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Dmitry V. Kovalevsky
Nansen International Environmental and Remote Sensing Centre, Saint Petersburg State University, Nansen Environmental and Remote Sensing Center, dmitry.kovalevsky@niersc.spb.ru

Klaus Hasselmann
Max Planck Institute for Meteorology, Global Climate Forum, klaus.hasselmann@mpimet.mpg.de

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Dmitry V. Kovalevsky[abc], **Klaus Hasselmann**[de]

[a]*Nansen International Environmental and Remote Sensing Centre, 14th Line 7, office 49, Vasilievsky Island, 199034 St. Petersburg, Russia (dmitry.kovalevsky@niersc.spb.ru, d_v_kovalevsky@list.ru)*

[b]*Saint Petersburg State University, Ulyanovskaya 3, 198504 St. Petersburg, Russia*

[c]*Nansen Environmental and Remote Sensing Center, Thormøhlens gate 47, N-5006 Bergen, Norway*

[d]*Max Planck Institute for Meteorology, Bundesstraße 53, 20146 Hamburg, Germany (klaus.hasselmann@mpimet.mpg.de)*

[e]*Global Climate Forum, Neue Promenade 6, 10178 Berlin, Germany*

Abstract: For a comprehensive analysis of climate mitigation policies, Integrated Assessment models (IAMs) of the coupled climate-socioeconomic system are needed. However, while there is general agreement on the physics of the climate system, the dynamics of the socioeconomic system is still the subject of considerable controversy. This has become particularly apparent since the recent global financial crisis. To explore the dynamics of the socio-economic system, a family of socio-economic models is proposed that incorporates the various alternative assumptions regarding the behaviour of the different economic actors that govern the evolution of the socio-economic system. The model family needs to be developed both horizontally, to capture the proposed alternative actor strategies, and vertically, to enable successive layers of model complexity to be introduced, once the lower hierarchy levels have been adequately understood. Examples are the model family MADIAMS (a Multi-Actor Dynamic Integrated Assessment Model System), based on an out-of-equilibrium description of economic dynamics (no market clearing assumption), and an earlier prototype model SDEM (Structural Dynamic Economic Model). Depending on actor behaviour, alternative realizations of the MADIAMS family can yield stable economic growth, business cycles, boom-and-bust events, or pronounced recessions. The present paper extends the original prototype model SDEM to compute the long-term impact of strongly nonlinear climate change in combination with various climate mitigation strategies.

Keywords: climate change; mitigation; carbon tax; economic growth; system dynamics.

1 INTRODUCTION

Integrated Assessment models (IAMs) of the coupled climate–socioeconomic system typically consist of an economic module describing the world economy (either in aggregate form, or sub-divided into a number of regions) and a module describing the global climate (usually reduced to a few dynamic equations). The global economy affects the climate system primarily through greenhouse gas (GHG) emissions, while the feedback from the climate module is usually parametrized by a (temperature-dependent) climate damage function that reduces the (global or regional) output of the economy.

Economic modules of IAMs are typically developed within one of the two dominant paradigms of mainstream economic theory: either the general equilibrium assumption of computable general equilibrium (CGE) models, or neoclassical growth theory based on intertemporal utility maximization. The recent global financial crisis, however, has challenged both of these two cornerstones of traditional economics, calling for the development of new approaches to macroeconomic modelling.

In the present paper, two IAMs (MADIAMS and SDEM) based on an alternative actor-based system-dynamic approach are presented. The models avoid both assumptions of market clearing and inter-temporal utility maximization. Instead, the coupled climate–socioeconomic system is treated as a complex nonlinear dynamic system governed by the strategies of key socio-economic actors. The approach is illustrated in detail for the model SDEM, a prototype of MADIAMS.

Our paper is organized as follows. Sec. 2 provides a brief overview of MADIAMS and MADIAMS-like models. In Sec. 3 the model SDEM is presented, together with some simulation results. Sec. 4 summarizes our conclusions and presents an outlook.

