. Exponential growth followed by sudden decrease in the values of supply (full line), demand/10 (dashed) and price (dotted) in a strongly nonlinear boom-and-bust cycle. Note the different scales of supply and demand. The price curve, which has different dimensions, is scaled independently. Whereas price and demand are strongly coupled via the positive feedback of herding, supply responds with more inertia. r Details are given in Hasselmann and Kovalevsky (2011).

Periodic business cycles result if the response of firms to reduced demand is not to reduce prices (as assumed in the efficient market paradigm) but rather to reduce supply by laying off workers. This feeds back, in turn, to lower demand of the affected households. Taken alone, this positive feedback would produce either a market collapse, in which all three economic variables decay exponentially, or (for initial conditions of opposite sign) an exponential growth until full employment is attained. This positive or negative exponential behavior can be converted into a periodic business cycle if there exists in addition a countering negative feedback process. An example could be a depression in wage levels as the employment level sinks, thereby stimulating more employment and countering the tendency to lay off workers as the demand decreases.

Boom and bust events characteristic of financial markets arise through herding behavior of investors. If the price of an asset is rising, the logic of the efficient-market paradigm assumes that the demand for the asset will fall. In fact, however, an investor is inclined to speculate that the price will continue to rise. Influenced by the similar thinking observed in other investors, investors in general become more rather than less inclined to buy. The herding speculation of investors then does indeed drive the price still higher. The boom finally breaks when investors begin to become nervous at the excessive price-to-earnings ratio of the asset. At the first sign that the boom is reaching a peak (for example, through a negative second time derivative of the price curve), investors start selling, and a rapid collapse sets in.

The simulation of these instabilities in a system-dynamic, actor based model is relatively straightforward. But do the instabilities have an impact on long-term growth relevant for climate mitigation policies, and need they therefore be included in a realistic assessment of climate policies? The answer to this question is strongly dependent, first, on one's measure of welfare and, second, on the form in which the instabilities are embedded in the full system.

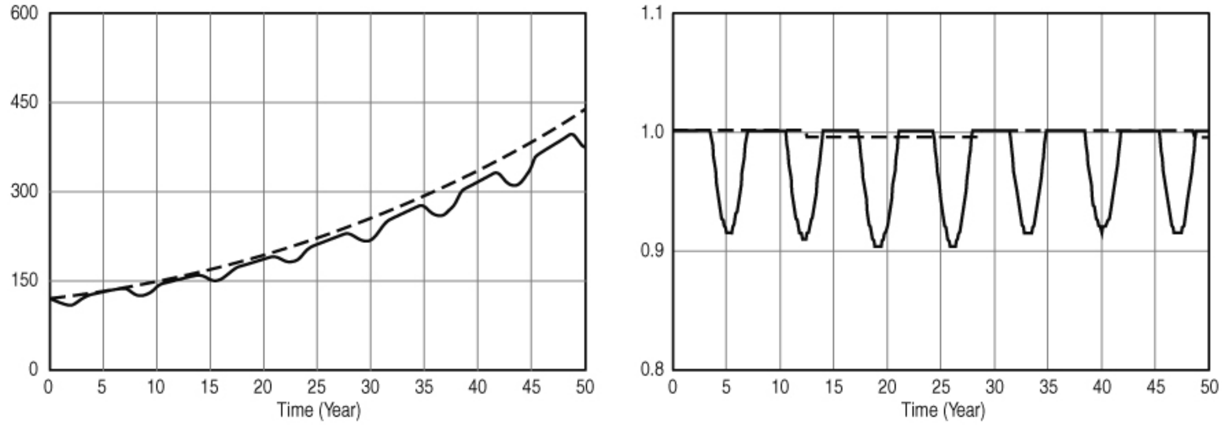

Figure 7. Comparison of GDP growth (left panel) and employment level (right panel) with and without inclusion of business cycle instabilities (from Hasselmann and Kovalevsky, 2011).

Figure 7 shows a comparison of the impact of a relatively small superimposed periodic business cycle on the long term GDP growth (left panel) and employment level (right panel). In the absence of nonlinearities in the system, the mean curves with and without a business cycle would be identical. The principal (clearly visible) nonlinearity responsible for the lower mean levels in the business-cycle case is the upper bound $q<1$ of the employment level q.

The weak impact of business cycles on the mean GDP growth could perhaps be regarded as acceptable economically, but a depression of the employment level by 5% in the mean, and 10% in the maximum of the cycle, is clearly much less acceptable socially. This points again to the need for a more relevant set of economic parameters for the measurement of socio-economic welfare than the single variable GDP.

In the case of boom-and-bust events, the strongly nonlinear character of the process implies a far greater disruption in the economic sectors affected than associated with typical business-cycles. The impacts on longer term global growth depends then, of course, on the number and scale of the economic sectors involved. These can range from regional housing markets to the global financial crisis of 2008.

Although the example shown in Figure 7 illustrated only the role of “animal spirits” of private investors (cf. Akerlof and Shiller, 2009), there exists generally a strong interaction between government fiscal and monetary policies and the investment strategies in the private sector. Regional instabilities resulting from inadequate government policies can then be rapidly projected onto the global scale. This was dramatically illustrated in the latest global financial crisis, which, although dependent on many factors, was widely seen as being triggered by the - basically laudable - promotion of home-ownership within the US through the semi-governmental agencies “Fanny May” and “Freddie Mac”.

Thus, for a realistic analysis of both regional and global climate policies, integrated-assessment models need to simulate the interdependent strategies of both government and private-sector actors, and to represent these within a system-dynamic model of the coupled climate-socio-economic system including interactions between the financial and real-economy sub-systems on both regional and global scales. The simulation of coupled actor behavior, including herding and the mutual strategy anticipations of investors and governments, is particularly important in modeling the dynamics of the transition from a fossil-based to a decarbonized economy

These considerations point to several directions in which the simple MADIAM model reviewed in Section 3 needs to be extended in order to create a realistic model family suitable for quantitative integrated assessment studies in support of climate policy (the models remaining, however, within a level of detail that can still be tested against data, cf. Figure 1). In addition to including actor-generated instabilities as discussed in the previous section, a more realistic model family would need to be generalized to a higher-dimensional set of actors representing several economic sectors, geographic regions and household-income levels.

In particular, when extending the model to several regions, we cannot ignore the very uncertain and often vague knowledge of the distribution of power in the real world. The formal façade of policy-making can differ significantly from what really drives decisions and policies. For example, the fact that much of the US government has very close ties to and is constantly influenced through lobbying and direct financial contributions from powerful corporations clearly questions any analysis based on purely objective concepts about the flow of information in the system (Taibbi, 2011). What models can do is produce baseline scenarios, which assume a balance of power according to the existing constitutional and organizational norms. Any departure from those scenarios could be further analyzed from the point of view of the driving forces that bend and distort the rules, producing the irregularities of real policy-making. Thus, if in spite of the very clear message that climate mitigation can actually be benign or even advantageous for socio-economic development, US policy makers choose to ignore climate change and portray climate science as a hoax, then this clearly indicates that scientific analysis and striving for the public good are not the only drivers of governmental decision making (cf. Hoggan, 2009, Dunlap. and McCright, 2010, Hoggan, 2009, and references cited therin).

As a first step towards a more realistic description of the information flows involved in climate policy formation and implementation, the models need to capture the influence of other actors than those of standard main-stream economic theory. This is addressed in the following section. We apply, however, a highly simplified and perhaps idealized representation of the influence of special-interest groups on decision making.

## 5. The transmission and delay chain from initial information dissemination to final climate-change mitigation.

We consider in the following the various actors engaged in the creation and dissemination of information and the subsequent negotiations and decision-making processes leading to the formation and implementation of climate policies. The actors form a chain extending from scientists, the media, the public, civil society organizations, special-interest groups to policy-makers and, finally, firms. Each link in the chain is associated with time delays and distortions which must be understood in order to implement an effective climate mitigation policy, since the entire process of transforming the present global socioeconomic system to a sustainable future system must be achieved within the limited period of a few decades dictated by the finite response time of the climate system.

Figure 8 shows a sketch of some of the various information streams and resulting activities, starting from the information produced by climate scientists and disseminated via the IPCC , which is then further communicated (and frequently distorted) via intermediate actors, before being translated, after time-consuming negotiations, into climate policy. This enables, finally, the technological investments leading to the abatement of emissions and reduced global warming.

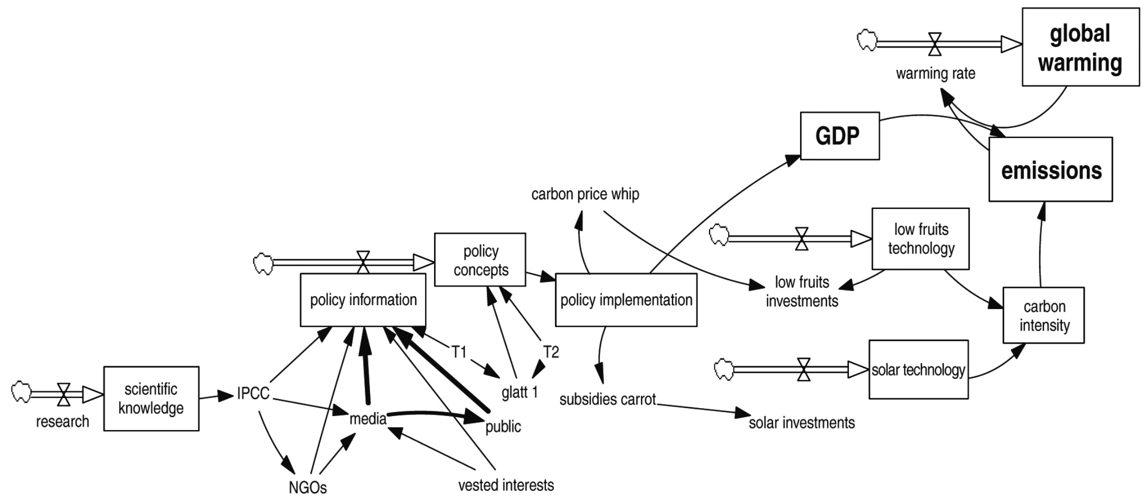

Figure 8. A sketch of the chain of information flow and actors engaged in transforming scientific climate-change knowledge into climate policy, stimulating investments in mitigation technologies that lead, finally, to reduced global warming. Hour-glasses denote integration steps, with associated time delays. (The sketch was produced using Vensim (2003) software tools for system-dynamic simulations.)