2 The MADIAMS model family

MADIAMS (a Multi-Actor Dynamic Integrated Assessment Model System) is a hierarchical, actor-based, system-dynamic model family of the coupled climate-socioeconomic system (Hasselmann [2010]; Hasselmann and Voinov [2011]; Hasselmann [2013]; Hasselmann and Kovalevsky [2013]). The model family shares with conventional system dynamics models (Forrester [1971]; Meadows et al. [2004]) a description of the social-natural system in the language of nonlinear ordinary differential equations (ODEs). The major innovative feature is a representation of the economic subsystem in terms of a small set of aggregated economic actors (firms, households, banks, governments etc.) pursuing different, often conflicting, goals. As discussed in Hasselmann and Kovalevsky [2013], we avoid the term "representative actor" — a concept that has been questioned by many, even traditional economics, authors (cf. Kirman [1992]; Beinhocker [2006]) — but assume nevertheless that the socioeconomic dynamics can be appropriately described by the strategies of few aggregated actors, similar to the phenomenological representation of non-equilibrium thermodynamics, which is often a good approximation to the more rigorous microphysical models of statistical physics. We use also the term "actor-based model" to distinguish our model from more conventional "agent-based models" (ABM) with a large number of individual agents (cf. Farmer and Foley [2009]; Filatova et al. [2011]; Wolf et al. [2013]) which are more analagous to the detailed multi-component models of statistical physics.

The decision-making process is formalized in terms of dynamic rules defining the actor control strategies. The actor-based system-dynamics approach yields a rich variety of macroeconomic dynamic evolution paths, including stable growth, business cycles, boom-and-bust events, and pronounced recessions – even for a simple two-actor prototype model hierarchy as reported in Kovalevsky and Hasselmann [2014]. More detailed model examples are given in Hasselmann and Kovalevsky [2013].

The first version of MADIAMS (reported in Weber et al. [2005] under the acronym MADIAM — a Multi-Actor Dynamic Integrated Assessment Model) was a global model calibrated against a set of macroeconomic stylized facts. Projections of the coupled climate-socioeconomic system dynamics were generated by numeric integration of systems of ODEs (currently performed in Vensim ® DSS software). The model NICCS developed in Hooss et al. [2001] was used as climate module. Demographic projections and estimates of fossil fuel reserves were exogenous, while technical change and climate projections were endogenous.

A newer version of the economic module of MADIAMS based on an out-of-equilibrium description of macroeconomic dynamics without the standard market-clearing assumption has been developed by Hasselmann and Kovalevsky [2013].[1] A family of MADIAMS-like models including a more detailed representation of the financial system has recently been applied by Hasselmann [2013] to demonstrate the close connection between the stabilisation of the global financial system and effective climate policies. Examples were given of alternative stabilisation policies that can lead either to major recessions and unemployment or to stable economic growth supported by an accelerated decarbonization of the

[1] The latest version of out-of-equilibrium economic module of MADIAMS can be downloaded from MADIAMS homepage at the Global Climate Forum website: http://www.globalclimateforum.org/index.php?id=madiams.

economy.

A summary of the various versions of MADIAMS/SDEM reported previously is given in Table 1.

In the spirit of the MADIAMS hierarchy, we develop in the next section the original prototype model SDEM (Structural Dynamic Economic Model) further to study the economic impact of possible abrupt/catastrophic climate change.

Table 1. Distinctive features of various versions of MADIAMS/SDEM

	SDEM/ SDIAM[a]	SDEM-2[b]	SDEM-iEMSs[c]	MADIAM[d]	MADIAMS[e]	Out-of-equil. model family[f]	Fin. stab. model family[g]
Climate module	NICCS[h]	No	Adopted from [i] and [j]	NICCS[h]	No	No	Linear
Economic module							
– Modelling framework							
– – System dynamics		+	+	+	+	+	+
– – Dynamic optimization	+						
– Distinction between physical and human capital	–	+	+	–	+	–	–
– Distinction between green and black physical capital	+	–	–	+	–	–	+
– Imbalanced growth simulated	–	+	–	–	+	–	–
– Out-of-equilibrium dynamics	–	–	–	–	+	+	+
– Financial sector represented	–	–	–	–	+	–	+

[a]Barth [2003]. [b]Kovalevsky [2014]. [c]Model presented in the present paper. [d]Weber et al. [2005]. [e]Hasselmann and Kovalevsky [2013]. [f]Kovalevsky and Hasselmann [2014]. [g]Hasselmann [2013]. [h]Hooss et al. [2001]. [i]Kellie-Smith and Cox [2011]. [j]Zickfeld et al. [2004].