To incorporate the additional actors and information-transfer processes in the new member of the model family, while still retaining a dynamically easily interpretable model, the nonlinear-impulse-response climate module NICCS of MADIAM was reduced from a system of five to two coupled first-order equations (reproducing the two principal integration stages of the climate system involved in transforming $CO_2$ emissions into concentrations, and $CO_2$ concentrations into global mean temperature). At the same time, however, to capture the time delays in the chain extending from the transfer of scientific information to the implementation of climate policies to the final impact of investments in renewable technologies, a distinction between shorter-term and longer-term investment options was introduced into the economic module. Shorter-term investments apply to "low fruits" renewable technologies such as wind power which are already close to becoming competitive with fossil fuels and can be brought into the market through the imposition of an acceptable carbon price ("whip" policy). Longer-term investments apply to currently more expensive, but potentially unlimited renewable technologies, such as large-scale solar power (say in North Africa), which can be developed and become competitive in the longer term only through the provision of subsidies ("carrot" policy). To avoid dangerous climate change, widely defined as a global warming of $2^0$C relative to the pre-industrial level, both short-term investments in low-fruits technologies and longer-term investments in large scale alternative energy projects are required.

Figure 9 illustrates the transfer of information from the scientific community to policy-makers in the first steps of climate-policy formation, while Figure 10 contrasts the global warming finally resulting for the example of a successful climate policy against the Business-as-Usual case. Essential for keeping global warming below $2^0$C in this case is the long-term investment in large-scale solar technology, which ensures a stable energy supply and a continual reduction in emissions after the low-fruits technologies have attained their maximal saturation level. The relatively small reduction in GDP growth resulting from the climate change mitigation efforts is consistent with the MADIAM predictions shown in Figure 4.

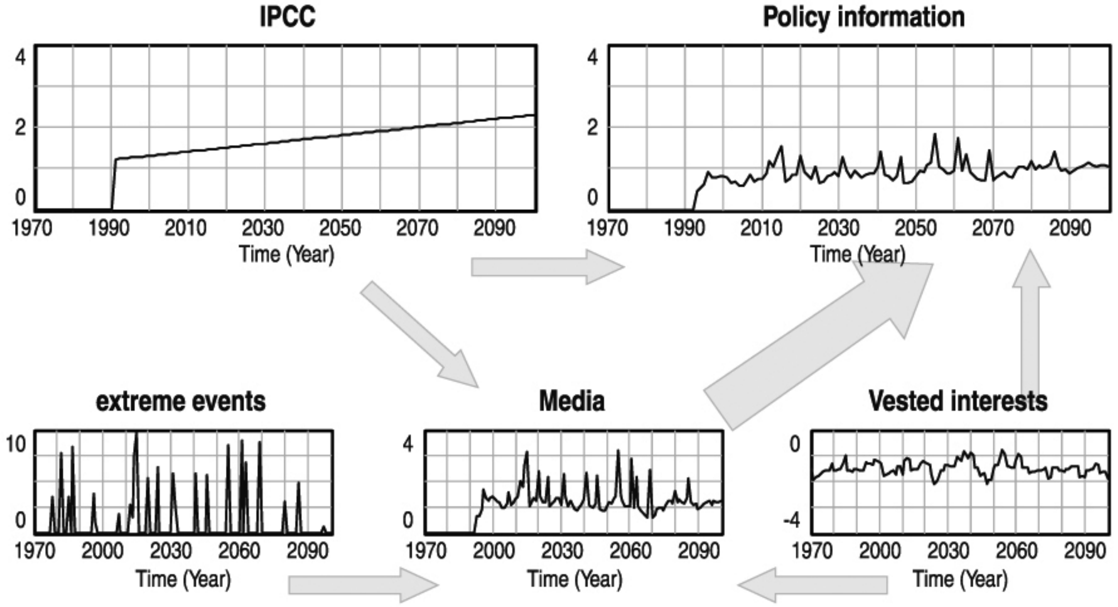

Figure 9. Transfer of scientific information from IPCC to policy-makers via the media, with superimposed noise generated through over-interpretation of extreme weather events and disinformation through vested interests.

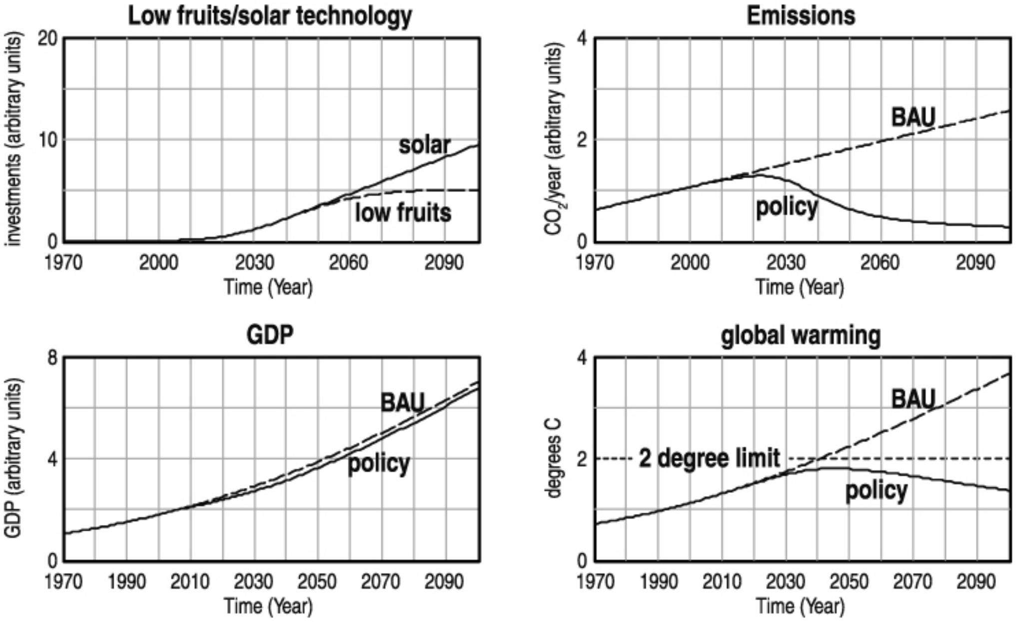

Figure 10. Comparison of the evolution of emissions (top panel, right), global mean temperature (bottom panel, right) and GDP (bottom panel, left) for the cases "BAU" (Business-as-Usual) and "policy" (successful climate mitigation). Investments in large-scale solar technology continue after investments in wind energy and other "low-fruits" technologies have reached their natural saturation level (top panel, left).

## Structural sensitivity

To what extent are the simulation results from the three different members of the model family briefly summarized above mutually consistent? Can one extract from the set of simulations a realistic integrated picture? And will the conclusions remain valid if the model family is extended, as indicated above, to further important issues, such as competition and conflicts of interest between different regions?

A rigorous test of the structural sensitivity of model families can be applied, of course, only to the specific set of models of a given family. However, the extrapolation of the lessons learnt from the three model examples discussed above to further aspects of climate policy is clearly a tempting exercise. We shall therefore attempt to address the question of structural sensitivity in a sufficiently general manner to permit some level of extrapolation.

Common to all simulations considered was the critical dependence on the assumed strategies of the actors. The actor strategies, in turn, were determined by the actor perceptions. Thus, the central conclusion, for example, that dangerous climate change can be avoided at a relatively minor cost of the order of 1% of GDP was based in all simulations on the assumption that firms have confidence in the long-term continuity of climate policies, that the governments that define the policies have confidence in the long-term public support for the policies, and that the public acceptance of the need to decarbonize the economic system is similarly stable. In addition, the conclusions were based on a number of technical assumptions shared by the firms regarding the rate of cost reduction through economies of scale and "learning-by-doing". The last two simulation examples demonstrated, furthermore, that a successful transformation of the present global socio-economic to a sustainable system requires an effective regulation of the global financial system that guides the transformation process, and that climate policies must be matched to fiscal and monetary policies on the basis of a common understanding of the dynamics and associated time lags of the actor strategies. These general assumptions regarding actor strategies permeate all three simulation examples. The introduction of new processes with the neglect or simplification of other processes in switching from one model realization to the next merely modified rather than changed the basic conclusions of the individual model simulations. Thus we conclude that the model family considered was structurally stable with respect to the actor strategies assumed.

However, it has not yet been investigated how modifications in the model structure by adding or removing whole variables or processes, say, to account for limited natural resources, will impact the overall results of the simulations. These problems of structural stability and sensitivity (Arnold, 2008) are difficult to test but are ultimately essential for understanding the full system.

Even if we focus mainly on actor strategies, how realistic are our assumptions? They can presumably be justified for the major economies of Europe. However, they are already questionable for some of the eastern European economies, and clearly do not reflect the current perspectives of policy-makers in the USA, China, India and other emerging or developing economies, - as demonstrated by the recent climate conferences in Copenhagen and Cancun. The observed or anticipated actions of policy-makers, in turn, determine the strategies of firms, households and other actors. At the same time, the perceptions (and interests) of firms, the public, etc. feed back on the actions of policy-makers. Thus, for a more realistic multi-regional model of the actor-dependent response of humankind to the climate-change challenge, the model family presented above would need to be generalized to describe the interaction between several regions governed by different sets of actors characterized by quite different perceptions and goals.

Assuming that the model family has then been suitably extended as indicated, and accepting the viewpoint that climate change mitigation is urgent, feasible and potentially beneficial for all, we return to our initial question: how can actor-based models contribute towards a common understanding of the climate-change problem as a win-win opportunity? Why are the conclusions that climate mitigation is perfectly affordable not widely accepted universal knowledge, although it has long been pointed out by Azur and Schneider (2002), Weber et al (2005), and many others, including, most forcibly, Stern (2007)?

Rather than seeking an explanation in the disinformation strategies of special-interest groups (although these are certainly non-negligible, cf. for example, Hoggan, 2009, Dunlap and McCright, 2010, regarding their impact in the US legislature), we argue that the lack of a widespread global commitment to climate change mitigation can be attributed to a large part to the adherence to standard economic monetary variables , in particular to GDP, rather than considering more general measures of human well-being. It has been shown in numerous studies that GDP is quite divorced from real human well-being and life quality (Costanza, et al., 2009; Berik and Gaddis, 2011). Some of the more obvious reasons are that GDP does not differentiate between ‘good’ and ‘bad’ spending. Natural and human made disasters (since they require mitigation efforts to rebuild and clean-up), disease and epidemics (since they require additional medical services), all sorts of wars and warfare (since they require new armament and ammunition, as well rebuilding after destruction) – all these are assessed as positive economic factors from the viewpoint of GDP, because they boost economic activity and GDP. Some economists have already announced expectations that the recent earthquake, tsunami and nuclear meltdown in Japan may pull Japan out of their current economic stagnation, which is viewed as a positive economic development.