3 Assessing abrupt/catastrophic climate change in SDEM

3.1 Model description

The Structural Dynamic Economic Model (SDEM, Barth [2003]) is a climate-economy model that was developed further in MADIAM (Weber et al. [2005]) and later in MADIAMS (Hasselmann and Kovalevsky [2013]). Initially SDEM was applied by Barth in a dynamic optimization mode. However, rather than following the utility maximization procedure typical for most neoclassical economic growth models, we apply SDEM in the present paper in a system-dynamics mode. Problems of abrupt/catastrophic climate/environmental changes have been addressed by other authors within the dynamic optimization paradigm using non-convex models (see, for example, Moles et al. [2004] for the application of a non-convex optimal-growth IAM for the assessment of climate mitigation policies, and Moghayer [2012] for the application of a non-convex optimal-control model to lake management). However, we believe that the system dynamics approach is a more natural language for the description of discontinuities, abrupt changes and irreversibilities. The following summary of SDEM follows Kovalevsky [2014], but with a number of changes.

SDEM is a model of a closed economy (for example, the aggregate world economy). The population is divided into two social classes: entrepreneurs and wage-earners, described by two aggregated actors. In the present version, we assume full employment. Consumption consists of two components: wage-earners, who consume everything they earn (i.e. consumption is equal to wages), and entrepreneurs, who also consume everything they earn, in this case the dividend on their capital.

The output of the economy depends on two primary production factors: physical capital and human capital. However, in contrast to standard economic growth models, the two forms of capital are assumed to be non-substitutable, the production function corresponding in the general case to the Leontief form (Leontief [1941]). In the present paper, we consider the particular case of balanced growth, in which the amount of physical capital perfectly matches the amount of human capital required to assure that there exists neither idle physical capital nor unemployment.

Entrepreneurs own the output (corrected for climate damage, dependent on global mean temperature T), from which they first have to make a payment of wages to wage-earners and carbon tax to the government. The latter is fully recirculated in the economy in the form of subsidies for carbon emission and energy efficiency improvement. Entrepreneurs are then free to choose the way in which they distribute the remainder between their dividend and investments in physical and human capital. In the present paper, we assume the simplest control strategy of entrepreneurs by setting the dividend as a constant fraction of output, after subtraction of wages and carbon tax. The investment, as remainder, is then distributed in the two investment streams in the required ratio to ensure balanced growth.

The socio-economic features of the model version applied in the present paper are strongly simplified relative to various alternative versions of the MADIAMS model family discussed in the papers cited above. These consider, for example, the impact of unemployment and idle capital, savings by workers, non-cleared markets, instabilities leading to business cycles or boom-and-bust events, and the role of the financial system. Since our focus in the present paper, however, is on the impact of a carbon tax in dependence on the climate damage function, we have ignored for illustrative purposes these additional factors, as important as they would be for a more detailed quantitative investigation.

The capital dynamics equations of the present model version take the conventional form. The wage dynamic equation represents a model of the wage negotiation process between trade unions and entrepreneurs. This is assumed to result in wages that adjust, at a given relaxation rate, to a constant fraction of a changing target wage rate that depends on the current state of the economy. The target wage rate represents the hypothetical wage rate in an imaginary state of the economy that corresponds – from the wage-earners perspective, – to an “ideal” state for a given level of output (after correction for climate damage). The imaginary “ideal” state of the economy is characterized by the following properties: (i) physical and human capital is maintained at a constant level; (ii) nothing is spent on dividend; (iii) nothing is spent on carbon tax; (iv) the economy is in a stationary balanced state; (v) the imaginary balance is maintained at the current real level of (climate-damage-corrected) output.

The dynamic equations of the normal economy are augmented by further dynamic equations for endogenous carbon emission reduction, enhanced renewable energy production and improved energy efficiency. The mitigation measures are promoted by a combination of carbon tax and the recirculation of the tax revenues into the economy for climate-related technological improvements.