The importance of considering non-monetary variables in assessing the many factors contributing to "human happiness", including the value of the environment, has been repeatedly emphasized in the recent socio-economic literature, but has yet to find general recognition in integrated assessments of climate-change policies. One of the problems in considering non-monetary variables is that they are strongly subjective: different individuals value different issues differently. Thus, it is difficult to define universally acceptable aggregate variables in assessing the social relevance of economic performance. However, it is precisely this property that marks non-monetary variables as ideal parameters for describing the social performance of a multi-actor system, in which each actor has different values and pursues different goals. Thus, firms will tend to judge general economic performance in terms of profits and growth expectations, households will assign more weight to a combination of income and job security, democratic governments will strive to satisfy the aspirations of a given electorate, while authoritarian governments will focus more on other power-preserving factors. In addition, all actors will presumably mix some level of concern for the future climate of the planet in their particular portfolio of socio-economic evaluators. To change perceptions leading to a re-evaluation of climate change and a stronger support for climate mitigation policies, it is important that the existing value scales of the individual actors (which, as pointed out, will generally be very different in different countries) are understood and properly addressed.

The shortcomings of assessing climate policies in monetary terms alone are particularly visible in the standard cost-benefit approach. The estimated costs of greenhouse house gas abatement measures can be readily expressed in monetary terms (cf. Figures 4, bottom panels, Figure 7, left panel and Figure 10, bottom left panel, or McKinsey, 2009). However, the benefits of avoiding dangerous climate change are largely non-monetary. They concern impacts such as the loss of arable land, population displacements and migration pressures, with an accompanying increase in the potential for regional and larger-scale conflicts, as well as general questions of equity arising from the distinction between the principal per-capita emitters of greenhouse gases, in the developed countries, and people in the less-developed countries, who will be most strongly affected by climate change,. All of these issues, in turn, are strongly coupled to other major global problems as summarized, for example, in the UN Millennium Development Goals.

## The Human Value of Production (HVP)

To present a more balanced picture, the results of the previous sections, which focused only on the monetary costs of emission abatement, would need to be translated into a more general assessment of both costs and benefits using, instead of GDP, a non-monetary variable HVP (Human Value of Production) as a measure of the global human value of economic production. Note that the "D" of GDP does not appear in HVP, as the value of the domestic production affects (through the global climate, but also via trade and other externalities) the world as a whole, not just the country c in which the production occurs (which can be indicated, where appropriate, by a subscript: $HVP_c$, otherwise HVP in the following refers to the global production).

There are several alternatives to GDP that have been proposed and are already implemented for local and regional assessments. They share the common idea of going beyond just the monetary evaluation and incorporating social and environmental factors into the analysis (Stiglitz et al., 2008). One of the most promising indicators is the ISEW (Index of Sustainable Economic Welfare), later revised and re- named the Genuine Progress Indicator (GPI), (Daly and Cobb, 1989). It has been shown that, in contrast to GDP, which continues to grow, GPI has stagnated after about 1974 (Talberth et al. 2007). We will use HVP as general name for such aggregated indices.

As emphasized above, although referring to the globe as a whole, HVP is dependent on individual actor values. Thus different actors in different countries may offer strongly differing estimates of HVP. The assessments are also strongly dependent on actor perceptions. The value of HVP can therefore change abruptly, without any change in real physical-goods production. An example is the publication of the Third Assessment Report of IPCC (2001), which strengthened the earlier conclusion of the Second Assessment Report (IPCC, 1996) that "The balance of evidence suggests a discernible human influence on climate change". The result was a sudden decrease of the estimated HVP of the Business-as-Usual path for all actors who accepted the scientific finding, while the so-called "denialists" continued to adhere to the old BAU curve, in which GDP was simply equated with HVP (cf. Figure 11). (A similar actor-dependent perception effect occurred also in the financial crisis, when prices collapsed without any change in the physical nature of the assets affected.).

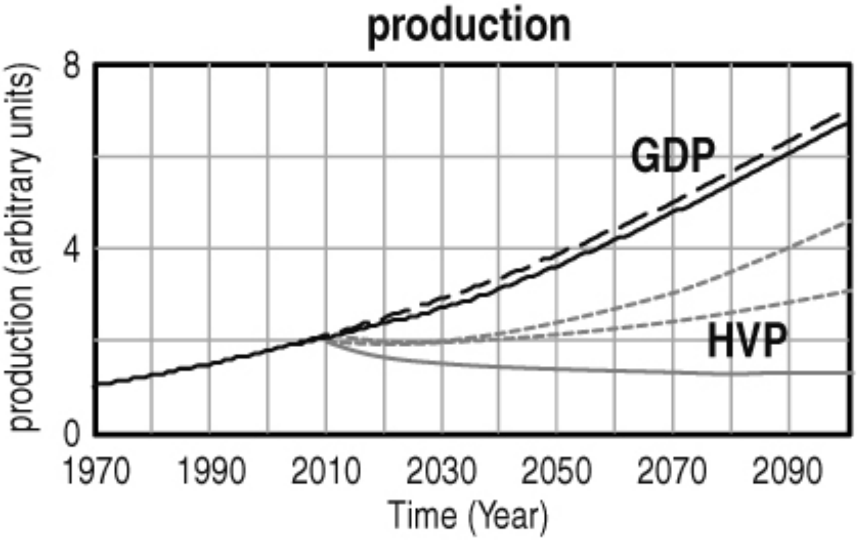

Figure 11. Impact of IPCC 3rd Asssessment Report (IPCC, 2001) on assessment of Human Value of Production for Business as Usual path (lower three curves, dependent on individual actors' Human Value factors). The BAU GDP curve (dashed) is unaffected by the climate change information. The full GDP curve shows the small decrease in conventional GDP resulting from climate mitigation policies (cf. Figure 10, lower left panel). The more relevant assessment of the impact of climate mitigation, however, is the raising of the HVP curves to the higher level of the full GDP curve though the removal of the negative climate change impacts. This is a far greater gain than implied by a comparison of the GDP curves.

Our qualitative sketch illustrates that while climate mitigation and adaptation is likely to reduce the conventional GDP growth (even though by a mere 1% or so), the HVP indices, which became strongly depressed through the scientific evaluation of the real impacts of climate change, show a far higher potential for improvement through appropriate climate policies. A quantitative analysis (which was not carried out in this illustrative example) would need to specify the factors that enter in the definition of the HVP measure used, and how the assumed mitigation policies would affect these factors. Thus one would need to quantify in terms of HVP, for example, how the transformation of the fossil fuel economy into a hi-tech economy based on renewable energy sources would not only save the environment from degradation, but also create social benefits through new opportunities, jobs, and technology transfer. Even more importantly, one would need to quantify the impact on

HVP achieved by shifting values and priorities towards lower consumption and less dependence on materialistic satisfaction, thereby contributing significantly to the stocks of natural and human capital in the system.

However, differences in the HVP value assigned to the BAU trajectory by different actors depend not only on the acceptance or rejection of the scientific findings of climate change and the impacts of future climate change on human wellbeing, but also on the weight attached to climate change impacts in relation to other concerns. Thus, in developed countries with high living standards, avoiding dangerous climate change is (or could be expected to be) at the top of the political agenda, while in emerging or less developed countries concern for the life of future generations must compete with the elimination of extreme poverty and hunger for the present generation. At the same time, economic development alone is not a sufficient prerequisite for adequate climate policy, as is demonstrated by the current inability of the USA to commit to meaningful decarbonization measures. Other necessary conditions are a sound scientific tradition, social equity and high levels of public education.. Independent of these considerations, however, to change perceptions and motivate climate policies, it is clearly more effective to emphasize the major win-win opportunities inherent in the large increase in the HVP values of the climate-policy path relative to the BAU path than to refer only to the minor decrease in GDP relative to the BAU path - although both considerations are, of course, relevant.

Among the many win-win options (see, for example, the Road Map of the European Commission, 2011), the following lists some of the more obvious opportunities that can be pursued - all of which depend strongly on actor initiatives, either on governmental, business, civil society or individual levels.:

- The general increase in employment associated with the introduction of renewable energy technologies (cf. Jaeger, 2010, and Chapter 4 for the case of Europe). This is an interesting example of the implicit acceptance by the public and policy-makers of HVP rather than GDP as a measure of economic progress. Although frequently cited by politicians as a success attributed to government supported green investment policies, an increase in the employment level does not necessarily imply an increase in GDP, but can result simply from the switch from a more efficient to a less efficient technology to produce the same output. It is invariably treated, however, as an unquestionably positive factor, independent of its relation to GDP. This is because the social implications of increased employment are valued higher than the production process as such.

- Specifically, investments in concentrated solar power (CSP) technology, an essentially unlimited source of renewable energy in the low-latitude regions, can open up major new markets. For example, the planned Desertec project (http://www.desertec.org/ ) for North Africa would provide not only a major boost to the economy of the region, but would also provide stable income through energy exports to Europe, thereby removing the present dependence of Europe and many North African states on oil. This is a good example of progressive business initiatives which should stimulate stronger government support. Similar arguments can be made for many desert, often low-income, regions in other parts of the world. Which actors in the system need to make what decisions to promote this kind of investments?

- The efficient use of renewable energy in the form of solar or wind power requires a redesign of the existing power grids in the form of "SuperSmart" grids (http://www.supersmartgrid.net/) extending over much larger areas in order to smooth out regional fluctuations in energy production. The backbone of the system would consist of a High Voltage Direct Current (HVDC) grid that can transmit energy over long distances at very small loss. The energy is then further distributed via local "smart" grids that can switch on power to individual users dependent on parameters governed by the instantaneous price and demand for power. The installation and operation of such grids would greatly enhance the level of international cooperation and interdependence, an important factor in overcoming the present competition mentality hindering progress in climate negotiations. This - as the following examples - is again an illustration of the opportunities opened by advanced technology, and pursued by progressive sectors of the business and public community, that call for stronger governmental support. A smart grid involves a hierarchy of actors (from residential users to local municipalities, cooperatives and to regional and international networks) where actors' decisions have to be coordinated and synchronized.