The current version of SDEM is a single-region model describing the world economy in aggregate. However, a more detailed multi-region member of the model family MADIAMS is under development in the framework of the on-going project EU FP7 COMPLEX.

The climate module is adopted from Kellie-Smith and Cox [2011] and consists of dynamic equations for CO_2 concentration and global mean surface air temperature T. For some simulations (see Fig. 3) a box model of the Atlantic thermohaline circulation (THC) developed in Zickfeld et al. [2004] is linked to this simple climate module.

All monetary variables are presented in constant 2000 USD.

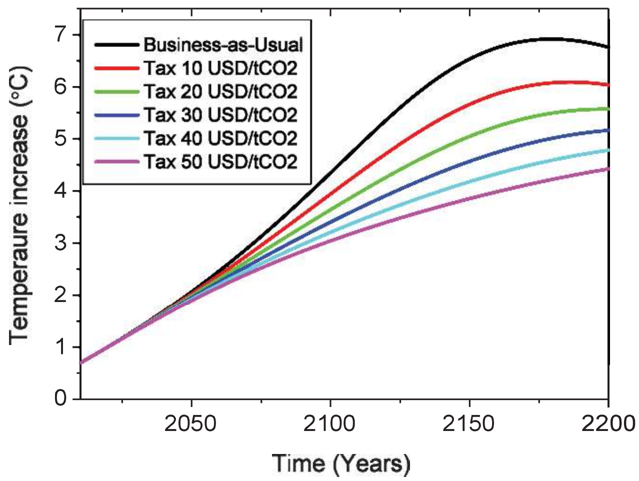

Figure 1. Global mean surface air temperature increase above pre-industrial level projected by SDEM for a business-as-usual scenario and five alternative mitigation scenarios assuming different global carbon tax rates.

3.2 Simulation results

It is well known that projections generated by IAMs are generally very sensitive to the specification of the climate damage function(-s). SDEM is no exception in this respect. We have performed simulations with SDEM for a business-as-usual (BaU) scenario (no mitigation policies) and for five alternative global carbon tax rates (10, 20, 30, 40, and 50 USD/tCO_2), assuming two alternative specifications of the climate damage function: the quadratic function

$$1 - d_N(T) = \frac{1}{1 + \left(\frac{T}{20.46}\right)^2} \tag{1}$$

proposed by Nordhaus [2008] for DICE model, and widely used later by other authors, and a strongly nonlinear function

$$1 - d_W(T) = \frac{1}{1 + \left(\frac{T}{20.46}\right)^2 + \left(\frac{T}{6.081}\right)^{6.754}} \tag{2}$$

recently proposed by Weitzman [2012]. Both functions produce virtually the same climate damages for moderate temperature increases, while the Weitzman function leads to significantly higher climate damages for high-end temperature scenarios.

The results for the 21st and 22nd centuries computed with the SDEM model using the climate module adopted from Kellie-Smith and Cox [2011] (no Atlantic THC components) are presented in Fig. 1 (global mean temperature) and Fig. 2 (effective GWP, i.e. Gross World Product, reduced through climate damage) for the Weitzman climate damage function (Eq. (2)). Fig. 1 indicates that a global carbon tax is

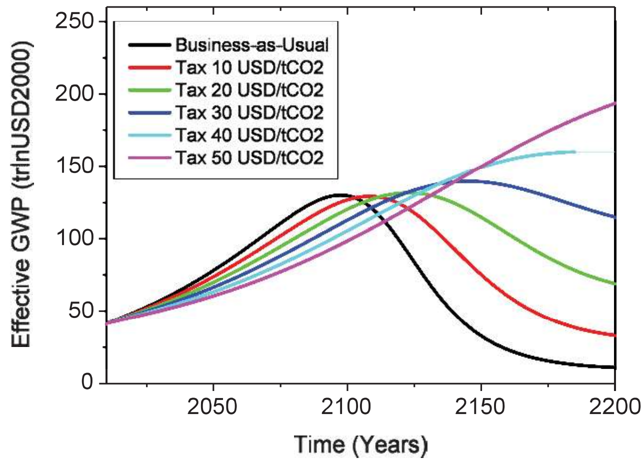

Figure 2. Effective GWP (corrected for climate damage) projected by SDEM for the business-as-usual scenario and five alternative mitigation scenarios with different global carbon tax rates.