- In addition to the smoothing of variable wind and solar power through larger grids, energy storage facilities in the form of hydraulic reservoirs, thermal storage, or the exploitation of the high potential of electrical vehicles as back-up storage capacity, are important areas of future investment. Developing better electrical energy storage facilities (batteries, condensers, etc.) for electro-mobility or on-site home storage can be yet another avenue. Huge investments in improved batteries are already happening. (see, for example, the recent news stories: http://www.chicagotribune.com/news/local/chi-ap-us-batteryresearch-c,0,6893182.story; http://news.yahoo.com/s/nm/20110302/tc_nm/us_usa_defense_energy_1)

- Although the UN Millennium Development Goals do not include climate as a specific topic, the transfer of technological know how and capital from developed to emerging and less developed countries to combat global warming would not only be one of the most efficient forms of investment for this purpose, it would also contribute to most of the millennium goals. Moreover, it is morally mandated by the high per capita emissions of the developed countries relative to the rest of the world. To ignore this equity issue carries a high potential for future conflict as the adverse affects of climate change become more evident with increased global warming. . It is encouraging that the recent creation by the UN Secretary-General Ban Ki-Moon of the Global Sustainability Panel consisting of 21 leading representatives of countries world wide explicitly recognizes the strong interdependency of climate change and global welfare (IGBP, 2011).

- In this context, sharing patents for advanced renewable energy production and efficiency is essential. Access to such technology can enable developing countries to significantly reduce their climate footprint, while at the same time contributing to poverty alleviation and food security world wide. It is not always realized that for some time patents have become a barrier for technological and scientific progress, rather than a booster, as originally conceived. The tremendous success in the open source software production is an impressive example of what can be achieved if patent hindrances are abolished.

- Since actors make decisions strongly dependent on their individual perceptions, communication of knowledge becomes paramount. Science should not shy away from active participation in media campaigns, aggressively delivering the findings in unambiguous ways that can be more easily understood and accepted by the public. The fact that much of climate related findings are 'inconvenient' within the prevailing consumerist paradigm calls for more efforts spent on changing these dominant value sets towards a less materialistic centered world view.

- Finally, as pointed out, our simulations underline that the commitment of governments to long-term climate policy depends on public support, while the willingness of firms to invest in renewable energy depends on long-term climate policy. With the growing evidence of the adverse consequences of climate change, these inter-dependent commitments of governments, firms and the public can be expected to become stronger. The greening of the economy will accelerate, and actors that anticipate the trend will have a head start. One can therefore expect a positive feedback as more and more actors recognize the win-win opportunities of climate mitigation policies.

Ultimately, the rate at which the transition to a sustainable low-carbon economy can be achieved depends on the willingness and ability of the actors involved to recognize and grasp the innumerable win-win opportunities that the transformation process offers. Scientists clearly cannot substitute for economic actors. However, scientists can assist in the recognition process by developing models that simulate the different roles and strategies of the economic actors involved. To achieve a successful green transformation, cooperation between actors is an urgent necessity. Cooperation can be built only on trust. But trust can develop only by recognizing and accepting the different perspective of different actors. Actor-based models can contribute to an improved joint understanding of these perspectives, and thereby to a greater level of trust and cooperation. .

## References

Arnold, V.I. (2008). Geometrical Methods in the Theory of Ordinary Differential Equations. Springer-Verlag, New York. 368p

G.A. Akerlof, G.A. and R.J. Shiller. (2009). *Animal Spirits. How Human Psychology Drives the Economy and Why it Matters*. Princeton U. P., Princenton.

Azar, C. and S.H. Schneider (2002) Are the economic costs of stabilising the atmosphere prohibitive? Ecological Economics, vol. 42, pp73– 80.

Beinhocker, E. (2006). *The Origin of Wealth,* Harvard Business School Press.

Berik, G. and E.Gaddis (2011). Genuine Progress Report Indicator (GPI). Progress Report for Utah, http://www.utahpop.org/gpi.html

Brown, P.G., (1997). 'Stewardship of climate; an editorial comment', *Climatic Change* vol. 37, pp329– 334.

Costanza, R., M. Hart, S. Posner, and J. Talberth (2009). *Beyond GDP: The Need for New Measures of Progress*. Boston. www.bu.edu/pardee.

Daly, H. E. and J. B. Cobb, Jr. (1989). *For the Common Good: Redirecting the Economy Toward Community, the Environment, and a Sustainable Future.* Beacon Press, Boston.

Dunlap, R.E. and McCright, A. M. (2010). 'Climate change denial: sources, actors and strategies', in C. Lever-Tracy (Eds) Handbook of Climate Change and Society, Abington, UK: Routledge, pp240-259.

European Commission (2011). Roadmap for moving to a low-carbon economy in 2050. COM(2011) 112 final. 16 p. http://ec.europa.eu/clima/policies/roadmap/index_en.htm

Farmer, D.J. and D. Foley, (2009). The economy needs agent-based modelling, Nature, vol. 460, pp685-686.

Hansen, J, M Sato, R Ruedy, P Kharecha, A Lacis, R Miller, L Nazarenko, K Lo, and G A Schmidt et al.. 2007. Dangerous human-made interference with climate : a GISS modelE study. *Atmospheric Chemistry and Physics* 7: 2287-2312. www.atmos-chem-phys.net/7/2287/2007/.

Hasselmann, K. (1999). Intertemporal Accounting of Climate Change-harmonizing Economic efficiency and Climate Stewardship. *Climatic Change,* Vol. 41(3-4), pp. 333-350

Hasselmann, K.(2009). What to Do? Does Science have a Role? , Proceedings of Heraeus Seminar on Energy and Climate, A Physics Perspective on Energy Supply and Climate Change Prediction, Mitigation and Adaptation, Bad Honnef, 26 - 29 May, 2008, *The European Physical Journal Special Topics*, vol. 176, pp37-51.

Hasselmann, K.(2010) Application of system dynamics to climate policy assessment, in Progress in Industrial Mathematics at ECMI 2008, eds. Fitt, A.D., J.Norbury, H.Ockendon and E.Wilson, 203-208, Springer.

Hasselmann, K., S. Hasselmann, R. Giering, V. Ocaña, and H. v. Storch (1997). Sensitivity study of optimal CO2 emission paths using a simplified Structural Integrated Assessment Model (SIAM), *Climatic Change,* vol. 37, pp345–386.

Hasselmann, K. and D,V. Kovalevsky (2011). Simulating animal spirits in actor-based environmental models, submitted to Environmental Modeling and Software.

Heal, G., (1997) Discounting and climate change; an editorial comment. *Climatic Change* vol. 37, pp335–343.

Hoggan, J. (with R. Littlemore). (2009). *Climate Cover-Up. The crusade to deny global warming,* Greystone Books, Vancouver BC, Canada.

Hooss, G., R. Voss, K. Hasselmann, E. Maier-Reimer and F. Joos (2001) A nonlinear impulse response model of the coupled carbon cycle-climate system (NICCS), *Climate Dynamics,* vol. 18, pp189-202

IGBP, *Global Change, Planet under Pressure, International Geosphere Biosphere Programme,* 76, January, 2011.

IPCC (1996). *Climate Change 1995: The Science of Climate* Change, Houghton J.T. et al, Cambridge U. P., Cambrigde.

IPCC (2001) Climate Change 2001: The Scientific Basis, Houghton J.T. et al, Cambridge University Press.

IPCC (2007). "IPCC Fourth Assessment Report: Climate Change 2007 (AR4)". Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press. http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml. Retrieved 2011-06-14.

Jaeger, C.C, Paroussos, L, Mangalagiu, D., Kupers, R.,Mandel, A. and Tàbara, J.D., (2011). *A New Growth Path for Europe. Generating Prosperity and Jobs in the Low-Carbon Economy*, ECF Synthesis Report, info@european-climate-forum.net, www.european-climate-forum.net

Jansen, M.A. and E. Ostrom (2006). Empirically based, agent-based models, Ecology and Society, Vol 11(37) http://www.ecologyandsociety.org/vol11/iss2/art37

Leontief, W. (1941). The structure of the American Economy: 1919-1929, Harvard U. P., Cambridge.

McKinsey, Project Catalyst, (2009). Towards a Global Climate Change Agreement. http://unfccc2.meta-fusion.com/kongresse/090601_SB30_Bonn/downl/20090606_Metz.pdf

Meadows D.H., D. H. Meadows, 1979. The Limits to Growth. Macmillan, 209 p.

Meadows, D. H., Meadows, D. L. and Randers, J. (2004). *Limits to Growth: The 30 Year Update,* Chelsea Green Publ. Co, 2004.

Nordhaus, W.D., (1997). Discounting in economics and climate change; an editorial comment. Climatic Change vol. 37, pp315– 328.

Nordhaus, W. D. (2007). 'A Review of the Stern Review on the Economics of Climate'. Journal of Economic Literature vol. 45(3), pp686–702. doi:10.1257/jel.45.3.686

Pahl-Wostl, C., (2005).'Actor-based analysis and modeling approaches', *The Integrated Assessment Journal*, vol. 5, pp97-118.

Stern, N. (2007) *The economics of climate change. The Stern Review.* Cambridge U. P.

Stiglitz, J. E., A. Sen, and J.-P. Fitoussi. (2008). *Report by the Commission on the Measurement of Economic Performance and Social Progress*. http://www.stiglitz-sen-fitoussi.fr/en/index.htm

Taibbi, M., 2011. Why Isn't Wall Street in Jail? Rolling Stone, February 16, 2011,

http://www.rollingstone.com/politics/news/why-isnt-wall-street-in-jail-20110216

Talberth, D. J., C. Cobb, et al. 2007. *The Genuine Progress Indicator 2006: A Tool for Sustainable Development.* Redefining Progress, Oakland, California.

Tesfatsion, L. (2006) Computational modelling and macroeconomics, in D. Colander, *Post Walrasian macroeconomics*, pp175-202, Cambridge U. P.

Tol, R.S.J. and G.Yohe (2006). 'A Review of the Stern Review'. *World Economics,* vol. 7(4), pp233–50.

Vensim Modelling guide (2003). Ventana Systems, Inc.

Voinov A. (2008). Systems Science and Modeling for Ecological Economics. Academic Press, 430p.

Voinov, A. and Farley, J. (2007) Reconciling Sustainability, Systems Theory and Discounting. *Ecological Economics,* Vol. 63, pp104-113.

Weber, M., V. Barth and K. Hasselmann, (2005). A Multi-Actor Dynamic Integrated Assessment Model (MADIAM) of Induced Technological Change and Sustainable Economic Growth, Ecological Economics, Vol. 54, pp306-327.