a highly efficient instrument for reducing GHG emissions: the long-term temperature increases are significantly lower for higher carbon tax rates. Moreover, Fig. 2 indicates that mitigation scenarios are also economically sustainable in the long term. While the BaU scenario maintains the most rapid economic growth throughout the 21$^{\mathrm{st}}$ century, it ultimately leads to a global economic collapse in the 22$^{\mathrm{nd}}$ century. In contrast, scenarios with stronger mitigation measures provide reduced growth rates in the short- and mid-term, but lead to sustainable economic dynamics in the 22$^{\mathrm{nd}}$ century. However, even the strongest mitigation scenario presented in the figures leads to a 4-degree world — a dangerous but unfortunately quite plausible option of global climate-socioeconomic dynamics broadly discussed in recent publications (Anderson and Bows [2011]; Peters et al. [2013]). To restrain global warming within the 2°C limit accepted internationally as target, significantly higher taxes (or assumptions regarding rapid learning-by-doing of renewable energy technology) will be needed (IPCC [2014]). Such pronounced temperature increases above the pre-industrial level require also consideration of strong non-linearities in the climate model — e.g. in the form of the strongly nonlinear Weitzman climate damage function given by Eq. (2).

Fig. 3 shows the SDEM simulations until the end of the 23$^{\mathrm{rd}}$ century using the climate module supplemented with the Atlantic THC box model developed in Zickfeld et al. [2004]. The overturning, measured in Sverdrups (Sv), is shown for the same six scenarios as before (BaU and five alternative carbon tax rates). We note that no additional climate damages arising from possible abrupt climate change have been introduced into the climate damage function (as considered, e.g. in Mastrandrea and Schneider [2001]). The BaU scenario and the scenario with the lowest carbon tax rate lead to a shutdown of the THC in the long term, while in scenarios with a stronger mitigation action an initial reduction of the THC is later reversed, the THC recovering in the long term.

4 Conclusions

One of the advantages of actor-based system-dynamic models is their flexibility, which allows easy modification of their economic and climate modules. As the current versions of MADIAMS and SDEM do not require substantial computational resources, the model runs being generated almost immediately, a large variety of modifications in the economic module structure and, particularly, in the assumptions about key economic actor behaviour, can be rapidly implemented and tested. Equally important, climate modules of significantly greater complexity than normally applied in mainstream

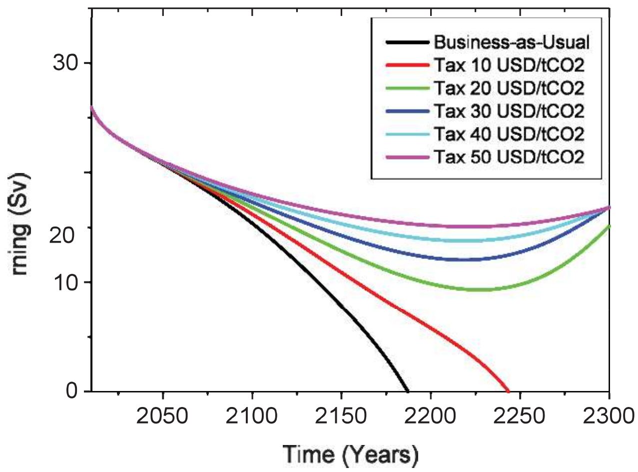

Figure 3. Strength of Atlantic thermohaline overturning circulation, projected by SDEM for the business-as-usual scenario and five alternative mitigation scenarios corresponding to different global carbon tax rates.

utility-maximizing IAMs can be readily linked to actor-based system-dynamic economic models. These advantages suggest that actor-based system-dynamic models can provide new insights into the assessment of climate mitigation policies, with a particular focus on features of real-world climate-socioeconomic dynamics which have been only seldomly addressed, such as strong nonlinearities, thresholds and irreversibilities, including various forms of abrupt climate change.

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